Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change

Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU

Bottom-up Analysis

UPDATED

Final Report (Updated version)
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Preface

On its way to its current form this report has received significant input from a considerable number of experts. In particular, a panel of experts in Brussels discussed a draft version of the report on November 24, 1999 (see Appendix A for a list of names), and made a number of specific and more general comments and suggestions. The author would like to thank these people for their valuable inputs into this study. For this “Final Report” it was attempted to consider their suggestions wherever possible.

This is a revised version of the final report that was posted to the EU website in December 2000. The revisions are to reflect updated 1990 figures from the UNFCCC for waste water treatment. The results presented in this report are consistent with the Summary report on the project.

EXECUTIVE SUMMARY

Greenhouse gases from Waste Management Activities in the European Union were in 1990 some 155Mt of CO_2 equivalent being some almost 4% of all greenhouse gas emissions. These emissions are coming from methane and do not include the emissions from the transportation of waste. While the methane emissions are projected to remain fairly stable with current environmental policies, the waste sector offers much low cost potential to reduce emissions.

Measures to reduce methane emissions from waste can be broadly divided into three categories:

- diversion of biodegradable waste away from landfill and using alternative disposal/treatment methods such as composting or incineration;
- collection and combustion of landfill gas;
- improved oxidation of fugitive landfill gas emissions in the landfill cap.

In this study, baseline trends have been estimated assuming that waste generation per capita, the proportion of waste disposed of to landfill and the landfill gas recovery remains constant. The landfill emissions were estimated using the time dependent IPCC methodology. To provide a 'no action' baseline the effects on methane emissions of the Landfill Directive were not included. The effect of the options to reduce emissions has been calculated assuming that the measures are implement in the order waste diversion, increased landfill gas recovery and increased oxidation in the cap. For waste diversion the implementation is split into reductions required by the Landfill Directive and those required by national policy.

Under the 'no action' baseline, landfill emissions in the EU rise slightly (by 2%) to 6672 kt methane (i.e. 140.1 Mt of CO_2 eq.) by 2010 due to the expected increase in population. The table below summarises the emissions in 1990 and the baseline emissions for 2010[1].

in Mt CO_2 eq.	Emissions 1990	Baseline 2010
Landfills	137,7	140,1
Wastewater handling	15,3	15.3
Waste incineration	0,5	0,5
Other (Waste)	1,5	1,5
Total	155,0	157,4

The total reduction potential taking into account interaction between options is

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[1] The emissions for wastewater handling, waste incineration and other waste have not been estimated, and thus assumed not to change from 1990.

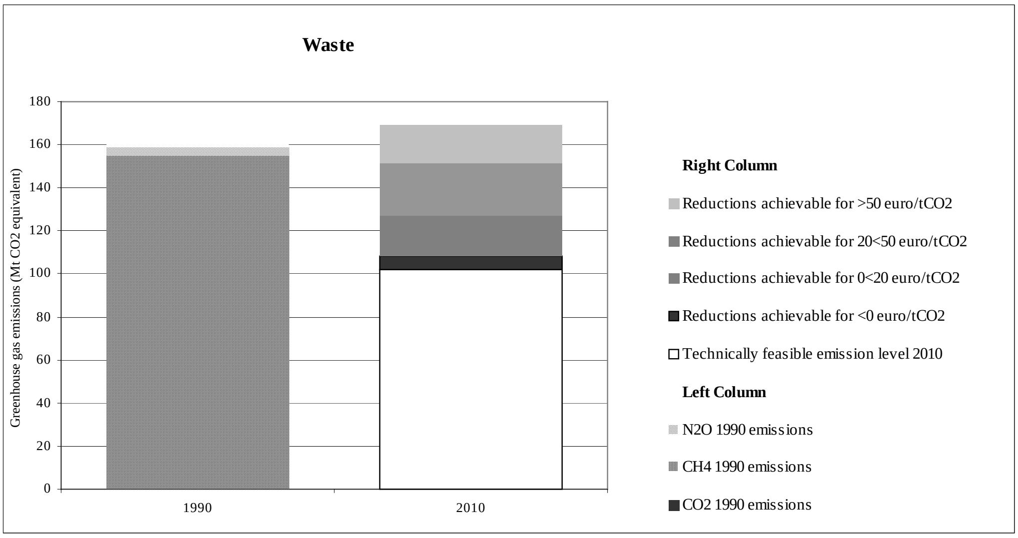
a reduction of 3194 kt methane (67Mt CO_2 equivalent). The exact mix of measures which are likely to be implemented in Member States is difficult to define as most have yet to devise a clear strategy.

Table 1 below gives an estimate of the specific costs of the measures and of the reduction potential for the individual measures (assuming no interactions). These measures are likely to be very dependent on local conditions and can only be estimated very approximately in this type of European level study. There is a greater level of confidence in the overall level of reductions calculated as described above. Figure 1 shows the share in emission reduction categorised in four cost brackets.

Table 1 EU15-average costs and total potential (Mt CO_2 equivalent) for emission reduction of methane options in the waste sector (summary table).

Pollutant	**Measure Name**	**Sector**	**Emission reduction**	**Investment**	**Yearly costs**	**Lifetime**	**Specific abatement costs**
			Mt CO2 eq.	**euro/tCO2 eq.**	**euro/tCO2 eq.**	**year**	**euro/tCO2 eq.**
CH4	Landfill diversion: Paper recycling	Waste	1	391	-70	15	-35
	Landfill: Heat production	Waste	1	20	-17	20	-16
	Landfill: Electricity generation	Waste	5	31	-5	15	-2
	Landfill: Upgrade to SNG (synthetic natural gas)	Waste	0	25	-2	20	0
	Subtotal : Cost range for < 0 euro / t CO2	**Waste**	**7**				
	Landfill: Flaring	Waste	6	5	0	10	1
	Landfill: Increased oxidation	Waste	11	72	0	20	5
	Landfill diversion: Anaerobic digestion (1)	Waste	2	422	-23	15	15
	Subtotal : Cost range for 0 < 20 euro / t CO2	**Waste**	**19**				
	Landfill diversion: Incineration (1)	Waste	23	539	-19	15	29
	Landfill diversion: Composting (1)	Waste	2	330	19	15	49
	Subtotal : Cost range for 20 < 50 euro / t CO2	**Waste**	**24**				
	Landfill diversion: Composting (2)	Waste	1	390	28	15	63
	Landfill diversion: mechanical-biological pretreatment (MBT)	Waste	7	330	49	15	79
	Landfill diversion: Anaerobic digestion (2)	Waste	1	489	49	15	93
	Landfill diversion: Incineration (2)	Waste	10	1223	-11	15	99
	Subtotal : Cost range for > 50 euro / t CO2	**Waste**	**18**				
	Total emission reduction potential		**67**				

Figure 1 Waste sector: 1990 base year direct emissions (left), 2010 frozen technology reference level and reduction potentials per cost bracket (right).



CONTENTS

APPENDIX A PARTICIPANTS AT EXPERTS WORKSHOP

1 INTRODUCTION

The extent to which landfills are currently deployed as a waste management option in Member States varies significantly, but for many it is still a major route for treatment and disposal of solid wastes (Table 1.1). The recent introduction of the Landfill Directive requires the amount of biodegradable waste going to landfill to be reduced, and is thus likely to bring about substantial changes in waste management practices. However, to develop a 'no action' baseline the effect of the Landfill Directive was not included.

Table 1.1 Treatment Routes for Municipal Waste in the EU (percentage to each route).

Country	**Year (1)**	**Total (kt) (2)**	**Landfill (2)**	**Incin-eration**	**Com-posting**	**Recy-cling**	**Other**
Austria	1996/7	2775	32%	16%	13%	32%	8%
Belgium	1996	2893	32%	25%	15%	28%	0%
Denmark	1997	2776	12%	58%	15%	14%	1%
Finland	1994	2100	65%	2%	3%	30%	0%
France	1995	20800	43%	47%	8%	2%	0%
Germany	1993	36976	51%	17%	5%	23%	3%
Greece	1997	3900	92%	0%	0%	8%	0%
Ireland	1995	1550	92%	0%	0%	8%	0%
Italy	1997	26605	94%	6%	0%	0%	0%
Luxembourg	1996	192	25%	26%	2%	47%	0%
Netherlands	1996	8716	20%	31%	25%	17%	7%
Portugal	1997	3800	95%	0%	5%	0%	0%
Spain	1996	15307	79%	5%	16%	1%	0%
Sweden	1994	3200	39%	42%	3%	16%	0%
UK	1996	26000	84%	8%	1%	6%	1%
EU15		**157590**	**64%**	**18%**	**6%**	**10%**	**1%**

(1) Latest year for which data available
(2) Total amount refers to total waste generated; landfill may include residues of some treatments (incineration, landfilling)

Source: OECD, 1999.

2 EMISSIONS

2.1 EMISSION MECHANISMS

In landfills anaerobic methanogenic bacteria break down biodegradable carbon compounds such as cellulose, fats, sugars etc and produce methane. Competing aerobic processes also occur, producing carbon dioxide. The resulting landfill gas which is released from the landfill is a mixture of approximately 60-40% methane and 40-60% carbon dioxide plus minor quantities of a large number of trace components.

The physical heterogeneity in a landfill, the many different types of bacteria involved, the extremely large number of different substrates and the fact that the degradation process may also involve several distinct stages means that the overall process is extremely complex. While the main factor affecting landfill gas generation is waste composition (particularly the amount of biodegradable carbon), methane generation is also influenced by:

- rainfall;
- atmospheric pressure;
- temperature;
- pH in the landfill;
- moisture content of the waste;
- presence of growth promoting and inhibiting compounds;
- oxygen infiltration;
- depth and age of the landfill;
- type of landfill gas collection system, and rate at which landfill gas is extracted;
- type of capping.

Gas production in a landfill can take between 80 and 500 days to reach reasonably steady state conditions, and there is then typically a 10 to 20 year period over which landfill gas production slowly decreases as the more degradable materials are broken down. After this emissions will decline until after about 100 years, approximately 99% of the methane which will be liberated from the site has been released.

In engineered landfill sites, methane may be:

- recovered and combusted to CO_2, either in a flare or in an energy recovery scheme;
- emitted from the landfill, through pipes and vents to the atmosphere;
- oxidised, usually to carbon dioxide, as it passes through aerobic regions near the surface of the waste or in a soil cap of the landfill;
- stored in the landfill (although this is typically a very small proportion of the methane generated).

The potential rate of landfill gas recovery is affected by the structure and properties of the landfill cap and membranes, and the efficiency of the gas collection pipework system. Achieving good gas recovery rates requires that the site be capped adequately on completion. Cellular operation, in which the site is divided into small cells which are filled in turn and capped when they are full, enables emissions to be captured while the site is still operational, and will improve recovery rates further. However even the best recovery system cannot capture all landfill gas that is produced, some will still escape through cracks in the cap or laterally through surrounding strata.

2.2 EMISSION IN EU-15

Methane emissions from landfill in 1990 and 1995 are shown in Table 2.1. These are releases of methane to the atmosphere, i.e. any methane which is collected and burnt in either a flare or engine is excluded from the estimate. These emissions are national estimates as reported by Member States to the UN Framework Convention on Climate Change (UNFCCC), and are made in accordance with agreed guidelines. They should include emissions from both all types of biodegradable waste sent to landfill, i.e. industrial and commercial as well as household waste, and from all types of landfill. However, the exact coverage of each national estimate is unknown.

Table 2.1 Methane Emissions from Landfill (kt).

	1990	**1995**	**Change**
Austria	193	185	-4.1%
Belgium	173	184	6.5%
Denmark	71	72	1.4%
Finland	230	150	-34.8%
France	780	606	-22.2%
Germany	1842	1029	-44%
Greece	102	105	2.8%
Ireland	136	136	0.0%
Italy	302	464	53.6%
Luxembourg	3	2	-27.0%
Netherlands	562	479	-14.8%
Portugal (1)	493	528	7.1%
Spain	471	659	39.8%
Sweden	85	61	-28.2%
United Kingdom (2)	1117	912	-18.3%
EU15	**6560**	**5101**	**-22%**

(1) No 1995 estimate available for Portugal so 1994 data substituted.

(2) UK estimates have recently been updated to 1117kt in 1990 and 912 in 1995.

Source: UNFCCC, 1999.

Between 1990 and 1995 emissions fell by 22% across the EU15 as a whole, although changes vary widely from one country to another. At one extreme, Germany's total methane emission from landfill was 44% less in 1995 than it was in 1990, while at the other, Italy's was 54% greater. While substantial reductions such as those in Finland could be achieved through the introduction of landfill gas recovery, and a reduction in the amount of waste landfilled, the reasons for such large increases are harder to explain[2].

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[2] It is possible that the estimation methodology has changed, and that the 1990 estimate has not

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 (see Section 2.1). 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. It is widely recognised that waste statistics in the EU are not as accurate or as reliable as is needed for effective monitoring of the implementation of Community policy on waste disposal. To improve matters there is currently a draft Council regulation on waste management statistics in the EU which aims to ensure more effective collection of statistics in the future.

There are some methane emissions from other waste disposal activities (wastewater treatment and waste incineration) but these are small compared to emissions from landfills (Table 2.2).

Table 2.2 Methane Emissions from Waste Management Activities in EU 15 in 1990 (kt).

	Emissions	**% of total CH_4 emissions (1)**
Landfills	6560	30%
Wastewater Handling	729	3.4%
Waste Incineration	26	0.1%
Other (Waste)	72	0.3%

(1) Total anthropogenic methane emissions in the EU15 in 1990 were 21 614 kt.

Source: UNFCCC, 1999

3 EMISSION REDUCTION OPTIONS

3.1 INTRODUCTION TO THE MEASURES

Measures to reduce methane emissions from landfills can be broadly divided into three categories:

(i) diversion of biodegradable waste away from landfill

By treating biodegradable waste by other means, rather than disposing of it to landfill, methane emissions from landfilling are avoided. Diversion of biodegradable waste (in municipal solid waste) from landfills in the future is required under the Landfill Directive. Alternative disposal/treatment methods for waste which allow the diversion of biodegradable waste from landfill include:

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been updated.

- composting of biodegradable components of waste;
- anaerobic digestion of biodegradable components of waste;
- bio-mechanical pre-treatment of whole waste;
- incineration of whole waste;
- recycling of paper and cardboard.

These options are discussed below in Sections 3.3 to 3.6, and the cost of each option in Section 3.7. It should be noted that each of these options is likely to find a role in future waste management practices. There are many aspects to consider in deciding on the optimum waste management strategy for any given region (e.g. practicality, transport logistics, existing infrastructure cost, environmental performance), and there are numerous local circumstances which will influence each of these parameters. Thus the ‘best’ option for any particular waste stream may vary at a very local level. This chapter only sets out to evaluate each of the options in terms of its impact on greenhouse gas emissions and is in no way intended to be a comprehensive assessment of waste management options, or to make recommendations as to the most desirable option.

(ii) collection and combustion of landfill gas
The landfill gas produced can be collected and either combusted in a flare, or used as an energy source, e.g. to generate electricity or heat, or by processing it to produce a substitute natural gas. Improved recovery and utilisation of landfill gas are required by the Landfill Directive. These options are discussed in Sections 3.8 to 3.11.

(iii) improved oxidation of fugitive landfill gas emissions in the landfill cap
Landfill gas which is not collected can escape through the cap of the landfill. These fugitive emissions can be reduced by improving the cap of the landfill to encourage greater oxidation of the methane to carbon dioxide. This option is described in Section 3.12.

3.2 COMPOSTING

3.2.1 Description

Composting involves degradation of the biodegradable portion of the waste under aerobic conditions. It can be done in private households (home composting) and in central locations, and as for anaerobic digestion, requires source separation of the waste. Some schemes use only ‘green’ garden waste, others a mixture of garden waste and kitchen waste, and some also include soiled paper.

Home composting has the benefit of eliminating transport costs and transport fuel use, which can be high in the case of garden waste, as it is very bulky.

Home composting is being heavily promoted in some countries (e.g. Italy, Belgium and Finland), and in many areas, compost boxes or bins for home composting are offered to householders at a subsidised price. Not all households will be able to home compost, e.g. those living in flats and houses without gardens, and of those that could technically participate, not all householders may have the necessary motivation. Data on the extent of home composting for some Member States is shown in Table 3.1; unfortunately a complete set of data for the EU is not currently available. When carried out properly, composting is an aerobic process, with carbon in the waste being converted to CO_2 rather than CH_4. If the process is not managed well however, the process can become anaerobic and release CH_4. No monitoring data assessing CO_2 and CH_4 emissions from home composting could be found for this study.

Table 3.1 Home Composting in Member States.

Austria [1]	280 kt in 1994 (estimated) ; 60% of kitchen and green waste)
Denmark [1]	20 kt in 1995; 4% of organic household waste
Ireland [1]	8 pilot projects on home composting started in 1995 involving 800 households
Italy[2]	Participation rates of 10 to 77% achieved in cases where tax savings of 20 to 30% were given in Northern Italy
Luxembourg[1]	29% of households involved in home composting in 1992
Sweden[1]	50 kt of kitchen and green waste home composted (40-95% of households compost garden waste and 10% compost food waste)

Source: [1] DHV Environment and Infrastructure, 1997 and [2] Favoino, 2000.

A wide range of methods are available to compost organic waste centrally, ranging from simple, cheap solutions such as open turned windrow, in which piles of waste are periodically turned over using tractors equipped with mechanical fork, to more complex and expensive large engineered systems. The capacities of plants may vary from 500 to 100,000 tonnes per year. The choice of system depends on many factors, but in general simple systems are appropriate for small volumes of waste in sites that are distant from the public whilst the more complex systems are more successful on large waste arisings and on sites closer to the public. The limitations of the less complex systems are that they require large areas and can emit odours and hence need to be separated from the public but they are significantly cheaper than the more complex alternatives.

Small ***windrow systems*** treat up to 25,000 tonnes per year (although there are a few plants much larger than this) and operate by shredding the waste and placing it in piles 2-3m high. These are then agitated or turned on a regular basis to introduce air and control the temperature of the waste. After composting the compost is matured, screened and sorted to remove contaminants prior to sale. This process can take between 3 and 6 months depending on the nature of the feedstock.

A typical ***tunnel composting*** plant will treat 10-50,000 tonnes per year of mixed compostable waste. The compost remains in the tunnel for between 10-30 days and is turned at least once during this period. Parameters such as temperature, humidity and the O_2 to CO_2 ratio are carefully controlled. After processing, the compost is matured, screened and graded. ***Building or hall*** composting is similar to tunnel composting but the container is a building and the compost is agitated by automatic devices as well as air being blown in to control the process.

Approximately 30-50% of the waste input will be turned into saleable compost; in high quality composting systems typically 10-15% will be reject material, although this may be higher (20 to 25%) in lower quality systems. This may be disposed of to landfill, but will have a minimal methane generation potential, as it is principally plastics and undegraded woody material. The remainder of the original feedstock is 'lost' in the form of moisture, which evaporates, or as CO_2 emissions.

Composting operates only on the degradable portion of the waste, so successful implementation requires separation at source, i.e. the degradable portion of the waste (food/kitchen waste and garden waste) must be collected separately. Many communities across Europe are now collecting organic wastes from households for organic waste treatment, although the coverage of schemes varies significantly between countries. 90% of the Dutch population have access to a scheme but Spain, Portugal, Ireland and Greece have zero or minimal coverage. In the UK approximately 1.5% of households have access to a kerbside collection for kitchen and/or garden waste, which collects about 0.25% (39 kt/a) of the waste stream. However, substantially more garden waste is collected via recycling centres which householders bring their waste to for disposal or recycling and this collection route provides 166 kt/a (1% of the waste stream) to composting schemes (Composting Association, 1997).

The market price for the compost produced varies considerably across the EU, and average market prices may change as production levels increase. In Northern Europe, a small amount of compost will go into high value markets such as retail and horticulture/landscape, where e.g. prices of up to 40 €/t are reported for many plants in Germany, and values of 10-15 €/t in Northern Italy. However as production increases, the main use is likely to be in agricultural where prices are likely to be lower (3 to 7 €/t). In Southern Europe (Southern Italy, and Mediterranean areas of Greece, Portugal and Spain) the price for soil improvers can be much higher (50 to 100 €/t) due to arid conditions and the need for organic matter in soils, particularly where there are intensive, high added value cropping conditions. Current markets for compost in selected EU countries are shown in Table 3.2. Based on this mix of markets, and average prices for landfill restoration of 0 €/t, for agriculture (field crops) and earth works of 5 €/t, and for landscaping, horticulture and private gardens of 40 €/t, then an average sale price is about 25 €/t. In the future, as compost production increased and the very large agricultural market was exploited further, then the average price might drop. The impact of this range in prices for compost and the uncertainty in future prices is discussed further in Section 3.7[3].

Table 3.2 Market Shares for Compost in Selected Countries (in %) 1998.

	Market size	**Austria**	**Belgium**	**Germany**	**Denmark**	**Netherlands**
Landscaping	Large	30	24	33	19	30
Landfill Restoration	Small	5	5	4	13	-
Agriculture	Very big	35 1)	5	21	10	40
Horticulture	Medium	5	6	7	3	
Earth works	Medium	5	33	10	-	
Private gardens	Large	20	18	19	48	20
Export	Very small		9	-	-	-
Miscellaneous			-	6	7	10

1) 60 % of the Austrian VFG and green waste is on-farm-composted

Source: Barth, 2000.

3.2.2 Current practice

Table 3.3 shows the estimated extent of composting (of all types of waste) (DHV Environment and Infrastructure, 1997). The potential production of compost was also estimated in the study, on the basis of the amounts of organic waste that could be collected for composting, and indicates that composting could be expanded considerably. For all countries except Luxembourg, it is estimated that sufficient agricultural land is available to provide a market for the potential amounts of compost which could be produced.

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[3] There was considerable disagreement at the workshop held to discuss this chapter over what a realistic future price for compost used as a soil improver might be.

Table 3.3 Composting in the EU.

Country	**Realised production (kt/yr)**	**Estimated potential production of compost (kt/yr)**
Austria	500	1000
Belgium	160	750
Denmark	250	500
Finland	30	400
France	150	7000
Germany	2000	4500
Greece	0	800
Italy	100	5000
Ireland	0	200
Luxembourg	3	25
The Netherlands	650	750
Portugal	0	600
Spain	0	3500
UK	159	4600
Sweden	100	800
Total	**4102**	**30425**

Source: DHV Environment and Infrastructure, 1997

3.3 ANAEROBIC DIGESTION

3.3.1 Description

This technique involves carrying out a controlled anaerobic decomposition of the waste in a vessel designed to exclude oxygen and in which the temperature, moisture content and pH can be maintained close to their optimum values. The process produces a gas with higher methane content, and therefore a higher calorific value, than that produced in landfills themselves, because of the absence of competing aerobic processes. The gas can be burned to produce heat and/or electricity. The solid residue from the process generally undergoes a ‘curing’ period under aerobic condition to further stabilise organic matter, make it hygienically safe, release excess ammonia and transform residual nitrogen into forms which will be released more slowly from the residue. Provided the residue is free of contamination from toxic substances such as heavy metals it can then be used as a soil improver. A liquor is also produced, which may be used as a liquid fertiliser, or if no use can be found for it must be disposed of as wastewater to sewer. As with composting, the value of these residues as soil improvers is likely to be higher in Southern Europe, where soils may be arid and lack organic matter, than in wetter climates of Northern

Europe[4].

As with composting, AD operates only on the degradable content of the waste. The degradable portion of the waste may either be collected separately, or the whole waste which is collected may be mechanically sorted to separate the biodegradable portion. However contamination levels in mechanically sorted waste mean that in many Member States (e.g. France, Italy, Spain) the solid residue from such AD plant may only be used as a soil improver under controlled conditions, e.g. in land reclamation projects.

AD can be used to treat both the biodegradable component of household waste (kitchen waste, garden waste, paper) and industrial biodegradable waste e.g. from food processing, sewage sludge, and animal manures, and plant can take waste from one or a mixture of sources. The use of anaerobic digestion plant to treat animal manures is discussed in the report on agriculture.

3.3.2 Current practice

Table 3. shows the estimated installed capacity, based on heat generation, of anaerobic digestion plant in EU Member States (ATLAS, 1997). The capacity is shown in megawatts (MW) of heat which can be generated (MW thermal). These figures include anaerobic digestion of animal and agricultural waste, sewage sludge, as well as source separated organic municipal solid waste; a split of capacity by type of material is not available.

3.3.3 Improvements and or alternatives of the option

Anaerobic digestion is a relatively well developed technology and technical advances are unlikely in the near future. More widescale deployment might lead to some reduction in costs.

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[4] There was considerable disagreement at the workshop held to discuss this chapter over what a realistic future price for compost used as a soil improver might be. Similarly some believed, that there would never be a market for the liquor produced from the AD plant in Northern Europe, and that it would always require disposal to sewer.

Table 3.4 Anaerobic digestion capacity in the EU in 1995.

	Heat Generation (MW thermal)
Austria	20
Belgium	negligible
Denmark	40
Ireland	negligible
Finland	not known
France	6
Germany	150
Greece	negligible
Italy	30
Netherlands	10
Norway	negligible
Portugal	6
Spain	15
Sweden	20
UK	10
EU	**307**

Source: Atlas, 1997.

3.4 MECHANICAL BIOLOGICAL TREATMENT

3.4.1 Description

In mechanical-biological pre-treatment (MBT), the whole waste stream is composted with the aim of aerobically degrading the organic fraction before landfilling. Unlike composting it does not produce a useable high quality by-product, and the residue is generally disposed of to landfill. As the residue contains little readily biodegradable content, any further emissions of methane once it is disposed of to landfill are minimised. In many countries, it is possible to use the product (under controlled conditions) for land reclamation and in some countries for application to agricultural land, but at present these are relatively minor routes for disposal of the residue[5].

Techniques are in principal the same as composting, although there are some differences. For example, MBT requires no final refining of the product (unless it is to be used in land reclamation or applied to agricultural soils), retention times may be different, and operating and maintenance costs may be higher due

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[5] To date, most MBT is meant to stabilise waste prior to landfilling, though a huge development in the “dry-stabilate” method (Trockenstabilat) has been lately recorded in Germnay: full description of the system and the way it affects GWP-related issues can be found in: Wiemer K, Kern M. : “Mechanical-Biological treatment of residual wastes based on the dry stabilate method”, Series: “Abfall-Wirtschaft: Neues aus Forschung and Praxis” Witzenhausen, 1995.

to the more aggressive nature of the material being treated.

3.4.2 Current practice

This technology was developed several decades ago but did not achieve widespread application. It is currently being re-assessed in a number of countries, as a way of meeting the commitments of the Landfill Directive. In Germany about 2 Mt/y are treated this way in 30 plants (Soyez *et al*, 1997). MBT is also being developed in Spain, Austria and Italy.

3.5 INCINERATION

3.5.1 Description

The most common type of incinerator currently in use is the mass burn incinerator in which the waste burns on a moving grate. Fluidised bed incinerators are being developed and should be more efficient.

Incineration treats the whole waste stream and does not require waste separation at source. Incinerators produce inert bottom ash which is generally landfilled, although it can be recycled in e.g. road coverings. Ferrous metal is separated from the bottom ash using a magnetic separator and can be sold for recycling, although in practice the price may be too low to make this worthwhile. Fly ash and flue gas treatment residues must be disposed of to a suitable landfill site.

Heat can be recovered from the incineration process and used e.g. to supply district heating schemes, or to generate electricity. Most new incinerators have an energy recovery facility, and the proposed Directive on Incineration (98/C 327/07) will require energy to be recovered as far as possible.

Incinerators require a fairly large waste throughput to be economical, and are therefore best suited to locations with high population density, where the necessary waste is available within a relatively small area, thus minimising transport costs.

Other incineration options include the firing in conventional boilers of refuse derived fuel (RDF) made from sorted municipal waste, and PDF, fuel derived from paper and plastics. RDF and PDF may be used as either the sole fuel or co-fired with conventional fossil fuels.

3.5.2 Current practice

Incineration is a common waste treatment option within the EU (Table 3.5), and its use is projected to increase in some Member States (e.g. Netherlands, UK). In others, it is possible it will decrease. For example in Germany, the acceptance of MBT as a method of pretreating waste before it is landfilled, and subsequent increased use of MBT is predicted by some to lead to a decrease in the volume of waste incinerated. Some believe that increasingly more stringent emissions limits and ever tightening regulation regarding air pollution and the composition of the ash, are likely to lead to increased costs in the future, which may limit its use. In Europe the draft incineration directive is the latest item of legislation in this process. Many plants built in the last few years have already anticipated the requirements of this directive.

Table 3.5 Fraction of MSW Incinerated.

Country	**Year**[1]	**% of MSW incinerated**
Austria	1996/7	16%
Belgium	1996	25%
Denmark	1997	58%
Finland	1994	2%
France	1995	47%
Greece	1993	17%
Germany	1997	0%
Ireland	1995	0%
Luxembourg	1997	6%
Italy	1996	26%
Netherlands	1996	31%
Portugal	1997	0%
Spain	1996	5%
Sweden	1994	42%
UK	1996	8%
EU15		**18%**

[1] Data is for latest year available.

Source: OECD, 1999.

3.5.3 Improvements and or alternatives of the option

Two advanced conversion thermal conversion technologies are under development: gasification and pyrolysis. In gasification plant, the waste is converted into a gas with a relatively low heat content (10 to 25% that of natural gas) by partially oxidising it, with air or oxygen, under the application of heat. After cleaning to remove tars and particulates the gas can be used as a fuel in boilers, internal combustion engines or gas turbines to produce heat and/or electricity. In pyrolysis plant, the waste is broken down thermally (at temperatures of 400-800°C in the complete absence of air to produce gas, liquid and char, which can be used for energy generation.

These advanced technologies tend to need a more homogenous feedstock compared to mass burn systems, and to date the most common feedstock's used in pilot and demonstration plants are sorted municipal waste refuse derived fuel and tyres. Although limited data on emissions is currently available, advanced technologies have emissions of pollutants which are comparable to those from mass burn systems and would meet current and proposed legislative limits (IEA Bioenergy/ IEA CADDET, 1998).

Once these systems are established, they offer the potential for higher levels of energy recovery than conventional mass burn systems, at similar costs (IEA Bioenergy/ IEA CADDET, 1998). They also have the advantage that they are feasible at much lower throughputs, so can be used in more rural areas, where smaller quantities of waste are available within a given area. Some believe they could account for a significant portion of the waste incineration market in the next 10 years (Waste Manager, 1999).

3.6 PAPER RECYCLING

3.6.1 Description

The main recycling option that is relevant is paper recycling i.e. collecting waste paper, de-inking, pulping and producing new paper from the pulp. This is already an established practice within Europe, with recycling levels determined primarily by the cost of pulp from waste paper compared to the cost of virgin pulp. The scope of increasing paper recycling levels depends on a number of factors:

3.6.2 Availability of paper for recycling

Some paper products are too soiled or contaminated for recycling, e.g. dirty wrappings, used tissue products, so not all of the paper in the waste stream can be recycled. Newspapers are one source which can be recycled relatively easily, and while in some Member States, there is considerable recycling of this source already, considerable opportunity still exists in others.

3.6.3 Quality of recycled paper products

Recycled paper cannot replace virgin pulp in many applications because of quality constraints e.g. for fine paper, graphics grades and grades with specific strength requirements. Its maximum market penetration is therefore considerably less than 100%, but further substitution is thought to be possible in several sectors, e.g. wrappings/corrugated case materials.

3.6.4 Price

The amount of paper that gets recycled strongly depends on the price of waste paper for recycling which in turn depends on the market for recycled paper products. The price of waste paper for recycling is determined by market forces and can fluctuate wildly. Increasing the supply of waste paper will depress the price, possibly dramatically if the increase in supply is large. In some Member States, National Agreements between industry and institutions have led to a fixed price for waste paper in order to avoid these fluctuations, e.g. in Italy, the price for comingled waste paper and packaging board have been set at 12 €/t and 60 €/t respectively (Favoino, 2000).

3.6.5 Plant costs

The higher the grade of recycled paper being produced, the more sophisticated will be the plant required to produce the paper and the higher the plant investment costs. For example, a 200 tonne/day de-inking plant producing pulp of an equivalent quality to virgin pulp will have capital costs about 50% higher than one producing pulp suitable for use in corrugated case materials.

3.6.6 Waste disposal

Paper manufacture produces solid waste with a high organic content and methanogenic potential. This takes the form of sludge. The way in which the sludge is disposed of can have a major impact on the methane reduction potential of paper recycling.

3.6.7 Current practice

Table 3. shows the fraction of paper consumption which was collected for recycling in Member States.

Table 3.6 Collection of Paper for Recycling in 1998
(as percentage of paper consumption).

Country	**Collection rate (%)**
Austria	65
Belgium	48
Denmark	52
Finland	63
France	41
Germany	70
Greece	21
Ireland	21
Italy	33
Netherlands	58
Portugal	42
Spain	43
Sweden	64
UK	40
EU	**49**

Note: Luxembourg not included in original source data
Source: CEPI, 1999.

3.6.8 Improvements in paper recycling

No developments in the technology of paper recycling are foreseen in the near future. Improvements in the waste collection infrastructure in some countries may enable a greater utilisation rate to be achieved, but this may be limited by transportation distances in countries with small populations and isolated communities. Agreements to stabilise and guarantee market prices for waste paper, can encourage the development of waste paper collection schemes.

Legislative developments could also have an effect on the amount of paper recycling. For example, market based instruments designed to improve the economic competitiveness of recycled paper products, or requirements for certain products (e.g. packaging material) to either contain a specified proportion of recycled fibre and/or to be recycled at the end of their lives.

3.6.9 Country specific implications

As already discussed current recycling rates vary considerably between Member States. Some have relatively small populations, long transportation distances or other infrastructure problems, which may make increased recycling uneconomic and carry larger CO_2 penalties from increased transport distances for the recycled paper. Social attitudes towards voluntary collection systems also differ from one country to another. The already high recycling rates achieved in some countries suggest that they may be close to the optimum level, and further substantial improvements may by difficult.

3.7 COST OF WASTE DIVERSION OPTIONS

3.7.1 Methodology and common assumptions

This section estimates the costs of each of the waste diversion options discussed above, per tonne of waste treated, and then estimates the reduction in greenhouse gas emissions achieved per tonne of waste treated. These two values are then combined to give the cost-effectiveness in $€_{1990}$/t CO_2-equivalent.

In estimating the cost per tonne of waste treated:

- All costs have been converted to $€_{1990.}$

- A discount rate of 4% has been used to estimate the annualised cost per tonne waste treated; estimates are also given for 2% and 6% to show the sensitivity to discount rate. The use of a 4% discount rate to evaluate the cost-effectiveness of options is common across all sectors examined in the study. It is much lower than the discount rates often used in assessing waste management projects, particularly those in the private sector, and the sensitivity of costs to higher discount rates (up to 25%) is discussed in Section 3.7.7.

- ***Capital/investment costs*** for each plant include (as far as is possible given information in the original source document) all initial costs associated with setting up the plant, including pollution control systems.

- ***Operating costs*** include the energy, labour and maintenance costs associated with operating the plant, the cost of disposing of any residues from the plant, and the income received for products from the plant (compost, heat, power).

- ***Value of compost***: as already discussed there is some divergence of opinion over the potential price that large volumes of compost produced if AD and composting were deployed widely. While some compost produced now is sold as a soil improver for gardens or landscape/horticulture at a relatively high price, it is unlikely that large amounts could be sold this way, and a more likely large scale use is as a soil improver on agricultural land, which would command a lower price. In view of the uncertainties in the value of compost produced, options are evaluated using a price of 25 €$_{1990}$/t which is thought to be an average sale price (i.e. considering all applications) at present, a lower value of 5 €$_{1990}$ /t which represents the price for large scale use in agriculture and a higher value, which may be more applicable in Southern European countries, of 50 €$_{1990}$ /t (see Section 3.2.1 for further details).

- ***Value of electricity and heat sales:*** this is taken as 0.03 €$_{1990}$/kWh of electricity and 0.012 €$_{1990}$/kWh of heat. These values are common across the study (e.g. in the assessment of renewable energy sources and of combined heat and power plants) and allow for the impact of current trends such as liberalisation of the energy market, on energy prices.

- ***Source separation costs***: as discussed earlier, anaerobic digestion and composting which are aimed at producing a high value saleable compost (which can be used without restrictions) require the biodegradable fractions of the waste to be collected separately. Some studies suggest that the cost of such source separation schemes can be high. For example, a Dutch study suggested an increase from 45 € per tonne for normal mixed waste collection to between 50 and 75 € per tonne for source separated organics collection, i.e. an increase of 5 to 25 € per tonne (DHV Environment and Infrastructure, 1997). Unpublished estimates in the UK suggest that collection costs rise from 27 to 40 €per tonne to 33-54 € per tonne, an increase of 6 to 14 € per tonne. As these are costs per tonne of collected waste, and the biodegradable fractions collected is only about 20% of this, the cost per tonne of collected organic waste is about 5 times these values, if all costs are ascribed to this portion of the waste. However, there may be other benefits from source separation (such as reducing pollution from leachate from landfills) in addition to the reduction greenhouse gas emissions which is evaluated here, which mean that not all of the cost of source separation should be included here. In addition, other studies have shown that in some situations, source separate collection of food waste may not lead to any additional costs. A recent study in Italy, (Favoino *et al*, 2000) showed that introducing intensive door to door collection of food waste from individual households did not necessarily lead to an increase in collection and transport costs. The high participation and yield rate which the door to door collection encouraged meant that the percentage of food waste in the residual waste was reduced, and residual waste could be collected less frequently, offsetting the costs of collecting the food wastes. (Waste may be collected daily in southern Europe as opposed to weekly or twice weekly in northern Europe, as the higher temperatures, mean that food waste begins to degrade quickly). The sensitivity of the overall cost of the compost and anaerobic digestion to source separation costs is examined in the relevant sections below.

- ***Avoided landfill costs***: all of the options considered mean that waste is no longer disposed of to landfill and there is thus a cost saving (termed avoided cost of landfill in the Tables below). The cost of landfill varies significantly not just between Member States, but also within any one Member State, or even a particular region of a Member State. Costs may vary due to availability and cost of land and to environmental requirements e.g. on the level of leachate treatment required. One study estimated that the average cost in the EU of disposal to landfill in the mid 1990s was 31 €$_{1993}$/t for an urban landfill site (with a range across the EU of 20 to 52 €$_{1993}$/t) and 19 €$_{1993}$/t (range 14-36 €$_{1993}$/t) for a rural site (Coopers and Lybrand, 1996). Average costs were predicted to rise by 2010 to 59 to 76 €$_{1993}$/t and 40 to 52 €$_{1993}$/t respectively. A more recent study which was examining the cost of incineration (Atlas, 1997) estimated that landfill disposal fees were 10 to 90 €/t but that they would rise to 30-110 €/t by 2010 due mainly to higher environmental requirements for sites. These costs may already be being exceeded in some Member States, e.g. landfill costs in Germany are reported to vary between about 25 and 135 €$_{1990}$/t (Koller, 2000). For this study a typical avoided cost of landfill of 30 €$_{1990}$/t is used to evaluate options, but due to the potentially wide range of costs the sensitivity of the cost of options to a low (15 €$_{1990}$/t) and high (120 €$_{1990}$/t) avoided cost is examined in Appendix 1 and summarised in Section 3.7.7[6].

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[6] Reviewers suggested anyway that even though in many sites gate fees are still below – sometimes by far - 5€ (e.g. UK, Portugal, Spain a rapidly decreasing number of sites in Southern Italy) the background situation is forecast to be rapidly and widely changing in the near future, due to the Landfill Directive and its provisions about management of landfilling. Further to the provisions of the Directive, a 30-year *"after care"* period has to be financially accounted for; this in itself is in their opinion likely to drive even lower landfilling fees well above 50 €/ton , even before any effect played by the tightening of environmental standards Obviously, any changing in the avoided landfilling cost per unit weight is to affect pretty evenly all waste management options, on the "diversion" side; though it is likely to make more cost-

- ***Reduction in greenhouse gas emissions***: the net reduction in greenhouse gas emissions offered by each option is calculated as the sum of:

(a) the reduction in methane emissions from not disposing of the waste to landfill;
(b) fossil fuel based emissions of CO_2 released during the process (e.g. from the incineration of plastics);
(c) the reduction in emissions associated with avoiding production of any heat and power in fossil fuel powered plants. The values used of 0.37 t CO_2/MWh electricity and 0.22 t CO_2/MWh heat are based on gas fired generation in a modern CCGT and boiler respectively and are consistent with values used in other parts of the study.

The quantity of avoided methane production depends firstly on the biodegradability of the waste, which determines the amount of methane generated if the waste was disposed of to landfill, and secondly on the amount of landfill gas control at the landfill. Total potential methane generation from the various waste fractions waste is estimated using the methodology recommended by the IPCC in its guidelines for compiling greenhouse gas inventories (IPCC, 1997). This is based on the degradable organic carbon (DOC) content of the waste. It is assumed that of this, 77% is actually biodegradable in the landfill, and that 50% is degraded to CH_4 and 50% to CO_2. Some of this methane is collected via the gas recovery system; of the remainder, the methodology assumes that 10% is oxidised in the upper layers of the landfill and the soil cap.

Using this methodology, municipal waste, which on average has a DOC of 14%, would generate (before accounting for any recovery and oxidation) 72 kg CH_4/t waste. ‘Green’ waste or kitchen waste typical has a higher DOC of about 16% and this gives a total potential methane generation of 82 kg CH_4 per t waste. These values are comparable to those estimated in other studies, e.g. an Austrian study (Hackl and Mauschitz, 2000) estimates that the CH_4 generation capacity of 1 t of municipal solid waste in Austria is about 250 m^3, of which 55% is methane; this is equivalent to about 90 kg CH_4/t waste.

Two recovery rates are assumed for methane, 20% which is approximately the average amount of landfill gas emissions recovered across the EU at present, and 70%, which is considered to be the maximum possible (over the lifetime of the site) at a well controlled site.

- No allowance is made for the potential benefits of possible sequestration of

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competitive those diversion options with a lower disposal of rejects (namely paper recycling and composting) than for instance MBT and incineration.

carbon in non-degradable waste in landfill, or increased sequestration of carbon in soils from application of compost, as at present no allowance is made for these in national emissions estimates. The issue of carbon sequestration in soils, and preserving the organic carbon content of soils is however being examined at present by the IPCC. This issue was examined in a US report which examined greenhouse gas emissions from the management of MSW (USEPA, 1998). The study concluded that there was a lack of data on this issue, and used a theoretical approach to estimate the carbon sequestered when yard trimmings (garden waste) which have been centrally composted are applied to the soil. Due to the uncertainty in the data, a bounding approach was taken which gave a range of 0.004 to 0.2 t CO_2 eq per t sequestered per tonne of material composted. While the lower range is insignificant compared to avoided methane production (see Table 3.7), if sequestration did approach the upper range, then it would start to become significant. This is obviously an area where more experimental data is required to make an accurate assessment of this potential sink[7].

3.7.2 Composting

Table 3.7 shows costs for a simple turned windrow plant and a 25,000 tunnel plant in the UK (derived from Bates, 1998), and a 50,000 t/yr tunnel plant in the Netherlands (de Jager and Blok, 1993). The turned windrow plant processes 8,000 t per year of source separated waste, and produces 1,000 t/yr of poor quality material which is disposed of to landfill and 3,000 t/yr of compost. (The remainder of the mass is lost as moisture which evaporates and CO_2). At the 25,000 t/yr tunnel plant, 10,000 t of high quality compost and 7,000 t of low quality material are produced, and at the 50,000 t/yr plant, 24,000 t of compost. For the UK plant where a more detailed breakdown of costs is available, the sensitivity of the costs to the potential range of values for source separate collection and value of compost produced are also shown.

There will be some fuel use at the site, and while this is not included in the overall greenhouse gas balance, it is likely to have a negligible impact as reductions are dominated by the methane reductions at the landfill site.

The simpler windrow site is more cost-effective (-12 $€_{1990}$/t CO_2-eq) than the more complex tunnel plant (12 $€_{1990}$/t CO_2-eq), but may be limited to use in rural areas. The price received for compost produced, significantly affects the cost-effectiveness with a range of 5 to 50 €/t compost giving a range in cost-effectiveness for the windrow site of –6 to –19 $€_{1990}$/t CO_2-eq. However the

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[7] Some reviewers quoted evaluations carried out e.g. by Sequi (1999), showing that the national CO_2 emissions in Italy get equalled by a loss of just 0,15% of organic carbon in the soil, thus asking for a “prevention policy” aimed at preserving organic matter in the soil as a ‘carbon sink’. The assessment is likely to hold more or less valid in other Member States.

cost-effectiveness is more sensitive to the potential additional cost of source separate collection, e.g. the cost-effectiveness of windrow composting increases from –12 to 23 €$_{1990}$/t CO_2-eq, if this additional cost is included.

Table 3.7 Cost-Effectiveness of Composting.

Country [Reference]		**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**Netherlands [2]**
Plant details		**Windrow**	**Windrow**	**Windrow**	**Windrow**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**
Size	t/year	8,000	8,000	8,000	8,000	25,000	25,000	25,000	25,000	50,000
Lifetime	years	15	15	15	15	15	15	15	15	15
Net energy production: electricity	MWh/yr	0	0	0	0	0	0	0	0	0
Net energy production: heat	MWh/yr	0	0	0	0	0	0	0	0	0
Compost production	t/year	3,000	3,000	3,000	3,000	10,000	10,000	10,000	10,000	20,000
Low quality residue for disposal	t/year	1,000	1,000	1,000	1,000	7,000	7,000	7,000	7,000	14,000
Additional source separation costs	€$_{1990}$/t	0	43	0	0	0	43	0	0	0
Value of compost produced	€$_{1990}$/t/compost	25	25	5	50	25	25	5	50	5
Methane generation potential of waste	kg CH_4/t waste	82	82	82	82	82	82	82	82	82
Cost data										
Investment cost	€$_{1990}$	643,140	643,140	643,140	643,140	3,841,500	3,841,500	3,841,500	3,841,500	9,079,197
Running costs (plant)	€$_{1990}$/yr	111,760	111,760	111,760	111,760	812,250	812,250	812,250	812,250	1,837,456
Additional cost of source separation	€$_{1990}$/yr	0	343,200	0	0	0	1,072,500	0	0	0
Disposal of low quality residues	€$_{1990}$/yr	30,000	30,000	30,000	30,000	210,000	210,000	210,000	210,000	420,000
Income from energy	€$_{1990}$/yr	0	0	0	0	0	0	0	0	0
Income from compost	€$_{1990}$/yr	-75,000	-75,000	-15,000	-150,000	-250,000	-250,000	-50,000	-500,000	-500,000
Avoided cost of landfilling	€$_{1990}$/yr	240,000	240,000	240,000	240,000	750,000	750,000	750,000	750,000	1,500,000

[1] Bates, 1998; [2] de Jager & Blok, 1993.

Table 3.7 Cost-Effectiveness of Composting continued.

Country [Reference]		**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**Nether-lands[2]**
Plant details		**Windrow**	**Windrow**	**Windrow**	**Windrow**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**
Cost data per t waste treated										
Investment cost	€$_{1990}$/t waste/yr	80	80	80	80	154	154	154	154	182
Running costs (plant)	€$_{1990}$/t waste	14	14	14	14	32	32	32	32	37
Cost of source separate collection	€$_{1990}$/t waste	0	43	0	0	0	43	0	0	0
Other - disposal costs	€$_{1990}$/t waste	4	4	4	4	8	8	8	8	8
Income from energy	€$_{1990}$/t waste	0	0	0	0	0	0	0	0	0
Income from compost	€$_{1990}$/t waste	-9	-9	-2	-19	-10	-10	-2	-20	-10
Net running cost	€$_{1990}$/t waste	8	51	16	-1	31	74	39	21	35
Avoided cost of landfilling	€$_{1990}$/t waste	30	30	30	30	30	30	30	30	30
Annualised cost per t waste treated										
at 2% discount rate	€$_{1990}$/ t waste	-15	28	-8	-25	13	56	21	3	27
at 4% discount rate	€$_{1990}$/ t waste	-14	28	-7	-24	15	58	23	5	29
at 6% discount rate	€$_{1990}$/ t waste	-13	30	-6	-23	17	60	25	7	32
Avoided emissions										
Avoided methane emissions from landfill:										
assuming 20% recovery of landfill gas	t CH_4/t waste	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
assuming 70% recovery of landfill gas	t CH_4/t waste	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
CO_2 credit for energy production	t CO_2/t waste	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO_2 emissions (fossil fuel based only)	t CO_2/t waste	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total reduction in GHG emissions										
assuming 20% recovery of landfill gas	t CO eq/t waste	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
assuming 70% recovery of landfill gas	t CO_2 eq/t waste	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47

[1] Bates, 1998; [2] de Jager & Blok, 1993.

Table 3.7 Cost-Effectiveness of Composting continued.

Country [Reference]		**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**UK [1]**	**Nether-lands [2]**
Plant details		**Windrow**	**Windrow**	**Windrow**	**Windrow**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**	**Tunnel**
Cost-effectiveness (CH_4 only)										
assuming 20% recovery of landfill gas										
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-12	22	-6	-20	10	45	17	2	16
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-12	23	-6	-19	12	46	18	4	17
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-11	24	-5	-18	13	48	20	5	19
assuming 70% recovery of landfill gas										
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-33	59	-17	-53	28	120	45	6	41
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-31	61	-15	-51	32	124	49	10	46
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-29	63	-13	-49	36	128	53	14	51
Cost-effectiveness (CH_4 and CO_2)										
assuming 20% recovery of landfill gas										
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-12	22	-6	-20	10	45	17	2	16
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-12	23	-6	-19	12	46	18	4	17
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-11	24	-5	-18	13	48	20	5	19
assuming 70% recovery of landfill gas										
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-33	59	-17	-53	28	120	45	6	41
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-31	61	-15	-51	32	124	49	10	46
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-29	63	-13	-49	36	128	53	14	51

[1] Bates, 1998; [2] de Jager & Blok, 1993.

3.7.3 Anaerobic digestion

Table 3.8 shows cost estimates for two anaerobic digestion plant, one in the UK and one in the Netherlands. The UK plant (Bates, 1998) processes 50,000 t/pa of source separated MSW and has a lifetime of 15 years. 5,000 t of poor quality material are produced and sent to landfill, and 34,500 t of compost and 3,000 t of liquor are produced. (The remaining mass is lost to the atmosphere as CH_4 and CO_2, and as moisture which evaporates). As in the case of composting, the sensitivity of the costs to the potential range of values for the additional cost of source separate collection and value of compost produced are also shown.

The Dutch plant (de Jager & Blok, 1993) is also a 50,000 t/yr plant, but additional costs for the separate collection of organic waste are not included (as this is common practice in the Netherlands). Two cases are evaluated, one where the methane is upgraded into a natural gas substitute and then sold, and another where electricity is produced and sold.

The AD plant itself can supply electricity used at the site, but there will still be some other fuel use such as diesel for machinery. This is not included in the overall greenhouse gas balance, but is likely to have a negligible impact as reductions are dominated by the methane reductions at the landfill site.

As with the composting plant, if there is an additional cost for source separate collection, then this significantly reduces the cost-effectiveness of the option (from –6 to 27 $€_{1990}$/t CO_2-eq). The range of potential compost prices (5 to 50 €/t) gives a range of 6 to –19 $€_{1990}$/t CO_2-eq. Costs for the Dutch plant are higher (giving a poorer cost-effectiveness), which may be due to higher pollution control requirements in the Netherlands, and/or a more complex, highly engineered plant.

Table 3.8 Cost-Effectiveness of Anaerobic Digestion.

Country [Reference]		**UK [1}**	**UK [1}**	**UK [1}**	**UK [1}**	**Netherlands[2}**	**Netherlands[2}**
Plant details		**electricity production**	**electricity production**	**electricity production**	**electricity production**	**gas substitution**	**electricity production**
Size	t/year	50,000	50,000	50,000	50,000	50,000	50,000
Lifetime	years	15	15	15	15	15	15
Net energy production: electricity	MWh/yr	8,000	8,000	8,000	8,000		5,625
Net energy production: synthetic gas	MWh/yr	0	0	0	0	15,993	
Compost production	t/year	34,500	34,500	34,500	34,500	24,000	24,000
Low quality residue for disposal	t/year	3,000	3,000	3,000	3,000	not given	not given
Liquor produced	t/year	5,000	5,000	5,000	5,000	not given	not given
Additional source separation costs	€$_{1990/}$/t	0	43	0	0	0	0
Value of compost produced	€$_{1990/}$t/compost	25	25	5	50	5	5
Methane generation potential of waste	kg CH_4/t waste	82	82	82	82	82	82
Cost data							
Investment cost	€$_{1990}$	8,575,000	8,575,000	8,575,000	8,575,000	10,376,225	10,376,225
Running costs (plant)	€$_{1990}$/yr	1,286,500	1,286,500	1,286,500	1,286,500	2,702,142	2,702,142
Additional cost of source separation	€$_{1990}$/yr	0	2,145,000	0	0	0	0
Disposal of low quality residues	€$_{1990}$/yr	150,000	150,000	221,010	150,000	0	0
Income from energy	€$_{1990}$/yr	-240,000	-240,000	-240,000	-240,000	-174,323	-168,750
Income from compost	€$_{1990}$/yr	-862,500	-862,500	-172,500	-1,725,000	0	0
Avoided cost of landfilling	€$_{1990}$/yr	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000

[1] Bates, 1998; [2] de Jager & Blok, 1993.

Table 3.8 Cost-Effectiveness of Anaerobic Digestion (continued).

Country [Reference] **Plant details**		**UK [1}** **electricity production**	**UK [1}** **electricity production**	**UK [1}** **electricity production**	**UK [1}** **electricity production**	**Netherlands[2}** **gas substitution**	**Netherlands[2}** **electricity production**
Cost data per t waste treated							
Investment cost	€$_{1990}$/t waste/yr	172	172	172	172	208	208
Running costs (plant)	€$_{1990}$/t waste	26	26	26	26	54	54
Cost of source separate collection	€$_{1990}$/t waste	0	43	0	0	0	0
Residue disposal costs	€$_{1990}$/t waste	3	3	4	3	0	0
Income from energy	€$_{1990}$/t waste	-5	-5	-5	-5	-3	-3
Income from compost	€$_{1990}$/t waste	-17	-17	-3	-35	0	0
Net running cost	€$_{1990}$/t waste	7	50	22	-11	51	51
Avoided cost of landfilling	€$_{1990}$/t waste	30	30	30	30	30	30
Annualised cost per t waste treated							
at 2% discount rate	€$_{1990}$/ t waste	-10	33	5	-27	37	37
at 4% discount rate	€$_{1990}$/ t waste	-8	35	7	-25	39	39
at 6% discount rate	€$_{1990}$/ t waste	-6	37	10	-23	42	42
Avoided emissions							
Avoided methane emissions from landfill:							
assuming 20% recovery of landfill gas	t CH_4/t waste	0.059	0.059	0.059	0.059	0.059	0.059
assuming 70% recovery of landfill gas	t CH_4/t waste	0.022	0.022	0.022	0.022	0.022	0.022
CO_2 credit for energy production	t CO_2/t waste	0.059	0.059	0.059	0.059	0.060	0.042
CO_2 emissions (fossil fuel based only)	t CO_2/t waste	0.000	0.000	0.000	0.000	0.000	0.000
Total reduction in GHG emissions							
assuming 20% recovery of landfill gas	t CO_2 eq/t waste	1.30	1.30	1.30	1.30	1.30	1.28
assuming 70% recovery of landfill gas	t CO_2 eq/t waste	0.52	0.52	0.52	0.52	0.53	0.51

[1] Bates, 1998; [2] de Jager & Blok, 1993.

Table 3.8 Cost-Effectiveness of Anaerobic Digestion (continued).

Country [Reference] **Plant details**		**UK [1}** **electricity production**	**UK [1}** **electricity production**	**UK [1}** **electricity production**	**UK [1}** **electricity production**	**Netherlands[2}** **gas substitution**	**Netherlands[2}** **electricity production**
Cost-effectiveness (CH_4 only)							
assuming 20% recovery of landfill gas							
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-8	27	4	-22	30	30
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-6	28	6	-20	32	32
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-5	30	8	-18	34	34
assuming 70% recovery of landfill gas							
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-21	71	11	-58	79	79
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-17	75	16	-54	84	84
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-12	80	21	-49	90	90
Cost-effectiveness (CH_4 and CO_2)							
assuming 20% recovery of landfill gas							
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-8	25	4	-21	28	29
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-6	27	6	-19	30	31
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-4	29	7	-18	32	33
assuming 70% recovery of landfill gas							
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-19	63	10	-52	70	73
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-15	67	14	-48	75	78
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-11	71	18	-44	80	83

[1] Bates, 1998; [2] de Jager & Blok, 1993.

3.7.4 Mechanical biological treatment

Costs are based on those for an UK tunnel composting plant in Section 3.7.2. As discussed there are some differences to the composting process in that some stages are not required, and the more aggressive nature of the material being treated can lead to higher O&M costs, but on balance costs are likely to be similar.

Table 3.9 Cost–effectiveness of Mechanical Biological Treatment.

Size	t/year	25,000
Lifetime	years	15
Residue for disposal	t/year	17,000
Methane generation potential of waste	kg CH_4/t waste	82
Cost data		
Investment cost	€$_{1990}$	3,841,500
Running costs (plant)	€$_{1990}$/yr	812,250
Disposal of low quality residues	€$_{1990}$/yr	510,000
Avoided cost of landfilling	€$_{1990}$/yr	750,000
Cost data per t waste treated		
Investment cost	€$_{1990}$/t waste/yr	154
Running costs (plant)	€$_{1990}$/t waste	32
Disposal costs	€$_{1990}$/t waste	20
Net running cost	€$_{1990}$/t waste	53
Avoided cost of landfilling	€$_{1990}$/t waste	30
Annualised cost per t waste treated		
at 2% discount rate	€$_{1990}$/ t waste	35
at 4% discount rate	€$_{1990}$/ t waste	37
at 6% discount rate	€$_{1990}$/ t waste	39
Avoided emissions		
Avoided methane emissions from landfill:		
assuming 20% recovery of landfill gas	t CH_4/t waste	0.059
assuming 70% recovery of landfill gas	t CH_4/t waste	0.022
CO_2 credit for energy production	t CO_2/t waste	0.000
CO_2 emissions (fossil fuel based only)	t CO_2/t waste	0.000
Total reduction in GHG emissions		
assuming 20% recovery of landfill gas	t CO_2 eq/t waste	1.24
assuming 70% recovery of landfill gas	t CO_2 eq/t waste	0.47
Cost-effectiveness (CH_4 only)		
assuming 20% recovery of landfill gas		
at 2% discount rate	€$_{1990}$/ t CO_2 eq	28
at 4% discount rate	€$_{1990}$/ t CO_2 eq	30
at 6% discount rate	€$_{1990}$/ t CO_2 eq	31
assuming 70% recovery of landfill gas		
at 2% discount rate	€$_{1990}$/ t CO_2 eq	75
at 4% discount rate	€$_{1990}$/ t CO_2 eq	79
at 6% discount rate	€$_{1990}$/ t CO_2 eq	83
Cost-effectiveness (CH_4 and CO_2)		
assuming 20% recovery of landfill gas		
at 2% discount rate	€$_{1990}$/ t CO_2 eq	28
at 4% discount rate	€$_{1990}$/ t CO_2 eq	30
at 6% discount rate	€$_{1990}$/ t CO_2 eq	31
assuming 70% recovery of landfill gas		
at 2% discount rate	€$_{1990}$/ t CO_2 eq	75
at 4% discount rate	€$_{1990}$/ t CO_2 eq	79
at 6% discount rate	€$_{1990}$/ t CO_2 eq	83

3.7.5 Incineration

Table 3.10 gives several cost estimates for mass burn incinerators with energy recovery, and also data for advanced technologies; all plant operate on a mixed MSW stream. The UK data is for a new incinerator exporting both heat and electricity and meeting current EU emissions limits; costs includes a semi-dry scrubbing system, fabric filter and active carbon injection for control of air emissions (Bates, 1998). Costs for plant in the Netherlands are based on a survey of existing plant, and a less detailed breakdown of operating costs is available. Average EU costs for two plant of differing sizes are taken from a European study assessing the potential of incineration for energy production (Atlas, 1997). Estimates of average costs for both conventional mass burn and more advanced gasification and pyrolysis technologies are also available from a review of technologies by the International Energy Agency (IEA Bioenergy/IEA CADDET, 1998).

Capital and operating costs reported for plant in the Netherlands are considerably higher than costs in the UK or the typical EU costs estimated. This was also noted in the IEA review which produced separate cost estimates for Dutch plant. One potential reason for the higher costs in the Netherlands is that typically a wet scrubbing system is used to control air emissions, which combined with strict limits on water discharges means that the plant must include a waste water treatment unit, increasing both capital and operating costs.

A range of costs is given for the advanced conversion technologies, and these should be treated with caution as they are principally derived from desk studies. Energy recovery rates and hence income from energy are potentially much higher than from conventional mass burn systems, but in plant designed to minimise environmental emissions to air, land and water, can be much lower as energy is required from ash vitrification and waste water treatment.

Incineration will produce some fossil fuel based CO_2 emissions from combustion of plastics in the waste, and these are accounted for in the calculation of greenhouse gas reductions.

Table 3.10 Cost-Effectiveness of Incineration.

Country [Reference]		UK [1]	Netherlands [2]	EU average[3]	EU average[3]	EU average [4]	Netherlands [4]	EU average [4]	EU average [4]
Plant details		**CHP**	**Electricity**	**Electricity**	**Electricity**	**Electricity**	**Electricity**	**Advanced technology**	**Advanced technology**
Size	t/year	200,000	285,000	150,000	400,000	400,000 to 100,000		up to 100,000	up to 100,000
Lifetime	years	20	20	20	20	20	20	20	20
Net energy production: electricity	MWh/yr	90,000	77,500	82,500	220,000	500 kWh/t	500 kWh/t	1000 kWh/t	260 kWh/t
Net energy production: heat	MWh/yr	90,000							
Iron recovered for sale	t/year	12,000	assumed included in running costs						
Residues for disposal (bottom and fly ash)	t/year	70,000	assumed included in running costs						
Methane generation potential of waste	kg CH /t waste	72	72	72	72	72	72	72	72
Cost data									
Investment cost	€$_{1990}$	60,276,000	243,602,779	43,792,000	153,864,000	see below			
Running costs (plant)	€$_{1990}$/yr	3,751,661	9,055,669	3,551,000	8,285,000	see below			
Additional cost of source separation	€$_{1990}$/yr	0	0	0	0	see below			
Disposal of ash	€$_{1990}$/yr	2,100,000				see below			
Income from energy	€$_{1990}$/yr	-3,780,000	-4,527,834	-2,475,000	-6,600,000	see below			
Income from recovered iron	€$_{1990}$/yr	-127,927				see below			
Avoided cost of landfilling	€$_{1990}$/yr	6,000,000	8,550,000	4,500,000	12,000,000	see below			

[1] Bates, 1998; [2] KEMA, 1995 [3] Atlas, 1997 [4] IEA Bioenergy/IEA CADDET, 1998

Table 3.10 Cost-Effectiveness of Incineration (continued).

Country [Reference]		UK [1]	Netherlands [2]	EU average [3]	EU average [3]	EU average [4]	Netherlands [4]	EU average [4]	EU average [4]
Plant details		**CHP**	**Electricity**	**Electricity**	**Electricity**	**Electricity**	**Electricity**	**Advanced technology**	**Advanced technology**
Cost data per t waste treated									
Investment cost	€$_{1990}$/t waste/yr	301	855	292	385	228	517	184	298
Running costs (plant)	€$_{1990}$/t waste	19	32	24	21	22	25	26	61
Cost of source separate collection	€$_{1990}$/t waste	0	0	0	0				
Ash disposal costs	€$_{1990}$/t waste	11	included in running costs						
Income from energy	€$_{1990}$/t waste	-19	-16	-17	-17	-15	-15	-30	-8
Income from recovered iron	€$_{1990}$/t waste	-1	included in running costs						
Net running cost	€$_{1990}$/t waste	*10*	*16*	*7*	*4*	7	10	-4	53
Avoided cost of landfilling	€$_{1990}$/t waste	30	30	30	30	30	30	30	30
Annualised cost per t waste treated									
at 2% discount rate	€$_{1990}$/ t waste	-2	38	-5	-2	-9	12	-22	42
at 4% discount rate	€$_{1990}$/ t waste	2	49	-1	3	-6	18	-20	45
at 6% discount rate	€$_{1990}$/ t waste	6	60	3	8	-3	25	-18	49
Avoided emissions									
Avoided methane emissions from landfill:									
assuming 20% recovery of landfill gas	t CH_4/t waste	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
assuming 70% recovery of landfill gas	t CH_4/t waste	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
CO_2 credit for energy production	t CO_2/t waste	0.266	0.101	0.204	0.204	0.185	0.185	0.370	0.096
CO_2 emissions (fossil fuel based only)	t CO_2/t waste	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Total reduction in GHG emissions									
assuming 20% recovery of landfill gas	t CO_2 eq/t waste	1.15	0.99	1.09	1.09	1.07	1.07	1.26	0.98
assuming 70% recovery of landfill gas	t CO_2 eq/t waste	0.47	0.31	0.41	0.41	0.39	0.39	0.58	0.30

[1] Bates, 1998; [2] KEMA, 1995 [3] Atlas, 1997 [4] IEA Bioenergy/IEA CADDET, 1998

Table 3.10 Cost-Effectiveness of Incineration (continued).

Country [Reference] Plant details		UK [1] **CHP**	Netherlands [2] **Electricity**	EU average [3] **Electricity**	EU average [3] **Electricity**	EU average [4] **Electricity**	Netherlands [4] **Electricity**	EU average [4] **Advanced technology**	EU average [4] **Advanced technology**
Cost-effectiveness (CH_4 only)									
assuming 20% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-2	35	-5	-2	-8	11	-21	38
at 4% discount rate	€$_{1990}$/ t CO_2 eq	2	45	-1	2	-6	17	-19	42
at 6% discount rate	€$_{1990}$/ t CO_2 eq	6	56	2	7	-3	23	-16	46
assuming 70% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-5	94	-12	-6	-23	29	-55	102
at 4% discount rate	€$_{1990}$/ t CO_2 eq	5	120	-3	6	-16	45	-50	111
at 6% discount rate	€$_{1990}$/ t CO_2 eq	15	148	6	19	-8	62	-43	121
Cost-effectiveness (CH_4 and CO_2)									
assuming 20% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-2	39	-5	-2	-9	11	-18	42
at 4% discount rate	€$_{1990}$/ t CO_2 eq	2	49	-1	2	-6	17	-16	46
at 6% discount rate	€$_{1990}$/ t CO_2 eq	5	61	2	7	-3	24	-14	50
assuming 70% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-4	124	-12	-6	-23	31	-39	137
at 4% discount rate	€$_{1990}$/ t CO_2 eq	4	158	-3	6	-16	47	-35	150
at 6% discount rate	€$_{1990}$/ t CO_2 eq	13	196	6	19	-8	65	-31	163

[1] Bates, 1998; [2] KEMA, 1995 [3] Atlas, 1997 [4] IEA Bioenergy/IEA CADDET, 1998

3.7.6 Paper recycling

Table 3.11 shows cost estimates for paper recycling for a 200 tonne/day deinking plant, producing pulp of equivalent quality to virgin pulp for use in newsprint or fine paper production, with a 25 year lifetime. The cost of waste paper to the plant is 59 €$_{1990}$/t, with an income equivalent to virgin pulp prices of 295 €$_{1990}$/t. It is assumed that sludge from the process is not disposed of to landfill. CO_2 emissions from transport of the waste paper and from the recycling process are not included, but it is likely that they will be more than offset by avoided CO_2 emissions from virgin pulp production. As with other waste diversion options, the CO_2 emissions are likely to be insignificant compared to the methane savings from avoided landfilling of the paper. The marginal cost of paper recycling might be expected to increase as more dirty and low quality sources are addressed.

Table 3.11 Cost-effectiveness of Paper Recycling.

Plant details		'Low'	Best estimate	'High'
Size of plant	t/year	69,350	69,350	69,350
Lifetime	years	25	25	25
Methane generation potential of waste	kg/t waste	82	82	82
Cost data				
Investment cost	€$_{1990}$	29,580,000	31,540,000	33,500,000
Running costs (plant)	€$_{1990}$/yr	9,483,227	10,714,190	11,945,152
Income from paper sales	€$_{1990}$/yr	-14,320,775	-14,320,775	-14,320,775
Avoided cost of landfilling	€$_{1990}$/yr	2,080,500	2,080,500	2,080,500
Cost data per t waste treated				
Investment cost	€$_{1990}$/t waste/yr	427	455	483
Running costs (plant)	€$_{1990}$/t waste	137	154	172
Income from paper sales	€$_{1990}$/t waste	-207	-207	-207
Net running cost	€$_{1990}$/t waste	-70	-52	-34
Avoided cost of landfilling	€$_{1990}$/t waste	30	30	30
Annualised cost per t waste treated				
at 2% discount rate	€$_{1990}$/ t waste	-53	-32	-11
at 4% discount rate	€$_{1990}$/ t waste	-34	-12	10
at 6% discount rate	€$_{1990}$/ t waste	7	32	57
Avoided emissions				
Avoided methane emissions from landfill:				
assuming 20% recovery of landfill gas	t CH_4/t waste	0.059	0.059	0.059
assuming 70% recovery of landfill gas	t CH_4/t waste	0.022	0.022	0.022
CO_2 credit for energy production	t CO_2/t waste	0.000	0.000	0.000
CO_2 emissions (fossil fuel based only)	t CO_2/t waste	0.000	0.000	0.000
Total reduction in GHG emissions				
assuming 20% recovery of landfill gas	t CO eq/t waste	1.24	1.24	1.24
assuming 70% recovery of landfill gas	t CO_2 eq/t waste	0.47	0.47	0.47
Cost-effectiveness (CH_4 only)				
assuming 20% recovery of landfill gas				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-63	-47	-32
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-58	-43	-27
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-53	-37	-21
assuming 70% recovery of landfill gas				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-167	-126	-85
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-156	-114	-72
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-143	-100	-57
Cost-effectiveness (CH_4 and CO_2)				
assuming 20% recovery of landfill gas				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-63	-47	-32
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-58	-43	-27
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-53	-37	-21
assuming 70% recovery of landfill gas				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-167	-126	-85
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-156	-114	-72
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-143	-100	-57

Source: This study

3.7.7 Summary of reference costs for waste diversion options

From the data above, ‘typical ‘costs for each of the options have been chosen and are summarised in Table 3.12; full details of the costs are in the earlier tables. Costs for composting are for a tunnel plant rather than windrow plant due to the latter’s wider applicability, and AD plant assume electricity generation. It is assumed that source separate collection is already either in place, or can, typically be carried out at no additional cost. (As already discussed this may not be the case across all of the EU.) Where compost is produced, an average current price of 25 $€_{1990}$/t is assumed. As the market for compost increases, and more compost goes to agricultural markets this average price might decline, particularly in the Northern European countries which have the largest potential volumes of compost generation (DHV Environment and Infrastructure, 1997). However in Southern European countries, compost may command may a higher value in agricultural applications.

Costs reported for plant in the Netherlands are consistently higher than those for other countries, or ‘typical’ EU costs, and as discussed above this appears to be the result of more stringent environmental standards requiring more highly engineered plant with more pollution control technology. This is likely to be the situation in some other Member States, and two sets of costs are therefore presented, one set applicable to Austria, Denmark, Finland, Germany, Netherlands, Sweden, and one for other Member States.

Table 3.12 Summary of 'Reference' Costs and Cost-effectiveness for Waste Diversion Options.

Option		**Composting**	**Composting**	**AD**	**AD**	**MBT**	**Incin-eration**	**Incin-eration**	**Paper recycling**
Applicability (see key at bottom of table)		**1**	**2**	**1**	**2**	**1+2**	**1**	**2**	**1+2**
Cost data per t waste treated									
Investment cost	€$_{1990}$/t waste/yr	154	182	172	208	154	228	517	455
Running costs (plant)	€$_{1990}$/t waste	32	37	26	54	32	22	25	154
Disposal of residues	€$_{1990}$/t waste	8	8	3	0	20	0	0	0
Income from energy	€$_{1990}$/t waste	0	0	-5	-3	0	-15	-15	0
Other income	€$_{1990}$/t waste	-10	-10	-17	0	0	0	0	-207
Avoided cost of landfilling	€$_{1990}$/t waste	30	30	30	30	30	30	30	30
Annualised cost per t waste treated									
at 2% discount rate	€$_{1990}$/ t waste	13	27	-10	37	35	-9	12	-59
at 4% discount rate	€$_{1990}$/ t waste	15	29	-8	39	37	-6	18	-53
at 6% discount rate	€$_{1990}$/ t waste	17	32	-6	42	39	-3	25	-46
Total reduction in GHG emissions									
Assuming 20% recovery of LFG	t CO_2 eq/t waste	1.2	1.2	1.3	1.3	1.2	1.1	1.1	1.2
Assuming 70% recovery of LFG	t CO_2 eq/t waste	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.5
Cost-effectiveness (CH_4 and CO_2)									
Assuming 20% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	10	16	-8	29	28	-9	11	-47
at 4% discount rate	€$_{1990}$/ t CO_2 eq	12	17	-6	31	30	-6	17	-43
at 6% discount rate	€$_{1990}$/ t CO_2 eq	13	19	-4	33	31	-3	24	-37
Assuming 70% recovery of landfill gas									
at 2% discount rate	€$_{1990}$/ t CO_2 eq	28	41	-19	73	75	-23	31	-126
at 4% discount rate	€$_{1990}$/ t CO_2 eq	32	46	-15	78	79	-16	47	-114
at 6% discount rate	€$_{1990}$/ t CO_2 eq	36	51	-11	83	83	-8	65	-100

Source: This study

1 Belgium, France, Greece, Ireland, Italy, Luxembourg, Portugal, Spain, UK; 2 Austria, Denmark, Finland, Germany, Netherlands, Sweden;

3.7.8 Sensitivities of cost to discount rate and avoided landfill cost

The sensitivity of the cost of treating waste in each waste diversion option (based on the reference costs above) to discount rate and to 'avoided' landfill cost is shown in Figure 3.1 and Figure 3.2 respectively; data are given in Table 3.13. Options with a high capital/investment cost (incineration and paper recycling) are very sensitive to a high discount rate, with costs per tonne of waste treated increasing much more than for other options. At higher discount rates the variation in the cost-effectiveness of the options is significantly reduced. Higher avoided landfill costs also significantly affect the cost of the waste treatment options, and with a high landfill costs, almost all options have a negative cost-effectiveness.

Figure 3.1 Sensitivity of Waste Treatment Costs to Discount Rate.

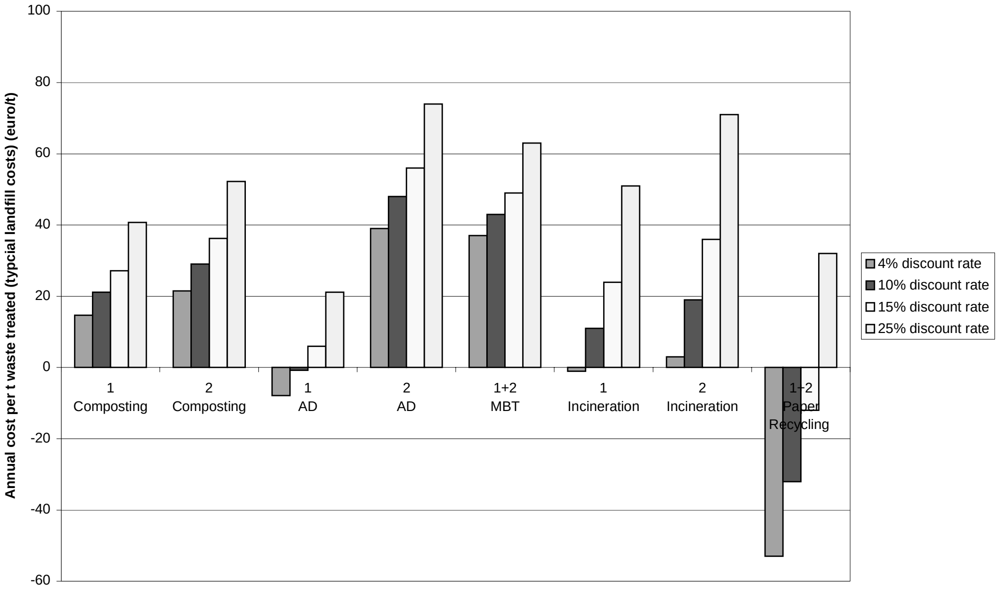

Figure 3.2 Sensitivity of Waste Treatment Costs to Avoided Landfill Costs.

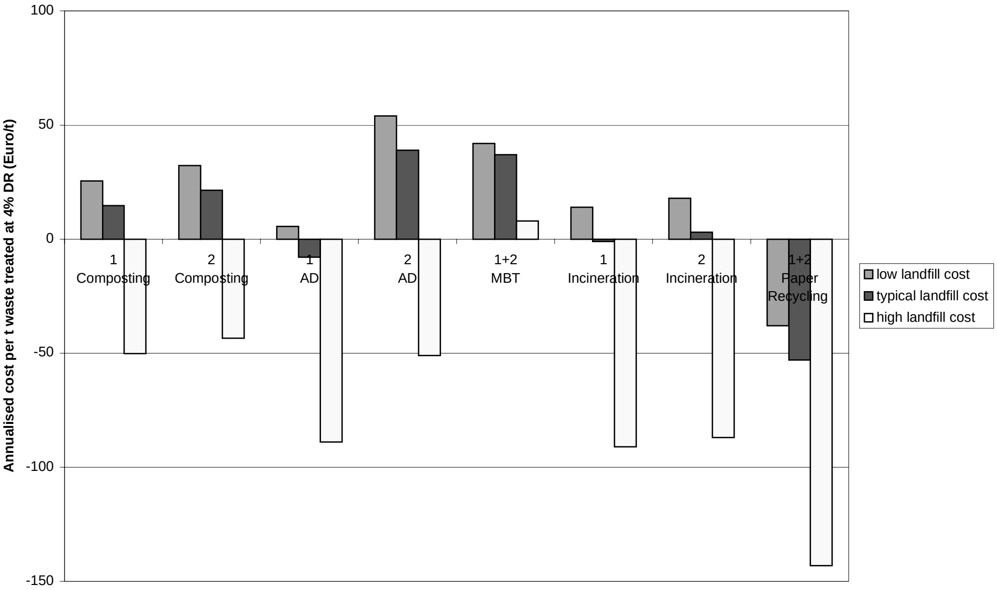

Table 3.13 Sensitivity of 'Reference' Waste Treatment Costs to Avoided Landfill Costs and Discount Rates.

Technology		Composting	Composting	AD	AD	MBT	Incineration	Incineration	Paper Recycling
Applicability		1	2	1	2	1+2	1	2	1+2
Annualised cost per t waste treated (typical landfill costs)									
4% discount rate	€$_{1990}$/ t waste	15	21	-8	39	37	-1	3	-53
10% discount rate	€$_{1990}$/ t waste	21	29	-1	48	43	11	19	-32
15% discount rate	€$_{1990}$/ t waste	27	36	6	56	49	24	36	-12
25% discount rate	€$_{1990}$/ t waste	41	52	21	74	63	51	71	32
Cost-effectiveness (assuming 20% recovery of landfill gas)									
4% discount rate	€$_{1990}$/ t CO_2-eq	12	17	-6	30	30	-1	2	-43
10% discount rate	€$_{1990}$/ t CO_2-eq	17	23	-1	37	35	11	18	-26
15% discount rate	€$_{1990}$/ t CO_2-eq	22	29	5	43	40	22	33	-9
25% discount rate	€$_{1990}$/ t CO_2-eq	33	42	16	57	50	47	66	26
Annualised cost per t waste treated (4% discount rate)									
low landfill cost	€$_{1990}$/ t waste	26	32	6	54	42	14	18	-38
typical landfill cost	€$_{1990}$/ t waste	15	21	-8	39	37	-1	3	-53
high landfill cost	€$_{1990}$/ t waste	-50	-43	-89	-51	8	-91	-87	-143
Cost-effectiveness (assuming 20% recovery of landfill gas)									
low landfill cost	€$_{1990}$/ t CO_2-eq	21	26	4	42	33	13	16	-31
typical landfill cost	€$_{1990}$/ t CO_2-eq	12	17	-6	31	30	-1	2	-43
high landfill cost	€$_{1990}$/ t CO_2-eq	-40	-35	-68	-39	6	-84	-80	-115

3.8 LANDFILL GAS RECOVERY AND UTILISATION

Installing an impermeable barrier or liner to contain the site, an impermeable cap, and a network of gas recovery wells can reduce fugitive emissions of methane emissions. The liner and cap prevent the landfill gas migrating from the site laterally or through the surface of the landfill, and the methane can then be extracted by pumping it out through the wells. The barrier or liner system may be clay if this is available on site or nearby, or sand enhanced with bentonite, or synthetic geomembranes. Capping materials may be clay (if available), soil, and may also incorporate a membrane. The gas recovery system generally consists of vertical wells made of perforated or slotted plastic (e.g. HDPE) pipes, surrounded with gravel or other permeable materials. Typically a fan is used to maintain a negative pressure in the system and draw the gas out.

The landfill gas, which is extracted, can then either be flared, or energy can be recovered by direct combustion to provide heat, electricity generation, or upgrading to substitute natural gas. The technologies for landfill gas collection and use are well understood and demonstrated in the EU. It should be noted that the liner and cap, which are necessary for gas collection, also fulfil other environmental objectives, e.g. preventing leachate and movement of pollutants into adjoining soils, and suppressing odours. Control of landfill gas is also required for safety reasons.

In general, tightening environmental standards for landfills across the EU have meant that installation of liners, caps and gas recovery systems is becoming more common, and is mandatory for new landfill sites in several Member States, with some also requiring retrofitting of gas recovery systems to existing sites (Table 3.14). Given the trend towards improving landfill standards and the need to install a cap and liner for other environmental reasons, the cost of these elements are not ascribed to the options discussed below.

Table 3.14 Requirements for Landfill Gas Recovery.

Country	**gas recovery required on new landfills**	**gas recovery required on existing landfills**
Austria	yes, since 1997	yes, since 1997
Belgium	yes	yes
Finland	yes	from 2002
France	Since 1995	
Germany	Since May 1993	from 2003 to 2006, varies between Länder
Greece	By 1999 for large sites	
Italy	yes	yes
Netherlands	Since 1994	
Spain	>100kt/y waste[1].	
UK	Since 1994	Since 1994 for sites with significant remaining capacity

[1] In Spain 30% of landfills have a passive collection system for gases and 12% have an active system. 10% of the landfills eliminate the gases by flaring and 6% use the energy of the gas (Rubio, 1997).

3.9 FLARING

3.9.1 Description

Modern flares are designed to work continuously and availabilities of 98% are not uncommon, with combustion efficiency of 99%, provided the air supply is well adjusted. Flares may be ‘open’ or ‘closed’. In the former; there is an open flame, often up to several metres in length, and combustion control is rudimentary. In the latter the gas is burned in an enclosure. Sometimes secondary air is introduced around the base of the enclosure. Combustion efficiency depends on temperature, residence time, turbulence and the amount of oxygen present. The flare exhaust gas is mainly CO_2, but also contains small amounts of carbon monoxide, nitrogen oxides, formaldehyde and other trace organic compounds. In poorly designed and operated flares there is a possibility that polyaromatic hydrocarbons, dioxins and furans may be produced (Frost *et al*, 1997).

Most landfill gas flares are relatively simple items of equipment and are supplied by many firms across the community.

3.9.2 Current practice

Flaring of landfill gas is common across the EU. Even on sites with energy recovery, a flare will also be installed and used to combust gas when generating equipment is offline, and at times when gas flow or methane concentration are too low for combustion in the generating plant.

3.9.3 Cost

Costs of flaring (Table 3.15) vary considerably depending on individual site characteristics, gas recovery capacities etc, and the amount of the gas recovery system which is attributed to the flare. The costs for the UK plant (Bates, 1998) are for a 500 m^3/hr flare and include the costs of the gas compound required to house the flare and associated pumps and compressors. The costs for the Netherlands plant (Hendriks *et al*, 1998) are for a 200 m^3/hr flare and include an elementary piping system. The costs for the Finnish plant (Lehtilä & Tuhkanen, 1999) are for a 500 m^3/hr flare, and include the costs of the gas recovery system; operating costs are for electricity consumption of the compressor and maintenance of the system.

Table 3.15 Cost –effectiveness of Flaring.

Country [Reference]		UK [1]	Nls [2]	Finland [3]
Plant details				
Size	m3/hr	500	200	500
Lifetime	years	10	20	20
Cost data				
Investment cost	€$_{1990}$	106,499	100,000	364,800
Running costs (plant)	€$_{1990}$/yr	5,917	0	23,868
Annualised cost				
at 2% discount rate	€$_{1990}$/yr	17,773	6,116	46,178
at 4% discount rate	€$_{1990}$/yr	19,047	7,358	50,711
at 6% discount rate	€$_{1990}$/yr	20,386	8,718	55,673
Avoided emissions	t CH_4/yr	1,073	429	1,073
Cost-effectiveness				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	0.8	0.7	2.1
at 4% discount rate	€$_{1990}$/ t CO_2 eq	0.8	0.8	2.3
at 6% discount rate	€$_{1990}$/ t CO_2 eq	0.9	1.0	2.5

[1] Bates, 1998; [2] Hendriks *et al*, 1998 [3] Lehtilä & Tuhkanen, 1999

3.9.4 Country specific implications

It is unlikely that there are any country specific implications for flaring, other than the necessity of having containment and recovery in place first.

3.10 ELECTRICITY AND HEAT GENERATION

3.10.1 Description

Electricity generation from landfill gas is a well established and proven technology in the EU. In most schemes the gas is burned in a reciprocating engine which turns a generating set, although a dual fuel or gas turbine can be used. Reciprocating engines tend to have a lower cost and are available in smaller unit sizes; they suffer from corrosion caused by acidic species in the landfill gas, although the lubricating oils used in spark-ignited engines do provide some protection against acidic combustion products. Gas turbines have less corrosion problems, but are more expensive and need a consistent gas quality; they also need a much higher gas delivery pressure, so that installation and operation of the gas compressors is also more expensive. There is generally no use for the power generated on the landfill site itself so that a connection to the electricity distribution network is necessary. Electricity generation plant for landfill gas is available in modular units that are installed as turnkey packages.

In some cases direct combustion of the landfill gas in industrial boilers, brick kilns and lime or cement kilns may be possible. Heat produced can be used for heating greenhouses, district heating and for drying purposes in industrial processes. Direct combustion is an efficient way to recover energy from landfill gas - over 80% of the calorific value of the methane can be recovered as useful energy. Burning landfill gas is similar to burning a dilute natural gas. If the combustion fuel is a mixture of natural gas and landfill gas, only simple modifications are required to adapt the burner. If the landfill gas is the predominant or only fuel, modifications are needed to balance the lower energy content of the gas compared to natural gas.

The main disadvantage to using landfill gas as a direct fuel is that the consumer must be located near the landfill site. The costs of transporting the gas over long distances are high and it may be difficult to obtain permission to lay pipework on or under intermediary land between the site and the end user. Ideally the end user should be able to use the landfill gas continuously because the flow from the landfill site cannot be turned on and off to match the end user needs.

3.10.2 Current practice

It was estimated in 1997 that 553 MW of generating capacity was operating in the EU (Table 3.16), with the potential for this estimated to significantly increase overall by 2010 (Atlas, 1997). This trend is borne out by more recent data for the UK (Hooper, 2000) which estimates that in 2000, 350 MW of generating capacity had been commissioned and that another 350 MW were planned, brining the total to 700 MW. Small downward trends are forecast in some countries (Netherlands, Sweden and Austria) because of national policies to severely restrict the amount of biodegradable waste going to landfill, and hence the amount of methane available for recovery, in the future (see Section 4). Deployment in some countries such as the UK has been encouraged by schemes designed to encourage renewable energy sources, which offered a premium price for electricity from such sources. In the UK now however, landfill gas generation schemes are generally competitive without any such subsidy.

Table 3.16 Deployment of Generating Capacity from Landfill Gas in the EU (includes electricity and heat production)

	1996 MW (electrical)	**2010 MW (electrical)**
Austria	10	2
Belgium	2	27
Denmark	10	23
Finland	0	11
France	20	69
Germany	170	286
Greece	0	12
Ireland	12	11
Italy	10	160
Luxembourg	0	1
Netherlands	120	100
Portugal	0	2
Spain	5	27
Sweden	49	20
UK	145	589
EU	**573**	**1366**

Source: ATLAS, 1997.

3.10.3 Cost

Table 3.17 shows the costs of generating electricity from landfill gas, using a spark ignition engine assuming sales of the electricity. Costs are fairly comparable for the three countries. The costs for the UK are based on a slightly older system, and newer engines can be up to 15% cheaper and 15% more efficient, which would give a cost-effectiveness closer to the costs for the systems in the Netherlands and Finland. More modern landfill sites in the UK are also typically larger and have better landfill gas recovery systems, so that larger generating sets can be installed, giving some economies of scale. Costs for individual sites may vary considerably, e.g. quoted grid connection costs for sites in the UK have varied between 10,000 and 1,400,000 € (Wake, 2000) but the costs below are thought to be representative of typical sites. Costs are also shown for a low-pressure boiler system, where the landfill gas is burnt to produce heat; the landfill gas is assumed to substitute for natural gas.

Table 3.17 Cost-effectiveness of Electricity and Heat Production from Landfill Gas.

Country [Reference]		UK [1]	Nls [2]	Nls [2]	Finland [3]	UK [4]
Plant details	m3/hr	650 m3/hr	500m3/hr	800m3/hr	500m3/hr	1000m3/hr
Size	MW	1.0	0.8	1.2	0.85	5.2
Lifetime	years	10	20	20	15	20
Cost data						
Investment cost	€$_{1990}$	634,850	907,920	1,253,794	699,587	450,516
Running costs (plant)	€$_{1990}$/yr	118,200	47,558	73,498	71,232	105,634
Income from energy		-210,240	-157,680	-252,288	-178,704	-451,259
Annualised cost						
at 2% discount rate	€$_{1990}$/yr	-21,364	-54,597	-102,112	-53,027	-318,073
at 4% discount rate	€$_{1990}$/yr	-13,769	-43,316	-86,534	-44,551	-312,476
at 6% discount rate	€$_{1990}$/yr	-5,784	-30,965	-69,479	-35,441	-306,347
Avoided emissions						
Avoided landfill gas emissions	t CH_4/yr	1,626	1,251	2,001	1,251	3,427
CO_2 credit for energy production	t CO_2/yr	2,593	1,945	3,112	2,204	9,147
Total reduction	t CO_2 eq/yr	31,556	24,324	38,918	24,064	62,821
Cost-effectiveness (CH_4 and CO_2)						
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-0.7	-2.2	-2.6	-2.2	-5.1
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-0.4	-1.8	-2.2	-1.9	-5.0
at 6% discount rate	€$_{1990}$/ t CO_2 eq	-0.2	-1.3	-1.8	-1.5	-4.9

[1] Bates, 1998; [2] de Jager and Blok 1993, [3] Lehtilä & Tuhkanen, 1999, [4] Wake, 2000.

3.11 PRODUCTION OF SYNTHETIC NATURAL GAS

3.11.1 Description

Landfill gas has too low a calorific value to enable it to be fed directly into the natural gas network, but it is possible to produce a synthetic natural gas from it. A number of techniques are available that can achieve this by removing non-combustible components such as carbon dioxide, and trace gases such as hydrogen sulphide. The main cleaning techniques include:

- water scrubbing
- solvent extraction
- membrane separation
- pressure swing absorption
- iron oxide beds
- activated carbon adsorption

The gas must then be pressurised before being fed into the gas distribution network.

This option is only feasible if there is an extensive natural gas distribution system, so that the gas does not have to be transported long distances from the landfill site. Thus while this option is relatively cost-effective in terms of methane abatement and would be profitable for a landfill owner (see Section 3.11.3), it is only feasible at landfill sites located close to a gas pipeline. This limits the applicability of this option.

3.11.2 Improvements and or alternatives of the option

The same technology used to provide substitute natural gas could be used to provide a high calorific value vehicle fuel to power conventional spark ignition or diesel engines that have been modified to run on natural gas. Using landfill gas as a vehicle fuel has been demonstrated in a number of plants world-wide, but most of these are prototype plants with a limited number of vehicles running and so the technology is unproven both technically and commercially. Technology using biogas produced from anaerobic digestion, is more advanced and is likely to soon become a commercial activity. For example, in Sweden bus fleets and an increasing number of private vehicles are using biogas, and public biogas filling stations have been set up. This suggests that that the use of landfill gas in vehicles may also become a proven technology in the future.

Fuel Cells offer a future option for the generation of electricity from landfill gas. Over 200 fuel cell systems running on natural gas have been demonstrated world-wide but to date there has only been one demonstration on landfill gas. At present, fuel cells are still at a relatively early stage of development and, although costs are reducing, they are substantially more expensive than equivalent conventional heat engines. Additionally, clean up of the landfill gas for use as a feedstock to the fuel cells needs to be much more effective than if the gas were to be used as a vehicle fuel, adding to the costs of the technology. Fuel cells do offer great environmental and electricity conversion benefits and it is likely that further development of the technology will eventually lead to their widespread use at landfill sites.

3.11.3 Cost

Costs for a typical upgrading plant in the Netherlands are given in Table 3.18 (De Jager and Blok, 1993). The plant has a capacity of 250 m^3 of landfill gas per hour, and operates for 7500 hours per year, with gas flared during the remaining time. 2% of recovered methane is released to the atmosphere during upgrading and 15% of recovered methane is flared. In general larger capacity systems (greater than 600 m3/hr) will be more profitable and for these size systems, upgrading the gas can be more profitable than electricity generation.

Table 3.18 Cost-effectiveness of Production of Synthetic Natural Gas.

Country [Reference]		**Nls [1]**
Plant details	m3/hr	250
Lifetime	years	20
Cost data		
Investment cost	€$_{1990}$	562,045
Running costs (plant)	€$_{1990}$/yr	84,307
Income from energy		-129,021
Annualised cost		
at 2% discount rate	€$_{1990}$/yr	-10,341
at 4% discount rate	€$_{1990}$/yr	-3,358
at 6% discount rate	€$_{1990}$/yr	4,288
Avoided emissions		
Avoided landfill gas emissions	t CH_4/yr	900
CO_2 credit for energy production	t CO_2/yr	2,475
Total reduction	t CO_2 eq/yr	16,425
Cost-effectiveness (CO_2 and CH_4)		
at 2% discount rate	€$_{1990}$/ t CO_2 eq	-0.6
at 4% discount rate	€$_{1990}$/ t CO_2 eq	-0.2
at 6% discount rate	€$_{1990}$/ t CO_2 eq	0.3

[1] De Jager and Blok, 1993

3.12 IMPROVED OXIDATION THROUGH IMPROVED CAPPING AND RESTORATION

3.12.1 Description of option

Improving the capping and restoration layers of a landfill site is a relatively low cost option to reduce methane emissions to the atmosphere. Capping landfills with impermeable clay layer, rather than permeable soily material will reduce the amount of methane being emitted to the atmosphere by providing a physical barrier. However, even the best engineered clay caps will allow small amounts of methane through. Over many years, the clay cap can deteriorate or may dry out and crack under dry weather conditions. But if the restoration layers above the clay cap are also engineered to take advantage of biological methane oxidation activity, then even these small emissions of methane can be controlled. Biological methane oxidation is a naturally occurring process whereby methane is oxidised to carbon dioxide and water by micro-organisms. To facilitate the process, the landfill restoration layer must contain a material with an open structure to allow methane to permeate upwards but more importantly to allow oxygen to diffuse into the restoration layer. Sufficient nutrients must be available for the micro-organisms to function and the depth of the restoration layer must be sufficient to allow complete oxidation of the methane within the restoration layer.

For modern landfills, where a large proportion of the landfill gas is collected and combusted, there is a relatively low flux of methane though the restoration layer so that it is possible to improve biological oxidisation of this methane as it passes through the restoration layer. Laboratory studies that show landfill cover soils have a large capacity to oxidise methane (Whalen *et al*, 1990; Kightley *et al*, 1995), and it has been estimated that under optimal conditions, a 500 mm layer of coarse, sandy soil could oxidise 100% of the methane from a 13m depth of waste. Allowing for sub-optimal conditions at an actual landfill site, it is considered that oxidation of fugitive emissions might be increased from about 10% to 50% by ensuring a good combined cap and restoration layer.

3.12.2 Current practice

As discussed previously capping and covering of modern landfills is already likely in order to reduce a number of environmental problems, and some biological oxidation will therefore already be occurring. Improving the cap and cover should however improve the oxidation rate.

3.12.3 Cost of option

The costs for a combined clay cap and soil restoration layer are very dependent on the local availability of materials, otherwise considerable transport costs will be incurred for importing the materials to the landfill site. Generally, the capital costs of installing a clay cap and soil restoration layer are associated with the hire of plant and equipment, the costs of the clay and soil materials and an annual maintenance cost. Costs are dependent on the surface area to be covered but are generally in the range of about 20-40 €$_{1990}$ per square metre for a clay depth of 1 metre and a soil depth of 1 metre. General maintenance costs are about 0.04 €$_{1990}$ per square metre per year (Bates, 1998).

Costs for a typical landfill of 1 million tonnes, with a surface area of 62,500m^2 (250m x 250 m), are shown in Table 3.19. One million tonnes of waste in the site is assumed to generate 72 kt of CH_4 over the lifetime of the site, of which 70% is recovered and combusted. Of the remaining fugitive emissions, it is assumed 10% would have been oxidised by a normal cap, but that the improved cap raises this to 50%. Methane savings are averaged over the 50 year lifetime of the measure.

Table 3.19 Cost-Effectiveness of Improved Capping and Oxidation of Fugitive Emissions.

Size of landfill		1 Mm^3/ 62,500 m^2	1 Mm^3/ 62,500 m^2	1 Mm^3/ 62,500 m^2
Lifetime	years	50	50	50
Cost data		Best guess	Lower range	Upper range
Investment cost	€$_{1990}$	1,627,063	1,220,297	2,181,743
Running costs (plant)	€$_{1990}$/yr	2,219	2,219	2,219
Income from energy				
Annualised cost				
at 2% discount rate	€$_{1990}$/yr	53,997	41,053	71,649
at 4% discount rate	€$_{1990}$/yr	77,959	59,024	103,779
at 6% discount rate	€$_{1990}$/yr	105,447	79,640	140,638
Avoided emissions				
Avoided landfill gas emissions	t CH_4/yr	194	194	194
Total reduction	t CO_2 eq/yr	4,075	4,075	4,075
Cost-effectiveness				
at 2% discount rate	€$_{1990}$/ t CO_2 eq	13.3	10.1	17.6
at 4% discount rate	€$_{1990}$/ t CO_2 eq	19.1	14.5	25.5
at 6% discount rate	€$_{1990}$/ t CO_2 eq	25.9	19.5	34.5

3.12.4 Summary of reference costs for landfill gas recovery and oxidation

From the data above, ‘typical ‘costs for each of the options have been chosen and are summarised in Table 3.20; full details of the costs are in the earlier tables.

Table 3.20 Summary of ‘Reference’ Costs and Cost-effectiveness for Landfill Gas Recovery and Oxidation Options.

Option		Flaring	Electricity Generation	Heat	Upgrade to Natural Gas	Improved oxidation
Plant details		500 m^3/hr	500m^3/hr	1000m^3/hr	m^3/hr	1 Mm3/ 62,500 m^2
Lifetime		10	15	20	20	50
Cost data						
Investment cost	€$_{1990}$	106,499	699,587	450,516	562,045	1,627,063
Running costs (plant)	€$_{1990}$/yr	5,917	71,232	105,634	84,307	2,219
Income from energy	€$_{1990}$/yrt	0	-178,704	-496,800	-129,021	0
Annualised cost						
at 2% discount rate	€$_{1990}$/ yr	17,773	-53,027	-363,614	-10,341	53,997
at 4% discount rate	€$_{1990}$/ yr	19,047	-44,551	-358,016	-3,358	77,959
at 6% discount rate	€$_{1990}$/ yr	20,386	-35,441	-351,888	4,288	105,447
Total reduction in GHG emissions						
Reduction in landfill gas emissions	t CH_4 eq/t waste	1,073	1,251	3,427	900	194
CO_2 credit for energy production		0	2,204	9,147	2,475	0
Total reduction	t CO_2 eq/t waste	22,525	24,064	62,821	16,425	4,075
Cost-effectiveness (CH_4 and CO_2)						
assuming 70% recovery of landfill gas						
at 2% discount rate	€$_{1990}$/ t CO_2 eq	0.79	-2.2	-5.8	-0.6	13.3
at 4% discount rate	€$_{1990}$/ t CO_2 eq	0.85	-1.9	-5.7	-0.2	19.1
at 6% discount rate	€$_{1990}$/ t CO_2 eq	0.91	-1.5	-5.6	0.3	25.9

Source: This study

4 BASELINE TRENDS

As already discussed, the landfill directive will require both the installation of gas recovery at all new sites in the future and diversion of biodegradable municipal solid waste from landfills in the future. In addition to this, a number of Member States have more stringent targets on landfilling of biodegradable waste (Table 4.1), and policies and measures to implement landfill gas recovery and reduce the amount of biodegradable waste landfilled are already in place.

Table 4.1 National Legislation relating to Landfill.

Country	**Legislation on organic waste to landfill**
Austria	no carbon – containing waste after 2004
Belgium	only pre treated waste after July 2000 (Flanders only)
Denmark	only pre treated waste after 1997
Finland	only pre treated waste after 2005
France	only “final” waste after 2002
Germany	only pre-treated “final” waste from 1999; no carbon containing wastes from 2005
Greece	no restrictions
Ireland	no restrictions
Italy	inert and residual wastes only from 2002
Netherlands	no combustible wastes to be landfilled after 2001
Portugal	no restrictions
Spain	no restrictions
Sweden	no organic material after 2005
UK	no restrictions

In order to provide a ‘no action’ baseline against which to assess the impact of implementation of the measures, future landfill emissions have been estimated assuming that waste generation per capita remains constant and that the proportion of waste disposed of to landfill remains constant. Furthermore, landfill gas recovery rates are assumed to remain constant (from about 1994/5 the last year from which emissions estimates were available at the time of the study). Waste generation rates have increased in the past and the assumption that the rate remains constant in the future may overestimate the effect that waste prevention may have in reducing rates. The landfill emissions were estimated using the time dependant IPCC methodology (IPCC, 1997), and values for the per capita waste generation rate, fraction of MSW disposed to landfill, and degradable organic content from the IPCC Guidelines (1997) unless new country specific data was available from Second National Communications on Climate Change (as submitted to the UNFCCC). The percentage of methane recovered was derived from information in the Second National Communications wherever possible; in all other cases, estimates were taken from Common Policies and Measures Paper on Landfill (CCPM, 1997).

Under this ‘no action’ scenario, landfill emissions in the EU rise slightly (by 2%) by 2010, reflecting the expected increase in population, and subsequent increase in waste generation (Table 4.). In practice emissions are expected to be considerably lower than this, due to the implementation of both the landfill directive and national policies.

As this baseline trend reflects a ‘no further action’ scenario, the estimate for some countries (e.g. Austria) where there has been substantial action on landfill gas recovery post 1994, differs considerably from national forecasts which take account of this action.

Table 4.2 Landfill Emissions in 2010 under a ‘No Action’ baseline (kt CH_4).

Country	**1990**	**2010**	**Change**
Austria	193	203	5%
Belgium	173	179	4%
Denmark	71	69	-3%
Finland	230	199	-14%
France	780	813	4%
Germany	1842	1892	3%
Greece	102	107	5%
Ireland	136	141	4%
Italy	302	310	3%
Luxembourg	3	3	5%
Netherlands	562	550	-2%
Portugal	493	508	3%
Spain	471	464	-1%
Sweden	85	76	-10%
United Kingdom	1117	1157	4%
EU15	**6560**	**6672**	**2%**

Source: This study

5 AGGREGATION OF OPTIONS

Three sets of options have been identified, diversion of organic waste from landfill and treatment by another waste management option, landfill gas recovery and combustion, and improved capping and oxidation. The reductions which might be achieved by these measures are interdependent - the less biodegradable waste going to landfill, the smaller the reductions achieved by landfill gas recovery. Improving the soil cap will only improve oxidation rates when fugitive fluxes are fairly low i.e. only if a substantial proportion of landfill gas is being recovered.

The overall reductions which might be achieved by each of these options has been estimated using the model described above, and making the following assumptions:

- Waste diversion options, i.e. those reducing biodegradable waste going to landfill, are implemented first. Implementation is split into reductions required by the Landfill Directive and those required by national policy.
- As nearly all Member states now have a policy of landfill gas collection at new sites, all new sites from 1995 are assumed to achieve 70% recovery and combustion of landfill gas. An average lifetime of 15 years is assumed i.e. every year an additional one-fifteenth of waste is disposed of to a new site. It is assumed that 10% of remaining fugitive emissions are oxidised in the cap.
- The final measure to be implemented is improved capping of the site. This improves oxidation of fugitive emissions from 10% to 50%. This is assumed to be implemented on all sites which close from 2005 onwards.

The standard of engineering in landfill sites may vary considerably across the EU at present, leading to substantial differences in landfill gas recovery rates which are achieved. However the increased emphasis on preventing environmental pollution of all types from landfill sites, and the improved construction and operating standards required by the Landfill directive, are likely to do much to harmonise standards for new sites across the EU. As only landfill gas recovery at new sites is considered here, a standard recovery rate of 70% is assumed for all of the EU.

The reductions from the 2010 ‘no action’ baseline achieved by each of the sets of measures are shown in, and assume implementation of the options in the order shown in Table 5.1.

Table 5.1 Reductions in Landfill Emissions in 2010 from Baseline Projection (kt CH_4).

Country	**2010**	**Waste diversion element of the Landfill directive**	**Waste diversion - additional national policies**	**Total reduction from waste diversion**	**Increased landfill gas recovery**	**Increased oxidation of fugitive emissions**	**Total all options**
Austria	203	24	48	72	10	14	97
Belgium	179	21	34	55	17	13	85
Denmark	69	8	28	36	0	2	38
Finland	199	21	44	65	7	12	84
France	813	98	232	330	20	54	403
Germany	1892	228	789	1017	2	67	1086
Greece	107	5	0	5	23	12	40
Ireland	141	6	0	6	31	16	53
Italy	310	11	122	133	6	17	155
Luxembourg	3	0	0	0	1	0	1
Netherlands	550	68	173	242	12	28	282
Portugal	508	58	1	59	86	53	198
Spain	464	18	0	18	105	55	178
Sweden	76	9	17	26	4	8	38
United Kingdom	1157	45	0	45	241	170	456
EU15	6672	620	1488	2108	564	522	3194

Defining the exact mix of measures which are likely to be implemented in Member States to achieve the diversion targets set out in the Landfill Directive is difficult as most Member States have yet to devise a clear strategy. In general it is considered that incineration is likely to be used where high population densities provide sufficient quantities of waste in within a relatively small area. Composting and possibly AD are options for less densely populated areas, and MBT could be used where source separated collection is not feasible, and/or there is public opposition to incineration. Paper recycling could be increased, particularly in some Member States, but in others it is already at a very high level. Overall it is assumed for this study that the reductions due to waste diversion estimated in Table 5.1 will be split between the options identified approximately as shown in Table 5.2. The exact mix of measures is likely to be very dependent on local circumstances and can only be estimated very approximately in this type of European level study (An estimate is however necessary due to the differing costs of the options). There is a greater level of confidence in the overall level of reductions which are achievable.

Table 5.2 Potential Reductions Achieved by Individual Waste Diversion Options in 2010 compared to Baseline (kt CH_4)

	Anaerobic digestion	**Composting**	**MBT**	**Incineration**	**Paper Recycling**	**Total**
Austria	3.6	3.6	10.9	54.3	0.0	72
Belgium	2.7	2.7	8.2	38.4	2.7	55
Denmark	1.8	1.8	5.3	25.8	0.9	36
Finland	3.2	3.2	9.7	48.8	0.0	65
France	16.5	16.5	49.5	230.8	16.5	330
Germany	50.9	50.9	152.6	762.8	0.0	1017
Greece	0.2	0.2	0.7	3.2	0.2	5
Ireland	0.3	0.3	0.8	3.9	0.3	6
Italy	6.6	6.6	19.9	92.9	6.6	133
Luxembourg	0.0	0.0	0.1	0.3	0.0	0
Netherlands	12.1	12.1	36.3	175.5	6.1	242
Portugal	2.9	2.9	8.5	42.2	2.9	59
Spain	0.9	0.9	2.7	12.4	0.9	18
Sweden	1.3	1.3	3.9	19.3	0.0	26
UK	2.2	2.2	6.8	32.8	1.1	45
EU15	**105.1**	**105.1**	**315.8**	**1543.3**	**38.2**	**2107.6**

For landfill gas diversion options, upgrading to synthetic natural gas and heat production may have limited use due to the need to have a suitable heat source or gas pipeline close to the site. While energy recovery is preferable, flaring is likely to be used at smaller, remote sites, at times when gas flows are too low, or contain too little methane to be used for energy recovery (e.g. towards the end of the main methane generating period of the site), or when energy recovery equipment is inoperational. Overall it is estimated that the reductions due to landfill gas recovery and combustion estimated in Table 5.1 will be split between the options identified approximately as shown in Table 5.3. Once again the exact mix of measures is likely to be very dependent on local circumstances and can only be estimated very approximately in this type of European level study. There is a greater level of confidence in the overall level of reductions which are achievable.

Table 5.3 Potential Reductions from Individual Landfill Gas Recovery Options in 2010 (kt CH_4).

	Flaring	**Electricity generation**	**Heat production**	**Gas upgrading**	**Total**
Austria	5.1	4.1	0.5	0.5	10
Belgium	8.6	6.9	0.9	0.9	17
Denmark	0.1	0.0	0.0	0.0	0
Finland	3.8	2.8	0.4	0.0	7
France	9.8	7.8	1.0	1.0	20
Germany	1.0	0.8	0.1	0.1	2
Greece	12.8	9.3	1.2	0.0	23
Ireland	16.9	12.3	1.5	0.0	31
Italy	2.8	2.2	0.3	0.3	6
Luxembourg	0.3	0.2	0.0	0.0	0
Netherlands	6.0	4.8	0.6	0.6	12
Portugal	43.2	34.6	4.3	4.3	86
Spain	57.6	41.9	5.2	0.0	105
Sweden	2.1	1.5	0.2	0.0	4
UK	120.6	96.5	12.1	12.1	241
EU15	**291**	**226**	**28**	**20**	**564**

6 REFERENCES

ATLAS, 1997. “Renewables Sector Report”, ATLAS Project, Thermie Report STR/519/95, 1997, European Commission.

Barth, J, 2000. "European Compost Production - Sources, Quantities, Qualities and Use in Selected Countries" ; Proc. SEP-Pollution, Padova 30 March 2000.

Bates JE, 1998; "Options to Reduce Methane Emissions (Final Report)", AEA Technology Report AEAT-3733 Issue 3, November 1998.

CCPM, 1997. “Measures to reduce landfill methane emissions in the EU”. A paper to the EU Ad Hoc Group on Climate, March 1997.

CEPI, 1999. “CEPI Newsletter”, Number 13, August 1999.

Composting Association, 1997. “The State of Composting in the UK- A blueprint for action.” Composting Association, Coventry.

Coopers and Lybrand, 1996. “Cost benefit analysis of the different municipal solid waste management systems: Objectives and instruments for the year 2000”, European Commission DG XI, March 1996

de Jager, D & Blok, K, 1993; "Cost-effectiveness of Emission reducing Measures for Methane in the Netherlands, Ecofys Report M702, May 1993.

DHV Environment and Infrastructure, 1997; “Composting in the European Union, Final Report”, DHV Report AT-973090, June 1997.

Favoino E, 2000. Personal Communication.

Favoino E *et al*, 2000. “Sorting Food Waste in Italy: optimising costs and benefits”, Warmer Bulletin 70, pp 4-7, January 2000.

Frost, RC; Pearson, JE & Campbell, DJV, 1997; “Landfill gas Flaring”, Proceedings of the Sixth International Landfill Symposium, Sardinia, October 1997.

Hackl A and Mauschitz G, 2000. “Greenhouse Gas Mitigation by Proper Waste Management”, Federal Ministry for Environment, Youth and Family Affairs, Vienna, Austria.

Hendriks C *et al*, 1998. “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU15”, M714, Ecofys, Utrecht.

Hooper D, 2000. “Generation of Renewable Electricity from Landfill Gas”, Article accepted for publication in Surveyor.

IEA Bioenergy/IEA CADDET, 1998. “Advance Thermal Conversion Technologies for Energy from Solid Waste”, A joint report of the IEA Bioenergy Programme and the IEA CADDET Renewable Energy Technologies Programme, IEA CADDETT Centre for Renewable Energy, ETSU, Harwell, UK.

IPCC, 1997. “IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual”, IEA/OECD, 1996 revisions.

KEMA, 1995. “Comparison between Thermal Destruction of MSW” (in Dutch), KEMA, Netherlands.

Kightley D, Nedwell DB and Cooper M (1995). “Capacity for Methane Oxidation in Landfill Cover Soils Measured in Laboratory-Scale Microcosms”, Applied and Environmental Microbiology, 61, 592-601.

Koller M, 2000. Personal Communication.

Lehtilä A and Tuhkanen S, 1999. “Integrated Cost-effectiveness Analysis of Greenhouse Gas Emission Abatement - The Case of Finland”, Technical Research Centre of Finland Report VTT 374, 1999.

OECD, 1999. “OECD Environmental Data 1999”, OECD/IEA, Paris.

Rubio, JG, 1997; "The role of landfills in the current management of household and industrial waste in Spain", ISWA Handbook 1997/1998, pages 339 - 342.

Soyez K, Thrän D, Völker D and Koller M, 1997; “The German Federal Research Programme on Mechanical-Biological pre-treatment”, Proceedings of the Sixth International Landfill Symposium, Sardinia, October 1997.

UNFCCC, 1999. Database of National Greenhouse Gas Emissions Estimates as submitted to the UN Framework Convention on Climate Change, July 1999.

US EPA, 1998. “Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste” EPA530-R-98-013, USEPA.

Wake JK, 2000. Personal Communication.

Waste Manager, 1999. “Small is Beautiful”, The Waste Manager, November 1999, pp19-21.

Whalen SC, Reeburgh WS and Sandbeck KA, 1990. “Rapid Methane Oxidation in a Landfill Cover Soil”. Applied and Environmental Microbiology **56**, 3405-3411.

APPENDIX A

Participants at Experts Workshop November 24 1999, DG Environment, Brussels

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