SERPECcc

Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC)

Methane in the waste sector

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Executive Summary

The aim of the project Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC) is to identify the potential and costs of technical control options to reduce greenhouse gas emissions across all European Unions sectors and Member States in 2020 and 2030.

In this SERPEC sectoral report, we determine the potentials and costs of control options in the waste sector. Overall, the waste sector in Europe produces about 130 Mt CO_2 eq per year from methane emission from landfills. This is around 2% of the overall greenhouse gas emissions in the EU in 2005. Methane emissions from landfills are expected to decrease to approximately 80 Mt CO_2eq in 2020 and 60 Mt in 2030 (the so-called baseline, see Figure 1). This is the result of improved landfill conditions and a strong reduction of biodegradable waste (BMSW) that goes to landfills; both developments result from the further implementation of the Landfill Directive.

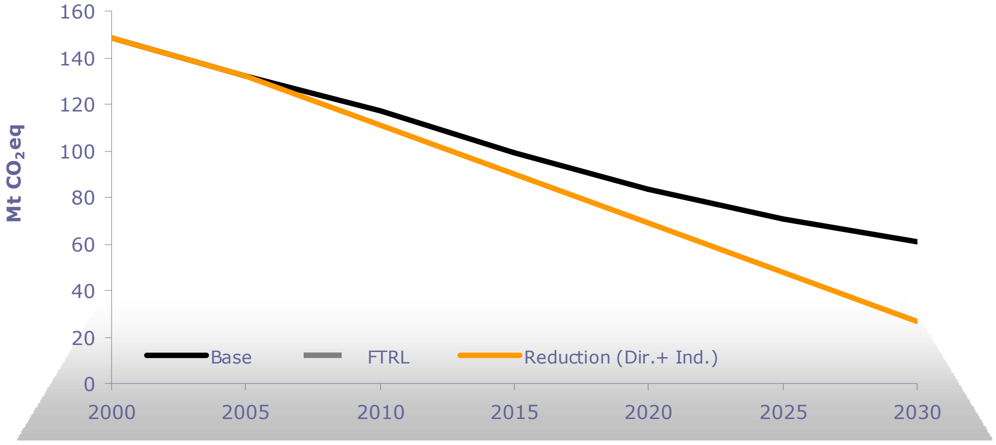

Figure 1. Baseline development and technical reduction potential of methane emissions from landfills in the EU-27.

As a scenario for the total amount of BMSW that can be further diverted from landfilling, we assumed that in 2020 the BMSW to landfill is reduced with 50% compared to the baseline development and in 2030 all biodegradable waste is diverted from the landfill. As a result, methane emissions reduce with around 60% compared to the baseline in 2030 (see Figure 1 and Table 1). The baseline emissions in 2030 do not drop to zero, because historically landfilled waste will continue to produce methane emissions.

BMSW can be diverted from landfill into five waste technologies: anaerobic digestion, composting, mechanical biological treatment, incineration and paper recycling. These technologies are mature but their uptake in the different Member States is not homogenous and far from optimal. The varying degree of penetration of these technologies has been heavily influenced by national policies, e.g. incineration in the Netherlands and Belgium.

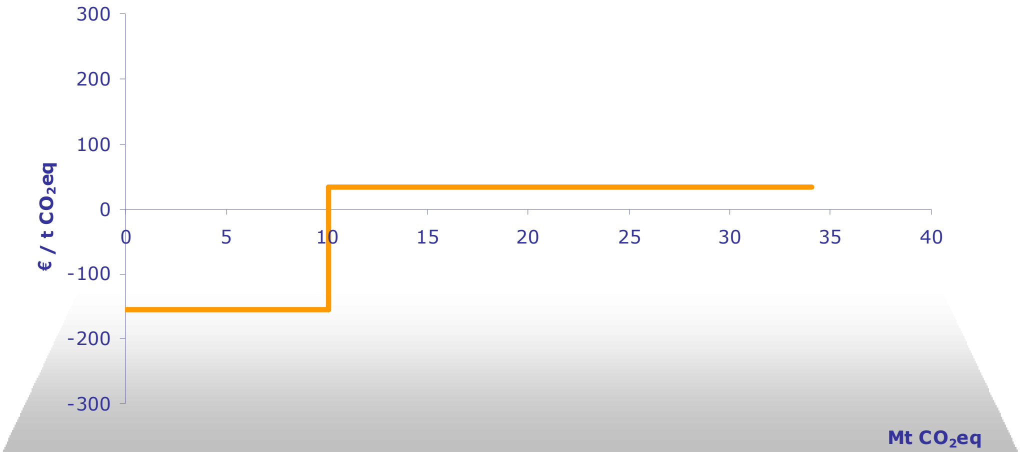

Figure 2. Specific costs and abatement potential of measures that reduce methane emissions from landfills in the EU-27 (year of 2020).

Some 25% of the BMSW volume consists of recyclable paper. Re-using this paper as input for pulp production is by far the most cost-efficient option (see Figure 2). This option has negative specific costs, because in the paper production process, pulp from waste paper can easily replace the much more expensive primary pulp. Attributing the remaining BMSW to composting, mechanical biological treatment, anaerobic digestion or incineration is difficult because these options are mutually exclusive and have comparable specific costs. Figure 2 therefore presents the remaining abatement potential at the average specific costs of these four options.

Table 1 Cost-efficiency of five SERPEC waste technology options.

Name	**SpecificCost (€/t-CO2)**
Recycling of paper	-155
Composting	28
Mechanical biological treatment (MBT)	32
Anaerobic digestion	36
Incineration with CHP	37

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1 Introduction

1.1 The SERPEC project, methane in the waste sector

The SERPEC project

The aim of the project Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC) is to identify the potential and costs of technical control options to reduce greenhouse gas emissions across all European Unions sectors and Member States in 2020 and 2030. The results are presented in so-called cost-abatement curves that provide a least-cost ranking of options across technologies and sectors in the EU. In general, cost-abatement curves provide strategic information for policy makers.

All identified abatement options refer to technologies that are applied already today. To identify their abatement potentials we estimated the maximum feasible implementation rates, often governed by the rate of turnover of existing technology stocks. Costs of already matured technologies were generally assumed constant over time, whereas either costs or performance of relative new technologies, e.g. wind turbines, were allowed decrease over time due to economies of scale and technology learning.

Methane from waste

In this SERPEC sectoral report, we determine the potentials and costs of control options of methane emissions from waste. The average waste production in Europe around 500kg per capita per year and ranges between 245 kg/cap in Poland and 759 kg/cap in Norway, see Figure 3. The way waste is managed differs by country; about 44% of the waste in Europe is landfilled (Figure 4). Landfilling remains the most popular disposal option in two thirds of the EU-27 countries.

The emissions of GHG from landfills can occur due to two degradation processes of biogenic material: the first is the *aerobic* process which produces CO_2 and occurs in the open air on the surface of the landfill, the second is the *anaerobic* process which produces methane and generally occurs in the inner layers of the landfill, away from the oxygen in the air. The CO_2 released into the atmosphere from the aerobic degradation is considered neutral because it has been stored in biogenic materials such as food, paper, cardboard, wood and textiles with the photosynthetic process[i]. Because of the stricter conditions for anaerobic bacteria to grow, methane is produced a few months after the opening of the landfill. However, once the production starts it remains high (at around 50-55% of total gas produced) for 5 to 10 years and then decreases gradually to zero[ii].

Today, methane emissions from landfills account for about 75 % of total greenhouse gas emissions from the waste sector.

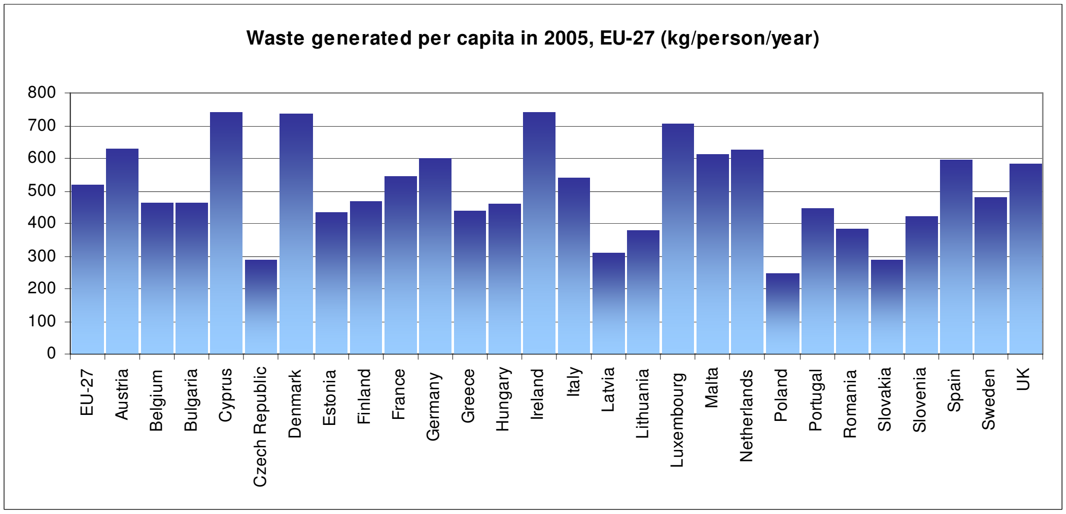

Figure 3 EU-27 per capita waste production by country (Eurostat)

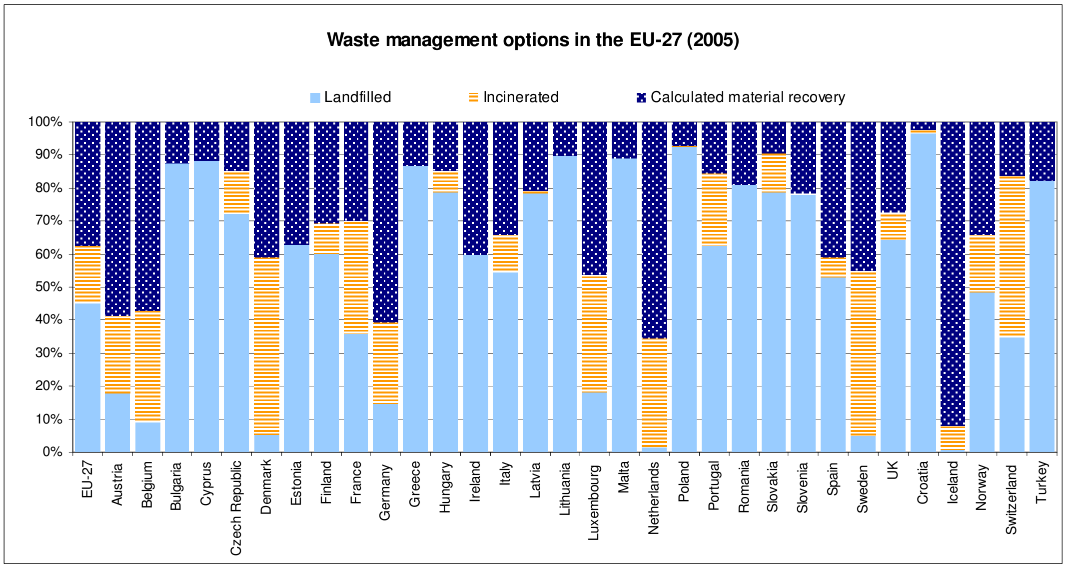

Figure 4 EU-27 waste treatment options by country (2005) (Eurostat)[1]

Although waste is a highly regulated sector, policies aimed at limiting GHG emissions, and therefore at addressing climate change, have only been implemented in the last decade. At the end of 2005, a new waste strategy was presented by the Commission called "Thematic

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[1] Note: To provide an estimate of material recovery, the above figure uses the municipal waste generated minus municipal waste landfilled and incinerated.

Material recovery includes recycling, composting and other types of recovery operations (except incineration with energy recovery).

Strategy on Waste Prevention and Recycling". The main elements of the proposed new strategy are[2]:

- **Life-cycle approach**: Looking at the potential contribution to a more sustainable use of natural resources and raw materials. This aspect is treated separately in another strategy document.
- **Prevention**: All Member states will be required to develop waste prevention policies that will "reach out to the individuals and businesses" responsible for waste generated in the first place. These will have to be adopted within three years following the adoption of the revised waste framework directive. Follow-up reports will have to be submitted every three years afterwards.
- **Recycling**: Will include the development of EU-wide environmental standards on recycling.
- **Simplifying existing legislation**: Follows the principles of the Commission's "better regulation" initiative and contributes to lowering the administrative burden on Member States.
- **Targets**: The new strategy has no quantifiable targets in place and the Commission is not expecting to observe any financial costs on member states and businesses.
- **Incineration**: A revision of the IPPC Directive (Integrated Pollution Prevention and Control) will be tabled that will set "an ambitious benchmark" to improve energy recovery from municipal incinerators. The Commission reports the new energy efficiency benchmark "will determine whether an incinerator can be identified as a recovery facility instead of a disposal facility."

The current EU waste policy is based on a concept known as the waste hierarchy. This means that waste should be prevented and what cannot be prevented should be re-used, recycled and recovered as much as possible, with landfill being used as a last resort. Since landfill is the least desirable disposal option, due to losses of the waste value and high environmental impacts compared to other management options in the hierarchy, the aim of EU waste policy is to move away from it and increase the levels or recycling and recovery.

1.2 Reference case –baseline

Abatement potentials in this study will be defined relative to a so-called business as usual (BAU) baseline scenario. Data on the future volumes of municipal solid waste (MSW) and biodegradable MSW (BMSW) to landfill was mainly taken from projections produced by the EEA's Topic Centre on Waste and Resources[iii], who based their projections on the key economic and demographic assumptions in the PRIMES baseline[iv]. For some of the new EU 12 countries, data on the percentage of waste currently landfilled was not available; in these

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[2] Euractiv: http://www.euractiv.com/en/sustainability/waste-prevention-recycling/article-128551

cases it was assumed that 90% of the waste goes to landfill. In some cases data on current waste was taken form national GHG inventories.

Typically, for methane from waste, this baseline is determined by the amount of biodegradable MSW (BMSW) going to landfill. This amount is strongly governed by the Landfill Directive[v], see next section.

Landfill Directive

The Landfill Directive sets three step-wise targets for the amount of BMSW that can be landfilled in the future, using 1995 values as a reference: member states have to reduce BMSW by 75%, 50% and 35% compared to 1995 levels, after 5, 10, and 15 years respectively, after the directive comes into force. The target year is delayed for countries which currently landfill over 80% of MSW. Countries are expected to meet these targets by linearly decreasing the amount of BMSW they landfill. However, for a country which has already achieved one of these targets when the directive comes into force they must maintain that performance until the next target period, e.g. if a country has already reduced BMSW to 50% below 1995 levels, they are required to maintain it at that level until the 10-year deadline at which point they are expected to start working towards the 15-year target. It is assumed that all of the new EU12 countries will implement the Landfill Directive, according to the timetable agreed at succession; Croatia is also assumed to meet this timetable.

First order decay model

Projections of methane emissions from landfill were made using a first order decay model recommended in the IPCC guidelines and the subsequent “Good Practice Guidelines” (IPCC 1997, IPCC 2000). The IPCC methodology calculates CH_4 emissions based on the quantity of BMSW waste going to landfill and its biodegradability (expressed in terms of dissimiable degradable organic carbon - DDOC). Emissions follow an exponential decay, so it is necessary to include waste deposited in previous years in the model, as this will still be generating methane. Once total methane generated has been calculated, recovered methane (i.e. land-fill gas which is extracted and either flared or burnt for heat or electricity production) is subtracted, and a proportion of the remaining methane is assumed to be oxidised by bacteria as it permeates through the soil cap.

A weighted average for Degradable Organic Carbon (DDOC) per tonne of MSW is calculated based on average waste composition and the DDOC content of each waste fraction taken from the IPCC Good Practice guidelines (IPCC 2000) for the EU15. For the new EU12, data on waste compositions was limited. Bulgaria, Croatia, Czech Republic, Latvia, and Poland give DDOC for waste in their inventory submissions, and these were assumed. For the other countries a value of 10% was assumed, based on the range for Member States where data was available.

The overall resulting baseline emissions are shown in Table 2. The methane emissions in 2020 are similar to the baseline emissions calculated by IIASA (2008) that served as input to the Commissions 2008 climate package impact assessments[3,4].

Table 2 Methane emissions from landfilled waste

Methane emissions from landfills (ktCO2eq)								
	1990	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Austria	5,868	4,623	2,238	1,935	1,658	1,445	1,283	1,163
Belgium	3,368	2,375	980	790	640	523	433	365
Bulgaria	18,016	4,893	6,991	6,320	5,399	4,417	3,597	2,958
Cyprus	469	556	579	559	482	398	328	274
Czech Republic	2,330	1,900	2,138	1,830	1,489	1,202	976	800
Denmark	1,560	1,425	1,260	1,063	900	778	683	615
Estonia	1,686	1,163	619	584	489	398	327	271
Finland	4,380	3,583	2,475	2,165	1,820	1,530	1,303	1,125
France	12,455	12,513	11,295	10,515	9,478	8,475	7,695	7,085
Germany	33,673	12,200	12,400	10,135	8,320	6,793	5,608	4,695
Greece	3,345	5,675	2,828	2,470	2,070	1,720	1,438	1,215
Hungary	1,700	2,300	3,370	3,290	2,882	2,391	1,978	1,655
Ireland	1,380	1,453	1,928	1,688	1,420	1,185	993	845
Italy	11,340	11,230	17,188	14,918	12,633	10,698	9,193	8,018
Latvia	640	755	574	551	469	385	316	263
Lithuania	4,050	1,699	1,131	1,073	938	776	638	531
Luxembourg	75	68	28	25	23	20	18	18
Malta	131	159	172	165	139	113	93	77
Netherlands	14,050	10,095	7,060	5,585	4,425	3,525	2,828	2,293
Poland	19,173	20,243	8,033	7,576	6,412	5,255	4,333	3,615
Portugal	2,883	4,048	5,733	5,008	4,213	3,510	2,940	2,495
Romania	5,270	14,852	5,123	5,087	4,500	3,750	3,110	2,611
Slovakia	1,257	1,207	1,600	1,476	1,256	1,043	869	734
Slovenia	951	1,218	476	459	399	330	272	227
Spain	6,418	12,023	10,273	9,043	7,658	6,488	5,575	4,865
Sweden	3,040	2,423	2,290	1,845	1,495	1,225	1,013	850
United Kingdom	28,285	13,805	23,270	20,925	17,985	15,248	12,985	11,225
EU 27	**187,789**	**148,479**	**132,048**	**117,074**	**99,586**	**83,615**	**70,817**	**60,885**
Croatia	1,902	2,437	1,225	1,116	901	728	601	503
Turkey	19,191	24,067	32,793	31,820	27,169	22,322	18,406	15,356

Source: AEA Technology

Note: Data for 2005 are from submissions to UNFCCC, apart from Malta and Cyprus , where no data is available and they are estimated using the projection methodology; Greece and Turkey values are for 2004 as no emissions data was available for 2005.

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[3] http://www.iiasa.ac.at/rains/reports/IR-07-nonCO2-final_27May2008.pdf

[4] Throughout this report we used Global Warming Potentials (GWP) from the fourth IPPC assessment report: a GWP factor of 25 was used to convert CH4 emissions to CO2 equivalent emissions. CO2-eq numbers may therefore slightly differ from other literature that used a factor of 21.

Table 3 shows the baseline developments of biodegradable MSW (B-MSW) volumes to landfill at the EU27 level as well as the modelled methane emissions over time. The resulting methane emissions per tonne of B-MSW are on average some 60 kg-CH4/t-BMSW. This emissions factor, that also represents the 'lifetime' emissions of a ton of BMSW, was used as in our cost-efficiency calculations (see Annex 1 for a more in depth explanation).

Table 3 Derivation of CH_4 emissions factor in the baseline scenario

EU27 totals	**1990**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Kt B-MSWI	122,158	119,021	111,071	91,837	57,031	49,591	49,655	49,722
Kt CH_4	7,512	5,939	5,282	4,683	3,983	3,345	2,833	2,435
Kg-CH_4/t-BMSW	61	50	48	51	70	67	57	49

1.3 Abatement measures

In this study, we identified five measures to further reduce emissions relative to the base line shown in Table 2. The measures analysed were: anaerobic digestion, composting, mechanical biological treatment, incineration with CHP and paper recycling. All measures reduce the landfilled amount of biodegradable MSW and the associated methane emissions. These technologies are mature but their uptake in the different Member States is not homogenous and far from optimal. The Landfill Directive makes it mandatory to cap open landfills and therefore the recovery of methane from capped landfills is already included in the baseline and will not be discussed here.

1.4 Abatement costs

The textbox describes the standard costs calculation method that we applied in the SERPEC project.

The specific costs of measures in € per tonne of CO2-eq abated

Abatement costs (in €2005) of measures are calculated from the sum of annualised investment costs and annual operating and maintenance costs minus the annual revenues that might occur from biodegradable waste-fuelled energy production, divided by mean annual emission savings of the measures:

$$\text{Specific costs} = \frac{\text{annualised capital costs + annual O\&M costs – annual (energy) production revenues}}{\text{Annual abated CO2}}$$

Capital costs are annualised over the technical lifetime of the measure using a discount rate of 4%. This value is similar to government bond rates. The annual operation and maintenance costs are assumed to remain fixed over the depreciation period.

For calculating the specific costs for measures that abate methane from landfilling, we applied a 'lifetime' emissions factor of 0.06 kg-CH4/kg-BMSW (see *annex 1*)

The overall costs calculation is also referred to as 'social costs'. The method allows for comparison of the 'bare' costs of technologies, across measures, sectors and countries. A negative cost number indicates that from a social perspective there will be a net welfare gain from taking these measures, a positive cost number indicates a net welfare loss.

Note, that the so-called 'end-user' perceives higher energy prices and discount rates. As a result the cost-curve from an end-users perspective looks different.

(Energy) revenue data used in this study are given in Table 4.

Table 4 Revenue numbers for (some) options that reduce landfilled waste

		Remark
Electricity whole sale price	55 €/MWhe	Revenue for the option of increased waste generation
Primary fuel price	5.5 €/GJ	Revenue for the option of increased waste generation, that saves primary fuels needed otherwise

2 Options to reduce CH_4 emissions from waste

Emissions reductions in the waste sector beyond the baseline development can be achieved diversion of the organic fraction of waste (BMSW) away from landfills.

Maximum deployment of abatement options

As a scenario for the total amount of BMSW than can be further diverted from landfilling, we assumed that:

- in 2020 the BMSW to landfill is reduced with 50% compared to the baseline development and
- in 2030 all waste is diverted from the landfill (see Figure 5).

Contrary to greenhouse gas emissions from fossil fuels, methane emissions from landfills are characterised by a large time delay. This is because waste decays slowly over time and the emissions originating from one kg of biodegradable municipal solid waste (BMSW) are released over a period of up to 30 years. As a result, methane emissions from landfills will also respond slowly to the abatement measures defined here. Annex 1 describes, how we attributed methane emission reductions to a volume of waste diverted from the landfill, acknowledging that this measures abates methane emissions that would otherwise have occurred in the landfill between year X and X + 30. Key results are illustrated in Figure 5, which shows that a 100% diversion of waste from the landfill in 2030, will result in a 59% emissions reduction, compared to the baseline, in 2030.

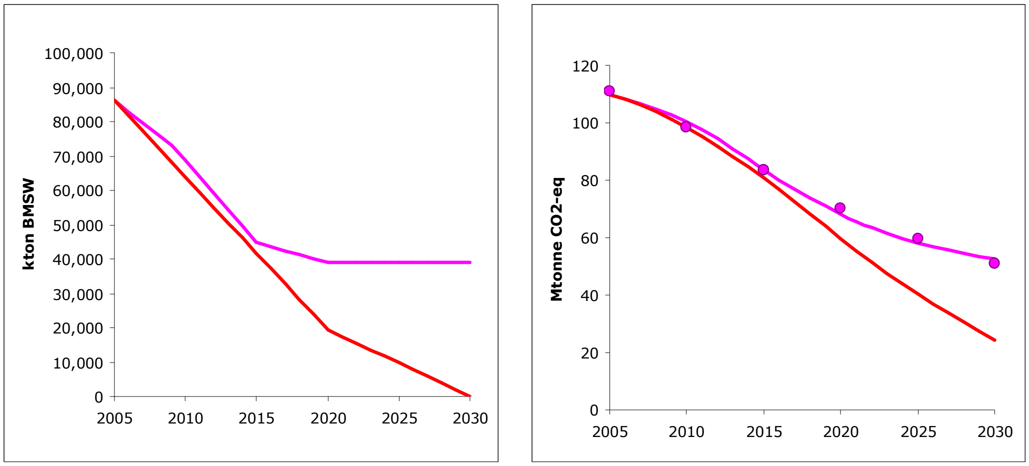

Figure 5 Left-hand graph shows EU27 BMSW volumes in the baseline (upper line) and in the SERPEC maximum abatement scenario. Right-hand graph shows the resulting pattern of CH_4 emissions from landfills in the baseline and in the abatement scenario. See annex 1 for explanation.

2.1 Anaerobic digestion

Anaerobic digestion (AD) is a biological process similar to composting which involves the break down of organic matter by bacteria but unlike composting, AD is performed in an oxygen free environment (anaerobic). The digesters are sealed vessels which allow the control of temperature, moisture, pH and other variables for the optimal growth of the bacteria.

Virtually all biological wastes (biodegradable MSW) can be treated with AD, e.g. food residues, farm manure (e.g. liquid manure, dung), vegetable residues from commerce and trade, waste water from food production, grease trap fat, etc. AD produces a biogas made up of around 60% methane (CH_4) and 40% carbon dioxide (CO_2). The gas can be burned to generate heat or electricity or can be used as a vehicle fuel. As the main purpose of the AD is to produce biogas that is subsequently used to generate power, we assumed a zero methane emissions from this option; although not all AD plants are equipped to produce electricity.

The emissions derived from the AD process and the production of electricity is given in the following table:

Table 5 Key characteristics of AD compared to landfill

	Unit	AD	Landfill (reference)
Lifetime:	y	20	40
Compost Production	kg/t waste	295	0
Energy Consumption	kWh/t waste	50	0
Energy Production	kWh/t waste	160	0
Primary energy saved	GJ/t waste	0.4	-

Cost data

Based on the literature[vi, vii] and publicly available commercial information, investment costs range between €350 and €620 per tonne of waste processed. Operation and maintenance costs instead are between €0, or even minor savings, and €25 per tonne of waste. Costs vary based on the quality and quantity of compost and electricity produced. Compost in southern states is more expensive than compost produced and sold in the UK, Ireland and Germany for example (see next section on composting). Here it is assumed that investment costs are €500 and running costs are €15 per tonne of waste.

2.2 Composting

Composting is a disposal option where the organic fraction of the waste is recycled and turned into compost that can be used as fertiliser. The degradable fraction is digested in aerobic conditions by microorganisms, usually bacteria and fungi. There is a range of composting systems available on the market, at one end there are household composter bins producing around 300kg of compost per year (for an average family of four), at the other end are municipal facilities with a capacity of 50,000 tonnes per year. There are different ways to make compost; these are described in the following sections.

Home composting

Home composting is particularly preferred by municipalities as it avoids transport costs and costs related to the construction, operation and maintenance of composting facilities. The separation of the organic fraction is done at the source and this is an additional avoided cost to the local authority. Despite these encouraging figures home composting has some limitations, notably:

1. The cost of bins which are typically in the range of €85 to €100 for ca.300 litres capacity bin. In some countries local authorities distribute composters for free or at subsidised rates, e.g. the UK, Italy, Belgium, Finland and France.
2. Public commitment
3. Unsuitable for some housing. Home composting is suitable for homes with gardens or land nearby. This limits the penetration rate of composting in urban areas.

Data for home composting is scarce and there are no official statistics for the EU-27.

Vermicomposting

Vermicomposting is a variant to traditional composting where organic material (mainly kitchen waste- green waste) is decomposed by some species of earthworms as opposed to bacteria. The two species mostly used are Red Wigglers (*Eisenia foetida*) and Red Earthworms (*Lumbricus rubellus*). Vermicomposting is generally faster than traditional composting due to the higher level of oxidation produced by the continuous movement of the earthworms in the soil. At present, the market for large scale plants is very limited, e.g. in the UK some 10,000 tonnes capacity systems have been commissioned recently[viii]. There is potential for future growth but the market penetration of this technology remains low across Europe.

Windrow composting

Windrow systems can be cheap solutions, where the biowaste is piled into an open windrow and regularly turned over with a tractor or, more sophisticated, where the waste is automatically turned via a built-in mechanism. The capacity generally ranges from 500 to 100,000 tonnes per year. The operating costs are smaller than the in-vessel system (see below) but more labour is needed and there is little control over aeration and temperature and limited possibility for gas recovery.

In-vessel composting

Organic materials are fed into a drum, silo or similar equipment where the operating conditions—including temperature, moisture, and aeration—are closely controlled. Normally the system includes an automated mechanism to turn the material regularly for optimal aeration. In-vessel composters vary in size and capacity and can process large amounts of waste but in smaller areas compared to the windrow method. In-vessel systems can be broadly categorised into five types: containers, silos, agitated bays, tunnels and enclosed halls. Virtually any kind of biological waste can be processed as the system is enclosed and controlled so no odours are released.

Although this is the most expensive composting option it offers the highest level of flexibility as the control of environmental parameters is fully automated and offers the greatest opportunity to recover off gasses and treat odours.

GHG savings

Although composting may result in some production of methane (due to anaerobic decomposition in the centre of the compost pile), most of it oxidises to CO_2 before being released into the atmosphere from the compost pile. Well-managed compost piles emit marginal amounts of methane. As this study concentrates on potential measures which can be applied consistently across the European Member States, we have assumed that the typical composting facility should follow best practice. Only direct emissions have been calculated and the results compared with our reference scenario, the uncapped landfill.

The direct emissions from composting are compared to the reference case in the table below; note that avoided indirect emissions, e.g. from fertiliser production and use, are not taken into account, but would yield additional potential.

Table 6 Key characteristics of composting compared to landfill

	Unit	Composting	Landfill (reference)
Lifetime:	y	15	40
CH_4 emissions	kg/t waste	0.983	50

Cost data

The price of compost varies depending on the final end-use. For agricultural purposes the average price per tonne is €8 in Europe but high quality compost for garden beds, horticulture and landscaping can cost up to €300 per tonne as shown in the table below[ix]. The price of compost varies geographically and is cheaper in Northern European countries where moisture is easily retained than in Southern Europe where soils are drier and higher in clay content.

Table 7 Compost prices in Europe

Sector	BE	CZ	DE	FI	ES	GR	HU	IE	IT	NL bio	NL green	SE	SI	UK	EU Mean
Agriculture (food)	1.1	-	14	0	27	-	15	-	3	4	2	0	-	2.9	6.1
Vineyards, orchards	1.1	-	-	-	-	-	-	-	12	-	-	-	-	2.9	5.3
Organic farming	1.1	-	-	-	-	42	-	-	-	-	-	-	-	2.9	15.3
Horticulture & green house production	1.1	-	15	-	-	42	-	-	-	-	-	-	-	2.9	15.3
Landscaping	2.5	4.5	15	2	-	-	18	-	25	4	-	-	-	6.5	9.7
Blends	-	-	2	-	-	-	-	3.5	-	-	-	2.9	2.4		
Blends (bagged*)	-	-	-	-	-	-	-	90	200	-	-	-	-	-	145.0
Soil mixing companies	-	-	-	2	-	-	-	-	-	-	-	-	-	6.5	3.2
Wholesalers	-	-	-	-	-	-	-	-	-	-	-	12	-	6,6	
Wholesalers (bagged1))	-	-	160	-	-	-	-	-	-	-	-	-	-	-	160
Hobby gardening	7.2	4.5	-	10	-	-	20	-	13	0.3	-	-	21	20	12.0
Hobby gardening (bagged*)	-	-	-	-	-	300	-	-	-	-	-	-	-	-	300.0
Mulch	-	-	-	-	-	-	-	-	-	-	-	-	3.6	3.6	
Land restoration, landfill covers	1.1	-	-	0.7	-	0	-	-	-	-	-	-	-	0.7	0.6
* High prices because sold in small bags (5 to 20 litres)															

Note: table adapted from Eunomia[viii]

Cost data are derived from the previous sectoral objectives study[x] and complemented with recent publications on UK waste disposal technologies[xi, xii]. The sectoral objectives study was adapted to reflect inflation and indicates that the likely range of investment costs is between €120/t waste and €270/t waste whereas most recent figures suggest costs ranging between €60[x] and €160[viii] per tonne of waste, the average being around €65 /t waste. Running costs are also quite diverse due to the variation of compost prices. The literature suggests running costs can range between around €18[viii] and €86[ix] per tonne of waste, the average being around €37/t waste.

In this case, it is assumed that investment costs are €65 and running costs are €37 per tonne of waste.

2.3 Incineration with CHP

The most dominant technology for municipal solid incineration is the mass-burn system. Fluidised-bed incineration is becoming increasingly popular but is less dominant compared to mass-burn incineration.

Mass-burn technology

In the mass-burn technology waste requires minimal processing with just a separation stage prior to incineration to remove large items such as refrigerators and domestic hazardous waste such as cleaning products and pesticides. The waste is tipped onto the floor and pushed by bulldozers into a pit. From the pit, the waste goes on to a grate system which moves the waste to the combustion chamber. The output of the incineration process are fly ash and flue gas treatment residues which can be disposed of in landfills or reused as inert material in the construction industry. A typical mass burner in the EU-15 has a capacity of 500 tonnes per day (range of 170-1400 t/day)[xiii]. Most of the incineration plants in Europe recover heat for district heating or to supply small industrial estates.

Fluidised beds

Fluidised beds incinerators are generally smaller with a capacity of 50 to 150 tonnes per day. The technology takes its name from a bed of sand or other inert materials such as limestone which bubbles due to direct heating from an upward flow of air. The bed offers a higher mobility than conventional incineration chambers and allows the waste to be efficiently put into contact with heat, disperse and burn. There are different types of fluidised beds: bubbling, turbulent or circulating. The differences lie in the relationship between air flow and bed material, and this defines the type of wastes that can be burned. The incineration of municipal solid waste using a fluidised bed system needs a pre-treatment process such as pre-screening and shredding or the production of RDF pellets. In general, fluidised-bed incinerators seem to be more efficient on smaller scales than mass-burn incinerators. This has implication with regards to their location but so far arguments for better cost-effectiveness of fluidised-beds compared to mass-burners have been inconclusive.

In the EU-27, the share of incineration varies greatly between Member States (MS).The percentage of incineration as waste treatment option is shown in Table 8. The amount of waste incinerated in the EU27 has increased on average over the past years.

Table 8 Share of MSW incinerated over total MSW generated (per capita) (Eurostat)

% of waste incinerated per capita (%)			
	1995	**2000**	**2005**
Austria	12%	11%	25%
Belgium	36%	33%	34%
Bulgaria	0%	0%	0%
Cyprus	0%	0%	0%
Czech Republic	0%	9%	13%
Denmark	52%	53%	54%
Estonia	0%	0%	0%
Finland	0%	10%	9%
France	37%	33%	36%
Germany	16%	21%	28%
Greece	0%	0%	0%
Hungary	7%	8%	7%
Ireland	0%	0%	0%
Italy	5%	8%	12%
Latvia	0%	0%	1%
Lithuania	0%	0%	0%
Luxembourg	53%	43%	37%
Malta	0%	0%	0%
Netherlands	25%	31%	32%
Poland	0%	0%	0%
Portugal	0%	20%	22%
Romania	0%	0%	0%
Slovakia	9%	15%	12%
Slovenia	0%	0%	0%
Spain	5%	6%	7%
Sweden	39%	38%	50%
United Kingdom	9%	7%	8%
EU27	**14%**	**15%**	**19%**
Iceland	19%	12%	7%
Norway	13%	15%	18%
Switzerland	49%	49%	49%
Turkey	0%	0%	0%

GHG Savings

The main GHG gases produced during the incineration of MSW are carbon dioxide (CO_2) and nitrous oxide (N_2O). According to the Fourth Assessment Report (IPCC, 2007)[xiv] the estimated total GHG emissions from incineration in the EU-15 are approximately 9 Mt CO_2 e per year.

In its Good Practice Guidance to the waste sector, the IPCC[xv] reports that the incineration of one tonne of municipal waste in MSW incinerators produces about 0.7 to 1.2 t of CO_2. Part of the CO_2 emitted derives from biogenic material and therefore those emissions are not considered as a contribution to the greenhouse gas effect. Only the CO_2 emitted from fossil sources can be accounted for. The IPCC reports that a typical proportion of fossil materials (i.e. plastics) in MSW ranges from 33 to 50% and an average emission value of 0.415 t CO_2 per tonne of waste is derived. SenterNovem, on the other hand, reports that 16.8% of MSW in the Netherlands is waste from fossil origin. In a recent report CEWEP[5] assumes that the total carbon content of residual waste in European incinerators is approximately 26% and that 40% of this is of fossil origin (13.8% of total MSW as opposed to the Dutch figure of 16.8%). In this report we will assume the same carbon content of fossil origin as assumed in the CEWEP study as this is more up to date with industry figures and is also based on European plants.

Most of the incineration facilities in the Member States have energy recovery systems to increase their efficiency and lower the costs. The recovery system has a positive effect on the net emissions as the waste displaces fossil fuels in the production of electricity and heat. Although part of the energy is used internally to run the plant the net result is still an incremental reduction of emissions.

Values for new incinerators in terms of emissions, electricity and heat are compared to the reference in the table below:

Table 9 Key characteristics of incineration compared to landfill

	Unit	**Incineration**	**Landfill (reference)**
Lifetime:	y	25	40
Electricity production	MWh/t waste	0.375	0
Heat production	GJth/t waste	0.221	0

Source: CEWEP

Cost numbers

The cost estimates are for mass-burn incinerators with energy recovery and therefore include income from electricity production. The investment costs are around 448 € per tonne of waste and running costs are estimated at 49 € per tonne of waste per year (source: CEWEP[xvi] and EIONET[xvii]).

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5 Waste-to-Energy and the revision of the waste framework directive, Kees Wielenga, Ffact and CEWEP, Feb 2008. Available at:

http://waste.eionet.europa.eu/wp/wp1_2007

5 Prices are for plants in the UK and Germany

2.4 Mechanical Biological Treatment (MBT)

Mechanical biological treatment or mechanical biological pre-treatment is a combination of solid waste treatment systems.

The process includes two steps:

1. Mechanical separation/sorting of the waste: electrical equipment is used to mechanically remove recyclable waste left in the waste stream (e.g. metals, plastics, glass). In this step, the plant is either configured to recover the individual elements of the waste or produce a refuse-derived fuel (RDF). RDF is becoming increasingly important in Europe as a substitute fuel in cement and lime manufacturing and also in incineration and power plants for energy generation.
2. Biological treatment: the waste is composted or anaerobically digested. In this step the waste is made biologically safe and inactive so it can be landfilled without releasing methane. If the residue is of good quality it can be used as a soil additive, if not it can be used as inert material for land reclamation and restoration, or sent directly to landfill.

The main output of an MBT facility is RDF. In the biological treatment step methane is produced in the same way as in dedicated AD facilities. In the majority of cases this gas is recovered either for internal use or sold to the grid.

This technology has seen a recent boom in capacity mainly due to policy drivers such as the Landfill Directive and the Packaging Directive which both aim to minimise landfill use. Due to this high dynamicity, any figure on the MBT market is purely indicative as every month new capacity is added and the market profile changes accordingly.

As described above, the advantage of MBT compared to AD or composting alone is that not only methane produced by the biodegradable fraction of the waste is collected for electricity generation, but the preliminary sorting process also helps to reduce energy use in plants where recyclate can be used as a substitute for raw materials. In this report reduced energy use from the use of scrap instead of virgin materials is not accounted for and therefore the potential for environmental benefits are underestimated.

Savings

MBT plants are effectively mechanically sorting plants where the output waste can then be recycled, composted, digested, incinerated and landfilled. The biogenic waste stream responsible for methane emissions is treated in an AD digester, after the sorting process, for neutralisation and recovery of the biogas. The remaining residues are landfilled if they do not comply with the European or national compost quality standards. As discussed in the previous paragraphs, methane emissions from composting, recycling and incineration are marginal if not zero, and therefore in this analysis the emissions savings only compare the

AD process to the reference landfill. The comparative savings are listed in the following table:

Table 10 Key characteristics of MBT compared to landfill

	Unit	MBT	Landfill (reference)
Lifetime:	y	20	40
Electricity production	kWh/t waste	81	0
Heat production	kWh/t waste	76	0
RDF production	% waste	40%	0%

Source: Haase Group, UK government, Juniper, and Friend of the Earth[xviii, xix, xx, xxi].

Cost numbers

In comparison to AD systems, MBT plants will incur higher electricity consumption for the waste separation phase but will also have a higher potential for displacing fossil fuel via the production of RDF burned in industrial furnaces and incinerators.

The cost estimates below include the mechanical operations (sorting, separation, size reduction and sieving steps) as well as the biological treatment (which can be aerobic for an RDF or compost output or anaerobic for a biogas output). Refuse derived fuel (RDF) is the main output of MBT plants and is a mixture of low calorific material such as plastics and degraded paper. RDF has become increasingly popular in the last 2-3 years in markets outside Germany and Austria, where MBT plants are very common, mainly because it is seen as a valid alternative to fossil fuels in incineration processes in a range of manufacturing industries (e.g. cement, bricks, but also in Energy from Waste facilities). The gate fees for RDF vary greatly between Member States and in some cases they can be negative (the MBT plant operators have to pay a fee to have their RDF incinerated).

The increase in interest in this technology has lowered the prices in recent years. Investment costs are now in the range of €240-250[6] per tonne for facilities which can process between 12 and 25 million tonnes of waste per year. For bigger plants costs are even lower at €185-190 per tonne of waste for a plant capacity of 37.5 million tonnes per year, [xxii].

Running costs are higher than other technology due to the different steps of the waste processing but remain contained to due recyclate and RDF revenues. Generally running costs are on average €0-65 per tonne of waste [xix, xx, xxi].

Here the cost curve was built using investment costs of €250/t waste and running costs of €35/t waste.

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[6] Prices are for plants in the UK and Germany , see reference xvii, xvii, xix, xx.

2.5 Paper recycling

Paper recycling is a viable alternative to landfill and is already well established in Europe. The recycling rates in Europe have significantly increased over the last decade and although most of the recycled paper comes from the industry sector, the rate of paper recycled from municipal solid waste is also steadily increasing.

The main problem in recycling is the quality of the recycled material: a high degree of separation between waste streams from the source (e.g. households) contributes to a more limited degree of contamination. Paper that is heavily contaminated with food, is glossy or has been processed already several times cannot be recycled and the higher the contamination level the lower quality of the material.

The quality of the recycled material also affects the price with higher quality paper being more expensive than corrugated cardboard.

Recycling paper however contributes to avoid emissions from landfills and from primary production of paper with additional beneficial effects in terms of wastewater treatment and soil contamination.

In this study only avoided emissions from landfills are included, whereas transport and paper making from virgin materials are not covered, but would in practice yield additional benefits.

Greenhouse gas savings

The savings were calculated based on the MSW composition as reported by the EU Commission[xxiii] , the EEA[xxiv] and OECD statistics[xxv]. The share of paper in BMSW was calculated as a percentage of paper over the sum of wood, paper, garden, food and textile waste. The resulting percentage for each country was then assumed to be constant over the years.

Table 11 Percentage of paper in biodegradable municipal waste

2005	Paper fraction in biodegradable waste (%)	Recyclable paper in BMSW
Austria	30%	24%
Belgium	30%	24%
Bulgaria	32%	26%
Cyprus	41%	33%
Czech Republic	14%	11%
Denmark	48%	39%
Estonia	33%	27%
Finland	34%	28%
France	46%	38%
Germany	25%	20%
Greece	23%	19%
Hungary	32%	26%
Ireland	54%	43%
Italy	41%	33%
Latvia	24%	19%
Lithuania	24%	19%
Luxembourg	30%	24%
Malta	41%	33%
Netherlands	25%	20%
Poland	24%	19%
Portugal	32%	26%
Romania	32%	26%
Slovakia	26%	21%
Slovenia	26%	21%
Spain	29%	24%
Sweden	34%	27%
United Kingdom	49%	40%
Croatia (Hrvatska)	26%	21%
Turkey	23%	19%

Note: Due to lack of data Cyprus was assumed same as Malta, Croatia same as Slovenia and Turkey same as Greece.

The maximum potential for paper recycling is estimated around 81%[xxvi]. Around 19% of paper products put on the market cannot be collected or recycled due to technical reasons or because they are used in permanent applications such as cigarette paper, tissue paper and archiving.

Costs data

The costs (revenues) from this option where estimated as follows. We took paper production from primary pulp as the a reference for secondary paper production (from collected waste paper) production. Here, the recovered-paper-pulp simply replaces the more expensive primary pulp. Paper mills can cope with a change from primary to secondary inputs without large investments in equipment. Thus, the net cost advantage from changing to recovered-paper pulp can be deduced from the price difference between primary pulp and recovered-paper pulp.

Market prices of primary pulp as well as collected waste paper vary strongly over time and with collected waste paper classes. We used an average price for collected waste paper of 80 €/ton and a primary pulp price of 500 €/ton[7]. To compare these prices, the waste paper prices need to be corrected, as replacement of 1 ton of primary pulp requires around 1.58 ton of waste paper (e.g. correcting for additives and poor quality of waste paper). Thus a waste paper price of 80 €/ton compared to a waste-paper-pulp price of 130 €/ton. The cost-advantage of shifting to waste-paper pulp is 370 € per ton of pulp (500 minus 130), which equals 232 € per ton of collected waste paper.

Sensitivities

As environmental savings for this recycling option we count the CH_4 emission abated at the landfill; emissions that would have occurred from decaying paper in case the paper was landfilled. From the environmental perspective, this is a *conservative* estimate, as we do not take into account the (complicated) assessment of CO_2-savings that could occur in the paper chain (saving primary pulp production and trees, etc.). Also, our simple cost estimate may be conservative (net revenues may be higher than estimated here) because we do not take into account secondary effects of saving energy on primary paper production. On the other hand, we assume infinite replacement of primary pulp by secondary paper pulp, whereas in practise such can become more difficult and more expensive when recycling increases and lower quality grades of waste paper are used.

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[7] Based on price information supplied by the Dutch paper and board association.

3 Conclusions

As a maximum deployment scenario for the amount of biodegradable municipal waste (BMSW) than can be further diverted from landfilling, we assumed that in 2020 the BMSW to landfill is reduced with 50% compared to the baseline development and in 2030 all waste is diverted from the landfill. This BMSW can be input to five waste technologies: anaerobic digestion, composting, mechanical biological treatment, incineration and paper recycling. As a result, methane emissions from the landfill will reduce with around 60% compared to the baseline in 2030 (see Figure 6). The baseline emissions in 2030 do not drop to zero, because historically landfilled waste will continue to produce (declining) methane emissions.

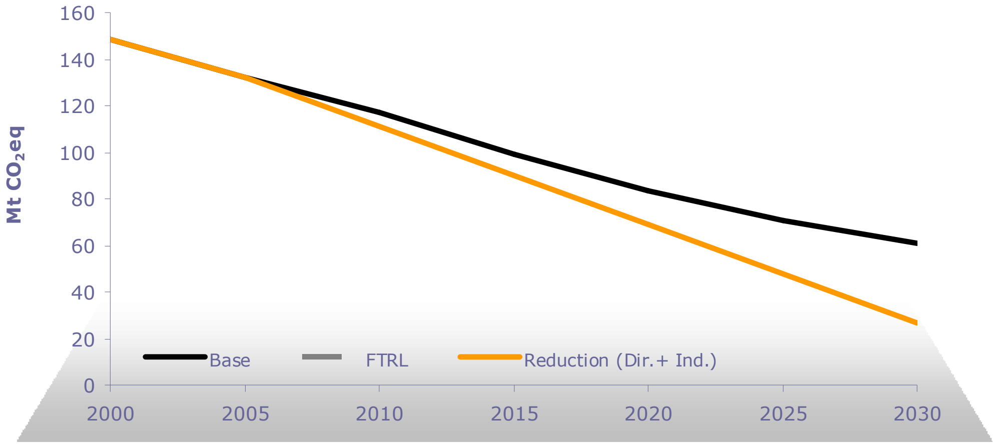

Figure 6 Baseline development and technical reduction potential of methane emissions from landfills in the EU-27.

From a cost-efficiency point of view, recycling of paper is clearly the favoured option (see Table 12). Some 25% of the BMSW volume consists of recyclable paper and therefore this option can abate a same share of the total methane abatement potential. Assigning an abatement share to the other individual technologies is difficult because they are mutually exclusive and have comparable specific costs. For presentation sake, we assumed that these options all have a same share in the remaining abatement potential (see Figure 7).

Table 12 Cost-efficiency of five SERPEC waste technology options.

Name	**SpecificCost (€/t-CO2)**
Recycling of paper	-155
Composting	28
Mechanical biological treatment (MBT)	32
Anaerobic digestion	36
Incineration with CHP	37

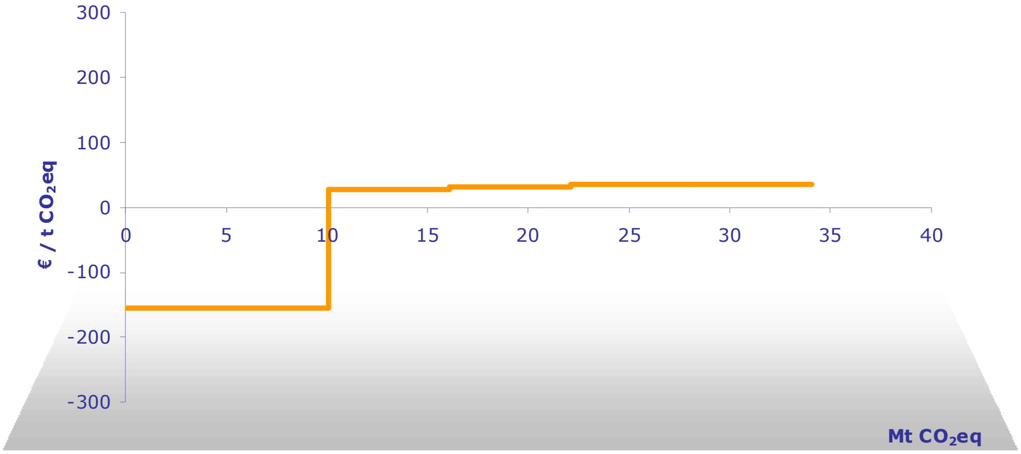

Figure 7 Specific costs and abatement potential of measures that reduce methane emissions from landfills in the EU-27 (year of 2020).

Annex-1 Assessing CH_4 emission reductions

1. The environmental perspective

Modelling delayed response of methane emission reductions to abatement measures

Contrary to greenhouse gas emissions from fossil fuels, methane emissions from landfills are characterised by a large time delay. This is because waste decays slowly over time and the emissions originating from one kg of biodegradable municipal solid waste (BMSW) are released over a period of up to 30 years, see Figure 8.

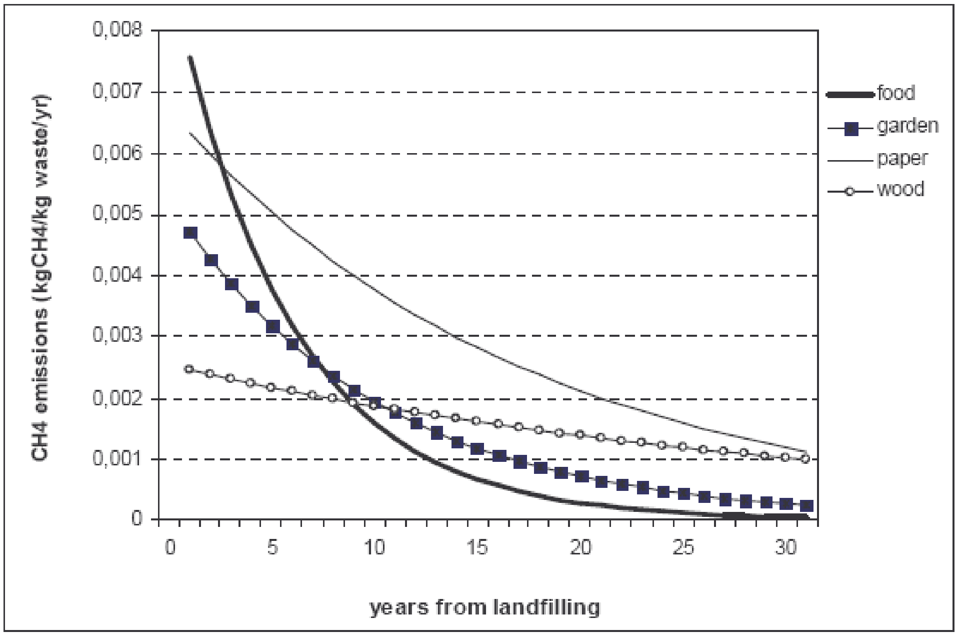

Figure 8 Example of methane emissions over time using a first order decay model (Source: Figure 5.3 from ETC/RWM, 2007)

In SERPEC, we define five options that can each divert waste from landfilling e.g. to composting or incineration. The question poses itself:

How can we attribute methane emission reductions to a volume of waste composted in year X that abates methane emissions that would have occurred in the landfill between year X and X + 30?

When reporting emissions to UNFCCC, most EU member states apply a first order decay model (so-called Tier 2 method) to estimate methane emissions from landfills. This is in line with IPCC good practice guidance. However, countries apply different Tier 2 models and assumptions.

For SERPEC we created a simplified first order decay model. A generic average emissions factor for biodegradable waste of 0.006 kg CH4/kg-BMSW in year X = 1 was used (see Figure 8) and an annual decay-factor of 0.9. These 2 parameters can be used to model, at an aggregated level, the exponential decrease of methane emissions of a kg of waste as shown in Figure 8. The life-time emissions of one kg of biodegradable waste add up to 0.06 kg-CH4/kg-BMSW.

We used these parameters to reproduce the baseline methane emissions from landfilling at the EU-level, which were derived elsewhere with a more detailed 1st order decay model. Results are shown in Figure 9. This figure shows the delayed response of baseline emissions (scenario-1) to the strong baseline decrease in BSMW between 2005 and 2020.

As a scenario for the total amount of BMSW than can be further diverted from landfilling, we assumed that

- in 2020 the BMSW to landfill is reduced with 50% compared to the baseline development and
- in 2030 all waste is diverted from the landfill (scenario-2).

The corresponding methane emissions graph (Figure 2, right-hand side) now shows the time delay in the emissions profile: in 2020, emissions are 14% below the baseline and in 2030 59% below the baseline. Scenario-3 shows that even when we assume a total stop on BMSW landfilling from 2011 on, the landfill will still emit some methane in 2030.

In SERPEC, we applied BMSW-reduction scenario-2. From our simple 1st order decay model we derive that this reduces baseline emissions with 14% in 2020 and 59% in 2030. This reduction was applied to landfill emissions in all Member States. While this approach does not account for Member State specific landfilling conditions, it does give a first approximation of the expected time delay in methane emissions reductions when BMSW is diverted from the landfill. For Member State specific studies, this approach should be refined.

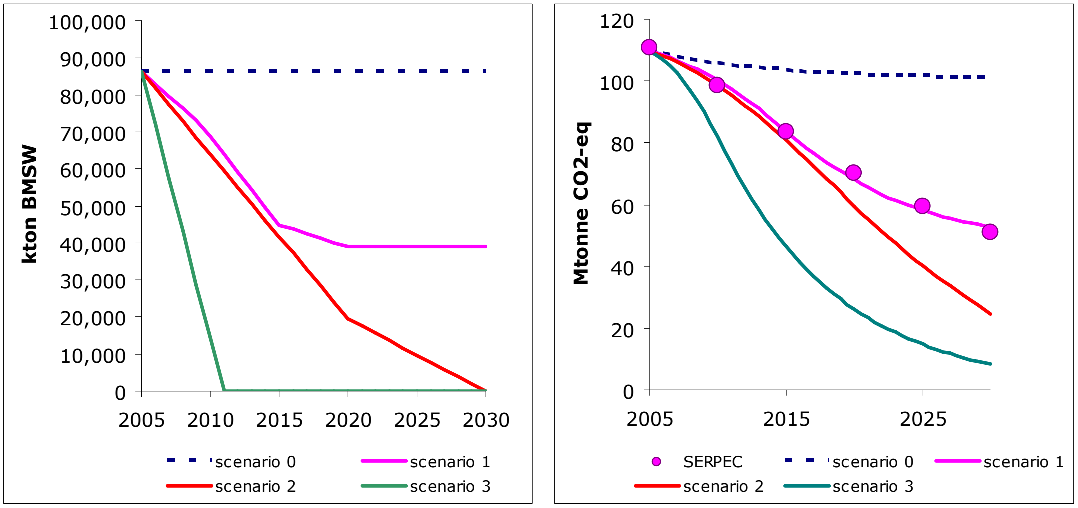

Figure 9 Left: scenarios for BMSW going to landfill at the EU27 level. Scenario-1 is the baseline scenario, scenario-2 the SERPEC scenario. Right: methane emissions from landfilling at the EU27 level, resulting from 1st order decay and BMSW inputs as shown in left-hand figure (further explanation, see main text).

2. The economic perspective

As shown in the previous section, estimating the ‘real life’, delayed, environmental response of methane emissions to waste measures requires a first order decay model.

In addition, we also need to determine the cost-efficiency of measures (€/t-CO_2-eq) for SERPEC, i.e. the ratio of the costs and the impact of a measure. Now the question becomes:

How many methane reduction ‘credits’ should we attribute to one kg of waste that is transferred e.g. to composting or recycling in Year X?

Here the perspective is different from the argument presented in the previous section .

Let us imagine a steady state situation where the owner of a composting unit continuously receives a batch of 1 kg of BMSW each year (e.g. during its life-time of 30 years). In the 20th year of its existence, the unit abates the methane emissions from the batch of waste that is composted in that year (0.006 kg-CH_4/kg-BMSW), but also receives the CH_4-credits of the batch that was composted in t = 19 (0.006*0.9 kg-CH_4/kg-BMSW) and also the credits from the batch that was composted in t = 18 (0.006*0.9*0.9 kg-CH_4/kg-BMSW) and so forth.

So, for the 1 kg batch processed in 2020 the unit actually receives in that year the array of credits representing the life-time emissions originating from one kg of BMSW, adding up to 0.06 kg-CH_4/kg-MBSW.

A similar method of assigning abatement ‘credits’ is applied in the UNFCCC CDM crediting procedure for composting units .

In summary, for calculating the cost-efficiency of measures that abate methane from landfilling we apply a ‘lifetime’ emission factor of 0.06 kg-CH4/kg-BMSW.

Glossary

(BAU)	business as usual
(BMSW)	Biodegradable Municipal Solid Waste
(REF)	Landfill Directive
(MSW)	Municipal Solid Waste
(DDOC)	Dissimiable Degradable Organic Carbon
(GJ)	Gigajoule
(AD)	Anaerobic digestion
(MS)	Member States
(RDF)	Refuse-Derived Fuel
(MBT)	Mechanical Biological Treatment
(MSW)	Municipal Solid Waste
(IPPC)	Integrated Pollution Prevention and Control
(MWhe)	Mega watt hour electric energy
(GJth)	Giga Joules thermic energy
(CHP)	Combined Heat and Power

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