Executive Summary

This document is the final report of a study undertaken for the European Commission Environment Directorate General by AEA Technology to assess the climate change impacts of options for municipal solid waste (MSW) management in the EU. The study covers the fifteen member states of the European Union and the time horizon 2000 to 2020.

The study is intended to inform developing EU-level waste policy, *in terms of climate change impacts only*. Climate change impacts are only one of a number of environmental impacts that derive from solid waste management options. Other impacts include health effects attributable to air pollutants such as NO_x, SO_2, dioxins and fine particles, emissions of ozone-depleting substances, contamination of water bodies, depletion of non-renewable resources, disamenity effects, noise, accidents etc. These environmental impacts are in addition to the socio-economic aspects of alternative ways of managing waste. All of these factors need to be properly considered in the determination of a balanced policy for sustainable waste management, of which the climate change elements are but one aspect. The study is not intended as a tool for municipal or regional waste planning, where local factors, such as the availability of existing waste management facilities and duration of waste management contracts, markets for recyclables, geographic and socio-economic factors, will exert the dominant influence.

The study assesses climate change impacts in terms of net fluxes of greenhouse gases from various combinations of options used for the management of MSW. The waste management options considered are:

- **Landfill of untreated waste.** Bulk untreated MSW is deposited in landfills. Alternative assumptions concerning the control of methane emissions in landfill gas (including the use of gas for electricity generation) are tested in the analysis.
- **Incineration.** Options assessed include mass-burn incineration of bulk MSW with and without energy recovery (as electricity only and combined heat and power - CHP), refuse-derived fuel combustion and pyrolysis and gasification;
- **Mechanical biological treatment (MBT)**. Bulk MSW, or residual wastes enriched in putrescible materials after the removal of dry recyclables, is subjected to a prolonged composting or digestion process which reduces the biodegradable materials to an inert, stabilised compost residue. The compost, which cannot be used in agriculture or horticulture because of its poor quality, is then landfilled. The treatment results in a significant reduction in methane forming potential of the compost in the landfill compared with untreated waste. Metals are recovered for recycling during the MBT process. Some of the paper and plastics in the incoming waste are diverted from the MBT process. These rejects are sent for either direct landfilling or incineration.
- **Composting.** Good quality garden and food wastes are segregated at source and composted, producing a bulk-reduced stabilised humus residue of compost that is of sufficient quality to be marketed as a soil conditioner or growing medium in agriculture or horticulture. Options of centralised composting facilities and home composting are considered.
- **Anaerobic Digestion** (AD). Like composting, this option produces a compost residue from source-segregated putrescible wastes for use in agriculture or horticulture. The

waste is digested in sealed vessels under air-less (anaerobic) conditions, during which a methane-rich biogas is produced. The biogas is collected and used as a fuel for electricity generation or CHP.

- **Recycling.** Paper, glass, metals, plastics, textiles and waste electrical and electronic equipment are recovered from the waste stream and reprocessed to make secondary materials.

Options are considered for MSW collected in bulk with limited recovery of recyclable materials and for materials segregated at source for more extensive recycling and (in the case of food and garden wastes) composting or AD. In addition to MSW, the study also assesses the greenhouse gas fluxes associated with managing waste electrical and electronic equipment (WEEE) disposed of with the MSW stream.

The principal processes quantified in the study that lead to *positive* greenhouse gas fluxes are as follows:

- Emissions of methane from the landfilling of biodegradable wastes (mainly paper and food and garden wastes – the latter known collectively as putrescible waste);
- Emissions of fossil-derived carbon dioxide from the combustion of plastics and some textiles in incinerators;
- Emissions of nitrous oxide during incineration of wastes;
- Emissions of fossil-derived carbon dioxide from the collection, transportation and processing of wastes, from the fuel used in these operations.
- Emissions of halogenated compounds with high global warming potentials used in WEEE (as refrigerants and insulating foam in fridges and freezers).

A number of processes lead to *negative* fluxes of greenhouse gases. These are as follows:

- Avoidance of emissions that would have been produced by other processes – for example:
  - energy recovered from incineration avoids the use of fossil fuels elsewhere in the energy system;
  - recycling avoids the emissions associated with producing materials recovered from the waste from primary resources;
  - use of compost avoids emissions associated with the use of any peat or fertiliser that it displaces.

- The study also takes account of non-fossil carbon stored (ie *sequestered)* in the earth's surface for longer than the 100-year time horizon for global warming adopted for the analysis. The main contributors to carbon sequestration are:
  - slowly degrading carbon stored in landfills receiving untreated biodegradable waste;
  - biodegradable waste stabilised by MBT treatment prior to landfilling, and
  - carbon in compost that is incorporated into stable humus in the soil

The net greenhouse gas flux from each waste management option is then assessed as the sum of the positive and negative fluxes. The study has also gathered information on the costs of alternative waste management options.

The **conclusions** are as follows:

1. The study has shown that overall, source segregation of MSW followed by recycling (for paper, metals, textiles and plastics) and composting /AD (for putrescible wastes) gives the lowest net flux of greenhouse gases, compared with other options for the treatment of bulk MSW. In comparison with landfilling untreated waste, composting / AD of putrescible wastes and recycling of paper produce the overall greatest reduction in net flux of greenhouse gases. The largest contribution to this effect is the avoidance of emissions from landfills as a result of recycling these materials. Diversion of putrescible wastes or paper to composting or recycling from landfills operated to EU-average gas management standards decreases the net greenhouse gas flux by about 260 to 470 kg CO_2 eq/tonne of MSW, depending on whether or not the negative flux credited to carbon sequestration is included.

2. The issue of carbon sequestration is a particularly important for landfills (and for MBT compost after landfilling), where the anaerobic conditions enhance the storage of carbon. Carbon sequestration plays a relatively small role in the overall greenhouse gas flux attributed to composting, because of the relatively rapid rate of decomposition of the compost after its application to (aerobic) soils.

3. The advantages of paper recycling and composting over landfilling depend on the efficiency with which the landfill is assumed to control landfill gas emissions. For sites with only limited gas collection, the benefits of paper recycling and composting are greater, but less when best practice gas control is implemented. In this case the net greenhouse gas savings from recycling and composting range from about 50 to 280 kg CO_2 eq/tonne MSW. If landfills further reduce methane emissions with a restoration layer to enhance methane oxidation, then recycling and composting incur a small net penalty, increasing net greenhouse gas fluxes to about 20-30 kg CO_2 eq/tonne MSW, if carbon sequestration is taken into account. If sequestration is neglected, then recycling and composting attract a net flux saving of about 50 (putrescibles) to 200 (paper) kg CO_2 eq/tonne MSW.

4. The study has also evaluated the treatment of contaminated putrescible waste using MBT, which may be appropriate if such waste cannot be obtained at high enough quality for composting with the aim of using the compost as a soil conditioner. MBT performed almost as well as AD with CHP in terms of net greenhouse gas flux from putrescible waste, but this advantage was largely determined by the credit for carbon sequestration. If this was not taken into account, then composting or AD of source-segregated wastes remained the best options. Omitting carbon sequestration significantly worsens the greenhouse gas fluxes calculated for landfills and MBT, but has a much smaller effect on composting or AD.

5. It must be emphasised that the apparent advantage of high-quality landfilling over composting and recycling of putrescibles and paper noted above refers only to greenhouse gas fluxes. Issues of resource use efficiency, avoided impacts due to paper making from virgin pulp and improvements in soil stability, fertility and moisture-retaining properties stemming from the use of compost in agriculture must all be considered as part of the assessment of the overall 'best' option. These factors are outside the remit of the present study, but their inclusion would almost certainly point to recycling and composting in preference to any form of landfill disposal for these waste components. Improving landfill gas management to reduce greenhouse gas emissions is

therefore essentially an ‘end of pipe’ solution, which reduces only one of the impacts of landfilling biodegradable waste without tackling the root cause.

6. For other materials (glass, plastics, ferrous metal, textiles and aluminium), recycling offers overall net greenhouse gas flux savings of between about 30 (for glass) and 95 (for aluminium) kg CO_2 eq/tonne MSW, compared with landfilling untreated waste. For these materials, the benefits are essentially independent of landfill standards and carbon sequestration.

7. For mainstream options for dealing with bulk MSW as pre-treatment for landfill, the option producing the lowest greenhouse gas flux (a negative flux of some 340 kg CO_2 eq/tonne MSW) is MBT (including metals recovery for recycling) with landfilling of the rejects and stabilised compost. MBT with incineration of rejects (energy recovered as electricity) gives a smaller net negative flux of about 230 kg CO_2 eq/tonne. Mass-burn incineration where half the plants operate in electricity only and half in CHP mode gives a net negative flux of about 180 kg CO_2 eq/tonne MSW. If all the incineration capacity were assumed to operate in CHP mode, then the net flux from incineration would be almost the same as from MBT with landfill of rejects. On the other hand energy recovery from incineration as electricity only would produce a net flux of only –10 kg CO_2 eq/tonne. These figures are based on EU-average landfill gas control, inclusion of carbon sequestered in MBT compost after landfilling and the replacement of electricity and heat from EU-average plant mix.

8. If the benefits of carbon sequestration are left out of the comparison of options just presented, then the MBT options both produce net positive greenhouse gas fluxes of 23 to 55 kg CO_2 eq/tonne MSW. Incineration is unaffected by assumptions on carbon sequestration.

9. The performance of MBT with landfilling of rejects is further improved as higher standards of landfill gas control are implemented, relative to mass-burn incineration, provided the contribution from carbon sequestration is included. If sequestration is omitted, incineration continues to perform better than MBT.

10. As stated in point 7 above, under the baseline assumptions used in this study, MBT with landfill of rejects gives rise to a lower (net negative) greenhouse gas flux than MBT with incineration of rejects. The main reason for this difference is lies in the source of greenhouse gas emissions in the two options. In MBT with landfill, methane emissions from the landfilled material is the main contributor to the positive flux, whilst for MBT with incineration, methane emissions are much lower but are more than outweighed by fossil carbon dioxide released from incinerating the plastic rejects. The relative performance of the two options depends crucially on the effectiveness of landfill gas control and, in the case of MBT with incineration, the energy source that is displaced by recovering energy from incineration. In the analysis performed here, we have assumed that electricity only is recovered, although in some cases there may be opportunities for recovering heat as well. This would further enhance the performance of MBT with incineration compared with MBT with landfill. It appears therefore that the choice between these options will largely depend on local circumstances, although either will offer a major improvement over current practices of landfilling untreated bulk MSW.

11. The issue of the source of displaced energy is critical to the performance of incineration in terms of net greenhouse gas flux. The base case is predicated on the assumption that energy from waste displaces electricity or heat generated at a CO_2 emission factor representative of average EU power and heat sources. For electricity, there has been an increasing trend to combined cycle gas turbine technology in recent years, but this has not been assessed separately because the emission factor from this technology is very close to average plant mix. Two alternatives to replacement of 'average' electricity are considered. They are (a) replacement of coal-fired power generation, and (b) replacement of electricity generated from renewable sources – in this case wind. The example given in (a) could come about, for example, from the accelerated retirement of an old coal-burning power station due to the commissioning of new incineration capacity, or through the use of RDF as a coal substitute. Example (b) may result from the inclusion of energy from waste (ie incineration) technology within a member state's target for renewable energy – as is the case in the UK. The greater the CO_2 emission factor of the replaced generation source, the greater the emission saved due to its replacement by incineration.

12. Replacement of coal-fired electricity generating plant by mass-burn incineration would result in a net negative greenhouse gas flux of almost 400 kg CO_2 eq/tonne MSW, with equal proportions of power only and CHP incineration capacity. Under these circumstances, mass-burn incineration would give practically the same emission saving as recycling and composting of source segregated materials. With all incinerators in CHP mode, mass-burn incineration would be the best overall option in terms of greenhouse gas flux. Combustion of RDF as a coal substitute in power stations or cement kilns gives rise to a net negative greenhouse gas flux of about half this sum.

13. A different picture emerges for the situation in which the electricity displaced by incineration comes from wind power, as an example of low-emissions renewable energy sources. Here the displaced generation source has almost no greenhouse gas emissions. In this case, mass-burn incineration is virtually neutral in greenhouse gas terms. In comparison, MBT with landfill of rejects produces a net negative flux of almost 340 kg CO_2 eq/tonne MSW, which makes it the best option for non-source segregated wastes. MBT with incineration of rejects gives a net negative flux of about 150 kg CO_2 eq/tonne MSW. These comparisons are on the basis of sequestered carbon being included in the overall flux from the MBT options.

14. If carbon sequestration is omitted, incineration and MBT with landfill of rejects have a similar net greenhouse gas flux in absolute terms (of 8 to 26 kg CO_2 eq/tonne MSW), whilst that for MBT with incineration is much higher, at about 135 kg CO_2 eq/tonne MSW.

15. Alternatives to mass-burn incineration have also been evaluated. From the perspective of greenhouse gas fluxes, emissions from pyrolysis and gasification are assessed as being similar to those of mass-burn incineration. Greenhouse gas fluxes from RDF manufacture and combustion (plus landfill of residues and recycling of recovered metals) depends highly on the fuel which they replace. Combustion as a replacement for average electricity plant mix results in higher greenhouse gas fluxes than for mass-burn incineration, due mostly to methane emissions from the landfilled residue left over from RDF manufacture. Improvements in landfill site gas control therefore improve the performance of this option relative to mass-burn incineration, although overall this RDF

option performs consistently worse in greenhouse gas flux than MBT with incineration of rejects.

16. Recycling of WEEE containing CFC refrigerants and foam agents now banned because of their ozone –depleting properties results in a net increase in greenhouse gas flux due to the escape of some of these agents during recycling operations. This leakage is more than sufficient to compensate for the considerable greenhouse gas benefits of recycling the metals from WEEE. Nevertheless, recycling of WEEE containing these materials is far preferable to landfill, where the greenhouse gas flux would be much higher. The use of less harmful refrigerants and foam agents and the adoption of more efficient collection procedures will largely eliminate the net positive greenhouse gas flux associated with WEEE recycling and result in substantial net greenhouse gas savings, due largely to the avoided emissions attributable to metal recycling. However, a considerable backlog of equipment containing CFCs remains to come through to the waste stream over the next 5-10 years and further efforts to minimise the release of GHG during recycling would be desirable.

17. Overall, emissions of greenhouse gas associated with transportation of waste, residues and recovered materials are small in comparison with the much larger greenhouse gas fluxes in the system, such as those related to avoided energy / materials, landfill gas emissions and carbon sequestration. Variations in emissions due to alternative assumptions about transport routes and modalities will therefore have a negligible impact on the overall greenhouse gas fluxes of the waste management options.

18. The study has evaluated four scenarios alternative scenarios of waste management in the year 2020 and compared the impacts on greenhouse gas fluxes with the year 2000. Achievement of the landfill directive's target to reduce the landfilling of untreated wastes in 2016 to 35% of 1995 levels is predicted to result in an overall reduction in greenhouse gas flux from a positive flux of 50 kg CO_2 eq/tonne in 2000 to a negative flux of almost 200 kg CO_2 /tonne in 2020. Even if achievement of the directive's target is delayed until 2020 (rather than 2016), then a negative flux of about 140 kg CO_2 eq/tonne results. Further reductions in greenhouse gas fluxes (to about –490 kg/CO_2 /tonne) could be achieved through investment in recycling, incineration with CHP and MBT. Alternatively, a scenario with no incineration and maximum biological treatment of waste achieves an overall greenhouse gas flux of –440 kg CO_2 eq/tonne.

19. The study has also examined the costs of waste disposal through the various waste management options, as reflected in disposal fees or the prices commanded by recycled materials. Wide difference in disposal costs exist between different member states. Landfill disposal, currently the cheapest option, will inevitably increase in cost with the requirement for higher environmental standards and the consumption of void space as existing sites fill up and close. Little information is available on the costs of MBT, but what there is suggests that this option may become increasingly competitive with landfill and incineration, especially when benefits of increased efficiency of landfill void space use and lower requirements for gas and leachate control are taken into account. Further growth in composting and AD for food and garden wastes will depend to a large extent on continuing success in reducing the costs of separate collection of feedstock and in establishing local markets for the compost product. Recycling remains highly dependent on the market value of the recycled product. With the principal exception of aluminium, the price of materials recovered from MSW does not cover the costs of

separating and reprocessing, compared with virgin materials, and such operations usually require subsidy. This is particularly so of plastic wastes. In this instance the option of co-incineration as a coal-replacement offers comparable greenhouse gas benefits to recycling but at a substantially lower cost.

20. Overall, the study finds that source-segregation of various waste components from MSW, followed by recycling or composting or AD of putrescibles offers the lowest net flux of greenhouse gases under assumed baseline conditions. Improved gas management at landfills can do much to reduce the greenhouse gas flux from the landfilling of bulk MSW, but this option remains essentially an ‘end of pipe’ solution. Incineration with energy recovery (especially as CHP) provides a net saving in greenhouse gas emissions from bulk MSW incineration, but the robustness of this option depends crucially on the energy source replaced. MBT offers significant advantages over landfilling of bulk MSW or contaminated putrescible wastes in terms of net greenhouse gas flux.

21. It must be emphasised that in practice other impacts of waste management options will need to be considered in addition to just greenhouse gas fluxes. These wider considerations will include factors such as resource use efficiency (which will, for example, impinge upon the choice between the *disposal* option of MBT and the *recycling* option of composting or AD) and the impacts of other emissions such as those associated with waste incineration. Furthermore, substantial environmental benefits are associated with the use of compost to improve soil organic matter status and more environmentally-benign methods of cultivation, but only the relatively modest benefits associated specifically with greenhouse gas fluxes have been considered in this study.

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