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Waste and climate

– energy recovery and greenhouse gases

Thomas H. Christensen

Introduction

Society is politically, economically and technically facing the increasing challenge of climate change and struggling to reach targets for reducing greenhouse-gas emissions. No single solution is available, and every sector of society must analyze its current contribution and consider how to improve performance.

This focus on climate change and greenhouse gases has also influenced waste management. The main purpose of waste management is to remove the waste from industrial and residential areas without adversely affecting public health and the environment. Nevertheless, society's need to find renewable energy sources and reduce greenhouse-gas emissions has given a new dimension to waste management: how and how much can waste management contribute to this societal challenge of reducing greenhouse-gas emissions?

Waste management primarily emits greenhouse gases because of fuel use in collection trucks and facilities and waste treatment: for example, incinerating plastic or releasing methane (CH_4) from an anaerobic digestion process. However, waste management can also produce energy that may replace the energy from fossil fuel and recover materials, thereby conserving energy in producing new resources and products. The challenge is to find a balance between emitting greenhouse gases and contributing to reducing the emissions of greenhouse gases at the societal level that lead to the best overall contribution to reaching the goal of reducing these emissions. A life-cycle perspective is needed to balance between aspects because the actual emissions and the reductions take place in different sectors of society and sometimes in different countries. The greenhouse-gas issues have been instrumental in changing the focus from managing waste as a problematic residue to managing waste as a potential residual resource.

During the past decade, the DTU Department of Environmental Engineering has performed laboratory research, pilot-scale experiments and full-scale testing with the aim of establishing mass balances, energy budgets and emission accounts for waste management technologies. The technological insight and data form the basis for modeling waste management technologies and systems with respect to resource and energy recovery. The EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) model integrates this in a life-cycle perspective and has been used for calculating the greenhouse-gas accounts presented here.

Greenhouse gases in waste management

The main greenhouse gases in waste management are carbon dioxide (CO_2) of fossil origin, CH_4 and nitrous oxide (N_2O). Occasionally, chlorofluorohydrocarbons (CFCs) from old refrigerators and insulation materials and sulfur hexafluoride (SF_6) from, for example, thermal glass may locally be a source of greenhouse gases.

CO_2 of fossil origin primarily originates from the use of electricity and fuel and from the combustion of plastic materials. Energy use is associated with all technical processes within waste management, while the contribution from plastic is from waste incineration or waste-to-energy plants. CO_2 of recent biogenic origin is considered neutral with respect to global warming. Most organic material in the waste originates from short-rotation crops and thus was recently synthesized by taking up CO_2 from the atmosphere. Forestry has a longer rotation period, but paper waste is only a small contributor to the stock of biological carbon bound by forestry, and this justifies the assumption that biogenic CO_2 from waste management can be considered neutral with respect to global warming. However, this implies that biogenic carbon not released to the atmosphere as CO_2, such as that stored in the soil after applying compost or buried in a landfill, avoids emission and should thus be ascribed a negative global warming potential of –3.67 kg of CO_2 equivalent per kg of carbon stored. The time horizon associated with the consideration of stored carbon is discussed later. Fig. 10.1 illustrates in an idealized world, using paper as a specific case, how carbon is circulated and used within and between the waste sector, the paper industry, the energy sector and the forestry sector. Modeling of the contributions to increased CO_2 in the atmosphere for a range of waste management scenarios involving recycling paper, incinerating paper with and without energy recovery, landfilling paper and using forestry biomass for energy production showed that this global warming potential is internally consistent and thus useful for assessing how waste management best contributes to reducing greenhouse-gas emissions.

CH_4 has a global warming potential 25 times higher than that of CO_2. It originates from degrading organic matter under anaerobic conditions. The main sources of CH_4 within waste management are landfills and anaerobic digesters. Microniches in composting processes may be anaerobic, and composting processes may thus also release small amounts of CH_4, but rarely does more than a few percent of the degraded carbon become CH_4. Given the high global warming potential of CH_4, strict control of release is important. The means include collection and flaring or using the gas or using biofilters in which biological processes oxidize CH_4 into CO_2.

N_2O has a very high global warming potential of 298 kg of CO_2-equivalent per kg of N_2O. N_2O is primarily formed during the biological conversion of nitrogen: during oxidation of ammonium into nitrite and nitrate and during reduction of nitrate into nitrite and free N_2. Very little of the nitrogen is released as N_2O, and its formation is hard to control. Composting processes and the use of compost in soil are likely to be the main sources within waste management.

Waste collection and transport

Waste collection and transport are primarily linked to diesel combustion and do not differ from any other bulk transport by truck. Much of the cost of waste management is associated with collecting and transporting waste, and much is done to minimize the costs. This usually involves optimizing collection schemes and transport routes, implicitly reducing fuel consumption. However, as illustrated later, the energy and global warming aspects of waste collection and transport are minor compared

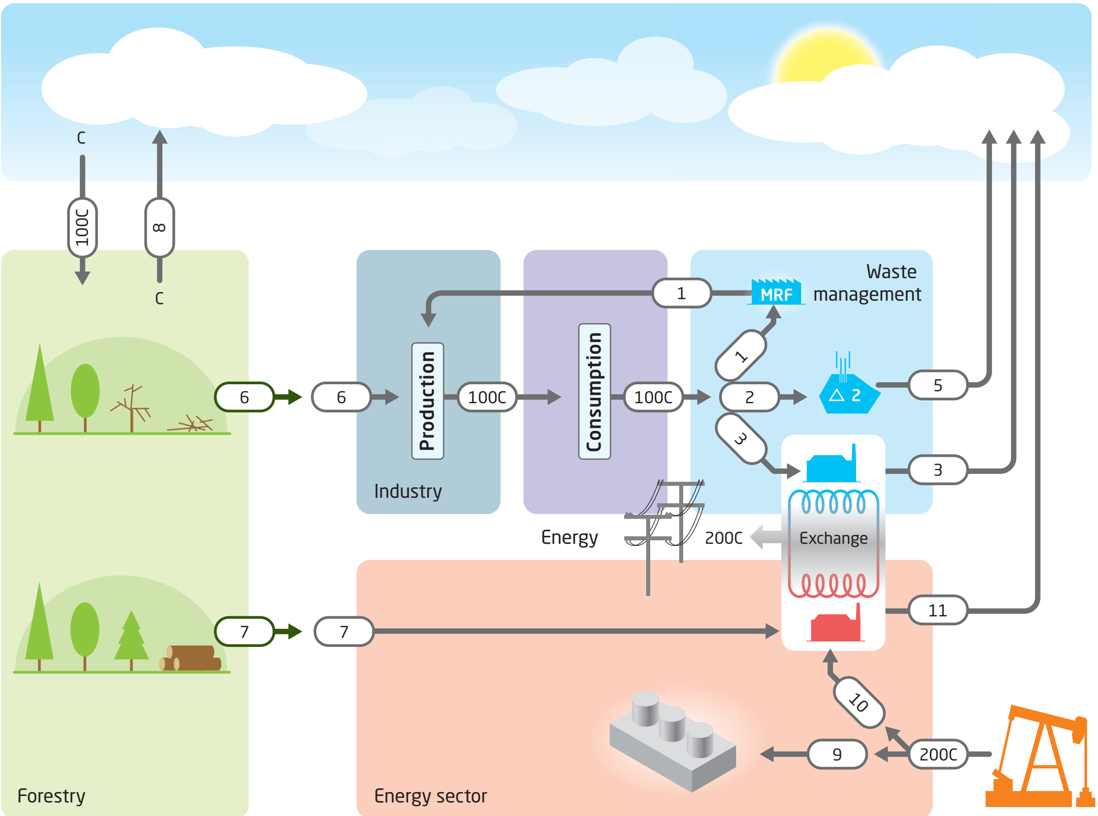

Fig. 10.1. Simplified model for calculating carbon (C) balances in waste management including allied industries (energy, paper and forestry). MRF: materials recovery facility.

with the recovery and recycling aspects of the collected waste.

Recycling materials

Recycling of materials in the waste often saves substantial energy in the industries using the recovered materials instead of virgin materials. These savings are accounted for in the involved industrial sectors, but since waste management provides the materials, these savings are considered indirect savings downstream to waste management.

Metals such as aluminum, steel, iron and copper require substantial energy to produce from ore, and scrap metal is a valuable material for smelters. Recovering the metals from scrap is less energy intensive, and the overall recycling process saves energy. The greenhouse-gas savings are substantial: for example, 5000–19,000 kg of CO_2 equivalent per ton of aluminum and 500–2400 kg per ton of steel. The actual value depends on the technology used and the location of the smelter. Smelters running on hydroelectric power may reduce greenhouse-gas emissions less.

Glass recycling involves cleaning and reusing bottles and remelting crushed glass (cullet) for producing new glass containers and bottles. Depending on purity, cullet can be added in significant quantities to the production of new glass from virgin materials (quartz sand, soda, lime, etc.), reducing the melting temperature and hence the energy needed. About 400 to 1400 kg of CO_2 equivalent is saved per ton of glass waste.

Recycling is simple for clean plastic of a single type, such as pure low-density polyethylene. The mechanical process involves melting, extrusion and granulate production. For dirty and mixed plastic, the process is more complicated and demanding. Virgin production of plastic uses about twice as much energy as the energy content bound in the plastic itself. Plastic recycling saves 0–1500 kg of CO_2 equivalent per ton.

Paper and cardboard recycling saves from minus 300 to plus 1200 kg of CO_2 equivalent per ton. The actual savings depend on the product quality and the pulping technologies. Most recycling processes are primarily based on fossil energy, whereas some virgin technologies use energy from biomass. If the biomass saved by recycling paper is assumed to substitute for fossil fuel, the overall saving is probably 1800–4400 kg of CO_2 equivalent per ton. This aspect nicely demonstrates that reprocessing the waste material requires energy but the savings depend on what it replaces, perhaps not directly but at the system boundary. The latter is not always easy to define, because it depends on so many other factors in society.

The stipulated greenhouse-gas savings from recycling waste are substantial, but the quantity and quality of materials are important from a waste management viewpoint. Thus, based on 1 ton of waste, paper recycling is by far the dominant recycling activity reducing greenhouse-gas emissions.

Incineration

Incinerating waste releases significant energy. The lower heating value of waste is typically around 10 GJ/ton depending on what the waste contains. Modern incinerators produce electricity and heat, with the heat often used for district heating. The electricity produced amounts to 20–28% of the lower heating value, and with flue gas condensation the overall energy recovery may be close to 100%. The electricity is sold to the grid, where it replaces electricity that elsewhere would have been produced at high marginal cost. The source of this marginal electricity determines the potential savings. In Denmark, this is usually electricity produced from coal without co-production of district heating. The savings are therefore likely to be high, probably about 0.9 kg of CO_2 equivalent per kWh of electricity produced. Elsewhere, the marginal production of electricity may differ. In the scenario calculations shown later, European mixed electricity was used, which is close to the greenhouse-gas emissions from electricity produced using natural gas: about 0.5 kg of CO_2 equivalent per kWh.

The substitution value of the heat produced largely depends on the local conditions, because hot water and steam cannot be transported very far without substantial losses. If the local district heating system is small and hosts a power plant, then producing heat in the waste incinerator, even if fed to the district heating system, may not substantially reduce greenhouse-gas emissions if the power plant already has excess heat. Thus, estimating the substitution value of the heat produced by incinerating waste may require more detailed analysis of the local conditions and heat market.

The incinerator itself also emits greenhouse gases from combustion of plastic materials and any use of fossil fuels for start-up operations, whereas the CO_2 from organic waste is considered neutral. Depending on the waste incinerated, about 30–50% of the CO_2 emitted is of fossil origin. The current information is based on calculations considering the expected composition of the waste and the observed energy content, but methods for direct measurement in the flue gas are underway. A precise estimate is important because waste incinerators, in contrast to power plants, are not subject to CO_2 quotas but part of the national reporting on greenhouse-gas emissions.

An additional option is producing fuel from the waste that can be used in power plants and industrial kilns (such as cement kilns) to replace fossil fuels, often coal. Power plants and industrial kilns usually have less extensive flue-gas cleaning systems, so using a refuse-derived fuel requires a clean waste fraction. In particular, the mercury and the chloride concentrations must be closely controlled. Refuse-derived fuel can be used flexibly and directly replaces coal based on the energy content. As shown later, this may provide some advantage compared with electricity production in an incinerator if this electricity replaces marginal electricity based on natural gas.

Balancing the direct emissions from the incinerator against the savings obtained from the electricity and the heat produced that otherwise would have been generated from fossil fuels, 100–800 kg of CO_2 equivalent per ton of waste may be saved overall.

Biological treatment

Composting organic waste involves aerobic degradation and generates CO_2 and compost. The composting process emits few greenhouse gases, primarily from the use of machinery and emissions of CH_4 from anaerobic niches in the waste and small amounts of N_2O from the mineralization of nitrogen. The overall emissions are believed to be about minus 10 to plus 300 kg of CO_2 equivalent per ton of organic waste.

Digestion of organic waste is an anaerobic degradation of the organic waste in a closed reactor. The main product is biogas, constituting about equal quantities of CH_4 and CO_2. The CH_4 is often used to produce electricity and sometimes heat for district heating. The greenhouse-gas emissions are related to the use of fuels and unintended leakage of CH_4. Savings are obtained from the electricity and heat delivered to society. The overall emissions are believed to be between minus 300 to 0 kg of CO_2 equivalent per ton of organic waste.

The stabilized organic products from biotreatment used on land for crop production supply the soil with nutrients and organic matter. If the organic residue is used rationally according to a fertilization scheme, it may substitute for the production and use of the mineral fertilizers N, P and K (N and P are the most important nutrients in this context). This may save 4–80 kg of CO_2 equivalent per ton of incoming organic waste. The carbon in the stabilized material will slowly decompose in the soil. This process may take decades; in particular, the compost has a high fraction of humus-like material that degrades very slowly. Model calculations show that, after 100 years in the soil, the compost may still have about 10% of the carbon left. This should be considered a saving in greenhouse-gas emissions of 2–70 kg of CO_2 equivalent per ton of organic waste.

Landfilling

Landfilling waste generates CH_4 and CO_2 from the anaerobic degradation of the organic matter. The degradation process continues for decades after disposal. Most of the CH_4 is generated within 30 years after disposal, but even after 100 years about half the biogenic carbon is left in the landfill.

In engineered landfills, the landfill gas is extracted by vacuum and burned to convert CH_4 to CO_2. If the amount of gas is limited or highly variable, the gas is burned in a flare, but substantial gas is often used to generate electricity by burning the gas in an engine with a generator. Sometimes the heat is also used, at least for internal purposes at the landfill.

Much of the gas is not collected unless the landfill is covered by a synthetic liner. The uncollected gas may escape through cracks or coarse soil and emits substantial greenhouse gases. If the gas flow is low and distributed over large areas of the landfill, the CH_4 may get oxidized passing through the soil cover. CH_4-oxidizing bacteria are present in most landfill cover soils and use oxygen diffusing in from the atmosphere to oxidize CH_4 rising from the waste below. The CH_4 is oxidized into CO_2, thus reducing the global warming potential from 25 kg of CO_2 equivalent per kg of CH_4 to 0 kg of CO_2 equivalent per kg of biogenic CO_2. However, if the flow is high or the soil too compact, CH_4 oxidization is limited.

The biogenic carbon left in the landfill after 100 years, the time period modeled, is a greenhouse-gas saving and ascribed a negative global warming potential as described earlier. For 1 ton of municipal waste with a substantial content of organic waste and paper (without separate recycling schemes), the biogenic carbon left equals as much as a saving of 130–180 kg CO_2 per ton of waste landfilled.

The overall greenhouse-gas contribution from landfilling may be minus 70 to plus 170 kg CO_2 equivalent per ton.

System considerations

The input to the waste management system is the waste in terms of quantity and composition. Municipal solid waste is often one third paper and paper products by weight, one third kitchen organic waste and one third other waste. Fig. 10.2 shows model estimations of the energy that can be recovered from 1 ton of waste by a range of waste management scenarios. For all the scenarios, collecting and transporting the waste is a very small part of total energy. Using 10–15 liters of diesel for collecting and transporting 1 ton of waste is not important when the waste contains the equivalent of

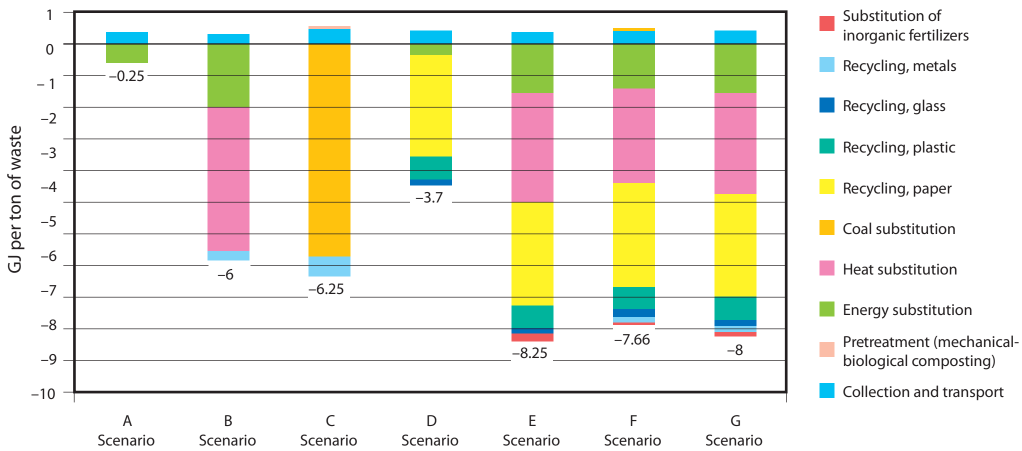

Fig. 10.2. Energy balance (negative values are recovered energy) for seven waste management scenarios. **A**. Landfilling. **B**. Incineration. **C**. Production of fuel for coal-fired power plants. **D**. Materials recycling and landfilling. **E**. Materials recycling and incineration. **F**. Materials recycling, organic waste composting and incineration. **G**. Materials recycling, organic waste digestion and incineration.

200–250 liters of diesel per ton. Seven scenarios have been modeled.

A: A modern landfill with a high level of gas collection using the collected energy for generating electricity recovers 0.25 GJ net per ton of waste. This scenario is included as a reference since landfilling organic waste is prohibited in many countries.

B: Incineration with 20% electricity generation and 40% heat recovery for district heating saves 6 GJ net per ton of waste. The heat recovery rate is typical for Europe but low for Denmark, with 65–80% heat recovery given the extensive district heating.

C: A refuse-derived fuel fraction is produced and used in a power plant instead of coal. The remaining waste is stabilized by composting and landfilling. This mechanical-biological treatment technology is common in central Europe. This saves about 6 GJ per ton, equivalent to the amount of coal saved without considering how the coal is converted into energy at this point. This emphasizes the fact that energy recovery not only depends on the amount recovered but also on the form. For the other scenarios, the energy is in the form of electricity and heat.

D: This scenario also focuses on landfilling, but much waste is recycled before landfilling: paper, plastic and metal. The overall savings are 3.7 GJ per ton, of which paper recycling is the major contributor.

E: This scenario has the same recycling scheme as in D, but the residual waste is now incinerated, with energy recovery similar to B. The overall energy saved is now about 8 GJ per ton: paper recycling, electricity generation and heat production are the three main contributors.

F and G. These two scenarios are identical to E except that an organic fraction is collected separately at the source: in F for composting and in G for anaerobic digestion. Digesting organic waste generates some electricity from the biogas produced, but the overall energy recovery is nearly identical, about 8 GJ per ton. Paper recycling and energy recovery from incineration are predominant.

Fig. 10.3 presents the same scenarios expressed in net CO_2 equivalent per ton of waste. The picture is somewhat similar to that in Fig. 10.2, since all waste-management scenarios emit negative greenhouse gases or reduce global warming. However, two issues are different.

The first difference between energy recovery and reductions in greenhouse-gas emissions is that the scenarios with significant landfilling (A and D) contribute relatively more to reducing greenhouse gases than they do to energy recovery. This is due to the biogenic carbon left in the landfill after the 100-year period considered for the modeling. About half the organic carbon is still present in the landfill and thus constitutes a saved emission since biogenic carbon, if released as CO_2, is considered neutral.

The second difference between the energy recovery and the reduction in greenhouse-gas emissions is that scenario C, which produces refuse-derived fuel for use in power plants, reduces greenhouse gases the most. This is because this scenario is credited the full greenhouse-gas emissions avoided from burning coal, whereas many of the other scenarios that recover the same amount of energy are credited the greenhouse-gas emissions from producing average European energy, resembling using natural gas, which produces less greenhouse gases than coal.

The scenario modeling shows that waste management can contribute to reducing greenhouse-gas emissions, primarily through energy recovery and paper recycling. Storing organic carbon in landfills is also an option but less attractive than recovering the energy in the waste. Waste management can probably recover net energy of about 8 GJ per ton of municipal waste, and the net reduction in greenhouse gases could be about 500 kg of CO_2 equivalent per ton of waste. The actual value depends strongly on the type of energy replaced by the energy recovered from incineration. This reduction in greenhouse-gas emissions from waste management corresponds to about 2% of the current load caused by an average European person.

Conclusion

Waste management can contribute to society's efforts to reduce greenhouse-gas emissions by minimizing its own use of fossil fuels, by increasing the recycling of materials and energy recovery and by binding biogenic carbon in soil and landfills. The

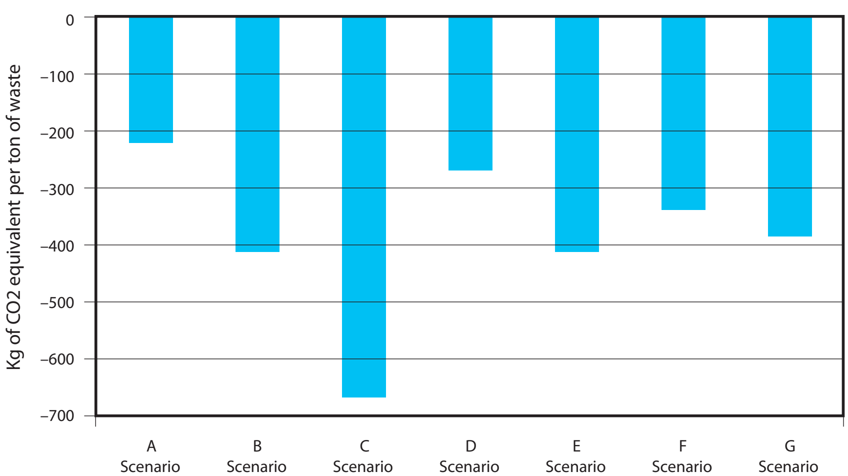

Fig. 10.3. Global warming contribution (negative values are reductions) for seven waste management scenarios with a 100-year time perspective. **A**. Landfilling. **B**. Incineration. **C**. Production of fuel for coal-fired power plants. **D**. Materials recycling and landfilling. **E**. Materials recycling and incineration. **F**. Materials recycling, organic waste composting and incineration. **G**. Materials recycling, organic waste digestion and incineration.

scenario modeling suggests that energy recovery and paper recycling are the most important factors in reducing greenhouse-gas emissions. Waste management may reduce current net greenhouse-gas emissions from an average European person by about 2%.

For waste management, the challenge is to develop a system that uses the least energy, minimizes greenhouse gases and maximizes energy recovery and material recycling. The challenge is to balance material recycling and energy recovery and to maintain the overall perspective, although much of the reduction in greenhouse gases is outside the waste management system. The solution is to develop transparent data on all levels and to establish models synthesizing the complex data into communicable terms. Climate-friendly waste management is not the solution but one of many necessary contributions to meeting targets for reducing greenhouse-gas emissions. The waste needs to be managed, so why not do it the climate-friendly way?

More to explore

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