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# Economic and Environmental Evaluations of Waste Treatment and Disposal Technologies for Municipal Solid Waste

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*ABSTRACT*

*MSW management can be defined as the discipline associated with the control of generation, storage, collection, transfer, processing and disposal of MSW, in a way which is governed by the best principles of public health, economics, engineering, aesthetics and other environmental considerations. The disposal of MSW has been the focus of environmental policy for several industrialised countries since the mid-1970s, when attempts were made to identify and categorise, in a systematic way, the waste fractions involved. This categorisation provided the policy makers with the necessary information, to determine the most appropriate option for dealing with the waste in a more economic and environmentally-sustainable way. This paper reviews the main economic costs and the environmental impacts of the widely-accepted waste treatment and disposal methods. Examples of successful waste-management schemes are presented and prospective future trends are assessed.* © *1998 Elsevier Science Ltd. All rights reserved*

## ABBREVIATIONS

| | |
|---|---|
| AOX | Adsorbable organic halogens |
| BOD | Biochemical oxygen-demand |
| COD | Chemical oxygen-demand |
| DoE | Department of the Environment (UK) |
| EC | European Commission |
| EDF | Environmental Defense Fund (USA) |
| EPA | Environmental Protection Act |
| ETSU | Energy Technology Support Unit (UK) |
| GLC | Greater London Council |
| HDPE | High-density polyethylene |

| | |
|---|---|
| ILSR | Institute of Local Self-Reliance (USA) |
| IPCC | Intergovernmental Panel on Climate Change |
| LFG | Landfill gas |
| MRF | Materials-recovery facility |
| MSW | Municipal solid waste |
| PCDD | Polychlorinated dibenzo-p-dioxins |
| PCDF | Polychlorinated dibenzofurans |
| PET | Polyethylene terephathalate |
| PVC | Polyvinyl chloride |
| RCEP | Royal Commission on Environmental Protection (UK) |
| $Nm^3$ | One cubic metre of LFG in atmospheric pressure and 15°C |

## GLOSSARY

| | |
|---|---|
| Fly ash | Small solid particles of ash and soot generated and discharged with the flue gases when coal, oil, or solid wastes are burnt. With proper equipment, fly ash is collected before it enters the atmosphere. |
| Diversion rate | A measure of the amount of material now being diverted for reuse or recycling, compared with the total amount of waste that was thrown away previously. |
| Compaction | The unit operation used to increase the specific weight of waste materials so that they can be stored and transported more efficiently. |
| Biodegradable material | A compound that can be degraded or converted to simpler compounds by micro-organisms. |
| Curbside collection | The collection of source separated and mixed wastes from the curbside where they have been placed by the householders. |
| Decomposition | The breakdown of organic wastes by bacterial, chemical or thermal means. Complete chemical oxidation leaves only carbon dioxide, water and inorganic solids. |
| Ferrous metals | Metals composed predominantly of iron. In the waste materials stream, these metals usually include tin cans, automobiles, refrigerators and other appliances. |
| Heavy metals | Metals such as cadmium, lead, mercury which can be found in MSW in discarded items such as batteries, lighting fixtures, colorants and inks. |

## A MAJOR PROBLEM OF OUR AFFLUENT SOCIETY

Solid-waste disposal creates difficulties primarily in highly-populated regions: usually the more populated the area, the greater the problem (the terms refuse and solid waste are used more or less synonymously). The common constituents of solid waste can be categorised in several different ways. The point of origin is important in some cases, so classification as commercial, domestic, institutional, industrial, street trash, demolition or construction may be useful. The nature of the material may be significant, so grouping can be made into organic, inorganic, combustible, non-combustible, putrescible and non-putrescible fractions.[1]

The huge quantities of solid waste to be disposed of daily, makes dealing with waste, once it has been collected, among the most difficult problems confronting local-community officials. An emergency situation can evolve quickly, for example, if an incinerator or a waste-disposal site was forced to shut down because of a failure to meet newly-passed environmental regulations. Alternatively, a crisis can build up gradually over a long period of time if needed new facilities are not properly planned and put into service. There are three basic alternatives for MSW disposal:

- direct dumping of unprocessed waste in a sanitary landfill;
- processing of the waste before final disposal; and
- processing of the waste to recover resources (materials and/or energy) with subsequent disposal of the residues.

Direct haul to a sanitary landfill is usually the cheapest disposal alternative in terms of both operating and capital costs needed. However, landfill space is becoming scarcer, so causing costs to rise sharply in populated areas. For the second alternative, the primary aim is to reduce the volume of waste. This reduces both the handling and ultimate-disposal costs. However, the capital and operating costs to achieve this volume reduction are significant and must be assessed relative to the savings achieved.

The third category of disposal alternatives includes those processes that recover energy or materials from solid waste and leave only a residue for ultimate disposal in a landfill. There are significant capital and operating costs associated with all these energy and/or materials recovery systems. However, selling both the energy and the materials will reduce the net cost of recovery. While resource-recovery techniques may be more costly than other disposal alternatives, they achieve resource conservation, and the residuals of the processes require much less space for land disposal than unprocessed wastes.

During the last 25 years, no dramatic changes have taken place regarding the technologies used to treat domestic and commercial waste streams which have been commonly known as MSW. These methods include:

- Landfilling the waste.
- Incineration with or without energy recovery.
- Recycling or composting the relevant fractions of the waste streams.

## LANDFILLING THE WASTE

In whichever form it arises, an irreducible minimum amount of MSW will probably need to be disposed to landfills. Landfilling is the controlled deposit of waste to land in such a way that no pollution or harm results to the environment. The design and construction of landfill sites therefore needs to include the control, in both the short and long terms, of the products of waste decomposition such as the liquid leachate and landfill gas.

The biological and biochemical decomposition of wastes takes place over a number of years and during this time the nature and quantity of the gas evolved will change significantly. Upon waste deposition, ambient air entrapped in the waste is consumed and rapidly (i.e. over a few days) replaced by a gas mixture containing carbon dioxide and hydrogen. With the onset of fully anaerobic conditions, typically after 3 to 12 months of deposition, significant quantities of methane will start to be produced (stage of methanogenesis). The concentration of methane increases until it reaches approximately 60–65% of the gas being produced, with a corresponding decrease in carbon dioxide to about 35–40% of the gas. In a modern site, with a waste depth exceeding 5 m and where progressively infilling and restoration takes place, the peak of degrative activity is normally reached within five years, with a gradual decline thereafter.

### Environmental impacts of landfilling

*Landfill gas*

The concern about the potential adverse environmental impacts of LFG is relatively recent,[2] so reflecting the developing awareness as a result of:

- changing practices, with the ban on burning of wastes in landfills;
- the move to larger and deeper sites;
- the changing composition of wastes, in particular the increasing amount of organic materials such as paper and packaging; and
- the resulting need and ability to control and monitor LFG.

The environmental impacts of landfilling the waste depend on the design of the landfill, method of operation and the nature of the waste deposited. Recently, there has been more focus on landfill siting and operation, with reference to improved gas and leachate containment and collection. Less emphasis has been given to the possible effects of future changes in packaging materials on the composition of the MSW landfilled. Since more and more materials would be recovered from the waste streams for recycling or composting purposes, the amount and the composition of the remaining waste will be altered.

A typical LFG composition is presented in Table 1. To evaluate the possible environmental impact of LFG, as a greenhouse gas, one needs to know its relative radiative effects. The concept of relative global-warming potential has been developed to take into account the radiative forcing and atmospheric residence times of different greenhouse gases.[4] The Intergovernmental Panel on Climate Change (IPCC) has developed an index that defines the time-integrated warming effect of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide (Table 2). In addition to the direct global-warming effects, the gases may also have indirect effects as a result of the gaseous products of their chemical reactions in the atmosphere, e.g. the breakdown of methane leads to the production of carbon dioxide

**TABLE 1**
Composition of landfill gas in the UK[3]

| *Component* | *% by volume* |
|---|---|
| Methane[a] | 63.8 |
| Carbon dioxide | 33.6 |
| Nitrogen | 2.4 |
| Oxygen | 0.16 |
| Hydrogen | 0.05 |
| Higher alkanes | 0.05 |
| Ethene | 0.018 |
| Unsaturated hydrocarbons | 0.009 |
| Ethane | 0.005 |
| Acetaldeyde | 0.005 |
| Butanes | 0.003 |
| Propane | 0.002 |
| Carbon monoxide | 0.001 |
| Helium | 0.00005 |
| Others | 0.00005 |
| Halogenated compounds | 0.00002 |
| Hydrogen sulphide | 0.00002 |
| Organosulphur compounds | 0.00001 |
| Alcohols | 0.00001 |

[a]The figure for methane reported here is considered high. A figure of 55% is considered more typical.

**TABLE 2**
Global warming potential of two of the main greenhouse gaseous components of LFG

| *Greenhouse gas* | *Period of residence (years)* | *Relative global-warming potential (direct effect only) over:* | | *Sign of indirect effect* |
|---|---|---|---|---|
| | | *20 years* | *100 years* | |
| $CO_2$ | 120 | 1 | 1 | None |
| $CH_4$ | 10.5 | 35 | 11 | Positive |

and tropospheric ozone. These indirect effects were included in the 1990 IPCC estimates, but excluded from the 1992 estimates owing to the uncertainty about how the residence times of these gases will change as the atmosphere warms in the future.

The potential impacts of LFG relate to the generation of the gas itself and also to the control measures needed to be implemented. In summary, these impacts are:

- *Explosions* due to LFG migration and accumulation in confined spaces with subsequent ignition, either within, or in the vicinity of the site, which can result in serious injuries, deaths and/or damage to buildings.
- *Flash fires* in open spaces with the potential for the waste in the landfill to be ignited if the release of the gas is through a fissure to the surface.
- *Asphyxiation* of people and fauna in confined spaces. This could include (i) workers on a site either in a trench or in an office where the gas is accumulating; (ii) trespassers on an affected site through a culvert; (iii) as well as people off-site.
- *Vegetation and crop stress and loss* due primarily to displacement of soil oxygen in the plant-root zone. The symptoms of damage tend to resemble those relating to drought (i.e. defoliation, twig and branch die-back and the withering of leaves). Some minor and trace components of LFG (e.g. ammonia, carbon monoxide, halo-organic compounds, hydrocarbons and volatile organic acids) are toxic to plants and have the potential to inhibit plant growth.
- *Nuisance effects* due to the odours from the landfill, as a result of trace components of the LFG and those arising from the flare stacks.
- *Visual impacts* owing to vegetation stress and from any gas plant, including the impacts of flare stacks and flares.
- *Noise* from compressors on the gas collection system and any generating plant.

- *Water pollution*: carbon dioxide is highly water soluble and increases the water's hardness, so producing an aggressive solution which accelerates corrosion. Water pollution can also be caused by the condensate arising from the de-humidification process on the gas plant.
- *Corrosion of equipment* by minor constituent gases, including acid-forming species such as hydrogen chloride and sulphur dioxide, leading to failure in gas abstraction and utilisation equipment.
- *Health effects* from the emissions of trace compounds and flare combustion-products. In relation to gas flares, there has been concern as to whether complete combustion of the trace components takes place and, if not, whether dioxins and furans may be produced.
- Contributions of carbon dioxide and methane to the greenhouse effect.

Complaints by local residents about odours from landfills have often led to questions about health impacts. Studies suggest that the odour from LFG is associated with a limited number of trace components which originate as the metabolic products and intermediates of degradation under anaerobic conditions. At a site where these processes are more efficient, odour problems are more likely to arise. The risk of odour occurrence is higher in the first year after deposition and it is the organosulphur compounds and esters which then contribute particularly to the problem. The presence of certain compounds, while exerting no odour themselves, may in a mixture heighten response to other compounds. Odours can be offensive to the extent that sensitive individuals can feel nauseated and, ambient dilution may be insufficient to achieve significant reduction of odour in the vicinity of landfilling operations. Odours from landfills may be experienced several kilometres from a site under certain adverse weather condition.[5]

One way of controlling the impacts of LFG is locating the site so as to minimise the number of sensitive targets in the vicinity. This first mitigation measure, must be backed by engineering and operational controls. An effective mitigation programme should have three main control activities:

- Active extraction of the gas from the waste as it is generated so as to prevent the build up of pressure and the of migration potential.
- Installation of a low-permeability barrier to prevent lateral migration.
- Monitoring gas migration by using boreholes located outside of the landfill area.

A gas-management system should have a built-in considerable margin of safety and the additional support of back-up systems. A gas-management plan should be established to identify management responsibilities, monitoring schedules, procedures in the event of an emergency and data-assessment protocols. In the past, there has been a tendency to install gas control measures only when the gas generation rate becomes high enough to extract it actively. Much cheaper passive vent systems, as means of mitigating the on-site explosion hazard increase local hazards and/or odour nuisances. Such a practice is becoming increasingly unacceptable and many licences now contain conditions requiring the existence of an adequate gas-management scheme before waste deposition commences.

Odour problems can be mitigated by effective and frequent waste covering during filling, as well as by the final cover over the landfill. Fine-grained materials can be particularly effective in attenuating odour. However, this may not be compatible with other objectives, such as the reduction of rain-water infiltration. Clay capping may prevent water ingress, but cracking of the surface during drying or settlement can lead to gas escape without attenuation of the trace components. Flaring of LFG can also provide a mitigation of the odour problem. The use of chemicals to mask LFG odours has been tried, although in some cases the odours from these chemicals may be equally objectionable. A limited evaluation to determine the level of odour emissions from a landfill can be obtained by continuous methane monitoring of the ambient air. Generally odours are detectable when the dilution of LFG indicated by the ambient methane levels is of the same order of magnitude as that suggested by comparing the gas analysis with individual odour thresholds.[6,7] De-odorisation of collected gas can be achieved by:

- wet gas scrubbing;
- thermal oxidation;
- activated carbon filtration; or
- biofiltration.

The objectives of LFG monitoring are to check that the control measures adopted remain effective and to identify any loss in efficiency in the control system. Any monitoring programme must be site specific, and the location of monitoring points are usually determined from the initial site investigation and baseline survey. Guidance is available for the principles of monitoring related to various sets of objectives, monitoring frequency, instruments, techniques, recommended spacing of monitoring boreholes and data interpretation. The details of the monitoring programme are usually those required by the licence conditions for the site, but still they may prove to be inadequate. It is also important that the monitoring programme is flexible enough to cope with possible changing conditions.

The proposed EC landfill directive[8] refers to the need to avoid the accumulation of LFG, the requirement for the gas generated to be collected and for post-closure monitoring. However, the policy regarding gas control appears only to be secondary to leachate control and protection of the groundwater resource. Nevertheless, some engineering containment measures, designed primarily to control leachate migration, do play a major role in controlling the lateral migration of LFG.

The current legislation, in many European countries and in the United States, requires testing for certain specified hazardous air-contaminants at all active and some inactive MSW disposal sites,[9] in order to determine:

- if there is any underground gas migration through the site's perimeter;
- the composition of gas streams inside the landfill and the amount and distribution of hazardous materials in the landfill; and
- the concentrations of specified air contaminants in the ambient air and the effect of the site on the surrounding air's quality.

*Leachate*

Leachate pollution is the result of a mass-transfer process. Waste entering the landfill reactor undergoes several transformations which are controlled by, among other influencing factors, the water input fluxes. In the reactor, three physical phases are present: the solid waste, the liquid leachate and the landfill gas. The liquid phase is enriched by soluble or suspended organic matter and inorganic ions from the solid phase. At present, restrictions are imposed upon the discharge of leachate into the environment as a result of:[10]

- many severe cases of groundwater pollution at landfills;
- the greater hazard posed by the present trend of using large-size landfills;
- the need to comply with the increasingly-restrictive legislation regarding the quality of waste-water discharges; and
- the implementation of an integrated waste-management strategy results in the volume of waste being reduced but then a greater proportion of the waste being landfilled will be hazardous.

Important variations in leachate generation which cannot be accounted for by the stated assumptions, may occur. For example, in practice, not all of the absorptive capacity of waste may be utilised, as water input to the site may infiltrate to the base of the site via preferential high-permeability pathways (e.g. if significant quantities of construction wastes are landfilled) and consequently, significant quantities of leachate may accumulate locally within the site. In addition, during the early stages of filling, leachate may be generated during periods of above-average rainfall or possibly owing to the compaction of wastes near the site's base as filling proceeds.

Table 3 presents an example of leachate composition from the degradation of different waste components in a landfill site. Predicting the quality of leachate is almost as difficult as predicting its quantity, as it varies with the rate of digestion of the waste within the site. Studies have indicated that wide variations in leachate composition occur both spatially across a site, seasonally, and with the age of the site.[11] However, an assessment of potential leachate quality is important to aid in landfill design and particularly in the choice of a leachate-treatment system.

The leachate will start to leak if a failure in the leachate-management system (e.g. the base liner) occurs. It is generally agreed that all membrane liners will leak, not through the intact membrane, but through holes or other defects. It has been suggested[12] that, depending on quality control, there can be 2 to 50 holes per hectare of which two thirds are associated with seams. Typical causes for these leak paths are:

- poor sealing of joints;
- puncturing during installation;
- settlement;
- chemical attack; and
- uplift from gas beneath the liner.

Clean-up costs are only a crude surrogate for damage costs. Technically, economic damage is measured by willingness to pay to avoid damage or willingness to accept compensation for the damage suffered. These need not coincide with the costs of clean-up or even with the legally-determined damages. Ground-water contamination is likely to be more expensive to mitigate than surface water contamination. The former will involve large retrofitting costs at the landfill site in addition to clean up costs relating to the ground-water supply (e.g. the introduction of granular activated carbon plants or other purification measures). Surface water contamination will typically involve only landfill retrofit costs and short-run water supply diversion costs.[13]

If a synthetic liner is holed, leachate leakage may produce a particularly large and acute release, which compares unfavourably with the type of slow and gradual leachate leakage which is characteristic of a landfill site with a low permeability natural barrier. The use of a layer of clay beneath the membrane, and bentonite-impregnated mats, can significantly reduce leachate leakage impact. The key components of a leachate-management scheme are:

- *Minimisation of leachate generation*: by the control of surface and groundwater inputs; minimisation of amount of precipitation coming into contact with waste by use of small cells; phased disposal and progressive restoration; use of a low-permeability cap; shaping of a final

**TABLE 3**

Leachate composition in a landfill site

| | Leachate composition ($g\,m^{-3}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Paper* | *Glass* | *Metal* | *Plastic* | *Textiles* | *Organic* | *Other* | *Compost* | *Ash* |
| BOD | 3167 | 0 | 0 | 0 | 3167 | 3167 | 0 | 1900 | 24 |
| COD | 3167 | 0 | 0 | 0 | 3167 | 3167 | 0 | 1900 | 24 |
| Suspended solids | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Total organic compounds | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0.39 | 0.021 |
| AOX | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0.86 | 0.011 |
| Chlorinated HCs | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 0.18 | 0.01 |
| Dioxins/furans | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $3.2\times10^{-7}$ | $1.6\times10^{-7}$ | $3.2\times10^{-9}$ |
| Phenol | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.1 | 0.005 |
| $NH_4$ | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 10 | 0.06 |
| Total metals | 96.1 | 96.1 | 96.1 | 96.1 | 96.1 | 96.1 | 96.1 | 1.37 | 0.21 |
| Arsenic | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.007 | 0.001 |
| Cadmium | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.001 | 0.0002 |
| Chromium | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.011 |
| Copper | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.044 | 0.06 |
| Iron | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 1 | 0.1 |
| Lead | 0.063 | 0.063 | 0.063 | 0.063 | 0.063 | 0.063 | 0.063 | 0.012 | 0.001 |
| Mercury | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.00002 | 0.001 |
| Nickel | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.12 | 0.0075 |
| Zinc | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.3 | 0.03 |
| Chlorine | 590 | 590 | 590 | 590 | 590 | 590 | 590 | 95 | 75 |
| Fluorine | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.14 | 0.44 |

landform to encourage surface water run-off away from active phases; control of, or enforcing a ban on, liquid-waste inputs; and the use of solidification/encapsulation processes as an alternative to the direct landfilling of the waste.

- *Containment of leachate within the landfill*: by the use of a double or composite liner system incorporating protection of the synthetic liner; construction of the liner above the maximum groundwater recovery level; retention of sufficient unsaturated zone to provide for attenuation of leachate; perimeter and cell bunding with low permeability bund walls; and employment of low permeability caps and quality control of liner installation.
- *Control over leachate quality*: by undertaking leaching tests on incoming wastes, refusing to accept specific wastes and stopping leachate recirculation.
- *Collection and disposal of leachate as it is generated*: via collection pipework system or leachate collection-sumps within each phase, and suitable pumps for the removal of leachate to be treated prior to discharge to the sewer system.
- *Monitoring*: the leachate monitoring is carried out by measuring the head of leachate.
- *Contingency plans* in the event of groundwater contamination being detected.

## Examples of successful landfill operations in the European Union

Over the past 20 years, the environmental requirements relating to landfills have been made more stringent. The oil crises of 1970s resulted in significant efforts to save energy, and increased research and development of programmes for the utilisation of alternative energy sources. In this context, the exploitation of LFG began in early 1975. Some representative landfill sites,[5] where LFG is exploited for energy purposes, are:

1. Viborg, Denmark: This has been the disposal site for MSW from 83 000 inhabitants since 1972. The current landfill covers almost 170 000 $m^2$ and had already received approximately more than 800 000 tonnes of MSW by 1989, with a present reception rate of around 60 000 tonnes per year. LFG (with 42.4% by volume $CH_4$) is recovered from one part of the landfill, involving 375 000 tonnes of wastes, with a potential extraction rate of 160 $Nm^3\,h^{-1}$. The current extraction rate is only 115 $Nm^3\,h^{-1}$. The LFG is used to fire a boiler to produce hot water, which has a consumption rate of 241 $Nm^3$ LFG $h^{-1}$, a potential efficiency of 77% and a nominal output of 785 MWh. Economically, the

site has not proven successful due to its high capital cost and the low flow gas achieved.

2. Modena, Italy: This site includes three parts, two of which are already completed: it received 1 500 000 tonnes of MSW between the years 1973 and 1989. Only one of these two parts is presently exploited for LFG recovery. This site now receives approximately 250 000 tonnes of waste per year. The current extraction rate is 370 $Nm^3 h^{-1}$ or 9000 $Nm^3 day^{-1}$ with a methane content of 52% by volume. The extracted LFG is used in one gas engine with a nominal output of 217 kW, to produce part of the electricity demand for the site.
3. Eberstadt, Germany: This site covers an area of 200 000 $m^2$. It receives approximately 130 000 $m^3$ of MSW annually, with a total estimated capacity of 3 200 000 $m^3$ of MSW. The present gas abstraction rate is approximately 700 $Nm^3 h^{-1}$ and the abstracted LFG has a methane content of 54% by volume. The gas is fired in two engines, each consuming 290 $m^3$ LFG $h^{-1}$ to generate electricity. Approximately 9000 MWh of electricity is produced and distributed to the public network each year. Economically, this site has been only marginally cost-effective.
4. Purfleet Board Mill, UK: This site covers approximately 240 000 $m^2$ and has a capacity of 3 000 000 $m^3$ of MSW. The site was receiving waste until 1987 and the produced LFG has a methane content of 48% by volume. The LFG is used in a nearby paper mill to fire a gas turbine and a water-tubed boiler coupled to a steam turbine. Both turbines generate electricity to meet most of the electricity demands of the plant. The gas turbine consumes 243 TJ of LFG and 7 TJ distillate fuel oil per year to produce around 25 500 electric MWh. The boiler consumes 211 TJ of LFG and 770 TJ of fuel oil to generate 445 000 tonnes of steam. From the 53 tonnes of steam produced per hour, 36 tonnes are used in the steam turbine to generate around 41 000 electric MWh. Economically, this combined heat and power (CHP) installation is a great success.
5. Packinghton, UK: This site has an area of 1 550 000 $m^2$ and receives around 600 000 tonnes of MSW annually. The produced LFG has a methane content of 42.5% by volume and is used to drive a gas turbine. The turbine receives approximately 56 700 $m^3$ LFG $day^{-1}$, while generating 31 200 MWh of electricity per year.

## Economics of landfilling MSW

The analysis of landfill costs is considered under six sections which conform to the generally-accepted stages of landfill development and operation[14,15] in the UK:

- *Site acquisition costs*: In general prospective operators are concerned with three main factors in valuing a voidspace:
  - the capacity of the voidspace;
  - the types and quantities of waste to be disposed; and
  - accessibility relative to urban and industrial locations, which generate the wastes in question.

  Although the waste density is typically assumed to be about 1 tonne $m^{-3}$, valuations obviously fluctuate considerably around this figure, depending mainly on the types of wastes to be handled. The scarcity of new landfill sites leads to an increase in acquisition costs. As the waste-management industry develops, the control over disposal capacity is increasingly recognisable as a valuable asset. However, the alternative to the capital purchase of a site is to lease it: in which case, the payment of royalties on a regular basis throughout the life of the site would replace the single up-front commitment. It is difficult to generalise about the pros and cons of royalty payments in comparison with purchase prices. The main difference is the pattern of spending, and hence the average annual cash-flow.

- *Assessment costs*: The allowance for site assessment is very modest in comparison with the total costs (i.e. less than 1% of total costs). However, these exercises are vitally important to the overall financial success of the operation. Improperly conducted site investigations, including geological and hydrogeological surveys, can result in incomplete understanding of the environmental risks of operation and consequently inappropriate site design. Planning legislation now requires an environmental assessment for developments of this nature.
- *Development costs*: The major expenses during this stage are for site lining, leachate-collection and treating systems and landfill gas-management systems. These three areas account for nearly 90% of the total development costs. A composite liner consisting of natural clay and high density polyethylene is assumed, which strictly would not be required in every situation although it is increasingly the standard approach. In the course of the technical assessment, the risk to the local environment of a liner failure has to be assessed and a decision made on the liner system to be employed. The proposed EC landfill directive[3] specifies criteria for site containment which make composite liners a recommended choice.
- *Operation costs*: Expenditure on daily operation is the largest cost incurred over the lifetime of a landfill. Operating costs will vary from year to year depending on fluctuations in waste intake rates and other local conditions. All major components of plant and equipment are assumed to be leased and usually appear as operating items instead of capital outlays.

- *Restoration costs*: The cost of restoration is primarily the cost of capping the site, which in our analysis, has an underlayer of clay and a two meter thick top layer of soil. No specific land use after restoration is assumed. The requirement for restoration expenditure relative to discounted costs is small (i.e. less than 5%).[16]
- *Aftercare costs*: Proper site development and operation should minimise the need for aftercare expenditure, but a certain amount of monitoring will always be required. For example, in the UK, under conditions established in the EPA 1990, licensing authorities are under no obligation to issue a certificate of landfill completion until they are satisfied that there are no further threats to the local environment. An aftercare period of 30 years has been assumed, but it should be recognised that there is no agreement on the precise time that would be required before leachate and gas were satisfactorily controlled. The 7th Draft of the EC landfill directive[8] called for a 50 year monitoring period: 30 years under the care of the operator and the remaining 20 years under the supervision of the licensing authority. The effect of extending the aftercare period does little to alter discounted costs, because these are incurred well into the future. What is most important to the operator and indeed to the licensing authority, is having to ensure that the funds are available when they are required. To guarantee that, the licensing authority is likely to require that a fund be established and contributed to during the operational lifetime of the facility. This additional fund could be in the form of a fixed landfill tax per tonne of input tonne of waste, as this has been introduced in the UK. However, only a small percentage of the landfill tax collected goes towards paying for environmental improvement projects, while the majority of it is going directly to the UK Treasury.

Modern landfill husbandry represents a considerable commitment of professional and financial resources for an operator, if it is to be commercially successful and environmentally acceptable. Landfills of this size (i.e. with an annual acceptance of 200 000 tonnes of waste) are operated in phases. Each phase consists of about 12 months of infilling, supplemented by several months of development and restoration, giving an appropriate timespan of 18 months for each phase. There is a distribution of the development and restoration costs over the operational life of the facility.

**Future trends for LFG operations schemes**

Finding a suitable site for a landfill is becoming more and more a problem, due to the local opposition for such operations in their "backyards". The strict regulation standards imposed in almost all industrialised countries make it necessary that higher costs will be incurred for the construction, operation, control and aftercare of the site. This will result in a smaller number of bigger capacity sites, due to the benefits of scale associated with these projects (Fig. 1).

## WASTE INCINERATION

Incineration, i.e. the combustion of MSW under controlled conditions, is an established means of processing combustible wastes originating from household, commercial and industrial sources. The principal aim of the process is to reduce the volume and thereby provide significant savings in transport costs and landfill requirements. It also destroys the organic, biodegradable waste components, thus eliminating the possibility of landfill gas and leachate generation when the residue is landfilled. The most important aspect of the MSW as a fuel is that is has a typical low calorific value (typically 30–40% of that of an industrial bituminous coal) and a density, as fired, of about 200 kg m$^{-3}$ (or 20% of that of coal). In the process of incineration, the waste material is combusted and thereby reduced by up to 90% in volume and by 70% in weight. The residue (i.e. ash) is much more easily and cheaply transported and dumped than the original bulk material.

The process of incineration must be strictly controlled to avoid emissions of pollutants to the environment. A large investment is typically required for even a small-scale commercial plant and a relative large space is usually taken up by the incineration building and the associated storage facilities. It is vital to achieve an efficient flow of the waste into and out of the storage area, as well as the smooth disposal of the incineration ashes.[17]

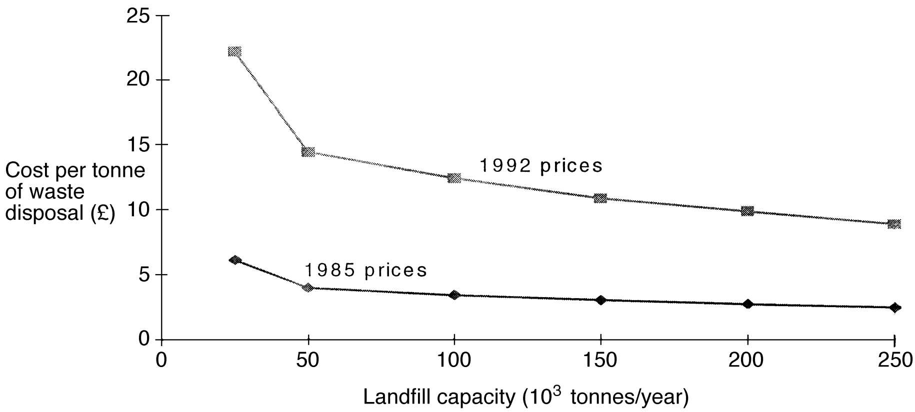


**Fig. 1.** Economies of scale for landfill sites in the UK.[16]

*Energy recovery* from the operation of an incinerator can provide a significant economic benefit, and thus help in decreasing the difference in cost between incineration and landfilling. The residual ash resulting from the incineration of household waste can be further processed to recover ferrous metals but otherwise has little value. Nevertheless, it has found limited use as a low-grade aggregate in the construction industry and, generally, is disposed of as a cover material for landfills. The fly ash, captured during flue cleaning operations, can contain heavy metals at high concentrations. Concern over the toxicity of the constituents of the ash has led to the introduction of national legislation by several countries to control its disposal. Major incinerator manufacturers are therefore investigating alternative post-treatment technologies for incinerator residues, including solidification and vitrification processes to form stable by-products suitable for construction use.

## Environmental impacts

The incineration of wastes (Fig. 2) produces:

- pollutant emissions to the atmosphere;
- contaminated waste water; and
- contaminated ash.

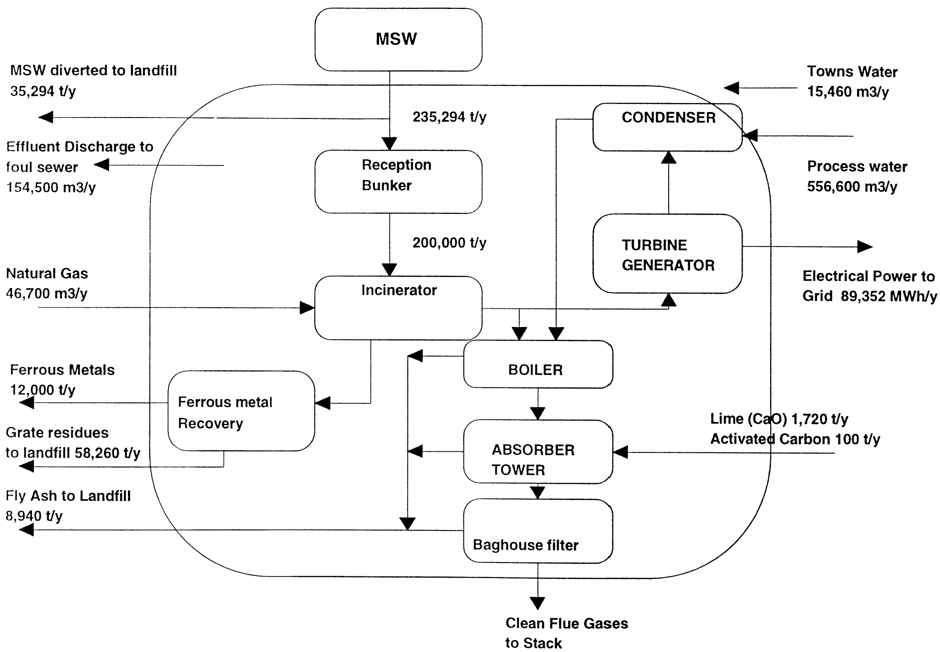


**Fig. 2.** Mass balance for an MSW incinerator with a capacity of 200 000 tonnes year$^{-1}$.[18]

*Air pollution* during waste incineration may occur in various ways:

- Odour, dust and litter problems may arise during the discharge, storage and handling of the waste.
- The gas stream while passing through the waste may extract ash, dust and char and carry them into the flue gas stream.
- Metals and metal compounds may evaporate in the furnace to condense eventually in the colder parts of the flues and generate an aerosol of sub-micron particles.
- Waste may include compounds containing chlorine, fluorine, sulphur, nitrogen and other elements which could result in the generation of toxic or corrosive gases. Nitrogen oxides may form at the temperatures of the flame.
- The pyrolysis products arising during the thermal decomposition of waste may be combusted incompletely, so resulting in the emission of carbon monoxide, volatile organic compounds such as polycyclic aromatic hydrocarbons, dioxins and furans, tar and soot particles.

The hydrocarbons that cause most concern are polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), commonly known as dioxins and furans respectively. They are formed as a result of incomplete combustion and both are found in flue gases and the fly ash. The effects that these compounds can have on human health vary from causing skin disease and liver disorders to cancer.

Of concern are also the emissions of particulates or dust, acidic gases (such as hydrogen chloride, hydrogen fluoride and sulphur dioxide) and heavy metals (such as mercury, cadmium and lead). In addition, the combustion efficiency is limited by the emission of carbon monoxide and organic carbon.

The origin of *hydrogen chloride* (*HCl*) in flue gases from incinerators has been the subject of much research due to its corrosive nature at low temperature (e.g. dew-point corrosion) and high temperature when it dissolves in molten salts.[19] The major source of HCl is regarded as PVC plastic, and a direct relationship between HCl in the flue gas and PVC in the waste has been demonstrated.[20] It has been shown[21] that HCl is important in the high-temperature corrosion of metal surfaces such as heat exchangers. High-temperature corrosion involves a series of interactions between metal, scale deposits, slag deposits and flue gases. The rate of corrosion is influenced by temperature, the presence of low melting phases such as alkali bisulphate and pyrosulfates, the nature of the metal and the periodic occurrence of reducing conditions. The low-melting phases are eutectic mixtures formed between metal salts and the metal surface, with metal chlorides as the most likely source of molten salt corrosion because of their low melting points.

*Hydrogen fluoride* (*HF*) is even more reactive and corrosive than HCl and arises from the combustion of fluorinated hydrocarbons. Emission levels of between 3 and 5 mg $Nm^{-3}$ of flue gases have been reported as typical average values. HF can be controlled by scrubbing the flue gases.[20] *Nitrogen oxides* ($NO_x$) arise from the nitrogen in the fuel and by the combination of the atmospheric nitrogen and oxygen present at high temperatures (i.e. thermal $NO_x$). In practice, thermal $NO_x$ is formed almost exclusively in the flame, particularly under oxidising conditions; in reducing conditions, little $NO_x$ is formed. $NO_x$ generation is increased with high-nitrogen content of the waste and high flame temperatures. Its generation is reduced by using either low-temperature combustion or high temperature combustion under reducing conditions.

*Chlorine, fluorine, sulphur and nitrogen* may also occur in the bottom ash, fly ash, or as dust in the form of thermally-stable compounds or incorporated by adsorption and reaction of for example HCl, HF and $SO_2$ with metal oxides and hydroxides present in the ash. The emission of these pollutant gases to the atmosphere contributes to the formation of acid-rain with its associated environmental damage. NO, is also responsible for the generation of photochemical smog.

*Metals and metal compounds* are present in the components of raw waste. For example, municipal refuse may contain lead from lead-based paints; mercury and cadmium from batteries; aluminium in the form of foils, zinc sheets and volatile salts. Table 4 shows the range of trace metals found in MSW from various countries. High levels can occur and the concentrations are very variable. The extent of evaporation in the furnace depends on complex interrelated factors, such as operating temperature, oxidative or reductive conditions and the presence of scavengers (mainly halogens).[23]

The *heavy metals* released into the environment are associated with the emission of particulates, because volatilisation of metals occurs during the

**TABLE 4**

The range of trace metals in typical municipal solid waste[22]

| *Trace components* | *Concentration (g per tonne of waste)* | |
|---|---|---|
| | *USA* | *Europe* |
| Ferrous | 1000–3500 | 25000–75000 |
| Chromium | 20–100 | 100–450 |
| Nickel | 9–90 | 50–200 |
| Copper | 80–900 | 450–2500 |
| Zinc | 200–2500 | 900–3500 |
| Lead | 110–1500 | 750–2500 |
| Cadmium | 2–22 | 10–40 |
| Mercury | 0.7–1.9 | 2–7 |

combustion of many wastes and subsequent condensation at lower temperatures and adsorption onto the fine particulates in the flue gases. There is an increasing concentration of metals with decreasing particle size for municipal waste incinerators.[24,25] A wide range of heavy metals, such as lead, cadmium, zinc, mercury, copper, antimony, nickel, vanadium and arsenic is present in fuels as intrinsic pollutants.

The rate of release of heavy metals during combustion is dictated by several process variables. In particular, concentration of heavy metals in the fuel feed; physical and chemical composition of the fuel feed; combustion-zone temperature; degree of turbulence in the combustion bed; and the performance characteristic of the air pollution control device employed. In two incineration plants wastes of similar metal concentrations but with different calorific values were burnt. Except for the throughput, the combustion parameters were kept the same. When incinerated, the waste with the higher calorific value, produced approximately double the concentrations of copper, zinc, cadmium and lead in the flue gases compared with the lower energy-content waste (Table 5).

*Particulate emissions* from incinerators are the most visual to the public and often lead to complaints. The particulate emission is largely composed of ash. However, pollutants of a more toxic nature are associated with particulate matter, either adsorbed on the surface of the particles (e.g. such as heavy metals, dioxins and furans) or emitted as individual particles. The dust loading of the flue gases has been shown to increase with the following factors:[27]

- the ash content of the waste;
- the load factor of the incinerator;

**TABLE 5**
Flue-gas trace-metal concentrations for two different wastes[26]

| | *Concentration of trace metals in flue gases particulate ($g\,kg^{-1}$)* | |
|---|---|---|
| | *Low calorific value waste* | *High calorific value waste* |
| Copper | 4 | 8 |
| Zinc | 33 | 76 |
| Cadmium | 0.8 | 1.3 |
| Lead | 18 | 26 |
| Other characteristics of the waste streams | | |
| Relative calorific value | 1 | 1.5 |
| Throughput (tonne $h^{-1}$) | 5.5 | 3.6 |
| $T_{furnace}$ (°C) | 706 | 726 |
| $T_{stack\ gas}$ (°C) | 176 | 174 |

- the degree of agitation of the waste;
- the degree of heterogeneity of the waste;
- too early or too late ignition;
- excessive velocity of primary air;
- improper balance between primary and secondary air;
- excessive draught or disturbance of the fire; and
- excessive height of the steps between successive grates in the combustion chamber.

Given the wide range and varying nature of pollutants of concern from waste combustion processes, there is no single technology available that can satisfactorily control the emissions of all the pollutants concerned. The most commonly-used generic technologies for each pollutant are shown in Table 6.

*Water pollution* from incinerators is not generally regarded as an important problem because of the limited amount of waste water generated, i.e. $\sim$2.5 $m^3$ per tonne of waste incinerated. However, the waste water from these plants is contaminated with heavy metals and inorganic salts, is at high temperatures and has a high acidity or alkalinity.[29] The main sources of waste water from incinerators are flue-gas scrubbing and the quenching of incinerator ash. Other sources include pre-treatment and the purification of boiler feed-water when a boiler plant is installed. Where an incinerator

**TABLE 6**

Generic control technologies for waste combustion[28]

| *Pollutant* | *Control technology options* |
|---|---|
| Particulate matter | Centrifugal separation<br>Electrostatic precipitation<br>Fabric filtration<br>Wet scrubbing |
| Hydrogen chloride (HCl) | Wet scrubbing |
| Hydrogen fluoride (HF) | Semi-dry scrubbing |
| Sulphur dioxide ($SO_2$) | Wet and dry scrubbing |
| Carbon monoxide (CO) | Catalytic oxidation |
| Nitrogen oxides ($NO_x$) | Selective catalytic reduction<br>Selective non-catalytic reduction |
| Mercury (Hg), cadmium (Cd), lead (Pb) | As for particulate matter<br>Scrubbing is also effective |
| Other heavy metals | As for particulate matter<br>Scrubbing is also effective |
| Polychlorinated biphenols | Semi-dry and dry scrubbing are claimed to be effective |
| Dioxins and furans (PCDD, PCDF) | As for particulate matter<br>Semi-dry and dry scrubbing are claimed to be effective |

incorporates no form of heat recovery, the gases from the furnace are cooled by water injection. The water is evaporated completely and passes to the gas clean-up system.

## Examples of successful waste incineration plants

In the early 1970s, one of the largest plants in the world came into full operation at Edmonton, UK. Initially there were some initial problems such as boiler failures, which were overcome and subsequent designs benefited from this experience. Some operating results are presented in Table 7.

Other incineration plants in the UK include the two units, with a capacity of 10 tonnes of MSW $h^{-1}$ each, in Sheffield, which have been in operation since 1975. The plant in Jersey is primarily used for electricity generation since the local climate conditions did not favour the option of district heating for domestic or commercial use.

Waste-incineration plants play a valuable part in the waste management in several European countries, with Denmark and Germany being the most advanced, in terms of the number of plants installed. In the USA and Japan, the need to properly manage the millions of tonnes of MSW has been highlighted over the last 20 years, along with the realisation of the scarcity of land for new landfill sites.

In the USA, the number of waste-incineration plants with energy recovery are 142, and there are some 34 plants with no energy-recovery facilities. The energy-recovery plants have a design processing capacity of

**TABLE 7**
Operational performance of the Edmonton plant in the UK[30]

| *Financial year*[a] | *Actual wastes throughput (tonnes year$^{-1}$)* | *Total boiler operating h per year* | *Average annual station thermal efficiency (%)* | *Plant capacity factor (PCF) (%)* | *Electricity exported (GWh)* | *Revenue from electricity sales (£000)* |
|---|---|---|---|---|---|---|
| 1974–1975 | 378.000 | 32 780 | 12.7 | 72 | 135.500 | 663 |
| 1975–1976 | 340.000 | 28 392 | 13.4 | 64 | 128.000 | 754 |
| 1976–1977 | 300.000 | 26 232 | 12.7 | 57 | 107.300 | 952 |
| 1977–1978 | 410.000 | 36 312 | 13.2 | 80 | 158.169 | 1520 |
| 1978–1979 | 316.200 | 29 328 | 13.0 | 60 | 117.289 | 1194 |
| 1979–1980 | 330.700 | 30 600 | 13.5 | 63 | 127.652 | 1581 |
| 1980–1981 | 398.700 | 34 992 | 14.2 | 76 | 158.676 | 2592 |
| 1981–1982 | 385.000 | 33 264 | 14.1 | 73 | 152.286 | 3243 |
| 1982–1983 | 402.000 | 34 230 | 12.7 | 76 | 151.781 | 3732 |
| 1983–1984 | 375.000 | — | — | 71 | 147.000 | 3900 |

[a]From the beginning of April to the end of March of the following year.

101 277 tonnes of MSW per day; an electricity generation potential of 2300 MW (which is equivalent to the electricity demand of 1.3 million households); and an associated energy saving of almost 31 million barrels of crude oil per year. There are five plants under construction, with an estimated design capacity of 2.5 million tonnes of MSW per year and, another 44 waste incineration plants, with no energy recovery are in the planning stage with an estimated handling capacity of 11.5 million tonnes of MSW per year.

Incineration developments have been influenced by:

- concerns over direct landfill of certain materials (e.g. clinical wastes) and identification of problem wastes for which incineration represents the only commercially-available method of disposal;
- legislative controls curtailing other disposal routes (e.g. for sewage sludge);
- identification of new environmental problems requiring remediation (e.g. contaminated soils); and
- recognition of the energy generation potential from burning wastes.

The case for constructing new municipal incinerators with heat recovery therefore turns primarily on financial viability. The sale of the energy recovered, must generate sufficient income to leave the net cost of waste disposal lower than the cost of the cheapest feasible alternative. However, an incineration plant might be producing energy for district heating. The problems of fluctuating demand are absorbed in this case by the electricity-supply system. The cost of doing this, should be reflected in the worth of the energy generated.[29]

Waste incineration is a capital investment process and the net costs are sensitive to both the scale of operation and cost of capital. Energy recovery can significantly reduce the net incineration cost, providing that the waste has a suitable calorific value and that the energy generated has a market. Waste combustion can generate energy in the form of heat or electricity, and in this way, displaces the use of fossil fuels. A municipal waste stream ofa400 000 tonnes per year, has the potential to supply approximately 30 MW of electrical energy, and surplus thermal energy in the form of hot water or steam.[31] It is unlikely that the costs of incineration could be economically or environmentally justifiable without the facility of energy recovery, which is then dependent on the availability of a market for the energy generated.

## Economics of waste incineration

The following analysis of the incineration costs will be based mainly on mass-burn incineration plants without energy recovery. For mass-burn incineration there are five main cost components:

- *Land-acquisition cost*. This is sometimes not included in assessments of combustion plants. However, the question of land use is important for the comparison with landfilling and an estimate is therefore required for consistency. The much smaller the amount of land required relative to that for landfilling, makes incineration a more flexible solution. However, stringent planning conditions along with the proximity to customers, if energy or heat distribution is involved, imposes restrictions on the choice of the site. There is also a need for a ready access to a secure, long-term landfill to accept the residues from incineration. The acquisition cost is typically a small percentage of the total cost.
- *Assessment cost*. This is the cost of site investigations, which include several management-related functions and all aspects of the plant's operation (e.g. the choice of technology, the securing of waste inputs as well as residue disposal capacity). It represents an extremely small fraction of the overall cost.
- *Development and capital cost*. This is assumed to be incurred prior to operation, although, in reality, it may be spread out over a longer time-frame according to predetermined financial schedules.
- *Operating cost*. Most of this is concerned with the monitoring and disposal of residues from the plant (transport prices to the landfill are not included in this study). Higher salaries are incurred because of the need for more skilled personnel.
- *Decommissioning cost*. This is commonly expressed as a proportion of the capital cost for all main engineering works. Currently, it is typically a small fraction (~5–10%) of the capital cost, with the value of 10% being more representative for the UK.

For illustration, an incineration plant with a capacity of 200 000 tonnes per year will be considered. The plant is located in a 10 ha site in or near a built-up environment with relatively high industrial land values (i.e. £50 000 $ha^{-1}$). A summary of the associated costs is presented in Table 8. A breakdown of these costs is illustrated in Table 9.

The case of recovering energy for electricity or steam generation purposes would require additional capital and operating costs. A summary of these additional costs are presented in Table 10. In this case, the cost per tonne of waste incinerated would be between the range of £20.8→29.1 per tonne, subject to the different unit selling prices for the electricity generated by the plant.[16]

**TABLE 8**

Summary of incineration costs for an incineration plant without energy recovery and with a lifetime of 20 years[16]

| *Stage* | *Total expenditure (£)* |
|---|---|
| Acquisition | 500 000 |
| Assessment | 155 000 |
| Development | 38 850 000 |
| Operation | 69 300 000 |
| Decommissioning | 3 250 000 |
| Total | 112 055 000 |

**TABLE 9**

Breakdown analysis of the incineration costs for a 200 000 tonne per year plant with a lifetime of 20 years[16]

| *Incineration cost item* | *Rate* | *Quantity* | *Amount (£)* |
|---|---|---|---|
| Site acquisition cost | £50 000 ha$^{-1}$ | 10 ha | 500 000 |
| Assessment cost: | | | |
| Full site investigation | | | 30 000 |
| Planning and meetings | | | 50 000 |
| Environmental assessment | | | 75 000 |
| Subtotal | | | 155 000 |
| Development and capital cost: | | | |
| Civil and buildings | | | 8 000 000 |
| Mechanical and electrical | | | 24 500 000 |
| Mobile plant (loading, shovels, containers) | | | 400 000 |
| Strategic spares | | | 1 200 000 |
| Engineering services | | | 1 850 000 |
| Promotion, management, legal | | | 2 900 000 |
| Subtotal | | | 38 850 000 |
| Operating cost: | | | |
| Wages salaries | Various | 26 staff | 80 000 |
| Maintenance: | | | |
| Civil and building | 1% of capital | | 80 000 |
| Mechanical and electrical | £5 tonne$^{-1}$ | 200 000 tonnes | 1 000 000 |
| Mobile plant | Sum | | 20 000 |
| Fuel | £0.2 tonne$^{-1}$ | 200 000 tonnes | 40 000 |
| Combustion additives | Sum | | 350 000 |
| Environmental monitoring (sample) | £3 tonne$^{-1}$ | 60 000 tonnes | 180 000 |
| Residue disposal | £15 tonne$^{-1}$ | 60 000 tonnes | 900 000 |
| Rates (per tonne) | £0.5 tonne$^{-1}$ | 200 000 tonnes | 100 000 |
| Contingency (10%) | | | 315 000 |
| Subtotal (annual) | | | 3 465 000 |
| Subtotal | | | 69 300 000 |
| Decommissioning costs | 10% of capital | | 3 250 000 |
| Total | | | 112 055 000 |

There is no assumption about salvaging equipment for sale at a discounted price.

**TABLE 10**
Economics of incineration with energy recovery[16]

| *Item* | *Value* |
|---|---|
| Calorific value of MSW | 8.5 GJ tonne$^{-1}$ |
| Additional capital (turbines, generators, grid connection) | £8 000 000 |
| Additional annual operating cost | £80 000 year$^{-1}$ |
| Incinerator utilization | 85% |
| Boiler efficiency | 70% |
| Total efficiency of heat-electricity conversion | 30% |
| Annual gross power output | 99.2 GWh year$^{-1}$ |
| In-house consumption | 65 kWh tonne$^{-1}$ |
| Annual power exported | 86.2 GWh year$^{-1}$ |

## Future trends

Waste incineration with its ability to maximise the recovery of energy and to reduce the volume of the waste to 10% or less of its initial crude form, can reduce the cost of waste disposal, if the residues are properly treated before being landfilled. The option of waste combustion with energy recovery tends to be a viable option only for populations of 100 000 or more, because a minimum amount of feed rate is required for an economically-viable operation. As it can be seen from Fig. 3, the economy of scale favours the option of higher handling capacity plants, because both the operation and maintenance costs per tonne decrease as the plant size increases.

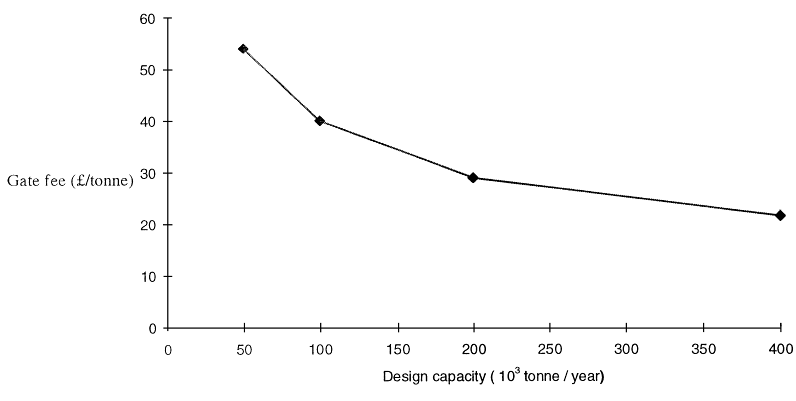


**Fig. 3.** Economies of scale for incineration plants.[16]

## COMPOSTING

*Composting* is defined as the biological decomposition and stabilisation of organic substrates under conditions which allow the development of thermophillic temperatures as a result of biologically-produced heat, with a final product sufficiently stable for storage and application to land without causing any adverse environmental effects.[32]

The main objectives of composting have traditionally been to biologically convert putrescible organic material to a stabilised form and to destroy organisms pathogenic to humans. If the compost product is reused, it can accomplish several additional purposes including:

- to serve as a source of organic matter for maintaining or building supplies of soil humus, necessary for proper soil structure and moisture holding capacity;
- to reclaim and reuse certain valuable nutrients including nitrogen, phosphorous and a wide variety of essential trace elements; and
- to improve the growth and vigour of crops in commercial agriculture or home-related uses.

### Key environmental and operational factors

Because the microbes are the main active agents in composting, it follows that those factors which affect their proliferation and activity will also play a major role in the composting-process rate and duration. Collectively, they are environmental in nature. The nature of the substrate is one of the most important factors. Substrate-related parameters are:

- *The Carbon-to-nitrogen (C/N) ratio*. All nutrients are adequately present in a typical organic waste. Requirements with respect to the C/N ratio depend on the metabolism of the microbes. A large percentage of the carbon is oxidised to carbon dioxide, while the remainder is converted into cell wall, membrane or protoplasm. The major consumption of nitrogen is in the synthesis of protoplasm. Therefore, more carbon than nitrogen is required. The ratio is in the order of ~20–25 parts of carbon to one part of nitrogen. Departures from this ratio will lead to a slowing of the decomposition process and hence to the composting rate.
- *Particle size*. The significance of this lies in the amount of surface area of the waste particles exposed to microbial attack: the greater the ratio of surface area to volume of the waste, the more rapid is the rate of the microbial attack. In practice, the minimum permissible particle size is

that at which the porosity required for proper aeration in a composting mass can be attained and maintained.

- *Temperature*. When the temperature exceeds 65 to 72°C, the tendency is for spore formers to pass into the spore-forming stages. The transition is undesirable because the spore-forming stage is a resting one, and the rate of decomposition is accordingly reduced. Moreover, microbes, incapable of forming spores are strongly inhibited or even killed at those temperatures. Consequently, the temperature should be maintained below 65°C. A typical temperature curve is presented in Fig. 4.
- *The pH value*. This usually drops somewhat (i.e. down to 5.0) during the early stages of the process, because of organic acid formation. The acids serve as substrates for succeeding microbial populations. Thereafter, the pH begins to rise and may reach levels as high as 8.5. Because it is unlikely that the pH will drop to inhibitory levels, there is no need to buffer the composting mass by adding lime (i.e. calcium hydroxide). An exception could be in the composting of fruit wastes. With such wastes, the pH can drop to 4.5. There is some evidence that, under such conditions, the composting process can be accelerated.[33]
- *Aeration conditions*. The theoretical amount of oxygen required is determined by the amount of carbon to be oxidised. However, it is impossible to arrive at a precise oxygen requirement on the basis of the carbon content of the waste, because an unknown fraction of it is converted into bacterial cellular material and another is so refractory in nature (i.e. remains inaccessible to the microbes).

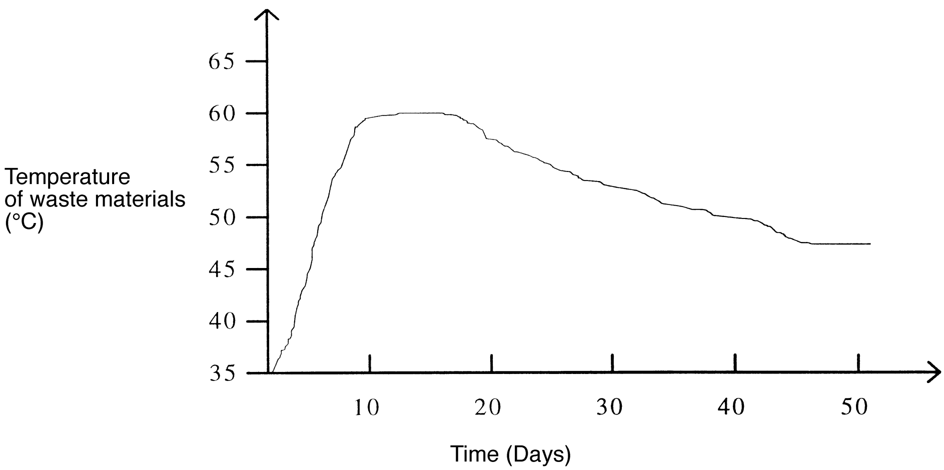


**Fig. 4.** Typical temperature curve for a composting process.[33]

- *Moisture content*. This is closely related to the oxygen requirements of the process. The oxygen supply to the microbes involves both the ambient air and the air trapped within the interstices (i.e. voids between the particles) of the waste. When the rate of diffusion of ambient air into the mass is inadequate, the air in the voids is the major source of oxygen. If the moisture content of the mass is so high as to displace most of the air from the voids, anaerobic conditions will develop within the mass.

**Environmental impacts of waste composting**

Principal potential negative impacts of a compost operation on the environment could be the lowering of the quality of a water resource or local air and the compromising of public health by attracting vectors and rodents. However, such impacts occur only when an inappropriate technology is used.

The quality of a water resource can be affected adversely through contamination with run-off from the compost operation or with leachate from raw, composting or composted refuse. Leachate is formed only when the moisture content of the material is excessively high ($>60$ to 65%). Uncontrolled addition of moisture can be minimised by sheltering the operation. As a precautionary measure, provision should be made to keep the leachate from reaching ground and/or surface waters by conducting all phases of the composting operation on a suitably contoured, paved surface.

Biological and non-biological agents from various stages of the composting operation most likely would be discharged into air, as dust particles and aerosols. Some of the microbes transported in this manner could be a hazard to the health of individuals, who might ingest these dust particle or aerosols.

**Examples of successful composting operations**

Factors that have influenced the development of new composting facilities in the USA include the closure of landfills, strong anti-incineration sentiments, the introduction of higher-technology systems to process mixed-waste streams, growing confidence in composting as an option to handle municipal waste and an economic environment that allows composting to compete against incinerators and landfills. These factors did combine in the late 1980s to spark interest in composting municipal solid waste. By 1990, there were only 79 USA-based projects in various phases of development and only nine full-scale facilities in operation. In 1992, there were 61 projects in development and 21 in operation. The significance difference between the data of the two surveys conducted in the USA is that in 1990, there were 14 projects under construction, whereas in 1992, there was only one.[34] Similarly there were 10 projects in design stages in 1990, compared with four in 1992.[35] New trends that have emerged in the 1990s are the cutbacks in state and municipal budgets that tightened up available funds for such new projects; closure of some of the larger mixed-waste composting plants and perhaps more significantly, declining landfill tips fees in some countries combined with the opening of mega-landfills.[36]

In Canada, the situation is similar to that in the USA. For the last 10 years, research has been undertaken to examine the possibility of diverting, to composting programmes, the degradable fraction of the MSW stream. Experience has shown that basic recycling programmes could divert at least a 10–20% of the total MSW, while the separation of the organic material could divert another 10–15%, depending on the pick-up frequency. Local communities that have applied year-round collection of food and yard waste, have appeared to achieve 50–60% diversion rate.[37,38]

In Germany, several pilot-scale projects have been involved in a programme aiming at diverting the organic fraction of the MSW from landfills. The decision of the German government not to permit open-air food composting sites to be of a capacity larger than 1000 tonnes per year, resulted in the development of these local-scale schemes. Each one of these sites is associated with a village and utilises kitchen and yard waste. The farmers who are responsible for the operation of the sites are paid an agreed tipping fee. The final product is basically used directly by the farmers or sold as an organic fertiliser.[39]

France and Italy are also among the European leaders in terms of the amount of household refuse composted. According to the official data, around 95 composting facilities operate in France, processing 1.5 million tonnes of mixed domestic wastes each year to produce 650 000 tonnes of organic compost. In Italy, there are several facilities, which process either mixed domestic wastes or segregated organic wastes (such as those collected from vegetables markets). In Switzerland and in The Netherlands, 2.3 and 1.18 million people, respectively, are involved in separate organic collection systems.[40]

## Economics of composting operations

The economics of running a composting scheme will be examined for the case of a system employing the windrow process. Three cost elements are considered:

- *Construction cost*, which includes all costs associated with land acquisition, site preparation and equipment purchase

- *Fixed cost*, which includes depreciation, interest on the un-depreciated's or remaining value of the facility, repairs or maintenance of fixed assets and insurance.
- *Operating cost*, which includes the costs of labour, materials and equipment operation.

Although the overall windrow process is simple, local solid-waste authorities involved in these operations face an array of choices regarding facility design and day-to-day operation. These choices are governed by:

- *The facility size*. This depends upon the size of the local population served, the composition of the housing (e.g. ratio of the number of apartments versus single family houses) in the area and the dominant types of local vegetation.
- *The ground cover*. Composting facilities may be paved or unpaved: in the latter case, facilities with a packed-earth floor are cheaper to construct. However such facilities experience considerable difficulties during periods of heavy rain. Gravel, asphalt or concrete may be used for the paved facilities.
- *The machinery used*. A variety of equipment is required for large-scale operations. Either a front-end loader or a specialist compost turner may be employed for the turning of the windows.[40–43]

The cost analysis is based on the following prototypes:

- *Simple passive pile or minimal-technology system* that requires minimal labour and mechanical inputs.
- *Low-technology system* requiring a paved surface and a front end loader for turning the windrows.
- *Medium-technology system* that features a paved surface, screening and shredding equipment to ensure uniform consistency of the finished product.

A series of different annual capacities has been examined,[40] involving 10, 25 and 100 thousand tonnes of waste processing material for each of the above options. Perhaps the most important feature that differentiates the prototype systems is the frequency of turning the windrows. This affects directly the quality of the finished product, the amount of volume reduction and the total time required to create a stabilised product. All of these factors affect the facility and operating costs. By examining the different cost element parameters, several conclusions can be drawn:

- The *low-technology* system is less costly to operate than the *medium-technology* system when the annual capacity is 10 000 tonnes. However as the annual throughput increases this cost advantage is reversed. For a given annual volume, however, minimal-technology facilities are considerably less costly than the other facilities.

- Fixed costs account for between 64–84% of the total costs for all prototypes. This is significant because these costs, which are mainly the interest payments necessary for financing the initial construction of the sites, will accrue regardless of the degree to which the facilities will be utilised.

## Conclusions and future trends

The future of composting depends largely on the advantages and disadvantages offered compared with other waste management alternatives. These advantages are many: it can convert putrescible organics to a stabilised form, destroy pathogenic microbes and provide significant drying of wet substrates such as sludge. All of these are obtained with minimum energy input. Drying reduces the cost of subsequent handling and increases the attractiveness of composted product for reuse. Furthermore, composting is compatible with a variety of feedstocks, including from raw and digested sludge, conditioned by heat, organic polymers or inorganic materials such as lime, and can use a variety of amendments as may be locally available. A general diagram relating the nuisance problems associated with composting with the degree of control involved in the system is shown in Fig. 5. Nuisance problems should be reduced as more control measures are included in the system design.

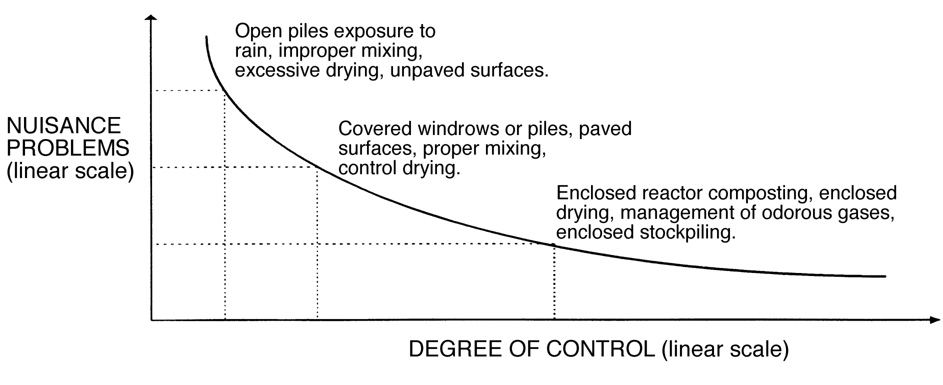


**Fig. 5.** Generalised diagram relating nuisance problems with the degree of control exercised over them.[32]

## WASTE RECYCLING

Recycling involves using materials which are at the end of their useful lives as the feed stocks for the manufacture of new products. Within recycling a further hierarchy can be defined:[44]

- *Primary recycling*. This is the use of recycled products to make the same or similar products. Examples include the recycling of aluminium cans and glass bottles. Because this is, at least partially, a closed-loop process, it can and should be regarded as having a high value.
- *Secondary recycling*. The use of recycled materials to make new products with less stringent specifications than the original. This allows for down-grading of the material to suit its possibly-diminished properties and hence is of lower value than primary recycling.

All recycling systems must have three major components in order to function, namely:

- there must be a consistent and reliable source of the recycled materials;
- methods for processing the recovered materials into a form suitable for reuse must be in place; and
- markets must exist for the reprocessed materials.
  It is only when all these components, function in an economically-viable manner that a successful recycling system exists.

Recycling differs from re-use because it includes the processing step. The term recycling is often used to describe the collection of materials separated from the waste. This operation is more correctly defined as reclamation. In addition to the collection and separation of materials from waste, recycling includes the subsequent processing to produce marketable products.[44] These marketable products can be in the form of:

- materials such as paper and board;
- finished products partly or totally consisting of recycled materials;
- solid, liquid or gaseous fuels or
- energy as heat or electricity.

Recycling is also different from resource recovery. In resource recovery, materials are recovered for reuse from a mixed stream of solid waste. Recycling programmes rely on the separation of recyclable materials rather than allowing them to be mixed with the rest of the waste (i.e. source separation).

Waste may be separated at source into a number of different categories, or simply only into recyclable and non-recyclable components.[45]

## Factors influencing recycling programmes

There are four main parameters that dictate the degree of success of a recycling programme:

1. *Technical limitations*. Estimates on the theoretically achievable recycling rate for municipal waste vary significantly depending on the assumptions made regarding the composition of the waste, the degree of material contamination and the technically-obtainable recycling rates for individual waste fractions. Estimates[46] range from about 40% to about 80% by weight.[47,48] Recycling rates above 50% have been based on the assumption that the recycling programme involves most of the fractions of the waste stream and that expensive curbside collection schemes are employed (i.e. segregated components).

2. *Level of public participation*. Public support for collection schemes is essential. Most of the sorting of the waste will then be carried out by householders instead of the use of centralised sorting plants. The role of the public in recycling so far has been a direct result of environmental campaigns. However, ''consumer awareness of the effects of purchasing decisions on waste volumes, disposal needs and the environment is only slowly emerging''.[49]

Gandy,[50] identified the following three main factors which affect the level of public participation:

- the general psychological aspects encouraging or inhibiting participation in the different types of schemes;
- the effect of different socio-economic householders characteristics on their likelihood to participate; and
- the general level of environmental concern in society.

The highest rates have been recorded for mandatory curbside schemes in affluent small towns, where households are required to set out segregated fractions of their waste for collection.[47] In these schemes, the level of participation has reached 85–95% of the entire population in the area. In the case of ''bring systems'', an important factor is the density of the waste collection facilities. A low-density scheme, is one which involves longer average distances for the residents to reach the collection points. If the facilities are placed close to shopping centres, then the motivation for taking part in the scheme is usually closely related to the convenience of simultaneously visiting the shops and transporting materials for recycling.

Several studies have been undertaken to examine the psychological rewards for participation in a recycling scheme. The effect that different types of rewards might have on participation rates has been the centre of debate. DeYoung[51] found that intrinsic satisfaction, associated with environmentally-responsible behaviour, contributed to citizens well being and that conservation behaviour might be carried out without the need of an external financial reward. Vining and Ebreo[52] suggested that financial inducements are always necessary to gain the participation of the less environmentally-motivated recyclers.

3. *Markets for secondary products*. Setting up a recycling scheme and maintaining its viability requires the existence of a market for the by-products produced. This is an important element in terms of the financial viability of the scheme, because the raised revenues will make the recycling option a more attractive waste-treatment option. However, it has often been found difficult to maintain a market for secondary materials due to:

- a miss-match between the supply of recycled materials and the demand for recycled products;
- the competition with virgin raw materials; and
- the difficulties of ensuring consistent supply of sufficiently uncontaminated material in economically-handleable quantities.

However, the capacity of secondary-materials market to absorb the collected materials could be improved by a variety of policy instruments aimed at the production cycle or in the consumption level of the associated products. Initiatives, such as government procurement of recycled products, government support for recycling as an economic-development strategy, export promotion campaigns and the introduction of financial incentives, are some of the measures that could be adopted.[47,53]

4. *Economic viability of recycling*. An important rationale for recycling is claimed to be its potential to cut waste disposal and collection costs and also to generate a net income form the sale of the recovered materials. Several studies have examined the economic viability of recycling. Some analyses suggest that the economics of a comprehensive collect system such as a curbside scheme are very favourable. In New York, it has been reported that a 40% recycling rate of MSW is a realistic target and that according to 1985 prices, recycling would be less expensive per tonne than incineration and landfilling the residual ash.[47] A study for California[54] claimed that the

average cost of collection and disposal was approximately \$60 per tonne, where the curbside recycling cost was less than \$40 per tonne. However, these figures are very site specific and should not be used as a clear indication of the recycling economics. A detailed assessment of each proposed application should be undertaken.

## Environmental impacts of recycling

The benefits derived from recycling include avoiding operational and external costs associated with waste disposal (i.e. costs of environmental damage by, for example, leachate leakage and emissions to air) and the possible revenue from the sale of the recycled materials. These should be balanced against the costs associated with recycling, such as: extra costs incurred due to the separation of used materials from mixed waste, the costs associated with any process involved (e.g. cleaning, de-inking and remelting) and any external costs (e.g. costs of environmental pollution from de-inking processes and health risks from the sorting and recycling processes).

There are a variety of environmental justifications for recycling:

- the conservation of the finite resources as a move towards the achievement of sustainable economies;[55–59]
- the reduction of energy consumption in production;[60–62]
- the limiting of pollutant emissions during production processes and the disposal of the wastes generated; and
- finally, the environmental-education benefits of participation in recycling.[60,63]

The relative importance of these different environmental objectives varies. The saving of energy is usually considered more important than the recovery of materials, if there is to be a trade-off between the two goals (Table 11). Furthermore, the environmental benefits of recycling of different components of a waste stream depend on which material forms the focus for the recycling policy (Table 12).

## Economics of recycling operations

Recycling is economically viable if the value of the resources used in the process do not exceed the value of the resources saved. In some cases, however, more resources are used in collecting, separating, transporting, cleaning and reprocessing used materials than can be justified by the value and quality of the recycled products, and more environmental damage results from the

**TABLE 11**

The environmental and economic objectives of a recycling policy in developed economies[64]

Environmental objectives:
- Important part of a sustainable industrial progress[55]
- Reduced energy consumption in production processes[65,66]
- Reduced pollutant emissions from production processes and the disposal of the waste[63]
- Environmental-education benefits[60]

Economic objectives:
- Regeneration of urban economies[67]
- Reduced expenditure on waste disposal[47,49]
- Income for charities and local authorities from the sale of recovered materials[60]
- Reduced balance-of-payments deficit in raw materials[68,69]
- Geo-political resource security against producer cartels[56,70]

**TABLE 12**

Environmental benefits from substituting secondary materials for virgin resources[71]

| *Item* | *Percentage reduction in the stated item as a result of recycling the following materials* | | | |
|---|---|---|---|---|
| | *Aluminium* | *Steel* | *Paper* | *Glass* |
| Energy usage | 90–97 | 47–74 | 23–74 | 4–32 |
| Air pollution | 95 | 85 | 74 | 20 |
| Water pollution | 97 | 76 | — | 35 |
| Mining wastes | — | 74 | — | 80 |
| Water usage | — | 40 | 58 | 50 |

recycling process than would have resulted from the deposition in a landfill or the incineration of the waste material. What is often overlooked when recycling targets are set, is that it is necessary to balance the costs and the benefits of recycling in order to determine the optimal recycling level, rather than just setting some arbitrary target.[62]

The use of a materials-recovery facility (MRF) in waste management aims at reducing the amount of the MSW going to landfills by maximising recycling potentials and increasing public participation in recycling programmes. MRFs are becoming more attractive because of the high costs of other solid-waste disposal methods, particularly landfilling.[72] This attractiveness is mainly due to fact that:

- the feedstock of most MRFs is mixed recyclables;
- collection needs can be simplified; and
- materials processed through MRFs are attracting more markets.

Even though many of the operations of an MRF are highly mechanised, there are still many jobs on the site that need manual labour (e.g. glass sorting by colour, which is still the more reliable approach to ensure quality of the end product). In any case, the trade-off between the manual and the fully-mechanised operation of an MRF is a function of capital versus operating costs. The highly-mechanised systems have capital costs that range from 75 to 100% higher than those for the manually-operated systems.[54]

Several approaches have been proposed for the design of MRFs. They range from *low-technology plants*, which are relatively simple in design, labour intensive, involve minimum hardware and typically are of low handling capacities, to *high-technology plants*, which can handle higher tonnage of waste, are relatively complex in design, mechanically intensive and involve higher capital, operation and maintenance costs.

The total cost of running an MRF site has been considered for throughput capacities between 10 and 500 tonnes per day. A range of costs is also presented in order to account for variations in engineering well as design and capital and operating costs, and to accommodate the wide variety of specific conditions that apply to MRF projects. Capital costs include the facility-construction costs and the equipment-purchasing costs. Construction costs vary depending upon the technology employed, site's specific conditions (e.g. subsurface conditions and local topography), structural materials used for building construction and local building-code requirements. Typical floor area requirements for major settings of the site are given in Table 13, as a function of the throughput capacity. The primary variables are the tipping floor and storage capacities desired. A general rule for that is to maintain sufficient tipping floor capacity to accommodate a reasonable worst-case scenario (e.g. unscheduled maintenance) and enough storage capacity for each material processed. The unit cost of equipment decreases as the capacity increases.

The costs presented in Table 14 are at the upper range of the cost scale for existing facilities. This is because, for many of the existing facilities:

- there is not an adequate floor area for unprocessed and processed material storage;
- they have been developed within existing structures, thereby avoiding stringent building codes; and
- the inclusion of mixed recycled materials in the facility design, increases the capital costs for both the sorting area and the associated equipment; usually most old facilities do not possess this capability.

**TABLE 13**
Typical MRF floor requirements (in m$^2$) by throughput capacity[54]

| Item | Throughput capacity (tonnes per day) | | |
|---|---|---|---|
| | 10 | 100 | 500 |
| Tipping floor: | | | |
| 2 day capacity | 278.71 | 696.77 | 2787.09 |
| 3 day capacity | 278.71 | 1045.16 | 4180.64 |
| Processing | 557.42 | 1858.06 | 4645.15 |
| Storage: | | | |
| 7 day capacity | | 812.90 | 3251.61 |
| 14 day capacity | 162.58 | 1625.80 | |
| 28 day capacity | 325.16 | | |
| Total (low) | 998.71 | 3367.73 | 10 683.85 |
| Total (high) | 1161.29 | 4529.02 | 12 077.39 |
| Total (average) | 1080.00 | 3948.38 | 11 380.62 |

**TABLE 14**
Estimated capital costs (in US$) for an MRF plant[54]

| Cost item | Throughput capacity (tonnes per day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10 | | | 100 | | | 500 | | |
| | Low | High | Average | Low | High | Average | Low | High | Average |
| Construction | 295 630 | 756 250 | 511 500 | 996 900 | 2 949 400 | 1 870 000 | 3 162 500 | 7 865 000 | 5 390 000 |
| Equipment | 259 990 | 424 910 | 342 450 | 2 055 400 | 3 285 800 | 2 670 600 | 4 265 500 | 6 608 500 | 5 437 000 |
| Engineering | 66 670 | 141 740 | 102 470 | 305 200 | 623 500 | 454 100 | 594 000 | 1 158 000 | 866 000 |
| Total | 622 290 | 1 322 900 | 956 420 | 3 357 500 | 6 858 700 | 4 994 700 | 8 022 000 | 15 631 500 | 11 693 000 |

The operating costs of a facility are divided into *labour*, *operation* and *maintenance costs*. The range of labour requirements is presented in Table 15. The data show a great variability associated with the sorting efficiency of the plant, which is highly dependent upon the facility design. In general, labour requirements for sorting processes decrease with increased capacity, due to the greater need for mechanical separation equipment such as classifiers and eddy-current separators. The operations and maintenance costs include:

- heating costs, which are dependent on of the geographical location and the building specifications;
- maintenance costs, which are functions of the type and quality of equipment as well as the diligence of routine maintenance; and
- the cost of disposal of residue materials.

**TABLE 15**
Estimated labour requirements for an MRF plant by throughput capacity[54]

| | *Throughput capacity (tonnes per day)* | | |
|---|---|---|---|
| | *10* | *100* | *500* |
| Manager | 1 | 1 | 1 |
| Foreman/operator | 1 | 1 to 2 | 3 to 4 |
| Sorters | 1 to 2 | 13 to 25 | 60 to 80 |
| Maintenance | 0 to 1 | 1 to 2 | 4 |
| Other[a] | 0 | 4 to 5 | 10 to 12 |
| Administrative[b] | 0 | 1 to 2 | 2 to 3 |
| Total | 3 to 5 | 21 to 37 | 80 to 104 |

[a]Includes rolling stock operators, equipment monitors and cleanup staff.
[b]Includes scale monitors, bookkeepers and clerical staff.

Debt service is also included in the operational costs, based upon an interest rate of 10% amortised over 20 years for facilities and 7 years for the equipment (Table 16).

## Examples of recycling schemes

Recycling has been considered as an alternative method for waste treatment over the last few years in the UK. The majority of the waste-collection authorities are operating or developing recycling programmes. However, the market prices for the recovered materials strongly depend on the geographic location.[73]

The facilities run by Cambridge City Council, Southampton City Council and Milton Keynes Council recycling schemes will be briefly described:

Cambridge City Council operates a high-density "Bring Scheme", which was launched in 1990 and consists of 28 Neighbourhood Recycling Centres comprising various sizes of wheeled-bin containers for the collection of paper, glass, metal cans and plastic bottles. In Southampton, the city council encourages the voluntary collection of aluminium cans and glass bottles/jars for recycling. Currently 75% of the city's schools and many other groups collect aluminium cans. Since 1990, eleven Community Recycling Centres have been introduced into the city at schools and community centres. These are seen as a partnership between the waste-collection authority and community groups in encouraging the provision and promotion of additional recycling facilities at points which are convenient and accessible to the public. In Milton Keynes, an extensive weekly curbside collection system was introduced in 1990, with 5600 out of the total 90 000 properties of the

**TABLE 16**

Estimated total operation and maintenance costs (in US$ per year) for an MRF plant by throughput capacity[54]

| *Cost item* | *Throughput capacity (tonnes per day)* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *10* | | | *100* | | | *500* | | |
| | *Low* | *High* | *Average* | *Low* | *High* | *Average* | *Low* | *High* | *Average* |
| Labour: | | | | | | | | | |
| Sorters | 12 480 | 24 960 | 18 720 | 162 240 | 312 000 | 237 120 | 748 800 | 998 400 | 873 600 |
| Others | 49 920 | 99 840 | 74 880 | 199 680 | 299 520 | 249 600 | 499 200 | 599 040 | 549 120 |
| Overhead[a] | 24 960 | 49 920 | 37 440 | 144 766 | 244 608 | 194 688 | 499 200 | 638 976 | 569 088 |
| Maintenance | 5200 | 6500 | 5850 | 52 000 | 65 000 | 58 500 | 260 000 | 325 000 | 292 500 |
| Insurance[b] | 7800 | 10 400 | 9100 | 78 000 | 104 000 | 91 000 | 390 000 | 520 000 | 455 000 |
| Utilities: | | | | | | | | | |
| Power | 1560 | 3640 | 2600 | 15 600 | 36 400 | 26 000 | 78 000 | 182 000 | 130 000 |
| Water and sewage | 36 | 73 | 55 | 473 | 910 | 692 | 2184 | 2912 | 2548 |
| Heating[c] | 0 | 1402 | 701 | 0 | 14 016 | 7008 | 0 | 70 080 | 35 040 |
| Fuel | 624 | 624 | 624 | 6240 | 6240 | 6240 | 31 200 | 31 200 | 31 200 |
| Outside services | 10 258 | 19 736 | 14 997 | 65 900 | 108 269 | 87 085 | 250 858 | 336 761 | 293 810 |
| Residue disposal | 6500 | 26 000 | 16 250 | 65 000 | 260 000 | 162 500 | 325 000 | 1 300 000 | 812 500 |
| Debt service | 93 749 | 188 635 | 139 319 | 560 258 | 1 068 325 | 801 155 | 1 284 745 | 2 361 396 | 2 180 344 |
| Total annual cost | 213 087 | 431 730 | 320 536 | 1 350 157 | 2 519 288 | 1 921 588 | 4 369 187 | 7 365 765 | 6 224 750 |
| Cost per tonne | 81.96 | 166.05 | 123.28 | 51.93 | 96.90 | 73.91 | 33.61 | 56.66 | 47.88 |

[a]Includes social security, sick leave and insurance.
[b]Includes workers compensation, property and liability.
[c]Range of use based on climatic conditions.

city participating in its first phase. In March 1992, when the last expansion of the scheme occurred, the participated properties were nearly 73 000 and it is expected that by the end of the decade an even greater percentage will be involved. Unfortunately there are no cumulative data concerning the actual cost of the separation and sorting process for each individual material. However, the average cost of this process is approximately £10 per tonne. Milton Keynes Council keeps records on the waste collected on a weekly basis.

In the USA, a large-scale survey of recycling schemes in rural, suburban and large urban areas was conducted in 1989–1990.[41,74,75] Seattle, the capital of Washington State, was considered to be a model city that incorporates as many recycling projects as possible. In 1971, Seattle was the first to pass a Litter Act in the USA, in order to create a recycling fund. In 1988, the city set an ambitious goal of recycling 60% of its waste by the year 1998 and since then, the city has utilised almost every recycling and source-reduction scheme in existence, in order to achieve that target. Simultaneously, a thorough public-education programme has been developed to ensure the success of the scheme. Tables 17 and 18 present the material breakdown analysis and the economics associated with Seattle recycling programme.

## Conclusions and future trends

Recycling is an alternative waste-treatment technology with acknowledged environmental benefits. It can be financially viable. However, designing a

**TABLE 17**

Material breakdown analysis (in tonnes) for 1990 for the Seattle recycling programme[75]

| *Material* | *Residential* | *Commercial/ institutional* | *Self-hauled* | *Total* |
|---|---|---|---|---|
| Newspaper | 40 102 | 11 123 | 182 | 51 407 |
| Corrugated cardboard | 7874 | 62 571 | 511 | 70 956 |
| High-grade paper | 4 | 57 496 | 4 | 57 504 |
| Mixed scrap paper | 13 218 | 4866 | 650 | 18 734 |
| Other paper | 346 | 498 | 7 | 851 |
| Glass | 12 905 | 4093 | 169 | 17 167 |
| PET plastic | 748 | 7 | 243 | 998 |
| HDPE plastic | 161 | 96 | — | 257 |
| Other plastic | — | 187 | — | 187 |
| Aluminium cans | 1589 | 303 | 2 | 1894 |
| Ferrous cans | 1565 | 296 | 1 | 1862 |
| Other post-consumer aluminium | 20 | 221 | 1 | 242 |
| Other post-consumer ferrous | 149 | 341 | 5855 | 6345 |
| Non-ferrous | 3 | 27 | 43 | 73 |
| Other | 227 | 12 074 | 370 | 12 671 |
| Total MSW recycled | 78 911 | 154 199 | 8038 | 241 148 |

**TABLE 18**
Economics of the Seattle recycling programme[75]

| *List of expenses* | *Cost* |
|---|---|
| Capital costs (US$) | 2 500 000 |
| Operating–maintenance costs (US$ per year): | |
| Collection–processing | 2 537 652 |
| Curbside | 2 481 386 |
| Sub-contractors fees | 1 481 386 |
| Transfer station | 56 266 |
| Administration | 300 000 |
| Education/publicity | 200 000 |

recycling scheme and operating it successfully are two different issues, because both the technical and economic barriers to recycling have to be considered. The technical barriers include:

- the composition and the physical characteristics of the waste, in particular the type and form of contaminant materials present;
- the availability of suitable technology and processing capacity for removing the contaminants and upgrading the recovered waste to marketable products; and
- the degradation of potentially-reusable materials during reclamation and reprocessing.

The economic constraints facing recycling include:

- Achievable market prices for recovered and processed materials, which depend on the presence of contaminants and the degradation of materials during the reprocessing stages.
- The demand for recycled products, which depend upon the level of industrial activity. As supply and demand change, the market prices are directly affected.
- The import and export trade of recycled materials, which also affect the market prices.

However, the constraints mentioned above are typical obstacles of industrial innovative technologies, which can be overcome. A change in the waste-management policy, combined with a transformation of the consumption patterns is considered to be vital for the success of recycling initiatives. Because the pricing of the alternative waste treatment/disposal technologies is expected to increase, the economic viability of waste recycling will improve considerably in the near future.

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