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SUMMARY

This report was prepared according to the BACAS objectives to inform responsible authorities and to recommend the measures to deal with the concerned topic.

The paper deals with the biodegradable part of waste generated by citizens in urban environments. This is essentially household waste and gardening waste. Assimilated to this category of waste is almost all that comes from restaurants, canteens and food shops inasmuch as its composition is similar to that of household waste.

In the European Union, people generate currently 523 kg per inhabitant and per year of municipal solid waste (MSW). Hazards and nuisances associated with dumping are deemed unacceptable. Very specific and mandatory regulations make landfilling very difficult to manage. The trend is, accordingly, to reduce as far as possible the residual amount of waste to dump. Today, in most developed countries, local programs aim to separate household hazardous wastes (chemical cleaners, pesticides, paints, batteries, oils, etc…) and to recover certain materials (metals, paper, cardboard, plastics, glass, textiles, etc…) at the source. There remains however currently 204 kg/inhabitant. year of biodegradable waste in MSW, and it is responsible for most of the waste's related disturbances in urban environments. For the European Union with its 500 millions inhabitants, this makes 102 million Mg (1Mg = 1 metric tonne) of biodegradable MSW, i.e. approximately 20% of all biodegradable waste generated by economic activities each year in the EU. This justifies fully the present report.

From a legal standpoint, the European Union adopts directives which must be transposed by Member States in their own legislation within a given period of time. This report includes a short analysis of the main directives of interest for the subject treated. The new Directive 2008/98/EC is examined in detail; it introduces a waste hierarchy in 5 points: prevention; preparing for re-use; recycling; other recovery, e.g. energy recovery; disposal. The present status of legislation in Belgium is also described briefly.

The best available techniques for the treatment of biodegradables contained in MSW are examined, restricting the scope to techniques that "have been developed and tried with success on an industrial scale allowing implementation in the relevant industrial sector, under economically and technically viable conditions" as defined in Directive 2008/1/EC. Accordingly, R&D processes and pilot plants are not included. However, some processes which still depend on subsidies for survival are discussed in the report.

Among the high temperature processes, incineration may be considered as pertaining to the best available techniques for the treatment of MSW, because it complies with all the conditions imposed by the relevant EU directives, including environment protection. Biodegradables contained in MSW are easily processed in mass-burn, modular or fluidized-bed incinerators. There is no need for separate collection or preliminary sorting out. They can be burnt as such, even in cardboard or plastics packaging. A preparation step is however required before introduction in a fluidized bed incinerator. If the incinerator plant generates enough energy to comply with the requirements defined in Annex II/R1 of the Directive 2008/98/EC, it can be called "Energy recovery plant".

Other high temperature processes (pyrolysis, gasification and plasma processes) are not considered today as "best available techniques" in the European Union for various reasons mentioned in the report. They should be monitored for their technical and economical progresses. The low temperature processes are not able to treat MSW as such. They can only cope with the biodegradables fraction contained in MSW, and necessitate either separate collection of the biodegradables at the source or adequate sorting of MSW before loading in the process. There are two possibilities: aerobic treatment (composting) and anaerobic digestion (biomethanisation). The two processes depend on microorganisms for their correct functioning. Only part of the carbon is converted to CO_2.

Composting can be operated over a large range of scale from very small (home and backyard) to large centralized composting plants. At the small scale, there is the advantage that biodegradables are removed from the waste stream. At the large scale, the process becomes more difficult to operate because of the need to feed correctly air and water to the load and also because the liquids must be recovered andtreated. There is no energy recovery. Good quality compost can be considered as a fertilizer and a soil amendment. However, a true market for this compost does not seem to exist.

Biomethanisation received a lot of attention during the past decades, because it generates methane that can

be used to recover energy. There are various ways to operate the process, and potential feedstocks from different origins may be envisaged (agricultural origin; industrial origin; MSW and sewage sludge). There are difficulties to control properly the process especially if the characteristics of the load change with time. Energy recovery is much lower than with incineration. Good quality digestate can be considered as a fertilizer. Again, a true market for this digestate does not seem to exist. The process is economically viable only when subsidies are available.

A detailed discussion is included in the report. In preliminary remarks it is stated that: any chemical element present in the incoming stream will anyhow be present in the outputs in the same quantity (this holds especially for heavy metals); no process may claim any "greenhouse effect" advantage (after decomposition, compost and digestate end up with CO_2 and H_2O); for energy recovery, when the global process is split into two partial processes, with the first of the partial exothermic, the net calorific effect of the second partial is reduced (this is the case for the combustion of methane from anaerobic digestion); most flawed waste policies forget and leave out thermodynamics; "not in my backyard" emotional reactions are ruled out if the technology does not justify them. The discussion is split in two parts: the first one is limited to scientific, technological, economical and environmental considerations; the second to legal considerations.

Finally, the conclusions present the necessary elements for the authorities to make correct decisions. After reducing by all possible means the amount of biodegradables contained in MSW, the main decision deals with proceeding or not to the separate collection of the biodegradables remaining in MSW at the source, taking all elements in consideration. There are also recommendations. Among them appears the need for new European directives and BREF documents for composting and anaerobic digestion: this could help in generating markets for compost and digestate.

RÉSUMÉ

Ce document a été rédigé selon les objectifs du BACAS d'informer les autorités responsables et de mettre à leur disposition tous les éléments nécessaires pour prendre les bonnes décisions.

Ce rapport concerne la partie biodégradable des déchets générés par les citoyens dans un environnement urbain. Il s'agit essentiellement de déchets ménagers et de jardinage. Sont aussi assimilés à cette catégorie de déchets presque tous ceux qui viennent des restaurants, des cantines et des épiceries pour autant que leur composition soit analogue à celle des déchets ménagers.

Dans l'Union Européenne, la population génère actuellement 523 kg par habitant et par an de déchets municipaux solides (MSW). Les risques et nuisances associés à leur mise en décharge sont jugés inacceptables. La tendance est donc à réduire autant que possible la quantité résiduelle de déchets à mettre en décharge.

Aujourd'hui, dans la plupart des pays développés, des programmes locaux permettent de séparer à la source les déchets ménagers dangereux (nettoyants chimiques, pesticides, peintures, batteries, huiles, etc…) et de récupérer certains matériaux (métaux, papiers, cartons, plastiques, verre, textiles, etc…). Il reste néanmoins actuellement 204 kg/habitant.an de déchets biodégradables dans les MSW, et ce sont eux qui sont responsables de la plupart des nuisances dues aux déchets en milieu urbain. Considérant environ 500 millions d'habitants dans l'Union Européenne, cela fait au total 102 millions Mg (1 Mg = 1 tonne métrique) de déchets biodégradables dans les MSW, c'est-à-dire environ 20% de l'ensemble des déchets biodégradables générés par l'activité économique dans l'UE. Ceci justifie pleinement le présent rapport.

D'un point de vue légal, l'Union Européenne édicte des directives qui doivent être transposées par chaque pays membre dans leur propre législation dans un délai limité. Ce rapport comprend une courte analyse des principales directives d'intérêt pour le sujet traité. La nouvelle Directive 2008/98/EC est examinée en détails; elle introduit une hiérarchie en 5 points: prévention; préparation pour la réutilisation; recyclage; autre récupération, par exemple récupération d'énergie; mise en décharge. L'état actuel de la législation belge est aussi inclus.

Les meilleures techniques disponibles pour le traitement de la partie biodégradable des déchets contenus dans les MSW sont examinées, en se limitant à "celles qui ont été développées et essayées avec succès à l'échelle industrielle de façon à permettre leur incorporation dans le secteur industriel adéquat, dans des conditions économiquement et techniquement viables", ainsi que prévu dans la Directive 2008/1/EC. Les procédés qui sont au stade de la R&D ainsi que les installations pilotes ne sont pas inclus. Toutefois, certains procédés dont la survie est assurée par des subsides sont discutés dans ce rapport.

Parmi les procédés fonctionnant à température élevée, l'incinération peut être considérée, au sein

de l'Union Européenne, comme appartenant aux meilleures techniques disponibles pour le traitement des MSW, parce qu'elle satisfait à toutes le conditions imposées par les directives européennes y relatives, y compris pour la protection de l'environnement. Les déchets biodégradables contenus dans les MSW sont aisément traités dans les incinérateurs à combustion de masse, modulaires ou à lit fluidisé. Il n'est pas nécessaire de procéder au préalable à une collecte séparée ou à un tri en usine. Ils peuvent être brûlés tels quels, même dans leur emballage en carton ou en plastique. Une certaine préparation est cependant nécessaire pour les incinérateurs à lit fluidisé. Si l'usine d'incinération satisfait à la formule définie dans l'Annexe II/R1 de la Directive 2008/98/EC, elle mérite l'appellation "Centre de valorisation énergétique".

Les autres procédés fonctionnant à température élevée (pyrolyse, gazéification et procédés plasma) ne peuvent être considérés actuellement comme figurant dans les meilleures techniques disponibles pour l'Union Européenne pour diverses raisons mentionnées dans le rapport. Il convient évidemment de suivre les progrès techniques et économiques qu'ils feront.

Les procédés fonctionnant à basse température ne sont pas capables de traiter les MSW tels quels. Ils ne peuvent traiter que la partie biodégradable des MSW, et nécessitent soit une collecte séparée de cette partie, soit un tri adéquat à l'entrée de l'installation de traitement. Il existe deux possibilités: le traitement aérobie (compostage) et la digestion anaérobie (biométhanisation). Les deux procédés dépendent de microorganismes pour leur fonctionnement. Seule une partie du carbone est convertie en CO_2.

Le compostage peut être réalisé depuis une échelle très petite (en appartement ou au fond du jardin) jusqu'à grande échelle (compostage centralisé). A petite échelle, il présente l'avantage de voir les déchets biodégradables retirés du circuit global des déchets. A grande échelle, le procédé devient plus difficile à exploiter à cause de la nécessité d'alimenter correctement la charge en air et en eau, et aussi parce qu'il faut récupérer et traiter les effluents liquides. Aucune énergie n'est récupérée. Un compost de bonne qualité peut être considéré comme un engrais et comme un agent d'amélioration des sols. Cependant, il ne semble pas qu'un réel marché existe pour ce compost.

La biométhanisation a fait l'objet d'une attention particulière au cours des décennies écoulées parce qu'elle génère du méthane qui peut être utilisé comme source d'énergie. Il y a différentes manières d'exploiter le procédé, et des matières d'origines diverses sont suceptibles d'être traitées (agricole, industrielle, MSW et boues d'épuration). On rencontre des difficultés dans le contrôle du processus notamment lorsque les caractéristiques de l'alimentation changent au cours du temps. La récupération d'énergie est nettement inférieure à celle obtenue par incinération. Un digestat de bonne qualité peut être considéré comme un engrais. A nouveau, il ne semble pas y avoir de réel marché pour ce digestat. Le procédé n'est économiquement viable que lorsque des subsides sont disponibles.

Le rapport comprend une discussion détaillée. Des remarques préliminaires font observer que: tout élément chimique présent dans le flux entrant doit se retrouver dans le flux sortant dans les mêmes quantités (ceci vaut spécialement pour les métaux lourds); aucun des procédés ne présente un avantage marqué en ce qui concerne les gaz à effet de serre (après décomposition, les composts et digestats terminent leur vie avec production de CO_2 et de H_2O); en ce qui concerne la récupération d'énergie, quand un processus global est scindé en deux parties dont la première est exothermique, le dégagement de chaleur de la seconde partie en est diminué d'autant (c'est le cas pour la combustion du méthane produit par digestion anaérobie); l'oubli de la thermodynamique explique la plupart des défauts de pas mal de politiques des déchets; les réactions émotionnelles du type "pas dans mon jardin" ne sont pas prises en considération si la technique ne les justifie pas. La discussion est scindée en deux parties: la première ne prend en compte que les considérations scientifiques, technologiques, économiques et environnementales; la seconde partie couvre les considérations légales .

Finalement, les conclusions reprennent tous les éléments nécessaires aux autorités pour prendre des décisions correctes. Après avoir réduit par tous les moyens disponibles la quantité de déchets biodégradables contenus dans les MSW, la décision principale porte sur la collecte séparée ou non de ces déchets à la source, prenant en compte tous les éléments à considérer. Les conclusions comprennent aussi des recommandations. Parmi elles figure la nécessité pour l'Union Européenne d'édicter de nouvelles directives et des documents BREF pour le compostage et pour la digestion anaérobie: ceci pourrait aider à la création de marchés pour les composts et pour les digestats.

SAMENVATTING

In overeenstemming met de door BACAS geformuleerde doelstellingen werd dit rapport opgemaakt om de bevoegde overheden te informeren en aanbevelingen te formuleren voor een gerichte aanpak van de erin beschreven problemen.

Deze tekst handelt over het biologisch afbreekbare deel van het afval geproduceerd door de bevolking in een stedelijke omgeving. Het gaat hierbij voornamelijk om huishoudelijk en tuinafval. Ook het afval van restaurants, eetgelegenheden en voedingswinkels, voor zover de samenstelling ervan vergelijkbaar is met die van huishoudelijk afval, wordt hiermee geassimileerd.

In de Europese Unie produceert de bevolking vandaag 523 kg vast huishoudelijk afval (MSW = municipal solid waste) per jaar en per inwoner. Risico's en hinder als gevolg van het storten ervan worden als onaanvaardbaar beschouwd. Zeer specifieke en bindende regelgeving maakt het storten erg moeilijk beheerbaar. Als gevolg hiervan is er een tendens ontstaan om de residuele hoeveelheid te storten afval maximaal te beperken.

In de meeste ontwikkelde landen bestaan er nu locale programma's om risicohoudend huishoudelijk afval (chemische schoonmaakmiddelen, pesticiden, verven, batterijen, oliën etc.) van de rest van het MSW te scheiden en bepaalde materialen (metalen, papier, karton, kunststoffen, glas, textiel etc.) aan de bron te recupereren. Toch blijft er vandaag nog 204 kg biologisch afbreekbaar materiaal per jaar en per inwoner in het MSW, en dat is meteen de hoofdoorzaak van overlast door afval in stedelijke milieus. Voor de Europese Unie, met haar 500 miljoen inwoners, betekent dit 102 miljoen Mg (1 Mg = 1 metrieke ton) biologisch afbreekbaar MSW, d.i. nagenoeg 20% van al het biologisch afbreekbaar afval gegenereerd door economische activiteiten in de E.U. Deze vaststelling was voldoende aanleiding voor het schrijven van dit rapport.

Wettelijk gesproken vaardigt de Europese Unie richtlijnen uit die door de lidstaten binnen een bepaalde tijd moeten omgezet worden in nationale wetgeving. In dit rapport wordt een korte analyse gemaakt van de belangrijkste richtlijnen die betrekking hebben op de afvalproblematiek. De nieuwe richtlijn 2008/98/EC wordt in detail besproken; zij definieert, in volgorde van prioriteit, vijf stappen in de afvalbehandeling, namelijk voorkoming, voorbereiding voor hergebruik, recycling, andere vormen van recuperatie, bv. energierecuperatie en tenslotte storten. De bestaande Belgische wetgeving ter zake wordt ook kort geanalyseerd.

De best beschikbare technieken voor de verwerking van biologisch afbreekbare materialen in MSW worden beschreven, zij het met een beperking tot die technieken die "met succes op industriële schaal ontwikkeld en getest zijn en in relevante industriële sectoren op economisch en technisch duurzame wijze inzetbaar zijn", zoals bepaald in richtlijn 2008/1/EC. Processen die nog in een onderzoeks- of pilootfase verkeren werden daarom niet opgenomen. Wel worden enkele processen, die nog steeds alleen maar mits subsidiëring leefbaar zijn, in dit rapport besproken.

Wat de hogetemperatuursprocessen betreft mag verbranding als een van de best beschikbare technieken voor de behandeling van MSW beschouwd worden, omdat zij voldoet aan alle voorwaarden opgelegd in de relevante E.U.-richtlijnen, met inbegrip van de eisen m.b.t. milieuzorg. Biologisch afbreekbare stoffen in MSW kunnen makkelijk mee verwerkt worden in modulaire of wervelbedovens voor massaverbranding. Het is niet nodig het biologisch afbreekbaar materiaal apart in te zamelen of vooraf uit te sorteren. Het kan als dusdanig verbrand worden, zelfs in zijn kartonnen of plastic verpakking. Bij verwerking in een wervelbedoven is echter wel een voorbereidende stap nodig. Indien de verbrandingsoven voldoende energie produceert volgens de vereisten gedefinieerd in bijlage II/R1 van richtlijn 2008/98/EC, kan over een "energieterug-winningsinstallatie" worden gesproken.

Andere hogetemperatuursprocessen (pyrolyse, vergassing en plasmavorming) worden vandaag in de Europese Unie om uiteenlopende redenen, die verder in dit rapport besproken worden, nog niet als best beschikbare technieken bestempeld. Hun technische en economische vooruitgang moet wel opgevolgd worden.

Lagetemperatuursprocessen zijn niet geschikt voor een ongeconditioneerde verwerking van MSW. Zij zijn enkel van toepassing voor de verwerking van de biologisch afbreekbare fracties in MSW en vergen ofwel een aparte inzameling aan de bron of een doelmatig uitsorteren van het MSW voor het in het proces ingebracht wordt. Er zijn twee mogelijkheden: aerobe behandeling (compostering) of anaerobe gisting (biomethanisering). Voor beide processen geldt dat hun goede werking afhangt van micro-organismen. Slechts een deel van de aanwezige koolstof wordt omgezet in kooldioxide.

Compostering kan zeer kleinschalig gebeuren (in de achtertuin) of in grote gecentraliseerde compostfabrieken. Toepassing op kleine schaal biedt het voordeel dat biologisch afbreekbare materialen uit de

afvalstroom verwijderd worden. Op grote schaal wordt het proces een stuk moeilijker omdat lucht en water heel precies in de lading gedoseerd moeten worden en ook omdat het afvalwater moet gerecupereerd en gezuiverd worden. Er is geen energieterugwinning. Compost van goede kwaliteit kan als meststof of grondverbeteraar gebruikt worden. Toch lijkt er niet echt een markt voor compost te bestaan.

Biomethanisering kreeg de voorbije decennia heel wat aandacht omdat in dit proces methaan geproduceerd wordt dat kan gebruikt worden om energie te recupereren. Er zijn verschillende mogelijkheden om dit proces uit te voeren en het kan met materiaal van diverse oorsprong gevoed worden (afval van landbouw of industrie, MSW en slib uit waterzuiveringsinstallaties). Een adequate procesbeheersing is niet eenvoudig, in het bijzonder wanneer de samenstelling van de lading varieert in de tijd. Energierecuperatie is veel geringer dan bij verbranding. Residu's van hoge kwaliteit kunnen als meststof ingezet worden. Ook hier lijkt er niet echt een markt voor dit soort reststoffen te bestaan. Het proces is economisch alleen maar leefbaar als het gesubsidieerd wordt.

Het rapport omvat een gedetailleerde bespreking van de diverse processen. In de inleidende bemerkingen wordt onder meer het volgende gesteld: elk chemisch element aanwezig in de ingangsstroom zal hoe dan ook in gelijke hoeveelheid aanwezig zijn in de uitgangsstroom (dit is in het bijzonder het geval voor zware metalen); geen enkel proces kan bogen op enig "broeikasgasvoordeel" (na ontbinding worden ook compost en residu's van gistingsprocessen omgezet in CO_2 en water); wanneer het globale proces opgesplitst is in twee deelprocessen, waarvan het eerste exotherm is, daalt het netto energetisch rendement van het tweede deelproces (dit is het geval met de verbranding van methaan verkregen uit anaerobe gisting); wanneer afvalbeleid mislukt is het meestal wegens een miskenning van de thermodynamische wetten; emotionele "not in my backyard" reacties worden niet besproken tenzij ze werkelijk op technische overwegingen gestoeld zijn. De bespreking bestaat uit twee delen: het eerste beperkt zich tot wetenschappelijke, technologische, economische en milieutechnische aspecten van afvalverwerking terwijl het tweede gaat over wettelijke overwegingen.
In de besluiten vindt men alle noodzakelijke elementen terug die de overheden in staat moeten stellen correcte beslissingen te nemen. Na in eerste instantie met alle mogelijke middelen het restaandeel aan biologisch afbreekbare stoffen in MSW verkleind te hebben, moet men beslissen of men al dan niet wil overgaan tot een aparte inzameling aan de bron van de biologisch afbreekbare stoffen die nog in het MSW aanwezig blijven, rekening houdend met alle aspecten die men in aanmerking moet nemen. De besluiten omvatten ook aanbevelingen, met name de nood aan nieuwe Europese richtlijnen en BREF -documenten voor compostering en anaerobe gisting: dit zou moeten bijdragen tot de ontwikkeling van een markt voor compost en restmateriaal uit vergistingsprocessen.

[1] BREF = best available technique ("BAT") reference.

Chapter 1

INTRODUCTION

This paper deals essentially with biodegradables in municipal solid waste (MSW) generated by citizens in urban environments. This is essentially household waste and gardening waste. Assimilated to this category of waste is refuse from restaurants, canteens and food shops as far its composition is similar to that of household waste.

Not included are agricultural and forestry waste, sewage sludge, industrial waste of any kind, hazardous substances, waste electric and electronic equipment (WEEE), medical waste, waste oils, end-of-life vehicles, batteries and accumulators, mining waste, nuclear waste, etc… Most of these wastes are subject to distinct legislation and Codes of practice.

Modern ways of life in developed countries have led people to generate more and more MSW: currently 523 kg per inhabitant and per year in the European Union. At the same time, landfilling has become more and more difficult to manage for many reasons: hazards and nuisances associated with dumping are deemed unacceptable and meet strong opposition, leading to very specific and compulsory regulations with, as a result, a dearth of suitable sites.

This has created a very complex political, technological and economical problem for decision makers involved in waste management, especially under urban conditions.

Sometimes, dramatic situations arise where waste is simply piling up in the streets with the associated disadvantages and health hazards. A situation of this kind occurred recently in Naples (Italy).

European Union Directives aim at reducing not only the amount of MSW but also the residues remaining after treatment to be dumped in dedicated landfills. As will appear in Chapters 2 and 3, the management of biodegradables in MSW needs some explicit decisions from the authorities, which are not so easy to make.

BACAS decided to set up a working group to gather as much information as possible on proven technologies that could be applied to these biodegradables and to consider their position in MSW treatment. The aim was to produce a document describing briefly the available technologies with their inherent advantages and disadvantages and including some cost estimates wherever available. This last exercise is risky, since cost factors are all but static, predictable and homogeneous.

Finally, some guidelines helping in decision-making should be proposed.

It should be emphasized that this report is not intended to waive the need for consulting appropriate specialists or to ask for competitive tenders for each specific situation.

At the outset, it immediately appeared that the amount of literature on the subject was far too large to be consulted and analysed in a reasonable timeframe. Experts were accordingly associated to the group, either as members or as lecturers on specific topics.

Chapter 2

LEGAL CONSTRAINTS

2.1. European Union

In order to address properly the problem of biodegradables in MSW in the European Union at large and in Belgium in particular, it is necessary at first to enlarge the legislative scope to waste management in general, because part of the broader legislation is concerned with MSW. It must be emphasized that the European Union adopts directives, which must be transposed in the legislations of the Members States within a given time period. Each Member State must also issue a report on how this task was implemented. This general procedure was decided because the context and starting point are too different between the Members States. This is especially true for waste management and in particular for the biodegradables in the municipal waste.

Although the E.U. directives have played an essential role in shaping the administrative structures responsible for waste management and in issuing rules for specific categories of waste, the biodegradables have until recently received only limited E.U. attention.

The European Union is currently working on Thematic Strategies in the frame of the Sixth Environment Action Programme of the European Community 2002-2012 (http://ec.europa.eu/environment/newprg/strategies_en.htm). The thematic strategies are key elements for better regulation and are all accompanied by economic, social and environmental impact assessments and extensive stakeholder consultations.

The fields covered are Air, Waste prevention and recycling, Maritime environment, Soil, Pesticides, Natural resources and Urban environment. The waste prevention and recycling strategy is of special interest for this report.

The European Union's approach to waste management was based until 12 December 2008 (see below Directive 2008/98/EC) on **three basic principles** (http://ec.europa.eu/environment/waste/index.htm):

- **waste prevention**: reducing the amount of waste as well as its hazardousness (improve manufacturing methods, stimulate consumers to demand greener products and less packaging)
- **recycling and reuse**: if waste cannot be prevented, recover as much matter as possible, mainly by recycling. Specific waste streams are defined (batteries, packaging waste, end-of-life vehicles, electrical and electronic waste, etc…)
- **improving final disposal and monitoring**: where possible, waste that cannot be recycled or reused should be safely incinerated, with landfill only used as a last resort. Strict guidelines must be followed in any case for incineration and for landfill.

An interesting background document entitled "EU Waste Policy – The story behind the strategy" may be downloaded for free on the site (http://ec.europa.eu/environment/waste).

As to legislation, most of it may be found on the site (http://europa.eu/legislation_summaries/environment/waste_management/index_en.htm).

Concerning **Waste Disposal**, Directive 2006/12/EC, which entered into force on 17 May 2006 aims to limit the generation of waste and to optimise the organization of waste treatment and disposal. Member States must prohibit the abandonment, dumping or uncontrolled disposal of waste, and must promote waste prevention, recycling and processing for re-use. Annex I defines categories of waste (MSW is not specified). Annex IIA lists disposal operations (incineration is considered here as a disposal operation). Annex IIB lists recovery operations (R1: use principally as a fuel or other means to generate energy).

Concerning a **Strategy on the Prevention and Recycling of Waste**, there is no specific directive. There is however a Commission Communication of 21 December 2005 COM (2005) 666. Emphasis is given on biodegradable waste, "two-thirds of which must be redirected to be disposed of using methods other than landfill as required under Directive 1999/31/EC"(see below specific directives after Directive 2008/98/EC).

Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 deals with **Integrated Pollution Prevention and Control** (the IPPC Directive). It defines the obligations with which industrial and agricultural activities with a high pollution potential must comply. These activities require having a permit that can only be issued if certain environmental conditions are met, so that the companies themselves bear responsibility for preventing and reducing any pollution they may cause. This Directive replaces the earlier Directive 96/61/EC. Its Article 2 (Definitions, point 12) is of special interest for this report: "**best available techniques**" means the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole:

- "**techniques**" shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned;
- "**available techniques**" means those developed on a scale which allows implementation in the relevant industrial sector, **under economically and technically viable conditions**, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator;
- "**best**" means most effective in achieving a high general level of protection of the environment as a whole.

In determining the best available techniques, special consideration should be given to the items listed in Annex IV (notably "**comparable processes, facilities or methods of operation which have been tried with success on an industrial scale**") ".

The IPPC Directive is completed with so-called "**BREF" documents** (Best Available Techniques REFerence documents); among these various BREF Documents, two are devoted to waste: the BREF on Waste Incineration and that on Waste Treatment facilities.

The **new Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives** was published in the Official Journal of the European Union of 22 November 2008 and entered into force on 12 December 2008. The deadline for transposition in the Member States is 12 December 2010. Its content is of special interest for this report.

- **In the introducing preamble** (Whereas), it is stated that: "(6) The first objective of any waste policy should be to minimise the negative effects of the generation and management of waste on human health and the environment. Waste policy should also aim at reducing the use of resources, and favour the practical application of the waste hierarchy"; "(8) It is (therefore) necessary to revise Directive 2006/12/EC in order to clarify key concepts such as the definitions of waste, recovery and disposal, to strengthen the measures that must be taken in regard to waste prevention, to introduce an approach that takes into account the whole life-cycle of products and materials not only the waste phase, and to focus on reducing the environmental impacts of waste generation and waste management, thereby strengthening the economic value of waste. Furthermore, the recovery of waste and the use of recovered materials should be encouraged in order to conserve natural resources..."; "(14)…encourage a harmonised classification of waste and ensure the harmonised determination of hazardous waste within the Community"; "(15) It is necessary to distinguish between the preliminary storage of waste pending its collection, the collection of waste and the storage of waste pending treatment…"; "(18) Definitions of prevention, re-use, treatment and recycling should be included in this Directive, in order to clarify the scope of these concepts."; "(20) This Directive should also clarify when the incineration of municipal solid waste is energy-efficient and may be considered a recovery operation"; "(22) There should be no confusion between the various aspects of waste definition, and appropriate procedures should be applied, where necessary, to by-products that are not waste, on the one hand, or to waste that ceases to be waste, on the other hand…"; "(28)… waste should be separately collected if technically, environmentally and economically practicable, before undergoing recovery operations that deliver the best overall environmental outcome…"; "(31) **The waste hierarchy generally lays down a priority order of what constitutes the best overall environmental option in waste legislation and policy, while departing from such hierarchy may be necessary for specific waste streams when justified for reasons of, inter alia, technical feasibility, economic viability and environmental protection**."; " (35) It is important, in accordance with the waste hierarchy, and for the purpose of reduction of greenhouse gas emissions originating from waste disposal on landfills, to facilitate the separate collection and proper treatment of bio-waste in order to produce environmentally safe compost and other bio-waste based materials…"; " (45) Member States should provide for effective, proportionate and dissuasive penalties to be imposed on natural and legal persons responsible for waste management, such as waste producers, holders, brokers, dealers, transporters and collectors, establishments or undertakings which carry out waste treatment operations and waste management schemes, in cases where they infringe the provisions of this Directive…" ; " (47) In particular, the Commission should be empowered to establish criteria regarding a number of issues such as the conditions under which an object is to be considered a byproduct, the end-of-waste status and the determination of waste which is considered as hazardous, as well as to establish detailed rules on the application and calculation methods for verifying compliance with the recycling targets set out in this Directive. Furthermore, **the Commission should be empowered to adapt the annexes to technical and scientific progress and to specify the application of the formula for incineration facilities referred to in Annex II, R1…**"

– **In Chapter I - Subject matter, scope and definitions**, are worth to be mentioned: in **Article 3 Definitions** 4. "**Bio-waste" means biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants**. 12. "**Prevention**" means measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life-span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products. 13. "**Re-use**" means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived. 14. "**Treatment**" means recovery or disposal operations, including preparation prior to recovery or disposal. 15. "**Recovery**" means any operation the principal result of which is waste serving a useful purpose by replacing other materials, which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a nonexhaustive list of recovery operations. 16. "**Preparing for re-use**" means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing. 17. " **Recycling**" means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic materials but **does not include energy recovery** and the reprocessing into materials that are to be used as fuels or for backfilling operations. 19 "**Disposal**" means any operation, which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy. Annex I sets out a nonexhaustive list of disposal operations. 20. "**Best available techniques**" means best available techniques as defined in Article 2(11) of Directive 96/61/EC.

In **Article 4. Waste hierarchy**

1. **The following waste hierarchy shall apply as a priority order** in waste prevention and management legislation and policy:

(a) **prevention**;
(b) **preparing for re-use**;
(c) **recycling**;
(d) **other recovery, e.g. energy recovery**; and
(e) **disposal**.

2. When applying the waste hierarchy referred to in paragraph 1, Member States shall take measures to **encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy**…

In **Article 5 By-Products**. 1.A substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste… but as being a by-product only if the following conditions are met: (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

In **Article 6 End-of-waste status** 1. Certain specified waste shall cease to be waste within the meaning of point (1) of Article 3 when it has undergone a recovery, including recycling, operation and complies with specific criteria to be developed in accordance with the following conditions: (a) the substance or object is commonly used for specific purposes; (b) a market or demand exists for such a substance or object; (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts… criteria shall include limit values for pollutants…

In **Article 7 List of waste** 4. **The reclassification of hazardous waste as non-hazardous waste may not be achieved by diluting or mixing** the waste with the aim of lowering the initial concentrations of hazardous substances to a level below the thresholds for defining waste as hazardous.

– In **Chapter II General Requirements**. Article 13. **Protection of human health and the environment**. Member States shall take the necessary measures to ensure that waste management is carried out without endangering human health, without harming the environment and in particular: (a) without risk for water, air, soil, plants or animals; (b) without causing a nuisance through noise and odours; and (c) without adversely affecting the countryside or places of special interest.

- In **Chapter III Waste Management. Article 22. Bio-waste**. Member States shall **take measures, as appropriate… to encourage**: (a) **the separate collection of bio-waste with a view to the composting and digestion of bio-waste**; (b) the treatment of bio-waste in a way that fulfils a high level of environmental protection; (c) the use of environmentally safe materials produced from bio-waste. **The Commission shall carry out an assessment** on the management of bio-waste with a view to submitting a proposal if appropriate. The assessment shall **examine the opportunity of setting minimum requirements for bio-waste management and quality criteria for compost and digestate from bio-waste**, in order to guarantee a high level of protection for human health and the environment.
- In **Chapter VII Final Provisions**. Article 41 Repeal and transitional provisions: Directives 75/439/EEC, 91/689/EEC and 2006/12/EC are hereby repealed with effect from 12 December 2010.
- **In Annex II Recovery operations. R1 Use principally as a fuel or other means to generate energy**: this includes incineration facilities dedicated to the processing of municipal solid waste only where their energy efficiency is equal to or above… (a certain value obtained by applying a formula given in the Directive).

Concerning **Waste Management Statistics**, there is only an EC Regulation n° 2150/2002 of the European Parliament and of the Council of 25 November 2002. Statistics are to be produced using a nomenclature set out in Annex III.

There is also a Communication from the Commission of July 1998 (COM(98)463) dealing with the **Competitiveness of the recycling industries**. This communication lists the major difficulties encountered by recycling businesses in achieving or maintaining viability, and proposes a package of measures capable of solving these problems.

Landfill of waste is the object of Council Directive 1999/31/EC of 26 April 1999, intended to prevent or reduce the adverse effects of the landfill of waste on the environment, in particular on surface water, groundwater, soil, air and human health.

It defines the different categories of waste (Article 2 (b)"**municipal waste**" **means waste from households, as well as other waste which, because of its nature or composition, is similar to waste from household**"). Landfills are divided into three categories: landfills for hazardous waste; landfills for non-hazardous waste; landfills for inert waste. Waste must be treated before being dumped. The following wastes may not be accepted in a landfill: liquid waste; flammable waste; explosive or oxidizing waste; used tyres, with certain exceptions; any other type of waste which does not meet the acceptance criteria defined in Annex II. Control and monitoring procedures in operation and after-care phases are described in Annex III. Article 5 states that "Member States shall set up a national strategy for the implementation of the reduction of biodegradable waste going to landfills, not later than two years after its entry into force". This strategy shall ensure that, not later than 5 years thereafter, biodegradable municipal waste going to landfill must be reduced to 75% of the total amount (by weight) of biodegradable municipal waste produced in 1995. This proportion must be reduced to 50% not later than 8 years (2009) and to 35% not later than 15 years (2016) after the entry into force. The Directive also states (article 6) that only waste that has been subject to treatment can be dumped. Treatment means the physical, thermal, chemical or biological processes, including sorting, which change the characteristics of the waste in order to reduce its volume or hazardous nature, to facilitate its handling or to enhance recovery.

Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 deals with **Waste Incineration**. This Directive introduces measures to prevent or reduce air, water and soil pollution caused by the incineration or co-incineration of waste, as well as the resulting risk to human health. There is a prior authorization requirement for incineration and co-incineration plants, and emission limits are given for certain pollutants released to air or to water. The Directive does not cover experimental plants for improving the incineration process and which treat less than 50 Mg of waste per year. Nor does it cover plants treating only: vegetable waste from agriculture and forestry, the food industry or the production of paper; wood waste; cork waste; radioactive waste; animal carcases; waste resulting from the exploitation of oil and gas and incinerated on board offshore installations. To guarantee complete waste combustion, all plants are required to keep the gases at a temperature of at least 850°C for at least 2 seconds. If hazardous waste with a content of more than 1% of halogenated organic substances, expressed as chlorine, is incinerated, the temperature has to be raised to 1100°C for at least 2 seconds. The heat generated has to be put to good use as far as possible: this is the reason why incineration is nowadays mostly called "Energy recovery" technology. Annex V gives limit values for incineration plant emissions to air. Corresponding limit values for co- incineration (notably cement kilns) are given in Annex II. Monitoring systems must be installed.

The Directive deals also with wastewater from the cleaning of exhaust gases as well as with residues resulting from the operation. Member States had to adopt appropriate measures before 28 February 2002. **Since the end of 2005 all existing plants in**

the European Union must satisfy to this Directive. The BREF Document on Waste Incineration introduces complementary recommendations, e.g. achievable emission values, sometimes more severe than the limit values of the Incineration Directive. In addition to this, the new Directive 2008/98/EC imposes even more severe constraints.

Although this falls out of the scope of this report, it is also interesting to mention Council Directive 91/689/EEC of 12 December 1991 on the Controlled **Management of Hazardous Waste**. The Directive does not cover domestic waste.

The Member States are to ensure that hazardous waste is recorded and identified.

They must also ensure that different categories of hazardous waste are not mixed and that hazardous waste is not mixed with non-hazardous waste, save where the necessary measures have been taken to safeguard human health and the environment.

2.2. Belgium

With a few exceptions, environmental policy is regionalized in Belgium. Thus EU directives are transposed in each Region separately, with the consequence that differences may appear between the actual regulations applying in each of the three Regions as well as their practical implementation. The 2008 waste framework directive (Directive 2008/98/EC) has to be transposed no later than 12 December 2010.

Flanders

The Vlaams Reglement inzake Afvalvoorkoming en Afvalbeheer (VLAREA) was promulgated on 17 December 1997. Implementation plans for household waste management were established successively, the last one dating from 14 December 2007 and covering the 2008-2015 period. Among its objectives are a limitation of waste production to 560 kg/inhabitant. year, with a maximum of residual waste of 180 kg/inhabitant.year by 2010 and 150 kg/inhabitant.year by 2015. This will require expanding the rate of selective collection to 75%.

According to the Order of the Flemish government of 5 December 2003, the following waste categories must be separated from household waste: hazardous waste, glass, paper and cardboard, metals, vegetables, textiles, electrical and electronic waste, tyres and demolition waste. The Order also stipulates that it is forbidden to dump unsorted household waste. Derogations are allowed under special circumstances.

Wallonia

The first waste decree dates from 27 June 1996. It was modified on 22 March 2007.

It acknowledges the waste management hierarchy of the EC, and prescribes among others the establishment of implementation plans (“Plans wallons des déchets”).

On 30 March 2006, the Walloon government defined new strategic orientations in order to reach the objective of a maximum annual per capita waste generation of 471 kg/inhabitant.year.

In compliance with the EC landfill Directive, by 1 January 2010, biodegradable waste will no longer be allowed in controlled landfills (“Centre d’enfouissement technique” or CET), except under exceptional circumstances such as the unavailability of treatment facilities.

A new regulation (“Arrêté”) on waste management is almost ready, supposed to take effect on 1 January 2010. It deals with the use on or in soils of composts coming from aerobic and anaerobic decomposition, and fermentation residues coming from anaerobic decomposition of waste.

Another “Arrêté” was issued on 18 June 2009 (published in the “Moniteur belge” on 11 September 2009). It deals with specific conditions to be applied to composting facilities having storage capacities equal or higher to 500 m3.

Brussels–Capital Region

From the on-line Documentation Centre of the Brussels Capital Region (Droit bruxellois de l’environnement): http://www.bruxellesenvironnement.be/Templates/DroitContent.aspx?langtype=2060 it appears that since 1991, 7 “Arrêtés” were taken concerning **incineration**. The last one was issued on 23 November 2000 and published in the “Moniteur belge” on 22 December 2000. It was dealing with maximum concentrations of dioxins and furans in exit gases taking into account the toxicity equivalent factor for each specific molecule. Concerning **landfills**, the “Arrêtés” of 18 April 2002 and of 13 November 2003, respectively published in the “Moniteur belge” of 17 May 2002 and of 18 December 2003 implement Directive 1999/31/EC and modify Annex II according to Council decision 2003/33/CE.

Chapter 3

GENERAL CONSIDERATIONS ON MUNICIPAL SOLID WASTE

3.1. Preliminary remarks

The waste statistics mentioned in this chapter originate from Eurostat and/or from OECD sources. The respective National Statistical Institutes and Ministries collect data on the environment each year. These institutions complete the section on waste in a joint Eurostat/OECD questionnaire. This questionnaire also contains data collected in previous years. Member States send updated tables to Eurostat and the OECD. Differences between statistics given by Eurostat and OECD should accordingly occur only when no data is available for a certain country and year since an estimate must be established to fill the gap in order to calculate aggregates at EU level.

At the Eurostat website http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/ data is also accessible concerning the generation of waste, sorted out by economic activities according to the NACE Rev.1.1. Code. An entry Waste from households is available.

Municipal waste consists of waste collected by or on behalf of municipal authorities. For areas not covered by a municipal waste collection scheme the amount of waste generated is estimated. The term ”Municipal” is used in different ways in the various countries due to different waste management practices. The bulk of municipal waste is originating from households, though similar wastes from sources such as commerce, offices and public institutions are partly included, depending on local collection practices, which may vary from place to place. Differences between countries are mainly the result of differences in the coverage of these “assimilated wastes”.

According to the OECD/Eurostat Joint Questionnaire municipal waste includes the following types of materials: paper, paperboard and paper products, plastics, glass, metals, food and garden waste and textiles. There are also data concerning the treatment of municipal waste: ***landfill*** is defined as deposit of waste into or onto land and thus covers both internal sites (where a waste generator is carrying out its own waste disposal at the place of generation) and external sites. ***Incineration*** covers incineration plants and co-incineration plants as defined in Directive 2000/76/EC.

Data for the year 2006 are used because they are available for every item considered. Data for the European Union come from Eurostat. For other countries, they come from OECD.

As a final remark, it should be noted that in the statistical classification used in the OECD/Eurostat Joined Questionnaire, the Waste section is currently under revision in the frame of the implementation of the Waste Statistics Regulation.

3.2. Data and discussion

Each year the 27 countries in the European Union discard approximately 3 billion Mg (1 Mg = 1 metric tonne) of waste generated by economic activity and consumption.

Among these some 60 million Mg are hazardous waste. In total, we throw away almost 6 Mg/inhabitant.year of waste. Among these, 523 kg/inhabitant.year are MSW (representing more than 260 million Mg), of which 204 kg/inhabitant.year are biodegradable waste: the fraction this report deals with essentially. Considering some 500 millions inhabitants, that makes 102 million Mg of biodegradable MSW in the European Union. A rough estimate of the total amount of biodegradable waste included in the 3 billion Mg of total waste falls in the range between 500 and 700 million Mg a year. Accordingly, this paper deals with approximately 20% (102 divided by 500) of the biodegradable waste generated by economic activities each year in the European Union. It should also be remembered that biodegradable MSW are responsible for most of the waste’s related disturbances in urban environments. This brief evaluation justifies fully the present paper.

As far as the composition of MSW is concerned, although there are differences between countries and cities, the following approximate percentages come out from an analysis of the literature on the subject:

– food and garden	39%
– paper and cardboard	25%
– plastics	7%
– glass	8%
– metals	5%
– textiles	1%
– others	15%

The percentage of biodegradable waste in MSW varies largely among the European Union Member States with a minimum in the UK (22%) and a maximum in Greece (49%). The percentage of garden waste (citizens and local authorities) also varies widely from 20-30 kg/inhabitant.year in cities to 150 kg /inhabitant.year and more in rural environment. The amount of kitchen waste (citizens, canteens, catering, retailers and supermarkets) is more constant and remains between 60 and 90 kg/inhabitant.year.

According to Eurostat, in 2006, 221 kg/inhabitant.year of MSW were landfilled in the EU27, decreasing from 289 in 1996. The amounts landfilled were very different from one country to another: between a maximum of 652 kg/inhabitant.year for Cyprus and a minimum of 4 kg/inhabitant.year in Germany (Belgium is among the "good" countries with 24 kg/inhabitant. year coming from 169 kg/inhabitant.year in 1996).
There is considerable pressure to decrease landfilling in the European Union.

Eurostat gives also statistics for MSW incineration. In 2006, 100 kg/inhabitant.year were incinerated in the EU27, increasing from 66 kg/inhabitant.year in 1996. Again, large differences are observed between the countries: between 0 kg/inhabitant.year for some of the new members to a maximum of 394 kg/inhabitant.year in Denmark.
Belgium is at 162 kg/inhabitant.year to compare with 182 kg/inhabitant.year for France, 184 kg/inhabitant. year for Germany and 233 kg/inhabitant.year for Sweden.

Today, the general trend is to enforce the **waste hierarchy** established by the European Union (Directive 2008/98/EC, Article 4):

- prevent waste in the first place
- preparing the product for re-use
- recycle
- other recovery (e.g. energy recovery by incineration)
- environmentally sound disposal of the waste (in a landfill)

Much is already done in this direction: paper and cardboards, plastics, glass, metals, textiles, batteries, electrical and electronic equipment, construction and demolition debris, waste clothing, medication, fluorescent tubes, paints, chemicals, spray cans, fertilizer and pesticide containers, shoe polish are sorted out at the source and recovered separately either on a door-to-door basis or in special collection centres (civic amenities). A big part of it is recycled or re-used after reconditioning. There is also an effort to decrease the packaging (plastics and paper or cardboards), eventually coming back to glass or metals. Of course, complete recycling is not possible: there is always an economic limit. For instance, in a document entitled "Support in the Drafting of an ExIA on the Thematic Strategy on the Prevention and Recycling of Waste (TSPRW)", Final Report submitted by EPEC (London) in preparation to the IPPC – Directive 2008/1/EC, on page 51 is given a Table with the optimal recycling rates for packaging materials:

- plastics: 28 to 38%
- steel: 60 to 75%
- aluminium: 25 to 31%
- wood: 47 to 65%
- paper and board: 60 to 74%
- glass: 53 to 87%
- composites: 0%

Taking this into consideration, what is left is to optimize the treatment of the biodegradables in MSW.

This is not an easy task because its content is not well defined:

- for food, there are fruits and vegetables residues either free or packed, the same already cooked or prepared with some kind of sauce, fast food packed meals eventually not even opened, various packed milk products, eggs, meat, bread, cakes, chocolates, ice cream residues, and various packages not accepted in the plastic recycling stream
- for garden waste, there are grass and bush or even tree residues (greens and browns) in variable amounts according to the season.

The question arises as to whether to impose a source separation at home. This is already done partially for the garden residues, and citizens can either deliver themselves the residues in containers parks, or ask to the municipal authorities to have these residues collected at their door at their own expense.

It remains finally to sort out very carefully the food residues in order to prepare separate uncooked fruits and vegetables residues that could be treated either by aerobic (compost) or anaerobic digestion (biomethanisation). A rough estimate is that the maximum amount that could be recovered this way is around 50 kg/inhabitant.year. The issues involved are to make sure that the citizens will agree to do so (some training will be necessary because for instance fruits that are treated chemically should not be introduced in composting facilities), to transform all collecting trucks in order to manage a separate bin for this new kind of residue, and to take into account the expenses associated with the new waste stream to treat and treatment properly speaking.

In the following chapters, the main high temperature (incineration, gasification, pyrolysis, and certain plasma processes) and low temperature processes (composting and anaerobic digestion) will be considered. After a short technical description, the main characteristic data will be given including economics where available, and their advantages and disadvantages will be discussed. Finally, after some general discussion, a scheme will be presented, aimed at helping decision makers in their final choice.

3.3. Final remarks – Definitions

Difficulties were encountered while writing these first three chapters, due to imprecise definitions of waste. This can lead to wrong statistics data: some residues could be counted twice (or more) or be deleted. It is evident that collecting data for residues or waste is very difficult anyway. Although an effort has already be done to better define "waste" in Directive 2006/12/EC and recently in Directive 2008/98/EC, a further effort could be done to improve definitions in the field of MSW. Here are some examples:

– In Directive 1999/31/EC, "municipal waste" is defined as "waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households". As there is no specification concerning neither the nature nor the composition of this kind of waste, and as Directive 2008/98/EC does not give any further information with this respect, the content of this paper could remain very imprecise.
– In the Glossary of statistical terms – OECD (http://stats.oecd.org/glossary/download.asp.) «municipal wastes are wastes produced by residential, commercial and public sectors that are collected by local authorities for treatment and/or disposal in a central location". Another definition concerns "municipal waste (for energy) consists of products that are combusted directly to produce heat and/or power and comprises wastes produced by the residential, commercial and public services sectors that are collected by local authorities for disposal in a central location. Hospital waste is included in this category". Another definition is given for "household waste: refers to waste material usually generated in the residential environment. Waste with similar characteristics may be generated in other economic activities and can thus be treated and disposed together with household waste".
– In the OECD/Eurostat Joint Questionnaire, "municipal waste" includes the following types of materials: paper, paperboard and paper products, plastics, glass, metals, food and garden waste and textiles.

In this paper, **MSW** are considered as produced by households, commercial and public services sectors and collected by local authorities. They include paper and cardboard, plastics, glass, metals, textiles, food and garden waste. Hospital waste is not included except if especially mentioned.

Another quite imprecise definition concerns **biomass** and **bio-waste**:

– In the abovementioned Glossary, "**biological waste** is waste containing mostly natural organic materials (remains of plants, animal excrements, biological sludge from waste-water treatment plants and so forth)"; "**biomass** is the quantity of living material of plant or animal origin, present at a given time within a given area"; "**solid biomass** is defined as any plant matter used directly as fuel or converted into other forms before combustion. Included are wood, vegetal waste (including wood waste and crops used for energy production), animal materials/wastes, sulphite lyes, also known as "black liquor" (an alkaline spent liquor from the digesters in the production of sulphate or soda pulp during the manufacture of paper where the energy content derives from the lignin removed from the wood pulp) and other solid biomass. Charcoal is included."
– Directive 2006/12/EC did not give any precision on the subject.
– In Directive 2008/98/EC, Article 3, Definitions, 4. "**bio-waste**" means biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants.

There are large discrepancies between the various estimates of the amount of bio-waste that could be used to produce energy or fuel of any kind, by a factor of at least 5 or 10!

Chapter 4

BEST AVAILABLE TECHNIQUES

4.1. General considerations

In this chapter, "**best available techniques**" are considered as defined in Directive 2008/1/EC (the IPPC Directive). They **must have been developed and tried with success on an industrial scale allowing implementation in the relevant industrial sector, under economically and technically viable conditions**.
Accordingly, research and development as well as pilot plant processes will not be discussed. Further, will only be considered techniques that are of interest for the treatment of biodegradables in MSW. Selective collection, recycling and manual or electromechanical sorting will only be briefly discussed, where appropriate.

A distinction can be made between processes operating at high temperature and those where the boiling point of water at atmospheric pressure is not exceeded.

4.2. High temperature processes

They include incineration, gasification and pyrolysis depending on the amount of air introduced in the heating chamber. Incineration is a combustion process conducted with an adequate amount of excess air to ensure that all carbonaceous materials introduced into the system are completely burnt to CO_2. In gasification, only part of these carbonaceous materials introduced in the system is burnt, delivering enough heat to allow endothermic reactions between carbon and H_2O, CO_2 and eventually H_2 to occur, and generating low calorific power gases containing CO, H_2, CO_2, H_2O and CH_4. In pyrolysis, no oxygen at all is introduced into the externally heated chamber containing the waste material, and carbonaceous materials undergo only thermal decomposition without any oxidization or gasification reactions. As gases produced by these processes must still be purified, plasma generators were tested, introducing heat by electricity instead of by combustion reactions in order to decrease the volume of gases to be cleaned.

4.2.A. Incineration

Incineration has been practiced already for centuries: old timers knew how to "purify by fire" especially in case of an outbreak of contagious disease. By the end of the nineteenth century, incineration of urban waste started to take place at a large scale in order to replace exports of MSW to the countryside. The first furnaces were operated manually with heavy air pollution caused by grit and smoke, resulting in strong public opposition. This should no more be the case as all incineration plants must comply with the European Directives on the subject, as mentioned in Chapter 2.

Incineration in the European Union may accordingly be considered as pertaining to the best available techniques for the treatment of MSW. When the incineration plant generates energy and satisfies to the formulae defined in Annex II/R1 of the Directive 2008/98/EC, it can be called "**Energy recovery plant**".

Without going into the details, here are some technological points of interest in the frame of this report.

According to the Solid Waste Management Sourcebook edited by the United Nations in the frame of the United Nations Environment Programme (available through the following website address: http://www.unep.or.jp/ietc/estdir/pub/msw/), there are four environmentally sound technical options: mass-burn systems, modular systems, fluidized-bed systems and refuse-derived fuel (RDF) firing.

Mass-burn systems

They are predominant in Europe and the USA for MSW incineration. They consist generally of two or three incineration units ranging in capacity from 50 Mg to 1,000 Mg per day, so that the facility capacity ranges from about 100 Mg to 3,000 Mg per day. They can accept waste almost without pre-processing except for removal of oversized items that could get stuck in the ash extractor. **Anyway, in most European countries, local programs aim to separate household hazardous wastes (chemical cleaners, pesticides, paints, batteries, oils, etc…) and to recover certain materials (metals, paper, cardboard, plastics, glass, textiles, etc…) at the source**.

Although the following description is general, specifics are inspired from the Bruxelles-Energie plant.

Trucks enter directly the intake area and tip their wastes either on the tipping floor (USA) or, even better, directly in the pit. From a feed chute, MSW is continuously fed to a grate system, which moves the waste through a combustion chamber using a tumbling motion. There are many grate systems: moving grates, reciprocating grates, reverse reciprocating grates, roller grates, etc… As the lower heating value of the waste has steadily increased, water-cooled grates are becoming more common. The residence time of the waste on the grate is large enough to ensure full combustion: more or less 50 minutes. Most systems are presently waste-to-energy plants and the combustion chamber walls are equipped with water tubes hidden from the flames by refractory silicon-carbide tiles to protect the steel tubes from the aggressive combustion gases and wastes projections. Water in the tubes is converted to steam that can either be used for heating (urban heating, swimming pools, industrial heating, etc…) or fed to turbines to generate electricity. In the latter case, superheating is necessary, achieved by fuel or gas injection in a separate boiler.

Waste combustion occurs with large excess air, injected at high velocity to mix the combustion gases and avoid any production of CO. When introduced on the grate, the waste is dried and dehydrated due to radiant heat coming from the walls of the combustion chamber: the surface of the refractory tiles is at least at 850°C.

Decomposition and combustion processes start accordingly, generating the necessary heat to the whole system. To avoid any gas leak to the ambient atmosphere, the whole system is under depression. Part of the combustion air is introduced underneath the grate as primary air while secondary air is introduced above the grate, enhancing turbulence. Retention time of the gases in the turbulent high temperature zone is higher than 2 seconds at more than 850°C to complete combustion and ensure decomposition of any dioxins. If the gases temperature does not exceed 950°C, NO_x production remains very small. In any case, flue gases treatment is compulsory and constitutes somehow a plant in the plant allowing the separation of fly ash, the neutralization of acids (HCl, SOx, HF), the abatement of heavy metals, the reduction of NOx, and the trapping of any remaining dioxins or furans by adsorption on activated carbon or oxidation on a DeNOx-catalyst. Flue gas treatment sharply increases the investment costs. Also, although the thermal efficiency of the boiler is better than 80%, global thermal efficiency falls to 60% due to all annex treatments. In many plants, activated carbon contaminated by dioxins and furans is reintroduced in the combustion chamber, and any water used for flue gas purification is recycled after treatment.

The main **advantages of mass-burn MSW incineration** are as follows:

– volume reduction of at least 90%
– weight reduction of 75%
– residues are sterile
– heat of combustion is recovered either to generate electricity or for heating
– there is a potential recovery of metals and construction materials
– the amount of final residue to dump in a hazardous waste landfill is low
– the process is capable to destroy most undesirable organic molecules

Disadvantages are as follows:

– capital intensive
– technically complicated plant, mainly due to gas purification
– special precautions must be taken during maintenance (dust, heavy metals, various hazardous organic materials)
– down time for maintenance is from 8 to 15% on a yearly basis
– cans, tarry materials, bulky tree roots and large pieces of plastics should be avoided

Here are **some quantitative data** (partly from experts and from CCE “Livre vert sur la gestion des biodéchets dans l’UE“ COM(2008)811 final – SEC(2008)2936, paragraph 4.2:

– investment costs: 300 to 360 Euros per annual Mg of waste
– total treatment cost, including capital charges: 100 Euros per Mg of waste
– power requirements: 40 to 120 kWh per Mg of waste (including some thermal energy)
– after deduction of the power requirements, there remains between 450 kWh/Mg and 500 kWh/Mg of waste for the electricity network
– after treatment, about 20% of the initial waste are recovered as bottom ashes partly sintered used for road embankment after removing metal inclusions, 1.5% are recycled as metals, 1.5% are recovered as fly ash to incorporate in porous cement blocks or in cement insulating products, 0.2% to 3% are finally dumped or retreated as hazardous sludge
– at the Brussels Region, the minimum acceptable lower heating value is 4 GJ/Mg of waste (i.e. one tenth of the lower heating value of fuel oil). In 1996, the actual value was 7.6 GJ/Mg. It increased steadily to the current value of 9 GJ/Mg. In 1986, the design value of the plant was for a lower heating value of 7.5 GJ/Mg of waste. The maximum acceptable lower heating value is 14.7 GJ/Mg of waste but it must be mixed with other waste to bring the average value below 12.6 GJ/Mg, acceptable on the grate of the furnace-boiler. In that case, the input of waste must be proportionally reduced.

Modular incinerators

Modular incinerators are usually prefabricated units with relatively small capacities, of between 5 to

120 Mg of solid waste per day. With one to four units, a typical facility reaches a total capacity of about 15 Mg to 400 Mg per day. Steam is usually the sole energy output.

They are used for smaller communities or for commercial or industrial operations. On average, capital costs per Mg of capacity are lower than for other incineration options. Gases generated in the primary combustion chamber flow to an afterburner secondary combustion chamber that ensures complete combustion and serves as the primary means of pollution control. Modular incinerators become less common because of concerns over the consistency and adequacy of air pollution controls.

Fluidized-bed incinerators

Fluidized-bed incinerators are used most extensively in Japan (currently more than 167 facilities). Japanese plants are typically of medium scale (50 Mg to 150 Mg of waste per day). The process is gaining interest on the European MSW incineration market, because of potential co-firing of other waste, although mass-burn still dominates.

In a fluidized-bed incinerator, a bed of limestone or sand, or other inert materials that can withstand high temperatures, is fluidized by air. Fluidisation causes the bed to expand and behave more or less like a boiling liquid. There are broadly two types of fluid-bed technologies: a bubbling bed and (for large plants) a circulating bed.

Fluidized-bed incinerators require front-end processing, also called fuel preparation.

They are also generally associated with source separation because glass and metals are not really compatible with the system: their removal requires circulating about ten times more bed material, in order to subtract them from the bed. However, they can successfully burn wastes of widely varying moisture and heat content, making them more compatible with high recovery-recycling practices. They can also be very effectively controlled to achieve higher energy conversion efficiency, less residual ash, and lower air emissions. Cost comparisons with mass-burn are inconclusive; despite their apparent simplicity fluid bed units tend to be more expensive. This could become a fully commercially proven practice in Europe in the near future.

Refuse-derived fuel

Refuse-derived fuel (**RDF**, sometimes called waste-derived fuel **WDF**) refers to solid waste in any form that is used as fuel. However, it refers primarily to solid waste that has been mechanically processed to produce storable, transportable, and more homogeneous fuel for combustion. Its production needs a number of processing stages: eventually a manual separation line, screening using trommel or vibrating screens, shredding or hammer milling with additional screening steps, magnetic separation, pelletizing or baling of combustibles. The complexity of this processing results in high operating and maintenance costs and in a reduced reliability of RDF production facilities. Also, capital costs are higher for RDF incineration units than for other incineration options. However, good quality RDF can be burnt in industrial rotating kilns like those used for cement production. Slightly apart from the RDF, **EBS** (in German, Ersatzbrennstoff) is obtained by sorting MSW in order to separate high calorific value parts. EBS is burnt in specialized plants to produce energy, mainly in Germany. Are also worth mentioning the Mechanical and Biological Treatment (**MBT**) processes mainly developed in Germany and in Austria. MBT typically includes a mechanical treatment stage to separate the biodegradable and dry fractions of waste. The biodegradable fraction undergoes biological treatment composting or anaerobic digestion). The dry fraction is either eliminated by incineration or discarded into landfill, or undergoes an additional treatment aimed at increasing its calorific value, reducing its particle size, and limiting its content in terms of undesirable substances (mainly chlorine and ash), with a view to recovering RDF in the cement-making process. MBT should be considered as a pre-treatment operation since waste is sorted, rather than eliminated.

Environmental impact of MSW incineration processes

This impact comes from potential emission of contaminants into the air through exhaust stacks and into water through ash leaching effluent.

Concerning **air emissions**, the main concerns are metals, especially mercury, lead and cadmium; organics such as dioxins and furans; acid gases such as sulphur dioxide and hydrogen chloride; particulate matter such as dust and grit; nitrogen oxides (ozone precursors); and other substances such as carbon monoxide.

Modern incinerators all include effective **flue gas cleaning** equipment. CO is controlled by combustion conditions, not by end-of-pipe flue gas treatment. Dust is retained either by electrostatic precipitators or (most frequently) by bag filters. Acid gases are neutralized by neutralizing agents, with various kinds of processes classified in three categories:

– dry systems featuring a dry neutralizing agent (lime or sodium bicarbonate) injected in the flue gas, collecting the dry residue at a filter;

- semi-dry systems using the injection (spray-drying) of a slurry containing the neutralizing agent (lime milk) and collecting the dry residue at a filter;
- wet systems using absorption columns where water and/or caustic soda solution neutralises the acids, the liquid effluent being thereafter processed and/or released in a receiving water.

Heavy metals and residual organic compounds are adsorbed onto an injected sorbent substance like activated carbon. NOx production is first reduced by controlling the temperature in the combustion chamber and finally neutralized either by urea injection or by catalytic reduction with ammonia injection combined with a catalyst bed. There are two options: Selective Non-Catalytic Reduction (SNCR) in a temperature window of 700°C to 1,000°C, and Selective Catalytic Reduction (SCR) in a temperature window of 300°C to 400°C.

These various processes have to be combined to obtain a layout achieving complete flue gas cleaning. There are a large number of possible combinations, especially because of extensive historical retro fitting. **The choice of a flue gas treatment layout** has to be made considering at least the following criteria:

- efficiency (ability and easiness to comply with emission limits, even with very variable flue gas pollutant contents – peak management);
- effect on energetic balance of plant (impact on the energy recovery efficiency);
- type, quantity and management of flue gas cleaning residues (e.g. recycling possibilities);
- ease of operation (reagent handling, equipment control complexity, etc…);
- economic balance (investment cost; operation costs: utilities, reagents, final residues);
- environmental balance: beyond the compliance with the requirements, includes elements like water consumption, assessment of type and quantity of final waste, transfer of pollution, etc…).

Residual incinerator ash can contain concentrations of heavy metals such as lead, cadmium, mercury, arsenic, copper, and zinc, which originate from plastics, coloured printing inks, batteries, certain rubber products, and hazardous waste from households and small industrial generators. Bottom ashes are generally less contaminated than fly ash recovered from bag filters, electrostatic precipitators or scrubbers. It is possible to reduce drastically the concentration of contaminants by removing at source from the mainstream household batteries, thermostats, fluorescent lamps, plastics and solder-bearing items (e.g. consumer electronics, light bulb sockets, and plated metals). Some incinerators (mainly in Japan) are equipped with small additional furnaces to melt bottom ashes, recovering separately a molten slag and a metallic phase containing most of the contaminants. It is also possible to treat separately fly ash by such a process, after fixation by cement.

Biodegradables in MSW

Biodegradables in MSW **are easily processed in mass-burn incinerators, modular incinerators and fluidized-bed incinerators without selective collection**. Kitchen and garden waste like vegetables, potatoes, fruits, gardening residues except wooden parts too large in diameter are very quickly dried/dehydrated and undergo combustion within the residence time. Meat, fish, bones, sausages, eggs, bread, any kind of cooked items can also be treated even if they are packed in plastics and/or cardboard. The only kind of organics that should be avoided is that contained in aerosol cans that were not emptied: they could result in small explosions in the combustion chamber. The same holds for closed cans containing liquids like milk, beer, soda, etc… As already mentioned above, waste must anyhow undergo a preparation step before introduction in a fluidized-bed incinerator. **RDF has one more advantage: it can be co-fired in existing cement, lime, or power plant**. However, in some countries such as Italy, RDF is made from mixed MSW, i.e. containing biodegradable waste.

4.2.B. Gasification and pyrolysis

While incineration aims at burning any carbonaceous material contained in the MSW completely to carbon dioxide, gasification and pyrolysis tend instead to generate combustible gases and/or solids to be converted further into power in a separate plant.

Pyrolysis

Pyrolysis processes are based on thermochemical decomposition by endothermic reactions under reducing, generally self-generated atmospheres. Heat is provided either by indirect heating from an external source or internally by partial combustion of the load. External heating generally proceeds through a wall (temperatures < 500°C). At higher temperatures a circulating heat carrier is preferred, as in double fluidized bed systems (cf. catalytic cracking in the oil industry). Pyrolysis products resulting at the same time from this decomposition are gases, condensable vapours, and solids (pyrolysis coke), their relative proportions depending on feedstock, temperature and retention time: fast pyrolysis at medium temperature (a few seconds at 600°C-900°C for MSW) favours liquids, while slow pyrolysis at low temperature (10 minutes at 400°C-500°C for MSW) favours coke formation. Usually, part of the produced gases is burnt to provide the heat needed for the process, characterised mainly by drying and endothermic reactions: the heat needed for drying biodegradable waste is substantial.

Pyrolysis is by no means a new process: charcoal from wood is still being produced worldwide along prehistoric methods, and metallurgical coke is also produced since more than a century by heating coal externally in large furnaces. When MSW is the load, although coke produced by the process is considered as a secondary solid fuel, it is of very poor quality: low carbon content and rich in ash, sulphur, chlorine, heavy metals, etc… initially present in the MSW. Extensive purification is necessary to allow its use as secondary fuel, but this is very difficult to achieve, which reduces the significance of the process. Also, besides light gases, heavy condensable gases are produced (tar) and special care must be taken to avoid any clogging in the system.

For one Mg of dry carbonaceous material contained in MSW, slow pyrolysis generates typically 570 kg/Mg combustible gases (a complex mixture of non condensable gases like hydrogen, carbon monoxide, methane, etc… for about 380 kg/Mg; plus heavy hydrocarbons or tar for about 190 kg/Mg); and 430 kg/Mg coke. In the case of fast pyrolysis, the gas fraction is increased to 840 kg/Mg (730 kg/Mg heavy hydrocarbons and 110 kg/Mg non condensable gases), while coke production decreases to 160 kg/Mg.

Heating of the system can be provided

– from an external source (indirect heating) by combustion of part of the gases or of the coke produced by the process; heating with a double envelope gives low heat transfer coefficients and is restricted to slow pyrolysis
– by internal heating, burning part of the load eventually in a counter-current system or by heating reducing gases by a plasma (see a separate paragraph on the subject of plasma)
– by means of an intermediate heat transfer medium (sand, ceramic balls, molten salts, etc…) heated in an external loop.

Special pyrolysis operations are sometimes operated under vacuum (rubber tyres), or under hydrogen pressure (plastics, not for MSW).

A number of pyrolysis processes were tried, mainly for solid industrial residues, sludge from water purification, paper and cardboard residues, plastics, biomass and wood residue, tyres, etc… Only a few were devoted to MSW: as an example, a rotary kiln process based on French technology was implemented in Japan with a capacity of up to 70,000 Mg MSW per year. It is still in operation, but no more offered because of a lot of problems linked to kiln sealing, tar condensation, duct clogging, heat transfer and corrosion. Also, the heavy hydrocarbons must be cracked to lighter fractions: distillation only gives a lot of separate products, many of them without possible market.

Gasification

Gasification processes essentially proceed in two steps: pyrolysis followed by gasification of the solid residue (coke) and of the light and heavy hydrocarbons, resulting in so called synthesis gas by means of a gasification agent: either air/water vapour or oxygen/water vapour. Heating in the second step the carbonaceous solid residue produced by the first step, under an atmosphere containing water vapour and carbon dioxide instead of oxygen will avoid combustion of the gases evolved from the residue. Combined carbon in the residue will react with water vapour and carbon dioxide at 850°C-900°C in endothermic reactions generating carbon monoxide, hydrogen and methane. Working at low pressure (usually near 1 bar) and high temperature (850°C-900°C) generates a gas rich in carbon monoxide and hydrogen called **synthesis gas**. On the contrary, working at high pressure (10 bars -20 bars) with hydrogen injection, and at lower temperature (700°C) generates a gas rich in hydrocarbons, mainly methane (**hydro-gasification**). The heat necessary for the process is generated by burning a small part of the load either with air or with oxygen: the process is thermally self-sustaining. Depending on the amount of nitrogen introduced in the system, the final gas produced will be lean (< 8 MJ/Nm3) or semi-rich (8-18 MJ/Nm3) compared to natural gas (35 MJ/Nm3). The final gas can be recovered, eventually thermally cracked to suppress any heavy hydrocarbons (tar), purified and cooled (in a boiler) to feed a piston or a turbine engine, provided that the characteristics of the purified gas are satisfactory. By this process, any combined carbon in the coke disappears entirely and the final solid residue is inert.

The process is not new: gas generators were used at a large scale for more than a century to convert coal to carbon monoxide and hydrogen for public lighting and home heating. During World War II, the process was also used for cars, trucks, and even (German) tanks.

Today, various reactors were developed: rotating kiln, fixed bed and fluidized bed.
Differences arise from means used to support the solids in the reactor (grates), the respective flow directions of load and oxidant (counter-, co-, and cross-current), and the heat source to the reactor.

Commercially developed processes pertain to four classes:

– fixed bed gasification with extraction of final ashes, either “dry” or molten
– fluidized bed gasification (dense, atmospheric circulating, pressurized, rotating)
– entrained flow gasification
– two steps pyro-gasification.

Plasma processes will be dealt with in a separate paragraph.

Most processes and reactors were developed to treat coal eventually bituminous, brown coal, petroleum coke, solid or liquid industrial residues, wood, wood residues, RDF, incineration residues, hospital residues, sludge, plastics residues, biomass, agriculture residues, crushed car residues, tyres, etc… **For MSW treatment there remain a few commercially operated processes**:

– a vertical shaft atmospheric pressure gasifier with co-current fixed bed developed by a big Japanese steel company, derived from blast furnace technology. After pre-processing, MSW is introduced with some lime (50 kg/Mg MSW) at the middle of the reactor acting as the pyrolyser, while coke (also 50 kg/Mg MSW) is introduced with combustion air at the lower part of the shaft, where temperature is high enough to obtain a molten slag and a molten metallic phase (bad iron). The upper part of the shaft works as a cocurrent gasifier. Besides gases, the outputs are granulated slag (90 kg/Mg MSW), iron (10 kg/Mg MSW) and fly ash (30 kg/Mg MSW), the latter being sent to landfill. This process is market leader for large scale MSW conversion in Japan. Plants capable of 110,000 tons MSW per year are in operation.
– another vertical shaft gasifier with fixed counter current bed working under pressure (24 bars) developed by a German engineering company, initially devoted to the treatment of coal or coke in connection with a British gas company, was further developed to treat various solid waste, including MSW at the scale of 250,000 Mg per year to produce synthesis gas (for the production of methanol). Bottom ashes are molten and recovered in water
– a pressurized (5 bar to 16 bar) rotating fluidized bed gasifier developed by a Japanese engineering company. The rotating bed allows separation of not combustible solids and of metal fractions to recycle. Temperature in the fluidized bed is between 600°C and 800°C. At the bottom of the shaft furnace, a cyclonic combustion chamber operated at high temperature (1,300°C to 1,500°C) allows sintering of fine ashes as granules. Furnaces capable of 50,000 Mg MSW per year are in operation in Japan. The process is offered for commercialisation in Europe.
– a two stages pyro-gasifier developed by a British engineering company. Two horizontal tubular pyrolysers making use of endless screws feed the intermediate coke to a vertical shaft gasifier. One furnace was installed in the United Kingdom in 2003 at the scale of 60,000 Mg MSW per year.

Of course, if the scope encompasses biomass and wood, the number of commercially operated processes is considerably enlarged.

As already mentioned, **pyrolysis of MSW is not successful so far**.

Considering only gasification (including pyro-gasification), the expected advantages compared to mass-burn incineration are

– a reduced volumetric flow (4,000 Nm3/Mg MSW for gasification instead of 6,000 Nm3/Mg MSW for incineration). This reduces the draft fan power requirements and, if a boiler is used to generate electricity, enhances its efficiency
– a wide flexibility with respect to their input (higher values of the lower heating value are acceptable)
– cleanliness of the residues, especially if they are molten
– excellent recovery of the metal values
– maximum diversion from landfill

Disadvantages are as follows

– MSW must be pre-processed, adding to the plant complexity and to power expenditure. Rotating fluidized bed are advantageous with this respect: they need only a rough preparation of the load
– the heat content of the molten slag is normally lost
– fouling and corrosion problems are numerous
– investment and operating costs are higher
– counter current vertical shaft reactors show some internal sintering /melting of the load, leading to preferential gas paths and eventually blockage of the downward move of the load. Accordingly, the load must be carefully prepared
– humid waste is not adequate as feedstock in terms of energy production
– although some processes aim at feeding gas turbines, the required purification level of the gases is in that case very difficult to achieve. A better choice would be burning the gases in a boiler to generate electricity via a steam turbine, gas purification occurring via a flue gas cleaning system similar to that in use for mass-burn incineration.

There is a **lack of quantitative data for MSW treatment**. Total costs, including investment are often cited between 100 Euros/Mg and 150 Euros/Mg MSW.

Environmental impact of MSW gasification processes

It is similar to that already mentioned for incineration. **Air emissions** could be worse than in incineration because of eventual leakage between the pyrolysis and the gasification steps of the process and also because a larger amount of metals is evaporated. **Residual solids** as bottom ashes are usually melted and granulated in water. In that case, they are inert. Fly ash must be further treated because it contains most of the hazardous materials.

Biodegradables in MSW could be treated in some of the above-mentioned gasifiers without selective collection. However, they must be compatible with the load preparation system and with the conditions prevailing in the pyrolysis part of the equipment. Other remarks are very similar to those presented above for incinerators.

4.2.C. Plasma processes

At first sight, the idea to make use of an expensive energy like electricity to provide heat for the treatment of MSW seems surprising. However, plasma processing shows advantages like reducing gas flow and separating heating requirements from synthesis gas production that give sense to examining its capabilities further.

Plasma is considered as the fourth state of matter besides solid, liquid and gas. In the universe, almost 99% of matter is in that state. In a laboratory, it is generally produced by electric discharge. Plasmas are gases containing atoms, molecules and ions in a fundamental or in an excited state, electrons and photons. Electrons are very light particles against ions and neutral atoms and molecules. They are strongly accelerated by electromagnetic fields and play a special role. There are various criteria allowing distinction between different types of plasma, but this is beyond the scope of this report. **All processes described in this section make use of thermal plasmas**. They are generated at pressures near atmospheric pressure (0.1 to 20 bars) mainly by electric arcs or by radio frequency discharges. At that pressure, particles collide very frequently and ionisation results mainly from a thermal effect, with elastic type collisions. At temperatures between 6,000 and 25,000 K, electron densities are between 10^{20} and 10^{24} m^{-3}. In the bulk, plasmas are electrically neutral. Thermal plasmas are at thermodynamic equilibrium provided they include no reactant other than the plasma generating gases: electrons, ions and atoms are at the same temperature. Plasmas are electrical conductors due to the presence of electrically charged free particles. Electrical conductivity is in the range of one thousandth that of metallic copper.

There are many industrial applications of thermal plasmas at moderate power (below 200-300 kW): cutting and welding metallic pieces, surface treatment and deposition, spheroidizing and purification of particles, chemical analysis, synthesis of nanopowders, etc… At higher power (between 0.5 and 100 MW) there are some applications in chemical synthesis and in extractive metallurgy. During the fourth part of the twentieth century, interest for their use in waste treatment started to grow.

Recovery and purification of machining residues of high value added metals (titanium, zirconium and super-alloys) as well as the treatment of steelmaking dust were first considered. Later, processes were developed for the treatment of toxic liquids like PCB, CFC and HCFC; of solid waste like contaminated soils, weakly radioactive nuclear residues, various army residues including destruction of conventional ammunition, asbestos fibres, industrial chlorinated residues, metallurgical slags, medical residues, all kind of waste on board of ships, etc…

Many improvements were introduced to plasma generators. However, there are power limits for each type. Radio frequency plasma torches remain under 400 kW.

Metallic direct current plasmas torches are built like water-cooled hollow cylinders and the electric discharge occurs either between two inside successive electrodes (cathode and anode), the discharge being blown out as a plasma “flame” protruding from the torch (blown arc), or between only a cathode built in the torch and the load of the furnace (transferred arc). Cathodes may be made of either thoriated tungsten (hot cathode) or of copper (water cooled cold cathode). In the latter case, a rotating magnetic field ensures that the hot spot on the cathode is always moving.

Superimposing a high frequency component on the direct current for a short while helps to shorten the time necessary to initiate the arcing (a few seconds). A maximum power of 3 MW per plasma torch can be achieved in both cases. Both radio frequency and metallic direct current torches can be operated with almost any kind of gas: argon, helium, hydrogen, nitrogen, methane, carbon monoxide, carbon dioxide, oxygen, air and mixtures. Much higher power values (100 MW) can be obtained with direct current graphite hollow electrodes working with axial injection of a non-oxidant gas like nitrogen. It should also be mentioned that some cold cathode metallic plasma torches working with alternating current are also available, up to 3 MW.

Concerning MSW, a few processes were developed at commercial scale:

– in Japan, an American electric engineering company installed an 8 MW MSW treatment plant capable of 300 Mg per day, working as a counter current vertical shaft gasifier, fed from the top. Coke is necessary to obtain a stable bed above the plasma torches, ensuring a relatively constant temperature. Below the torches, temperature reaches 1500-1700°C to obtain a metallic phase and a slag phase in the molten state. Above the coke bed, air is injected for a secondary combustion to generate hydrogen and carbon monoxide. After dust separation by a cyclone, the flue gases are sent to a boiler to generate steam to produce electricity

- another process makes use of a furnace inspired from an arc steelmaking furnace where the graphite electrodes are replaced by arc blown plasma torches. The load is introduced via an endless screw feeder. Water vapour is injected in the reactor that works like a gasifier. Secondary water vapour is injected to cool down the gases at their exit from the furnace
- another process makes use of a cylindrical arc furnace with two graphite electrodes fed with direct current and generating the electric arc between them above a molten slag. Three other graphite electrodes dip in the molten slag for further heating with alternating current by Joule effect in the slag
- in France, a plasma torch gasifier aiming to treat 50,000 Mg MSW per year is under construction in Morcenx. It should produce enough synthesis gas to generate 12 MW electrical power.

Vitrification of fly ash coming from MSW incinerators in plasma torch furnaces is more common. They contain alkaline salts, heavy metals and chlorinated or fluorinated organic compounds. Accordingly, they must be dumped in hazardous waste landfills after stabilization by means of hydraulic binders. A first plasma plant capable of 2,500 Mg per year was built at Cenon (near Bordeaux - France) in 1995 and was successful. At least ten plants are presently in use in Japan, based either on the French technology or on an American one.

Advantages claimed by plasma torch processes promoters are

- the heating energy delivered by the torch is independent of the nature of the wastes: any change in MSW composition can be faced easily
- the heating energy available at temperatures above organic compounds dissociation is much larger than with combustion processes
- there is no need for an excess of air like in normal combustion
- the total flow of gases is minimum. However, for copper cathodes, the minimum air flow is in the range of 0.1 kg/MW, and plasma temperatures are between 6,000 and 10,000 °K
- decomposition of organic materials occurs at high speed and it is easy to generate synthesis gas by controlled injection of air or of oxygen in the reactor
- the bottom glass obtained from the mineral part of the waste could be recycled
- reactors are relatively small, allowing compact plant design, eventually mobile
- plasma torches can be switched on or off in a few seconds only

Disadvantages are

- short life time of copper electrodes (500 to 3,000 hours)
- high power density results in high load evaporation losses
- large amount of dust can be carried along, due to strong turbulence of the gas flow
- possible generation of nano-particles if the very high temperature zone of the plasma flame hits the load
- flue gas cleaning necessitates special consideration: very quick cooling at the exit of the furnace in order to avoid generating new complex hazardous organic molecules; special care for NOx and for heavy metals
- high investment and operating costs
- in the case of MSW containing 30% humidity, the plasma reactor working as a gasifier and delivering the synthesis gas to a conventional coal-fired power plant, taking into account the global efficiency for converting heat of combustion to electricity, the energetic ratio between electric power delivered by the power plant and electric power consumed by the plasma furnace is only around two.

There is a **lack of reliable quantitative data** for MSW treatment. However, here are some estimated data appearing in literature:

- investment between 120 Euros and 280 Euros per annual Mg MSW at the scale of 1,000 Mg MSW per day; the most favourable case is when the synthesis gas is fed in a coal-fired power plant to replace part of the coal, assuming that the flue gas cleaning of the power plant does not need any change to accommodate the new feed
- electric power needed to generate synthesis gas from MSW at 30% humidity: 600 kWh/Mg
- operating costs, besides investment, are cited between 25 Euros and 80 Euros per Mg MSW, depending largely on the cost of electricity.

The environmental impact of plasma treatment of MSW should be similar to that mentioned for incineration. **Air emissions** could be worst because of the very high temperature generated by the plasma torches, resulting in heavy metals evaporation and possibly in nano-particles generation, very difficult to recover by the flue gas cleaning system. **Residual solids** recovered at the bottom of the furnace as vitrified glass could be recycled, as well as the eventual metallic phase, reducing landfill concern. However, flying ashes remain a problem as hazardous materials.

Biodegradables in MSW could be considered for plasma treatment, but this does not look very attractive due to high investment and operating costs.

4.3. Low temperature processes.

These processes are not able to treat MSW as such. They can only cope with biodegradables contained in MSW, and necessitate either separate

collection of these biodegradables at the source or adequate selective sorting of MSW before loading in the process.

There are two possibilities: aerobic treatment (composting) or anaerobic digestion (biomethanisation). The two processes depend on microorganisms for their correct functioning.

4.3.A. Composting

According to the above-mentioned Solid Waste Management Sourcebook issued by the United Nations Environment Programme (see: incineration), composting solid waste for use as a soil amendment, fertilizer or growth medium is important in many countries. Some Asian countries have a long tradition, while Western Europe avail of a range of modern technologies. However, composting is the waste management option with the highest rate of failed facilities worldwide, due to high operation and management costs, high transportation costs, lack of markets and/or poor quality product as a result of poor pre-sorting (especially plastic and glass fragments), poor understanding of the composting process and competition from chemical fertilizers. It is accordingly necessary to build enough knowledge to avoid mistakes.

To start with, it must be clearly stated that **composting does not allow the recovery of a substantial amount of energy** from the partial oxidation of the biodegradables in MSW.

Scientific considerations

From a scientific standpoint, composting is part of the global biogeochemical cycles of our planet. During each cycle, mineral elements from soil and air are captured by plants and later by animals during their growth to constitute part of their organic materials. After their death, they go back to the environment to be used again by other plants and animals after going through complex processes. The main biogeochemical cycles in the biosphere deal with carbon, water, nitrogen, phosphorus and sulphur. **The two main cycles for composting are carbon and nitrogen**.

The carbon dioxide contained in the atmosphere or dissolved in water delivers the **carbon** necessary to constitute organic materials contained in plant material and other living bodies. It is first captured by chlorophyll containing plants to be transformed by photosynthesis into carbohydrates (sugars) and further in protides (proteins) and lipids (fats). These substances feed animals and other organisms containing no chlorophyll, such as mushrooms. All living organisms respire and reject carbon dioxide in the atmosphere. After their death, the remains undergo decomposition and are mineralized by other living organisms. Finally, carbon is recycled as carbon dioxide. This process occurs also for all residues coming from living organisms like dejections and secretions.

For **nitrogen**, the major reservoir is the atmosphere, almost 80% of which is molecular nitrogen. To be used by living organisms, it must first be mineralized.
Microorganisms, living freely in the soil or in symbiosis with legumes are able to break the molecular bond, fix nitrogen in an organic form and provide it to their host plants or release it in the soil. Other microorganisms transform it, successively, into soluble ammonium-, nitrite- and nitrate- nitrogen. Plants generally absorb it in the latter form, even if the nitrogen comes from decaying organic matter in the soil, such as manure or compost. The absorbed nitrogen is used to synthesize amino-acids and proteins. The organic nitrogen in dead plants and animals is mineralised by bacterial consortia and converted in a series of steps to nitrates that are taken up again by plant roots. Under anaerobic conditions, part of it may be transformed to molecular nitrogen or nitrous oxide and released to the atmosphere (denitrification).

Whereas most organic residues feed microorganisms with all nutrients necessary for their growth, **there is still an optimum value of the carbon to nitrogen (C/N) ratio**.
The ideal value to start the composting process is C/N = 30. If the ratio is higher than 50, the time necessary for composting will be too long because some microorganisms will start consuming other dead microorganisms instead of decomposing the waste. At the end of the composting process, the ratio C/N in the compost is around 15: **compost is an intermediate state between death of living organisms and their final mineralization**. It contains not only minerals but also enough organic materials and a number of living microorganisms and even insects necessary to feed plants. It should be stated that **these living organisms are no pathogens**: they are only able to decompose plants and animal wastes.

During the process of composting, **it is necessary that both water and oxygen (air) reach easily the organic materials** undergoing decomposition, otherwise anaerobic conditions will occur with generation of methane, 30 times more efficient than carbon dioxide as greenhouse gas. Also, carbon dioxide evolution and venting must be easy. Accordingly, a composting bed must be highly porous (not too much water, between 40% and 60%) and must be regularly turned up. It is advantageous to alternate layers of various kinds: grass (high nitrogen content), finely ground wooden parts (high carbon content), vegetables and weed (more equilibrated C/N ratio), manure (if available, well equilibrated C/N ratio provided it contains enough straw), etc…

During composting, there is an initial steep increase in **temperature**: easily degradable materials undergo decomposition through the action of bacteria during the first days raising the temperature up to 60-65°C after approximately 10 days. It is essential to reach high enough a temperature to kill all pathogen microorganisms and destroy all undesirable seeds. After this maximum, the decomposition process goes further under the action of the remaining microorganisms and insects, involving progressively parts that are not so finely divided in the waste, and temperature decreases slowly. After each turning of the bed, there is an increase in temperature.
After a period of 3 months, the temperature remains under 30°C. The process is not completed at that stage and must go on (for instance in a static pile) for several months.

Unpleasant odours occur only during the first days of the composting process when the protein content (from meat, diary products and certain vegetables) of the load is too high. This is a major objection against the process, even if smells can be attenuated, e.g. using compost or bark filters or operating in a confined building. It is accordingly recommended to avoid these types of organic waste while collecting selectively for composting.

Practical considerations

In practice, a certain number of **conditions** are **necessary for composting to be successful**. Some **depend on the scale** at which the process occurs. Usually, composting processes are divided in two categories: decentralized and centralized composting.

Decentralized composting

Home composting, also called backyard composting covers already different ways to proceed.

- **When the amount of biodegradable matter is small and contains only kitchen residues, worm composting** (also called vermicomposting or vermiculture) is a favoured option. Redworms and earthworms break down compostables by eating them. Biochemical decomposition occurs via bacteria and chemicals in the worm's digestive system. The worms take care of aeration by digging galleries. The only remaining care is to ensure appropriate humidity. Special containers are commercially available. Some of them allow recovery of the liquid aqueous residue: after diluting 10 times with water, this is a valuable fertilizer for green plants.
  Vermiculture does not kill all pathogens: some viruses and parasites can survive the process. The input materials must accordingly be selected to avoid any risk: no meat or dairy products.
- **When the garden is very small (less than 30 m²)**, or if worm composting is not favoured, **barrel composting** should be used. Suitable barrels are commercially available. They must allow good aeration from the bottom and have a ventilated lid to protect the load from rain. The barrel should receive heat from the sun. It is necessary to add some wooden chips if only kitchen residues are processed, to maintain a favourable C/N ratio.
- **When the garden has a medium size (30 to 100 m²)**, **box or silo composting** prevails. At least two boxes are easily built one against the other e.g. with wooden boards, leaving enough apertures for air to circulate easily. The two cubes have open bottom to allow access to the compost for living organisms coming from the earth beneath. Turning of the bed is needed. After 3 months, part of the compost of one box should be transferred to the other to start another compost. Finally, after 6 months the compost is ready for screening and use as a soil amendment or fertilizer.
- **When the garden is larger than 100 m²**, **pile composting** should be considered.
  It is operated like for larger facilities (see below).
- **Collective composting (neighbourhood-, block-, or business-scale composting)** provides a waste management opportunity to a small group of people living or working in the same area: households, shops, institutions, etc… Composting is done on unused land beside community gardens, or in parks. These sites usually process less than 5 Mg of waste per day. The site must be accessible to all who want to use them, be clearly designated with signs easy to interpret, be sited with the agreement of the surrounding land users, have adequate fencing or control to prevent their becoming an open dump, and have appropriate soil to absorb the leachate. A compost monitor or supervisor should be responsible for maintaining order and cleanliness. Back up from the municipal government is needed to remove undesired items and for turning the piles.
  Decentralized composting at the village and community scale usually process between 2 Mg and 50 Mg of waste a day. The guidelines are the same as above, but the site must accommodate more turning, processing, and storage than at smaller scales.

Centralized composting

- **Centralized composting at the municipal scale** refers to composting animal and plant wastes from multiple sources, where the wastes are transported from several points to a facility that can often receive between 10 Mg to 200 Mg per day. Siting the compost facility is a formal process including technical and environmental assessment of the potential sites; a formal evaluation and selection involving all stakeholders; a formal remediation or compensation programme to minimize and/or compensate for nuisance effects of traffic, odour,

leachate and noise; a separate collection and/or pre-processing system; and a formal system for using and/or marketing the finished compost.
- **Centralized composting at the regional scale** deals with facilities capable of more than 50 Mg and as much as 1,000 Mg per day. In addition to the siting and design requirements cited above, agreements between the various participating municipalities or jurisdictions must be reached including waste delivery and – very important – the uses and outlets of the finished compost.

All large scale composting facilities should include
- **a pre-processing stage**, necessary to create the conditions for bacterial action. It includes three separate types of operations: separation or removal of oversize, non-compostable, or dangerous materials; size reduction (chipping, grinding, or shredding) to create many small particles suitable to sustain bacterial action; blending and compounding to adjust the C/N ratio, moisture content, or structure of the materials to be composted. Mechanical preprocessing is often the most costly part of the composting system and also the most vulnerable to breakdown. Source separation and separate collection is necessary to minimize preprocessing
- **one of the available composting systems**:
  - **windrow and active pile systems**, simple and easy to manage. The size of the windrows must be large enough to allow adequate heat build-up. Their shape is related to the type of aeration and the type of equipment used to aerate. They can be either open or covered depending on climate and moisture content of the waste. The spacing of the windrows depends on the site and on the equipment used for turning: crews with shovel and rakes, or more often bulldozer, tractor or windrow turning machine
  - **static pile systems** do not turn the windrows: they are aerated continuously or periodically using blown air fed through channels built into the pad on which the piles sit
  - **in-vessel systems** represent a higher technology approach: much of the composting process is carried out inside a large, enclosed chamber in which mechanical mixing and/or forced aeration are performed where moisture, air and temperature can be controlled. The residence time in the vessel is between 3 days and 30 days, followed by a period of 21 days to 180 days of active composting in an active or a static pile. Once the active composting is completed, the material is stored in piles or windrows for curing for up to 2 years.
  - **appropriate leachate recovery and treatment** to avoid problems linked to high levels of biological oxygen demand and phenols, plus eventual heavy metals and undesired chemical organic compounds present when inputs other than selected biodegradables from MSW are accepted (sewage sludge, manure, residues from the food industry, domestic or industrial waste water,…).

For the composting process to succeed, it is absolutely necessary to sort out the input stream, avoiding plants with seeds (the seeds only start to decompose above 60°C and could remain in the final compost, resulting in undesired plants growing where the compost is spread), any plant treated with chemicals, plants residue showing any kind of disease (should be burnt), large pieces of wood (more than a few millimetres in diameter: would take too much time to compost); cat litter except if fully biodegradable, coal cinder (too rich in mineral salts and acts in the compost as a weed killer), plastics and textiles, glass, metals, paper and cardboard (could be composted, but can be recycled instead), sand and soil. Should also be avoided meat, diary products and cooked items (source of bad odours, generate pathogens, and attract undesirable flies and rodents). Of course, unopened cans or boxes must be rejected.

The advantages of composting are
- generation of a solid soil amendment and/or fertilizer of high quality when fed only with well selected biodegradables; in that case, the leachate has also rich fertilizer properties
- in the case of home composting and collective composting, the process occurs at the source of the waste, reducing the waste stream volume and the associated costs; in that case, total costs are minimum
- reduction of transport needs and the associated CO_2 emissions in the case of decentralized composting
- the weight of waste that is suitable for composting is reduced by the process: 100 kg of waste give 30 kg to 40 kg of compost

The disadvantages of composting are
- there is no energy recovery: there is in fact energy consumption
- for medium or large scale composting, preprocessing is needed and is a source of malfunctions
- people must be trained for the process to succeed: compost monitors are needed
- for small scale composting, leachate must be absorbed by the soil underneath; if it is not, it should be recovered and treated (if left running as a surface stream, it could be a vector of pathogens): this is compulsory at large scale
- bad odours are generated by the incoming stream or during the first stages of the process (can be partially tackled by using bio-filters if these activities occur in a closed building)

– there does not seem to be a real commercial market for the final compost, due to mistrust by farmers and the public in general because of uncertain quality level; this is reinforced by the occasional practice of adding metalcontaining sewage sludge to the material used for composting

There is a **lack of reliable cost data** for composting. This is not surprising because the ground belongs usually to a local public authority, handling equipment for feeding the windrows and for turning them also belongs to that authority and is used for other activities (except for large composting plants). This is also the case for the manpower. Despite that, operating costs are evaluated between 35 Euros/Mg and 75 Euros/Mg of feed. When leachate treatment is necessary, the costs are substantially higher. As the process is slow, large ground surfaces are needed. Energy consumption is around 50 kWh/Mg of waste. The price of good quality compost could reach 14 Euros/Mg.

The environmental impact of composting is mainly linked to **bad odours** generated by the incoming stream and during the first stages of processing. Gas emissions and noise generated by the combustion engines used to power windrow turning machines and grinders add to the discomfort. If turning the windrows is not correctly done, anaerobic bacteria develop and methane evolves. **Rich leachate** production is important. It has high levels of biological oxygen demand (BOD) and phenols (by-product of the decomposition of the lignin in leaves). It poses few problems if absorbed into the ground or passed through a sand filter. High concentrations of BOD in runoff to surface water is on the contrary a problem because this can reduce the amount of dissolved oxygen in lakes and streams that is available for aquatic life. High organics content and highly mineralized nitrogen concentration could also be a problem (eutrophication). **An environmental problem due to compost use** is its possible role in transferring heavy metals and undesired chemicals to the soil (see above at appropriate leachate recovery and treatment).
Problems could also be linked to poor sorting of kitchen and garden waste, introducing contaminants to the final product (mainly metals, plastics and glass used for packaging).

In summary, composting biodegradables contained in MSW is possible. However, they must be carefully sorted out, preferably at the source (by householders). Home composting reduces the waste stream as well as costs (collection and treatment) for municipalities and should be encouraged. Large scale processing requires severe control. Marketing the final product remains a not so easy task.

4.2.B. Anaerobic digestion (biomethanisation)

The first substances that were digested anaerobically were human and animal waste.

Such operations already appeared in the antiquity and countless small units have been operated in India and China, as well as in western farms. However, industrial operations need sufficient know-how.

During more than three decades, national and European Union subsidies helped financing R&D and demonstration plants, resulting sometimes in successful processes. Both technical difficulties and costs have hampered a more widespread application. The promise of green subsidies will probably give a positive impulse.

Scientific considerations

To start with, it must be clearly stated that **anaerobic digestion allows recovery of only part of the potential oxidation energy** of biodegradables in MSW.

From a scientific standpoint anaerobic digestion, like composting, is also part of the global biochemical cycles of our planet, as already described above, and carbon and nitrogen cycles are again the two most important ones.
The term **digestion** refers to the process by which food is dissolved and chemically converted so that the cells of a living body can absorb the food to maintain its vital functions. Thereby, complex carbohydrates, fats, fibres and proteins are converted into simpler compounds before being assimilated into cells. During digestion, these organic compounds are reduced to monomer units by hydrolytic and other enzymes secreted by bacteria and glands.

The process of **anaerobic digestion** (AD) employs specialised bacteria to break down organic waste, converting it into **biogas** (a mixture of carbon dioxide and methane), and a stable semi-solid (**digestate**). In most cases, complex populations develop that are able to conduct consecutive processes capable to break down biodegradable waste in a sequence of **hydrolysis**, **acidogenesis** (formation of fatty acids), **acetogenesis** and eventually **methanogenesis**, in a balanced, steady and controllable fashion.

These four consecutive steps normally proceed side by side, but the first and the last ones are sometimes singled out because they may require specialized conditions, controls and auxiliaries. **Hydrolysis** may be conducted with separate aerobic, thermal, chemical or enzymatic means. **Acidogenic** bacteria then turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids or alcohols and acetone. The specific concentrations of products formed at this stage vary with the type of bacteria as well as with feed and conditions such as temperature and pH. **Acetogenesis** occurs through carbohydrate fermentation and other metabolic processes with acetate as the main product. Long chain fatty acids, formed from the hydrolysis of lipids, are oxidised to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits oxidation, so that bacteria consuming hydrogen are required to ensure the conversion of all acids. The transition from organic material to organic acids causes the pH of the system to drop. This is beneficial for acidogenic and acetogenic bacteria, but problematic for **methanogens**, which prefer neutral or slightly alkaline conditions and are very sensitive to abrupt changes: if the pH falls below 6, they cannot survive. Since they are slow to develop, they may fail to adapt to changes, e.g. in inlet temperature, concentration, or other conditions. Therefore, for the digester to remain stable an equilibrium based on complex interactions of several varieties of bacteria is required.

Practical considerations

Anaerobic digestion is conducted in a variety of modes and **processes**: batch or continuous, single, double or multiple steps (staged digesters), vertical or horizontal treatment units, static units or others, using various mixing methods, and “dry” (high solids) or “wet” (low solids concentration) digestion. A simple digester consists of a single, suitably shaped, static or mixed digester, in which the most desirable operating conditions are carefully maintained, yet in a robust manner.

Batch versus continuous processes

- in the **batch process**, the substrate is sealed in the digester for the complete retention time. When unmixed, the content of the digester stratifies into layers of gas, scum, supernatant, an active layer, and stabilized solids at the bottom. Retention times range from 30 days to 60 days, with typically a biodegradable loading rate between 0.5 kg and 1.6 kg total volatile solids per cubic meter reactor volume per day. Long retention times, low biodegradables loading rates and the formation of a scum layer are obvious disadvantages. Also, the production of biogas follows a bell curve with time.
- in the **continuous process**, fresh material either continuously or periodically (e.g. daily) enters the tank and an equal amount of digested material is removed. Ideally, all processes occur at a fairly steady rate, resulting in a constant biogas production. Because of flow, there is some movement, material is somewhat more mixed and does not become stratified so easily inside the tank. The removed effluent is, however, a mix of completely and partially digested material. Some of the more successful designs dictate the path of the digestate inside the chamber, or use either plug-flow or a cascade of consecutive units. Some designs take advantage of the successive phases of digestion, optimising each one under distinct conditions.

Single stage versus multiple stage digester

- in a **single stage** digester, all bacteria inhabit the same volume and their relative growth rates are kept in balance. The operating conditions are not optimal for any bacteria, but are acceptable to all. The most crucial parameter is pH, kept close to neutral to ensure survival of methanogens.
- in a **multiple stage** digester, the substrate passes progressively through sequential chambers, where AD occurs in a staged approach. If two tanks are used, the first tank features hydrolysis, acidogenesis and acetogenesis, while the second optimizes methanogenesis conditions from volatile acids.
  The first tank is heated to a uniform temperature and mixed and fed continuously. The pH is allowed to fall. The residence time in this chamber is 10 days to15 days. The second tank must maintain a higher pH and provide capacity for gas collection or storage. Two-stage digesters can be more efficient because the microorganisms have specific nutrient needs, growth capacities, and abilities to cope with environmental stress. In more complex, multiple stage digesters, each tank has a unique purpose and living environment, but this advantage is compensated by higher investment and operating costs.
- there are also **multiple stage systems with different criteria for solids and liquids**. Incoming waste is pulped, and the liquid, which contains soluble biodegradables, is sent immediately to a methane-producing tank. The remaining solid is hydrolized under more drastic operating conditions in a different tank, dewatered, and the liquid from that tank is also sent to the methane production tank. This system can take advantage of the significantly lower retention time required of liquids compared to solids.

Dry versus wet digestion

- digestion is subdivided into two categories of solids content: **dry digestion**, with a typical dry solids (DS) content of 25-30% and **wet digestion**, with a DS value of less than 15%. When the feedstock is derived from MSW, both systems require adding water to the feedstock to lower the total solids (TS) content. A higher TS content leads to smaller, less costly digesters, but requires more expensive pumps and more maintenance. Systems will lower TS have better mixing and are amenable to co-digestion with dilute feedstock like sewage sludge

or manure. They allow also easier settling of dense particles like sand and glass to the bottom.
- for many waste streams, large amounts of water must be added to reduce the solids content, thereby adding to the cost of dewatering the digestate to reuse the process water.

Global flow and mixing
- in a **gravity driven system**, the material is fed from the top into a vertical chamber and effluent is removed at the bottom, with gravity being the only driving force to bring the waste through the bacterial population living in the chamber. For this system, the ideal solids content is 2-10%. A **plug-flow digester** is suitable for higher solids content, because the more viscous material may move as a plug through the tank.
- **mixing** can take place as a result of the pathway the waste must travel before its removal. Some systems have interior walls that increase (static) mixing. More intense mixing results through the use of mechanical, hydraulic, or gas mixers to keep solids in suspension. Mechanical mixing is less common because of a difficult maintenance. Mixers also get wrapped with solids or entangled. Recirculating heated digested waste inoculates the fresh waste, improves mixing and ensures temperature control. Biogas is bubbled through the digester for mixing.

Control parameters
- **control parameters** are of two types: physical (temperature, mixing, space loading rate, food to micro-organisms ratio) and chemical (Redox potential, pH, carbon to nitrogen ratio, nutrient balance and alkalinity). The following parameters are typically **monitored**: physical (temperature, pressure, residence times, flow rates, biogas production) and chemical (pH, volatile fatty acids, alkalinity and hydrogen).
- **temperature is the most critical process parameter**. Anaerobic bacteria survive from freezing to 70°C, but thrive best in either a **mesophilic** (25°C to 40°C, preferably 35°C) or a **thermophilic** range (50°C to 65°C, preferably <55°C). Thermophilic digestion allows higher loading rates and achieves a more complete pathogen destruction and degradation efficiency of the substrate, yet it is more sensitive to toxins and changes in the environment and less attractive from an energetic point of view. Furthermore, a month or more is required to establish a population. Mesophilic bacteria tolerate greater changes in their environment, including temperature. The stability of the mesophilic process makes it more popular, albeit at the expense of longer retention times.
- **pH is a major variable to be monitored and controlled**. The range of acceptable pH is theoretically from 5.5 to 8.5. However, most methanogens function only in a pH range between 6.7 and 7.4. A falling pH can point toward acid accumulation, which typically occurs if there is an overload of volatile solids in the digester. The acidogenic bacteria then thrive, producing more organic acids and lowering the pH to a level lethal to methanogens. A declining methanogen population leads to further acid accumulation and action to restore process stability is required, such as recycling more water.
  Conversely, prolific methanogenesis may result in a higher concentration of ammonia, increasing the pH above 8.0, which will impede acidogenesis. This is opposed by adding fresh feedstock, spurring acidogenesis and acid formation. Maintaining pH is especially delicate at start-up because fresh water must undergo acid forming stages before any methane forming can begin.
- as with composting, the **optimum C/N ratio** is between 20 and 30.
- a **practical difficulty** is that the substrate in some cases is available only on a cyclic basis (e.g. in case of an annual harvest). In most plants feeding occurs once a day whereas residence times vary from 10 days to rather long time periods (one or more months). AD is a slow process and the **reactor concept and operating conditions must be carefully adjusted towards the feed** or the mix of feedstocks employed.

Feedstocks, pre-and post-treatments, major outputs
- **potential feedstocks** are from different origins: **agricultural origin** (animal waste, crop waste, dedicated energy crops), **industrial origin** (waste water, sludge, by-products) and **municipal origin** (sewage sludge, MSW).
- **bio-waste** contains components that are not readily available as substrates for anaerobic digestion. Consequently, **a substantial portion of potentially available carbon is not converted into methane** and the incompletely digested residues require additional processing prior to their return to the environment.
- some **pre-treatment and post-treatment** are often required: waste storage and pre-treatment (sorting, chopping, warming, acidification, mixing, recycling); biogas storage, treatment and upgrading (storage at low, medium, or high pressure, elimination of water and sulphur and nitrogen compounds, removal of carbon dioxide). **The treatment of biodegradable fractions from MSW necessitates selective collection of garden waste and kitchen waste, and/or mechanical sorting of residual MSW**. The most common treatment is separation (remove metals, glass, plastic, etc…) and shredding (to reduce size of the solids).
- **major output flows** are:
  - the **gas phase (biogas)**, with as quality criteria the biogas formation rate and the relative amount of the main compounds (methane and

carbon dioxide), the level of fatty acids and of acetic and formic acids, and the level of impurities (sulphur and nitrogen compounds, mainly as hydrogen sulphide and ammonia). Options of usage of the gas phase are heat generation, substitute natural gas (upgrading to pipeline quality is needed), power generation (spark ignited and Diesel engines), motion of motor vehicles, and combined heat and power generation. The gas phase strictly requires separation of entrained droplets and of condensable water vapour (using cooling, condensers and demisters), and also of corrosive gases. Before upgrading to pipeline quality, the pressure will be raised, generally to 10 to 30 bars, rendering the treatment operations more efficient and compact.

– the **solid and liquid effluents (digestate)**. Part of it is recycled with process water, with the aim of reducing the volume of effluent liquids; however, there are limits to recycling, since toxic or undesirable compounds, such as salts and heavy metals, should be sluiced out continuously or periodically. Success stories on a prosperous application of the resulting solids as a soil structure improving substrate are scarce and relatively less documented in AD literature. The digestate after aerobic post-treatment is a stable, organic humus-like material, the subsequent use of which depends on market conditions for compost and on the feedstock characteristics of the AD process. In the case of MSW the digestate will be contaminated with sand, plastics, heavy metals and eventually stable undesired organic molecules, severely limiting the scope of its eventual application.

Advantages of anaerobic digestion are
- production of biogas that can be used for heat and/or power generation
- reduction of weight between the loaded biodegradable MSW and the digestate cake (for 100 kg MSW at 30% humidity, there remains 67 kg digestate cake at 45% humidity; or for 70 kg dry MSW, there remains 37 kg dry digestate cake). If there is no market for the digestate cake, there is anyhow some weight reduction of the residue to be landfilled (or incinerated)
- allows treating humid biodegradable waste

Disadvantages of anaerobic digestion are
- although the process does not make use of pathogens, if bacteria or viruses of that type are introduced in the process, they will not be killed and will remain in the digestate; a post-treatment at 70°C during an hour is needed for sanitary reasons
- for the process to succeed, it is absolutely necessary to sort out the input stream (almost like for composting; the process is capable to treat meat, but this should be avoided due to the odours during sorting out and preprocessing)
- bad odours are generated by the incoming waste and during sorting out and pre-processing (could be partially tackled by using bio-filters if these activities occur in a closed building)
- being a slow process, relatively large plants are necessary, to be maintained under moist and corrosive conditions
- there does not seem to be any true commercial market for the final compost (see above at composting) or digestate; there are however special agreements with farmers who provide manure and straw to the plant and are obliged to recover the final digestate
- the process concentrates heavy metals and undesirable chemical compounds eventually present in the input in the final digestate or compost.

Following are some **approximate data for anaerobic digestion** (which should be defined for each specific case; plants are capable to treat between 20,000 Mg/y to 100,000 Mg/y):
- **biogas production**
  depends largely on the type of feedstock (from 25 m^3/Mg for bovines manure to 800 m^3/Mg for waste grease; source: IRCO); however, production speeds are very different. For biodegradables in MSW, values fall between 80 m^3/Mg to 150 m^3/Mg of waste feedstock
- **biogas composition**
  after purification, contains from 50 to 80% methane, usually 65%; remainder mainly carbon dioxide with trace elements of other gases like hydrogen sulphide, siloxanes, ammonia, water vapour and organochlorines
- **biogas net calorific value**
  at 65% methane, approximately 24 MJ/m^3N
- **electrical power to sell**
  as approximately 30% of the electrical power is used for the plant itself, there remains between 70 kWh/Mg to 200 kWh/Mg of waste treated. For biodegradables in MSW, values are above 100 kWh/Mg (source: ACR+).
- **digestate and/or compost**
  they are very difficult to sell, due to poor quality: in Flanders, prices vary from 1 Euro/Mg to 2.5 Euros/Mg
- **investment costs**
  350 to 500 Euros per annual Mg of feedstock
- **operating costs**
  after separate collection, 70 Euros/Mg to 150 Euros/Mg of feedstock; the additional cost for source sorting and separate collection ranges widely between 15 Euros/Mg and 135 Euros/Mg

Without subsidies, including so called “green certificates” for the electricity produced, **the process is not economically viable**.

The environmental impact of anaerobic digestion is mainly linked to **bad odours** generated by the incoming stream and during the first stages of processing. Biofilters in the roof of buildings can somewhat reduce the emissions. Despite of that, all plants are built at a certain distance from cities, though not too far to enable the use of the cooling water of power generators for urban heating (loss of one degree temperature for each km).

Environmental problems due to compost or liquid digestate use are linked to the potential convey of heavy metals and of undesired chemicals to the soil and also to poor properties as soil amendment.

In summary, the anaerobic digestion of biodegradables in MSW is possible. However, they must be carefully sorted out, preferably at the source, and the technique is economically dependent on subsidies.

Recently, **biochar has received increased interest**. The idea is to remove water from the digestate and to perform pyrolysis on the remaining solids. The process is in fact similar to the production of charcoal from wood. Biochar sequestrates carbon very efficiently under an almost inert form, and can be used for soil amendment.

However, its production requires additional funds to cover investments and operational costs, consumes energy, produces CO_2, and concentrates further heavy metals present in the digestate in the biochar, while the destruction of undesirable organic molecules depends on the temperature conditions prevailing during pyrolysis.

Biochar production applied to other biodegradables than those found in MSW is mentioned in the literature, but falls beyond the scope of this report.

Chapter 5

DISCUSSION

5.1. Preliminary remarks

It should be clearly stated that all processes considered in this report deal with chemistry and biochemistry and necessarily follow the principles of mass conservation. Accordingly, **any chemical element present in the incoming stream will anyhow be present in the outputs in the same quantity**. It could be present though, in different chemical compounds and/or under another physical form.

Whatever the process considered in this report, any carbon present in the biodegradables in MSW will end as carbon dioxide, eventually after combustion of biogas (some methane could be released in the atmosphere e.g. in poorly aerated composting operations) and despite some short term carbon sequestration in the case of composting or biomethanisation. **None of these processes can claim any 'ab initio' "green house" effect advantage. Detailed Life Cycle Assessment (LCA) should be carried out to compare specific cases**.

From a thermodynamic standpoint, as enthalpy is a function of state, **for any reaction starting with the same agents and ending with the same products, the total enthalpy change (heat of reaction) remains the same, whatever the path followed**. Accordingly, consider a combustion reaction starting with biodegradables in MSW and ending with CO_2 and H_2O and showing a net calorific effect called Q. If this process is split into two partial processes, with the first of the two exothermic with a net calorific effect q, then the net calorific effect for the second partial will be reduced to Q-q. This is the case for biogas combustion.

Most flawed waste policies forget and leave out thermodynamics.

Whatever the process, people tend to have "**not in my backyard" (NIMBY)** emotional reactions against it. In this report, these **reactions are ruled out if the technology does not justify them**.

The following discussion is divided into two parts: the first considers only scientific, technological, economical and environmental factors; the second legal or regulatory considerations.

5.2. Scientific, technological, economical and environmental considerations

Economic comparison between the different processes is difficult because the net results of the process (the boundaries of the system) are not identical. More over, various subsidies or local conditions influence the investment and operating costs.
Accordingly, a general but sound discussion should be based mainly on the merits of the processes with respect to reliability, possible material and/or energy recovery, decrease of volume and/or weight of residues eventually to be dumped in landfills, environmental impacts, and capability to treat correctly the biodegradables contained in MSW after or without preliminary sorting out.

Starting with high temperature processes, **incineration** appears as a fully mature technology. The process is reliable; it leads to satisfactory energy recovery (economic especially if the steam produced can be delivered to a nearby electric power plant); there is a strong decrease in volume and/or weight of residues to be dumped in landfills; European directives guarantee now a very low level of environmental impact, especially due to efficient flue gas cleaning systems; and it is capable to treat correctly the biodegradables in MSW without any need for a preliminary sorting out neither at the source nor before feeding the furnace at the plant. Of course, vegetable matter having a high water content, it is at the lower end of the lower heating value in the feed of the furnace; but this is an advantage because the mean lower heating value of the load introduced in the incinerators has steadily increased with time and approaches values at which it would be necessary to decrease the rate of combustion. Improvements could deal with further processing of the bottom residues and of the fly ash: the advantage is that all heavy metals could be recovered in a separate molten phase and/or condensate suitable for eventual recycling through adequate metallurgical treatment. It should also be emphasized that incineration allows destruction of most undesirable organic chemicals.

Other high temperature processes are more questionable: **pyrolysis and gasification cannot be assessed as being reliable and proven in Europe, even though the Japanese experience appears more positive**. More time is needed for the largest scale European plants to demonstrate their capabilities. **Plasma processes** suffer from their need for electric power consumption: this is a high cost energy, and in most cases generates carbon dioxide for its production. These processes could be of interest for small quantities of special types of waste.

Low temperature processes are also of interest and have been operated for a long time. **Composting** as well as **anaerobic digestion** will concentrate any heavy metal or undesirable organic chemicals present in the incoming stream in the compost and its leachate for the first one, and in the liquid digestate or in the dried compost for anaerobic digestion. As a result, although high concentrations would kill the active microorganism and block the production, people who should use it, especially farmers, are very reluctant to do so. Accordingly, there is no real market for these products. If nobody wants them, they should go either to landfills or, if the remaining lower heating value is high enough, to incineration. Anyway, both processes need efficient sorting out and pre-processing of the incoming stream. Moreover, a number of failures have been reported due to various malfunctions either of the process or of the equipment. Both processes are able to treat biodegradables contained in MSW.
However, preliminary sorting out is needed, preferably at the source. Backyard or locally decentralized composting should be encouraged. Anaerobic digestion is interesting because of energy recovery for heating and/or for electric power generation. It operates at best with feedstock coming from agriculture: in that case, the quality of the incoming stream is under control and farmers are less reluctant to spread the digestate on their fields. However, the digestate has a lower agricultural value than the feedstock because of a reduced C/N ratio, mineralization of nitrogen and loss of soil amendment properties. Extra costs for selective collection of biodegradables sorted at source in MSW are very high. Carbon dioxide generated during handling and transportation must also be taken into consideration.

Without subsidies, a further **comparison** can be made **between incineration and anaerobic digestion**, considering both processes under their best operational conditions: a mass-burn incinerator producing steam fed to a nearby electric power station, and an anaerobic digestion plant with a feedstock coming mainly from agriculture and producing electricity by means of spark ignition engines.

For the incinerator capable to treat between 150,000 Mg/y to 450,000 Mg/y MSW, investment costs are between 300 and 360 Euros per annual Mg of waste; operating costs including capital charges are approximately of 100 Euros per Mg of waste without supplement for feeding biodegradables contained in the MSW; 450 kWh/Mg to 500 kWh/Mg of waste are sold to the distribution network.

For the anaerobic digestion plant capable to treat between 20,000 Mg/y to 100,000 Mg/y biodegradable feedstock, investment costs are between 350 and 500 Euros per annual Mg of waste; operating costs in the case of selective collection are between 70 Euros/Mg and 150 Euros/Mg of waste, but source sorting and selective collection add between 15 Euros/Mg and 135 Euros/Mg of waste, so that if only 20% of the feed comes from biodegradables in MSW, the total operating costs should be between 73 Euros/Mg and 177 Euros/Mg of waste; 70 kWh/Mg to 200 kWh/Mg of waste (more than 100 kWh/Mg for biodegradables in MSW) are sold to the distribution network.

Accordingly, an incinerator shows an economical advantage versus anaerobic digestion and also produces more electrical energy. This is not surprising: the incinerator needs neither a selective collection nor sorting out of biodegradables contained in MSW; concerning energy, in an incinerator all the organics are burnt to CO_2 whereas in anaerobic digestion, only part of the carbon is finally burnt through biogas combustion and moreover, as the digestion is exothermic, the thermal energy to be recovered from methane is also reduced for a given amount of carbon contained in the feedstock and finally converted to CO_2. The difference increases with the proportion of biodegradables in MSW.

5.3. Legal considerations

Directive 2008/98/EC introduces in its Article 4, point 1, **a hierarchy in five steps** to apply as a priority order in waste prevention and management legislation and policy

(a) prevention
(b) preparing for re-use
(c) recycling
(d) other recovery, e.g. energy recovery
(e) disposal.

However, in the same Article, point 2, it is stated that "Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy…" Further in the same Article, point 2, "Member States shall take into account the general environmental protection principles of precaution and sustainability, technical feasibility and economic viability, protection of resources as well as the overall environmental, human health, economic and social impacts, …"

Accordingly, the hierarchy is not mandatory and for instance economical or technical considerations could justify departing from it.

Everybody would agree with processes dealing with **prevention**. The first efficient way to reduce the biodegradables fraction in MSW consists in leaving freshly cut grass on the lawn, and leaves and branches of bushes and trees on the spot after grinding. The second is home-, collective-, and possibly small scale decentralized composting provided the feedstock is not collected by municipal services and the compost is used on the spot. However, some training is necessary (compost monitors). Of course, decreasing kitchen waste by improving the behaviour of people dealing with food is also very efficient. All these methods reduce the extent of the waste stream.

In Chapter I, Article 3 Definitions "13. "**Re-use**" means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived". This is **not applicable to biodegradables in MSW**. In the same Article 3 Definitions "14. "**Preparing for re-use**" means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other preprocessing".
Again, this is **not applicable to biodegradables in MSW**.

In the same Chapter I, Article 3 Definitions "17. "**Recycling**" means any recovery operations by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic materials but **does not include energy recovery** and the reprocessing into materials that are to be used as fuels or for backfilling operations". This is **applicable to the biodegradables collected selectively from MSW**. According to the hierarchy, this would give the **priority to large scale composting facilities**, provided that the quality of the compost is such that people agree to make use of it.
That does not seem to be the case. **Up to now there are no European standards for compost quality**. However, a survey by ACR+ (Municipal Waste in Europe – Collection Environnement – Victoires Editions – Paris – 2009 – p. 185) shows that concentrations of heavy metals in compost from Member States are high: for instance for lead between 100 ppm and 180 ppm. The "Arrêté du Gouvernement wallon" of 18 June 2009 authorizes to incorporate in the feedstock for composting, biomaterials containing up to 500 ppm of lead. The same concentrations are accepted for final digestates from biomethanisation (see Table 3 in the "Arrêté du Gouvernement wallon" in preparation as introduced in Chapter 2 of this report).

In the same Chapter I, Article 3 Definitions "15 "**Recovery**" means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.
Annex II sets out a non-exhaustive list of recovery operations." **This is applicable to the biodegradables in MSW**. In this particular case, as mentioned in R1 of Annex II "Use principally as a fuel or other means to generate energy", **biomethanisation and incineration are included**. **There are many constraints on incineration** (Directive 2000/76/EC; BREF documents linked to Directive 2008/1/EC; and a formula in Directive 2008/98/EC Annex II R1 imposing minimum values for the efficiency for incinerators to be considered as "energy recovery" plants). **No similar constraints appear for anaerobic digestion or for composting**.

In the same Directive, Chapter III Waste Management Article 22 "Bio-waste" "Member States shall take measures, **as appropriate**, and in accordance with Articles 4 (waste hierarchy) and 13 (protection of human health and the environment), to **encourage**:

(a) the **separate collection of bio-waste with a view to the composting and digestion of bio-waste**;
(b) the treatment of bio-waste in a way that fulfils a high level of environmental protection;
(c) the use of environmentally safe materials produced from bio-waste."

The same article mentions that **an assessment will be performed, leading to eventual "setting of minimum requirements for bio-waste management and quality criteria for compost and digestate …**".

Taking into account all legal constraints, it can be concluded that **separate collection of bio-waste is not mandatory**, and that large scale composting appears in the hierarchy in preferred position compared to biomethanisation and incineration considered as energy recovery systems. **Owing to the facts that composts and digestates do not show so far satisfactory properties, and that biomethanisation delivers less energy than incineration (essentially massburn), the latter should be preferred**.

Chapter 6

CONCLUSIONS.

The initial question was "MSW: What to do with biodegradables"? The final answer is as follows, keeping in mind that:

– none of the available processes can claim any greenhouse effect advantage as the final products are anyway CO_2 and H_2O
– maximum energy recovery is obtained by incineration, followed by biomethanisation; composting consumes energy.
– biomethanisation has the advantage of producing gas that could be used for automotive vehicles; technical and economical constraints remain to be studied
– incineration is the only available process satisfying all the "best available techniques" criteria
– although Directive 2008/98/EC introduces a hierarchy in 5 steps, step 2 (preparing for re-use) is not applicable to biodegradables in MSW; the hierarchy is not mandatory: technical and economical feasibility and environmental factors must be taken into account; if there were markets for composts and digestates, the hierarchy would give an advantage to composting and place at the same level biomethanisation and incineration.
  The directive also encourages selective collection of bio-waste; again, this is not mandatory.

Accordingly, **priority** should be given in all circumstances to **reducing the amount of biodegradables contained in MSW**: decrease kitchen waste by improving the behaviour of people dealing with food (buy no more than you can eat; if there are remains from a meal, keep them at low temperature and cook them again for another meal; buy items without unnecessary packing); leave freshly short cut grass on the lawn, and leaves and branches of bushes and trees on the spot after grinding; encourage home-, collective-, and possibly small scale decentralized composting provided the feedstock is not collected by municipal services and that the compost is used on the spot. For efficient composting, some training is needed (compost monitors).

For garden and park waste directly collected and brought by citizens or by the park owners to special large containers park, they can be used either for large scale composting or for biomethanisation.

For what is left as biodegradables in MSW, a decision has to be taken whether or not to proceed to their separate collection at the source. The following points should be considered:

(a) the costs of separate management of this special waste stream from the collection point to the plant where it will be used as a feedstock, not only in terms of expenditure (investment in modified trucks; eventual intermediate storage; land area; man power) but also in terms of impact on the environment (CO_2 emissions; odours; recovery and eventual treatment of liquids)
(b) the interest of feeding that waste to a large scale composting plant (no energy recovery: energy consumption instead; lack of control on the content of the collected bags could result in problems with the composting process and products; need to establish a contract with the composting plant owner concerning processing fees and possible uses of the final compost)
(c) the interest of feeding that waste to a biomethanisation plant (partial energy recovery; lack of control on the content of the collected bags could result in problems with the process and products; need to establish a contract with the plant owner concerning processing fees and possible uses of the final liquid digestate or solid compost)
(d) the interest of not proceeding to the separate collection at the source and instead feed the MSW containing the biodegradables as such in an incinerator, preferably mass-burn (high energy recovery mainly as electric power and/or for urban heating; minimum amount of residues to landfill; low environmental impact due to EU directives; concentration of heavy metals in separate residues and destruction of most undesirable organic chemicals)

Further points of interest are:

– citizens have already to cope with a large number of source separations. Sorting out is not so easy. It is not evident that it will be done properly, even when another difficult source separation and the associated costs are accepted.
– large scale composting is not that easy to operate successfully. The final compost is usually contaminated with heavy metals and undesirable organic chemicals. Accordingly, people, and especially farmers, are reluctant to use compost as soil amendment or fertilizer.
– anaerobic digestion (biomethanisation) is not economically viable without substantial subsidies. It allows partial energy recovery, but requires expen-

sive sorting out and pre-processing of the incoming stream. The final liquid digestate and/or solid compost show the same problems of contamination as already mentioned. On top of that, soil amendment properties are lost (except perhaps if biochar is produced from the digestate, but as already explained, this would be expensive and lead to further concentration of heavy metals)

A true market does not seem to exist for compost and digestate. If they must go to landfill, the volume and weight reduction is too small. Their incineration would be more interesting, but in that case unsorted incineration would be more advantageous.

– if no subsidies are involved, incineration is economically more advantageous than anaerobic digestion, and the advantage grows when the percentage of biodegradables coming from MSW in the feed increases. Also, the amount of electrical energy produced is in favour of incineration.

Final recommendations are as follows:

– the bio-waste suitable for anaerobic digestion is largely over evaluated in the literature; it should be estimated again taking into account technical, economical and environmental factors. Feeding the gases from biomethanisation to automotive vehicles should be further investigated
– new EU directives and BREF documents are needed for composting and anaerobic digestion. They should define the minimum quality requirements for composts and/or digestates. Current practice of introducing various contaminated waste (sewage sludge, industrial residues, etc…) in the feedstock should be drastically reduced or even suppressed. Water effluents should be treated. Any new legislation should aim at protecting not only the upper layers of soil in the short term, but also the deep underground soil and water in the long term. It should be remembered that on the long term soil contamination is more dangerous than air contamination, although less visible
– incineration (especially mass-burn) is the only MSW treatment process allowing to recover heavy metals and to destroy most of the undesirable organic chemicals with a very small amount of hazardous waste to landfill. It is also the only process satisfying to all conditions required for a best available technique. European Directives and BREF documents introduce already many constraints on the process. Instead of looking for additional constraints like efficiency limits imposed to incinerators qualified as energy recovery centres, it would be better to encourage further treatment of bottom residues and of fly ashes aiming at zero landfill and recovery of metals by chemical or metallurgical processing. Detailed flying ash analysis would probably identify costly and less common chemical elements of industrial interest. Research dealing with the last two points should be encouraged
– some more time is needed for correctly evaluating pyrolysis and gasification processes
– plasma processes should be further evaluated for the treatment of specific waste available in small quantities
– many industrial processes should be equipped with proven flue gas cleaning systems. The same should also be envisaged for wood burning systems.

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NB : As mentioned at the end of the Introduction, many technical and scientific references were provided by the experts. No attempt was made to list them.

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