WASTE MANAGEMENT FROM PULP AND PAPER PRODUCTION IN THE EUROPEAN UNION

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Abstract

Eleven million tonnes of waste are produced yearly by the European pulp and paper industry, of which 70% originates from the production of deinked recycled paper. Wastes are very diverse in composition and consist of rejects, different types of sludges and ashes in mills having on-site incineration treatment. The production of pulp and paper from virgin pulp generates less waste but the waste has similar properties to waste from the production of deinked pulp, although with less inorganics. Due to legislation and increased taxes, landfills are quickly being eliminated as a final destination for wastes in Europe, and incineration with energy recovery is becoming the main waste recovery method. Other options such as pyrolysis, gasification, land spreading, composting and reuse as building material are being applied, although research is still needed for optimization of the processes. Due to the large volumes of waste generated, the high moisture content of the waste and the changing waste composition as a result of process conditions, recovery methods are usually expensive and their environmental impact is still uncertain. For this reason, it is necessary to continue research on different applications of wastes, while taking into account the environmental and economical factors of these waste treatments.

KEYWORDS: Paper industry wastes, pulp and paper sludge, solid waste generation, waste recovery, waste minimization

1. Introduction

Different processes in the pulp and paper industry result in the formation of different solid wastes and sludge. Solid waste is mainly generated from pulping, deinking unit operations and wastewater treatment. The amount and the composition of the solid waste depend on the paper grade produced, the raw materials used, the process techniques applied and the paper properties to be achieved. The significant residual waste streams from pulp and paper mills include wastewater treatment sludges, lime mud, lime slaker grits[1], green liquor dregs[2], boiler and furnace ash, scrubber sludges and wood processing residuals. In terms of volume, most solids or liquids are those from the treatment of effluents, although waste from wood is also produced in large quantities (IPPC, 2001; CANMET, 2005).

In general, solid wastes from pulp production and paper mill operations are humid and contain some organic compounds in the form of wood or recycled paper fibres, chlorinated organic compounds and pathogens, significant amounts of ash and trace quantities of heavy metals.

Whereas the solid waste composition from pulp and paper mills is known and constant, as a result of the current, highly controlled production processes, sludge compositions, on the other hand, vary widely throughout the industry and are dependent on the type of operations carried out at the mill. The wastes can be reused and valorised in a safe and

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[1] “slaker grits”: lime mud that pebbled in the kiln but did not calcine, from chemicals used in Kraft pulp mills.

[2] “dregs”: in general, are defined as the sediments that have settled at the bottom of a liquid. In the case of pulp mills, these sediments consist of the matter which does not decant in green liquor clarifier.

environmental way, so landfill is strongly being reduced as their final destination. In fact, in countries such as Germany, Spain and the Netherlands, waste streams cannot go to landfill sites. In addition, current legislation and increased taxes have resulted in the research on non-conventional methods for the management or new uses of pulp and paper industry solid wastes. However, the difficult physical form of these wastes poses problems in waste handling and disposal, with the biosludge formed during biological effluent treatment being particularly problematic. These sludges have a low dry solid content requiring conditioning before they can be properly handled. Such sludges are usually thickened, and then either burned in a bark-fired boiler together with bark from wood handling, or used for landfilling. The problems associated with the landfilling of sludges and other wastes are the large volumes involved and the possibility of hazardous substances leaking into the environment. The share of residues disposed of in landfills has constantly decreased in Europe in recent years as shown in Figure 1, in favour of the use as secondary raw material in other industries and other applications (e.g. soil improvers, in road construction, land reconstruction applications and for co-combustion in heat or power generating plants). This justifies the high number of studies carried out during the last decade focused on the research of alternative waste treatments, to minimize their possible adverse effects and on new waste applications such as, for example, road building, the brick industry, forestry and horticulture (Van Horn, 1997; Hynninen, 1998; Christmas, 2002; Cernec and Zule, 2005).

Through the increased use of recycled paper, the increased application of water treatment, tightening legislation and increasing costs of landfill, the pulp and paper industry is forced to put more and more emphasis on waste management.

2. Legislation

The basis of the European waste legislation is the *Framework Directive on Waste* that is set out in the *Council Directives on Waste 75/442/EEC* (amended by 91/156/EEC) and *Hazardous Waste 91/689/EEC*. The Waste Framework includes two categories of directives: those setting requirements for the permission and operation of waste disposal facilities, and those dealing with disposal options for specific types of waste (Figure 2). In addition to these directives, Regulation 259/93/EEC establishes a system for controlling the movement of waste within, into and out of the European Union (Papoulias, 2005). The *Framework Directive on Waste* will be revised, probably in 2008, in order to modernise, simplify and clarify where necessary, and to reinforce standards and waste prevention (Speight, 2006).

The directive 75/442/EEC defines waste as "*any substance or object which the holder discards or intends or is required to discard*". Its aim is to force Member States to encourage the prevention or the reduction of waste and its harmfulness by encouraging the development of clean technologies, technical product improvements and disposal techniques. Member States should take the necessary measures to ensure that waste is disposed of without endangering human health, as well as:

- without posing a risk to water, air, soil and plants and animals,
- without causing nuisance through noise or odours,
- without adversely affecting the countryside or places of special interest.

The EU currently recognises five main principles for waste management:

- *Waste Management Hierarchy*. Waste management strategies must aim to prevent or reduce the generation of waste and decrease its noxious nature by developing clean technologies. In addition, efforts must be made in order to contribute, first to the development and marketing of products designed to have the smallest possible impact in terms of pollution, if any, and secondly to the development of appropriate techniques for the final disposal of dangerous substances contained in waste destined for recovery.
- Where the aforementioned strategies are not possible, or fail to be environmentally and economically viable at the same time, waste materials should be reused, recycled or recovered, or used as a source of energy, provided that these practises improve or, at least, do not significantly decrease the quality of the final product. As a final option, waste should be safely disposed of, e.g. in landfill sites (Figure 3).
- *Self-Sufficiency at the Community and, if possible, at Member State level*. Member States need to establish, in co-operation with other Member States, an integrated and adequate network of waste disposal facilities, taking into account geographical circumstances or the need for specialized installations for certain types of waste.
- *Best Available Techniques Not Entailing Excessive Cost (BATNEEC)*. Emissions from installations to the environment should be reduced as much as possible and in the most economically efficient way.
- *Proximity*. Wastes should be disposed of as close to the source as possible, by means of the most appropriated methods and technologies in order to ensure a high level of environment and public health protection.

- *Producer Responsibility*. Particularly, manufacturers have to be involved in closing the life cycle of their products, from production and throughout their useful life, until they finally become waste.

The principles of the waste management strategy in the European Union are implemented, primarily by EC Directives, regulations and decisions that create binding legal obligations:

- At the beginning of 2004, the Council and the European Parliament adopted *Directive 2004/12/EC* amending *Directive 94/62/EC on Packaging and Packaging Waste*. The target of this new Directive is to "*harmonise national measures concerning the management of packaging and packaging waste*". In addition, it has the dual aim of protecting the environment and, at the same time, optimising the functioning of the internal market. The limited review foresees that Member States will need to have reached a minimum recycling rate of 55% and a minimum recovery rate of 60% by the end of 2008. The overall recovery target for packaging waste is 60% as a minimum by weight, and the overall recycling target is 55% as a minimum and 80% as a maximum by weight. Part of the revision is a proposal of a minimum recycling target of 60% for paper and board packaging by the end of 2008. It also states that when it comes to used recycled paper and board packaging, "*alternative waste management methods such as composting and incineration with energy recovery can, for certain fractions and under certain conditions, be comparable to recycling*".

  The paper industry (represented by the Paper Packaging Coordination Group, PPCG) has expressed several concerns with respect to paper recovery, but they are confident that the minimum recycling target can be met, mainly because the minimum recycling target is comparable to the industries´ voluntary commitment to raise the recycling level up to 60%, by 2008, across Europe.

- The objective of the *Landfill Directive 1999/31/EC* is to prevent or reduce, as far as possible, the negative effects of waste landfilling on the environment, by introducing stringent technical requirements for wastes and landfills. For the paper industry, it significantly limits the landfilling possibilities for biodegradable wastes. This European Directive imposed a reduction of biodegradable municipal waste to be landfilled to 75% of the total biodegradable municipal waste produced in 1995 by the year 2006, to 50% by 2009, and to 35% by 2016.

  The Directive does not yet cover site landfills, but the Commission intends to extend the scope of the Directive as soon as more reliable statistics on industrial landfills are available.

  Several Member States have already implemented waste legislation and imposed higher taxes to restrict landfilling and encourage the development of more sustainable waste management practices. As an example, in England, taxes of £7/t for active waste (secondary or biological sludge) and £2/t for inactive waste (primary sludge) were imposed in 2002. These values were increased until 2004, reaching £15/t (Kay, 2002; OECD, 2004). For the period 2006-07, the standard landfill tax rate levied on active wastes was £21/t. The tax increases annually by at least £3/t to reach a medium to long-term rate of £35/t. The objective is to landfill only 85% of the amount of waste landfilled in 1998 in order to reduce the amount of industrial and commercial wastes sent to landfill.

- In addition, *Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture* is currently being amended and a new directive will be enacted. This new proposed Directive almost completely revises the previous. Its purpose is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil, vegetation, animals and humans. The most important new aspect deals with the introduction of precise requirements for defining the advanced and conventional treatments, mainly addressed to sludge hygienization and odour reduction. The proposed values for limits of heavy metals, organic compounds and dioxins are stricter than in the past and new values for the limits of phosphor content are also proposed. It seems clear that the limitations imposed by this new Directive will make it more difficult to use sludge in agriculture and that considerable investments will be needed to fulfil the new requirements (Kay, 2002; Carpentier, 2002; Spinosa, 2004). On the other hand, a directive on composting (*Biowaste Directive*) is expected in the near future, and will set specifications for waste allowed in composting, the technical criteria to be fulfilled in the composting process and the quality specifications of the compost. Currently the Commission is working on six thematic areas, including a strategy on recycling, soil and the sustainable use of natural resources.

- The *Integrated Pollution Prevention & Control Directive* (96/61/CE) also applies to the pulp and paper industry. It lays down measures designed to reduce, or if possible, eliminate emissions to air, water and land. It also includes measures concerning waste, in order to achieve a high overall level of environmental protection. It also includes the Best Available Techniques (BAT) that define the most effective and advanced stages.

- Finally, the objective of the *Incineration of Waste Directive* (2000/76/EC) is to prevent or reduce, as much as possible, air, water and soil pollution caused by the incineration or co-incineration of waste, reducing at the same time the risk to human health that incineration processes entail. It does not cover:
  - Fibrous vegetable waste from virgin pulp production and from the production of paper from pulp, as long as it is co-incinerated at the place of production and the heat generated is recovered.
  - Wood waste, with the exception of wood waste which may contain halogenated organic compounds or heavy metals as a result of treatment with wood preservatives or coating, such as wood waste from construction and demolition sites.

Black liquor is not mentioned because it is not included in the European Waste Catalogue and does not need to be excluded since it is part of the production process (Carpentier, 2002).

3. Waste generation

The main types of solid waste generated in pulp and paper mills are briefly described below (IPPC, 2001; CANMET, 2005):

- From pulp mills:
    - Rejects: The rejects from virgin pulps consist of sand, bark and wood residues from woodhandling, which are undesirable for papermaking. Rejects typically have a relatively low moisture content, significant heating values, are easily dewatered and are, generally, burned in the mill's bark boiler for energy recovery.
    - Green liquor sludge, dregs and lime mud: These are inorganic sludges separated from the chemical recovery cycle. These sludges are normally landfilled, after dewatering and drying.
    - Wastewater treatment sludge: It comes from two sources: primary sludge and biological sludge generated in the second clarifier. These sludges are generally blended together, a polymer added and dewatered together to a 25-40% dry solid content.
    - Chemical flocculation sludge: It arises from water treatment and is often transported to the landfill site due to the high content of inorganic matter and water.
- From paper mills:
    - Rejects: The rejects from recovered paper are impurities and consist of lumps of fibres, staples and metals from ring binders, sand, glass and plastics and paper constituents as fillers, sizing agents and other chemicals. Rejects also have a relatively low moisture content, significant heating values, are easily dewatered and are, generally, incinerated or disposed of in landfills.
    - Deinking sludge: This residue contains mainly short fibres or fines, coatings, fillers, ink particles (a potential source of heavy metals), extractive

substances and deinking additives. It is normally reused in other industries (e.g. cement, ceramics), or is incinerated, even though it has a poor heating value.

- Primary sludge: This sludge is generated in the clarification of process water by kidney treatments, e.g. dissolved air flotation. The sludge consists of mostly fines and fillers depending on the recovered paper being processed and it is relatively easy to dewater. This sludge can be reincorporated into the process for board industry, but for high grade products can be incinerated, dumped or, otherwise, mixed with deinking or secondary sludge.
- Secondary or biological sludge: This sludge is generated in the clarifier of the biological units of the wastewater treatment, and it is either recycled to the product (board industry) or thickened, dewatered and then incinerated or disposed of in landfill. Secondary sludge volumes are lower than those corresponding to the primary sludge, since most of the heavy, fibrous or inorganic solids are removed in the primary clarifier.

In general, wastewater treatment sludge constitutes the largest residual waste stream generated by the pulp and paper industry in terms of volume. Sludge generation rates vary widely among mills (Lynde-Maas et al., 1997; Reid, 1998; Elliott and Mahmood, 2005; Krigstin and Sain, 2006).

Data on total waste generation are scarcely available as most of the pulp and paper mills already have processes applied to internally treat the wastes which reduce the solid waste initially generated. This, for instance, applies to bark residues from debarking, which are incinerated in the bark boiler and, as a result, only ashes remain as waste. The same can apply to sludge incineration. Some figures on generated waste found in environmental reports from different European pulp and paper mills are shown in Table 1.

The quantity of waste generated when virgin fibres are used as raw material depends mainly on the pulping process applied (Table 2). In Europe, 65% of total pulp production is kraft pulp which produces about 100 kg/Adt of wastes. Semi-chemical and mechanical processes produce about 60 kg/Adt (IPPC, 2001).

In 2005, the total production of paper in Europe was 99,3 million tonnes which generated 11 million tonnes of waste, representing about 11% in relation to the total paper production. The production of recycled paper, during the same period, was 47,3 million tonnes generating 7,7 million tonnes of solid waste (about 70% of total generated waste in papermaking) which represents 16% of the total production from this raw material (CEPI, 2006).

The amount of wastes generated in paper mills based on recycled fibre depends on the quality of recovered paper employed as raw material, and on the effort and expenses made in preparation of secondary fibres for certain product and process requirements. The average quantities of waste generated by paper grade are summarized in Table 3.

4. Composition

It is difficult to determine the composition of solid wastes from pulp and paper mills due to its dependence on the process, type and grade of paper products manufactured, methods used for production of pulp from either virgin or recycled fibres, type and efficiency of equipment used both in the main process and in wastewater treatment processes, and specific operating practices. Therefore, the waste composition corresponding to each kind of process may approximately be as follows.

4.1. Pulping

The solid waste removed from mechanical pulping consists mainly of bark and wood residues from debarking, washing and screening of chips, primary sludge, ash from energy production and biological sludge.

The main waste associated with this operation consists of different types of sludge, mainly fibre, containing primary sludge, and sludge from biological wastewater treatment. A chemical analysis of primary and secondary or biological sludge from a mechanical pulp mill is shown in Table 4.

As has been mentioned, the kraft pulping process is the most common pulping process in Europe. The main solid by-products are lime-mud, green liquor sludge (dredge), recovery boiler ash, grits, bark, ashes and wastewater treatment sludge. If bark and other wood residues are not burned for energy recovery, they would represent the major fraction of the residues (Axegard and Backlund, 2002; Demir et al., 2005; Martins et al., 2007).

Green liquor, lime mud and sludge mainly consist of $CaCO_3$. Ash from the recovery boiler mainly consists of sodium sulphate (approx. 85%) and, to a lesser extent, sodium carbonate (15%). Most of the recovery boiler fly ash and ESP dust is returned to the chemical cycle. Around 5 kg/t of these residues is removed to control the sulphur balance. Bark ash consists mainly of $CaO/CaCO_3$ and potassium salts. Grits mainly consist of $CaCO_3$.

Green liquor sludge, dredges and lime mud are often mixed and constitute the largest fraction of the overall solid waste generated in the kraft pulping process. The composition in such a mixed waste varies widely, containing different amounts of metals as barium, chromium, copper, lead, nickel or zinc.

The sulphite pulping production is related to the generation of different types of manufacturing-specific wastes, the majority of which can be further utilised. The wastes are generated at different stages of the production process namely in the debarking, chipping, screening and cooking liquor clarification operations, in the maintenance of the plant and also in the treatment of fresh water and wastewater.

4.2. Papermaking using virgin fibre

The waste generated in a paper mill producing paper from virgin pulp is quite small compared to recycled paper production and pulp production. Waste from paper production consists of rejects from stock preparation and sludge from water treatments. The rejects are normally led to the effluent treatment (IPPC, 2001), but they may also be directly led to sludge dewatering. Most of the solids will end up in the primary sludge.

Sludge from fresh water and wastewater treatments represents, in many mills, the main source of wastes. Different types of sludge can be distinguished:

- Sludge from chemical pre-treatment of surface water to obtain process water by means of chemical precipitation/flocculation. This residue is only generated in those mills using surface water with low quality. In that case, the amount of sludge can be significant.
- Sludge from primary clarification is generated in most mills. It consists primarily of fibres, fines and inorganic material in mills that employ fillers in their products.
- Sludge from biological treatment contains a high proportion of organic material. This sludge and the sludge from primary clarification represent the bulk of the wastes when using virgin fibres.
- Sludge from chemical flocculation is generated at mills with tertiary effluent treatment. This treatment produces a considerable amount of sludge. The amount of organic/inorganic material in the sludge varies from mill to mill, depending on the dosage and type of flocculants used.

4.3. Papermaking using recovered paper

The use of recovered paper as raw material presents several economic and environmental advantages, although many cleaning processes are needed to remove the contaminants that this feedstock introduces into the papermaking process (Blanco et al., 2004). Most of the impurities present in recovered paper end up as waste. The major waste materials are rejects, different types of sludges and ashes when the paper mill has an on-site waste incineration system. Depending on the grades of raw material, process design, manufactured product and wastewater treatment, different amounts and qualities of wastes are generated.

The residues can be roughly subdivided in heavy and coarse rejects, light and fine rejects and sludge. Depending on its origin and nature, sludge again may itself be subdivided into deinking sludge, sludge from process water clarification in micro flotation units, and sludge from waste water treatment (primary sludge and secondary sludge from biological treatment).

Rejects are impurities present in the recovered paper, consisting mainly of lumps of fibres, staples, metals from ring binders, sand, glass and plastics, and constitute about 6,5% of the purchased recovered paper. Rejects are removed as much as possible in the earliest stage in the stock preparation section.

In general, the paper sludge contains very high levels of dry solids because it is rich in fibres and therefore dewaters quite easily. All pulp and paper sludge is a mixture of cellulose fibre (40 to 60% of dry solids), printing inks and mineral components (40 to 60% dry solids: kaolin, talc, and calcium carbonate). Paper sludge is largely carbon (around 30% C dry solids) and mineral matter (clay and calcium carbonate, 5 to 25 % dry solids) with a high C/N ratio (50-200). It has low levels of fertilising elements and a low metal content (European Commission, 2001).

Deinking sludge mainly contains fines, fillers, coatings, ink particles, extractive substances and deinking additives. Ink particles are a potential source of heavy metals.

However, in general, they have comparable pollutant loads as biological sludge with slightly higher values of copper and zinc and lower values of BOD. There are relatively significant variations in the pollutant content of the recovered paper and, consequently, in the deinking sludge (IPPC, 2001).

The sludge from process water clarification is generated in the fibre recovery process from white waters and in the physical waste water treatment process. It consists of mostly fines and fillers (both around 50%) depending on the recovered paper being processed. Typical composition of sludge is given in Table 5.

Paper industry waste, whether of primary, biological or de-inking origin, is heterogeneous in nature, ranging from a viscous paste to a solid material. The dry solids content of the residues can vary from 20 to 60% depending on the degree of dewatering. Therefore, the wastes have to be handled, usually blended and treated (thickened and dewatered) to obtain a residue with a high dry solid content.

To summarise, paper mill sludge tends to be highly fibrous. Chemical pulp mill sludge has a higher content of sulphurous compounds, which originate from the process chemicals (Na_2S or H_2SO_3 and bisulphite ion, HSO_3^-) specific to chemical pulping. Bleached pulp mill sludge may contain high levels of chlorinated organic compounds, originating from bleaching agents (Cl_2, ClO_2 or NaOCl). Deinking plant sludges, however, have high ash contents due to a high inorganic filler content in the recovered paper. In terms of residual moisture content before disposal, bark and other mill rejects tend to dewater easily and have a high solids content, making them suitable for mass combustion as hog fuel in the bark boiler. Deinking sludges also typically have a low moisture content due to the large fraction of ash and reject material in the flotation unit foams. Sludges from primary clarifiers dewater more readily than those of secondary clarifiers due to the higher concentration of bio-solids and the hydrous material of the latter.

5. Minimization of waste generation

According to the IPPC, installations must be operated in such a way as to meet six prime objectives:

- Application of best available techniques (BAT) to prevent pollution.
- No significant pollution.
- Waste minimization and the recovery of unavoidable waste.
- Efficient use of energy.
- Prevention of accidental releases.
- Remediation of the plant site back to its original state after plant closure.

An effective waste minimization program can reduce the costs, liabilities, and regulatory burdens of hazardous waste management, while potentially enhancing efficiency, product quality, and community relations (Rouleau and Sasseville, 1996; Holland, 1997). Waste minimization techniques that can help to reduce the amount of hazardous waste generated include:

- Production planning and sequencing.
- Process/equipment adjustment or modification.
- Raw material substitution.
- Loss prevention and housekeeping.

- Waste segregation and separation.
- Recycling.

Concerning waste hierarchy, many paper mills are challenged with the task of using high levels of secondary fibre, recovering and “upcycling” the fibre to papermaking specifications and, at the same time, reducing waste generation. Without recourse to the selection of virgin or low-contaminated secondary fibre sources, the remaining options for mills under such constraints include:

- Maximising fibre yield from secondary fibre sources, thereby reducing the losses of raw material in the effluent.
- Reducing raw material losses with the effluent by “closing up” mill systems.
- Engineering paper which can be recycled without generating waste during production.
- Upgrade paper finishing techniques to enable increased sludge reuse.
- Adoption of friendly recycling techniques in packaging and printing.

6. Waste recovery

Nowadays there are several waste recovery options. These include thermal processes such as incineration with energy recovery, pyrolysis, steam reforming, wet oxidation and supercritical water oxidation; composting; recycling; land reclamation and soil enhancement; production of mineral fillers for building materials and cement; production of insulating and fire-resistant materials and other uses (eg. pet litter, barrier materials, conversion to fuel components, carriers for artificial fertilizers) (Moss and Kovacs, 1995; Zippel, 2001; Cernec and Zule, 2005; Hamm, 2005; Fytili and

Zabaniotou, 2006). However, the wastes, especially sludges from the wastewater treatment, require further processing before recovery. Sludge from mills typically requires some form of conditioning, thickening and dewatering to reduce volume prior to its disposal (Springer, 1993; Kantardjieff et al., 1997; Kerr, 1997). Dewatering, almost always practised, enables the volume of sludge to be reduced. Dewatering can be carried out through a variety of processes, some of which are complementary: centrifugation, band filters, filter presses and screw presses. Deinking or mixed sludge tends to be drier than primary and biological sludge. Sludge containing a high level of lignin is easier to dewater than other types of sludge. As mentioned above, the dry solids content of the sludge can vary from 20 to 60%, depending on the level of dewatering (European Commission, 2001).

It is evident that the final use of the waste depends on its physico-chemical and microbiological characteristics. For example, if sludge from papermaking is used as a raw material for brick production, given that brick manufacture is restricted to the warmer months of the year, while paper mills produce all year round, the sludge has to be stored until further processing. However, in order to employ the sludge as feedstock in the manufacture of bricks, it is essential to avoid significant chemical and microbiological decomposition of the residue during storage. Several parameters can be used as indicators to monitor ongoing deterioration processes, among them, solid content, combustion residue, fibre length distribution, water absorbance, viscosity, compressibility, chemical composition, microbiological contamination and leaching of various compounds into water (Cernec and Zule, 2005).

The main options for waste recovery are described below in further detail, including their characteristics. The main factors that drive a mill to choose a particular disposal option may be attributed to various factors such as local infrastructure, costs, competition with residues from other industries and local policies.

7. Thermal processes

7.1. Incineration or Combustion

The incineration of residues (both rejects and sludge), combined with power and steam generation, is one of the most commonly applied disposal methods in Europe. This technique can be applied to almost all types of sludge, including secondary or biological sludge. However, due to the high moisture and ash content of most sludges, the incineration process overall balance can be energy deficient. Fluidised bed boiler technology provides a means for successful thermal oxidation of high ash, high moisture wastes, producing process steam and/or electricity and reducing at the same time the mill's dependence on costly fossil fuels for steam production. These systems not only utilize deinking and paper sludges, but also material mined from existing on-site landfills to mitigate ground water contamination problems. Fluidized bed combustion is rapidly becoming the ultimate solution for the final disposal of paper mill wastes (Busbin, 1995; Fitzpatrick and Seiler, 1995; Davis et al., 1995; Albertson, 1999; Porteous, 2005; Oral et al., 2005).

Table 6 summarizes installations at pulp mills which burn some portion of pulp sludge (CANMET, 2005).

The main achievement of the incineration is the reduction of the amount of material to be landfilled by about 80-90%. For the final disposal or use of the ashes there are different options depending on the ash qualities achieved. In some cases ash is simply landfilled, whereas in others it is used by the building industry or in other added-value applications. Special attention has to be given to the chlorine content of the rejects due to potential problems of corrosion and air contamination that chlorine-containing compounds may cause. Ash rinsing technology constitutes an effective option for the removal or dilution of chlorine and heavy metals enabling a decrease in the chlorine concentration to levels lower than those required for the agricultural application of ash (Matsuto, 1999; IPPC, 2001; Christmas, 2002; Tomita et al., 2006).

The combustion behaviour of several paper mill residues, namely deinking sludge, rejects from cleaning and screening, or sludge from wastewater treatment is shown in Figure 4. The graph depicts the relationship between combustible/organic content, ash content and water content. The area of self-supporting combustion where additional fuels are not necessary is also indicated (IPPC, 2001).

The incineration of this kind of waste is regulated in Europe by *Directive 2000/76/EC* on waste incineration (*Waste Incineration Directive*), which requires all plants to keep the incineration at a temperature of at least 850°C for at least two 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 two seconds.

The set of values for the limits of incinerator air emissions concern heavy metals, dioxins and furans, carbon monoxide (CO), dust, total organic carbon (TOC), hydrogen chloride (HCl), hydrogen fluoride (HF), sulphur dioxide (SO_2), nitrogen monoxide (NO) and nitrogen dioxide (NO_2). As an example, the emission limit value for total concentration of dioxins and furans is 0,1 ng/m^3, and for CO, 50 mg/m^3 as a daily average value.

7.2. Pyrolysis

In the pyrolysis process, also called destructive distillation, the organic waste is heated in the absence of oxygen to produce a mixture of gaseous and liquid fuels, with a solid inert residue (mainly carbon).

This technology consists of the breakdown of organic matter between about 400 to 800ºC through the application of indirect heat, in an anaerobic atmosphere, all the while ensuring a capture of the volatiles. By applying indirect heat to a hyperbaric revolving retort, the sludge is broken down and fractionated into gases, tars and heavy/light oils. Long exposure times are required to optimize the production of char (CANMET, 2005). No oxygen is allowed to enter the retort during the decomposition operation; hence no “combustion” can take place. This technology is an alternative to incineration and landfill of paper mill wastewater sludge, although it generally requires a consistent waste stream such as tyres or plastics to produce a usable fuel product (Fio Rito, 1995; Frederik et al., 1996; Kay, 2002; Fytili and Zabaniotou, 2006).

This technology has been developed for wastes with a high carbon content, such as wood, petroleum and plastic wastes, but it is not yet sufficiently mature enough for application for paper sludge. However, some investigations are being carried out by different European Research Centres, aimed at adapting this technology to paper process sludge.

7.3. Steam reforming

Steam reforming is based on an innovative pulse combustion technology carried out in a steam reforming reactor system. Pulse combustion is a phenomenon of combustion-induced oscillations which are incorporated by design to achieve a high heat release and more complete combustion. The technology not only offers enhanced heat transfer rate but also low NO_x emissions. In addition, operating the steam reformer at a lower temperature (500-600ºC) minimizes the vaporization of toxic metals which remain in the char (Durai-Swamy et al., 1991; Aghamohammadi and Durai-Swamy, 1995; Demirbas, 2007).

This technology is currently used for treatment of sewage sludge, and is still considered an emerging technology for the treatment of paper sludge.

7.4. Wet oxidation

Wet oxidation can be defined as the process through which organic contaminants, in liquid or solid form, are extracted into water where they come into contact with an oxidant under conditions that promote their rapid destruction. The process takes place in the aqueous phase at temperatures of 150-330ºC and pressures of 1-22 MPa using pure or atmospheric oxygen. Because it applies a direct chemical oxidation process, the process is not susceptible to toxicity-related problems that can occur in biological treatments. Oxidation takes place in an aqueous environment, where water provides a medium for the dissolved oxygen to react with the organics and other oxidizable components. Water is an integral part of the process acting both as a catalyst and a hydrolysis reactant. Oxygen- and water-derived radicals attack organic compounds, forming organic radicals. Such free radicals are a suspected key factor in wet oxidation chemistry. Catalysts, such as homogeneous copper and iron, their heterogeneous counterparts or precious metals, can be used to enhance the reaction (Fytili and Zabaniotou, 2006).

The chemistry of wet oxidation is characterized by the formation of carboxylic acids as well as the primary end-products: CO_2 and water. These acids, mainly acetic, formic and oxalic acids are biologically degradable and can generally be removed using a cost-effective conventional biological post-treatment.

The gas released from wet oxidation contains traces of NO_x, SO_x and particulate matter. Depending on the feed stream composition, volatile organic compounds such as aldehydes, ketones and alcohols may be in the gas but can be removed by thermal oxidation. In a general wet oxidation process, the waste is delivered through a high-pressure pump. Ambient air or pure oxygen supplies the required oxygen (Maugans and Ellis, 2004).

As a result of the wet oxidation process, waste pulped with water is carbonised, which increases its fuel value to the equivalent of medium-grade coal. In a reactor, the preheated slurry is oxidised under pressure, producing high-pressure steam that can drive turbines to generate energy. The waste does not produce any air pollution because it combusts without flame or smoke (Kay, 2002).

This technology is also considered an emerging technology for the treatment of paper sludge in Europe, but it is an interesting technology because in comparison to incineration, it is easier to get the corresponding operation permits, it is less affected by high moisture contents and the destruction efficiencies are less sensitive to changes in the waste stream fuel properties. In comparison to biological systems, this technology is compact and can treat hazardous wastes and biologically toxic materials at high concentrations achieving high destruction levels. Some case studies have shown treatment cost reductions of up to 50% compared to existing treatment options (Johnson, 1996).

7.5. Super Critical Water Oxidation

The supercritical water oxidation (SCWO) is an innovative and effective destruction method for organic wastewater and sludge. When heated beyond its critical temperature of 374 ºC (400-600ºC) and compressed beyond its critical pressure of 221 bar (250 bar), water acquires a new set of chemical properties. In this supercritical region of temperature and pressure, water can be used for the remediation technique known SCWO. It exploits the capacity of supercritical water to dissolve both oxygen and nonpolar organic compounds, thereby allowing organic waste to be oxidised into carbon dioxide and water. Compounds such as salts and fillers precipitate out of supercritical water and are available for recovery and reuse (Modell et al., 1992; Dahlin, 2002; Kay, 2002).

A SCWO system can handle aqueous streams containing organic material in relatively low concentrations and offers inherent control over emissions and coupling to energy recovery systems. To achieve a process with good economics, the dry substance of the sludge should be maximised (more than 20% dry solids content). It is also important to ensure a constant supply of sludge without large particles to the high pressure pump (Gidner and Stenmark, 2002).

7.6. Gasification

Gasification is not a new technology, although the application to pulp and paper is considered to be in its early stages of development with a limited number of commercial installations.

Gasification is a thermal process during which a combustible material is converted into an inflammable gas and an inert residue employing air or oxygen. It has been used for a long time to produce gas with coal. This process is performed at a high temperature: between 900°C and 1100°C with air, or between 1000°C and 1400°C with oxygen. Gasification with oxygen, which is more often performed, generates a gas containing 55 to 60 % N_2, with a calorific value of 4 to 7 MJ/Nm^3.

The gasification process enables the flue gas volume to be drastically reduced since the internally formed carbon dioxide and water participate in the reaction and the unwanted N_2 may be avoided by supplying pure oxygen. Pyrolysis can also be considered as a gasification process, but performed in the absence of oxygen. Both processes may also be performed together: gasification can be applied to the solid residue of the pyrolysis. It is a new method when applied to sludge, and therefore not very well documented. The material input to the process can either be digested or undigested mechanically dewatered sludge (European Commission, 2001; CANMET, 2005)

The differences in the chemistry of pyrolysis and gasification have been defined by the biomass industry as the differences in operating temperature and control of oxidation by air. In general, pyrolysis may require an extensive residence time to achieve an optimum quality of char. Since the use of thermal oxidation reactions may have stages or zones for optimum pyrolysis and gasification reactions, the subject study has defined the classification of technologies based on the selective end product, such that gasification technologies optimize the production of produced gasses and pyrolysis technologies optimize the production of char, as well as heavy and light oils (CANMET, 2005).

The advantages and drawbacks of each thermal process applied to wastes and sludges are summarised in Table 7.

It is very difficult to estimate the costs of the different thermal technologies, because treatment costs are dependent on waste composition, their concentrations, the level of destruction required and the volumes requiring treatment, etc. Due to the significant differences that change in these variables may have, cost comparisons are only relevant on a clearly defined case, or on a relative basis. As it is known, the main problem concerning thermal processes includes excessive energy to reach high temperatures, need for extensive air pollution equipment, and, therefore, high capital costs.

8. Utilisation in the cement and brick industry or other building material

In the cement industry both the material and energy content of the paper residues can be recovered. For the use in cement industry, sludges from primary clarifiers (or mixed with sludge from biological treatment) are especially suitable (Ahmadi and Al-Khaja, 2001; Cernec et al., 2005). However, its suitability depends on the amount and type of inorganic compounds present in the residue. The sludge (about 50% moisture content) is dried with waste heat from the pre-dryer of the cement kiln so that no additional thermal energy is needed to reduce the moisture of the sludge down to 10-15%. Thus, when burning the dried sludge in the cement rotary kiln, the calorific value of the organic substances, with a high carbon content is used and the ash resulting from incineration of the sludge remains in the product. The inorganic substance of the ash of the incinerated sludge is also a compound of the cement clinker. This sludge disposal option is viable when the paper mill and the brick cement (or brick) manufacturing industry are in the neighbouring area and the latter has the capacity to use the sludge in its process (IPPC, 2001).

In the case of brick production, the addition of 5-15% of paper sludge as raw material improves both the final product and the process. First, since its fibre content increases the porosity of the matrix, it enables the manufacture of lighter bricks; secondly, it saves fuel in the oven; decreases the cooking time and makes the product more resistant to cracking during the drying and cooking stages (Cernec and Zule, 2005; Cernec et al., 2005).

9. Composting

The composting solution consists of letting the wastes or sludges sit until most of the paper fibres and organic materials have been stabilized (odour/chemically) through the action of micro-organisms with minimal carbon loss. Sometimes fertilizers are added to the wastes or sludges in order to increase the nutrient content. This produces a humus-like material that can be used for house plants and green houses. This is one of the lowest cost disposal routes. Excluding the large land requirement in order to spread the sludge, there are few additional costs incurred by composting (Jokela et al., 1997; Hackett et al., 1999; Christmas, 2002; Gea et al., 2005).

Commercial composts must fulfil a set of technical requirements such as degree of maturity or suitability for plant growth. Composts made from organic waste mixed with different quantities of recovered paper and wastes of the paper industry satisfy the mentioned requirements. Furthermore, some compost parameters, such as salt and organic substance content and the process specific leachate emission are positively influenced by the addition of paper industry wastes to the composting matrix. The concentration of harmful substances, especially those of heavy metals must be considered as a limiting factor (IPPC, 2001).

10. Land application

Due to its $CaCO_3$ content, application of sludge on land has been one of the preferred disposal methods for the deinking industry for many years in the United Kingdom and Northern Europe, areas where the soil is mainly acidic. Before their application to the soil, wastes undergo a dewatering or/and incineration treatment in order to reduce their volume (Carr and Gay, 1997; Van Horn, 1997). Land application itself consists of transporting the sludges or the wastes, in cake form, from the factory to the fields, and then either spreading them on the land in a thin layer or by ploughing them into the surface bi-annually between harvests (Christmas, 2002).

The feasibility of land spreading is strongly dependent on the acceptance in Member States to apply sludge to agricultural land. One important aspect is that sludge needs to contain nitrogen for this application, which generally is not the case in pulp and paper sludges, and it must be supplied. Other concerns are possible contamination of soils with low concentrations of heavy metals and organic micro-pollutants. However, sludge from paper mills usually does not contain more pollutants than municipal wastewater treatment sludge, and its controlled application can have some positive effects on the soil ($CaCO_3$, as a neutralising agent of acidic soils, moisture retention by fibres and fines on dry soils, low nitrogen content). The possible benefits vary according to the soil type. The periods of land spreading are restricted to a few months of the year. It is therefore necessary to build sufficient storage capacity for the sludge (IPPC, 2001). The use of solid waste as the main constituents in the topping of landfill, mine dumps, hydraulic barrier, etc. is less strictly regulated than land application since the ground will not be used for crops (Kahmark and Unwin, 1996; Peters, 1998; Malmstead et al., 1999; Christmas, 2002).

Due to the geotechnical properties of the waste, paper sludge is very similar to those of compacted clays used as a sealing layer and, therefore, can also be applied as covering material in landfills. If used as covering material, it must be ensured that these wastes do not decompose chemically and/or microbiologically due to leaching.

11. Anaerobic digestion

Historically, in case of solid wastes, this practice has been associated with the treatment of animal manure and sludge from aerobic wastewater treatment plants. At present, anaerobic digestion is applied for the treatment of different kinds of organic solid wastes, for example municipal wastes, agricultural wastes and different industrial wastes (Mata-Alvarez et al., 2000; Mshandete et al., 2005).

By definition, anaerobic digestion requires that the given waste/wastewater contains a substantial amount of organic matter so that it can be converted (in the absence of oxygen) to biogas (methane and CO_2) and humus (an organic fertilizer) from sludge digestion. However, recent, high-rate reactor configurations and sophisticated process control have allowed anaerobic digestion to enter application areas that were previously dominated by aerobic systems such as the treatment of industrial effluents with low COD levels. In general, among biological treatments, anaerobic digestion is frequently the most cost-effective, due to the high energy recovery linked to the process and its limited environmental impact (Verstraete and Vandevivere, 1999; Mata-Alvarez et al., 2000).

Anaerobic digestion is normally carried out at mesophilic temperatures, 35±5°C. At these conditions, approximately one-half of the organic matter is susceptible to anaerobic biodegradation, resulting in the formation of biogas. In order to increase the gas production rate and the destruction of pathogens and/or to enhance the sludge digestion, several modifications in the digestion process can be applied, such as the operation at the thermophilic temperature range, the splitting of the process into two stages or the pretreatment of the sludge in order to reduce the retention time required for its degradation (Thompson et al., 2001; Mshandete et al., 2005).

Industrial wastes are used as additional feedstocks to supplement the main agricultural residues being “digested”. For example, paper sludge may be used as an additive in the anaerobic digestion of agricultural residues. The methane gas can be used to meet on-site power and process heat requirements, while the digestate can be used as a soil improver. However, it has been recognized that transport costs of residual inputs (manure) to processing plants can make the difference between the success of one scheme and the failure of another (Kay, 2003; CANMET, 2005).

12. Other options

Other options described in literature are (Kahmark and Unwin, 1996; Christmas, 2002; Kay, 2002; CANMET, 2005; Cernec and Zule, 2005):

- Cat litter: Dried sludge can be used as cat litter. This option does not seem to be very promising in terms of costs and volume.

- Absorbents: Dried sludge could be used as an absorbent, e.g. for spreading on oil spills. The limitations of this use are the same as those of cat litter production.
- Pesticide/Fertilizer carrier: The active sludge is dried and the active ingredients are absorbed. After spreading and decomposition the active ingredients are released. This gives a slower and more controlled addition of perticides/fertilizers to the soil. Contamination associated with the sludge would be the ongoing threat to such a disposal route.
- Conversion to fuel components: Levulinic acid has been found to be economically produced from paper sludge and converted into an alternative fuel component called methyltetrahydrofuran which can be used with ethanol and natural gas liquids to create a cleaner-burning fuel.
- Bioconversion of the cellulosic fraction of sludge to ethanol. The cellulosic fraction is hydrolyzed by enzymes to produce glucose and, subsequently, the glucose is converted to ethanol by fermentation. In general, the kraft and sulphite sludge are more amendable to ethanol production than sludge from thermomechanical mills. Deinking sludge is not suitable for bioconversion due to the low content of cellulose fibres associated to the high papermaking process efficiency currently achieved.

13. Conclusions

The European paper industry generates about 11 million tonnes of waste, 70% of which originates from recycled paper production. The waste is very diverse in composition and consists of rejects, different types of sludges and, in case of on-site incineration, ashes.

The production of pulp and paper from virgin pulp generates less waste and the waste has the same properties as deinking waste, although with less inorganic content. Within the European Union several already issued and other, foreseen directives have great influence on the waste management strategy of paper producing companies. Through legislation, the landfill option is restricted, although it has not phased out on-site landfills. Due to the large quantities of waste generated, the high moisture content of the waste and the changing composition, some recovery methods, for example, conversion to fuel components, are simply too expensive and their environmental impact uncertain. The thermal processes, gasification and pyrolysis, seem to be interesting emerging options, although it is still necessary to improve the technologies for sludge application. Other applications, such as the hydrolysis to obtain ethanol has several advantages (wet sludge and applicable technology to pulp and paper and paper sludges) but it is not well developed for pulp and paper sludges. Therefore, at this moment, the minimisation of waste generation still has the highest priority.

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References

- Aghamohammadi, B., Durai-Swamy, K., 1995. A disposal alternative for sludge waste from recycled paper and cardboard. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 445-449.
- Ahmadi, B., Al-Khaja, W., 2001. Utilization of paper waste sludge in the building construction industry. Resour., Conserv. and Rec., 32 (2), 105-113.
- Albertson D.M., 1999. Paper sludge-Waste disposal problem or energy opportunity. Energy Products of Idaho.
- Axegard, P., Backlund, B., 2002. Solid waste from pulping process. Minimization and conversion to useful by-products. COST Workshop Managing Pulp and Paper Residues. Barcelona, Spain.
- Blanco, A., Negro, C., Monte, M.C., Fuente, H.,Tijero, J., 2004. The challenges of sustainable papermaking. Environ. Sci. Technol. 38(21), 414A-420A.
- Busbin, S.J., 1995. Fuel specifications-sludge. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 349-353.
- CANMET Energy Technology Centre, 2005. Pulp and paper sludge to energy-Preliminary Assessment of Technologies. Canada.
- Carpentier, A., 2002. European legislative Framework for the management of pulp and paper residues. COST Workshop Managing Pulp and Paper Residues. Barcelona, Spain.

- Carr, J.M., Gay, C.L., 1997. Demonstrating the environmental benefit of land application of kraft mill biosolids. Environmental Conference & Exhibit. TAPPI Proceedings, Book 2, Minneapolis Convention Center, 849-852.
- Cernec, F., Zule, J., 2005. Chemical stability of papermill sludges. COST Action E26 "Effective solutions to reduce the impact of waste arisings from papermaking". Worshop "Solid waste management in the papermaking prevention, creation of new products and energy recovery" Milan, 17-18 March.
- Cernec, F., Zule, J., Moze, A., Ivanu A., 2005. Chemical and microbiological stability of waste sludge from paper industry intended for brick production. Waste Management Research. 23, 106-112.
- Christmas, P., 2002. Building materials from deinking plant residues- a sustainable solution. COST Workshop Managing Pulp and Paper Residues. Barcelona, Spain.
- Confederation of European Paper Industry, 2004. Discovering the high potential of pulp and paper production residues.
- Confederation of European Paper Industry, 2006. Special Recycling 2005 Statistics, 2006 (http://www.cepi.org).
- Dahlin, J., 2002. Oxidation on deinking sludge in super critical water in practice. COST Workshop Managing Pulp and Paper Residues. Barcelona, Spain.
- Davis, D.A., Gounder, P.K., Shelor, F.M., 1995. Combined cycle-fluidized bed combustion sludges and other pulp and paper mill wastes to useful energy. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 379-381.
- Demir, I., Baspinar , M.S., Orhan, M., 2005. Utilization of kraft pulp production residues in clay brick production. Building and Environment, 40 (11), 1533-1537.

- Demirbas, A., 2007. Progress and recent trends in biofuels. Progress in Energy and Combustion Science. 33(1), 1–18.
- Directive on Waste 75/442/EEC.
- Directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture 86/278/EEC.
- Directive 89/369/ECC.
- Directive 89/429/ECC.
- Directive 91/156/EEC.
- Directive on Hazardous Waste 91/689/EEC.
- Directive on Packaging and Packaging Waste 94/62/EC.
- Directive 94/67/EC.
- Directive Integrated Pollution Prevention & Control 96/61/CE.
- Directive Landfill 1999/31/EC.
- Directive Incineration of Waste 2000/76/EC.
- Directive 2004/12/EC.
- Durai-Swamy, K., Warren, D.W., Mansour, M.N., 1991. Indirect steam gasification of paper mill sludge waste. Tappi J., 137-143.
- Elliott, A., Mahmood T, 2005. Survey benchmarks generation, management of solid residues. Pulp Pap. 79 (12), 49-55.
- EPA Office of Compliance Sector Notebook Project. Profile of the Pulp and Paper Industry. 2nd Edition. Washington, November 2002.
- European Commission, 2001. Survey of wastes spread on land. WRc Ref: CO 4953-2/11768-1, July 2001.

- Fitzpatrick, J., Seiler, G.S., 1995. Fluid bed incineration of paper mil sludge. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 369-376.
- Fio Rito, W.A., 1995. Destructive distillation. Paper mill sludge management alternative. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 425-427.
- Frederik, W.M.J., Iisa, K., Lundy, J.R., O'Connor, W.K., Reis, K., Scott, A.T., Sinquefield, S.A., Sricharoenchaikul, V., Van Vooren, C.A., 1996. Energy and materials recovery from recycled paper sludge. Tappi J., 79(6), 123-131.
- Fytili, D., Zabaniotou, A., 2006. Utilization of sewage sludge in EU application of old and new methods-A review. Renewable and Sustainable Energy Reviews (in press).
- Gidner, A., Stenmark, L., 2002. Oxidation of deinking sludge in supercritical water. COST Workshop Managing Pulp and Paper Residues. Barcelona, Spain.
- Gea, T., Artola, A., Sanchez, A., 2005. Composting of deinking sludge from the recycled paper manufacturing industry. Bioresour. Tech. 96, 1161-1167.
- Hackett, G.A.R., Easton, C.A., Duff, S.J.B., 1999. Composting of pulp and paper mill fly ash with wastewater treatment sludge. Bioresour. Techn., 70(3), 217-224.
- Hamm, U., 2005. Deinking waste management in Germany. COST Action E26 "Effective solutions to reduce the impact of waste arisings from papermaking". Worshop "Solid waste management in the papermaking prevention, creation of new products and energy recovery" Milan, 17-18 March.
- Holland, R.M., 1997. A unique approach to solid waste reduction. Environmental Conference & Exhibit. TAPPI Proceedings, Book 1, Minneapolis Convention Center, 489-490.

- Holmen and its World 2005 (http://www.holmen.com)
- http://es.epa.gov
- http://www.aspapel.es
- Hynninen, P., 1998. Environmental Control. Book 19. Papermaking Science and Technology Series. TAPPI PRESS. ISBN 952-5216-19-5. Finland.
- Integrated Pollution Prevention and Control (IPPC), 2001. Reference Document on Best Available Techniques in the Pulp and Paper Industry. European Commission. December.
- Johnson, W., 1996. Wet oxidation for pulp & paper industry waste. (http://www.esemag.com/0796/oxidatio.html1996).
- Jokela, J., Rintala, J., Oikari, A., Reinikainen, O., Mutka, K., Nyrönen, T., 1997. Aerobic composting and anaerobic digestion of pulp and paper mill sludges. Water Sci. and Tech., 36(11), 181-188.
- Kantardjieff, A., Jones, J.P., Bergeron, J., Massini, M., 1997. Improved dewatering of pulp and paper mill sludges. Environmental Conference & Exhibit. TAPPI Proceedings, Book 2, Minneapolis Convention Center, 723-727.
- Kay, M., 2002. Development of waste management options for paper sludge. 4th Annual Dutch International Paper & board Technology Event. Pira International.
- Kay, M., 2003. What to do with sludge? It's best to determine local needs before choosing an option. Pulp Pap. Int., 45(8), 19-21.
- Kahmark, K.A., Unwin, J.P., 1996. Pulp and paper effluent management. Water Environment Research, 68 (4), 551-564.
- Kerr, J.C., 1997. New wet waste dewatering technology. Environmental Conference & Exhibit. TAPPI Proceedings, Book 2, Minneapolis Convention Center, 729-735.

- Krigstin, S., Sain, M., 2006. Characterization and potential utilization of recycled paper mill sludge. Pulp and paper Canada, 107 (5), 29-32.
- Lynde-Maas, M.K., Unwin, J.P, Miner, R.A., 1997. Preliminary results from the NCASI 1995 wastewater and solid waste survey. Environmental Conference & Exhibit. TAPPI Proceedings, Book 1, Minneapolis Convention Center, 239-241.
- Malmstead, M.J., Bonistall, D.F., Van Maltby, C., 1999. Closure of a nine-acre industrial landfill using pulp and paper mill residuals. Tappi J., 82 (2), 153-160.
- Martins, F.M., Martins, J.M., Ferracin, L.C., da Cunha, C.J., 2007. Mineral Phases of Green Liquor Dregs, Slaker Grits, Lime Mud and Word Ash of a Kraft Pulp and Paper Mill. Journal of Hazardous Materials (in press).
- Mata-Alvarez, J., Macé, S., Llabrés, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectivas. Biores. Tech., 74(1), 3-16.
- Matsuto, T., 1999. Problems in leachate treatment systems caused by incineration. Waste Manage. Res., 17, 505-510.
- Maugans, C.B., Ellis, C., 2004. Age Old Solution for Today's SO_2 and NO_X. Pollution Engineering.
- Modell, M., Larson, J., Sobczynski, F., 1992. Supercritical water oxidation of pulp mill sludges. Tappi J., 195-202.
- Moss, C.S., Kovacs, D., 1995. Recovering usable fiber from pulp mill/paper mill sludge. Environmental Issues and Technology in the Pulp and Paper Industry. A TAPPI PRESS Anthology of Published Papers, 1991-1994, 475-480.
- Mshandete, A., Björnsson, L., Kivaisi, A.K., Rubindamayugi, S.T., Mattiasson B., 2005. Enhancement of anaerobic batch digestion of sisal pulp waste by mesophilic aerobic pre-treatment. Water Res., 39(8), 1569-1575.
- Norske Skog Environmental Report 2005.

- Oral, J., Sikula, J., Puchyr, R., Hajny, Z., Stehlik, P., Bebar, L., 2005. Processing of waste from pulp and paper plant. J. of Cleaner Production, 13, 509-515.
- Organisation for Economic Co-operation and Development, 2004. Addressing the economic of waste, ISBN 9264106189
- Papoulias, F., 2005. EU waste management policy. Seminar on Environmental Requirements in Cohesion Fund Projects, Prague.
- Peters, C.S., 1998. Investigative and management techniques for cement kiln dust and pulp and paper process wastes. Environmental Progress, 17 (3), 142-147.
- Porteous, A., 2005. Why energy from waste incineration is an essential component of environmentally responsible waste management. Waste Manag., 25, 451-459.
- Regulation 259/93/EEC.
- Reid, I.D., 1998. Solid residues generation and management at Canadian pulp and paper mills in 1994 and 1995. Pulp & Paper Canada 99(4), 49-52.
- Rouleau, G., Sasseville, M., 1996. Waste reduction: A sound business decision. Pulp & Paper Canada 97:12, 114-116.
- SCA Environmental and Social Report 2005 (http://www.sca.com).
- Speight, P., 2006. The revision of the Waste Framework Directive. European Paper Week, Brussels, 28-30 November.
- Spinosa, L., 2004. EU Strategy and practice for sludge utilization in agriculture, disposal and landfilling. J. of Residual Science and Technology, 1(1), 7-14.
- Springer, A.M., 1993. Industrial environmental control. Pulp and paper industry. TAPPI PRESS, Atlanta, USA. ISBN 0-89852-057-6.
- Stora Enso Sustainability 2005 (http://www.storaenso.com).
- Thompson, G., Swain, J., Kay, M., Forster, C.F., 2001. The treatment of pulp and paper mill effluent: a review. Biores. Tech., 77, 275-286.

- Tomita, R., Hirao, H., Tochigi, T., Tamashige, T., 2006. ECOCEMENT. Innovative cement for contributing to sustainable societity. (302-303), 44-54.
- Van Horn, J.T., 1997. Land application of solid waste Stone Container Corporation. Environmental Conference & Exhibit. TAPPI Proceedings, Minneapolis Convention Center, 845-848.
- Verstraete, W., Vandevivere, P., 1999. New and broader applications of anaerobic digestión. Crit. Rev. in Environ. Sci. and Techn., 29(2), 151-173.
- Zippel, F., 2001. Water management in paper mills. Voith Paper. Darmstadt. ISBN 3-00-008247-6.

Table 1. Destination and specific generated waste from European pulp and paper mills of several companies in 2005 (Source: 2005 Environmental Reports)

	Holmen	**SCA**	**Norske Skog**	**Stora Enso**
Mill production (millions of tonnes)	2,3	9,9	4,8	15,1
Total waste generated (kg/ton product)	160	163	155 (dry)	23
Recovered waste (kg/ton product)	136	115	138	-
Waste sent to landfill (kg/ton product)	23 (wet)	47	16	22
Hazardous waste (kg/ton product)	0,2	0,3	1,5	0,3

Table 2. Waste generated in Europe (IPPC, 2001)*

Process	Kraft pulp	Mechanical Semi-chemical	Sulphite pulp Other	Non wood fibres	Recycled paper
Specific waste (kg/Adt)	100	60	80	-	185
Used in Europe* (million tonnes)	26,5	14,1	2,3/ 0,9	14,6	42
Waste generated through paper production (million tonnes)	2,1	0,8	0,2	-	7,7

* Europe includes CEPI members.

Table 3. Waste generated through production of different paper grades from recycled fibre (RCF) (Kay, 2002)

Grade	Packaging paper	Newsprint	LWC/SC paper	Tissue and market pulp
Solid waste (dry basis, kg/Adt)	50-100	170-190	450-550	500-600

LWC: light-weight coated paper
SC: super-calendered paper

Table 4. Composition of primary sludge and biological sludge from mechanical pulp mill (IPPC, 2001)

Component	Primary sludge	Biological sludge
Dry solid content (%)	48	32
Volatile solids (% DS)	33	48
TOC (%)	19	23
Lead (mg/kg DS)	41	22
Cadmium (mg/kg DS)	<0,7	<0,7
Chromium (mg/kg DS)	24	17
Copper (mg/kg DS)	238	71
Nickel (mg/kg DS)	6	8
Mercury (mg/kg DS)	0,1	0,09
Zinc (mg/kg DS)	141	135

Table 5. Composition of the sludge from process water clarification (IPPC, 2001)

Component	Process water clarification
Dry solid content (%)	29-53
Volatile solids (% DS)	26-76
Lead (mg/kg DS)	10-210
Cadmium (mg/kg DS)	0,01-0,98
Chromium (mg/kg DS)	9-903
Copper (mg/kg DS)	20-195
Nickel (mg/kg DS)	< 10 – 31
Mercury (mg/kg DS)	0,1-0,9
Zinc (mg/kg DS)	34-1320
Chlorophenols (µg/DS)	-
PCB’s (µg/DS)	-

Table 6. Some European pulp mills which burn some portion of pulp sludge

Plant	Year	Fuel	Capacity
Cartiere Burgo Verzuolo, Italy	2001	Paper sludge and wood waste	27 MW_{th} 29 tonne/h steam; 86 bar; 490ºC
Cartiere Burgo Mantova, Italy	1999	Production paper/deinking sludge and landfill reclaimed sludge, 43% ash, 55% moisture	13,5 MW_{th} superheated steam to 3,2 MW_c turbine/generator set
Jamsankosken Voima Oy, Finland	2002	Peat, bark, wood chips, sludge, oil	185 MW_{th} 252 tonne/h steam; 107 bar; 535ºC
Katrinefors Kraftvarme, Sweden	2002	Sludge, wood residue, wood waste	36 MW_{th} 47 tonne/h steam; 80 bar; 480ºC
Aanevoima Oy, Finland	2002	Bark, wood residue, sludge, peat, oil	157 MW_{th} 217 tonne/h steam; 105 bar; 535ºC
Vamy Oy/Vattenfall Oy, Finland	2001	Bark, secondary sludge, natural gas, peat, wood residue	88 MW_{th} 130 tonne/h steam; 115 bar; 525ºC
Modo Paper AB Husum, Sweden	2000	Bark, sludge, oil	87 MW_{th} 112 tonne/h steam; 60 bar; 450ºC
Sodra C ell AB Monsteras, Sweden	2000	Bark, sludge, oil	105 MW_{th} 133 tonne/h steam; 61 bar; 480ºC
Elektrocieplowni Ostroleka, Poland	1997	Bark, primary and secondary sludge	35 MW_{th} 47 tonne/h steam; 40 bar; 450ºC
Metsa-Serla Oy Simpele, Finland	1997	Peat, bark, sludge, oil	113 MW_{th} 144 tonne/h steam; 115 bar; 525ºC
Oy Metsa-Botnia Kaskinen, Finland	1997	Bark, sludge, oil	96 MW_{th} 126 tonne/h steam; 85 bar; 500ºC

Table 7. Advantages and disadvantages of thermal processes for wastes from pulp and papermaking

Thermal process	Advantages	Disadvantages
Incineration	- Reduction of the amount of residues to be landfilled - Nearly complete elimination of the organic materials - Possible applications for the ashes obtained	- Incineration process can be energy deficient - Air pollution problems (NO_x and SO_2 emissions) - Toxic metals in residue ashes - Source of chlorinated compounds - High cost due to the increasing demand on the flue gas cleaning
Pyrolysis	- Non-burning process - Production of a mixture of gaseous and liquid fuels and a solid inert residue - Can be sited at most existing plants - Minimization of air, land and water pollution - Conversion of all sludge biomass fractions into useful energy - Volume reduction by as much as 90% and production of a sterile carbon char	- A consistent waste stream such as tyres or plastics is required to produce an usable fuel product - Pyrolysis technologies based on the recovery of liquid fuel require low moisture in the sludge (< 20%) - Low technical maturity for application to paper sludges
Steam reforming	-Higher heat transfer rate -Low NO_x emission -Low operating and maintenance costs -Production inhibition of dioxins and furans -Vaporization minimization of toxic metals	- Application to specific wastes
Wet oxidation	-No air pollution -Production of high-pressure steam	- High cost
Super Critical Water Oxidation	-Complete destruction of organic material -No NO_x and dioxins formation due to low operating temperature -Recovery and reuse of salts and fillers precipitated out of supercritical water -Recovery of all heat of reaction as steam and as hot water	- Specifications for the sludges: high content of dry substances and small particle size - Traces of acetic acid and nitrous oxide may be formed
Gasification	-Higher efficiency of energy recovery -Reduced environmental emissions -Ability to handle most inorganic compounds found in sludge -Ash sintering does not impact on reliability -Production of an inert solid waste	- Dewatering and drying of sludge - Not commercially developed for pulp and paper sludge treatment - Complexity of technology - Sludge characteristics which limit gasification efficiency is not fully understood

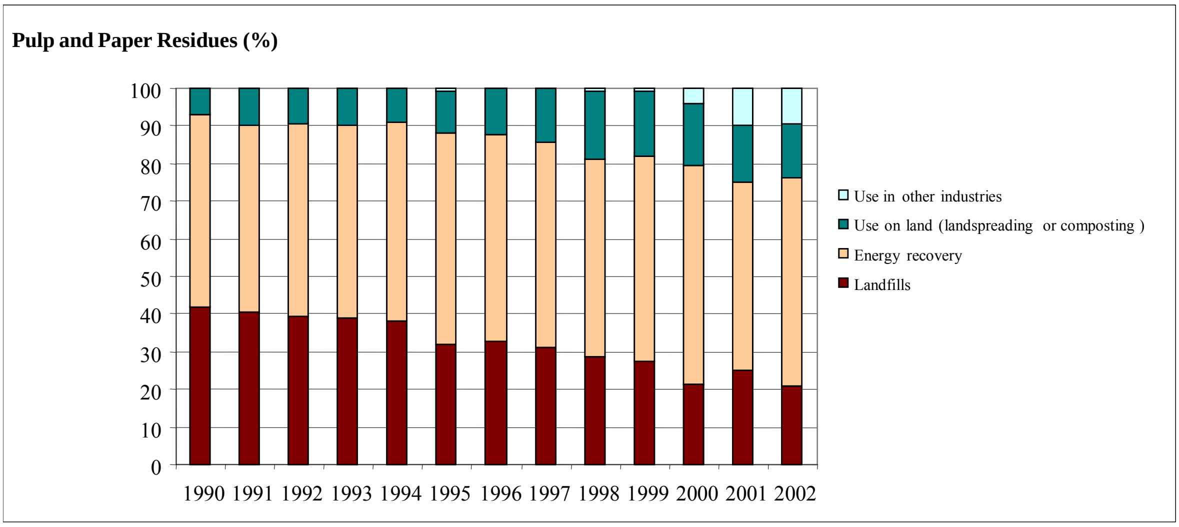


Figure 1. Applications of the pulp and paper residues (CEPI, 2004)

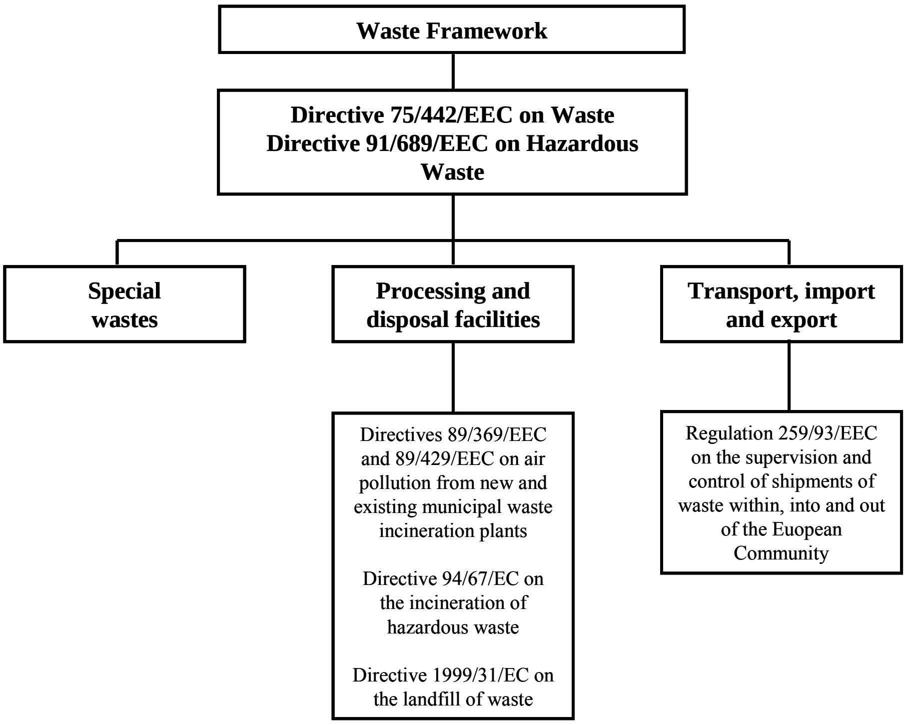
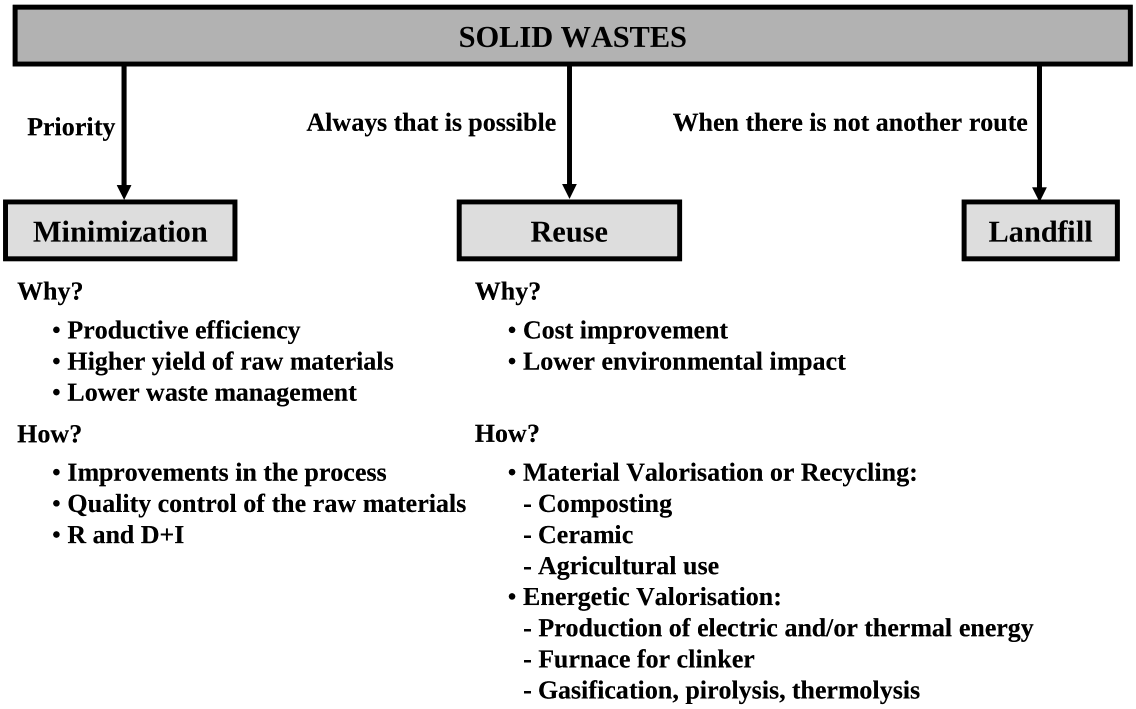


Figure 2. European waste management legislation



Why?

- Productive efficiency
- Higher yield of raw materials
- Lower waste management

How?

- Improvements in the process
- Quality control of the raw materials
- R and D+I

Why?

- Cost improvement
- Lower environmental impact

How?

- Material Valorisation or Recycling:
  - Composting
  - Ceramic
  - Agricultural use
- Energetic Valorisation:
  - Production of electric and/or thermal energy
  - Furnace for clinker
  - Gasification, pirolysis, thermolysis

Figure 3. Management of the solid wastes in papermaking

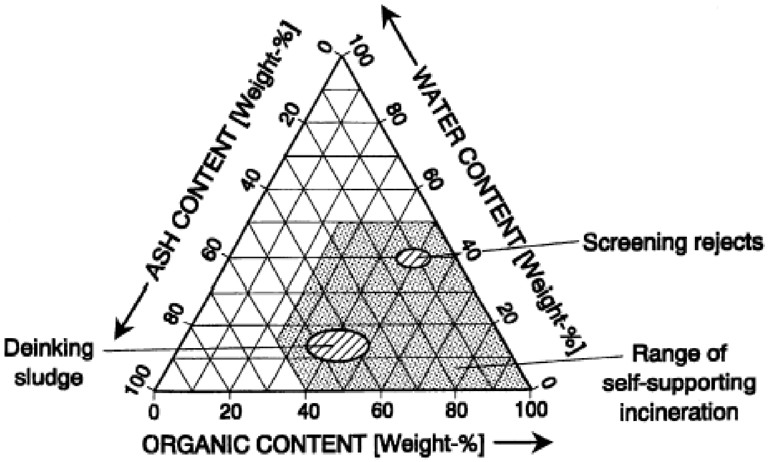


Figure 4. Fuel triangle for residues from paper industry (IPPC, 2001 and provided by IFP)