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Waste-to-energy plant for paper industry sludges disposal: technical-economic study

Antonio C. Caputo, Pacifico M. Pelagagge*

Faculty of Engineering, University of L'Aquila, 67040 Monteluco, L'Aquila, Italy

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Abstract

In this work, a detailed technical-economic analysis of a fluidized bed based waste-to-energy system for disposal of paper manufacturing sludges has been carried out. Specific reference is made to a case study represented by the largest plant in Italy producing recycled paper, with a daily sludge output of about 52 t.

The adopted plant has been sized for a nominal capacity of 140 t per day also allowing the progressive elimination of sludges accumulated in a previously utilized landfill, giving a nominal electrical power output of 3.5 MW.

The main plant sections have been described and the adopted technical solutions have been outlined. A detailed process and equipment characterization has been carried out leading to a thorough evaluation of capital investment, operating costs and revenues. A differential analysis has been performed with respect to the alternative solution represented by the disposal of untreated sludges in an external landfill in order to highlight the savings obtainable. The economic profitability of the investment has been evaluated regarding several performance indices. The economic evaluation has been completed by a sensitivity and risk analysis in order to assess the effects of uncertainties in the economically significant parameters. Adopting most probable values, the savings obtained with the considered waste-to-energy system are evaluated in the 15–20 million Euro range during the estimated plant life of 15 years with a foreseen pay back time of 4 years. Moreover, many environmental benefits result such as the remediation of existing landfill, the avoidance of new landfills opening and very low air pollutants emissions.

Keywords: Sludge combustion; Waste-to-energy plant; Fluidized bed; Paper manufacturing; Economic analysis

1. Introduction

Pulp and paper manufacturing is one of the most pollution intensive and energy consuming industries, justifying a major effort in reducing its environmental impact [1–5]. One of the

* Corresponding author. Tel.: +39-0862-434316; fax: +39-0862-434303.
E-mail address: pelmar@ing.univaq.it (P.M. Pelagagge).

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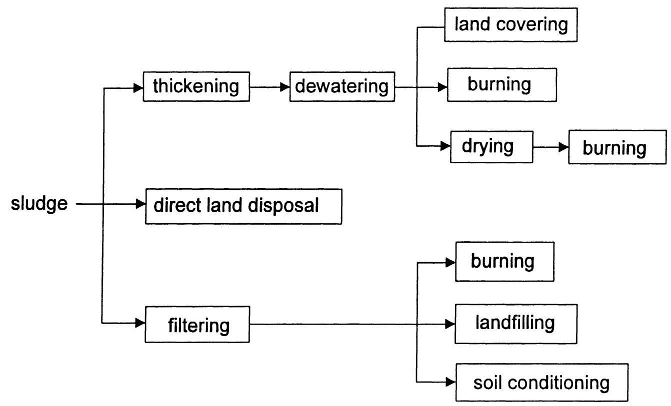

Fig. 1. Sludge disposal options.

main concerns is the sludge disposal problem arising from treatment of the large quantity of water utilized in the production process. After wood or recycled waste processing, in fact, water is discharged with the addition of several contaminants and waste materials, such as fibers, soluble organics from the wood lignin and process chemicals. In particular, the recycling process requires de-inking of waste paper prior of recovery of the fiber, generating a sludge containing particles of ink and fibers too short to be converted to a finished paper product. Typical wastewater treatment processes, thoroughly described in the literature, generate great quantities of sludges either from primary (clarifiers) and secondary treatments (anaerobic and aerobic biological processes). As an example in the mechanical pulping industry, the removed primary and secondary sludges are about 25 and 12 kg/t of processed pulp, making sludge disposal a major environmental problem. Several sludge handling options are available as shown in Fig. 1 [4–9] including either thermal and non-thermal solutions. Traditionally, sludge landfilling has been the preferred sludge disposal solution in Italy. However, beside the risks of ground water contamination, landfill disposal is not a reliable solution as existing sites are reaching capacity and the possibility of opening new ones is questionable, which also makes future disposal costs higher and difficult to forecast. Thermal utilization of sludge generated by the pulp and papermaking processes may be instead an economic and sustainable disposal solution. When compared to other non-thermal forms of disposal like direct land covering, soil conditioning or landfilling, combustion presents many advantages, such as: reduction of the disposed solid mass and volume leading to lower disposal cost; destruction or reduction of the organic matter present in the sludge and the potential for energy recovery which may also benefit from state economic incentives enabling the sale at attractive rates of produced electric energy.

However, careful evaluation of waste-to-energy plants includes the relatively high capital investment, the necessity of ash disposal and the potential for air emissions of pollutants. Moreover, in the considered industrial application, critical emphasis is assumed by the poor low heating value (LHV) characterizing wet sludge, requiring preliminary dewatering and/or drying treatments to bring solids content above 30–35% in order to enable a self-sustained combustion [10].

In order to evaluate the economic feasibility of a thermal approach in this work an in-depth technical-economic analysis of a waste-to-energy plant for disposal of paper manufacturing sludges has been performed with reference to an actual industrial facility. Having this in mind, a detailed process and equipment characterization has been carried out leading to a thorough quantification of capital investment and operating costs/revenues. A differential comparison was also performed with respect to the alternative solution represented by the disposal of untreated sludges in an external landfill in order to highlight the possible savings. The economic desirability of the investment was then assessed resorting to several performance indices: net present value; internal rate of return; pay back time and profitability index. The analysis was completed by a sensitivity and risk assessment in order to evaluate the effects of uncertainties in the economically significant parameters. Results of the case study provide a quantitative basis for the technicians involved in selecting the most cost-effective sludge disposal solutions in similar plants, while pursuing high environmental compatibility performances.

2. Problem statement

Specific reference is made to a facility located in northern Italy, representing a large plant producing paper containing a 65–70% of recycled fiber, with a daily sludge output of about 52 t. The foreseen start-up of a second production line will double this figure in the near future. Sludge characteristics are described in Table 1, referring to fresh process sludges, to sludges already landfilled and to the typical mix of fresh and landfill sludge that will be fed to the combustor. Besides the fairly low LHV, it can be observed that, due to the de-inking process adopted for paper regeneration, the presence of potentially hazardous elements, like sulfur, chlorine, cadmium and fluorine also occurs requiring a complete gas cleaning.

Table 1
Sludge characteristics

	Process sludge	Landfill sludge	Mix to combustor (at maximum load)
LHV (kcal/kg)	1150	570	1000
Moisture (wt.%)	45	70	54.7
Ash (wt.%)	23.1	7.5–12.9	∼20
Combustible matter (wt.%)	31.9	22.5–17.1	∼29
Composition of combustible matter (wt.%)			
C	16.6	9.93	14.01
H	2.18	1.37	1.86
N	0.32	0.2	0.273
O	12.69	8.26	10.97
S	0.056	0.050	0.054
Cl	0.012	0.003	0.0085
F	0.030	0.020	0.026
Hg (mg/kg)	Not significant	Not significant	Not significant
Cd (mg/kg)	0.5	0.3	0.45
Specific weight (kg/m^3)	800	1100	877
Ash softening temperature (°C)	920	920	920

Table 2
Reference operating plant loads

	Process sludge	Landfill sludge	Mix to combustor
Nominal load			
Dry sludge flow rate (t per day)	104	16	120
Moisture content (wt.%)	45	70	50.5
Actual sludge flow rate (t per day) (kg/h)	189.1–7880	53.3–2220	242.4–10100
Maximum design capacity			
Dry sludge flow rate (t per day)	104	36	140
Moisture content (wt.%)	45	70	54.7
Actual sludge flow rate (t per day) (kg/h)	189.1–7880	120–5000	309.1–12880
Reduced load operation			
Dry sludge flow rate (t per day)	52	16	68
Moisture content (wt.%)	45	70	54
Actual sludge flow rate (t per day) (kg/h)	94.5–3940	53.3–2220	147.8–6160

Up to now, sludges have been disposed of in the plant's internal landfill. However, as the landfill is reaching capacity and a new production line will became operational in a short time, an alternative disposal solution had to be defined.

The use of external landfills seemed unfeasible as it would lead to a strong increment in disposal costs with a foreseen heavy penalization of the plant economic performances. This circumstance has prompted the plant owner to install an on-site waste-to-energy disposal facility based on a fluidized bed combustor in order to pursue a sustainable and environmentally conscious development of manufacturing operations. This solution, apart from cutting to one fifth the amount of waste to be landfilled, would allow the progressive elimination of accumulated sludges thus remediating the current landfill site.

The choice has been strongly favored by the possibility of selling the produced electric energy to the local utility at an attractive price compared to the cost of energy paid by the plant to the same utility. According to existing Italian government incentives, in fact, a price increment of about 0.098 Euro/kW h is acknowledged to the energy sold to the utility during the first 8 years of operation.

The incineration plant has been sized (Table 2) for a capacity of 140 t per day of dry sludges enabling the disposal of the daily sludge production from both the existing and the planned production lines plus an amount of already accumulated sludges. The maximum amount of landfill sludges has been set at 36 t per day in order to maintain a sufficient LHV to support self-combustion. Operation at a reduced load of 52 dry sludge tonnes per day is also considered before the start-up of the second production line. Plant operation is foreseen at 330 days per year, 7 days per week and 24 h per day. At full load the combustor heat rate is 11,900 Mcal/h.

3. Waste-to-energy plant

3.1. Overall plant architecture

Process and landfill sludges are separately stored due to their different LHV. Process sludges are transported by trucks to a 40 m^3 cement storage basin equipped with a screw feeder and a chain conveyor to feed two 300 m^3 storage silos. A similar system exists for landfill sludges with the addition of a clods crusher, due to sludge compaction, and a single storage silo. Before feeding the combustor, the two kinds of sludges are homogeneously mixed in the proper proportions to obtain the minimum target LHV. Combustor fumes pass through a heat recovery steam generator (HRSG) which also includes two preheating stages for combustion air. At the HRSG exit, the fumes enter the air pollution control section comprising a cyclone, a dry absorption reactor with sodium bicarbonate and pulverized activated carbon injection for acid gas and air toxics removal plus dust collection utilizing a fabric filter. An induced draft fan after the fabric filter enables the passage of fumes through a gas–gas exchanger acting as a further air preheater, prior to final discharge through the stack. The electricity generating plant utilizes a steam turbine with turbogenerator, degaser and a condenser with a cooling tower. The main sections of the thermal process in the waste-to-energy plant are schematically shown in Fig. 2.

As far as incineration concerns different technologies may be used including multiple hearth furnaces, fluidized bed combustors (FBC), electric furnaces, co-incineration with refuse, single hearth cyclone, rotary kilns, and high pressure wet air oxidation. The first two kinds are the most widely employed in sludge applications [11–14]. FBC technology has been adopted in the present case study due to the higher combustion efficiency and previous successful experiences in hazardous waste combustion [15–17].

The bubbling fluidized bed combustor usually consists of a refractory-lined cylindrical vessel that contains a windbox, where the fluidizing air is introduced by a distributor ensuring uniform dispersion over the vessel cross section. The injected sludge burns into a fluidized bed of inert material, while in the upper disengagement section (freeboard) oxidation of any

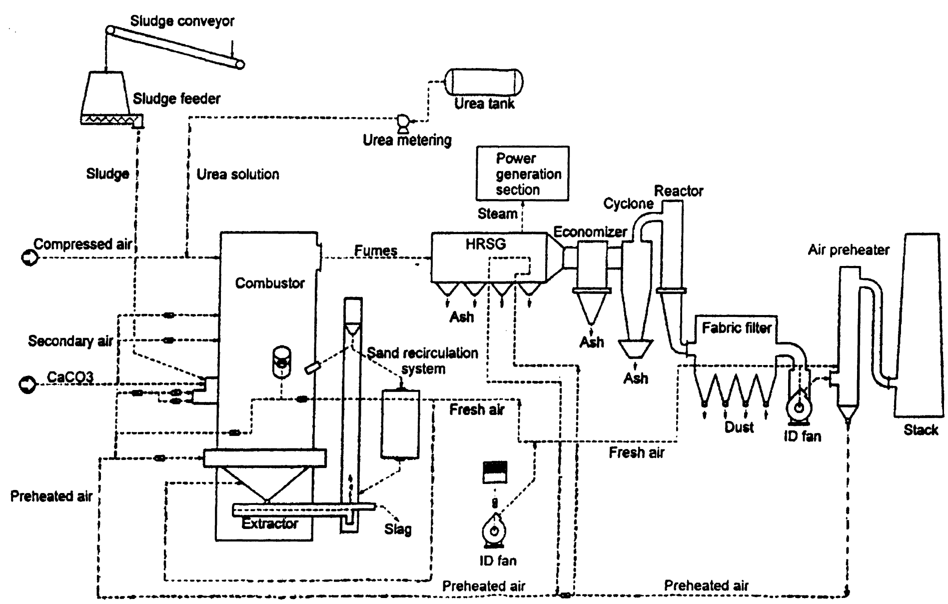

Fig. 2. Process scheme.

unburnt organic occurs [11,18], and elutriated fines are deentrained and allowed to return to the bed. This technique results in a significant improvement in combustion efficiency especially of high moisture containing fuels. In fact, the turbulence in the combustor vapor space, combined with the tumultuous scouring effect and thermal inertia of the bed material, provide for complete, controlled and uniform combustion.

Strong bed agitation by coalescing bubbles greatly increases gas–solid mixing, contact time, heat and mass transfer, thereby reducing the temperature needed to achieve requisite destruction and removal efficiency, also reducing the risk of ash melting. The most noticeable impact of the improved mixing and combustion provided by a fluidized bed combustor is the lower excess air required for complete combustion of the sludge. Normally, FBC can achieve complete combustion with 20–50% excess air, about half the value required by multiple hearth furnaces. As a consequence, FBC have generally lower fuel requirements compared to multiple hearth furnaces. These factors are key to maximize thermal efficiency, minimize char and control emissions making the fluidized bed combustor particularly well suited to problem fuels with low heating value as in the present application. Emissions from a fluidized bed unit are inherently lower than conventional technologies due to the absence of a flame front, to the low and uniformly distributed combustion temperatures and to low excess air within the bed which reduce the formation of certain emissions such as NO_x. The high combustion efficiency lowers the CO amount in flue gas, while the possibility of injecting limestone into the bed and ammonia into the vapor space, to carry out desulphurization ($DeSO_x$) and denitrification ($DeNO_x$) processes obtaining easily disposable by-products, contributes to reduced pollutants emission. Other advantages are the simple construction, easy operation and reduced maintenance due to the absence of moving parts. Moreover, the high thermal inertia of the combustor reduces temperature fluctuations due to variation of sludge feeding rate or heating value, and enables rapid start-up after short stoppages.

In the following paragraphs, some design details of the fluidized bed combustor, the steam production and power generation sections, and the pollution control system have been presented.

3.2. Fluidized bed combustor

In this plant a boiling atmospheric fluidized bed combustor has been adopted, supplied from Energy Products of Idaho (EPI). EPI has installed 76 fluidized bed plants worldwide, six of which burn paper manufacturing sludges [12,19]. The actual combustor is shown in Fig. 3 during the construction phase.

Combustion data (Table 3) and exhaust gas composition (Table 4) have been evaluated considering plant operation at maximum rated capacity (140 t per day of dry sludge, i.e. 12,880 kg/h of wet sludge), complete combustion, ambient air at 25°C and 70% relative humidity.

Preliminary $DeNO_x/DeSO_x$ treatment is carried out inside the combustor through limestone and urea injection. $CaCO_3$ is injected in the combustor in order to increase the ash softening temperature above that of the fumes (950°C) and to carry out a desulphurization reaction:

$$CaCO_3 + SO_2 + \tfrac{1}{2}O_2 \leftrightarrow CaSO_4 + CO_2 \qquad (1)$$

Fig. 3. FBC plant during installation.

The SO_2 amount in the fumes has been computed from literature data [18]. A 70% efficiency of in-furnace desulphurization process at 877°C and Ca/S = 2 was assumed, requiring 43.34 kg/h of injected $CaCO_3$, of which 21.77 kg/h leave the combustor unreacted together with 29.61 kg/h of produced $CaSO_4$. Limestone is fed from a 30 m^3 silo, a screw conveyor (0.55 kW, 100 kg/h) and a pneumatic conveyor utilizing a 2.2 kW, 1000 Nm^3/h blower.

Table 3
Combustion calculations

Stoichiometric air (kmol/kg sludge)	0.0692
Excess air (%)	65
Actual combustion air (kmol/kg sludge)	0.1142
Actual combustion air (Nm^3/h)	32968.6
Actual combustion air (kg/h)	42504
Fumes temperature (°C)	954
Fumes flow rate (Nm^3/h) (Nm^3/s)	44314.2–19.97
Fumes mass flow rate (kg/h)	52679.2
Fly ash (kg/h)	2310.98
$CaSO_4$ produced (kg/h)	29.61
Unreacted $CaCO_3$ (kg/h)	21.77

Table 4
Exhaust gas composition

Fumes composition	Units	
	kmol/kg sludge	vol.%
CO_2	0.0117	7.62
O_2	0.0094	6.12
N_2	0.09	58.63
SO_2	5.07E − 6	0.0033
HCl	2.43E − 6	0.00158
HF	1.37E − 5	0.00892
H_2O	0.0424	27.62

Denitrification is obtained by injecting a urea solution (32.5% bw) through a selective non-catalytic reduction process:

$$CO(NH_2)_2 + 2NO + \tfrac{1}{2}O_2 \leftrightarrow 2N_2 + CO_2 + 2H_2O \qquad (2)$$

The amount of NO produced has been estimated at 0.54 kg/Gcal. With a combustor heat release of 11.9 Gcal/h, it follows that 6.42 kg/h of NO are produced requiring 28.22 kg/h of urea solution with a theoretical 70% removal efficiency. Urea is fed from a 14 m^3 tank equipped with a 3 kW electric heater and a distribution piping utilizing several pumps and electrical heaters with a total power consumption of 7.2 kW.

It is also assumed that 10 kg/h of bottom ash and 95 kg/h of sand are collected at the bottom of the combustor and eliminated, the sand being reintegrated from a 30 m^3 silo equipped with two 0.65 kW motors.

The adopted fluidization velocity for primary air is 1.75 m/s giving a vessel cross section of 15.7 m^2, while fluidization pressure drop is about 9000 Pa.

A natural gas burner ensures proper bed temperature at start-up. Primary fluidization air is preheated in three successive stages due the high moisture content of the sludges. In the first stage, ambient air is heated in a gas-to-gas heat exchanger by a cleaned gas stream exhausted at 170°C from the fabric filter. Fumes are thus cooled to 130°C before being discharged into the atmosphere through the plant stack. The second and third preheating stages are integrated in the HRSG: in the second stage, the air is heated by hot fumes, while in the third stage by produced steam. Combustion air is preheated to 380–390°C. Primary air is about 70% of the total air enabling fluidization and combustion at stoichiometric conditions. The remaining secondary combustion air is uniformly injected along the combustor lateral walls and also utilized to facilitate sludge injection. The bed operates at slightly negative pressure (100 Pa lower than ambient air) to avoid fume leaks.

Combustion air is blown by a 187 kW centrifugal blower having a capacity of 33,000 Nm^3/h.

3.3. Steam production and power generation section

The plant has been sized allowing for a steam production of 15.37 t/h at 48 bar and 460°C when the combustor operates at the rated dry sludge capacity of 140 t per day, enabling an

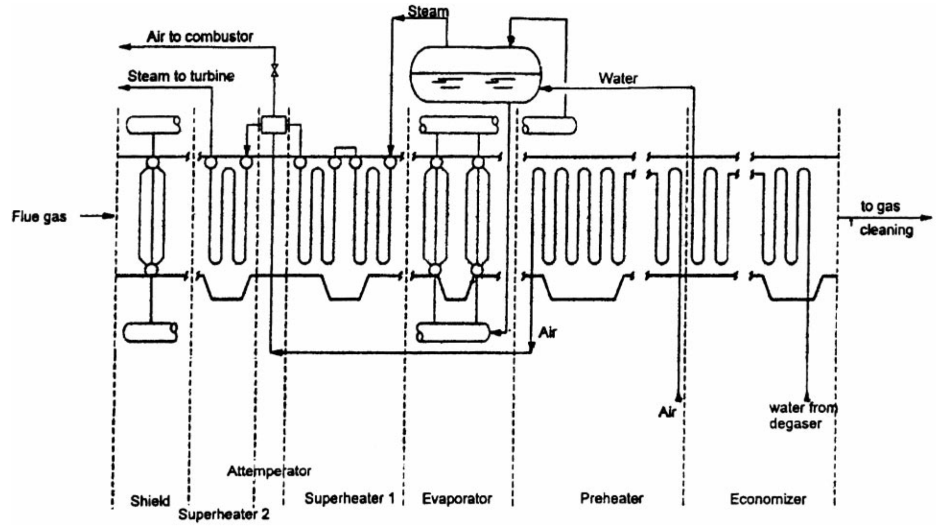

Fig. 4. Scheme of the heat recovery steam generator.

electric generator nominal power output of 3.5 MW. The HRSG is a natural circulation water tube boiler with single pressure level and is composed of the following sections (Fig. 4):

- a heat shield, where hot gas exchanges heat with a steam–water mixture in order to reduce gas temperature to a level of 750°C, compatible with superheater tube corrosion resistance;
- two superheating sections with an interposed third air preheating stage with finned tubes;
- an evaporation section;
- a second air preheater and, finally,
- an economizer.

Fumes enter at 954°C and exit at 170°C. Assuming a heat loss of 2.5%, the energy balance gives a steam flow rate of 15.37 t/h at 48 bar. The feed water flow rate is 15.52 t/h considering a bleeding of 1% of produced steam. Boiler cleaning is carried out by mechanical rappers and an iron ball circulation system consuming 12 kW. It is assumed that 50% of the entering fly ash (1180 kg/h) is deposited inside the HRSG and collected. The HRSG has been designed specifying a low gas velocity (5 m/s) in order to reduce the fume pressure drop to 200 Pa. Technical details of the various HRSG sections are shown in Table 5.

In the power generation section the steam expands in turbine from the boiler outlet condition to 45°C and 0.098 bar. A single steam extraction of 1950 kg/h for the degaser (which operates at 120–150°C and has a volume of 8 m^3) is performed at 5 bar and 252°C (its pressure reduces to 2.6 bar minimum at reduced load operation). In case of turbine outage, steam is by-passed through a lamination-desuperheating valve and discharged at 3 bar in the facility steam distribution network. The turbine is coupled to a 6 kV/50 Hz 4-pole generator rotating at 1500 rpm. Voltage is raised to 15 kV in a transformer before connection to the

Table 5
HRSG details

	Shield	Superheater 2	Attemperator	Superheater 1	Evaporator	Preheater	Economizer
Hot fluid							
Fluid	Fumes	Fumes	Steam	Fumes	Fumes	Fumes	Fumes
Flow rate (kg/h)	52679	52679	15370	52679	52679	52679	52679
T_{in} (°C)	954	750	440	726	623	453	274
T_{out} (°C)	750	726	410	623	453	274	170
Exchanged heat (Mcal/h)	3842.14	437.71	254.76	1844.22	2921.74	2911.25	1613.26
Cold fluid							
Fluid	Steam	Steam	Air	Steam	Steam	Air	Water
Flow rate (kg/h)	15370	15370	42504	15370	15370	42504	15370
T_{in} (°C)	263	410	365	263	221	92	120
T_{out} (°C)	263	460	388	440	263	365	221
Surface (m^2)	152	45	146	168	294	1126	812

utility grid. The steam condenser and a three-module cooling tower complete the thermal cycle section. Total installed power in this section for the circulation pumps is 160 kW.

3.4. Pollution control system

Pollutants concentration in flue gas are shown in Table 6 along with current emission limits (referred to dry flue gas at STP and 10 vol.% O_2 content) and design specifications for the control system. It can be seen that even if some toxic compounds are present, mainly due to the de-inking process, the overall concentration of pollutants in the flue gas is relatively low, making compliance with regulations a fairly easy task [20,21]. In fact, literature data confirm that as far as gaseous pollutants are concerned, the environmental burden is significantly less if paper is recycled, as in the present case, while in overall sludge derived from de-inked recycled paper manufacture is comparable to, or less harmful than, municipal wastewater treatment sludges [3,22–25].

Fume temperature in the cleaning section is 170°C. Following a mechanical cyclone precollector, a fluidized bed dry absorption tubular reactor is adopted, where $NaHCO_3$ powder is pneumatically injected and the following reactions take place:

$$2NaHCO_3 + SO_2 \leftrightarrow Na_2SO_3 + 2CO_2 + H_2O \tag{3}$$

$$NaHCO_3 + HCl \leftrightarrow NaCl + CO_2 + H_2O \tag{4}$$

$$NaHCO_3 + HF \leftrightarrow NaF + CO_2 + H_2O \tag{5}$$

Hazardous air pollutants are adsorbed on separately injected powdered activated carbon. The reaction tower is 12 m long and the gas residence time is 1.1 s, the tower volume being

Table 6
Gaseous emission limits and pollutant concentration in flue gas

	Initial pollutant concentration (mg/Nm^3)	Final pollutant concentration (mg/Nm^3)	Average 1 h limit (mg/Nm^3)	Average 24 h limit (mg/Nm^3)
Dust	45000	4.5	30	10
SO_2	150	9	200	100
NO_2	200	35	400	200
CO	50		100	50
HCl	30	2.5	40	20
HF	95	0.8	4	1
HF + HBr			2	1
HCN	0.5		0.5	
P_2O_5	5		5	
VOC	10		20	10
PCB + PCN + PCT	0.1		0.1	
PAH	0.01		0.05	
Heavy metals (total)	11400		0.5	
Cd + Tl	0.3		0.05	
Hg	0.2		0.05	
Cd + Tl + Hg	0.5		0.2	
PCDD + PCDF[a]	5×10^{-6}			0.1×10^{-6}

[a] Expressed as 2,3,7,8-TCDD equivalent concentration.

about 22 m^3. A sorbent excess of 50% of stoichiometric value is injected, i.e. about 42 kg/h, to absorb SO_2, HCl, HF, while activated carbon injection rate is 7.5 kg/h.

$NaHCO_3$ is stored in a 30 m^3 silo equipped with a mill and pneumatic conveyor with a total power consumption of 12 kW. The activated carbon injection system has a total installed power consumption of 4.4 kW.

Particulate is collected in a pulse-jet fabric filter having a filtering surface of 1255 m^2 subdivided in 475 bags 6 m long, with a permeation velocity of 0.95 m/min. Compressed air at 7 bar is produced by two 8 kW screw compressors with refrigerating dehumidifier and a 2 m^3 storage tank. The final induced draft fan has a 157 kW power consumption and conveys fumes to the existing paper mill stack. Collected ash is conveyed to two 110 m^3 silos through a cooler and screw conveyor system consuming 40 kW.

4. Feasibility study

4.1. Cost evaluation of waste-to-energy plant

The economic evaluation of the waste-to-energy plant has been carried out on the basis of the total capital investment (TCI), of annual costs (AC) and revenues (R).

Total capital investment has been evaluated as the sum of all direct costs (including purchased equipment cost, direct installation costs, plus site preparation and buildings) and indirect installation costs (comprising engineering, contractor fees, start-up, etc.). A breakdown of capital investment cost items is given in Table 7.

Annual costs include operating materials and consumables, maintenance costs (either labor and materials), operating labor, energy costs, ash transport and disposal plus overheads. A list of annual costs is given in Table 8.

Maintenance cost is considered as 1.5% of TCI. Fuel costs are low because it is only used at plant start-up. Ash transportation cost is computed on the basis of a truck cost of 155 Euro per day. General costs and overhead are assumed as 15% of labor cost.

Ash disposal cost is based on a landfilling fee of 0.062 Euro/kg. Electric energy cost is not included as electricity consumption is satisfied by on-site generation. Revenues from sale of produced electricity are included in the following economic analysis section.

4.2. Economic performance measures

The following indices have been used as economic performance measures:

Net present value (NPV)

$$\mathrm{NPV} = \sum_{k=1}^{N} F_k/(1+i)^k - \mathrm{TCI} \qquad (6)$$

Profitability index (PI)

$$\mathrm{PI} = \frac{\sum_{k=1}^{N} F_k/(1+i)^k}{\mathrm{TCI}} \qquad (7)$$

Table 7
Investment cost items

Cost item	Cost (MEuro)	Weight (t)	Manhours
Equipment costs			
Sludge storage unit	0.8728	50	
Air pollution control equipment	0.6574	50	
Ash handling and storage unit	0.0991	10	
Cooling towers	0.0438	10	
Metering and injection systems	0.0883	10	
Tube heat exchangers	0.1162	10	
Bridge crane	0.0165	5	
Belt conveyors	0.0774	5	
Tanks and degaser	0.0495	6	
Pumps	0.1714	6	
Combustor and HRSG	3.2872	350	
Turbine	0.5526	150	
Piping	0.3315	70	
Fumes ductworks	0.0273	5	
Instrumentation			
Fumes analysis	0.1931	10	
Gas meter	0.0165	1	
Field instruments	0.1322	7	
Digital control system	0.3925	20	
Electrical materials	0.2478		
Metal structures	0.0826	50	
Frie-fighting/insulation	0.0108	3	
Chemicals, lubricants	0.0108	2	
Construction: installation costs			
Buildings and civil works	1.3556		60000
Mechanical mountings	0.8893		37000
Carpentry works	0.0599		2500
Piping installation	0.3253		13500
Instruments installation	0.1466		7000
Electrical installations	0.0490		2500
Painting/insulation installation	0.1084		7000
Precommissioning	0.1518		7000
Other yard expenses	0.1518		
Indirect costs			
Field supervision	0.2633		9700
Commissioning/test run	0.1549		3600
Suppliers specialists	0.3873		2700
In-house specialists	0.9864		22000
Mark-up (15% of TCI)	2.2052		
Internal committer costs	0.6197		15000
Allowance for funds during construction	0.4214		
Total capital investment	15.75		

Table 8
Operating cost items

Materials	Cost (kEuro per year)	Annual consumption	Unit cost (Euro)
Demineralized water	1.0329	4000 (t)	0.2582
Industrial water	0.5164	160000 (m^3)	0.0774
Instruments air	2.0658	160000 (Nm^3)	0.0129
Compressed air	15.4937	2000000 (Nm^3)	0.0077
FBC sand	0.8263	7800 (kg)	0.1032
FBC limestone	18.5924	360 (t)	51.6456
Urea solution	86.7647	240 (t)	361.5198
Sodium bicarbonate	67.1393	360 (t)	185.9244
Activated carbon	46.4811	60000 (kg)	0.7746
Sodium hypochlorite solution	0.1549	1800 (kg)	0.0774
Sulphuric acid	0.2582	3000 (kg)	0.0774
Corrosion inhibitor	10.8455	3200 (kg)	3.3569
Biocide	0.5164	110 (kg)	5.6810
Phosphate	0.5164	260 (kg)	1.9108
Deoxygenator	0.5164	130 (kg)	4.1316
Total operating materials cost	263.3930		
Maintenance cost	236.5372		
Operating labor	346.0261		
Fuel	2.5822		
Ash transport	53.1950		
Ash disposal	1239.4966		
Overhead	52.1621		
Annual cost	2193.3925		

Internal rate of return (IRR), defined as the i value that makes null the NPV value.

Pay back time (PBT), discounted or not, defined as the time required to recover the initial investment.

In Eqs. (6) and (7), F_k is the annual cash flow at the kth year, N the plant life and i the interest rate.

4.3. Economic analysis

In order to carry out a thorough evaluation, two scenarios are compared:

1. Sludge landfill disposal.
2. Sludge combustion in waste-to-energy plant.

4.3.1. Scenario (1)

In this scenario, the waste-to-energy plant is not built. TCI is obviously null, while F_k is given by annual sludge disposal cost:

$$F_k = -C_\mathrm{D}\,\mathrm{OH}\,\mathrm{SP} \tag{8}$$

where C_D (Euro/kg) is the landfill disposal cost including transportation, OH (h per year) the annual operating hours of the papermaking plant, and SP (kg/h) the hourly process sludge production.

However, this disposal solution is not reliable in fact, due to scarcity of landfill, costs are likely to grow in an unpredictable manner and as existing nearby landfills became unavailable transportation costs are likely to increase strongly.

4.3.2. Scenario (2)

In the case of waste-to-energy plant operation, the annual cash flow should subtract the computed annual costs to revenues R (MEuro per year) coming from the sale of produced electric energy:

$$F_k = R - \mathrm{AC} \tag{9}$$

As the waste-to-energy plant power consumption is about 590 kW and the generator output at plant rated capacity is 3470 kW, the net power output available for sale is roughly $P =$ 2870 kW. If P_E (Euro/kW h) is the price of electric energy sold to the utility then

$$R = P\,\mathrm{OH}\,P_E \tag{10}$$

Two cases have been considered: in the first case electricity is sold at current market value without incentives during the whole plant life, and in the second one electricity is sold during the first 8 years of plant operation at a higher price according to existing government incentives.

4.3.3. Differential treatment

From the two scenarios a differential investment has been considered in order to highlight possible savings obtained in both cases of presence and absence of government incentives. The differential investment has been defined by subtracting Eq. (8) from Eq. (9) and introducing Eq. (10), giving the following expression of the *k*th cash flow

$$F_k = P\,\mathrm{OH}\,P_E + C_\mathrm{D}\,\mathrm{OH}\,\mathrm{SP} - \mathrm{AC} \tag{11}$$

The NPV of the differential investment, computed assuming the most probable parameters values indicated in Table 9 and electricity price incentives, is 17.33 MEuro after 15 years of

Table 9
Adopted parameters values

Parameter	Value
Interest rate (per year)	0.08
TCI (MEuro)	15.75
Process sludges flow rate (kg/h)	7880
Sludge disposal cost (Euro/kg)	0.056
Operating hours (h per year)	8000
Operating costs (Meuro per year), excluding ash disposal	0.954
Turbine power output (kW), available for external sale	2870
Electricity price (Euro/kW h), with incentives	0.144
Electricity price (Euro/kW h), without incentives	0.046
Plant life (years)	15
Ash disposal cost (Euro/kg)	0.062

Table 10
Economic performance evaluation indices of the differential investment

	NPV (Meuro)	IRR (% per year)	PI	PBT (years)	Discounted PBT (years)
Incentives	17.33	26.64	2.1	3.5	4.1
No incentives	4.40	12.34	1.27	6.8	9.9

plant operation, while without incentives it falls to 4.40 MEuro. Table 10 shows the values of the other economic analysis indices computed for the differential investment.

Fig. 5 shows the cumulative discounted cash flow trends of the differential investment with or without incentives. The single cases of landfill disposal or waste-to-energy system (with or without incentives) are also shown for sake of comparison, always computed adopting the values of influencing parameters shown in Table 9.

Inspection of Fig. 5 shows that the waste-to-energy solution is always preferable to landfill case, considerably reducing overall disposal costs. The total cost break-even point with respect to landfill disposal is reached after 10 or only 4 years of plant operation, respectively, in the absence or presence of incentives for the sale of produced electric energy.

Adopting the most probable parameter values the savings obtained with the considered waste-to-energy system are evaluated in the 15–20 million Euro range during the estimated plant life of 15 years with a foreseen pay back time of less than 4 years.

However, the investment profitability could be much higher if the current internal landfill could be re-utilized for combustor ash disposal instead of being entirely remediated. This possibility would eliminate the need of an external landfill and related disposal and transportation cost which are the main operating cost items of the waste-to-energy solution. Even

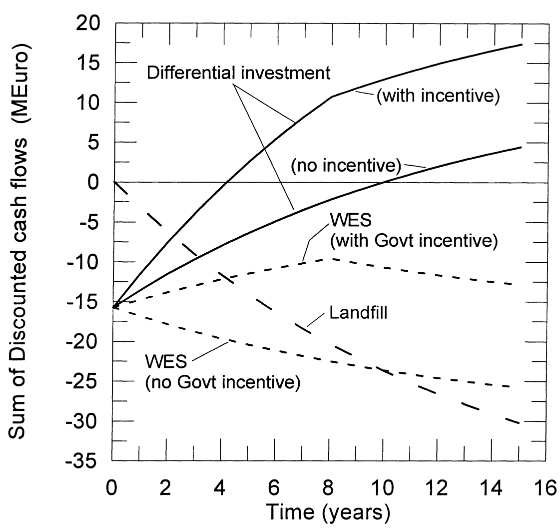

Fig. 5. Discounted cash flows comparison.

Table 11
Sensitivity analysis parameters values

Parameter	Pessimistic value	Optimistic value	Variation respect modal differential NPV value
Interest rate (per year)	0.1	0.05	+34.04/−18.28%
TCI (MEuro)	19	12.5	+18.76/−14.08%
Process sludges flow rate (kg/h)	5800	10000	+64.04/−62.81%
Sludge disposal cost (Euro/kg)	0.072	0.051	+49.82/−15.55%
Operating hours (h per year)	7500	8200	+5.96/−14.86%
Operating costs (MEuro per year), excluding ash disposal	1.24	0.760	+9.50/−14.11%
Turbine power output (kW), available for external sale	2300	3450	+25.62/−25.15%
Electricity price (Euro/kW h), with incentives	0.046	0.155	+8.38/−74.57%
Electricity price (Euro/kW h), without incentives	0.041	0.056	+3.7/−1.85%
Plant life (years)	10	20	+17.08/−25.15%
Ash disposal cost (Euro/kg)	0.077	0.056	+6.11/−15.25%

if combustion ash landfilling may require the upgrading of the internal landfill and some specific authorization, it could be a viable option as recent studies based on the analysis of data available in the scientific literature and in regulatory agencies files demonstrate that much of the concerns regarding the quality of ash leachate are groundless [26].

4.3.4. Sensitivity and risk analysis

In order to assess the influence of economic and operational variables on the investment profitability, a sensitivity analysis has also been carried out by considering possible variations of the most influencing parameters from their assumed modal value shown in Table 9.

The range of variation of the considered parameters and their percent influence on the NPV value of the differential investment is shown in Table 11. Four parameters, namely the interest rate, process sludge flow rate, sludge disposal cost and electric energy sale price with incentive, show significant influence causing NPV deviations greater than 30%.

Associating a probability of occurrence to such parameter values, as shown in Table 12, it is possible to compute the combined effects of their variation and the corresponding probability of each value of the considered economic evaluation index. The risk analysis is based again on the differential investment.

Table 12
Probability of most influencing parameters values

Parameter	Value	Probability	Value	Probability	Value	Probability
Interest rate (per year)	0.05	0.3	0.08	0.5	0.1	0.2
Sludge flow rate (kg/h)	5800	0.15	7880	0.7	10000	0.15
Sludge disposal cost (Euro/kg)	0.051	0.1	0.056	0.5	0.072	0.4
Electricity selling price (Euro/kW h)	0.046	0.3	0.144	0.6	0.155	0.1

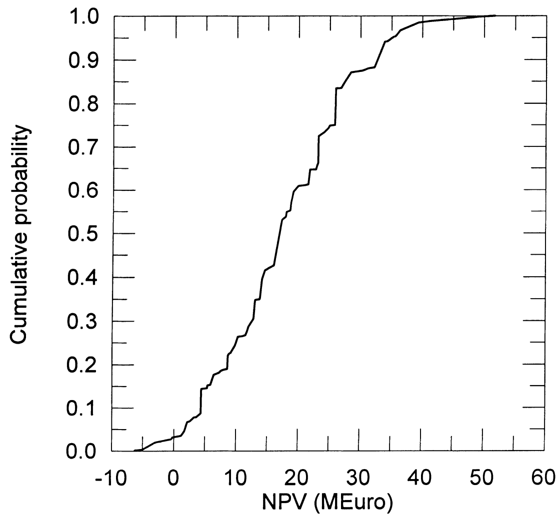

Fig. 6. Cumulative probability of NPV (differential investment).

Fig. 6 shows the obtained cumulative probability curve of NPV for the differential investment, showing negligible risk of a monetary loss compared to landfill disposal and of not recovering the invested capital.

5. Conclusions

In this study, a detailed technical-economic analysis of a fluidized bed based waste-to-energy plant for disposal of paper industry sludges was carried out with reference to an actual recycled paper manufacturing plant. This solution has been compared with a sludge landfilling option pointing out the significant cost savings and environmental benefits obtained by thermal utilization of waste sludges. A sensitivity and risk analysis has also been carried out in order to assess the effects of uncertainties in economically significant parameters, showing that a negligible risk ($<$3%) occurs of either a monetary loss with respect to landfill disposal and of not recovering the invested capital.

Adopting most probable values, the savings obtained with the considered waste-to-energy system are evaluated in the 15–20 million Euro range during the estimated plant life of 15 years with a foreseen pay back time of about 4 years. The positive results of the feasibility analysis, and the consideration of the significant cost savings obtained compared to the landfilling option, convinced plant owners of the advisability of adding a waste-to-energy plant to their facility. Therefore, the waste-to-energy plant has been built, it underwent the start-up during the summer of 1999, and now it is fully operational.

As concluding remark, the investment profitability of the plant could be much higher if the current internal landfill could be utilized for combustor ash disposal instead of being entirely remediated. This possibility would eliminate the need of an external landfill and related costs which are the main operating cost items of the waste-to-energy solution. Finally, significant environmental benefits also come from adoption of a waste-to-energy solution, such as current landfill remediation, avoidance of new landfills opening, resource recovery, very low air and soil pollution impact.

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