

Sustainability in the urban environment by thermal processing of waste

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ABSTRACT

In the developed world, 75% of the population live in urban areas, a figure projected to rise to nearly 83% by 2030, while in the developing world, this rate of urbanisation is even faster. One of the most important environmental problems associated with urbanisation is the amount of waste that is generated at a rate that outstrips the ability of the natural environment to assimilate it and authorities to manage it. Therefore, if we are to deliver a more sustainable economy, we must do more with less by making better use of resources and putting these materials to good use. The use of municipal solid waste (MSW) to produce energy or fuel is not only an important waste treatment option but it also saves fossil fuels and hence can help meet renewable energy targets, address concerns about global warming and contribute significantly to achieving Kyoto Protocol commitments.

This paper reviews the state of the art technologies used in the thermal treatment processes of waste, which include combustion, gasification and pyrolysis. Within this framework and from a sustainable waste management prospective, a combustion plant was studied to investigate the flue gas cleaning systems and in particular the effects of replacing the conventional calcium hydroxide sorbent with sodium bicarbonate in the removal of gaseous acids from the combustion gas stream (flue gas). This was done to evaluate both the improved efficiency and the economic evaluation of the plant. The work presented in this paper will be further developed to investigate the efficiency of energy recovery and gas cleaning systems using fluidised bed combustion and gasification technologies.

Keywords: Municipal solid waste; Combustion; Gasification and Pyrolysis.

1. INTRODUCTION

The issue of waste is not new to anyone and in recent years, one cannot argue that the total quantity of waste has increased significantly in the EU countries and the rest of the world raising the critical question of its safe disposal and management. Hence, it is necessary to optimise the recovery of resources from waste, whether as materials through recycling and composting or as energy or fuel through efficient biological and thermal processes. The use of MSW to produce energy or fuel is not only an important waste treatment option but it also saves fossil fuels and hence can help meet renewable energy targets, address concerns about global warming and contribute significantly to achieving Kyoto Protocol commitments (Yassin et al., 2005).¹

The main objective of this work is to investigate the sustainability of alternative approaches to thermal processing of urban wastes namely combustion, pyrolysis and gasification, with a particular focus on the application of fluidisation technology to optimise the potential for generating energy from renewable sources and for improving waste management systems. This project is part of the Sustainable Urban Environment (SUE) Waste Management Consortium, which is created by several UK university groups including UCL and is sponsored by EPSRC. The Consortium carries out research relevant to the problems of waste resource management in urban environments through a combination of scientific, technological and multidisciplinary projects.

The overall aim of the Consortium is, in the short to medium term, to contribute towards meeting impending legislative requirements without making an inappropriate and irrevocable commitment to any particular type of treatment technology, while, in the medium to long term, to contribute to the development of waste management strategies that are optimal in environmental, societal, technological and economic terms.

2. WASTE, THE BURNING ISSUE

It is estimated that more than 3000 million tonnes of waste are generated in Europe every year.² The UK alone produces about 434 million tonnes of solid wastes per year, enough to fill the Royal Albert Hall in London every hour. Of this, about 28.8 million tonnes of MSW was collected in England and Wales in 2001/02. 77% of the MSW was landfilled while 13% was recycled and composted and only 9% was incinerated with energy recovery.³

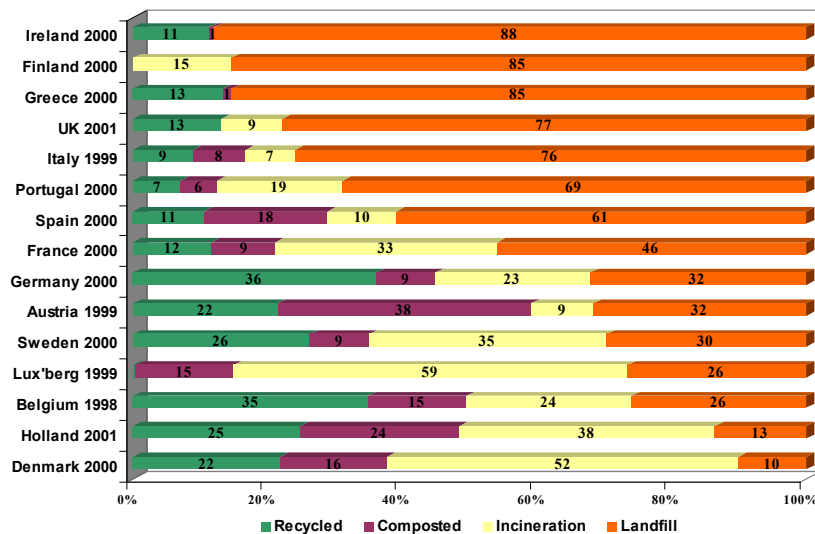


Figure 1. MSW management in Europe

In the following sections, a brief review is reported on the state of the art technologies used for the thermal processing of waste, which includes combustion, gasification and pyrolysis. The review focuses on the current and future status of these technologies with

reference to a number of existing plants at various levels of operation worldwide and the role of fluidised beds in contributing towards sustainable waste management systems.

Fluidisation, in general, is *'the operation by which solid particles are transformed into a fluid-like state through suspension in a gas or liquid'* (Kunii, Levenspiel, 1991).⁴ Fluidised beds are extensively employed in many industrial applications due to advantages such as;

- rapid mixing of solids, which leads to isothermal conditions throughout the bed and hence the operation can be controlled simply and reliably;
- high heat and mass transfer rates between gas and particles.

3. COMBUSTION

Combustion reduces the volume of waste by approximately 90% and the remaining inert bottom ash residue can be used in road-building or landfill construction and therefore, reducing the need to quarry new materials. This technology converts heat energy into steam and/or electricity for residential and industrial use. The annual amount of energy generated in 2000 from incineration was estimated to be equivalent to the electricity demand of Switzerland (49.6 TWh).⁵

3.1. Status of combustion technology

Moving grate, rotary kiln and fluidised bed combustors are widely used commercially because of their applicability to large-scale use and their versatility. Fluidised bed combustors, in particular, are becoming more popular because of their ability to handle wastes of widely varied properties and the many advantages in controlling emissions. They float waste in a bed of sand that is fluidised by the air needed for combustion and either are bubbling or circulating beds operating at both atmospheric pressure and elevated pressures. Both atmospheric fluid bed configurations have achieved commercial status while pressurised fluid beds are still in an early commercial scale-up phase. Other advantages of fluid bed combustors include:

- higher combustion efficiency that is comparable to pulverised fuel-fired combustors;
- reduction in boiler size;
- low corrosion and erosion with easier ash removal;
- simple operation with fast response to load fluctuations.

The commercial capacity of the fluid bed combustors are influenced mainly by the cross-sectional area of the vessel. Therefore, fluidised bed designs need to be optimised with the emphasis on outstanding engineering innovations to achieve economical vessel arrangements and reach large commercial scales. An emerging technology in this field is the revolving fluid bed developed by Ebara Corp. and which is installed in more than 100 facilities worldwide. These facilities include a plant in Madrid, which takes in about 10% of the city's waste, around 1200 t/d, recovers compost and valuable substance after pre-processing and burns the rest to produce energy for electric power. In Germany, another plant processes

about 204 t/d of waste from the city of Berlin and produces high-pressure, high-temperature steam for connection to existing facilities.

This internally circulating fluid bed boiler, ICFB, is shown in Figure 2 and has a fairly simple mechanism with no moving parts inside the furnace. It has a slanted bed floor and the air flow rate is controlled to produce a revolving sand motion. It is this mixing effect that produces a combustion performance superior to that of conventional fluidised bed furnaces.⁶

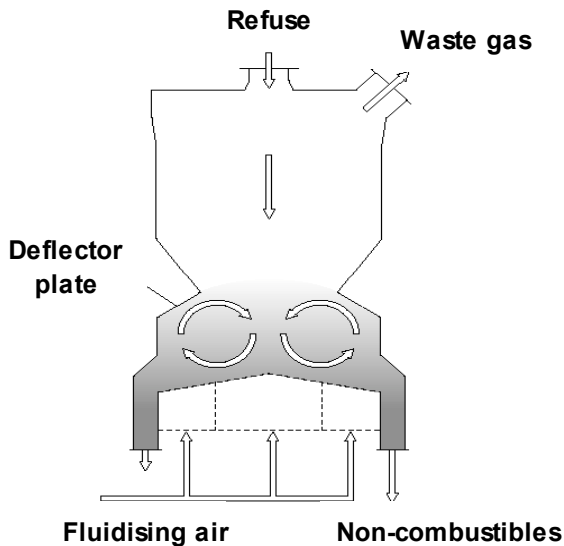


Figure 2. An internally circulating fluid bed

ROWITEC[®] is another emerging technology developed by Lurgi Lentjes in Germany and is licensed by Ebara. The ROWITEC[®] firing technique is an advantageous combination of the stationary and circulating fluidised beds. It is modified especially for the combustion of MSW and other residual materials, such as sewage sludge. Other advantages include:

- high burnout (typical residues level in bed ash is < 0.1 %);
- low flue gas emissions;
- minimum mechanical fuel preparation.

Although Lurgi and other European companies, such as Foster Wheeler (FW) in Finland and Termiska Processor (TPS) in Sweden, have been developing and optimising fluid bed techniques for decades, there is a lack of successful operational experience at commercial scale here in the UK. This is mainly due to the potential operational issues with the pre-treatment front end of the process, which is required to be robust to homogenise municipal wastes for delivery into the fluid bed. Lurgi is currently working with the Waste Recycling Group Ltd in the UK to build an integrated waste management facility at Allington in Kent. The facility will incorporate the ROWITEC[®] technology and will have a capacity of 500 kt/y of MSW with a total electricity output of 29 kWhe.⁷

4. GASIFICATION

Gasification is the thermal conversion of organic matter by partial oxidation into a gaseous product called *syngas*, which mainly consists of H_2 , CO with small amounts of CO_2 , H_2O , CH_4 , N_2 and tar. The reactions are carried out at elevated temperatures of about 500-1400°C and pressures up to 33 bar. The syngas can replace fossil fuels in high efficiency power generation, heat, combined heat and power applications and in the production of liquid fuels and chemicals via synthesis gas.

The oxidant used can be air, pure oxygen, steam or a mixture of these gases. Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value of about 5 MJ/m³. Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and CO with a heating value of 10-12 and 15-20 MJ/m³ respectively. The main gasification applications are summarised in Table 1.

Table 1. Main gasification applications

Heat
<ul style="list-style-type: none">• District & industrial heating
Electricity only
<ul style="list-style-type: none">• Co-firing• Integrated gasification combined cycle (IGCC)
Combined heat and power
<ul style="list-style-type: none">• Pulp and paper industry• District heating/electricity
Synthesis gas
<ul style="list-style-type: none">• Hydrogen• Ammonia• Methanol, ethanol, dimethyl ether (DME), etc.• Fischer-Tropsch liquids• Chemicals

4.1. Status of gasification technology

A variety of biomass gasifier types have been developed. The main reactor types are fixed beds, either downdraft or updraft, and fluidised beds, either bubbling or circulating. For large scale applications, above 25-50 MWe, circulating fluidised bed gasifiers are preferred while for the small scale applications, up to 0.5 MWe, downdraft gasifiers are mainly used. Bubbling fluidised bed gasifiers can be competitive in medium scale applications.

Large scale fluidised bed systems have become commercial due to the successful co-firing projects. Nevertheless, fluidised beds have the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions and efficient reactions. The technology is more suitable for generators with capacities greater than 10 MW as it can be used with different fuels, requires relatively compact combustion chambers and allows for good operational control. A schematic diagram for bubbling and circulating fluid bed gasifiers are shown below in Figure 3.

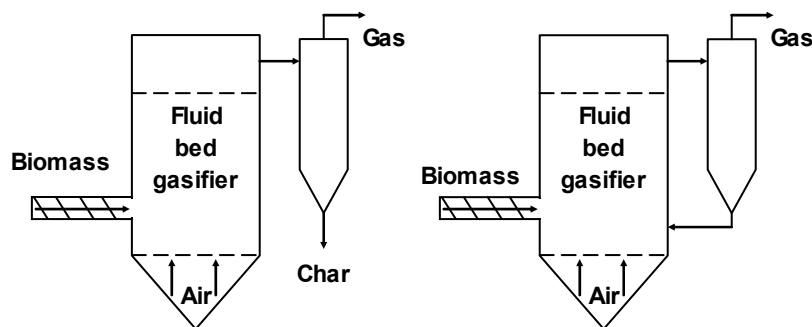


Figure 3. Bubbling (Left) and circulating (Right) fluidised bed gasifiers

Gasifiers are available from Foster Wheeler and Bioneer in Finland, Lurgi in Germany, Vølund in Denmark, Termiska Processor in Sweden, PRM Energy in the USA, Repotec in Austria and Ebara in Japan. In addition there is extensive research and development at universities, research institutes and companies around the world. Table 2 summarises these leading biomass gasification systems.^{8,9}

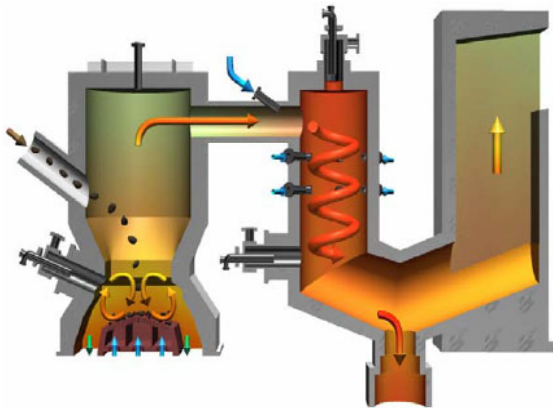
Recently, gasification-melting systems have been developed due to needs of effective reduction of dioxins and detoxifying ash; material and thermal recovery; effective use of ashes and simple and compact facilities. The demonstration unit in Burlington USA, for example, uses an indirectly heated gasification technology developed by Battelle Columbus. The process features two combined ACFB reactors for separate steam gasification in one reactor and residual char oxidation with air in the second one with solids exchange between the two reactors. The indirect processes takes advantage of a unique thermo-chemical characteristic of biomass in that it will volatilise to about 70-85% fuel gases, leaving a char of around 15-20% of the input energy that is separated and burnt with air to produce heat for the pyrolysis, volatilisation gasification process.¹⁰

Table 2. An overview of fluidised bed biomass gasification projects

Plant	Gasifier	Fuels	Product gas use
ARBRE / UK	8MWe ACFB, TPS	Willow, poplar	IGCC
Bahia/ Brazil	32 MWe ACFB, TPS	Wood	IGCC
Burlington/ USA	50 MWe ACFB, Battelle	Wood chip	Steam generation
Grève-in-Chianti / Italy	6.7 MWe ACFB, TPS	RDF ^a	Steam cycle
Hawaii / USA	PBFB, IGT ^b	Various	Gas cleanup testing
Lahti/ Finland	40-70 MW ACFB, FW	Wood, REF ^c , various	PC/ NG co-firing
N.V. EPZ/ Holland	85 MWth ACFB, Lurgi	Wood waste	PC Co-firing
Norrundet/ Sweden	27 MW ACFB, FW	Bark, wood waste	Lime kiln (Heat)
Pietarsaari/ Finland	35 MW ACFB, FW	Bark, wood, waste	Lime kiln (Heat)
Pisa / Italy	12 MWe ACFB Lurgi	Wood chips	IGCC
Rüdersdorf / Germany	100 MWth ACFB, Lurgi	Wood, RDF, lignite	Cement kiln (Heat)
Tampere/ Finland	7 MWe PBFB ^d , Carbona	Various	IGCC
Värnamo/ Sweden	18 MW PCFB, FW	Wood	IGCC
Zeltweg/ Austria	10 MWth ACFB ^e , AEE ^f	Wood	PC ^g Co-firing

(a) RDF = Refuse derived fuel, (b) IGT = Institute of Gas Technology, The Renugas process.
 (c) REF = Recovered fuel, (d) PBFB = Pressurised bubbling fluid bed,
 (e) ACFB = Atmospheric circulating fluid bed, (f) AEE = Austrian Energy & Environment,
 (g) PC = Pulverised coal.

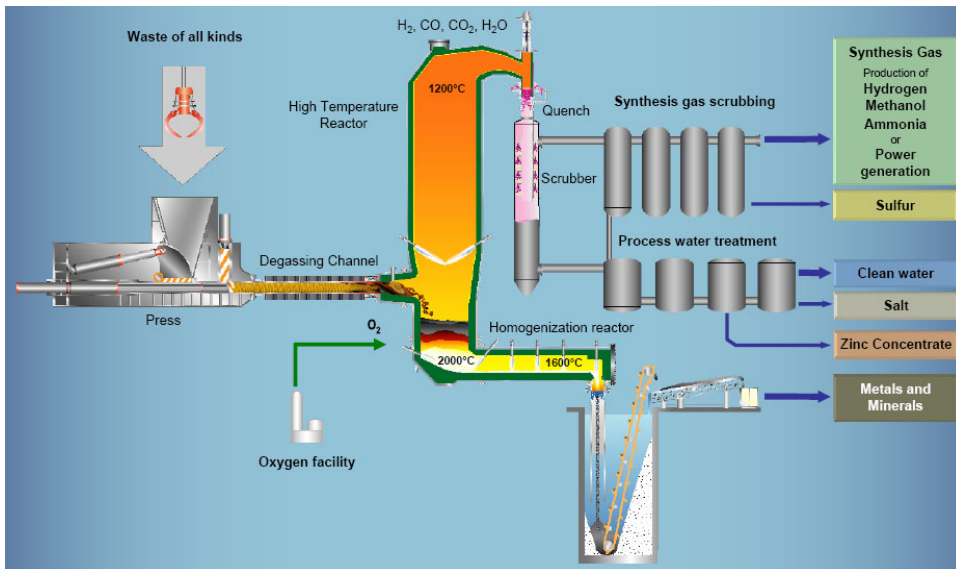
Ebara's TwinRec is state of the art twin internally circulating fluidised bed gasifier. It is designed with ash vitrification technology for material recycling, energy recovery and detoxification of wastes in an integrated and economical process. The gasifier, shown in Figure 4, is a revolving fluidised bed incinerator, which gasifies the wastes first and the produced heat content of the gases is used to raise the temperature in the next-stage slag combustion furnace. Due to the high temperatures, dioxins are decomposed and the ash is converted to a slag under its own heat. Aomori is the largest gasification and slagging combustion system in Japan with a capacity of 450 t/d and a power output of 17.8MWe.¹¹



Source: Ebara

Figure 4. Ebara's TwinRec

Thermoselect of Switzerland, on the other hand, is regarded as one of the market leaders for combined pyrolysis/gasification systems of MSW in Europe. Its process, shown in Figure 5, consists of a high temperature recycling, closed loop process, which recovers pure synthesis gas, useful mineral and iron rich materials as products. Commercial plants have been recently erected in Karlsruhe, Germany, and in Tokyo-Chiba, Japan with waste treatment capacities of 225,000 t/y and 100,000 t/y respectively.¹² The technical challenges facing gasification are summarised in Figure 6.



Source: Thermoselect

Figure 5. The Thermoselect Process

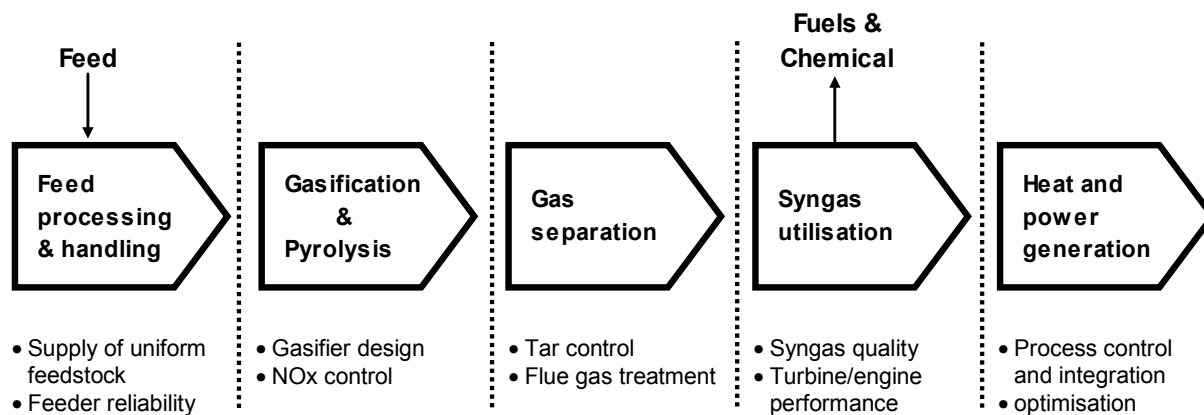


Figure 6. Gasification technical challenges

5. PYROLYSIS

Pyrolysis involves heating in the absence of oxygen rather like traditional charcoal production to produce a liquid fuel, a solid char and some combustible gas, which are used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash. The product char can be used in effluent treatment applications.

The composition of pyrolysis products depends on the heating rate, residence time and temperature, as well as on the composition of the fuel as shown below. Although most of the work is carried out on wood due to its consistency and comparability between tests, nearly 100 different biomass types have been tested by many laboratories ranging from agricultural to solid wastes.

Table 3. The different modes of the pyrolysis¹³

Mode	Conditions	Liquid	Char	Gas
Fast pyrolysis	Moderate temp, short residence time	75%	12%	13%
Carbonation	Low temperature, very long residence time	30%	35%	35%
Gasification	High temperature, long residence times	5%	10%	85%

5.1. Status of pyrolysis technology

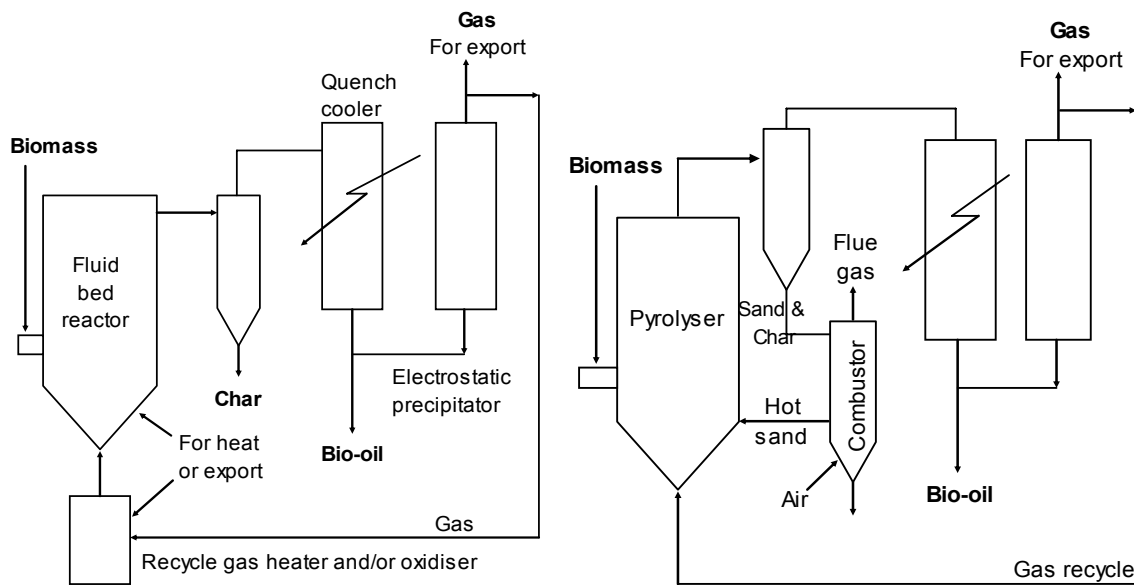
The liquid bio-oil product from fast pyrolysis has the considerable advantage of being storable and transportable as well as the potential to supply a number of valuable chemicals. In this respect it offers a unique advantage and should be considered complementary to the other thermal conversion processes. Up to 1989, the Alten plant in Italy was the only European plant with a slow pyrolysis demonstration plant of 500 kg/h for liquid and char production with approximately 25% yield of each. A comprehensive survey of fast pyrolysis processes has been published that describes all the pyrolysis processes for liquids production that have been built and tested in the last 10-15 years.¹⁴ The main fast pyrolysis technology users are listed in Table 4.

Table 4. Main fast pyrolysis technology suppliers

Technology	Major developers
Bubbling fluid beds	Dynamotive (Canada); VTT (Finland); Wellman (UK); University of Waterloo (Canada)
Circulating fluid and transported beds	Ensyn (Canada); CRES (Greece)
Ablative pyrolysis	NREL (USA); Aston University (UK)
Entrained flow	GTRI (USA); Egemin (Belgium)
Rotating cone	Twente University; BTG (Netherlands)
Vacuum pyrolysis	Pyrovac (Canada)

Although the best reactor configuration is not yet established with most processes giving between 65-75% liquids based on dry wood input, fluidised bed technology, as for gasification, is one of the most efficient and economic technologies of actualising fast pyrolysis as it offers high heating rate, rapid devolatilisation, convenient char collection and re-utilisation. A schematic diagram for bubbling and circulating fluid bed pyrolysers are shown below in Figure 5.

Fast pyrolysis technologies for liquid fuel production have been successfully demonstrated at small-scale and several large pilot plants and demonstration projects are in operation or at an advanced stage of construction. Nevertheless, they are still relatively expensive and thus face economic and other non-technical barriers when trying to penetrate the energy market. There are also no standards for the production and use of bio-oil resulting in large variations in the fuel quality. Hence, common standards and markets need to be developed, which require the networking between research institutions, industries and governments on national and international levels. Network activities can also support development and fundamental research into the production and application of bio-oil. The main pyrolysis applications with their technical challenges are summarised below in Table 7.



Source: Bridgwater, 2003

Figure 7. Bubbling (Left) and circulating (Right) fluidised bed reactors.

Table 5. Main pyrolysis liquid applications and technical challenges

Application	Properties	Challenges
Combustion	<ul style="list-style-type: none"> • Bio-oil burns readily on ignition • Emissions are controllable 	<ul style="list-style-type: none"> • Slight equipment and procedure modifications • Scale-up
Power generation	<ul style="list-style-type: none"> • Fuel production is de-coupled from power generation • Dual fuel diesel engine successful at 250 kWe • Gas turbine successful at 2.5 MWe 	<ul style="list-style-type: none"> • Durability • Adaptation to bio-oil characteristics • Optimisation of combustion system and determination of improved engine operating and emission characteristics • Stability uncertainty and effects of ash & char • Scale-up
Liquid upgrading	<ul style="list-style-type: none"> • Hydro-treating to naphtha and upgrading to diesel • Zeolite cracking to aromatics 	<ul style="list-style-type: none"> • Hydro-treating is costly • Zeolite cracking is less expensive but less efficient and developed
Chemicals	<ul style="list-style-type: none"> • Specialty chemicals • Intermediates e.g. polyphenols, fertilisers, environmental chemicals 	<ul style="list-style-type: none"> • Improvement of bio-oil quality • Process integration • Cost reduction

6. NON- TECHNICAL BARRIERS FOR COMMERCIALISATION

6.1. Economics Issues

Cost is the main barrier for the commercialisation and development of any process. The cost of thermal treatment varies from one country to another and the trend towards stricter emission controls has led to significant increases in the treatment cost. However, these costs are decreasing with the introduction of the new state of the art facilities with more efficient flue gas cleaning systems. Incentives are essential for commercially viable biomass and waste projects as all bio-fuels have to compete with fossil fuels, which are relatively cheaper. These incentives need to be both of sufficient significance and of sufficient duration to provide enough encouragement for companies to invest and operate the plant. In the case of pyrolysis, this would also help to provide more substantial quantities of much needed bio-oil for extended testing in applications so the process can prove itself and gain full commercialisation.

In countries where cheap or negative cost biomass and waste exists, the employment of biomass is very competitive. In Sweden and Denmark, where a carbon and energy tax have been introduced, more expensive wood fuels and straw are now utilised commercially. In Brazil, ethanol produced from sugar cane is competing with petrol.

In the UK, a subsidy scheme to encourage the deployment of renewable energy schemes in the form of the Renewables Obligation came into force on 1st April 2002. This obliges all electricity suppliers to source a percentage of their electricity from renewable sources. The percentage will increase in stages from 3% in 2002 to 10.4% in 2010.¹⁵ The Performance and Innovation Unit (PIU) in the Cabinet Office has recently recommended that a further target of 20% of electricity from renewables by 2020 should be adopted.¹⁶ An

exemption of renewable energy from the Climate Change Levy has also been in place since April 2001. This is a tax on business use of energy and the normal rate for electricity of 0.43p/kWh is not paid by users of renewable energy.

6.2. Social Issues

The public considers the disposal of waste as a significant environmental concern but '*it is not an issue at the forefront of their minds*'.¹⁷ There is also a widespread approval and interest in renewal energy and bioenergy as long as it is *not in my back yard!!* This is also referred to as the *BANANA* syndrome, i.e. *Build Absolutely Nothing Anywhere Near Anybody!*

Hence, there is a great need for more open debate and greater effort to achieve a degree of informed consensus amongst all interested parties including the public. Indeed this requirement is at least equal to, if not greater than, continued technical development. There is also a potential to increase public's awareness of waste issues through association with environmental issues such as:

- Linking waste with global issues such as climate change, which is an issue that people appear particularly aware of and concerned about.
- Linking waste to local issues, including street cleaning and litter. These are all currently high on the public's agenda.

6.3. Regulatory Issues

There are multiple policies at international, European and national level which have an impact on the development of bioenergy. These include the Kyoto Protocol, EU directives on electricity from renewable energy and biofuels, waste management and water quality Directives and the energy efficiency commitments (EEC). Unless these policies are integrated, barriers to development can be 'unwittingly' put in place. However, through integration and synergy it may be possible to maximise the development of the resource. This requires communication and dialogue, in particular at a national level.

6.4. Technological issues

The trend towards pre-treatment of the waste with the view to separate and recycle affects the caloric value of the residual waste. The end result is normally a reduced volume of wastes with an increased calorific value leading to financial and technical difficulties for dedicated incinerators. The large investment costs of waste technologies and the need for high tech emissions control systems create a trend towards the elimination of small plants and the building of large centralised ones, as in the UK. This has a great influence on the structure of the whole waste management chain and penetration of the emerging gasification and pyrolysis technologies, making smaller units viable, can modify this trend if commercial development brings their investment costs down.¹⁸

7. ENERGY FROM WASTE: A CASE STUDY

This case study presents the work being carried out at Germanà and Partners Consulting Engineers in Rome where the process design of an EfW combustion plant is studied for the initial stage of the work on the sustainability of the thermal treatment processes of urban waste. The plant, shown in Figure 8, is designed by Germanà & Partners for Technip Italy S.p.A and it uses 2 stoker grates supplied by MARTIN GmbH with each process line treating 17.24 tonnes of MSW per hour. The total electric power generation is 34 MWe.

The flue gas cleaning system of the plant consists mainly of a conditioning tower; a dry venturi reactor; fabric filters; a recirculation loop and storage silos for the dry calcium hydroxide reagent and activated carbon. The recycle loop is incorporated in the plant design to ensure maximum reagent utilisation by sending partly reacted material collected by the bag filters to the dry reactor. Activated carbon is injected in the venturi reactor to separate dioxins, furans and residual mercury from the flue gas (combustion products) while, calcium hydroxide (hydrated lime) neutralises gaseous acids such HCl , SO_2 and HF .

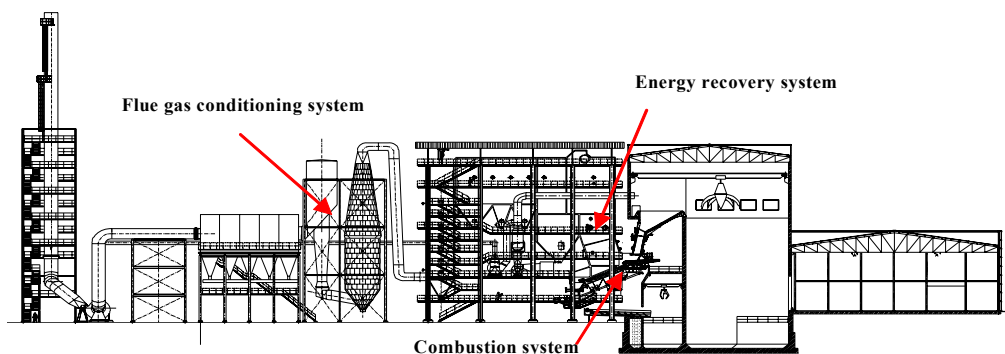
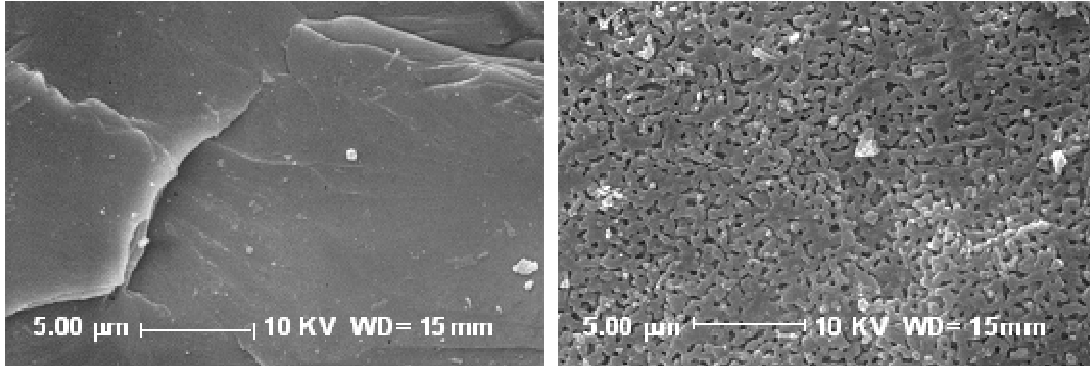


Figure 8. External layout of the case study combustion plant

From a sustainable waste management prospective, the effects of replacing the conventional calcium hydroxide reagent ($Ca(OH)_2$) with sodium bicarbonate ($NaHCO_3$) in the removal of gaseous acids from the flue gas is investigated. A mathematical model is developed and applied to compare the two reagents in terms of their efficiency in removing the gaseous acids and for the subsequent economic evaluation of the plant which will be carried out in a later work.

Although $Ca(OH)_2$ is commonly used in the major air pollution control systems as it is readily available and is much cheaper than $NaHCO_3$, it is corrosive and irritating to handle, required in excess and needs lower operating temperatures unlike $NaHCO_3$ which, is easier to handle, has lower stoichiometric ratio and higher removal efficiencies at a wide range of temperatures. This superior performance of $NaHCO_3$ has not fully been explained in the literature but nevertheless its reactivity can be attributed to its physical properties and chemical behaviour. The reactions of the reagent with the gaseous acids are in fact neutralisation reactions and involve a thermal activation stage where $NaHCO_3$ converts rapidly into Na_2CO_3

when brought into contact with the hot flue gases which, in turn neutralises the acid gases to form inert solid salts. The Scanning Electron Microscope Analysis in Figure 9 shows that the particle has a high specific surface area and porosity, which may explain its superior removal powers. NaHCO_3 has also been claimed to partially reduce the amount of NO_x in the flue gas by reacting with NO_2 and forming a solid salt, NaNO_3 .¹⁹



A. Very smooth grain surface

B. Highly porous grain surface

Figure 9. SEM Analysis for NaHCO_3 prior and after thermal activation.

8. THE MODEL

The reaction between the reagent and the flue gas is of a gas-solid non-catalytic heterogeneous reaction and hence a simplified version of the *unreacted-core* model is used. For a reaction in the form of $aA (g) + bB (s) \rightarrow \text{product (solid)}$, two different cases are considered for this model. The first assumes that the continuous formation of solid product and inert material, without flaking off, would maintain the particle size unchanged as in the reactions of calcium hydroxide. In the second case, the particle size changes as the reaction progresses due to the formation of gaseous products flaking off of the solids as in the case of sodium bicarbonate reactions.²⁰

8.1. Case One: Fixed-sized Particle

Three process steps are identified to may control the overall reactions rate;

- Diffusion through gas film

$$\frac{t}{\theta_1} = x_B \quad \text{and} \quad \theta_1 = \frac{a\rho_B R}{3bM_B k_g C_{Ag}} \quad (1)$$

where θ is the time required for complete conversion for individual controlling steps in (s); x_B is the conversion fraction of the solid reagent B at time t ; ρ_B is the density of unreacted core in (kg/m^3); R is the outside radius of the fixed-size particle or the initial radius of the shrinking particle in (m); M_B is the molecular weight of unreacted core in (kg/kmol); k_g is the mass transfer coefficient in (m/s) and C_{Ag} is the concentration of the gaseous acid A in main fluid stream in (mol/m^3).

- Diffusion through ash layer

$$\frac{t}{\theta_2} = 1 - 3(1 - x_B)^{2/3} + 2(1 - x_B) \quad \text{and} \quad \theta_2 = \frac{a\rho_B R^2}{6bM_B D_e C_{Ag}} \quad (2)$$

where D_e is the effective diffusivity of A in a porous structure in (mol/m^3).

- Chemical reaction

$$\frac{t}{\theta_3} = 1 - (1 - x_B)^{1/3} \quad \text{and} \quad \theta_3 = \frac{a\rho_B R}{bM_B k_s C_{Ag}} \quad (3)$$

where k_s is the reaction rate constant respectively in (m/s).

8.2. Case Two: Shrinking sphere

Two process steps are identified to may control the overall reactions rate;

- Diffusion through gas film

$$\frac{t}{\theta_4} = 1 - (1 - x_B)^{2/3} \quad \text{and} \quad \theta_4 = \frac{y\rho_B R^2}{2bM_B D_e C_{Ag}} \quad (4)$$

where y is the mole fraction of A in the fluid.

- Chemical reaction

$$\frac{t}{\theta_3} = 1 - (1 - x_B)^{1/3} \quad \text{and} \quad \theta_3 = \frac{a\rho_B R}{bM_B k_s C_{Ag}} \quad (5)$$

9. RESULTS

Applying the kinetic model to the reactions between the gaseous acids namely hydrogen chloride (HCl) and sulphur dioxide (SO_2) and the solid reagents, Figures 10 and 11 are obtained showing the profiles of the effects on reaction rates by the various controlling steps.

Figure 10 illustrates the predicted effects on the reaction rates using $Ca(OH)_2$ as the solid reagent while Figure 11 shows the same effects but using $NaHCO_3$ as the solid reagent. From these profiles, one can state that diffusion through the ash layer for the reactions between $Ca(OH)_2$ and the acid gases controls the overall reaction rate as the ash layer thickness increases with the extent of the reaction. For the second case, the reactions between $NaHCO_3$ and the acid gases are entirely controlled by the chemical reaction step.

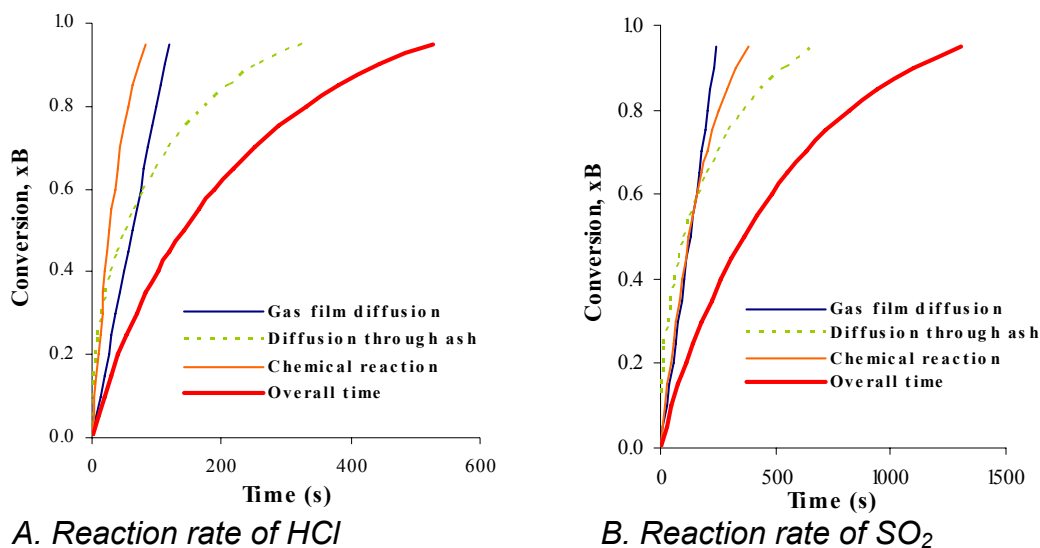


Figure 10. Predicted effects of controlling steps on the conversion rate of HCl and SO₂ using Ca(OH)₂.

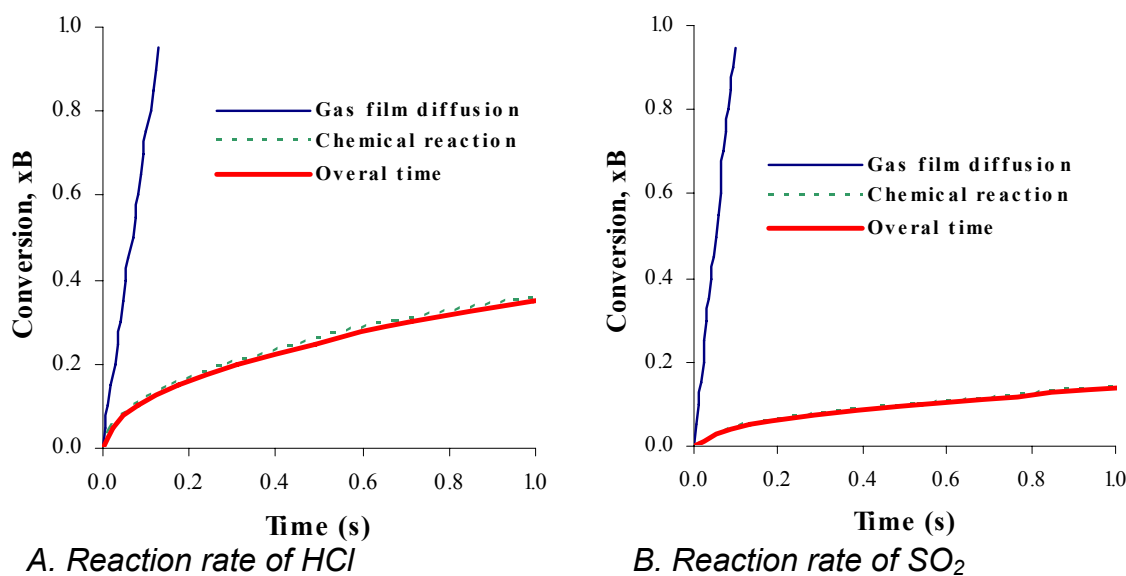


Figure 11. Predicted effects of controlling steps on the conversion rate of HCl and SO₂ using NaHCO₃.

Table 6 summarises the overall reaction times for 95% removal of the acid gases using both reagents and the number of recycle stages taken to achieve it. This demonstrates clearly the superior efficiency of sodium bicarbonate in removing the acids from the flue gas stream compared to the conventional calcium hydroxide reagent. The acid gases are converted into salts and hence removed from the stream within few minutes of the reaction taking place using sodium bicarbonate and within fewer recycle stages.

Table 6. Neutralisation times and numbers of recycle stages for reactions using $\text{Ca}(\text{OH})_2$ & NaHCO_3 .

Reagent	Time required for the reagent to neutralise 95% of the acid gases (s)		Number of recycle stages required to neutralise 95% of the acid gases	
	<i>HCl</i>	SO_2	<i>HCl</i>	SO_2
$\text{Ca}(\text{OH})_2$	515	1959	83	315
NaHCO_3	12	95	2	15

In fact, the neutralisation reaction slows down after the initial surface of sodium carbonate has reacted with *HCl* and SO_2 due to pore blockage but nevertheless, the particle decomposes further evolving H_2O and CO_2 gases into the surrounding atmosphere. This creates a network of void spaces throughout the particle, a *popcorn effect*, which exposes more fresh reactive sites allowing the acid gases to diffuse through them.

10. COSTING

A full study of the economic feasibility for the installation of EfW fluidised bed combustion and gasification plants alongside this mobile-grate combustion plant will be presented in a later work. Therefore for the purpose of this study, only the economic viability of replacing the conventional calcium hydroxide reagent with sodium bicarbonate within the flue gas treatment system is presented.

A material and energy balance of the process has been developed to carry out the cost implications and this evaluation is based on the combustion plant having 2 treatment lines each with a capacity of 17.24 tonnes of MSW per hour.

The plant operates for 312 working days per year and having already determined the total amount of waste treated and the amount of reagents required for the neutralisation of the acids from the mass and energy balance, the amount of reagents required per tonne of MSW and their final total cost are reported in Table 7.

Table 7. Amount of reagents required and their final cost

Reagent	Amount ($\text{kg}/\text{tonne}_{\text{waste}}$)	Cost ($\text{€}/\text{tonne}_{\text{waste}}$)
$\text{Ca}(\text{OH})_2$	16.85	1.40
NaHCO_3	1.88	0.38

11. CONCLUSIONS

Energy from waste should not be seen as a one-step disposal process but as an integrated strategy that incorporates several handling and treatment steps, such as waste separation, recycling, energy recovery and residue management. It is also an alternative source of energy, which by displacing fossil-fuels can help meet renewable energy targets, address concerns about global warming and contribute to achieving Kyoto Protocol commitments.

A review on the state of the art technologies using combustion, gasification and pyrolysis has been reported in this paper. Gasification and Pyrolysis offer more scope for recycling than combustion with: 1) better energy efficiency, 2) contribution to reducing global warming; 3) more flexibility of scale. However, it is worth noting here that many current projects do not implement these advantages, preferring instead to use cheaper and proven conventional incinerators but with lower efficiencies. Within this framework, a combustion plant was studied to investigate the flue-gas cleaning systems and in particular the effects of replacing the conventional calcium hydroxide sorbent with sodium bicarbonate in the removal of gaseous acids from the flue gas. This was done to evaluate both the improved efficiency and the economic evaluation of the plant.

From the review, it can be concluded that at the present, gasification and pyrolysis can best penetrate into the energy markets via economic development through biomass system integration. Therefore, technical superiority and the ability to integrate these technologies into existing and/or newly developed systems, where it can be demonstrated that the overall system offers better prospects for economic development, are some of the key factors for the commercialisation of these technologies. Although there is no obvious "best" technology nevertheless, fluid beds offer robust and scalable reactors with better energy efficiencies and greater pollution controls.

The design process of an EfW combustion plant has been studied for the initial work of this project on the sustainability of alternative approaches to thermal treatment of urban waste. The technical and cost implications of replacing calcium hydroxide with sodium bicarbonate in the flue gas treatment system have been investigated. Although the latter is a more expensive reagent, it proves to be a more efficient and economically an attractive option for the removal of acid gases than calcium hydroxide. A full study of the economic feasibility for the installation of EfW fluidised bed combustion and gasification plants alongside this mobile-grate combustion plant will be presented in a later work.

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