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Technology Status Review of Waste/Biomass Co-Gasification with Coal

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Abstract

Coal might be co-gasified with waste or biomass for environmental, technical or commercial reasons. It allows larger, more efficient plants than those sized for the biomass grown or waste arisings within a reasonable transport distance; specific operating costs are likely to be lower; and, fuel supply security is assured.

This review paper assesses the current status of co-gasification technologies and quantifies the potential future demand for such plant. It aims to identify and prioritise areas where further R&D activities need to be focused to enhance the commercial opportunities for these technologies. The paper contains:

- A survey of the market potential for co-gasification having regard to influences such as national and international environmental legislation, energy policies, targets for sustainable development, and public opinion.
- An objective assessment of the current status of co-gasification and supporting technologies world-wide, including associated gas clean-up and utilisation technologies.
- A critical assessment of the strengths and shortcomings of existing technologies in relation to commercial, or near-commercial needs and information on manufacturers.
- Suggestions for R&D and identification of other measures which would improve market opportunities for co-gasification, paying particular attention to UK stakeholders.

All types of co-gasification technology are addressed in the review. At the largest scale, these include the well proven fixed bed and entrained flow gasification processes. At smaller scales, emphasis is placed on technologies which appear closest to commercial operation. Pyrolysis and other advanced thermal conversion processes are included where power generation is practical using the fuel produced.

The review covers three main areas: (i) the core fuel handling and gasification/pyrolysis technologies; (ii) fuel gas clean-up; and, (iii) conversion of fuel gas to electric power. The integration of these into commercially viable systems is considered in general terms.

In this paper, the term "waste" is used in the broadest sense to include municipal solid waste (MSW), refuse derived fuel (RDF), scrap tyres, sewage sludge, wood waste and any other commercial/industrial waste but excluding hazardous wastes. Although the latter can usually be safely gasified, the special handling precautions upstream of the gasification process have not been considered.

1 Introduction

This paper examines how the use of coal as a feedstock can improve the technical and commercial viability of waste and biomass gasification processes. Such a co-gasification approach provides economies of scale that should reduce operating costs and improve process efficiency to allow better use of waste or biomass than would be the case in smaller, dedicated processes.

After a brief summary of the chemistry of gasification and pyrolysis, the paper looks at the technical issues of co-gasifying different materials with coal. These, along with commercial constraints identified in an economic analysis and regulatory constraints, place boundaries on the size and configuration of a plant design if it is to be successful. Public opinion and the attitude of those companies with the experience to develop projects are both explored since they are crucial to any progress.

It would not be possible to review all the numerous technologies that are commercially available, or close to being commercial in a short paper. Section 9 provides an overview of the most promising technologies for co-gasification projects and identifies others of interest.

The paper concludes with some comments on where coal is most likely to add value to waste and biomass projects in the future.

2 The drivers for waste/biomass co-gasification with coal

Sustainable development underpins much of today's policy debate and no more so than in policies on energy and waste. The European Commission's White Paper on renewable sources of energy sets out a European Union (EU) wide target for 12% of primary energy to come from renewable sources by 2010 (COM(97)599). The Commission has proposed more recently, a directive to promote electricity from renewables with a 22.1% target for 2010 (COM(2000)279). The UK has its own national target of 10% by 2010. However, governments are cognisant of the costs involved; the UK has capped these by introducing a *buy-out* premium (*ie* a fine) of 3 p/kWh if suppliers are unable to source competitive supplies of green energy. Across the EU, the installed capacity of biomass/waste fuelled plants is forecast to grow from around 4.4 GW in 2000 to 6.0 GW in 2020 (EC, 1999), suggesting perhaps as many as 150 new plants worth over €3 billion.

Waste policies are generally based on a hierarchy in which energy recovery sits just below the least attractive disposal option, as illustrated in Figure 1 taken from the European Community's strategy for waste management (OJ C 076, 11/03/1997, p. 1).

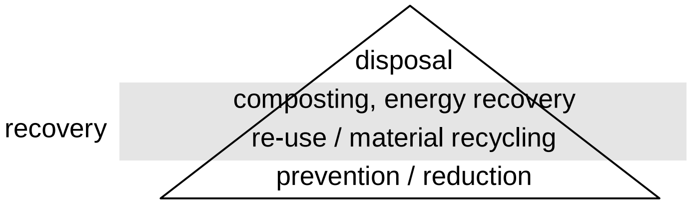


Figure 1 - Waste hierarchy

With disposal to landfill becoming more expensive as new environmental legislation and taxes bite, along with a scarcity of sites, there is a growing demand for energy recovery. For example, the Landfill Directive (1999/31/EC) sets binding reductions on the quantity of biodegradable MSW going to landfill: a 25% reduction on 1995 tonnages by 2006 rising to 50% and then 65% by 2009 and 2017 respectively. Waste tyres are given special consideration with landfill of whole tyres to be banned from 2003 and shredded tyres from 2006. There remains much uncertainty about how these reductions will be achieved, but there are many companies offering and developing waste to energy solutions.

The traditional waste to energy plant, based on mass-burn combustion on an inclined grate, has a low public acceptability despite the very low emissions achieved over the last decade with modern flue gas clean-up equipment. This has led to difficulty in obtaining planning permissions to construct the new waste to energy plants that are needed. After much debate, the UK government decided to exclude mass-burn plants from the proposed obligation to support renewable sources of electricity; however, it left the door open for advanced waste conversion technologies (gasification, pyrolysis and anaerobic digestion), but will only give credit to the proportion of electricity generated from non-fossil waste. This actually contradicts the waste hierarchy since the fossil element might genuinely have no further use (*eg* disposal of plastic wastes from anaerobic digesters).

Co-utilisation of waste and biomass with coal may provide economies of scale that help achieve the policy objectives identified above at an affordable cost. In the UK, the government proposes to limit incentives for co-firing of biomass to 2011, so beyond then only the advanced conversion processes considered in this report are likely to receive State support. Moreover, the UK government sees these as "*well suited for community-sized developments*" (DTI, 2001), suggesting that waste should be dealt with in smaller plants serving towns and cities, rather than moved to large, central plants (satisfying the so-called *proximity principal*).

3 Advanced thermal treatment processes

Gasification processes have the potential to be more efficient than conventional combustion processes; principally because the higher temperatures reached in gas turbines and gas engines

(Carnot cycle) allow higher efficiencies to be achieved than is possible with steam plant (Rankine cycle).

There is also the possibility of designing very clean gasification processes where noxious gases are removed from the syngas fuel prior to combustion rather than from post-combustion flue gases. With the greater power density of gas turbines, and the smaller size of equipment needed to clean fuel rather than flue gases, the capital cost of gasification processes should, in theory, be lower than combustion processes. In practice, these multiple benefits have yet to be realised, but industry and governments continue to invest in R&D on the assumption that they will be.

There are also other possible benefits of gasification:

- more stable solid waste residues;
- ability to safely destroy hazardous wastes;
- lower visual impact; and
- greater public acceptance.

The last point is significant to developers seeking planning permission for new plant, not only waste to energy plants but all types. With many non-governmental organisations (NGOs) favouring gasification processes over other alternatives for the final disposal of wastes and the production of electricity from biomass, the opposition to new development is likely to be less than for other infrastructure development.

4 The chemistry of gasification and pyrolysis

Gasification and pyrolysis are complex processes and for a deeper understanding, the reader is referred to the overview prepared by IEA Coal Research, a co-operative project supported by members of the International Energy Agency (Kristiansen, 1996). The short account below is largely based on an earlier Technology Status Review of gasification systems for utility-scale power generation which complements this review (Tabberer, 1998).

Gasification: the partial oxidation and conversion of a carbonaceous solid or liquid substance into a synthesis gas (syngas) in which the major components are carbon monoxide (CO) and hydrogen (H_2).

Pyrolysis: the thermal decomposition of a carbonaceous material in the absence of oxygen (sometimes more correctly referred to as thermolysis). Fast pyrolysis or thermal gasification maximises the production of syngas, whereas slow pyrolysis or carbonisation maximises the production of char, tars and oils.

Table 1 - Typical analyses of coal, biomass and waste fuels by decreasing oxygen content (Davidson, 1999; Hein and Scheurer, 2000; Optimat Ltd, 2001)

ar - as received daf - dry ash free	straw	wood	dried sewage sludge	MSW (UK av)	RDF	brown coal	hard coal	TDF
Proximate analysis, wt% (ar)								
moisture	10.6	7.2	3.0	31.4	4.1	50.4	5.1	0.4
ash	5.5	2.9	45.1	27.8	11.7	2.5	7.8	5.8
volatile matter	66.5	74.6	49.5	36.8	79.2	25.8	32.9	68.2
fixed carbon	17.4	15.3	2.4	4.1	5.0	21.2	54.2	25.6
Ultimate analysis, wt% (daf)								
carbon	50.7	49.3	48.1	54.2	64.7	69.4	79.2	84.7
hydrogen	4.8	6.3	9.4	7.8	9.0	5.2	6.2	8.0
oxygen	43.2	43.2	34.0	34.8	24.3	24.2	12.1	4.8
nitrogen	0.64	0.44	6.16	1.50	0.84	0.73	1.40	0.42
sulphur	0.08	0.11	2.12	0.29	0.28	0.41	1.03	1.59
chlorine	0.59	0.60	0.19	1.35	0.93	0.11	0.14	0.51
Ash fusion temperature, °C	850	1200	1200		1120	1050	1250	
Calorific value, MJ/kg (ar)								
higher heating value	17.1	15.6	11.6	9.4	23.5	10.6	29.2	36.8
lower heating value	16.0	14.3	10.6	8.0	21.9	9.0	28.0	35.2

The material to be gasified or pyrolysed is composed principally of carbon, hydrogen and oxygen (Table 1). Fuel analyses are important: chlorine in MSW leads to high temperature corrosion problems; ash in sewage sludge can lead to plant erosion; straw's low ash fusion temperature can lead to sintering problems; and, fuel-bound nitrogen may lead to increased NO_x emissions, especially from sewage sludge (Davidson, 1997). The wide variation in sulphur content means that it is difficult to optimise the design of sulphur removal processes in mixed fuel applications.

Combustion and gasification begins with pyrolysis when hydrogen-rich volatile components evolve from heated material, leaving behind a char residue containing inert mineral matter and carbon (see Figure 2). The aim of gasification is to partially oxidise this carbon to provide sufficient energy for the further reaction with water to release molecular hydrogen (Table 2).

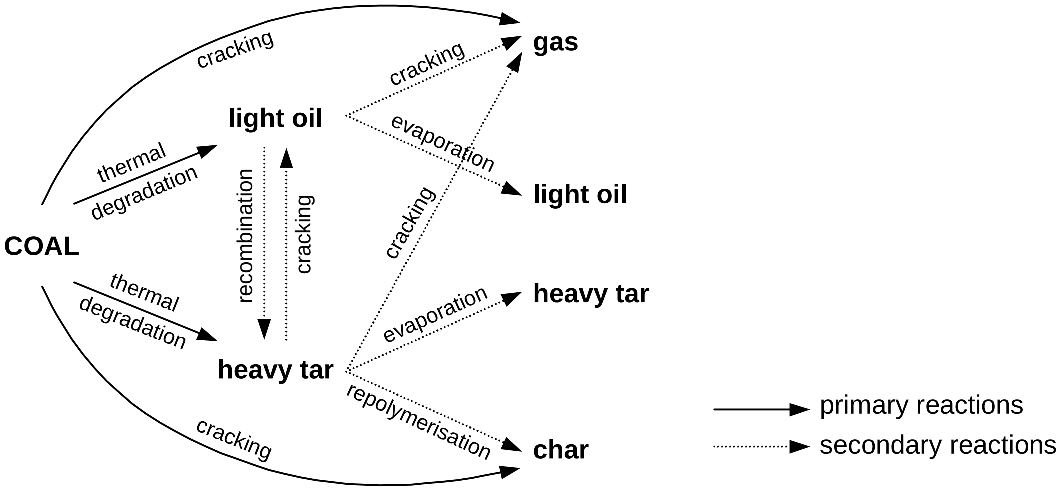


Figure 2 - A mechanistic model of the primary and secondary coal pyrolysis reactions (Gönenç and Sunol, 1994)

Table 2 - Gasification reactions

	solid carbon - gas reactions	gas phase reactions	
exothermic	$C + O_2 \leftrightarrow CO_2$ (combustion)		↓ heat of formation
		$CO + 3H_2 \leftrightarrow CH_4 + H_2O$ (methanisation)	
	$2C + O_2 \leftrightarrow 2CO$ (partial combustion)		
		$CO + H_2O \leftrightarrow CO_2 + H_2$ (water gas shift)	
	$C + 2H_2 \leftrightarrow CH_4$ (hydrogasification)		
endothermic	$C + H_2O \leftrightarrow CO + H_2$ (water gas)		
	$C + CO_2 \leftrightarrow 2CO$ (Boudouard)		

Hydrogasification and methanisation are very slow at the pressures found in most industrial gasifiers, so methane is usually only a minor component of syngas. To provide the energy needed for drying, pyrolysis and the endothermic water gas and Boudouard reactions requires the exothermic oxidation of a proportion of the carbon. Water for the water gas reaction is usually supplied as steam (to reduce chemical energy demand) and the chemical equilibrium of the water gas shift reaction determines the $CO:H_2$ ratio of the syngas

Sulphur and halogens found in the feedstock, along with some nitrogen, form gaseous compounds (*eg* ammonia (NH_3), hydrogen cyanide (HCN), hydrogen sulphide (H_2S), carbonyl sulphide (COS), hydrogen chloride (HCl) and hydrogen fluoride (HF)) which must be removed from the syngas to prevent environmental pollution. The quantity of trace metals found in the syngas (*eg* sodium, potassium, mercury, cadmium) depends largely on the feedstock. Some potential pollutants may be retained, to an extent, in the ash or captured by additions of mineral sorbent.

Oxygen-blown gasification produces a medium calorific value (CV) syngas of perhaps 10 MJ/Nm^3, whereas air-blown gasification yields a low CV syngas of perhaps just 4 MJ/Nm^3 containing a large volume of molecular nitrogen. The net CV of natural gas is around 36 MJ/Nm^3 - a high CV gas.

Gasification processes are typically classified into the three types shown in Figure 3 according to their flow geometry. Moving or fixed beds may be updraft as shown (*eg* **British Gas Lurgi**) or downdraft (*eg* **Ventec**) depending whether feedstock and syngas flow is counter- or concurrent.

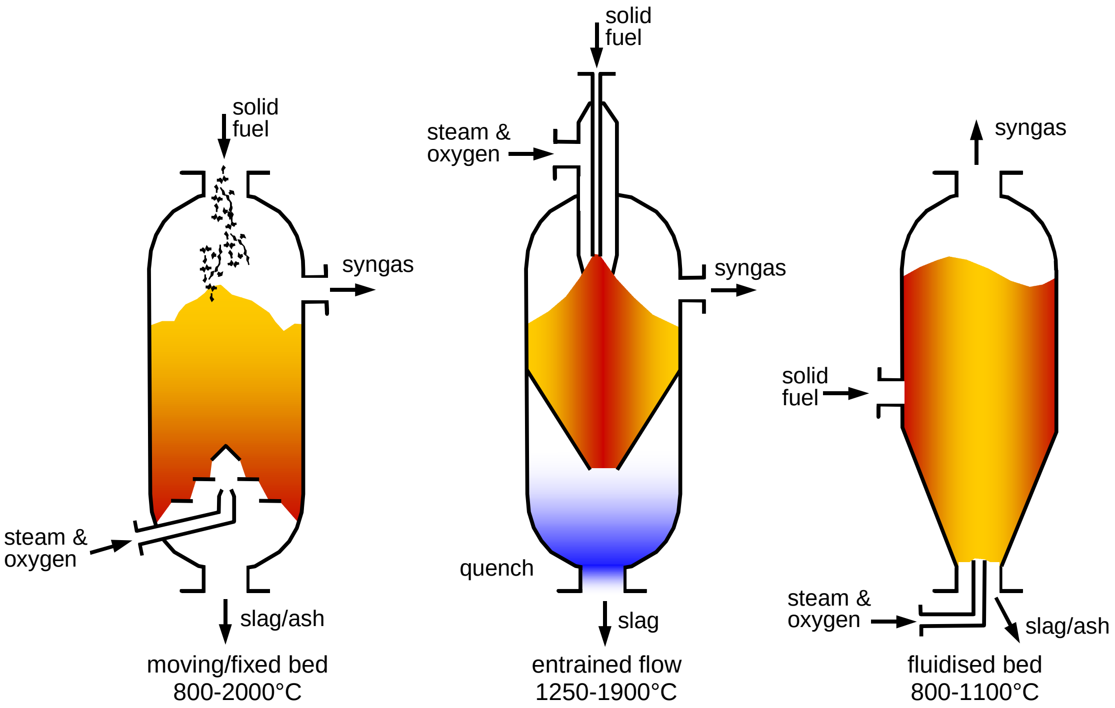
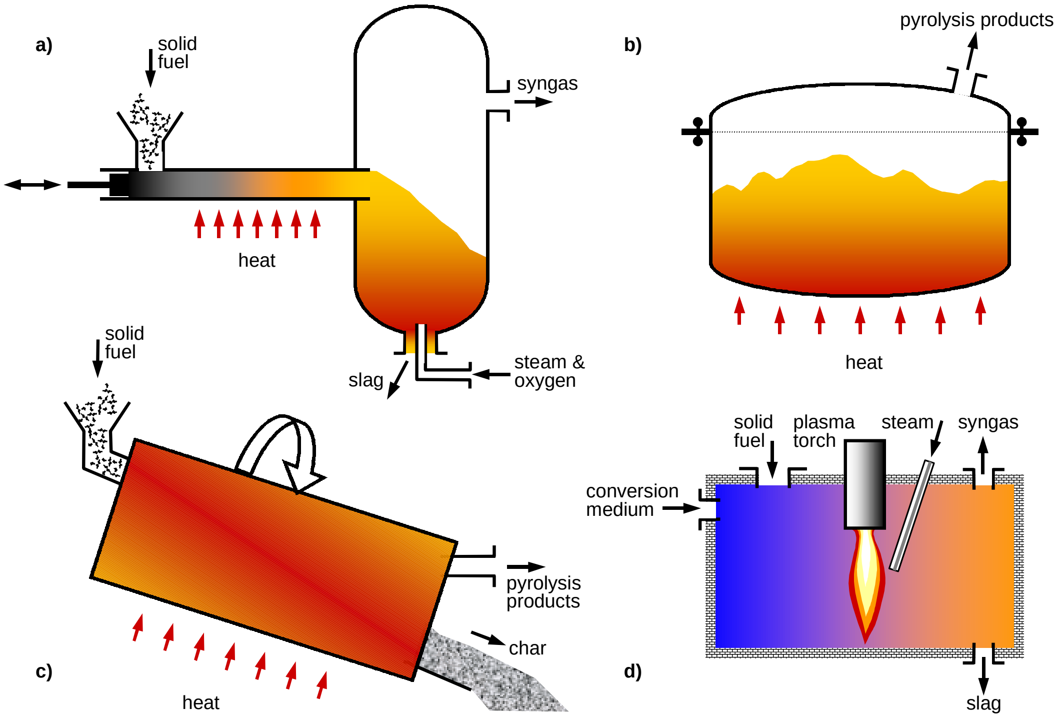


Figure 3 - Principal gasifier types for power generation applications

Interestingly, there is a greater variety of arrangements for waste and biomass gasification processes. Whilst the three principal types are all employed, Figure 4 shows a number of other arrangements that are either well established (*eg* rotary drum) or continue to be developed (*eg* transport reactor). For a more detailed review of these processes, and how they have been developed to treat solid wastes, see Whiting (1998).



a) transport reactor
c) rotary drum

b) batch
d) plasma

Figure 4 - Alternative gasifier types applicable to waste and biomass applications

5 The role of co-gasification

Coal can be thought of as a ‘flywheel’ to smooth out the variability in thermal systems designed to convert biomass or waste into electricity. It might mitigate the effect of short term variations in feedstock quality, or buffer the system when there is insufficient feedstock quantity, perhaps for seasonal reasons. Coal can also be thought of as a means to scale economies, especially since the transport of feedstocks with low energy densities limits the maximum sensible size of biomass and waste plants. If a system can tolerate a wide range of coal:feedstock ratios, then all these benefits are available together with tangible environmental benefits, including fossil fuel resource conservation and reduced CO_2 emissions.

The co-processing of waste with coal has been studied by IEA Coal Research (Davidson, 1997). In its report, all types of waste are examined with the conclusion that co-gasification looks to be a more attractive option than co-liquefaction or co-pyrolysis. What is clear is that gasification conditions must allow for the lower reactivity of coal and its char when compared with biomass and most wastes. The reactivities of coals are related to their rank, which in turn is correlated with volatility. However, this is a complex subject still under research with porosity, morphology, catalytic effects and other characteristics all playing a part (Messenböck *et al*, 2000). To achieve good carbon conversion with high rank, low reactivity coals requires high temperatures. In entrained flow gasifiers operating above the ash melting (fusion) temperature, conversion rates can be expected to be very high; in dry ash, fluidised bed gasifiers, favoured for biomass and waste, the conversion achieved with bituminous coals might be poor. For this reason, not all of the gasification processes developed for biomass or waste are suitable for co-gasification with coal.

6 Regulatory considerations

Emissions from large combustion plants (>50 MWth) in the EU are limited by Council Directive 88/609/EEC of 1988 and revisions to this will shortly become law (COM(1998)225). The Large Combustion Plants Directive (LCPD) is concerned with the major pollutants: sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulates or dust. Figure 5 illustrates the proposed limit values for new plants fuelled with solid fuels (*eg* coal) and biomass, along with the corresponding limits from the Waste Incineration Directive (WID, 2000/76/EC). Despite its title, the WID limits apply to waste to energy plants including gasification plants (although presumably not if syngas is converted to a fuel, such as methanol, for use off-site). For co-gasification of coal with waste or biomass, the LCPD and WID set pro-rata limits based essentially on the thermal input mix. The concept of *best available techniques* (BAT) enshrined in the Integrated Pollution Prevention and Control Directive (96/61/EC) may result in the imposition of tighter limits by national authorities, such as the Environment Agency in the UK, especially where technological advances allow.

> ***Incineration plant** means any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without energy recovery of the combustion heat generated. This includes the incineration by oxidation of waste as well as other thermal treatment processes such as pyrolysis, gasification or plasma processes in so far as the substances resulting from the treatment are subsequently incinerated.* (Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste)

The WID, which applies to plants with a capacity above 3 T/hr (~2 MWe), introduces emission limits for a wide-range of other noxious pollutants which are outside the scope of the LCPD. These limits, outlined in Table 3, mean that the monitoring requirements on co-gasification plants fuelled with coal/waste mixtures are far more onerous than for straight coal-fuelled plants.

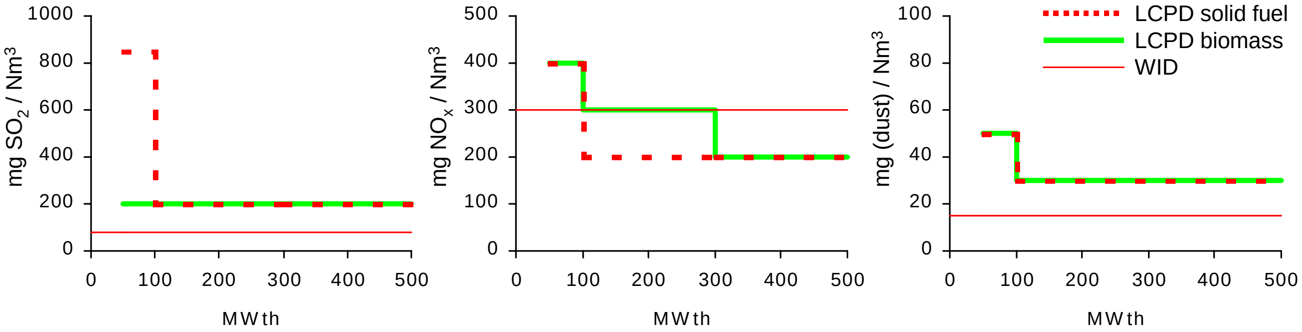


Figure 5 - Emission limits applying to co-gasification plants (LCPD and WID, 6% O_2)

Table 3 - Waste Incineration Directive air emission limit values (273 K, 101.3 kPa, 11% O_2, dry)

	daily averages	half-hourly averages (97%)	half-hourly averages (100%)	30 min to 8 hour averages	6 hour to 8 hour averages
total dust	10 mg/Nm^3	10 mg/Nm^3	30 mg/Nm^3		
total organic carbon	10 mg/Nm^3	10 mg/Nm^3	20 mg/Nm^3		
hydrogen chloride (HCl)	10 mg/Nm^3	10 mg/Nm^3	60 mg/Nm^3		
hydrogen fluoride (HF)	1 mg/Nm^3	2 mg/Nm^3	4 mg/Nm^3		
sulphur dioxide (SO_2)	50 mg/Nm^3	50 mg/Nm^3	200 mg/Nm^3		
nitrogen oxides (NO_x)	200 mg/Nm^3	200 mg/Nm^3	400 mg/Nm^3		
carbon monoxide (CO)	50 mg/Nm^3		100 mg/Nm^3		
cadmium (Cd) thallium (Tl)				0.05 mg/Nm^3 total	
mercury (Hg)				0.05 mg/Nm^3	
antimony (Sb) arsenic (As) lead (Pb) chromium (Cr) cobalt (Co) copper (Cu) manganese (Mn) nickel (Ni) vanadium (V)				0.5 mg/Nm^3 total	
dioxins & furans					0.1 ng/Nm^3

7 *Economic analysis*

As much ingenuity can go into the financing of a capital project as into its engineering. If a technology is not commercially viable it will never contribute to society's needs, regardless of how ingenious the technology might be. Here, a very simple economic analysis is presented which can be used to give an initial assessment to separate the non-starters from the runners. We have normalised this assessment around the costs of power generation, rather than tonnes of material processed, since we believe electricity is likely to be the universally desired product. Whilst bio-oils, carbon black, activated carbon, charcoal and other more exotic chemicals might appear attractive, high value by-products, we view these as niche markets and question whether they can be served by small-scale gasification processes in competition with the large petrochemicals industry. If hydrogen was adopted as an energy carrier, then production of this might offer a viable alternative to electricity.

Table 4 presents a comparative assessment of large-scale power generation and mass burn incineration projects alongside co-gasification projects at various scales from 5 MW to 400 MW. The calculations can easily be repeated with different assumptions.

Capital cost The normalised cost of a power generation plant is expressed in terms of £/kW. The cost of a waste to energy plant is expressed as £/tonne of annual capacity which can easily be converted to a £/kW basis. The capital cost must include land, permitting, infrastructure, equipment, project management, interest during construction and contingencies. To calculate an annual capital charge, we have assumed a real rate of return of 12% over 15 years - numerically equivalent to a simple, straight line depreciation over 7 years.

Fuel cost Coal is assumed to cost 120 p/GJ (net); gas 20 p/therm (gross) or 210 p/GJ (net); biomass £40/odt (oven dried tonne) or approximately 300 p/GJ; MSW -300 p/GJ, equivalent to a gate fee of around £30/tonne; RDF is available at no cost; and, tyres at -150 p/GJ, a gate fee of £50/tonne.

Staff cost A staff cost of £50,000 per man per annum is assumed. This includes all employment and training costs. To safely man a plant 24 hours per day, 7 days per week requires 5 shifts of 2-3 men, implying a minimum of 12 men for even the smallest plant, unless it is automated or operates as a batch process.

O&M cost It is extremely difficult to estimate operation and maintenance (O&M) costs without detailed information from suppliers. Those quoted are best estimates and include for all consumables and maintenance costs.

The most startling fact to emerge from this analysis is that none of the technology options is currently viable. With market prices in the UK for electricity hovering around 2 p/kWh, no type of power plant, whatever the fuel, is competitive; this might explain the absence of new build. Coal-fired IGCC is more expensive because of the high capital cost, but could become competitive if governments chose to reward its environmental benefits in a similar manner to renewables. Also apparent, is the rising COE at the smaller size as scale economies are lost. For example, the 8 MWe **ARBRE** biomass IGCC at **Eggborough** in the UK has a contract, administered by the State, to sell electricity at 8.65 p/kWh (HoL, 1999). Add to this the £10 million capital subsidy under the EU Thermie programme, and the COE rises above 10 p/kWh. This is not competitive, even with the subsidy proposed under the Renewables Obligation, and raises a big question mark over such small-scale biomass gasification projects.

Table 4 - Cost of electricity (COE) from different technologies and fuels

		CCGT	IGCC	IGCC	IGCC	W2E	IGCC	adv.W2E
capacity	MW	400	400	400	100	20	10	5
efficiency	%	55%	45%	45%	36%	23%	31%	25%
load factor	%	89%	89%	89%	89%	89%	89%	89%
capex	£/kWh	400	1,000	1,020	1,400	2,000	3,000	2,500
	£/tpa					160		780
	£m	160	400	408	140	40	30	12.5
fuel		nat. gas	coal	coal/RDF	coal/biomass	MSW	biomass	tyres
ratio				9:1	9:1			
CV	MJ/kg	50	25	24.5	24	10	14	35
consumption	kt/yr	408	998	1,018	326	244	65	16
cost	p/GJ	210	120	108	138	-300	300	-150
staffing	no.	50	84	86	30	32	15	12
	£k/man	50	50	50	50	50	50	50
	£m	2.5	4.2	4.3	1.5	1.6	0.75	0.6
O&M	£m	8	14	15	5	4.5	0.7	0.35
capex	p/kWh	0.75	1.89	1.92	2.64	3.77	5.66	4.71
fuel	p/kWh	1.37	0.96	0.86	1.38	-4.70	3.48	-2.16
staffing	p/kWh	0.08	0.13	0.14	0.19	1.03	0.96	1.54
O&M	p/kWh	0.26	0.45	0.48	0.64	2.89	0.90	0.90
COE	p/kWh	2.5	3.4	3.4	4.9	3.0	11.0	5.0

It is only co-gasification at the larger scales where the marginal economics have any attraction. If co-gasification can be arranged at an existing plant, then the COE might be competitive. Section 9 gives more details on projects where this has been the case.

8 Public opinion and business attitude

The opinions of NGOs and the public have been referred to above to the extent that gasification and pyrolysis processes might be viewed more favourably than mass-burn incineration. However, until there are a number of plants built and running, we can only speculate on how opinion will influence planning decisions. Recent experiences have not been good for developers of generation plant of almost any type, and the environmental impact of moving waste or biomass using road transport cannot be ignored. If proper effort is put into informing the public, and if new development is undertaken in a professional manner, then logic suggests that advanced conversion processes will succeed - eventually.

Which companies will emerge as market leaders is more debatable. There are clearly very many small companies promoting technologies who simply do not have the resources to execute a commercial project. Potential owners must be wary of this. Even the larger, reputable companies have sometimes had embarrassing experiences with advanced conversion technologies that have coloured their judgement. For example, the **Siemens TWR** process looked to be fully commercial at the **Fürth** plant in Germany, yet Siemens abandoned the technology after a relatively minor accident led to appalling consequences when workers suffered CO poisoning. No company wants such bad publicity and, in the case of Siemens, the perceived risk became unacceptable. Fortunately, there remains a large number of international companies willing to persist.

Finally, there are the project developers: perhaps a local authority, a utility company or a private developer. Developers make a project happen and unless they are prepared to embrace new technologies then there will never be a market for them. Whilst biomass projects have a generally acceptable image, though NIMBYism might mean strong local opposition, the same cannot be said of waste to energy projects. A utility company with a large customer base may not wish to compromise customer goodwill by tarnishing its name with waste. Yet another hurdle to overcome which one UK water company has addressed by establishing a separate subsidiary with its own identity.

9 The technologies and developers

Table 5 presents a list of companies offering technologies of interest to this review. This is not an exhaustive list and for more detailed information, the reader is referred to the excellent technology and business review carried out by Juniper (2001). For an extensive survey of biomass gasification equipment suppliers, developers and projects, see the IEA Bioenergy gasification activity report (IEA, 2001) and the British BioGen website (www.britishbiogen.co.uk). The US Center for Renewable Energy and Sustainable Technology (CREST) has an archive of project databases and Internet links related to bioenergy, including gasification (solstice.crest.org). Some key companies belong to the Gasification Technologies Council (www.gasification.org) from where much useful information can be obtained, and members of the International Flame Research Foundation (www.ifrf.org) have access to other information (Spliethoff, 2001).

Table 5 - Technology developers

primary process	primary reactor type	technology developer (and licensees)	web site or principal location
gasification	fixed bed (downdraft)	ASCENT (BG Technologies LLC)	www.bgtechnologies.net
		B9 Energy Biomass Ltd	www.b9energy.co.uk
		Melima	www.melima.ch
		MFU GmbH - 2SV	mfu.com
		Organic Power ASA (Egmasa, Nordan Electro, Energy from Waste, Waste Welcome, Kongshavn Shipping, Kentec Corp, Putklyhtyma)	www.organicpower.com
		Rural Generation Ltd	Londonderry, Northern Ireland
		Shawton Engineering Ltd (Biomass Engineering Ltd)	www.shawton.co.uk
		Kwikpower Waste to Energy Ltd (aka Ventec)	www.waste-to-energy.co.uk www.kwikpower.com

	fixed bed (updraft)	Ambiente RGR srl	Verona, Italy
		Babcock & Wilcox Vølund ApS	www.volund.dk
		Heuristic Engineering Inc - EnvirOcycler	www.heuristicengineering.com
		Lurgi Envirotherm - BGL British Gas Lurgi	www.lurgi.de
		Nippon Steel Corp - Waste Melting	Tokyo, Japan
		PRM Energy Systems Inc (Grupo Guascor)	www.prmenergy.com
		Thermogenics Inc (Growth & Development, Ontario Hydro, Bio-Lec)	www.thermogenics.com
		Wellman Process Engineering Ltd	www.wellmangroup.co.uk
		Xylowatt SA	www.xylowatt.ch
	entrained flow	Chemrec AB (ex Kvaerner)	www.chemrec.se
		Dow Chemicals (Global Energy - E-Gas)	www.globalenergyinc.com
		Kruppe Uhde - Prenflo	www.thyssenkrupp.com/uhde/
		Noell Technologies GmbH (Babcock Borsig Power)	www.babcockborsigpower.de
		Shell Chemicals Europe - SGP	www.shellglobalsolutions.com
		Texaco	www.chevrontexaco.com
	fluidised bed	Babcock Borsig Power (aka Austrian Energy & Env)	www.bb-power.at
		Battelle - BHTGS (Ferco - SilvaGas)	www.future-energy.com
		Ebara - TIFG (Alstom Power - TwinRec)	www.alstom.com
		EPI Energy Products of Idaho	www.energyproducts.com
		Enerkem Technologies - Biosyn (EIE)	www.enerkem.com
		Foster Wheeler Energia Oy	www.fwc.com
		HOST bv	www.host.nl
		Lurgi Envirotherm - ZWS, Öko-Gas, Wikonex	www.lurgi.de
		MTCI Inc (ThermoChem Inc, Spirit of Technology)	Baltimore, MD, USA
		Rheinbraun - HTW (Kruppe Uhde - PreCon, Sumitomo - N3T)	www.thyssenkrupp.com/uhde/
		TPS Termiska Processor AB	www.tps.se
pyrolysis	moving bed	GEM Graveson Energy Management Ltd	www.gem-ltd.co.uk
	fluidised bed	RTI - BioTherm (Dynamotive)	www.dynamotive.com
	rotary kiln	Balboa Pacific Corp - BAL PAC	Long Beach, CA, USA
		Basse Sambre ERI - Serpac PIT Pyroflam	www.bseri.com
		CPL Biomass Ltd	Stockport, UK
		ESI Environmental Solutions Int Ltd - Enersludge (Mitsubishi Electric)	www.oberon.com.au/esi/
		JND Jenkins Newell Dunford Thermal Process Ltd	www.jnd.co.uk
		Noell KRC Energie und Umwelttechnik GmbH	www.noell.de
		PKA GmbH - PKA (Toshiba, Halla Engineering, Gibros, PROMARCON)	www.p-k-a.com
		Siemens - TWR (Mitsui - Recycle 21, Takuma)	www.mitsuibabcock.com
		Technip - Pyropleq (Mannesmann)	Düsseldorf, Germany
		Thide Environnement - EDDITh (Hitachi)	www.thide.com
		Waste Gas Technology UK Ltd	www.wgtuk.com
	transport reactor (tubular)	Brightstar Environmental - SWERF	www.brightstarenvironmental.com
		Compact Power Ltd	www.compactpower.co.uk
		Thermoselect SA - HTR (Kawasaki Metals / Kawasho, IWT / Caribe, Daewoo, Thermolink)	www.thermoselect.com
	transport reactor (various)	Alcyon Engineering SA	www.alcyon.ch
		BPI Projects Ltd	Manchester, UK
		Ensyn Technologies Inc	www.ensyn.com
		Lurgi Envirotherm - LR Lurgi Residue	www.lurgi.de
		Nexus Technologies SA - Softer	www.nexus-tec.com
		Traidec SA - DTV	www.traidec.com
		Von Roll Umwelttechnik AG - RCP/Holderbank - HSR	www.vonroll.ch
		Waterwide (Renewable Energy Corp)	www.renrg.com
	vacuum	Pyrovac International Inc - Pyrocycling	www.pyrovac.com
	batch retort	Beven Recycling (UK) Ltd	Cheltenham, UK
		IET International Envionmental Technologies - TOPS	www.ietenergy.com
plasma/melting		PEAT Plasma Energy Applied Technology Inc - TDR	www.peat.com
		PKA GmbH - Coras-H	www.p-k-a.com
		Resorption Canada Ltd (US Plasma, Tobago, GTI)	www.rcl-plasma.com
		ScanArc Plasma Technologies AB - PyroArc	www.scanarc.se
		Westinghouse Plasma Corp	www.westinghouse-plasma.com

Few of the processes in Table 5 have been developed with the aim of co-gasifying waste or biomass with coal. The large, utility-scale, entrained flow gasification processes (**E-gas**, **Prenflo**, **Noell**, **Shell** and **Texaco**) have greatest potential for use in modern, clean coal power stations, but little evidence of successfully introducing waste or biomass exists. If these alternative fuels can be homogenised with coal, then the economics are attractive since the marginal cost is lower than that of a dedicated plant (see Table 4). Sewage sludge, plastics wastes (liquefied in some cases), petcoke and processed biomass are all candidate fuels, but not raw MSW.

At **Elcogas's** 320 MWe **Puertollano** IGCC plant in Spain, petcoke is fed into a **Krupp Uhde Prenflo** gasifier as a 50:50 mix with coal to reduce fuel cost (petcoke is less than half the cost of coal) and improve the CV of the rather poor quality coal used. Although petcoke has a high sulphur content, this potential pollutant is of little concern in an IGCC plant with a high sulphur removal efficiency.

Foster Wheeler's vision is to fire syngas from gasification plants in conventional, coal-fired power station boilers. As the leading manufacturer of CFBCs, they are well positioned since a CFBC can easily be starved of oxygen and run in gasification mode. The efficiency achieved with such an arrangement is relatively high (>35%) even though the gasifier itself can be small to suit the quantity of biomass or waste available. The potential to use syngas as the reburn fuel in NOx reduction projects has also been explored and offers a means of stretching the environmental benefits of biomass far beyond those achieved in a stand alone biomass plant.

Lahden Lampovoima Oy's Kymijärvi plant at **Lahti** in Finland uses a 45 MWth CFB to gasify biomass and RDF to part fuel the adjacent 167 MWe coal-fired pf boiler. The gasifier was constructed by **Foster Wheeler Energia Oy** with funding from the EU Thermie programme. Start-up was in January 1998 since when very high availability has been reported.

Construction of the **EPZ Amergas** plant at **Geertruidenberg** in the Netherlands was completed in 2000 (Willeboer, 2000). 150,000 tpa of wood waste is gasified in an 85 MWth **Lurgi** atmospheric CFB prior to combustion of the syngas in a conventional 600 MWe coal-fired pf boiler to produce 29 MWe. After cooling in a hot gas cooler, treatment of the syngas is limited to particulate removal in a bag-house filter and an ammonia wash. Waste water from the ammonia stripper and separated oil is injected into the boiler to avoid any liquid effluent. Gasification was chosen over co-combustion to keep ash from the contaminated wood separate from the saleable coal ash. Experience gained by EPZ at **Demkolec's Buggenum** plant helped in the design of this plant, one of the largest biomass gasifiers in the world. A similar project using a 38 MWth **Lurgi** gasifier for MSW was proposed for the **Stadtwerk Flensberg** coal-fired CFB power station in Germany but was cancelled due to local economic conditions.

A very significant demonstration of co-gasification is the EU-funded **BioCoComb** (Biofuel preparation for Co-Combustion) project at **Verbund's** 137 MWe coal-fired **Zeltweg** pf plant in Austria (Mory and Tauschitz, 2000). A 10 MWth atmospheric CFB gasifier built by **Austrian Energy and Environment** (a subsidiary of **Babcock Borsig Power**) in 1997 consumes bark, sawdust, wood chips, waste wood, plastics and sewage sludge. Unlike the Amergas project, the biomass is only partially gasified such that a mixture of syngas and char fines is fired in the adjacent boiler. There is no gas clean-up, but the product gas is used as a reburn fuel to reduce NO_x emissions from the main boiler.

The difficulties of handling MSW makes it awkward to gasify. Two projects that have successfully demonstrated conversion of MSW are at Berrenrath and Schwarze Pumpe.

The 140 MWth **High Temperature Winkler** (HTW) gasifier at **Berrenrath** near Cologne supplies syngas for methanol production (Klein and Mittlestädt, 2000). During three 3-day tests conducted in 1997 by the project partners, **Rheinbraun** and **Krupp Uhde**, it was fuelled with a mix of MSW pellets (RDF) and lignite. The partial gasification process continued to operate as normal, even with RDF making up 50% of the mass input. The aim is now to develop the process to allow gasification of untreated MSW.

Also in 1997, the massive **Schwarze Pumpe** town gas plant was converted to process wastes of all types alongside local lignite to produce syngas for methanol synthesis and electricity generation (Buttker *et al*, 2000). The plant, 150 km south of Berlin close to the Czech border, used to supply 75% of the former GDR with town gas but production ceased in 1995 after the introduction of natural gas. Now called **SVZ**, the intention is to replace the seven **Lurgi** fixed bed, rotating grate gasifiers with efficient **BGL** slagging gasifiers, and the first of these has been commissioned (200 MWth). There are also two **Noell** pressurised entrained flow gasifiers for converting liquid wastes. This development is perhaps the most important one studied in this review since it sees the commercialisation of the BGL process in an application where its high efficiency and vitrified ash product are valued. New 400 MWe projects are proposed at Fife, Scotland and Kentucky, USA by **Global Energy** who have reportedly acquired SVZ.

There are many other companies developing technologies of interest, some intent on generating electricity at very small-scales, others aiming to produce fuels that can subsequently be used for power generation.

Babcock & Wilcox Vølund operates a 700 kW and 6 MWth updraft gasifier demonstration plant designed for straw and other biomass at its R&D centre in Kolding, Denmark. The 6 MWth plant now fuels two 1.5 MWe **Jenbacher** gas engines yielding an overall conversion efficiency of 32%. The plant is fully automated and it is intended to scale-up the design to 10-40 MWth for gasification of plastics and other difficult wastes.

A Jenbacher engine is also used at the 2 MWe **Güssing** biomass CHP plant in Austria built around the **FICFB** gasifier designed by the Technical University of Vienna (**TU-Wien** www.renet.at).

At **UNA's Hemweg** coal-fired power station in Holland**, Pyrovac** has a project to co-fire bio-oil and char produced from its vacuum pyrolysis process

10 Future directions

As a support or backup fuel, coal should have real value. For example, the **Nippon Steel** and **MFU** processes require 4-5% coke. However, the low reactivity of higher rank coals (*ie* bituminous and anthracitic coals such as mined and used in the UK) means that only those processes operating at high temperatures (>1250°C) offer any real potential for co-gasification unless a char combustion stage is included.

From the economic analysis, it is clear that economies of scale are essential if projects are to be commercial. To this end, the most promising route for co-gasification lies not in the physical mixing of waste or biomass with coal, but in their separate treatment in small, dedicated gasifiers supplying syngas to large, coal-fired plants. The capital cost of this approach can be less than half that of a small, bespoke power plant; whilst the environmental benefits of reduced NO_x emissions through gas-over-coal reburn are an added bonus.

If and when governments properly reward the environmental benefits of modern, clean coal plant, then co-gasification of waste or biomass in IGCC will become an economic option. **Global Energy** looks set to become a leading player if financial incentives are available.

An alternative to scale economies is automation to reduce staff costs. Few of the processes examined lend themselves to unmanned operation, those that do may have an as yet unexploited commercial advantage. Ingenuity in the design of reliable feedstock handling systems will, as ever, be crucial. The **Babcock and Wilcox Vølund** process is one of the few examples.

European-wide agreement on which wastes qualify as renewables are needed to give manufacturers a degree of market certainty. If wastes used in an advanced conversion process meet the waste hierarchy then they should be afforded the same benefits as other renewable sources.

Finally, if these advanced processes are to become accepted, then more work is needed to demonstrate good pollution control with soundly based mass balance analyses. Recognised standards to be met for ash/slag utilisation are also needed.

11 Conclusions

- There are environmental, technical and commercial reasons why coal might be co-gasified with biomass and waste. Conservation of fossil fuel resources and reduced CO_2 emissions are real and tangible environmental benefits. The technical benefits are less certain and the separate gasification of biomass or waste materials may prove to be more practical. Coal offers a high level of fuel supply security and this can be important for commercial reasons.

- The economics of small scale gasification power systems are unattractive, whatever fuel is used.
- Dedicated, small scale gasifiers fed with waste or biomass and supplying syngas to the coal-fired boilers of large power stations are more attractive, especially if the syngas is used as a reburn fuel for NO_x reduction.
- Certain large scale IGCC technologies lend themselves to co-gasification and this will become attractive as coal-based IGCC is adopted by the market.

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