OPPORTUNITIES AND MARKETS FOR CO-UTILISATION OF BIOMASS AND WASTE WITH FOSSIL FUELS FOR POWER GENERATION

Executive Summary

Throughout the world, coal is used extensively to generate electricity and process heat for industrial applications. There are significant numbers of coal-fired utility-scale power plants currently installed in some 80 countries throughout the world. For most of these countries, coal will continue to figure significantly in any future expansion of the electricity market required to meet increased consumer demand. In the industrial arena, coal is used as a source of energy for large energy intensive industries such as paper production, cement manufacture, food processing and steel manufacture. Again, there are large numbers of coal-fired boiler plant encompassing a range of technologies already installed throughout the world. The extensive use of coal poses significant world environmental problems. The power stations and industrial boilers emit substantial quantities of $CO_{2,}$ which can contribute to global warning. In addition, they contribute significant emissions of acid gas species such as NO_x and SO_2. The ash produced from coal burning also requires disposal in an environmentally acceptable manner.

There is now considerable interest in the utilisation of biomass and municipal/industrial wastes within existing coal-fired plant. The use of biomass and wastes in such plant is now perceived by governments and industry as a viable option. This area is now the subject of a number of on going research activities within the European Union and USA. Due to the varied and diverse initiatives in this area, all available information has been collated and summarised in this report.

The different sources of statistics on biomass/waste reserves illustrate that there is an enormous potential reserve of biomass and wastes that could be utilised for energy production. The huge installed capacity of existing coal-fired power plant consumes 50,000 PJ of coal each year; if all were to be co-fired at a rate of 10% (thermal), this would require 5,000 PJ of biomass/waste per year. The proximity of biomass and wastes to power stations or other potential co-utilisation sites will influence the scope for market size. On the basis of this and the biomass/waste fuel production potential, the co-firing potential has been estimated at 500 PJ per year in existing coal-fired generating capacity, equivalent to one tenth of existing capacity being modified to take 10% thermal input of biomass. New plant could increase this level further.

Industry and commerce also account for significant coal use (e.g. 8% of OECD coal use and 30% of China's coal use, excluding iron and steel production). Introduction of a co-utilisation element could result in significantly increased biomass/waste utilisation, perhaps to around 50 PJ or more per year.

There are a number of international environmental legislative initiatives that require a substantial reduction in the production of greenhouse and acid gases; this is achievable through reducing the proportion of fossil fuels utilised for energy production. This reduction can be achieved by the greater use of natural gas or nuclear power or the increased use of renewable energy, including the utilisation of biomass and waste. The utilisation of these energy streams can take place in purpose-designed plant, for which many countries have subsidised support programmes, such as NFFO in the UK. Alternatively, it can take place in existing coal-fired plant in a co-fired application. The advantages to this route include:

- There is an established market for the heat and power produced.
- A relatively small capital investment requirement compared to those for a new plant dedicated to biomass processing.
- There are favourable impacts on emissions from the coal-fired plant.

The technology review indicates that there are a number of industrial and utility-scale coal-fired technologies that have the potential to co-fire coal and biomass and/or waste. These technologies include stokers, BFBC, CFBC, Cyclone combustors, pulverised coal plant, advanced coal gasification plant and carbonisation plant. For some of these technologies (BFBC, CFBC and cyclone burners), co-fired plant can be regarded as commercially proven and off-the-shelf designs are available.

Pulverised fuel plants comprise the largest installed capacity for coal use in the world. The technology is suitable, with limited modification for co-firing. Pulverised coal plant therefore represents the single largest potential market for co-firing. The near-term market potential is for retrofitting existing pulverised coal plant, which will require, primarily, new biomass/waste handling plant and burner systems.

In all of the co-utilisation technologies considered, there are technical problems and limitations that have not yet been fully resolved. However, it is considered that none of the perceived technical issues are unresolveable and that with continued R&D these technical risks can be overcome.

A number of barriers to the deployment of co-firing technology have been identified which include:

- Public perception of the plant as a result of the stigma associated with the use of waste-derived materials; potentially, this could compromise planning procedures.
- Additional gas cleaning equipment could be required if environmental legislation is tightened; this would add to capital and operating costs.
- The need for secure, long-term quality controlled biomass/waste supply schemes, otherwise plants will merely burn 100%coal.
- Pricing arrangements for biomass/waste streams need to be agreed and fixed for long periods (10 to 15 years).

Review Recommendations

1. The area of biomass and waste co-utilisation is one undergoing rapid development, with many potential fuels being investigated by the utility operators. Unfortunately, many of these trials are being undertaken under rules of commercial confidentiality, and it has not been possible to include them in this study. It is recommended that an update to this review is undertaken in approximately six to twelve months time to incorporate the results of the most recent trials where information has passed into the public domain (e.g. through Member States' environmental monitoring and control agencies)

2. A considerable body of expertise has been developed across the European Union in techniques for the co-utilisation of biomass and waste, and equipment for dealing with the specific problems that these fuels pose. It is considered that this expertise represents an opportunity for EU companies and organisations to market their skills and capabilities in the developing markets (e.g. China, India) where co-utilisation has yet to become firmly established. It is recommended that a first step to exploiting this opportunity might be through a series of workshops or seminars presenting the results of EU experience to invited potential customers and policy makers in appropriate locations within the developing world.

3. The largest market for the co-utilisation of biomass and waste lies in exploiting the huge installed capacity for power generation from pulverised coal. Despite the significant work that has already been undertaken on co-combustion of coal and biomass/waste, a number of technical issues require further work (e.g. reliable handling systems for biomass and waste fuels). It is recommended that these issues remain a priority for support within EU research programmes.

4. This review has concentrated largely on the technical issues associated with the co-utilisation of biomass and waste. However, the economic viability of a successful co-utilisation process is highly dependant upon local conditions, such as the availability of fuel without incurring excessive transportation costs, and EU and Member State legislative and taxation policy (e.g. landfill tax levels, recent and forthcoming EU Directives). It is recommended that this study is complimented with a comprehensive review of these legislative and taxation drivers.

OPPORTUNITIES AND MARKETS FOR CO-UTILISATION OF BIOMASS AND WASTE WITH FOSSIL FUELS FOR POWER GENERATION

Page No.

1. INTRODUCTION 1

2. SOURCES AND TYPES OF BIOMASS AND WASTE MATERIALS AVAILABLE WITHIN THE EU 3
2.1 Present waste utilisation/disposal options within the EU 5
2.2 Advantages and disadvantages of co-firing 6

3. THE POWER GENERATION MARKET WITHIN THE EU AND ACCESSION COUNTRIES 8
3.1 Electricity markets in individual member states 9

4. REVIEW OF CO-FIRING APPLICATIONS 17
4.1 Fuel preparation and handling technologies 17
4.2 Design considerations 17
4.3 Storage 17
4.4 Size reduction and handling 18
4.5 Feed/handling design issues 24
4.6 Review of direct co-combustion technologies 24
4.6.1 Pulverised coal boilers 24
4.6.2 Stoker systems 31
4.6.3 Fluidised bed combustion 33
4.6.4 Cyclone furnaces 41
4.6.5 Summary 44
4.7 Review of co-utilisation techniques within Europe 44
4.7.1 Direct co-utilisation 44
4.7.2 Indirect co-utilisation 46
4.7.3 Pyrolysis systems 50
4.7.4 Hybrid systems 50
4.8 Application to markets 51
4.8.1 Power generation markets 51
4.8.2 Industrial markets 52
4.9 Review of co-firing in the USA 53
4.9.1 Lessons learned from US co-firing test programme 57
4.10 Economics of co-firing 58
4.10.1 Direct co-utilisation techniques 59
4.10.2 Indirect co-utilisation techniques 62
4.10.3 Maintenance and performance issues 64
4.10.4 Summary of economic issues 65

5. MARKET POTENTIAL FOR CO-FIRING 65
5.1 Legislative drives influencing uptake of biomass/waste feedstocks 68
5.2 Market stimulation 70
5.3 Market opportunities and technology transfer issues 70

6.0 **BARRIERS TO CO-FIRING** 72
6.1 Direct co-utilisation techniques 72
6.2 Indirect co-utilisation techniques 74
6.3 Risks and barriers to technology deployment 75

7.0 **CONCLUSIONS** 77

8.0 **RECOMMENDATIONS** 79

9.0 **REFERENCES** 80

List of Tables

	List of Tables	Page No.
1	Proximate analysis of German sewage sludges	5
2	Environmental impact of landfilling and incineration	5
3	Overall electricity generation (TWh) within the European Union	8
4	Overall electricity generation – thermal power plant contribution	8
5	Pulverised coal plants co-utilising coal and biomass/wastes	30
6	Typical pulp and paper mill waste stream	35
7	Examples of BFBC units supplied by Ahlstrom/Foster Wheeler	36
8	Circulating fluidised beds co-utilising coal and biomass/wastes	40
9	Tests of co-firing in full-scale utility coal-fired boilers	57
10	Major US R&D studies and reviews carried out	58
11	Summary of capital costs	60
12	Summary of biomass/waste fuel costs	61
13	Assumptions made in assessment of 10% wood co-firing in a 500 MW_e pulverised coal unit	62
14	Results of pulverised coal-wood co-firing assessment – differential cost components	62
15	Results of pulverised coal-wood co-firing assessment – sensitivities	63
16	Summary of capital cost estimates for new biomass/waste and coal IGCC	63
17	Assumptions used in assessment of 10% wood co-fired IGCC plant	64
18	Results of assessment of 10% wood co-fired IGCC plant – differential cost components	64
19	Results of assessment of 10% wood co-fired IGCC plant – sensitivities	64
20	Energy content of selected biomass residues, world-wide	66

List of Figures

1	Straw harvesting, Denmark	4
2	Drax Power Station, UK	13
3	Wood chip stockpile	20
4	The EPON coal/wood-fired facility in The Netherlands	21
5	Rheinbraun AG's Berrenrath site, Germany.	23
6	The coal/wood-fired spreader stoker plant at Ryaverket	31
7	Bubbling FBC facility, Tacoma, USA	33
8	Vaertan PFBC plant, Stockholm	41
9	British Coal fluidised bed gasifier, UK	48

Glossary

AFBC	Atmospheric pressure fluidised bed combustion
BFBC	Bubbling fluidised bed combustion
CFBC	Circulating fluidised bed combustion
dRDF	Densified refuse derived fuel
EPRI	Electric Power Research Institute (of the USA)
FGD	Flue gas desulphurisation
IEA	International Energy Agency
LNG	Liquefied natural gas
MSW	Municipal solid waste
NFFO	Non Fossil Fuel Obligation
PFBC	Pressurised fluidised bed combustion
RDF	Refuse derived fuel
SCR	Selective catalytic reduction
SNCR	Selective non catalytic reduction
TDF	Tyre derived fuel

OPPORTUNITIES AND MARKETS FOR CO-UTILISATION OF BIOMASS AND WASTE WITH FOSSIL FUELS FOR POWER GENERATION

1. INTRODUCTION

Coal continues to be used extensively by the developed and developing nations to generate electricity and process steam/heat for a variety of commercial and industrial applications. Most of the present electricity generation capacity relies on the use of pulverised coal-firing although other technologies such as fluidised bed combustion and stoker-firing are utilised in some areas. There are a significant number of coal-fired utility-scale power plants operating in ~80 countries worldwide, and despite the increased uptake of renewable energy sources and the on-going use of natural gas and nuclear power for power generation purposes in the West, coal will continue to play a major role in this area. Indeed, for many industrialised nations such as the USA, Russia, China, India and Germany, plans for future expansion of their respective power generation industries centres on an increased use of coal. However, the increased use of coal poses significant worldwide environmental problems. Utility and industrial boilers emit substantial quantities of CO_2 that contributes to global warming. In addition, they can generate significant emissions of acid gas species such as NOx and SO_2 unless pollution control technology is fitted. In addition, they can generate significant emissions of acid gas species such as NOx and SO2 unless pollution control technology is fitted. Also, the ashes and other residues produced by coal burning require disposal or utilisation in an environmentally-acceptable manner.

A number of possibilities have been examined to mitigate these problems, including the co-firing of coal with a variety of biomass and/or municipal/industrial wastes within existing coal-fired plant. Much of the initial impetus for this co-utilisation results from concerns over the production of CO_2 from coal burning and its impact on global warming processes. However, other advantages have become apparent, and include the reduction of waste materials being land-filled (e.g. wood waste), plus increased process flexibility through enhanced fuel diversity. In summary, fuel blends may be produced using combinations of zero/low cost feedstocks with coal that impact positively on plant economic and environmental performance. In particular:

- There is an established market for the heat and power produced.
- A relatively small capital investment may be required, compared to the costs of a new plant dedicated solely to biomass and/or waste processing.
- There may be favourable impacts on emissions from the coal-fired plant.
- The displacement of a proportion of coal by biomass/wastes helps to preserve strategic coal reserves and may reduce the requirement for imported supplies.
- The use of wastes (agricultural and municipal/industrial) as fuels reduces landfill requirements.

The co-utilisation of biomass and/or wastes in various combustion technologies is now perceived by governments and industry as a viable option and this area has been the subject of increasing development activities, particularly within the European Union and the USA. Several programmes have examined options for co-utilisation, and a number of plants are now operating on a commercial basis.

The aim of the present report is to review and summarise the current status of the various technologies for co-utilisation of coal and biomass/waste for power generation applications. This is realised through:

- Examining the availability, characteristics and merits/demerits of biomass and wastes suitable for co-firing within the European Union.

- Reviewing the size of the markets for power generation in member states, the fuels utilised and the type/scale of typical plant in use.
- Reviewing the current status of the various co-firing options within the both EU and North America.
- Examining process economics in terms of additional costs that may be associated with the adoption of co-firing.
- Carrying out a market review for co-firing within the EU.
- Investigating the barriers that might limit the uptake of co-firing technology.

2.0 SOURCES AND TYPES OF BIOMASS AND WASTES AVAILABLE WITHIN THE EU

There is currently no widely adopted definition of materials classified as biomass. However, waste fuels and biomass are often grouped together as ‘renewable’ energy. In the terms of this review, biomass is defined as organic material produced directly or indirectly from living organisms without contamination from other substances or effluents. This includes materials such as straw, wood and bark in its various forms, grasses and animal dung (including poultry litter). Other materials such as domestic sewage sludge, refuse derived fuel (RDF) and black liquor from paper manufacture are also used as fuel feedstocks for energy production processes and are classified as wastes.

The range of biomass and waste feedstocks available for utilisation is very wide. A general categorisation can be considered which comprises:

- Energy crops - biomass fuels grown specifically for use as a fuel for energy production. These include woods (e.g. willow, popular, eucalyptus) and perennial grasses such as miscanthus, sweet sorghum, and phalaris.

- Forestry Residues - wood fuels produced from existing lumbering and coppicing operations in established forestry (e.g. wood chips, forestry trimmings, sawdust, bark)

- Agricultural Wastes- biomass wastes produced by agricultural farming practises for food production (e.g. straw, bagasse, poultry litter)

- Municipal Waste - wastes generated from household, industrial and commercial sources. This waste can be raw, i.e. unsegregated or segregated (glass, metal paper etc., removed). It can also be in its “as produced” form or densified to form a pellet, commonly known as dRDF (densified Refuse Derived Fuel)

- Specialised Industrial Wastes- there are a range of waste materials generated by industry that have the potential to be used for energy production. Examples include tyres, clinical waste, waste solvents and other chemicals, car fragmentation waste, meat processing wastes and waste wood-derived products.

In terms of their physical and chemical characteristics, the various biomass materials available may differ from coal in a number of ways that include:

- Lower density.
- Higher moisture content, often up to 50%.
- Lower calorific value.
- Broader size distribution, unless pre-conditioned by screening, crushing or pelletising.
- The variability of the material as a fuel will be greater.
- The sulphur and nitrogen contents are often lower.

Such variations in fuel quality, compared to coal, may have a number of implications for plant applications that include process design and operation, and potentially, plant availability.

In addition, waste materials are often categorised based on their physical properties; these include sized solid material (wood chips and tyres); wet fibrous material (litter and bagasse); irregular sized/variable density material (municipal waste); and sludges and liquid wastes. Each waste will therefore require the development or application of specialist techniques for the storage, handling and feeding of the materials to the plant being co-fired. The full application of co-firing will therefore require novel fuel handling equipment to operate alongside existing facilities.

Within the EU, the total amount of waste generated annually is of the order of ~2000 Mt, of which, >40 Mt is classified as hazardous. During the 1990s, the total amount of waste generated within the EU, including Central and Eastern Europe, continued to grow at an estimated 10% per annum. The types and quantities of particular wastes produced vary between countries; Western Europe tends to produce a greater proportion of industrial and municipal wastes, compared with Central and Eastern Europe.

It many Western industrialised nations, the full range of these biomass and waste fuels are likely to be available for energy production purposes. However, in some Accession States, the situation may differ as not all have yet established appropriate collection practises for wastes.

It is often difficult to identify and quantify the biomass and wastes available within the EU for power generation applications, partially as a consequence of its inherent diversity. Statistics on biomass and waste production, characteristics, transport and treatment are not collected in the same way in each member state, thus making it difficult to obtain an overall picture of the European waste situation (1).

In many situations, biomass and waste-derived feedstocks are generated locally and in limited quantities, this clearly impacting on their potential for co-utilisation purposes. In addition, it is not uncommon for the properties and availability of biomass to vary significantly throughout the year. For instance, in Denmark, there is a theoretical annual surplus of some 3.5 Mt straw. Of this, ~1 Mt is utilised in energy production, with ELSAM currently utilising ~140 kta, equivalent to 2 PJ (2).

Figure 1. Straw Harvesting, Denmark

However, because of climatic variations, this surplus can vary enormously and in certain circumstances, there can even be a deficit. Similar results have been reported for the Netherlands where straw harvests have fluctuated between 440-900 kta. Variations in harvests have also been reflected in the market price for straw (3).

Clearly, straw is not always available for energy-related purposes and a similar situation can occur with the use of wood. However, some EU countries have significant reserves of wood, and its use in energy production is better established. For instance, Finland relies heavily on this natural resource, and wood, predominantly from forestry operations, provides 14-17% of the country's total energy requirement. During the 1990s, between 4.5-5.3 Mtoe were utilised annually in the energy industry(4,5).

Wood also plays an important role in Denmark where it is estimated that the total biomass available for energy production is ~127 PJ. This amounts to ~16% of total Danish energy consumption. Around 50% of the total available comprises forest residues, although a significant contribution is also provided by Municipal Solid Waste (MSW).

Even in countries where forests are not abundant, wood can form an important fuel source. For instance, although The Netherlands is not heavily forested, considerable quantities of wood are available from wood processing industries (200 kta), demolition sources (500 kta), plus wood from domestic sources, parks, etc. In addition, there is the potential of a further 500 kta from existing forestry reserves, not currently being utilised.

To be suitable for co-firing at an economic level, biomass and waste sources need to be available close to an existing power station. As these feedstocks are usually of minimal value, additional transport costs invariably have a negative impact on economic viability. Thus, to support a power generation facility of economic scale, adequate supplies of biomass feedstock must be available locally. Several studies have suggested that, for instance, in the case of miscanthus, for practical purposes, the maximum capacity for a power plant fired exclusively with this feedstock is ~100 MW_e. Beyond this, greater land area is required, and transport costs begin to assume a greater significance. However, in such situations, the attractions of co-firing with coal become apparent, as larger plants can be considered as well as smoothing out seasonal variations in terms of biomass tonnages available and material properties.

Whereas some biomass sources are not available in all Member States, the occurrence of waste materials such as sewage sludge, is more widespread, although availability is clearly linked with the size of the population in the particular region. Sewage sludge is generated predominantly from domestic households although also it includes some industrial wastes. In Germany, for instance, ~2.7 Mta (dry solids) of sewage sludge is generated. As a result of EU Directives, marine disposal of sewage sludge is now prohibited within the EU. In addition, the EU Directive on Urban Waste Water Treatment now requires significant improvements to be made in the treatment of sewage, particularly from coastal and estuarial conurbations. This higher level of treatment will invariably result in increased volumes of sludge for disposal; sludge production within the EU is expected to increase by 50% to the year 2005; in the case of Germany, levels of sludge generated are increasing towards the 4 Mta amount (6).

As with many biomass and wastes, the composition of sewage sludge is variable, even within a particular region. For instance, sewage sludges within a region of Germany were found to have the following properties (Table 1):

Table 1. Proximate Analysis of German Sewage Sludges (8)

Origin	**Water content (%)**	**Carbon content (%)**	**Ash content (%)**	**Volatile matter (%)**	**LHV (MJ/kg)**
Mainz	8	25	46	44	10
Saarbrucken	5	23	52	37	9
Ruhr 1	2	22	66	19	8
Nurnberg	11	26	39	44	10
Ruhr 2	3	27	52	35	10
Dusseldorf	4	31	39	50	12

The utilisation of sewage sludge for co-firing with coal would provide benefits in reduced landfill and agricultural disposal, a reduction in groundwater contamination by heavy metals, reduced methane emissions, and reduced odour problems.

2.1 Present Waste Utilisation/Disposal Options within the EU

There are a number of options available for the utilisation and/or disposal of the wastes generated within the member states of the EU, each impacting on the environment in different ways. Currently, despite the introduction of landfill taxes, the least expensive option often remains disposal to landfill with incineration as the main alternative. The environmental impact of landfilling and incineration are compared below (Table 2) (8):

Table 2. Environmental impact of landfilling and incineration

	Landfill	**Incineration**
Air	Emissions of CH_4, CO_2, odours	Emissions of SO_2, NOx, HCl, HF, NMVOC, CO, CO_2, N_2O, dioxins, dibenzofurans, heavy metals
Water	Leaching of salts, heavy metals, biodegradable and persistent organics to groundwater	Deposition of hazardous substances in surface water
Soil	Accumulation of hazardous substances	Landfilling of slags, fly ash and scrap
Landscape	Soil occupancy; restriction on other land uses	Visual intrusion; restriction on other land uses
Ecosystems	Contamination and accumulation of toxic substances in food chain	Contamination and accumulation of toxic substances in food chain
Urban Areas	Exposure to hazardous substances	Exposure to hazardous substances

Thus, despite the environmental drawbacks and the introduction of landfill taxes, the majority of European municipal and hazardous wastes continue to be landfilled. This option is likely to persist into the foreseeable future although the European Commission has taken steps to minimise landfilling through a Directive introduced in 1999 aimed at reducing the amount and toxicity of landfilled waste, improving the design and operation of landfill sites, encouraging the pre-treatment of waste prior to landfill, and minimising the mixing of certain waste streams. A further proposed Directive is focusing on incineration, and is aimed at tightening up emission standards for new, existing and co-incinerators, and setting strict limits on levels of furans and dioxins permissible.

As part of its overall strategy to control and minimise the generation of wastes, the European Commission has identified several major waste streams for priority attention. One stream is packaging waste; this comprises a variety of paper- and plastic-based materials used widely throughout society. It is estimated that up to half of the municipal waste in Western Europe comprises these materials, with ~30-40% of the space in municipal landfills being occupied by them. To date, only ~10-15% of such waste is recovered or re-used although significant efforts continue to be made to reduce the sources of waste.

In Finland, ~218 kta of (fibre-based) packaging waste is generated from domestic, commercial and industrial sources. Of this total, 80 kta is sent to landfill, 95 kta is recycled, and 42 kta is utilised for energy recovery purposes. In addition, a further 83 kta of plastic-based packaging is disposed of to landfill. The breakdown clearly varies from country to country. However, there is considerable potential for the greater utilisation of these materials as an energy source (9).

In the UK, a small quantity of commercial and packaging wastes are currently being used for energy recovery through co-firing with coal in an industrial-scale CFBC-based power plant, operating in Slough.

2.2 Advantages and Disadvantages of Co-Firing

As noted, the range of biomass and waste materials potentially suitable for co-firing applications is diverse, hence it is difficult to generalise. However, the following issues have been noted:

Advantages:

- Some biomass fuels can be grown on redundant agricultural or set-aside land, improving local economies and creating jobs.
- Increased plant flexibility in terms of fuels utilised.

- Improved plant economics through the use of zero/low/negative cost fuel feedstocks. In some cases, a "gate fee" may be payable to facilitate disposal.
- Fuel feedstocks may be available locally, reducing transport costs.
- Replacement of part of the coal feed can reduce dependence on imported fuels and help maintain strategic national reserves of coal.
- Reduced emissions of main classes of pollutants through reduction in amount of coal burned. This can occur through simple dilution or *via* synergistic reactions between biomass feedstocks and coal.
- Biomass fuels are CO_2-neutral, hence reduce global warming effects.
- Reduction in quantity of waste-type materials disposed of to landfill, through their adoption as fuel feedstocks. Minimisation of methane formation from landfilled materials, hence reduced global warming impact.
- Reduced level of solid wastes generated, compared to firing coal alone.
- Several types of combustion and gasification technology may be applicable to a particular combination of feedstocks. These may include pulverised fuel, bubbling fluidised bed combustion (BFBC) and circulating fluidised bed combustion (CFBC).

Disadvantages:

- Supplies of low-value feedstocks need to be sourced locally in order to capitalise on economic advantages.
- Some feedstocks may only be available seasonally. Amounts available may vary throughout the year. Thus, availability of fuel may impact on plant siting and/or economic viability.
- The chemical and physical properties of biomass and wastes may vary significantly, either through natural fluctuations or climatic effects. Many refuse-derived fuels can be extremely variable in composition.
- Feedstock pre-preparation may be required. For instance, MSW/RDF-type fuels require separation of non-combustible materials prior to preparation. In addition, wood requires chipping, straw may require chopping up, etc. resulting in increased energy requirements.
- Some biomass materials have low bulk density (e.g. straw), this resulting in the handling and storage of large quantities of materials.
- Moisture content may be high, reducing overall plant efficiency. In situations where slurry-type materials are used, moisture content may require reduction. In the case of sewage sludge, the material is usually de-watered and granulated.
- Depending on the feedstock, the complexity of fuel feeding requirements may be increased; some materials can be co-fed using a single feed system whereas others require a separate, dedicated system.
- Some feedstocks, such as straw, can have high levels of alkali species present. This can impact adversely on plant operations and cause high temperature corrosion in some types of power plants. The presence of some materials can also increase the propensity for slagging and fouling phenomena to occur.
- Fuels such as MSW can contain large amounts of chlorine-containing materials, resulting potentially in increased gas cleanup requirements and plant component corrosion.
- Some biomass fuels generate higher levels of particulates in the flue gas, resulting in increased particulate control requirements.
- Co-firing can reduce the quality of ash produced, compared to using coal alone, restricting potential utilisation outlets.

Thus, where a power plant co-firing coal and/or biomass/wastes is contemplated, there are various issues that require consideration. These range from initial availability of feedstocks through to control and disposal of gaseous and solid residues generated.

3.0 THE POWER GENERATION MARKET IN THE EUROPEAN UNION AND ACCESSION COUNTRIES

Europe's energy supply and economic well-being will remain heavily dependent for the foreseeable future on the use of fossil fuels for electricity generation purposes. At present, the EU depends on natural gas, oil and coal for ~82% of its overall primary fuel sources.

Predictions of future energy scenarios suggest that natural gas will continue its penetration into European markets, even if transport over considerable distances, either as LNG or in gaseous form, imposes a number of technical and economic constraints. Conversely, the petroleum share will continue to grow steadily, although only at a low level. Much of the latter growth will be associated with the transport sector. Coal's contribution to European power generation in the future will be maintained. Coal will also continue to be used extensively in Central and Eastern Europe.

Accurate predictions of the degree of future growth in the EU electricity market are difficult to due to uncertainties involved. These include:

- Economic output and structure, and population growth.
- Technical change and capital stock turnover. The nature and pace of technical change are inevitably uncertain. Furthermore, as new types of energy-related equipment become available, the rate at which they are adopted will influence market trends.
- Human attitudes and behaviour. Rising incomes impact on overall electricity demand.
- Fossil fuel supplies and extraction costs.
- Energy market developments. Many electricity and gas markets are undergoing restructuring, privatisation, aimed at achieving more competitive organisations.
- Energy subsidies.
- Changing environmental objectives and policies.

Recently, the DG XVII of the European Union carried out a study using three possible future scenarios (10), each dependent on different levels of growth and activity. It was suggested that, in terms of electricity generation within the EU, the following range of capacities were possible (Table 3).

Table 3
Overall Electricity Generation (TWh) Within the European Union

Scenario	**1995**	**2000**	**2010**
A	2309	2531	2882
B	2308	2561	2691
C	2304	2451	2746

The contribution of thermal power generating plant to the overall totals were as follows:

Table 4
Overall Electricity Generation (TWh) – thermal power plant contribution

Scenario	**1995**	**2000**	**2010**
A	1190	1366	1770
B	1187	1396	1511
C	1188	1290	1446

Although the overall totals vary, there is continuing steady growth under all scenarios assessed. Similarly, the contribution of fossil fuel-fired generation continues to grow.

In the following section, the makeup of the electricity industries of the individual Member States of the EU are addressed.

3.1 Electricity Markets in Individual Member States

The power generation sector in Europe has undergone substantial change in the last decade. Changes of ownership, significant changes in the fuel mix fired in certain Member States, and the restructuring and reorganisation of facilities make it difficult to establish an up-to-date baseline for use in this study within the constraints of the existing contract. Consequently, the extensive study undertaken by IEA Coal Research in 1994 has been used to establish a consistent baseline for the relative comparison of opportunities for biomass and waste combustion within the EU. It is recommended that this should be updated with current information at an early opportunity.

In addition to changes in installed capacities and fuelling methods, a number of utility companies have been undertaking trials of co-combustion with biomass and waste materials. These trials are governed by considerations of commercial confidentiality and it has not been possible to gain the agreement of these companies to incorporate data within the constraints of the present contract. Again, it is recommended that these data should be revised for the most-up-to-date view.

In the following review, unless otherwise stated, the Consultants have used data sourced predominantly from: C W Maude *et al.* ***World coal-fired power stations. Europe and Russia***. IEA publication IEACR/70.

Austria

Net maximum generating capacity based on solid fuel utilisation is ~2.4 GW. Some units are CHP plants. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	5.0	10.0
Other solid fuels	0.3	0.6
Oil	3.0	6.0
Natural gas	6.8	13.6
Nuclear	---	---
Renewables	34.9	69.8
TOTAL	50.0	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Belgium

Net maximum generating capacity based on solid fuel utilisation is ~5.5 GW. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	18.5	25.6
Other solid fuels	0.9	1.2
Oil	1.5	2.1
Natural gas	6.7	9.3
Nuclear	43.5	60.2
Renewables	0.4	0.5
Pumped storage	0.8	1.1
TOTAL	72.3	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Denmark

Net maximum generating capacity based on solid fuel utilisation is ~8.5 GW. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	26.7	89.0
Other solid fuels	0.5	1.7
Oil	1.2	4.0
Natural gas	0.7	2.3
Nuclear	---	---
Renewables	0.9	3.0
TOTAL	30.0	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Finland

Net maximum generating capacity based on solid fuel utilisation is ~6 GW. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	7.6	13.8
Other solid fuels	8.6	15.6
Oil	1.0	1.8
Natural gas	4.7	8.6
Nuclear	18.2	33.0
Renewables	15.0	27.2
TOTAL	55.1	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

France

Net maximum generating capacity based on solid fuel utilisation is ~13.5 GW. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	41.0	8.9
Other solid fuels	1.0	0.3
Oil	8.7	1.9
Natural gas	2.8	0.6
Nuclear	338.4	73.6
Renewables	67.7	14.7
TOTAL	459.6	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology. There are also several CFBC plants in operation.

Germany

Net maximum generating capacity based on solid fuel utilisation is ~58 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	304.1	57.0
Other solid fuels	6.5	1.2
Oil	13.6	2.6
Natural gas	33.3	6.2
Nuclear	158.8	29.8
Renewables	16.9	3.2
TOTAL	533.2	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology. There are also several CFBC and CFBC/CHP plants in operation.

Greece

Net maximum generating capacity based on solid fuel utilisation is ~4.5 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	26.9	71.9
Other solid fuels	---	---
Oil	8.1	21.7
Natural gas	0.1	0.3
Nuclear	---	---
Renewables	2.3	6.1
TOTAL	37.4	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Ireland

Net maximum generating capacity based on solid fuel utilisation is ~1.3 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	6.7	43.7
Other solid fuels	2.2	14.4
Oil	2.4	15.7
Natural gas	3.5	22.9
Nuclear	---	---
Renewables	0.5	3.3
TOTAL	15.3	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology. Several other facilities use peat-fired fluidised bed combustion.

Italy

Net maximum generating capacity based on solid fuel utilisation is ~11 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	21.3	9.8
Other solid fuels	1.6	0.7
Oil	113.3	52.2
Natural gas	35.2	16.2
Nuclear	---	---
Renewables	45.8	21.1
TOTAL	217.2	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

The Netherlands

Net maximum generating capacity based on solid fuel utilisation is ~4 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	25.2	32.6
Other solid fuels	1.1	1.4
Oil	3.4	4.4
Natural gas	43.4	56.3
Nuclear	3.8	4.9
Renewables	0.3	0.4
TOTAL	77.2	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Portugal

Net maximum generating capacity based on solid fuel utilisation is ~1.5 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	10.3	34.2
Other solid fuels	0.9	3.0
Oil	13.9	46.2
Natural gas	---	---
Nuclear	---	---
Renewables	5.0	16.6
TOTAL	30.1	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Spain

Net maximum generating capacity based on solid fuel utilisation is ~12 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	65.4	40.6
Other solid fuels	1.0	0.6
Oil	14.9	9.2
Natural gas	3.5	2.2
Nuclear	55.8	34.6
Renewables	20.6	12.8
TOTAL	161.2	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Sweden

Net maximum generating capacity based on solid fuel utilisation is ~1 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	2.9	2.0
Other solid fuels	2.4	1.7
Oil	1.9	1.3
Natural gas	0.6	0.4
Nuclear	63.8	43.8
Renewables	73.9	50.8
TOTAL	145.5	100.0

Most major coal-fired power generation installations comprise chain grate stokers, CFBC, a PFBC plant, and variants of pulverised coal technology.

United Kingdom

Net maximum generating capacity based on solid fuel utilisation is ~39 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	220.3	62.1
Other solid fuels	1.4	0.4
Oil	27.7	8.6
Natural gas	8.7	2.7
Nuclear	77.7	24.1
Renewables	6.9	2.1
TOTAL	322.7	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Figure 2. Drax Power Station, United Kingdom

Electricity Industries of Accession Countries

As well as the member states of the EU, a number of Accession Countries also host significant electricity generating capacity. These include:

Bulgaria

Net maximum generating capacity based on solid fuel utilisation is ~6 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	13.6	35.0
Other solid fuels	---	---
Oil	1.9	4.9
Natural gas	6.3	16.2
Nuclear	13.2	33.9
Renewables	3.9	10.0
TOTAL	38.9	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Czech Republic

Net maximum generating capacity based on solid fuel utilisation is ~7 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	46.0	76.0
Other solid fuels	---	----
Oil	0.8	1.3
Natural gas	0.4	0.7
Nuclear	12.1	20.0
Renewables	1.2	2.0
TOTAL	60.5	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology with a few CFBC plants operational.

Estonia

(Source: *Energy Overview of Estonia*. US DOE. 1997.
http://www.fe.gov/international/estnover.html)

Net electricity generation in 1997 was:

Fuels	Electricity production (TWh)
Coal	---
Oil shale	8.5
Oil	---
Natural gas	---
Nuclear	na
Renewables	na
TOTAL (1997)	8.5

Major electricity generating capacity is based on oil shale-fired pulverised coal technology.

Hungary

Net maximum generating capacity based on solid fuel utilisation is ~2 GW. Electricity production is as follows:

Fuels	Electricity production (TWh)	% of Total
Coal	9.4	31.3
Other solid fuels	---	---
Oil	1.8	6.0
Natural gas	4.9	16.3
Nuclear	13.7	45.7
Renewables	0.2	0.7
TOTAL	30.0	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Latvia

(Source: Energy Overview of Latvia. US DOE. 1997.
http://www.fe.gov/international/latvover.html)
Net electricity generation in 1997 was:

Fuels	Electricity production (TWh)
Thermal	1.6
Hydroelectric	2.0
Natural gas	Na
Nuclear	Na
Renewables	Na
TOTAL (1997)	3.6

Lithuania

(Source: Energy Overview of Latvia. US DOE. 1997.
http://www.fe.gov/international/lithover.html)
Net electricity generation in 1997 was:

Fuels	**Electricity production (TWh)**
Thermal	1.7
Hydroelectric	0.3
Natural gas	Na
Nuclear	10.8
Renewables	na
TOTAL (1997)	12.8

Poland

Net maximum generating capacity based on solid fuel utilisation is ~27 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	120.4	96.6
Other solid fuels	---	---
Oil	0.6	0.5
Natural gas	<0.1	0.2
Nuclear	---	---
Renewables	3.5	2.8
TOTAL	124.6	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology although several CFBC plants are also operational or under construction.

Romania

Net maximum generating capacity based on solid fuel utilisation is ~9 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	15.6	27.5
Other solid fuels	---	---
Oil	6.1	10.7
Natural gas	20.5	36.1
Nuclear	---	---
Renewables	14.6	25.7
TOTAL	56.8	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Slovakia

Net maximum generating capacity based on solid fuel utilisation is ~2.9 GW. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	7.1	31.3
Other solid fuels	---	---
Oil	0.9	4.0
Natural gas	1.1	4.8
Nuclear	11.7	51.5
Renewables	1.9	8.4
TOTAL	22.7	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

Slovenia

Net maximum generating capacity based on solid fuel utilisation amounts to ~4 TWh. Electricity production is as follows:

Fuels	**Electricity production (TWh)**	**% of Total**
Coal	4.0	40.0
Other solid fuels	---	---
Oil	1.0	10.0
Natural gas	---	---
Nuclear	2.0	20.0
Renewables	3.0	30.0
TOTAL	10.0	100.0

Most major coal-fired power generation installations comprise variants of pulverised coal technology.

4.0 REVIEW OF CO-FIRING APPLICATIONS

Irrespective of the type of combustion or gasification technology adopted, or the particular combination of fuel feedstocks being utilised, in all cases the consistent supply of the feedstock in the appropriate grade and quality is the single most critical factor in ensuring adequate operational performance of the particular plant, allowing it to meet production and emissions targets.

4.1 Fuel Preparation and Handling Technologies

For the purposes of this study it has been assumed that the fuel is supplied to the plant by a contracted supplier and for that reason, no discussion has been included on issues such as in-field harvesting, chipping, baling for biomass fuels and establishment of collection systems for industrial wastes or transportation of sewage type wastes.

4.2 Design Considerations

For the purposes of this study specific design issues relating to the operation of combustion and gasification plant have been covered within the sections relating to the technology concerned. This section has concentrated on the front-end issues that include storage, preparation and handling prior to plant injection.

As noted, the range of biomass and wastes is diverse and covers a wide range of substances that differ considerably in chemical and physical character. Many have high water contents and are softer than most coals. These differences in physical and chemical properties can have implications for storage, preparation and handling techniques of the fuels in co-fired applications.

4.3 Storage

For biomass, a logical approach is a combination of air drying by storage in the open, followed by further drying (if required) immediately prior to use.

Bauer (11) has described storage trials in summer and winter for wood chips used in commercial-scale (100 MW_e) tests of co-firing wood at 10 t/h with lignite at Lubbenau power station. Natural drying to ~30% moisture content occurred in summer in five weeks. Free convection within the pile allowed sufficient heat dispersion to avoid spontaneous combustion. The winter tests showed that drying also proceeded in cold and wet weather. In commercial application, progress in drying will be readily determinable by temperature monitoring. It is noted that the drying requirements will be very climate-dependant. In the UK, for instance, where the summer periods are generally wetter than in continental Europe, 30% natural drying may not be feasible.

The storage of softer materials, such as straw, is now established practise in many countries such as the UK and Denmark. Moisture control in the stored straw is important to ensure that a consistent fuel is supplied to the plant. Meschgbiz and Krumbeck report that when the material became wet, chopped and milled biomass could not be emptied from standard European large bags, making feeding to the plant almost impossible.

Spontaneous heating tests in air and simulated flue gas mixtures by the British Coal Corporation (12) showed that the ignition temperatures for various biomass materials were generally higher than that for coal. Explosion tests showed that explosion indices were less severe for coal than for biomass.

Studies at Braunschweig University showed that dried sewage sludge required storage in mass flow silos, with stationary storage time being limited to five days in order to prevent sticking. Wide silo outlet openings and steep sides, plus discharge aids such as air guns, were useful precautions.

4.4 Size reduction and handling

In combustion systems, a common handling and feeding train may sometimes be used, but more commonly, additional systems may be required for separate sizing of biomass. The degree of size reduction required depends on the nature of the biomass/waste and the nature of the utilisation technology. A major problem highlighted in a number of co-firing trials and demonstrations has been the lack of reliability of feed preparation and handling systems currently available. Fuel variability poses particular difficulties for the size reduction and handling systems, especially for the softer types of biomass.

In any co-firing situation, there exists a range of potential alternative concepts for feed handling. The extreme options are:

- separate reception, comminution, conveying and utilisation systems for biomass and coal.
- separate reception, followed by combined comminution, conveying and utilisation systems for biomass and coal.

Grinding equipment appropriate to the particular feedstock must be selected carefully. Hey *et al* at DMT(13) described laboratory evaluations of fuel preparation methods for co-firing biomass with coal as granulates in a fluidised bed and for grinding sewage sludge for co-firing with coal as pulverised coal. Grinding of straw and miscanthus in vibration or hammer mills was accompanied by stickiness or dust evolution and these methods were therefore not recommended. Combined grinding of coal with chopped barley and wood pieces was possible in a hammer mill, provided conditions were carefully optimised. However, a ball mill proved unsuitable for this application. Grinding energies were of the order of 1-2% of the feed calorific values.

The size reduction of several categories of commonly used biomass and waste feedstocks is reviewed briefly below:

Straw and miscanthus

Size reduction of these soft fuels at the point of use generally requires a chopping action and grinding is often not feasible. Consequently, very fine particle sizes are not easy to achieve.

However, the reactive nature of straw and miscanthus enables relatively large sizes to be utilised satisfactorily, once handling and transport to the reaction zone can be achieved smoothly.

In the Vestkraft coal-fired power station at Esbjerg, tests of straw and wood co-firing with hard coal were carried out; some 15,000 tonnes of straw were combusted in the 125 MW_e Unit 1. The baled straw was fed in two trains to a shredder, followed by a cutter. Air blowers then conveyed the straw to the straw burners. As at other locations, straw feeding was accompanied by difficulties and below-design feed rates (2 x 5 t/h instead of 2 x 8 t/h). Biomass humidity variation was an influencing factor, 15% moisture content being the preferable maximum, and operation generally being impossible at 25%. Foreign bodies in the fuel caused breakdowns, and wearing parts had very short lifetimes (less than 1 week).

Straw/hard coal co-firing tests (up to 20% straw by thermal energy) were carried out at the 250 MW_e wall-fired pulverised coal Amager Power Plant Unit 3 in Denmark in 1994. Straw was delivered as cylindrical pellets of ~9% moisture content (no binder) to avoid the need for shredding. The pellets were mixed with coal before feeding to the mills for co-grinding. Co-grinding caused no problems in the mills.

At the IFRF, Morgan and van der Kamp(14) also found difficulties with straw chopping, handling and feeding; testing was carried out using a 2.5 MW_{th} test rig fired on straw/coal mixtures and sewage sludge mixtures. The straw size was 10-40 mm. Equipment used for straw and straw + paper included a straw chopper, a bunker at 4 bar pressure discharging to a screw feeder, which fed a rotary valve (itself fed with pressurised air) and a pneumatic delivery line to either the burner’s central orifice or an annulus surrounding the coal pathway. Although some success was achieved in feeding the biomass, further engineering development of the feed handling was recommended.

In their tests on the co-firing of biomass with brown coal in 1 MW_{th} pulverised coal and fluidised bed combustion systems, Meschgbiz and Krumbeck (15) used a mobile straw mill designed for agricultural use at 10-100 kg/h; however, hazardous operation, a low feeding rate, plus noise and dust production frequently occurred. During feeding to the dosing screw feeder that added the biomass to the coal feed leaving the coal belt conveyor, segregation occurred in the biomass bunker with miscanthus and irregular addition rates resulted. The latter was largely overcome by limiting straw length to <50 mm. Pre-mixing of straw and (brown) coal was not feasible due to segregation of straw from coal(16).

Lauridson et al co-fired mixtures of straw and straw + wood chips in a 20 MW_{th} MCFB plant. A dosing screw feeder at the base of a silo was used for the coal, wood chips and manure. Straw was supplied as 500 kg bales and simply torn apart (not chopped) prior to combustion. The flow was regulated by the speed of the bale feeding table. Uniform straw feed rates were not always achieved, due partly to excessive moisture contents of some batches (>40%). Wood chips and manure could be fed smoothly.

Rasmussen *et al* described the straw handling system used at the 78 MW_{th} Grenaa coal/straw dual fuel CFB plant in Denmark (Figure 1). Straw is delivered by truck as 450 kg bales, which are lifted, 12 at a time, by automatic crane to storage or directly to the feed system. An automatic drag chain conveying system moves 12 bale batches from storage to the feed line, from where they move on to four parallel shredders. The shredded straw is fed pneumatically through air locks to the boiler injection loop seals. Even with this purpose-designed system, several short duration failures occurred during the test, due to excessive cutter wear and compacted bales with wet intrusions.

The much longer residence time in circulating fluidised bed combustion systems makes this particular technology more tolerant of feed, in terms of moisture or size. For straw combustion, only pneumatic feeding of prepared feed was employed.

For preparing the co-fired fuel for their 1.6 MW_{th} PFBC system, Andries *et al* at Deft Technical University(17) used up to 20% additions of crushed pelletised straw, crushed pelletised miscanthus and a granulated mixture of milled straw and pulverised coal, which were premixed with the coal and fed into the combustor using a lock hopper system, screw feeder and pneumatic feed line. Again, these workers recommended that preparation and handling of biomass should receive careful attention: in fact, it proved impossible to feed the granulated mixture as the lock hopper system was unable to accommodate it.

ELSAM/ELKRAFT have undertaken considerable development work in the area of straw handling for utility-scale plant. The development work has brought them to the point where they are now confident of designing straw systems for larger boiler plant. Plans are being taken forward to demonstrate these systems on a 90 MW_e CFB unit at the Midkraft Arhus site. This plant is expected to come on-line in 2000. It will form the first step in the Danish Government's plans to develop 250 MW_e utility-scale CFBC units for straw/coal firing(18).

Wood/Waste Wood

A number of studies have examined the potential of co-firing wood with coal. Several have suggested that few plant modifications would be needed for wood co-firing; undried, hogged wood (<12 mm) would be blended with crushed coal on the feed belts supplying the bunkers. An alternative strategy suggested was to feed very fine wood, if available (e.g. dried wood sandings) with the secondary air.

Figure 3. Wood chip stockpile; an increasingly popular feedstock for co-combustion and co-gasification applications

Boylan(19, 20) has described tests in 1992 of co-firing of waste wood consisting of tree trimming and garden waste. This mixture of sticks, leaves, pine needles and branches was passed through a tub grinder and screened to produce an approximate size range of predominantly 12-25 mm. This was mixed with sawdust then added to the coal (3:1 by volume). The mixture (average 11.5% wood by mass, 6.5% thermal), was passed successfully to ball mills of a wall-fired pulverised coal power plant; no blockages occurred. Mill performance was not markedly affected, and 70% of the wood was ground to below 75 um. Milling power increased by 10-15%. Higher primary air rates meant that 13.5% was close to the maximum co-firing rate attainable at MCR. Other studies have suggested that 1 mm is the maximum acceptable size for wood combustion in pulverised fuel systems, and that preparation to such a degree necessitates drying to moisture contents of <8%.

Wood co-firing tests at Esbjerg were carried out in a 125 MW_e unit. Wood waste was supplied, from a furniture works, as loosely pressed pellets (density 500 kg/in^3, CV 19 MJ/kg, ash content 0.45%). These were fed to the second stage (cutters) of straw shredders and transported with air to conventional coal burners. There were apparently no problems with this feed preparation arrangement, although finer grinding of the wood using hammer mills was suggested in order to reduce the concentration of carbon in fly ash.

Plants firing low grade coals possess certain features, e.g. beater mills that would be expected to make biomass co-firing easier. In the 100 MW_e tests at VEAG's Lubbenau plant, 7% by mass of pine wood chips were fired with lignite. The wood chips were mixed with the lignite before dropping through recirculating flue gas into the fan mills, and preheated combustion air; in addition, fuel mixture was then injected through wall burners at the top of the combustion chamber. The grinding energy of the mills was increased by 10%, an effect also observed by some workers in the USA. The Lubbenau plant trials showed that co-firing of wood with lignite could be carried out successfully without detriment to the combustion process.

The Netherlands utility EPON has, since 1995, been engaged on what appears to be the largest scale application of co-combustion to date, firing waste wood *via* separate wood-burners retrofitted to a 635 MW_e wall-fired pulverised coal boiler, Centrale Gelderland at Nijinegen. A 4.5% (thermal input) co-firing rate with an anticipated 60,000t of waste wood can be co-fired annually(21). Wood waste is collected, sorted and processed into raw wood chips of ~30 mm size, then transported to the power plant. The wood is ground to a particle size of <1-8 mm, at up to 10 t/h, in two hammer mills. The material is then further ground in four pulverisers whilst being dried in pre-heated air. Fines are separated in a static classifier and the oversize material subsequently sieved for the separation of additional fine material. Oversize material is returned to the pulverisers for further size reduction. The <1 mm fines are fed pneumatically to a storage silo from where they are transferred *via* a dosage system to the wood burners. Separate wood burners are mounted in the side walls of the boiler (two on each side). Total wood burning capacity is 54 MW_{th} and power generated from the wood component is 20 MW_e.

Figure 4 The EPON coal/wood-fired facility in The Netherlands

In some examinations of wood co-utilisation, difficulties have been encountered in obtaining uniform addition rates; this stems partly from the low bulk density. For instance, the test work on the

Royce-International Combustion Ltd. (UK) test rig used in the Imperial College *APAS* studies necessitated development of a dedicated feeding system for sawdust. A belt feeder with a simple feedback loop carrying half the sawdust back to the hopper was eventually found to be effective. Greater success has been achieved in work carried out by VTT Energy in Finland, where limited amounts of sawdust were simply added to a coal feed system without any apparent problem.

Grinding tests carried out by International Combustion Ltd. using wood pellets confirmed that milling capacities are decreased. Consequently, all primary air fans and mills were required to be in operation in order to maintain full output; this could clearly limit the degree of co-firing attainable as this effectively removes the normal margin of mill redundancy, and also impacts on plant maintenance and availability.

Sewage sludge

Dried sewage sludge can be ground down more to smaller particle sizes than most biomass materials. However, there can be grinding difficulties if dried sludge shipments already contain fines(22). Sewage sludge may also be fibrous and have a wide size range, resulting in handling problems. Pellets may become plastic as they warm during grinding, with consequent blinding of screens(23). A table mill however performed well and workers at the IFRF had no difficulties in pulverising dried sewage sludge.

Probst and Wehland(24) described the production of tonnage quantities of fuel granulates containing sewage sludge, hard coal and limestone for firing in a 10 MW_{th} CFB plant. A continuous dual-shaft paddle mixer was used to process the mixture of pulverised coal (40%) and dried sewage sludge (60%). The 75 t/d granulated product was air-dried under cover for several weeks to 25% moisture content. Separate tests of preparation using wet sludge and dried sludge powder were also carried out using different equipment incorporating a dual-shaft paddle mixer plus a mill.

Billotet described the handling and preparation systems being developed at a sewage sludge drying facility at Weiher II power station, equipped with slag tap furnaces. The plant dries the sewage sludge to <10% moisture content by indirect heat exchange with steam. A coarse fraction of the dried product is stored before being pneumatically transferred to the fuel feed system and beater mill of the combustor at a rate of 0.4-4 t/h. Mixing dried sludge with coal in the coal storage area was found to be unsatisfactory from the point of view of dust emissions and odours. The feed handling system adopted suffered from problems of excessive wear of the storage tank extraction systems. Leakages also occurred in the tanks and handling of dried matter <0.5mm size led to some clogging and flow problems. Larger flows were easier to accommodate than smaller flow rates.

As part of Rheinbraun's contribution to the *APAS* Project, Adlhoch *et a1*(25) successfully co-fed >500t of dried sewage sludge with brown coal to the HTW demonstration gasifier. The dried sludge was delivered in silo trucks or transport containers and pneumatically conveyed to an existing solids silo. From the silo, the sewage sludge was metered (using star feeders and screw feeders) into one of the pneumatic conveying vessels used for sending fuel to the gasifier's lock hopper system. During the tests, no problems were encountered in any of the handling systems, despite dust being formed upon initial unloading. Supporting studies at Braunschweig University (summarised in the same source) on the storage of dried sewage sludge showed that, although flow properties were initially good, after ~21 days of storage, it could be classified as 'non-flowing'. Storage is therefore required to be in mass flow silos with stationary storage time being limited to five days. Wide silo outlet openings and steep sides plus discharge aids such as air guns were useful precautions suggested.

At British Coal's CTDD, Kelsall and Laughlin(26) fed dried pelletised (<6 mm) sewage sludge *via* lock hoppers, together with coal to a pressurised gasifier. Separate pneumatic conveying trials established that very little degradation of the pellets occurred, even at high delivery rates and gas rates. No handling or feeding difficulties were encountered during the gasification tests. At a commercial plant, 30% moisture sewage sludge would be pre-dried to 5% moisture using indirect steam heating to facilitate keeping steam addition to the gasifier broadly constant.

The above findings suggest that there may be greater problems with the preparation and handling of biomass, compared to coal. This stems largely from the inherent variability of these fuels. This can lead to difficulties in feeding of, particularly, the softer fuels at reproducible rates, presenting potential problems in the downstream utilisation process. The choice of preparation and handling systems for co-utilisation requires basing on the biomass/waste properties, including its moisture content, ease of grinding, extent of variability, co-firing ratio, and the technology being utilised.

Figure 5. Rheinbraun AG's Berrenrath site, Germany. HTW gasification technology has been used to co-gasify brown coal, sewage sludge and scrap plastics.

Municipal/Industrial Wastes

Unlike many other feedstocks, the use of municipal solid waste and derived fuels such as a dRDF is commercially established. There are large mass burn incinerators in most EU countries and many plant (stoker, FBC and CFBC) burning dRDF. However, information on the feed systems utilised in such plants is limited.

A major drawback with the use of MSW as a fuel feedstock is its heterogeneous composition, which can present problems when co-firing in a boiler. In most cases, the practical option utilised is to segregate the materials present, recycle appropriate materials (glass/cans, etc) then dry and densify the material to produce dRDF (Refuse Derived Fuels). There are dRDF plants now operating in most EU countries. The dRDF is handled easily in conventional handling systems, although careful attention is required to avoid water contamination prior to boiler feeding in order to maintain pellet integrity.

At Slough Estates in the UK, a *Fibre Fuel* plant has been constructed in a joint venture with UK Waste. The Fibre Fuel or Packaging Derived Fuel (PDF) is made from segregated paper, packaging material, plastics, and board; unlike conventional dRDF, no domestic waste is included. The PDF therefore has a higher overall calorific value and is currently being used in the fluidised bed boilers of Slough Heat and Power Ltd. The Association of Plastic Manufacturers of Europe has been leading similar initiatives to turn plastic wastes into a form suitable for the substitution of coal in boilers. The core of the process is segregation, followed by densification to form a durable, dense pellet for ease of handling/distribution. The fuel will be substituted for coal, displacing fossil fuels and reducing disposal costs. Utilisable industrial types include tyres, post-consumer carpets, autoshredder residues and clinical waste. Typically, tyres are chipped to produce Tyre Derived Fuel (TDF), carpet is shredded and pre-mixed with coal, and autoshredder residues are usually conveyed pneumatically.

4.5 Feeding/handling Design Issues

Depending on the feedstocks in question, careful attention may be required when designing an appropriate feeding system. As noted, generally, compared to coal, biomass and waste feedstocks are more difficult to prepare and handle as a consequence of their:

- Low heating value
- High moisture content
- Low bulk density
- High fibrosity
- Great size variability

Several of these factors can influence significantly the design and operation of the feeding system adopted. For instance, bulk density can influence the size of conveyors, storage and feed bins, screw feeder size, etc. Frequently, a separate feeding system is used for the biomass component of the fuel mix. For instance, most grain-producing countries produce substantial tonnages of surplus straw as a by-product; in Denmark there can be an annual straw surplus of over 3 Mta, equivalent to 1.7 Mt imported coal. The straw available is a low grade, non-homogenous fuel source, characterised by high volatile content, plus high chlorine and alkali levels. Despite this, there are clear incentives to develop the use of this indigenous fuel source and several CFB power plants regularly co-fire coal with straw. Feeding systems adopted tend to be relatively complex and involve a number of separate stages. Sorting, blending and preparation of fuels derived from wood and RDF can be equally complex.

Because of the high chlorine and alkali levels often encountered in fuels such as straw, careful monitoring of downstream components has proved to be necessary in order to minimise corrosion problems. Thus, careful selection of the appropriate materials of construction has proved to be of importance in plant operations.

Work carried out in Italy investigated the co-combustion of wood (eucalyptus and poplar) with coal. Both woods were fast growing; however, their handling presented problems in achieving stable plant operating conditions. In particular, the bark of both trees proved very difficult to handle, transport and feed. Its moisture content played a critical role in this context, influencing both grinding characteristics and flowability.

4.6 Review of Direct Co-combustion Technologies

4.6.1 Pulverised Coal (pf) Boilers

Technology and Market Status

Pulverised coal combustion is the most widely used technology for utility-scale power generation in the world. Since its initial introduction, considerable development of the pulverised coal power generation cycle has been undertaken in order to optimise efficiency and availability. Modern pulverised coal plants typically operate at electrical generation efficiencies of ~38% although several new advanced pulverised coal plant, with particularly favourable local conditions, have demonstrated efficiencies of ~43%.

In a pulverised coal plant, coal is ground to a fine powder then blown pneumatically, with the combustion air, into the boiler plant. Almost all the carbon and volatiles in the coal are consumed and the heat released is used to produce high pressure superheated steam. This steam is used to drive a turbo-alternator that produces electricity. Typical modern practise is to build units in which a single boiler provides all the steam necessary to operate a dedicated turbo-alternator set. Hence, plants are typically 300 to 500 MW_e in size.

After the boiler, the flue gas passes to an electrostatic precipitator or bag filter to remove particulate matter. Sulphur can be removed using flue gas desulphurisation plant and oxides of nitrogen can be controlled by modifications to the burners. Further clean up systems for NOx such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) can also be adopted to reduce levels further.

Design Considerations

A biomass or waste fuel can be introduced into an existing pulverised coal boiler in several ways:

- Firing the pre-prepared biomass through dedicated burners.
- Mixing the pre-prepared fuel and coal upstream of some or all of the burners, before firing through those burners.
- Premixing the biomass with coal upstream of the existing coal preparation plant and co-preparing and firing the fuel mixture.

The lower energy density of most biomass and wastes compared to coal, necessitates a relatively high volume flow into the boiler. The properties of the biomass/waste are likely to be different to those of coal and will impact on the performance of the boiler and associated equipment. Areas of potential impact include:

- Fuel supply, storage and handling.
- Combustion-related behaviour.
- Boiler performance and efficiency.
- Emissions.

Each of these areas is discussed below, with emphasis on the alternative methods of introducing the biomass into the boiler.

Fuel supply, handling and storage

Coal handling is important to the operation of any power generation plant. Trouble-free transportation is important, as is good discharge from storage and buffer hoppers. The characteristics of biomass/wastes are very different to those of coal and are likely to require different solutions in respect of storage and handling. Where the biomass/waste is to be introduced into the boiler *via* a dedicated supply stream and set of burners, the most appropriate technologies can be utilised to minimise problems. However, this will involve increased capital expenditure for separate hoppers, mills, transport lines and burner installations, compared to situations where the biomass is mixed directly with the coal. In the latter, the biomass will almost certainly have an impact on the coal's handling, milling and transport properties. This may require specific pre-treatment to minimise these effects (e.g. extra drying) and the relative increased operational costs need to balanced against those for a dedicated supply stream.

A utility trial co-firing wood fuel with coal at Georgia Power's Hammond Unit in the USA demonstrated that the mill power requirements were raised by 10-15% by the incorporation of wood fuel into the coal stream. In addition, the primary flows required increasing in order to accommodate the need for increased drying of the wood. These factors will have a direct impact on plant operating costs and hence the cost of electricity sent out.
The Dutch experience at EPON is similar in that the associated milling costs for wood are ~10% of the total energy production. This cost will again be reflected in the electricity.

Combustion-related behaviour, boiler performance and efficiency

Most biomass/wastes have combustion characteristics different to those of coal and their behaviour in a boiler originally designed to fire pulverised coal will influence the overall combustion process. Similarly, any change to the basic boiler configuration in order to accommodate biomass combustion will impact on boiler operation. This is particularly true if a separate set of burners is the preferred method of introduction. Changes in combustion efficiency and heat release patterns may have a direct effect on boiler efficiency, and a knock-on effect on emissions and ash collection.

The elements associated with biomass ash have a composition different to that of coal ash and may introduce an increased risk of ash deposition problems. The experience of Danish utility companies co-firing straw and coal in pulverised coal boilers is that an increase in superheater fouling and corrosion is likely to occur. This is a direct consequence of the higher alkali metal concentrations introduced into the boiler by the straw combustion.

Emissions

The principal emissions from coal-fired plant are particulates, sulphur dioxide and oxides of nitrogen Emissions of sulphur dioxide are approximately in proportion to the fuel's sulphur content, if sulphur capture is not included in the plant design. The effect of incorporating biomass will therefore depend upon the fuel's sulphur content. For fuels such as straw and wood, the sulphur content is lower than for coal and so will tend to reduce overall SO_2 emissions.

Emissions of NOx cannot be predicted solely from the coal's nitrogen content since they are strongly influenced by plant design and operation. Changes in boiler configuration to accommodate biomass firing may have an impact here. This is especially true if a dedicated set of burners are introduced into the boiler.

Particulate ash collection is an important part of plant operation to minimise dust emissions and several plants have reported that there can be a slight increase in particulate emissions when co-firing with wood.

Ash disposal and/or utilisation is another area where the properties of the coal ash may be modified by the incorporation of biomass. In both this area and that of particulate emissions, the use of municipal solid waste as a co-feedstock could introduce elements into the ash that could present an environmental hazard. This would require careful attention.

Review of Co-firing Information

Much of the recent experience in Europe with co-firing of commercial pulverised coal plant with biomass and wastes has been obtained in the *APAS* and Joule III Programmes. For instance, important initiatives were carried out at the 125 MW_e scale in the ELSAM Vestkraft power plant at

Esbjerg, at 100 MW_e at VEAG's Lubbenau plant and at The Netherlands utility EPON's plant, co-firing of waste wood in separate wood-burners retrofitted to a 635 MW_e pulverised coal at Nijmegen. Straw co-firing tests (up to 20% straw by thermal energy) have also been carried out at the 250 MW_e pulverised coal Amager Power Plant Unit 3 in Denmark. A considerable effort on supporting studies has been conducted in laboratory and pilot plants. An example of the latter is the Rolls-Royce-International Combustion Limited 88 MW_{th} test rig in the UK. In addition, there is considerable interest and experience in the USA, encouraged by EPRI. Much of this work has shown that, once feed preparation, metering and conveying difficulties have been overcome (the main problem areas), biomass and waste generally exhibit rapid devolatilisation, ignition and burnout.

Several of the most significant European projects are reviewed briefly below:

- Co-firing with straw and miscanthus

Straw/hard coal co-firing tests (up to 20% straw by thermal energy) were carried out at the 250 MW_e wall-fired pulverised coal Amager Power Plant Unit 3 in Denmark. Straw was delivered as cylindrical pellets of ~9% moisture content to avoid the need for shredding. The pellets were mixed with coal prior to entering the mills for co-grinding. No severe problems were observed in sustaining stable combustion, or with deposition in the boiler. For sulphur control purposes, the plant is fitted with limestone/gypsum FGD; no deleterious effects on the overall performance of the FGD plant occurred, although a decrease in limestone reactivity was observed in laboratory tests. The tests were not sufficiently long for boiler corrosion, or the accumulation of undesirable species in the FGD plant to be assessed.

In the Vestkraft 125 MW_e pulverised coal Unit 1 at Esbjerg, Denmark, tests of straw and of wood co-fired with hard coal were carried out. In this work, 15,000 t of straw were combusted with 63,000t of coal. The baled straw was fed in two trains to a shredder, followed by a cutter. Air blowers conveyed the straw to separate straw burners; these were based on coal burners but with fixed cones instead of impellers to spread the injected straw. Straw feeding was accompanied by difficulties and below-design feed rates.

In order to avoid the impingement of straw on the far boiler wall, the air flow required moderating. Two straw burners were used in conjunction with 10 coal burners, the latter located above and to either side of the straw burners. The slagging and fouling and corrosion effects were of particular interest to the utility: significant higher levels of both chlorine and potassium, compared to coal, were present in the straw.

In the boiler itself, although there were no deposits on boiler tubes, superheaters and preheaters, slag did accumulate around the straw burners. No extra accumulation occurred after some time and operation of the burners was not significantly impeded. Deposits were easily removed. There also appeared to be little change in rates of corrosion.

Operation and control of the boiler during straw addition was found to be satisfactory at up to 25% straw addition. Boiler load was typically 80% of rating. The tests also showed that there was a small tendency for the level of carbon in the fly ash to rise with the presence of straw particles. At levels >10% straw addition, co-firing would preclude the use of fly ash for cement manufacture. The slag ash contained rather more carbon, with many unburned straw particles. In addition, SCR catalyst samples were found to have suffered a degree of deactivation.

Work carried out at the IFRF firing mixtures of straw/coal and sewage sludge in a 2.5 MW_{th} test rig also noted difficulties with straw chopping, handling and feeding. The straw size noted was 10-40 mm. Equipment used for straw and straw/paper blends examined included a straw chopper, a bunker at 4 bar pressure discharging to a screw feeder, which fed a rotary valve (itself fed with pressurised air), and a pneumatic delivery line to either the burner's central orifice or an annulus surrounding the coal pathway. Although some success was achieved in feeding the biomass, further engineering development of the feed handling was recommended. In other tests, sewage sludge was pulverised separately from coal to 80% <75 um and fed to a similar burner arrangement.

It was concluded that feed rate irregularities during combustion could be minimised by taking into account the cut length of the biomass and avoiding feeding large particle sizes. Straw lengths <50 mm were found necessary to achieve smooth feeding to the beater mill used in trials of brown coal/biomass size reduction prior to combustion in a down-fired pulverised coal rig. Premixing of straw and (brown) coal was not feasible due to segregation of straw from coal. Pulverised fuel combustion tests on straw briquettes (bound with molasses) were unsuccessful as flame stability was poor.

- Co-firing coal and wood

The 100 MW_e tests at VEAG's Lubbenau pulverised coal plant noted above involved co-firing 7% (by mass) of pine wood chips with lignite. The test programme, using two boiler units, showed that a single recycle of wet ash (added to the fuel before it reached the feed mills) was needed in order to obtain no additional carbon in the coarse ash. The fly ash contained no additional unburned carbon even without this recycling. CO emissions remained lower than the 250 mg/m^3 limit when the ash was recycled. These large-scale trials showed that co-firing of wood with lignite could be carried out successfully without detriment to the combustion process. Further trials, using 10,000t of wood chips were subsequently carried out successfully.

The wood co-firing tests at Esbjerg were also carried out in the 125 MW_e Unit 1. Wood waste was supplied, from a furniture works, as loosely pressed pellets, of density 500 kg/m^3, CV of 19 MJ/kg, and ash content 0.45% These were fed to the second stage (cutters) of straw shredders then transported with air to conventional coal burners. Polish coal was fed to the other burners (CV of 24.8-26.9 MJ/kg, ash content ~18%). Co-firing of up to 20% wood was possible without detriment to the plant; no fouling or slagging occurred and little increase in carbon in fly ash was noted. Consequently, the latter still met cement and concrete specifications. NOx was reduced by 35% at the higher co-firing rates. A total of 1,300t of wood waste were combusted.

Design studies for co-firing the larger 250 MW_e Vestkraft Unit 2 at Esbjerg and a unit at Herningvaerket (89 MW_e) were developed, based on the use of wet wood (50% moisture -300,000 tpa at Esbjerg and 126,000 tpa at Herningvaerket), grinding in a hammer mill to <30 mm, then drying in warm air to 10% moisture. Subsequent grinding would reduce particle size to <1.0 mm, prior to combustion. A revised configuration at Herningvaerket would use dried wood (120,000 tpa a 50% moisture basis) and dried sawdust (67,000 tpa).

As noted above, since 1995, The Netherlands utility EPON has been co-firing waste wood in wood-burners retrofitted to a 635 MW_e wall-fired pulverised coal boiler (Centrale Gelderland) at Nijmegen. A 4.5% (thermal input) co-firing rate with an anticipated 60,000 tpa of waste wood can be co-fired. The wood is ground in two stages to a particle size of <1 mm. Separate wood burners are mounted in the side walls of the boiler. Total wood burning capacity is 54 MW_{th} and power generated from the wood component is 20 MW_e. Plan operating experience suggests that wood ground to a particle size of 2-3 mm may be adequate for acceptable combustion efficiency and ash carbon levels.

Investigations carried out at KEMA using a 1 MW_{th} test rig in support of the commercial scale co-firing at Nijmegen, noted that pulverised wood waste needed to be no larger than 400 um in order that unburned carbon levels remained essentially the same as when firing coal alone. The lowest NOx emissions were achieved by combined introduction of wood and coal into the centre of the flame. No additional dioxin emissions occurred, but at the maximum co-firing rate 13% wood (weight), dioxin levels in the ash increased. No increase occurred in heavy metals emissions, although levels were elevated in the ash. However, leachability was not affected adversely.

Wood waste co-firing at up to 40% thermal, has been demonstrated successfully at Savannah Electric and Power Co's 54 MW_e Plant Kraft Unit 2 in Port Wentworth, Georgia. The waste wood was initially shredded to <6 mm in three stages. The fuel was then fed at up to 14 t/h to four burners, coal to four others, and natural gas to the remaining four for flame stabilisation. Boiler efficiency losses of 1.5-5% occurred, depending on load. However, the test period was too short for firm conclusions to be reached regarding deposition and fuel handling.

EPRI have co-sponsored extensive testing of wood co-firing at Tennessee Valley Authority power plants. A preliminary case study(30) for the utility indicated that co-firing was a feasible and attractive way to cut sulphur dioxide emissions on at least some coal-fired stations.

Two conceptual designs for 15% wood fuel co-firing modifications to the 135 MW_e Kingston #1 tangentially-fired unit(31) in the USA were produced. The first included fuel reception, stock-out, reclaim, chip to <12.5 mm, dry to <25% moisture, pulverise to <1.5 mm, and transport in flue gas to the existing third row of burners. The second configuration assumed that <12.5 mm, <25% moisture wood chip was bought in and involved pulverising and transport to the third burner row, as in the first system. A number of successful wood co-firing tests have since been carried out at Kingston.

The EPRI programme has shown that small amounts (up to 5% of thermal input) of waste wood chips from the wood processing industry can be co-pulverised with coal fed to pulverised coal boilers simply by adding the wood to the coal pile. For more significant biomass additions (e.g. >10%, thermal), individual processing of the wood is necessary, involving drying and size reduction, probably both in two stages, to <20% moisture and <1.5 mm, in order to allow feeding through pulverised coal burners. An alternative strategy is to carry out major boiler modifications, involving new penetrations, with additional burners that will accept wood chips. This approach is less attractive to EPRI since it entails significant boiler downtime as well as higher costs associated with the requirement for additional wood fuel handling and combustion equipment; however, it should enable better control of technical risk and it is a strategy of interest to European utilities. In Europe, smaller quantities of fine waste wood is available in the vicinity of large coal-fired power stations, compared to some regions of the USA.

Tests carried out by Southern Company on co-firing waste wood, consisting of tree trimmings and yard waste (prepared and screened to produce an approximate size range of 12-25 mm), then mixed with sawdust and added to the coal, (6.5% of wood, thermal), entailed passing the mixture through four ball mills of the 112 MW_e wall-fired pulverised coal Plant Hammond Unit 1. Good combustion efficiency, with only 0.2-0.5% increases in combustible losses compared with 100% coal firing were obtained. The moisture content of the wood was higher than that of the coal (19%, compared with 6%), hence latent heat losses increased very slightly (by 0.25%). Higher primary air rates meant that 13.5% was close to the maximum co-firing rate attainable at MCR.

Environmental Aspects

Numerous tests have shown, as expected, that burner configuration has a considerable influence on the formation of oxides of nitrogen during co-firing. The high volatiles content (and often, low nitrogen content) of biomass gives enhanced scope for limiting NOx in conversion of coal plant to co-firing by combustion measures. For instance, some tests have noted that NOx levels from down-fired pulverised coal co-combustion of straw were reduced by, typically, 30% during staged combustion, compared with firing on brown coal alone. The NOx emissions from higher rank coals are improved most markedly. Addition of the coal is best made into the substoichiometric zone, with the biomass into the more air-rich zones. Biomass has also proved to be suitable for reburning(32) applications.

Reductions in SO_2 emissions result from the lower sulphur content of biomass compared with coal; retention of SO_2 by biomass ashes has not been observed in pulverised coal systems because of the high combustion temperatures.
The high temperatures in pulverised coal systems also generally prevent any increase in the emission of dioxins, despite the chlorine that is often present in biomass feedstocks such as miscanthus or straw. This has been demonstrated at 125 MW_e scale at Esbjerg. The chlorine is released mainly as HCl, as in the case of coal chlorine(33, 34). This can increase corrosion of superheater tubes but not to unacceptably high levels. Slagging and fouling have been found to increase only slightly with co-firing of straw in test rigs and in the 125 MW_e boiler at Esbjerg. The performance of limestone-gypsum FGD systems and gypsum quality appear to be unaffected. Pilot studies have shown a decline in SCR catalyst activity with increasing straw addition.

Pilot-scale co-firing of sewage sludge in various locations has revealed a much greater sensitivity of NOx emissions to co-firing conditions than for biomass. Sewage sludge has a higher nitrogen content than biomass. The preferred position for sewage sludge addition is therefore through the central, oxygen-deficient burner zone. Either higher or lower emissions than for 100% coal may be obtained, depending on the co-firing rate: the first 15% of sewage sludge generally increases emissions. However, air staging and fuel staging can prevent this difficulty and NOx levels below 300 mg/mn^3 at 6% oxygen have been achieved, as for the biomass fuels.

Sewage sludge also contains high sulphur levels and overall SO_2 emission is related to total fuel S content. Heavy metals can be in high concentration in sewage sludge although emissions of these when co-firing of the sludge were not increased to unacceptable levels(35) and ash quality, important in maintaining by-product outlets in the construction industry, was largely maintained. Sewage sludge also has a much higher ash content than biomass and the co-firing rate is therefore best limited to ~10% to avoid problems with slagging.

Thus, overall, biomass and waste co-firing of pulverised coal has been successfully demonstrated at the commercial scale in units of up to 635 MW_e. A list of the pulverised coal plants operating as co-fired units or that have been used for trials is given in Table 5.

Table 5. Pulverised Coal Plants Co-utilising Coal and Biomass/wastes

Client	**Location**	**Country**	**Fuel**	**Capacity (MW)**
Ames Municipal	Iowa	USA	Coal, RDF	75e
EPON	Nijmegen	Holland	Coal, waste wood	602e
GPU GENCO	Illinois	USA	Coal, waste wood	130e
Iowa Light & Power	Iowa	USA	Coal, agri-wastes	45e
Lakeland Electric	Florida	USA	Coal, RDF	350e
Saarberwerke AG	Saarberg	Germany	Coal, sewage sludge	75e
TVA	Tennessee	USA	Coal, waste wood	150e
SEPCO	Savannah	USA	Coal, waste wood	54e
Georgia Power	Hammond	USA	Coal, waste wood	100e
VEAG	Magdeburg	Germany	Coal, wood	350e
Vasthamnsvert CHP	Halsingbourgi	Sweden	Coal, wood	180e
Stockholm Energy	Hasselbyvaerket	Sweden	Coal, wood, olive waste	54e
Midkraft	Esjberg	Denmark	Coal, straw	150e
Uppsula Energi	Uppsala	Sweden	Coal, peat, wood	320e
Bayernwerke AG	Bavaria	Germany	Coal, straw	108e
Elsam	Amager	Denmark	Coal, straw/miscanthus	250e

4.6.2 Stoker systems

Technology and Market Status

Stoker systems for the combustion of coal have been commercially available for some years; the term refers to several types of combustion plant. However, for power generation purposes, the variants known as Chain Grate, Travelling Grate and Spreader Stoker Systems predominate. Chain and travelling grate-plant are similar in characteristics and are manufactured typically for boiler plant up to 80 MW. An example of a plant utilising a Spreader Stoker System is shown in Figures 3 and 4.

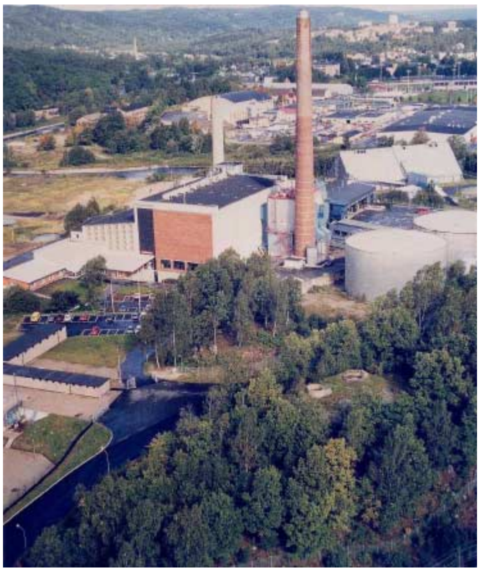

Figure 6. The coal/wood-fired Spreader Stoker Plantt Ryaverket in Sweden.

In these systems, fuel is fed continuously onto a moving grate or chain forming a "moving mat" of burning fuel. The grate speed can be controlled to ensure that the fuel attains sufficient residence time to ensure complete combustion. The fuel enters the furnace through a guillotine door and its temperature is raised by radiation from a refractory arch inside the doorway. Initially, moisture and volatile matter are driven off. Ignition is established and as the temperature zone moves down through the bed, the remaining volatile matter is driven off to burn above the grate. The carbon in the fuel burns off towards the back of the grate leaving the ash that drops into the ash pit and is then removed for disposal. The ash provides an insulating layer to protect the grate from burn-out.

In spreader stokers, a high-speed rotor is used to throw fuel into the furnace in order to ensure even fuel distribution throughout. A grate-type arrangement is, again, used and the combustion technology principle is similar to that of the chain and travelling grate plant.

In terms of overall number of individual plants, this type of technology comprises the most common coal-fired boiler plant in the world. Countries which use these types of plant extensively include Russia (and former Soviet Republics), China and India.

Design Considerations for Co-firing

In general terms, these types of combustion plant are not suited to fuels with high moisture, volatile contents and low calorific values, as ignition problems can occur as well as poor combustion performance resulting in unburned carbon loss and high CO, particulate and hydrocarbon emissions. The use of over-grate air can reduce this problem but does not totally eradicate the problem. In addition, they are not well suited to applications with fuels of varying consistency.

The plant can comprise stand-alone boilers or in cases such as China, can form part of a large boiler house of 6-8 boilers used for process/site heating. Often, the coal is stored in the open and subject to the vagaries of the climate. The most acceptable method of co-firing would be to blend the fuel feed prior to boiler addition. This can lead to potential problems with open-air storage of fuel blends.

The gas cleanup systems adopted with such boilers are simple, often merely a cyclone for dust removal. The use of some waste fuels could necessitate the addition of additional gas cleanup plant that would undoubtedly preclude their use in regions where emissions are effectively monitored. If unstable combustion occurs, intermittent or continuous high emissions of CO and organics could occur which would be unacceptable in most EU countries. Unless the fuel is adequately blended and distributed on the grate, there is the potential for hot spots to be generated leading to grate damage and increased maintenance outages and costs. These issues would not be acceptable to a small boiler operator who requires guaranteed steam supply with minimal cost and maintenance.

Review of Co-firing Information

In 1992, New York State Electric & Gas Corporation began co-firing coal with tyre-derived fuel (TDF) at its 74 MW_e Jennison Station. The plant uses four stoker-fired boilers that burn the coal/TDF mixture without any significant impact on plant operations or emissions. Within a year of start-up, the plant had consumed around 1 million tyres and is capable of burning up to 45kta TDF. The four co-fired travelling grate stokers generate steam for two 30 MW steam turbines. The fuel mix usually consists of 25% TDF:75% coal(27). The addition of TDF can have a beneficial effect on the economics associated with older stoker-fired plants.

Another co-firing development has centred around Northern States Power Co., which has been co-firing up to 200 kta wood waste in recent years using two stoker-fired plant.

The co-firing of coal and dRDF was studied in the UK in the mid 1980s by Warren Springs Laboratory on behalf of ETSU. At that time, four stoker-fired boilers were operating on dRDF in the UK. The study showed that the fuel could be co-fired successfully with higher grate speeds and with the use of under-grate air. The main problem encountered was related to environmental emissions. Acid gas and heavy metal emissions were higher than with coal and there was also concern regarding dioxin emissions

Environmental Considerations

It is considered that there may be potential problems associated with biomass/waste firing on these type of plant. The problems include:

- There is the potential for unstable combustion which, if it occurs, can result in intermittent or continuous high emissions of CO, NOx, particulates and organics which would be environmentally unacceptable.

- The gas cleanup plant used with such boilers are simple; often, only a cyclone for dust removal is used. The use of some waste fuels could require additional gas cleanup equipment in order to meet modern emissions requirements.

4.6.3 Fluidised Bed Combustion

Atmospheric Fluidised Bed Combustors

Technology and Market Status

Atmospheric fluidised bed combustion (AFBC) technology was developed in the late 1960s/early 1970s and is considered to be commercially proven technology. The simplest form is the bubbling fluidised bed combustor (BFBC), this holding a market niche between large grate-fired boilers (up to 4O MWth) and circulating fluidised combustion plant (see below). In a BFBC, coal is burnt in a fluidised bed of sand or other inert material at ~850^{0}C, along with limestone for *in-situ* desulphurisation. The air is normally staged to reduce NOx emissions. In-bed tubes are sometimes used to control the bed temperature and to raise steam. The exhaust gases are cleaned (e.g. in a cyclone) and pass through a heat exchanger to raise steam for the steam cycle. Solid fuels are fed to the furnace *via* a rotary air lock and feeding screws or chutes. Around 30% of the combustion air is provided by the grate nozzles, with secondary and tertiary air entering the furnace at points above the grate. This allows for the optimum combustion environment to be achieved. Beds generally operate between 750-950^{0}C.

The main advantages of BFBC compared to conventional grate-type combustion plant include reduced emissions of SO_2 and NOx, plus improved combustion control, resulting in lower emissions of CO and organic species. In addition, the technology is considered to be fuel-flexible and therefore amenable to co-firing.

BFBC plant can operate a steam cycle for power generation applications with an electrical generation efficiency of typically 35-38%. Alternatively, such plant can be used solely for process steam raising. Several thousand BFBC plant have been installed world wide since the mid 1980s. The principal countries utilising this technology include China, Finland, France, Germany, India, Japan, Sweden, and the USA. An example of a BFB boiler is shown in Figure 7.

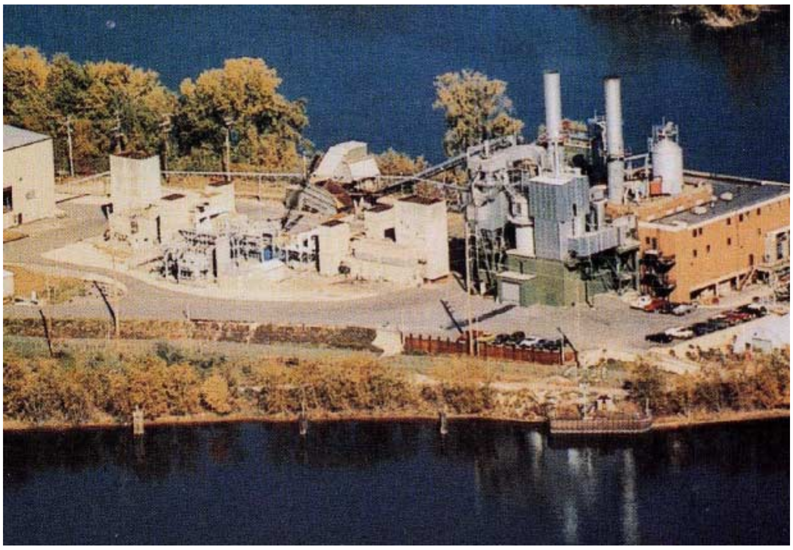

Figure 7. The 50 MWe Tacoma (USA) bubbling fluidised bed combustion facility, co-fired on coal, wood, and RDF.

Design Considerations

BFBC plants are considered to be relatively easy to design for co-firing applications. A separate biomass or waste handling/metering plant will be required to deliver the co-fired fuel to the existing coal feed system. Typically, this involves belt or screw conveyors that can be adapted to incorporate the new fuel before entry to the combustor. In overall terms, it is considered feasible to incorporate a new feed port at low cost to the plant if required.

The combustor unit itself is suitable for firing these types of fuel. NOx, CO and organic control is built into the combustor units through the air staging systems. Typically, such units incorporate high efficiency bag filters for particulate removal. Limestone injection to the bed or off-gas can be used for acid gas control. Combined lime/active carbon mixtures can also be added to the off-gas ducts for additional dioxin control.

Review of Co-firing Information

BFBCs fired on mixtures of coal with wastes have been used for some years, especially in North America, Sweden and Finland. Most are located at industrial sites, particularly at pulp and paper processing mills.

The range of scale of units currently in operation reflects the variety of uses for which they have been adopted. Typically, these include steam and hot water boiler applications, some connected with district heating schemes. In a number of instances, bubbling bed installations have replaced pulverised coal units. Their increased efficiency and ability to burn a wider range of fuels have been cited as important factors in such retrofit situations. In addition to units co-fired with coal, there are also numerous others that rely exclusively on waste-type fuels as their primary fuel source, sometimes using oil or gas for supplementary purposes when required.

The majority of the bubbling beds units (fired on mixtures of fuels) operating in Sweden and Finland utilise fuels that often combine imported hard coal with various combinations of locally-sourced fuels such as peat and more importantly, wastes produced from pulp and paper mills. The latter generate substantial amounts of wood wastes and in some situations, various forms of de-inking sludge and Kraft Black Liquor, the latter being a cooking liquor component produced as part of pulp production. The organic content is sufficient for the material to be burnt as part of a suitable fuel mix. The makeup of the waste stream generated by a typical pulp and paper mill is given in Table 6 below(28).

Bubbling fluidised bed boilers are tolerant to a variety of fuel sources that are inhomogeneous in terms of particle size, often accommodating a size range from sawdust to 3 inch hog fuel. Moisture contents can range between 35-60%. As a result, storage and blending requirements for coal/waste mixtures are often relatively simple and inexpensive.

Combustion of combinations of these various wastes with coal can result in cost reductions through the minimisation of bought-in fuel, as well as the minimisation of unwanted by-products and wastes. Considerable cost savings can also be made by avoiding disposal of sludges and other wastes to landfill sites. In both Scandinavia and North America, rising landfill taxes make the latter an increasingly uneconomic option. Depending on the application, steam is usually raised for the site or a district heating scheme, and electricity may also be generated. Paper mills consume considerable amounts of electricity and through the use of a bubbling bed system co-fired on coal and zero-cost fuels, can generate electricity sufficient to meet a significant portion of their needs.

Table 6
Typical Pulp and Paper Mill Waste Stream

Waste	**Moisture content (%)**
Bark	50
Sawdust	15
Woodwaste/hog fuel	55
Paper waste	10
Primary sludge	55
Secondary/biosludge	60
Deinking sludge	55
Wood chips	50

In some situations, BFBC technology has proved to be cost-effective for unique market applications. The sources of biomass and waste considered in this review are generally "renewable" sources in that they can be harvested, as is the case of wood fuel, or are routine arisings from anthropogenic activities (e.g. sewage sludge). However, there are occasions where significant quantities of material may become available that could be considered as a potential co-combustion source. A recent example of this is the arising of large quantities of rendered material as a consequence of the UK Government's response to the "BSE Crisis" through the implementation of a policy which includes a ban on sale for human consumption of meat from cattle over 30 months old (cases of BSE are very rare in cattle below this age); and the slaughter, rendering and incineration of all bovine animals over 30 months at the end of their useful lives. This has resulted in the slaughter of over 60,000 animals since May 1996, and the total will reach 1 million in the first year of operation. Several investigations have been undertaken on the possibility of using the rendered cattle remains as a co-fuel in large utility plant, but to date no large-scale trials have been announced and it is thought unlikely that this route will be taken up. However, a number of BFBC plants are being constructed specifically to utilise these materials, although these will probably be fired alone, as opposed to co-fired with coal. It is anticipated that once these cattle remains have been disposed of, the various BFBC plants constructed will be turned over to biomass and/or waste firing, in some instances, possibly co-firing with coal.

Environmental Considerations

In terms of environmental effects, BFBC co-utilisation can have a significant effect on a site's impact and beds co-fired with plant wastes and coal are generally capable of meeting local emissions limits. Depending on the particular coal and waste(s) being used, both NOx and SO_2 levels usually fall below mandatory limits. Where further NOx reductions are necessary, this can be achieved by ammonia injection into the furnace. Similarly, sulphur levels can be reduced through in-furnace limestone addition; sulphur capture levels of 70-80% are generally achievable. Particulates can be controlled using conventional electrostatic precipitators or bag filters.

An example of a typical bubbling bed installation is the United Paper Mills plant in Kaipola, Finland that was commissioned in 1991. As in a number of other instances, a Tampella (now part of the Kvaerner group of companies) bubbling fluidised bed was used to replace existing boilers that were reaching the end of their lives. In addition, increased steam capacity was required by the mill as well as improved means for the disposal of deinking and other sludges. The company previously installed new paper-making machines plus a deinking plant for recycled paper utilisation, up to 100 kt of sludge being produced annually. Combustion of the sludge was considered to be the only acceptable means for its disposal. The main advantage of the Tampella BFBC system was that it provided a cost-effective and environmentally-acceptable route for the utilisation of mixtures of pulverised coal, sludge, peat and wood waste, with plant-produced wastes being utilised as part of the fuel mix. Overall, the plant has exhibited high availability. In its first year of operation, it used 7000t bark, 5500t of mechanical and biosludge, and 2200t of deinking sludge. Peak loads have been levelled off using coal as the remainder of the fuel mix. Through co-firing waste materials, the mill has been able to meet a large proportion of its electricity needs. Examples of BFBC units supplied by Ahlstrom/Foster Wheeler are given in Table 7.

Table 7
Examples of BFBC Units supplied by Ahlstrom/Foster Wheeler

Delivery date	**Site**	**Capacity (MWth)**	**Fuels**	**Comments**
1977	Outokumpo Oy, Finland	17.5 & 24	Coal, peat, wood waste	Pyrite roasting plant
1982	Seinajoki Energy, Finland	20	Coal, peat, wood waste, HFO	Hot water boiler for district heating
1983	Pieksamaki District Heating, Finland	20	Coal, peat, wood waste, HFO	Hot water boiler
1985	Skelleftea Kraft, Sweden	25	Coal, peat, wood waste, HFO	Hot water boiler for district heating
1985	Lohja Paper Mill, Finland	36	Coal, wood waste, paper waste	Steam boiler
1986	Ostersund District Heating Plant	25	Coal, peat, bark, wood waste, oil	Hot water boiler
1990	Rauma Paper Mill, Finland	60	Coal, bark, sludges, fibre wastes	Recovery boiler
1993	Ocean Sky Co, Indonesia	155	Coal, peat, bark, oil	Steam boiler
1993	PT Inhad Kiat Pulp & Paper, Indonesia	218	Coal, peat, wood chips, bark, oil	Steam boiler
1995	Nykopping Energy, Sweden	100th,35e	Coal, wood waste, peat, oil	Steam boiler
1995	Soderenergi AB, Sweden	120	Coal, wood waste, peat, oil	Retrofit to pf boiler

Circulating Fluidised Bed Combustion (CFBC)

Technology and Market Status

As with BFBC technology, in a circulating fluidised bed combustor (CFBC) coal is burnt in the combustor along with limestone for sulphur reduction. However, in a CFBC, the gas velocity is such that a substantial part of the bed material is entrained in the upward gas flow. The entrained hot solids then leave the combustor reactor and are captured in a high efficiency external cyclone and are returned, often *via* heat exchangers, to the base of the combustor unit. Steam can be generated in the water-wall construction of the combustor and/or in external heat exchangers. Some designs also incorporate superheater panels in the combustor freeboard. The units are used for process steam generation or more typically, for power generation in a steam cycle system (electrical efficiencies 39-41%). The advantages of CFBCs are similar to those of BFBCs and include:

- Ability to utilise low grade coals and other fuels due to the long combustion residence times and good combustion control in the plant.
- Low NOx emissions.
- Low sulphur emissions with *in-situ* sulphur retention.
- Low CO and organic emissions as a result of the good combustion control and long gas/solid residence times.

For power generation applications, CFBC is regarded as a commercially viable option and is particularly suited to plants below 250 MW_e. This is currently the maximum capacity of a single unit although there are several on-going initiatives examining the scale-up of the technology to 500-600 MW_e. There are >300 CFBC plant operating commercially worldwide, the two major technology vendors being Foster Wheeler and Lurgi Lentjes Babcock (LLB). Substantial niche markets are catered for by a number of smaller organisations.

Design Considerations

The basic design principles of the CFBC are similar to those discussed earlier for BFBCs.

Review of Co-firing Information

As with BFBC, CFBC units have been adopted widely in a number of countries in, for instance, paper and pulp mills; examples are in operation in the UK, USA, Taiwan, Finland, Sweden, Norway and Austria. A list of CFBC plant in paper mill applications is given in Table 8. The majority of these plants are based on Ahlstrom Pyroflow (now part of Foster Wheeler) technology although an increasing number of Tampella/Kvaerner units are also in operation. The same advantages as noted for BFBCs apply, namely cost and environmental improvements, with various plant waste streams being co-fired with coal. In some cases, CFBC units installed at industrial sites are used solely for the provision of process steam although at others, they also produce electricity. Some co-fired units are operated in cogeneration form and comprise part of a district heating scheme. For instance, the Tampella CFBC that form as part of Norrkoping Energi AB's Handeloverket power station, is fired on a blend of wood and coal, the station supplying all of the heating capacity of a district heating scheme; the CFBC supplies ~700 GWh of the city's heat and electricity demand. In this particular case, not only was the fuel mix required to meet clear economic targets, strict environmental limits also had to be accommodated. The design fuel mix was 60 coal:40 wood and using this combination, SO_2 and NOx levels fell to <50% of those produced by the site's existing pulverised coal boilers. The plant has since been successfully operated on a ratio of 10 coal:90 wood. Tampella/Kvaerner CFBC units appear to be particularly well suited to firing mixtures of coal/biomass/wastes, with NOx formation being limited by the relatively low combustion temperature and staged air distribution system. In the case of Norrkopings, NOx levels were further reduced through the adoption of a plate-type selective catalytic reduction (SCR) system located in the flue gas duct between the economisers. SO_2 is controlled through the usual technique of adding limestone to the furnace.

In terms of overall capacity, co-fired CFBC units vary widely, from small industrial-based sites such as the 25 MW_{th} Ostersunds Fjarrvarme plant in Sweden, to the Rumford Cogeneration company in the USA. The latter uses 2 x 130 MW_e Ahlstrom units co-fired on coal, oil and wood. Larger facilities generally use multiple units in order to increase overall capacity.

In mainland Europe, only a limited number of co-fired CFBC-based projects exist, one example being the HUNOSA 50 MW_e La Pereda power station in Spain. The fuel-flexible nature of the CFBC is apparent from the fuel mix that consists of a combination of run-of-mine coal, waste anthracite (culm), plus some wood waste. This results in a heterogeneous fuel with a very high ash content (65%) and a low CV. The various fuels utilised with coal consist of tailings generated from mining activities, wood waste generated from pit-propping, and culm sourced from abandoned waste dumps. The CFBC unit was based on Foster Wheeler technology with Babcock & Wilcox Espanola (BWE) acting as the main contractor, responsible for the design and construction of the plant. For an annual operating period of 6500 hours, the total fuel requirements are 242 kt culm, 143 kt run-of-mine coal and 2O kt wood wastes. However, the wood content of the fuel mixture has recently been lower as a consequence of the lower than anticipated availability of wood in the region.

Clearly, many CFBC units co-utilise mixtures of coal with a single other fuel. In this context, of increasing interest is the use of fuels derived from scrap tyres (Tyre-Derived Fuel - TDF). Particularly in North America, significant efforts have been made to utilise TDF in a variety of situations including co-firing with coal in electric utility plants. Disposing of scrap tyres has become increasingly difficult as they are often not accepted at landfills where they have a tendency to trap methane and rise to the top of the heap. Equally, where large collections of tyres have ignited, the fires can sometimes burn uncontrollably for months or even years.

From the late 1980s, US electric utilities have been using TDF and by 1995, at least eight were co-firing tyres in their coal-fired boilers. The overall economics have been enhanced by disposal/gate fees which has resulted in very low fuel costs. The content of the fuel mix generally consists of no more than 10% TDF but even at 3%, a 365 MW plant consumes 6-7 million tyres.

Historically, utilities co-firing coal and TDF have used either cyclone boilers or stoker/grate-fired units; however, CFBC technology has been adopted increasingly in recent years. For instance, in the US, the United Development Group's Goodyear plant at Niagara uses a 200t/h Ahlstrom CFBC-based cogeneration system that was brought on-line in 1991. The plant is operated by Southern Electric Inc. and supplies steam to the manufacturing plant as well as selling electricity to the local utility. The fuel source consists of coal with ~20% shredded tyres. It is anticipated that further CFBC-based operations co-firing coal and tyres will be established, particularly in North America within the next few years.

The range of biomass and waste fuels that can be co-fired with coal in a CFBC is wide and the fuel-flexible nature of CFBC technology is better suited to such diversity than most other forms of combustion technology. There are numerous CFBCs in operation throughout the world that are either co-fired on biomass and/or waste fuels with coal or peat. This co-firing technology is, like BFBC, commercially established in the market place. The prospects for further CFBC plant particularly in some developing countries are considered to be good. The technology therefore has considerable potential to gain an increased market share in areas of the world where there is a continuing reliance on coal for energy production and an increasing energy demand.

Table 8
Circulating Fluidised Beds Co-utilising Coal and Biomass/wastes

Client Name	Location	Country	Capac. (th,e)	Fuel	Manufacturer
Avesta Energiverk	Alvesta	Sweden	15th	Coal, peat, wood	Gotaverken
Ba Yu Paper	Peikang	Taiwan	NA	Coal, sludge	Ahlstrom
Black River Partners	Fort Drum	USA	168th	Coal, anthracite, wood	Ahlstrom
Brista Kraft AB		Sweden	80th, 40e	Coal, wood, various wastes	Ahlstrom
Caledonian Paper plc	Scotland	UK	43th	Coal, wood, oil	Ahlstrom
Etela-Savon Energia	Mikkeli	Finland	84th	Coal, lignite, wood waste, oil, gas	Ahlstrom
Hunosa power station	La Pereda	Spain	50e	Coal, Coal wastes, wood waste	Mitsubishi
IVO	Kokkola	Finland	98th	Coal, peat, RDF, wood	Ahlstrom
Kainuun Voima Oy	Kajaani	Finland	240th, 85e	Coal, peat, wood, sludge	Ahlstrom
Karlstad Energiverken	Karlstad	Sweden	90th	Coal, wood waste	Ahlstrom
Kuhmon Lampo Oy	Kuhmo	Finland	18th	Coal, peat, wood waste	Ahlstrom
Lenzing AG.	Lenzing	Austria	94th	Coal, lignite, wood, sludge	Waagner Biro
Lieska, Finland	Lieska	Finland	22th, 8e	Coal, peat, bark, sawdust	Tampella
Metsa-Sellu Oy	Aanekoski	Finland	76th	Coal, wood waste, peat, oil	Ahlstrom
Midkraft Power Co	Grena	Denmark	60th, 17e	Coal, straw	Ahlstrom
Norrkopings Kraft	Norrkoping	Sweden	125th	Coal, wood	Tampella
Nukoping Energiverk	Nukopoing	Sweden	80th	Coal, wood, peat	Gotaverken
Ostersunds Fjarrvarme	Ostersund	Sweden	25th	Coal, wood, peat	Ahlstrom
P.H.Glatfelter Co	Spring Grove	USA	132th	Coal, anthracite, wood, oil	Pyropower
Papyrus Kopparfors AB	Fors	Sweden	56th	Coal, peat, wood	Ahlstrom
Patria Papier & Zellstoff	Frantschach	Austria	55th	Coal, lignite, oil, wood	Waagner Biro
Rauma Mill	Rauma	Finland	160th	Coal, peat, sludge, bark	Tampella
Rumford Cogen Co.	Rumford	USA	260th, 76e	Coal, oil, wood	Pyropower
Slough Estates	Slough	UK		Coal, waste paper	Foster Wheeler
Sande Paper Mill A/S	---	Norway	26th	Coal, wood, RDF	Gotaverken
Solvay Osterreich	Ebensee	Austria	38th	Coal, lignite, gas, oil, wood	Waagner Biro
Southeast Paper	Dublin, GA.	USA	125th, 65e	Coal, sludge	Pyropower
UDG Niagara Goodyear	Niagara Falls	USA	149th	Coal, tyres	Pyropower

Pressurised Fluidised Bed Combustion

Technology and Market Status

Pressurised fluidised bed combustion (PFBC) is an advanced clean coal technology which has been under development since the mid 1970s and is now becoming established firmly in the commercial power station market place. The main technology developer has been ABB Carbon (now part of ABB Alstom Energy) who have commercialised their bubbling bed-based technology. However, circulating-based based systems are currently under development by LLB and Foster Wheeler.

ABB have a number of plants installed or under construction in Sweden, Spain, USA, Czech Republic, Germany and Japan; total installed capacity is >600 MW_e, and proposed installed capacity is about 1100 MW_e. In an ABB-based PFBC plant, coal is burnt in a bubbling fluidised bed with *in-situ* limestone addition for sulphur removal. The combustion air is provided by the compressor section of the gas turbine. The hot combustion gases, after cleaning, pass to a gas turbine whilst steam is raised from tubes in the fluidised bed and from the gas turbine exhaust. The PFBC system therefore is a combined cycle with an electrical generation efficiency of typically 41-43%.

Design Considerations

Many of the design considerations are similar to those for BFBC and CFBC plant. The added complication is the requirement for feeding of biomass across the pressure boundary into the PFBC reactor. No information is publicly available from ABB to allow the status of their feed system development to be determined although they have recently carried out a series of tests using a range of coal/biomass fuel mixtures with a view to increasing the fuel flexibility of the technology (see below).

Review of Published Information

Although there are now a number of PFBC power plants in operation, until recently, relatively little work had been carried out to investigate the possibilities of co-firing with coal and other fuels. As part of their contribution to the *APAS* programme, the Technical University of Delft carried out small-scale investigations using a 1.6 MW_{th} bubbling PFBC. This pilot plant was co-fired on pre-blended mixtures of coal and straw or miscanthus. No operational problems were encountered and emissions levels remained virtually unchanged apart from some reduction in SO_2 levels.

On a larger scale, ABB Carbon in Sweden have been carrying out co-utilisation trials in their 1 MWth bubbling bed PFBC Process Test Facility in Finspong, where coal has been co-fired with biomass in varying proportions up to 40%. Biomass-derived fuels included woodchips, olive pips and palm nut shells. With all fuels, >99% efficiency was achieved with no detrimental effects on plant operation, bed stability, hydrodynamics and controllability. In 1996, in a further development, the Vartan PFBC cogeneration plant in Stockholm, which uses 2 x ABB P200 bubbling bed PFBC units, carried out trials co-firing coal with olive pips imported from Spain.

Environmental Aspects

The use of co-firing in PFBC plant is at an early developmental stage, hence there is currently little available information to enable an assessment of the potential environmental benefits of co-firing in this application to be determined.

PFBC is now slowly gaining a share of the power market, albeit not a large one. It is the first of the advanced, high-efficiency clean coal plant to do so. Compared to other technologies such as BFBC, CFBC and pulverised coal, its market share remains small. This is likely to increase although its overall impact is expected to remain limited compared to competing technologies.

Figure 8. The Vaertan PFBC-based CHP plant, Stockholm.

4.6.4 Cyclone Furnaces

Technology and Status

The cyclone combustor is a form of slagging combustor primarily used in utility boilers. The basic design consists of a water-cooled, refractory-lined combustor mounted horizontally at the edge of a main furnace area. The first commercial system was introduced in 1944 in the USA and since then, it is estimated that >1000 individual combustors have been installed in the USA and Europe.

Coal and primary air are introduced tangentially into the combustor where the fuel is fired at high temperature and heat release rates. Typically, coal is crushed to a size range where 95% is <4.75 mm and injected into the combustor with primary air. This primary air supplies about 20% of the total air required for combustion. Secondary air is also introduced tangentially into the combustor *via* the top of the main barrel to impart further centrifugal action. The fuel is combusted at temperatures of over 1650^0C and heat release rates of between and 4.6 and 8.3 MWm^{-3}(29). The high temperatures (caused by high heat release rates and low absorption of heat through the refractory walls) allows the mineral matter present in the coal to melt into a liquid slag. This is forced to the walls of the combustor by the centrifugal action of the swirling gases. The incoming coal particles are also thrown to the side of the combustor walls where they are held in the molten slag layer and contacted with the secondary air.

In this manner, the air required to burn the coal and remove combustion products is supplied quickly and uniformly thus promoting complete combustion. The products of combustion and the molten slag leave the combustor *via* a throat and enter the main furnace area where the molten slag continuously drains to slag tap openings for subsequent quenching and disposal.

This method of combustion allows the fuel to be burned in a small cyclone chamber with the main furnace area used only to cool the gases in order to raise steam. Up to 70% of the ash is retained as molten slag, thus reducing the amount of fly ash entering the downstream particulate abatement equipment.

Design Considerations

A wide variety of fuels can be burnt in cyclone combustors. This includes most ranks of coal, fuel oil, natural gas and other solid fuels such as wood, bark, refuse, tyre derived fuels and petroleum coke. The suitability of coal types for use in cyclone combustors has been investigated widely and is dependent on the coal composition. The principal criteria are:

- Ash content >6% (to provide an adequate coating of slag on the combustor walls).
- Volatile matter content >15% (db) in order to provide sufficient combustion intensity.
- A ratio of iron oxide to calcium and magnesium oxides of between 25 and 10, depending on sulphur content. This gives a measure of the tendency for a fuel to form iron sulphide in the cyclone combustor that can adversely effect slag mobility.

An additional requirement is that the slag should have a viscosity of 250 poise at temperatures below 1400^0C. This provides a measure of slag mobility within the combustor and can be calculated from the composition of the fuel ash.

Review Information

Particularly in the USA, cyclone boilers have been utilised for co-firing coal with a number of waste-derived fuels and biomass. In terms of the latter, a number of US power plants regularly co-fire biomass in commercial-scale cyclone boilers as these have shown themselves to be well suited to co-firing requirements and require little in the way of modification. The New York State Electric & Gas Corporation has been co-firing coal and wood in two of its plants for well over a decade.

Studies carried out by EPRI have indicated that using cyclone boilers, up to 20% by mass (9% by heat content) biomass can be readily co-fired, and as part of the project, a series of different types of plant belonging to the Tennessee Valley Authority were assessed for the suitability; these included a 250 MW_e cyclone boiler. It was confirmed that co-firing offered low capital costs amounting to ~$100-200kw when co-firing wood under these conditions. The study concluded that the most appropriate level of wood was in the 1-15% (by heat content) region for cyclone boilers.

One waste fuel that has been used increasingly for co-firing in cyclone boilers is Tyre-Derived Fuel (TDF). As a consequence of the growing environmental problems associated with the USA's scrap tyre mountains, TDF has been adopted in a number of situations. Using discarded tyres as a fuel source reduces the bulk of material to be landfilled by ~97% and can reduce emission levels when burnt with coal. In a number of states, landfilling of tyres has now been prohibited and this has acted as incentive for developing alternative disposal routes. As a fuel source, tyres are attractive; studies carried out by Wisconsin Power & Light Co. estimate that 1 million tyres will generate 2OM kW hours of energy, sufficient to provide an annual power supply to 3000 homes in the region. The company uses shredded tyres co-fired with coal in a number of its cyclone boilers supplying steam to steam turbines. The company bums tyres in its power plants at Edgewater, Rock River and Nelson Dewey; between them, they burn 20 kta scrap tyres.

A number of other US utilities also co-fire TDF in cyclone-based power plants. These include Otter Tails Power's 440 MW_e Big Stone Plant at Milbank, South Dakota, which has been co-firing tyres since 1990. The plant usually operates on a fuel mix consisting of 97% coal, 2% TDF, and 1% pelletised refuse-derived fuel (RDF). The plant is expected to take significantly increased tonnages of TDF and RDF in the future. In addition, Illinois Power has also been co-firing ~2% TDF since 1991 at one of its power plants.

Environmental Considerations

Cyclone combustors emit significantly more NOx than dry ash systems, the high flame temperatures required to melt the fuel ash to slag promote thermal NOx formation, resulting in significant emission levels of between 820-1850 mg/m^3. These emission levels lie above the limits set by most environmental protection legislation in developed countries. As such, new boiler plant built to these designs would require flue gas clean-up systems (such as SCR) to reduce the levels of NOx to acceptable levels. In Germany, the NOx emission limit for wet bottom boilers of <300 MW$_e$ already in operation is set at 1300 mg/m^3. These older, existing units, can reduce NOx emissions by a variety of methods:

- Flue gas recirculation (FGR) into the lower furnace area can achieve a 10% reduction in NOx emissions.
- Injection of 30% of total air requirements as tertiary air in the combustor, coupled with FGR has demonstrated a 40% reduction in emissions.
- Fuel reburning; this process involves the injection of 20-30% of the total fuel requirements into a reburning zone above the cyclone combustor. The NOx formed in the cyclone burners reacts with reducing gases in the reburning zone to form molecular nitrogen and water. The combustion process is then completed at the top of the furnace area in a burnout zone. This method has been investigated as part of the US CCDP by Babcock and Wilcox on a 100 MW$_e$ cyclone fired boiler in the USA and could reduce emissions of NOx from cyclone boilers by between 50-60%.
- Careful air staging and modification to cyclone burner design, coupled with FGR can achieve a 33% reduction in emission levels.

Emissions of particulate matter from slagging combustion systems can be significantly less than comparable dry ash units. This is achieved by the majority of fuel ash (up to 90% in some designs) being captured as a molten slag before entering secondary combustion zones and heat exchange surfaces. This has additional advantages in terms of the required capacity of flue gas cleaning equipment and reduced boiler erosion/corrosion and fouling

Combustion of coal in cyclone combustors is characterised by the requirement to merely crush the coal prior to combustion. This results in reduced capital, operating and maintenance costs of mill systems in comparison to dry ash pulverised coal units. Cyclone combustors also benefit from the smaller furnace areas required and exhibit better part-load performance and response time than slag tap furnaces. In addition, full load operation can be achieved with auxiliary fuels such as oil and gas. The high retention of coal ash as slag (up to 70%) decreases the required size and capacity of downstream particulate collection devices. This can lead to lower capital costs compared to dry ash systems. The lower auxiliary power consumption of smaller particulate collection equipment is, however, partially offset by increased forced draft (FD) fan power requirements. The high temperatures of combustion also lead to significant emissions of NOx, although these can be reduced in some units by combustion modifications such as reburning, FGR and air staging. The high velocity of coal in cyclone combustors can cause erosion of the burner linings and regular replacement of the silicon carbide wear liners is generally required.

Thus, cyclone boilers have been successfully modified to co-fire coal and wood/TDF. The work has demonstrated that this technology is fully developed for biomass and waste co-firing. The technology is being utilised for this application is situations where the economics are favourable, particularly in the USA. However, this utilisation only involves the conversion of existing cyclone combustors and it is unlikely that any new plant will be built. This is due to current overcapacity in the US electricity generating market and the higher efficiencies and more favourable economics found with other technologies such as BFBC/CFBC systems. The market opportunity for new technology therefore seems limited, although there could be potential for retrofitted technology in countries such as Russia, where there are limited capital reserves coupled with waste disposal problems in large cities.

4.6.5 Summary

The high moisture and volatiles content (and often the low nitrogen content) of biomass gives enhanced scope for limiting NOx in conversion of coal plant to co-firing by combustion measures. Emissions of sulphur dioxide can also generally be reduced substantially. Dioxins and heavy metal emissions and ash quality are not necessarily affected. However, successful feeding of the softer fuels at reproducible rates remains a common problem, partially as a consequence of their lack of consistency, and *ad hoc* solutions have frequently been employed. Wood is probably easier to introduce than straw and miscanthus, although, considering its nature, it appears to require surprisingly fine grinding for satisfactory burnout (<1 mm). Greater care in firing configuration is needed in co-firing sewage sludge if increases in NOx are to be avoided or contained.

There is continuing supporting R & D effort to ensure that the minor materials and deposition issues, plus issues concerning the quality of ash and FGD by-products are well understood. None of these aspects currently appears likely to limit deployment of the technology.

Considerable expansion in the number of large-scale co-firing projects therefore appears technically feasible in the future. The continuing interest of utilities in large-scale trials is encouraging in this respect, although legislative drivers are clearly having an influence on the situation.

4.7 Review of Co-utilisation technologies within Europe

Some of the more significant initiatives within Europe, adopting direct applications, completed recently or on-going are noted below.

4.7.1 Direct Co-utilisation

- *Prediction of ash and deposit formation for biomass co-combustion*

As a consequence of the variable nature of biomass-derived fuels, a programme is underway examining corrosion, slagging and fouling, as well as related chemistry. Eleven partners are investigating a range of fuel mixtures at a variety of scales, up to industrial scale. The fuels under investigation include straw, energy crops, wood, sewage sludge and RDF. It is anticipated that the project will provided useful data and prediction tools for the prediction of corrosion, slagging and fouling, enhancing the attractiveness of biomass utilisation in large-scale power plants.

The project (Ref: JOR3980198) will be completed in 2001 as forms part of the EU 4th Framework Programme. Project partners are the University of Stuttgart, ECN, RWE Energie AG, TPS, University of Cambridge, ABB Combustion Services Ltd, Vattenfall AB, ENEL, Aabo Akademi University, MBEL, and the TU Denmark.

- *Simultaneous combustion of wastes and residues in Buxieres les Mines.*

The aim of this project is the construction of a multi-fuel power plant in France, capable of burning household wastes and residues from coal cleaning operations. The primary aim is to demonstrate that such a plant can be operated using different feedstock combinations, whilst meeting all required environmental legislation. The combustion system will comprise a Foster Wheeler CFBC-based unit

of 32 MW_{th} capacity, producing 43.3 t/h superheated water. The turbo alternator will generate 8.6 MW_e.
The project (Ref: SF/00406/93) has been completed to the design phase.

- *Demonstration of utility-sized CFB plant for coal and CO_2 neutral fuel (CFB-Arhus)*

This project is focused on the demonstration of a utility-scale CFBC-based power plant firing coal and biomass combinations. Ultrasupercritical steam data and improved plant operability are characteristics of the project. Thus, a 90 MW_e CFBC cogeneration plant was built by Midkraft for Elsam. The plant is capable of firing biomass in the range 0-60% (on an energy basis), will utilise USC steam conditions, and be characterised by improved operational processes. The technical, environmental and economic features of the project will be assessed.
The project (Ref: SF/00366/94) has passed the design and authorisation stages and the plant is expected to be operational by 2000.

- *Combined combustion of RDF and coal in large utility boilers.*

The aim of this project is to demonstrate the technology of burning RDF in coal-fired utility-scale boilers *via* minor modifications to the fuel feeding system. In addition, there must be no adverse effects on the plant's environmental or operating performance. It is anticipated that the data obtained during the course of the project will be of benefit in developing further the commercial exploitation of the technology.

The project (Ref: SF/00115/96) has ENEL as the main contractor. To date, information has been obtained on the characteristics of different RDF sources, in order to provide data to predictive models designed to assess the potential for fouling, slagging, gas-side corrosion, and possible changes in ash characteristics.

- *Low emission co-combustion of different waste wood species and lignite derived products in industrial power plants.*

The project is focusing on the demonstration of the feasibility of co-combusting contaminated wood waste with lignite in CFBC-based power plants. This is taking place in the CFB boilers located at Rhenbraun's Berrenrath site. This consists of a 235 MW_{th} cogeneration facility supplying electricity and process heat. A variety of issues are being addressed during the course of the project including the pneumatic conveying of chipped wood and an examination of deposition and corrosion phenomena.
The project (Ref: SF/00261/97) is progressing.

- *2 x 30 MWe Bagasse/coal power plant*

This project, carried out by SIDEC of France, examined the construction of a power plant designed to burn bagasse (~300 kta) from a sugar mill, with coal. During the sugar cane cutting season, the plant generates 50 MW_e and supplies process steam to the plant. For the remainder of the year, it operates as a normal coal-fired unit producing 55 MW_e. The project investigated the addition of bagasse to the plant's fuel input. The project (Ref: BM/00267/93) has been completed successfully. In 1998, it was estimated that the plant produced some 300 GWh of electricity.

- *Dual fuel (coal/wood) as an innovative energy utilisation technology for a 600 MWe coal fired power plant.*

The project (Ref: SF/00465/93) undertook the conversion of the EPON NV power plant from coal, to coal + wood firing. The project included assessment of a range of issues that included the development of an innovative wood milling system, and the installation of innovative burners in the boiler dedicated solely to wood burning. Each burner is capable of combusting 13.5 MW_{th} (2.5 t/h) wood power an hour. Plant commissioning took place in 1997, the plant now being is commercial operation.

Considerable energy savings have been made through the replacement of a proportion of the coal feed with wood: savings amount to ~44 kta coal. Additional advantages include the reduction in wood going to landfill, a reduction of 110 kta CO_2, and a reduction on ~4 kta fly ash generated.

4.7.2 Indirect Utilisation Technologies

Gasification-based Systems

Technologies and Market Status

There is substantial interest throughout the world in the development of coal-based gasification plant for utility-scale power generation. The potential advantages of gasification plant are higher efficiencies and significantly lower environmental impact than conventional coal-fired plant. These advanced clean coal systems fall predominantly into two categories, namely Integrated Gasification Combined Cycle (IGCC) and Topping Cycles.

In an IGCC system, coal is gasified to produce a fuel gas that is then burnt and the hot combustion products expanded through a gas turbine. A high thermodynamic efficiency is achieved by using the full potential working temperatures of gas turbines (i.e. 1260^0C inlet temperature) and utilising the waste heat in a steam turbine. IGCC systems involve the complete gasification of the coal in air or oxygen/steam atmospheres to produce a medium calorific value fuel gas whose principal combustible components are carbon monoxide and hydrogen. Three main generic types of gasifier have been developed. They differ in the characteristics of the gas-solid contact zone where the gasification reactions take place. These types are known as entrained, fixed bed and fluidised bed gasifiers.

- Fixed bed gasifiers operate with low product gas temperatures (~450^0C) and hence produce high levels of tar and oil, which complicates the heat recovery and gas cleaning process. A separate sulphur removal process is also necessary. In addition, they require a closely graded lump coal feed with minimum fines content. Special handling arrangements must be made to accommodate the high fines content generated by modern mechanical mining methods.

- Entrained gasifiers operate at high temperatures and hence generate high alkali salt contents and sticky ash. The gas must be cooled to remove these species and for sulphur removal. In addition, because of a low carbon inventory in the gasifier, variations in coal feed may make control difficult.

- Fluidised bed gasifiers operate in a relatively narrow temperature window that may make high conversions difficult. In nearly all gasifiers, and especially when using hard coal, the necessary operating temperatures and the requirement for high carbon conversions makes often it essential to use oxygen rather than air as the main reactant gas. This can have a major impact on the cost and overall plant efficiency.

An alternative way to achieve a high overall efficiency without the need for complete gasification is the use of so-called Topping Cycles. In these systems, gas is first generated from coal, then cleaned and burned in a gas turbine. Unconverted material from the gasification system is burned in a combustion system that forms part of the steam cycle. The advantages are that air-blown partial gasifiers can be used that are of simple design and tolerant to a wide range of coal properties. The use of a separate solids combustor means that high temperature heat is available in an oxidising environment to ensure that state-of-the-art steam conditions can be used. There is a wide range of possible options for Topping Cycles. Many of the normally oxygen blown gasification systems can be air-blown under milder conditions to achieve partial gasification.

Currently, the advanced gasification plant can be considered at the introductory commercial stage. There are a small number of plants in operation, the largest of which is the 253 MW_e Demkolec plant, based on Shell gasification technology, in Holland. The other main plant within Europe is the 335 MW_e Puertollano Project in Spain, based on Krupp Koppers technology. As far as most Western utilities are concerned, the technology has not yet been demonstrated fully at a commercial scale although development continues. Several plants are now in commercial operation in the USA.

Co-gasification of coal and biomass/wastes

Considerable efforts have been made in recent years to identify technologies suitable for the co-gasification of coal with biomass and waste-derived fuels. Particularly, under the auspices of the European Commission's DG XII *APAS* Programme (1992-1994), efforts were made to establish techniques suitable for the co-utilisation of a wide range of materials with coal. As part of this programme, various wastes and biomass-derived fuels were evaluated for co-gasification with coal using the three established coal gasification techniques, namely fluidised bed, fixed bed and entrained flow. Overall, the objects of the programme were successful, with a number of co-gasification techniques being established. All three types of gasifier proved to be satisfactory for the gasification of both biomass and sewage sludge with coal.

Several types of fluidised bed gasifier were used during the programme. CTDD utilised a pressurised fluidised bed gasifier fired on a mixture of coal and sewage sludge. No adverse effects on gasifier operability or process performance were noted, providing the carbon (in fuel) to oxygen (in fluidising air) input ratio was fixed. Sustained agglomeration-free operation was attained with sludge levels up to ~25%. In Germany, Rheinbraun also used a fluidised bed gasifier. This was based on High Temperature Winkler (HTW) technology and formed parted of the Berrenrath methanol production plant. The work showed that when co-utilised with coal, the organic portion of the sewage sludge gasified almost completely. Again, no serious operational or environmental problems were experienced, the syngas produced continuing to meet the requirements of the downstream methanol plant. In subsequent work, the HTW plant was also used successfully to evaluate the co-gasification of municipal solid waste and scrap plastics(36). In Finland, VTT Energy used a pressurised fluidised bed gasifier fired on mixtures of coal and wood. Their findings confirmed the technical feasibility of using such mixtures up to 50:50 levels. KTH in Sweden utilised a small PFBG to investigate synergetic effects when co-gasifying mixtures of coal and wood. Their findings showed that the use of such mixtures resulted in significantly increased overall reactivity and increased gas yield.

An entrained flow gasifier was adopted for the co-utilisation work carried out by the Danish utilities ELSAM and ELKRAFT. Here, mixtures of straw and coal were successfully gasified in a series of experiments carried out using the entrained flow unit of NOELL in Freiberg, Germany and in a small entrained reactor at RISO. The NOELL unit had a throughput of 300 k/h fuel and could be operated at pressures between 3-25 bar. Other tests using straw were also carried out for ELSAM using the PFBG units of VTT Energy and Enviropower (now Carbona), the latter being based on U-Gas technology. Through optimisation of the operating parameters of the various gasifiers, successful co-gasification of coal and straw mixtures was obtained, some units being easier to adapt to mixed feeding than others. Thus, the project demonstrated the feasibility of co-utilising straw in two of the three main generic types of gasification system.

The use of the third type of gasifier (fixed bed) was examined as part of the work carried out by ECN in the Netherlands. Here, a fixed bed downdraught gasifier was used to assess the feasibility of co-gasifying coal/biomass and coal/waste mixtures. Overall, the tests showed that it was feasible to use coal/wood and coal/straw mixtures in this type of gasifier. Levels of biomass fraction in the range 10-30% were utilised successfully.

Thus, the *APAS* Programme established the feasibility of co-gasifying coal in mixtures with various biomass and waste-derived fuel sources using different gasification technologies. It also helped to establish areas that required further development in order to ensure that such technologies could be developed to the commercial scale.

Clearly, a significant proportion of the work carried out during the *APAS* Programme was on a relatively modest scale; however, commercial-scale activities have also been taking place. For instance, in Finland, Foster Wheeler Energia Oy have supplied a Pyroflow circulating fluidised bed gasification unit, designed to co-utilise a mixture of coal with wet biomass and municipal waste, at the Lahti cogeneration plant. It is estimated that the use of biomass and waste will reduce the coal used by 30%. The plant is owned by Lahden Lampovoima Oy and consists of a gas-fired turbine with a steam power plant. The existing boiler has multi-fuel burners, allowing the use of coal and gas as primary fuels. When the plant load is high, the gas turbine is operated with the steam cogeneration plant. The plant generates a maximum of 150 MW_e and 240 MW_{th} district heat. The total cost of the project is $13M. The plant and its configuration is shown in Figures 8 and 9.

Figure 9. The British Coal Corporation 5 MWth fluidised bed gasifier, .used to successfully co-gasify coal and sewage sludge.

Further large-scale work is also being undertaken in East Germany by SVZ Schwarze Pumpe to convert mixtures of coal with a variety of waste materials, for use in cogeneration schemes and methanol production. As part of a plan to improve energy efficiency and reduce environmental problems, SVZ is burning gas produced from Lurgi-type fixed bed gasifiers, co-utilising mixtures of coal with pelletised refuse. The gas produced is used in a cogeneration plant as well as a high grade feedstock for methanol production on the same site. In the second phase of the development, the site's capacity is being increased to handle much greater volumes of solid municipal waste and semi-liquids. In this phase, the Lurgi-type gasifiers will be replaced with BGL slagging fixed bed gasifiers. It is anticipated that when complete, the plant will handle ~220kta wastes.

As noted above, the HTW process has also been investigated for its suitability for co-utilising plastics wastes. In the case of the work carried out at the Berrenrath plant, municipal solid waste was sorted in order to segregate the plastics component. In practice, this consisted of a combination of mixed packaging plastics with paper and other residues. These did not affect performance during gasification. Overall, the plastics content amounted to ~58% of the feedstock. This was co-fired with brown coal, the latter being required to ensure stable gasifier operating conditions. A total of 800t pelletised mixed plastics (0-10mm) were co-gasified in combination with packaging plastics/paper and other residues. No operating problems were encountered and syngas quality was unaffected. Thus, it was concluded that the use of this feedstock with brown coal in the HTW process was technically feasible

Overall, it appears that there is considerable potential for co-firing blends in the various gasification technologies available. Some of the more significant European-based projects using gasification-based technology completed recently or on-going include:

- *The operational problems, trace elements and by-product management for industrial biomass co-combustion.*

This project examined issues associated with slagging, fouling, corrosion, ash utilisation, and trace elements generated through testing in different co-combustion systems. Two options were examined, namely direct co-combustion of coal/biomass in existing pulverised coal boilers, and pre-treatment of the biomass in order to remove undesirable components prior to combustion. In the latter, the gasification or pyrolysis of the biomass was examined. The low CV fuel gas produced was then fired in a pulverised coal boiler.

The project (Ref: JOR3950057) was completed in 1999 as part of the EU 4th Framework Programme. The project partners comprised the University of Stuttgart, TU Denmark, Imperial College, Termiska Processer AB, LLB, Aabo Akademi University, Vattenfall AB, CRE Group Ltd, Elsamprojekt A/S, CERCHAR, and the National TU Athens.

- *Co-combustion of wood in a coal fired power plant*

This project examined the gasification of contaminated waste wood in a CFB gasifier. The gas generated was cleaned and fired in an existing 600 MW_e pulverised coal boiler; firing was *via* four dedicated burners located within the boiler.

The project (Ref: SF/00323/95) was completed in 1999 as part of the EU 4th Framework Programme. The main project contractor was Noordbrabantse Energie-Maatschappij NV (PNEM) of The Netherlands.

- *Co-utilisation of gasified biomass and REF and coal in CHP plant (Parts I and II).*

This project examined economic and technical issues associated with the use of biomass and REF in an existing pulverised coal plant. The biomass feedstocks were firstly gasified in a large-scale CFB gasifier and the low CV fuel gas generated fired in a pulverised coal boiler. Results to date have been very positive, with the calculated fuel gas values being close to actual figures. Plant emissions of NOx and SO_2 have decreased, and levels of particulates and dioxins have remained unchanged. When using refuse-derived feedstock, a slight increase in heavy metals was noted, although this remains very low and is comparable with levels obtained when firing coal alone.

The project (Ref: BM/00015/96) was completed in 1999 as part of the EU 4th Framework Programme. The main project contractor was Lahden Laempoevoima Oy of Finland. Part II of the project is now being covered by Project BM/15/96

- *Combined use of coal and waste/alternative solid fuels using Lurgi CFB gasification technology.*

This project is focusing on the construction and operation of a 2-stage air-blown CFB gasification plant (~38 MW_{th}) integrated into an existing coal-fired power plant. This will result in the combined use of coal and waste/alternative fuels for the efficient generation of electricity and provision of district heat. The plant will generate vitrified ash suitable for utilisation in the building and construction industries.

The project (Ref: SF/00107/96 and SF/00044/97) has Standwerke Flensburg GmbH of Germany as the main contractor. To date, environmental impact studies and plant permitting stages have been completed.

- *Preparation of biofuel for co-combustion (BIOCOCOMB)*

The project is demonstrating a method of using biomass as an additional fuel (up to 10%) in pulverised coal units. The biomass feedstock is fed to a separate air-blown CFB gasifier where it is partially gasified and broken up by the effects of attrition and heat. The product gas generated is fed to the pulverised coal boiler where it is burned. In addition, fine char particles are carried with the gas to the furnace where they are also combusted; total contribution of biomass, in the form of wood, bark and forest residues, to the overall thermal input is of the order 3-5%. This arrangement avoids the necessity of pre-drying or grinding of the biomass feedstocks prior to gasification.

The project (Ref: SF/00010/96) was the first gasification project to come on stream. The main contractor for the project is Draukraft of Germany. It is anticipated that plant operations will confirm the effectiveness of the process and that existing plant systems, such as the SCR system, will be unaffected. The low CV gas generated may prove to be useful for reburn application in the main plant boiler.

4.7.3 Pyrolysis Systems

An emerging technology for biomass/waste utilisation is pyrolysis. Pyrolysis is a process in which the biomass/waste can be converted to gas or oil products and char, in the absence of oxygen. In the EU there are a number of pyrolysis processes under development for biomass but these have only reached the pilot-plant scale at present. The technology is used commercially at four plants for municipal waste utilisation in Japan although little data on the economics and technical success have been made public.

No information has been obtained on the co-pyrolysis of biomass/waste and coal. It is considered that the technology is more appropriate to biomass or waste use alone.

4.7.4 Hybrid Systems

There are a number of potential hybrid systems involving combinations of biomass gasification plant and both conventional and advanced clean coal technologies that are being researched or are proposed.

Separate Plant

The Danish utilities have studied their programme results and concluded that the preferred option to maximise electricity production from biomass at an existing site is to construct a separate biomass plant and incorporate the steam cycles. In the case of straw, this allows the plant operators to reduce boiler steam temperatures in the straw unit in order to minimise corrosion, whilst maintaining higher steam conditions in the coal plant. Superheating can then be carried out in a separate wood-fired superheater where, again, corrosion problems are minimal. A new boiler unit of this type, incorporated into an existing coal-fired pulverised coal unit, is being developed by ELSAM at the Sonderjylands Hojspoendingsoerk site. ELKRAFT are retrofitting an existing coal-fired boiler at Asnaes with a 44 MW_e straw/wood boiler and are developing a new coal-fired plant at Avedore, which incorporates a 47 MW_e straw/wood boiler.

Reburning

In this technology, a gasifier is utilised to generate a low calorific value fuel gas that is then injected with the coal in a conventional pulverised coal plant. The technique is known as 'reburning'. In a boiler retrofitted for reburning, a layer of fuel rich sub-stoichiometric combustion is generated high in the boiler. Some of the NOx and NO, precursors passing through this region, are transformed into N_2. If the flue gas is coming from low NOx burners fitted low in the boiler, this system in combination with reburning can result in significant reductions in NOx levels. As part of this development, R&D work has been undertaken by TPS Termiska Processer AB using biomass-derived low CV gas; this showed that despite its high nitrogen content, it was effective for reburning. In Holland, PNEM is developing a 55 MW_e gasifier to connect to a large existing pulverised coal unit and in Finland, Foster Wheeler and Lahden Lampovoima Oy (a utility) are also engaged in a potential project. In Austria, Draukraft are leading a project, called 'Biocomb' that involves partial gasification and reburning in a utility boiler.

4.8 Application of Co-utilisation Technologies to EU Markets

4.8.1 Power Generation Sector

The power generation market is the largest single market for coal (50,000 PJ) and presents the greatest potential market for co-utilisation, partly because it is so large, but also, particularly, because the technologies used in large-scale power generation are well-suited to co-utilisation. The descriptions of the technologies noted above have confirmed there are a number of power generation technologies that are suited to co-utilisation, including pulverised coal combustion, BFBC, CFBC, and gasification. The first three are well-established technologies. In addition, many pulverised coal plants are at a late stage in their operating life and adapting them for co-firing can, in some cases, rejuvenate them. Two methods that could be used are:

(1) biomass/waste gasification plus firing of a combustion turbine on the gas with exhaust gas feeding to the coal boiler in place of primary air.

(2) direct co-firing of the biomass in the coal boiler.

The latter has been demonstrated in several commercial boilers and offers the lower installation cost although the gasification method would raise the unit's thermal efficiency. It seems likely that direct combustion technology will find greater application as a result of its relative simplicity. A market penetration of 500 PJ/year has been suggested (*via* retrofits), equivalent to retrofitting 10 GWe of coal-fired plant for 10% co-firing.

In contrast, greenfield site power generation projects adopting co-utilisation are more likely to use gasification combined cycle technology, since there is then the opportunity to integrate environmental controls without additional costs, whilst achieving a high thermal efficiency.

Forecasts by the World Energy Council of future electricity requirements world-wide are of a doubling between 1990 and 2020, from 11,600 TWh to 23,000 TWh. This would imply a doubling of present capacity. Even though such predicted scenarios may be influenced by many factors, it does indicate that, worldwide, there is likely to be a substantial requirement for new generating capacity for many years. Much of this new capacity could be clean coal-fired and hence, there could be considerable opportunity for co-utilisation technologies, perhaps eventually adding another 100-200 petajoules/year to the input from biomass/waste.

4.8.2 Industrial Sector

Because biomass and wastes can present difficulties in handling, co-utilisation of these materials with coal is best suited to the larger systems, for which the flows are higher. This permits economies of scale and enables easier achievement of uniform feed rates. Industry is more likely than the commercial sector to be willing to examine new fuel options as it is more likely to have expertise available to examine them and put them into practice. The industrial coal-burning sector is therefore a potential market for co-utilisation of biomass and waste.

There are over 300 CFBC boilers around the world and coal-fired industrial CFBC boilers should, in principle, be readily adaptable to accept substitution of part of their coal feed with biomass fuels. BFBC and CFBC systems are already one of the most widely used methods of burning biomass.

Many ageing, conventional stoker-fired boiler plant can readily co-fire wood without problems, as has been proved over many years. Additionally, within industry there exist many pulverised coal boilers and furnaces that could adopt some of the co-firing techniques currently being developed for power generation applications.

Potentially, some fuels feedstocks could find increasing use *via* co-firing for industrial-type applications. For instance, MSW and RDF, will be available for combustion in increasing quantities in the many parts of Europe as existing incinerators are closed and the volumes sent to landfill sites are restricted further. RDF and straw can both be burnt successfully on chain grate stokers and co-firing would reduce the negative effects on output, corrosion and fouling and emissions. There is therefore scope for co-firing these fuels in existing stokers.

New combustion facilities burning municipal waste, are most likely to be 100% waste-fuelled CHP schemes encouraged by projects such as the UK’s NFFO: co-firing seems likely only if existing industrial coal-fired boiler owners take these fuels. The selection of co-firing would be aided by the geographical spread in the availability of these materials: relatively small volumes of the material over wide areas would favour the less capital-intensive retrofitting of co-utilisation over new-build dedicated biomass consumption plant. Large industrial boilers providing heat and power to industrial sites are the most likely candidates for new co-firing installations.

The future scope for co-firing of sewage sludge is governed by the geographical spread of resources. Incineration schemes need to be sited close to major sewage sludge production centres. Exclusive sewage sludge combustion has tended to be the solution adopted in the past and the uptake of co-utilisation is likely to remain small.

4.9 Review of Cofiring Activities in the USA

During the past few decades, considerable effort has been made in the USA to investigate a variety of co-firing options for a number of commercial, industrial and utility applications. Recently, as part of the US DoE's efforts to achieve a balanced portfolio of power generation technologies, aimed at reducing environmental impact whilst sustaining energy growth, a number of projects have been created examining coal/biomass co-firing and reburning technologies. In most of these projects, biomass is providing 2-15% of the heat input. Advantages are that in many cases, biomass incorporation into the fuel mix can increase overall capacity and reduce emissions of SO_2 and NOx and greenhouse gases. Much of the drive behind these initiatives has come from coal-fired utilities, anxious to have future options open should the need arise. Other factors have included the establishment of green pricing structures, the minimisation of industrial waste-related problems, and the development of fuel crops as an aid to US agriculture.

As elsewhere, it is considered that large, coal-fired boilers offer economic and efficiency advantages over smaller boilers where biomass is likely to be burnt on its own. As a result of the low heating value, high moisture content, and low density, it is only practicable to burn such fuels locally, in order to avoid transport costs.

Although a number of efforts have previously been made in the co-utilisation of coal and biomass in the USA, there are still considered to be significant areas requiring further research and development effort. These areas include biomass fuel handling equipment, fireside impacts (such as carbon burnout), ash fouling, ash disposal and NOx-related issues.

The main participants, apart from utilities, that have been actively engaged in US-based development programmes include the DoE's Energy Efficiency Office, EPRI, FETC, the Department of Agriculture, the USDA Forestry Service, Coalition of Northeastern Governors (which administers the DoE's Northeastern Regional Biomass Energy Program), Sandia National Laboratories, and the National Renewable Energy Laboratory. Joint efforts between such organisations and utilities, universities, private sector firms and trade organisations have resulted in the prioritisation of a number of key issues intended to lead to increased commercial uptake of co-firing. These issues are:

- Co-ordinated co-firing R&D – researchers at FETC, SNL and NREL are engaged in a 3-year project evaluating combustion behaviour and synergies.
- Utility demonstrations – through a multi-year FE/EPRI co-operative agreement, with >50% industry cost sharing, a number of US utilities have successfully conducted demonstration tests in seven boilers of different scale and configuration, co-firing various energy crops and waste/biomass fuels. In addition to these evaluations, long-term demonstrations are underway at the General Public Utilities Seward station and Northern Indiana Public Service Company (NIPSCO) Bailly Station. The Seward project includes the use of sawdust and utility-generated wood co-firing in a 32 MW_e wall-fired boiler, using a separate biomass injection system. The Bailly project includes blends of clean urban wood waste, petcoke, and coal in a 160 MW_e cyclone-fired boiler that features an advanced scrubber system.
- Advanced biomass reburning – through an FE co-operative agreement, Energy and Environmental Research (EER) Corporation is evaluating advanced biomass reburning with the potential for >90% NOx removal. This advanced reburn technology was originally developed and funded by FETC in order to build upon conventional reburning technologies that have been demonstrated successfully in the DoE Clean Coal Technology Program. The EER biomass reburning project involves Niagara Mohawk Power Company, Antares Corporation, and FETC.
- Stoker co-firing – the University of Pittsburgh is carrying out urban waste wood resource assessments for industrial stoker boilers. As part of this, demonstration tests of shredded pellet

co-firing are being carried out at industrial organisations.

- Advanced power systems development – FETC are examining advanced turbine system combustion issues with biomass-derived syngas. In related projects, coal/wood co-gasification tests are being carried out in a pilot-scale PFBG/hot gas cleanup facility. FETC and NREL are conducting life cycle assessments for biomass gasification. These activities are helping to support FETC's initiative to develop high efficiency, near-zero emission coal-based "Vision 21 EnergyPlexes" intended to be both fuel-flexible and allow for the co-production of power and fuels/chemicals.
- Advanced coal/biomass fuel handling – there are currently four projects on-going that are supporting novel concepts in waste coal/biomass fuel preparation for co-firing applications. Several other initiatives are investigating the development and evaluation of prototype mills for biomass and coal processing; these include mills for co-pulverisation and mills that are used in other industrial applications.
- International activities – a comprehensive review has been carried out to document biomass and waste co-firing commercial experiences in the US and overseas.
- Industry consortium – FETC is supporting an industry-led consortium that is sponsoring research to expand utilisation of novel coal combustion by-products, including ash from biomass co-firing.

There is the general recognition within these initiatives that co-firing can be more complex than stand-alone renewable generation, since two fuels are combined in a single plant. As well as hardware requirements, this concept requires plant operators to change working practices.

A number of the more significant recent co-utilisation programmes are reviewed below:

Major US Co-firing Programmes

Allen Fossil Plant

This project focused on the co-firing of moderate levels of wood waste with coal in a cyclone boiler. Wood/coal blends, up to 20% wood:80% coal, were burned; a variety of coal types were evaluated, including Eastern high-sulphur coal and Utah bituminous coals. At some points during the test programme, waste tyres were added to the fuel mix. The experience confirmed that biomass-type fuels can accomplish the following:

- Achieve a trade between boiler efficiency and fuel cost.
- Reduce SO_2 emissions, particularly when wood is co-fired with Eastern coal.
- Reduce NOx emissions.
- Reduce fossil-derived CO_2 emissions through fuel displacement.
- Achieve customer service and fuel diversity goals.

Kingston and Colbert Fossil Plants

The Kingston plant is based on tangentially-fired pulverised coal technology. TVA tested low percentage co-firing at this installation, limiting the biomass (wet sawdust) addition to <5% (by weight) of the coal supply. The Cobert plant is based on wall-fired pulverised coal technology; TVA also tested co-firing at this site, focusing on levels of addition of up to 5% (by weight).

Experience at the two sites confirmed that pulverisers could perform adequately at these low levels of wood addition, and that boilers could operate at capacity in a stable manner. Indications are that 5% addition may be an approximate upper limit for transporting fine wood through ball mills or bowl mills.

Shawville Generating Station

Low levels of wood addition were evaluated at the station. The Shawville Station uses both tangentially-fired and wall-fired boilers, and all units are equipped with low NOx burners. The tests carried out confirmed that sawdust, poplar and tree trimmings could be co-fired successfully in pulverised coal boilers at low (nominally 3% by weight) percentages. Boiler stability and operability were not compromised and overall plant efficiency was not affected adversely. However, some difficulties were experienced when feeding some of the more fibrous materials to the pulverisers, limiting their capacities through reduced feeder speeds or increased mill outlet temperatures.

Plant Hammond

The Southern Company conducted extensive co-firing tests using a wall-fired pulverised coal boiler. Wood percentages in the fuel mix ranged between 9.7-13.5%. The test programme highlighted several issues:

- Boiler efficiency losses were modest when co-firing wood.
- Unburned combustibles were higher when co-firing.
- Mill energy requirements increased when co-grinding wood and coal.
- Mill fineness decreased modestly when co-firing.
- No positive impacts on emissions were noted when co-firing.

The boiler operated at full capacity during the tests.

Plant Kraft Station

Southern Company tested co-firing higher percentages of wood in a 55 MW_e boiler at the Plant Kraft of Savannah Electric. The boiler, a tangentially-fired unit, was equipped with a separate wood feeding system that directed a flow of dry sawdust into the exhauster of the bowl mill. Wood and coal were co-fired, with coal being fired in one row of burners and wood being fired in a separate row. The tests demonstrated that high percentages of wood could be co-fired in this type of pulverised coal boiler, using a separate dedicated wood feeding system.

Other test programmes

As well as the above test programmes, a number of other evaluations have been carried out in the USA. These include a programme carried out by NYSEG where wood was successfully co-fired in a tangentially-fired pulverised coal boiler of 108 MW_e capacity. The wood was fired separately from the coal up to levels of 10% of the heat input of the boiler. Santee Cooper also carried out a test programme of co-firing up to 8% (by weight). Wood was received in chip form, mixed with coal on the belt feeding the crusher, then pulverised prior to feeding to the boiler.

In another project, Tacoma Public Utilities repowered one of its units through the addition of two fluidised bed boilers fired with locally-sourced wood waste, RDF and coal. The plant uses two 25 MW_e turbines, each fired by a single boiler. In addition, Northern States Power has carried out co-firing at its King Station, a 550 MW_e cyclone boiler fired with subbituminous coal. Finely divided wood waste is fired in the cyclones using the secondary air system for fuel transport.

A summary of major co-firing initiatives is given in Table 9.

Table 9
Tests of Co-firing in Full-Scale Utility Coal-Fired Boilers

Project	**Host**	**Funders**
Sander dust with coal in a cyclone boiler	Northern States Power	Northern States Power
Co-firing forest debris in a pulverised coal boiler	Santee Cooper Electric Coop.	Santee Cooper
Coal/biomass co-firing using FBC	Tacoma Public Utilities	Tacoma Public Utilities
Waste wood co-firing in pulverised coal boiler	Georgia Power and Southern Company Services	Georgia Power and Southern Company Services
TDF co-firing in wall-fired grate-equipped pulverised coal boiler	City of Ames, Iowa State University	South Carolina E&G, Penelec, Centerior
Co-firing of low % of wood in wall-fired pulverised coal boiler	TVA	TVA
Co-firing of low % of wood in tangentially-fired pulverised coal boiler	TVA, Foster Wheeler	TVA
Plastic fibre waste co-firing in pulverised coal boiler	South Carolina E&G	South Carolina E&G
High percentage wood co-firing in pulverised coal boiler	Savannah Electric and SCS	Savannah Electric and SCS
Wood co-firing up to 20% mass in cyclone boiler	TVA, Foster Wheeler	TVA, EPRI
Mid % co-firing in pulverised coal boiler	NYSEG	NYSEG, NYSERDA, ESEERCO
Wood and tyre co-firing up to 15 % by mass in cyclone boiler	TVA, Foster Wheeler	TVA, EPRI
Wood co-firing up to 20% in cyclone boiler	TVA, Foster Wheeler	TVA, EPRI
Wood preparation and co-firing in pulverised coal boiler	GPU/Penelec, Foster Wheeler	State of PA, DOE/PETC. EPRI, GPU/Genco
Plastics, mill residues co-firing in pulverised coal boiler	Duke Power	Duke Power
Switchgrass co-firing in wall-fired, grate-equipped pulverised coal boiler	Madison G&E, University of Wisconsin	EPRI, DOE, MG&E

In addition to the large-scale implementation tests carried out, in recent years there have been a number of major R&D and review-type studies carried out; some of the major ones are noted in Table 10.

Table 10
Major US R&D Studies and Reviews Carried Out

Project	**Participants**
RDF co-firing in utility boiler via RDFCOAL Program	MRI, Iowa State University, EPRI
RDF co-firing update	Iowa State University
Strategic analysis of biomass/wastes for utilities	Iowa State University, Appel, SFA Pacific, EPRI
Wood fuel sources, transportation and cost/supply for co-firing at TVA plants	University of Tennessee
Case studies of wood co-firing concepts and costs for TVA power plants	Ebasco (Foster Wheeler)
Conceptual designs and costs for co-firing wood in systems based on natural gas-fired turbines	Ebasco (Foster Wheeler)
Wood reburn for NOx control in coal-fired boilers	REI, Foster Wheeler, University of Utah
Wood reburn concept design/cost for NOx control in TVA cyclone boilers	REI, Foster Wheeler
Wood/coal blends – storage and cold flow tests simulating bin feeding for cyclone boilers	REI, Foster Wheeler
Fuel characteristics of mill residues for TVA co-firing	TVA, Foster Wheeler
Biomass fuel resources for Indiana; designs and costs	NEOS, Foster Wheeler
Biomass resources and power plants for potential co-firing at Union Electric	Foster Wheeler
Wood resources and power plants for potential co-firing projects at Pennsylvania Electric	Foster Wheeler
Willow energy crop and wood co-firing in NY state	Antares, NYSEG, NMPC, SUNY
Grass crops and wood crops for co-firing in coal-fired power plants in Iowa	Iowa State University, EIS, others
Bench-scale testing of switchgrass co-firing	DOE, PETC
Drop-tube test and engineering study of waste plastic co-firing in pulverised coal boiler	ABB-CE, Duke Power
Biomass co-firing prospects for Northern Indiana Public Service	Foster Wheeler
Biomass co-firing and CO_2 options for NIPSCO	Moll Associates
Wood fuel preparation at NYSEG. Equipment selection and tests	NYSEG

4.9.1 Lessons Learned from US Co-firing Test Programmes

A number of significant lessons have been learnt from the various co-firing exercises carried out to date. These include:

- Co-firing can be carried out at moderate and high percentages in cyclone boiler, with significant environmental benefits and site-specific boiler efficiency and economic impacts.
- Co-firing can be carried out at low percentages in pulverised coal boilers with potentially beneficial economic impacts, depending on the particular site and its local fuel supply conditions.
- Co-firing in pulverised coal boilers, feeding wood *via* the pulveriser, is usually limited by pulveriser performance; this can vary as a function of the biomass being fired.
- Co-firing in pulverised coal boilers at 3-10% (weight basis) input in the fuel blend may necessitate a separate fuel feeding system, depending on the boiler and the capacity of the existing pulverisers, the type and properties of the biomass being fired, and the type of pulveriser being used.

Importantly, the results generated by the various tests noted above confirm the site-specific nature of biomass co-firing with coal. To date, the majority of large-scale plant tests have been carried out using various forms of wood; experience with other forms of biomass and/or wastes is still relatively limited.

4.10 ECONOMICS OF CO-FIRING

The economics of biomass/waste co-utilisation are very site specific and depend on a variety of factors. These include availability of processed fuel and, for retrofit applications, the site layout and plant design. At existing power generation units, it should, in principle, be possible to install co-firing capacity at a lower investment cost than that of new biomass/waste-dedicated plant, thereby achieving an increased level of power generated by the use of renewable energy sources. Clearly, other costs are involved, and the economic impact on the operating and maintenance costs of the existing plant must be considered as part of the decision to co-fire the facility. The economic environment in which the plant will operate also impacts on the viability of the project. Examples of these would be environmentally inspired tax breaks or power price support mechanisms such as the Non Fossil Fuel (NFFO) system operated in the UK.

However, despite the site-specific nature of most co-firing projects, some general conclusions can be reached from the individual cases reviewed below.

4.10.1 Direct Co-utilisation Technologies

Capital costs

Capital costs for the two conceptual designs for 15% waste wood fuel co-firing modifications to TVA's 135 MW_e Kingston #1 tangential-fired power generation unit were estimated in 1993 by Tillman *et a1*(37) at \$8.5-\$12.5 million and \$5-\$7 million, respectively. The cost of modifying a 330 MW_e cyclone-fired boiler (Allen station) for 10% wood co-firing was estimated at \$5-\$6 million.

More recently, EPRI have quoted the capital cost of co-firing as being in the range \$100-\$200 per kWe. The lowest cost opportunities are for co-firing of cyclone boilers with up to 10-15% wood and to co-fire pulverised coal boilers with 1-3% wood, based on thermal input. Higher co-firing rates for pulverised coal units increase costs through the requirement for biomass preparation and separate feed systems to deliver the biomass to the boiler. Swanekamp(38) gives \$200-\$400/kWe for co-firing retrofits to coal-fired plant.

McGowin and Wiltsee cite EPRI estimates of \$90/kWe for wood co-firing of a 200 MW_e pulverised coal unit, based on the studies in an earlier comprehensive analysis for EPRI by Appel Consultants.

For a 250 MW_e pulverised coal plant retrofit utilising wood, the incremental cost given by McGowin and Hughes(39) was \$8200/ton/day of wood, which equates to \$9.7 million for the cost of the retrofit, or \$39/kWe in 1990 \$. McGowin and Wiltsee(40) give the thermal efficiency of a co-fired pulverised coal plant as 0.5% points lower than for the reference plant. Equipment to pelletise waste paper, office waste, waste wood, scrap wood and wood chips at the Idaho National Engineering Laboratory cost \$1.65 million to pelletise 65% of the 48,000 cubic yards of waste available.

Beekes of KEMA, in The Netherlands(41), cited investment costs of co-utilisation between 250,000-50,000 Guilder/MWe. The apparently very high value here presumably indicates that the power denominator refers to the co-fired element only. The total investment cost of the wood co-firing installations at the 635 MW$_e$ boiler at Nijmegen (20 MW$_e$ from wood) has been given as 30 million Guilders(42).

Bestebroer *et al* cite costs at $4835-$10,000/kWe for grate and CFBC systems for biomass co-utilisation and the incremental cost for co-firing a pulverised coal unit at $365/kWe, based on a 1995 report by KEMA on behalf of NOVEM (The Netherlands Agency for Energy and the Environment). These seem high estimates but again, the MWe may refer to co-fuel contribution to power only. A thermal efficiency of 33% was given by Bestebroer *et al* for co-fired plant.

Sundermann *et al*(43) give, respectively, DM 56 million and DM 24 million for co-fired CFBC CHP plant using coal, sewage sludge and municipal solid waste at 20 MW$_{th}$ and 12 MW$_{th}$ input.

Investment cost data are summarised in Table 11:

Table 11
Summary of Capital Costs
(for retrofits of direct co-firing to pulverised coal unit, except where stated)

Reference	Tillman at al. nd	EPRI 1996	Swanekamp 1995	McGowin/ Wiltsee. 1993	McGowin/ Hughes 1992	EPON 1995	Bestebroer 1995	Sundermann 1995
Capital cost per retrofit total plant	135 MWe $10.5M – unpprepared fuel. $6 – prepared fuel	$100-00 kWe	$200-400 kWe	$90 kWe	$39 kWe	30M Guilders for 635 MWe	$365 kWe	DM 56M for new 20 MWth CFBC
Capital cost ((£/kWe) for biomass-produced electricity	52 – unprepared 30-prepared	63-125	133-267	60	26	18	243	~3200 @£=DM 2,45

As can be seen from the above, cost data are wide ranging, emphasising the site-specific nature of such projects. From the data, a representative specific capital cost of £60/kWe (nominal £1996) for a wood co-firing retrofit to a pulverised coal unit has been used in a simplified comparison with 100% coal firing. This specific investment cost equates to a cost of £30M for equipping a 500 MW$_e$ unit for co-firing and compares with the £40 million estimate in earlier studies. A sensitivity case for a specific capital investment increase of 100% is included.

Fuel costs

The driving forces affecting the prices of biomass feedstocks are generally not energy market-related, as most materials are predominantly produced from agricultural or forestry activities. Relative biomass costs are cited by Bauer(44) as currently around twice those for a raw lignite of 50% moisture content and calorific value of 9.3 MJ/kg.

The Danish experience is that straw can be an expensive fuel feedstock, often costing ~50-80 ECU/t. i.e. 3-5 ECU/GJ (US $3.8 $6.4/GJ)(45). 75% or more of the cost is accounted for by handling, baling and storage. It is considered that there is scope for reducing these associated costs in order to achieve a total of 1.8-2.5 ECU/GJ (US $2.3-3.2/GJ).

Meschgbiz and Krumbeck cite recent prices (in Germany) for straw and wood at ~80 DM/t (dry) and for energy crops at 150-175 DM/t (dry); however, they anticipate a future decrease in price as a result of improved processing. Transport costs are estimated at 15-20 DM/t.

Bestebroer *et al* cite wood costs at $21-$28/tonne (dry) and rising, based on a report by KEMA on behalf of NOVEM.

Hughes and Wiltsee projected that fuel costs from short rotation crops of fast growing, clonal varieties of trees would range from $1/GJ to $4/GJ, depending on conditions. Willow would be lower cost than poplar and eucalyptus. Agricultural subsidies, very high yields and development of harvesting machinery will be necessary to keep competitive with fossil fuels.

EPRI give the actual cost of biomass fuels from dedicated crops as $1.95-$3.50/GJ. Projected fuel costs of between $1.35 and $2.65/GJ emerged from six recent EPRI member feasibility studies.

ETSU, in an analysis of potential options for a wood co-firing demonstration for large-scale power generation in the UK, assumed a cost of £2.40/nGJ for delivered wood.

A UK Government review of biomass(46) gives £30/t (dry basis) for chipped and delivered forest waste and wood processing wastes at £0-£30/t. Short rotation coppice was noted as £45/t (dry). Prices in Europe can be up to £60/dry tonne for regular bulk supplies. Costs of straw of £22/t (delivered) have also been suggested.

Exelby and Davison(47) drew together some literature costs of straw and found values of from £15 to £39/t. Sewage sludge is expected to have a negative cost, reflecting current gate fees. The disposal cost for dry sewage sludge was given as £100/t in the UK. This would need to be offset by transport costs for significant usage. A Government review of biomass gave £50/dry tonne for disposal cost.

A summary of biomass/waste fuel costs is given in Table 12.

Table 12
Summary of biomass/waste fuel costs

Mosbech 1994	Meschgbiz 1995	KEMA 1995	Beekes 1995	Hughes/ Wiltsee 1995	EPRI 1996	ETSU 1 1996	ETSU 2 1996	Exelby & Davison 1994
50-80 ECU/t straw	80 DM/t wood, straw	$21-28/t wood	Incineration cost of MWS 180 Gu/t	$1-4 GJ wood	$1.95-3.95 GJ. Projected $2.65 GJ	£2.4GJ. Delivered wood	£30/t – dry forest waste. £45/t – SRC. Sewage sludge disposal £50/t	£15-39/t straw. Dispposal cost for sewage sludge of £100/t
£52/t	£33/t	£17/t	£70/t	£2 GJ	£1.25 GJ	See above	See above	See above

Other operating costs

These include raw materials, maintenance, auxiliary power, labour costs, land taxes, disposal costs, by-product credits, etc. Other contributions may come from external factors such as tax breaks or environmental credits for coal plant emissions minimised through the use of co-firing systems. A New York co-firing project took into account a \$ 1/t offset for net CO_2 abated, based on a valuation by the State's utility regulators. A proposed alfalfa gasification project in Minnesota included the effect of that State's CO_2 offset of \$5.99 to \$13.60/t.

EPRI's recent calculations(49) show that the cost of avoiding CO_2 emissions by using biomass in a pulverised coal boiler firing 15% biomass by heat would <\$5/t of carbon, compared with \$50 or even \$100-\$200/t of carbon for some other CO_2 reduction options, such as fuel switching or direct emissions control. A CO_2 offset of £5/t was examined in the evaluation below. The CO_2 offset required for breakeven with 100% coal firing was also assessed.

Overall costs

These are the total of the capital repayments, fuel costs and other operating costs. These components have been aggregated in a simplified calculation of the generating cost change on retrofitting a 500 MW_e coal-fired plant for 10% wood co-firing using the set of assumptions shown in Table 13.

Table 13
Assumptions used in assessment of 10% wood co-firing on a 500 MW_e pulverised coal unit

	Base	Co-fired
Capital cost of conversion	30	60
Difference in boiler efficiency when co-firing	0.8% (worst case scenario)	3%
Difference in auxiliary power when co-firing	2 MWe (assumption)	5 MWe
Delivered ad prepared wood price (£/nGJ)	2.70	1.5 & 3.0
Delivered coal price (£/nGJ)	1.30	---
Fossil fuel CO_2 emission abatement credit (£/t)	5	Breakeven
Coal CV (nGJ/t)	26	---
Coal ash content (%)	10	---
Discount rate (real) (%)	20	15
Amortisation period (y)	15	25
Load factor (%)	60	---

The evaluation concluded that the main contribution to increased generation cost comes from the increased fuel cost and the capital charges. The latter clearly depend on the economic criteria applied; fairly stringent ones were used in this examination.

Table 14
Results of pulverised coal-wood co-firing assessment - differential cost components
(10% wood co-firing minus 100% coal reference), p/kWh

Component	Differential costs (p/kWh)
Capital	0.28
O & M	0.04
Fuel	0.16
Total	0.48
CO2 abatement credit	-0.07
Diff. Gen. Cost with CO_2 credit of £5/t	0.41

Sensitivity analysis (Table 15) revealed that sensitivities were influenced primarily by wood price, capital cost, and capital repayment conditions. Carbon dioxide abatement credit for breakeven was £37/t for the base economic assumptions used. This decreased to only £30/t for the more relaxed economic assumptions in one of the step-out cases.

Table 15
Results of pulverised coal-wood co-firing assessment - sensitivities

Changed input	**Effect on differential costs excluding capital repayments (p/kWh)**	**Effect on total differential costs (p/kWh)**
Capital cost increased by 100%	+0.04	+0.32
DCF decreased by 15%, amortisation period increased to 25 years	0.00	-0.08
Boiler losses increased four-fold to 3%	+0.03	+0.03
Wood price reduced by 44% to £1.5/nGJ	-0.12	-0.12
Wood price increased by 11% to £3/nGJ	+0.03	+0.03
Differential auxiliary power increased by 150% to 5 MWe	+0.01	+0.02

4.10.2 Indirect Co-utilisation Technologies

Capital costs

The cost of an IGCC-based 60-70 MWe paper mill CHP plant project in Finland, using 60% biomass and 40% coal, has been given as $100 million. McGowin and Wiltsee give EPRI estimates of 100% wood-fired IGCC at $1765/kWe at 100 MW_e scale.

Bestebroer *et al* cite costs at $5835-$8335/kWe for fluidised bed gasification combined cycle systems for biomass and an incremental cost of $2000/kWe for retrofitting fluidised bed gasification to either a coal-fired plant or a natural gas-fired CCGT plant, based on a 1995 report by KEMA on behalf of NOVEM. These appear to be high estimates; however, as noted above, it may be that the power denominator refers to the co-fired element only. A thermal efficiency of up to 47% was given by Bestebroer et al for a co-fired IGCC plant using a pressurised gasifier.

Exelby and Davison quoted a specific cost of £1035/kWe for a dry feed entrained flow gasifier-based IGCC, based on several European studies. Thermal efficiency in an entrained gasifier 1GCC was estimated by the same authors at ~46% (LHV basis) for 10% straw co-firing, and 44% for 10% sewage sludge co-firing. A minor decrease in thermal efficiency on straw co-firing of 0.6% points was predicted with 10% straw addition.

The above capital cost data are summarised in Table 16.

Table 16.
Summary of capital cost estimates for new biomass/waste and coal IGCC

Reference	**Gas Turbine World 1996**	**McGowin & Wiltsee EPRI 1996**	**Bestebroer 1996**	**Exelby & Davison 1994**
Total capital costs	60 MWe CHP £100M 60% biom:40% wood	$1765/kWe 100% wood	$5835-8335/kWe 47% LHV effic.	£1035/kWe Dry entrained feed. 100% coal. 46% LHV effic.
Investment cost/total power output	£1042/kWe	£1180/kWe	£3650-5210/kWe	£1035/kWe

Fuel and Operating costs

Discussed above.

Overall costs

The indicative relative economics of a 10% biomass co-fired IGCC plant and a 100% coal-fired IGCC were examined in a simplified calculation using the set of assumptions shown in Table 17.

Table 17
Assumptions used in assessment of 10% wood co-fired IGCC plant

	100% coal	**10% wood co-firing**	**Step-off for co-firing**
Capital cost (£/kWe)	1053	Base + 5%	Base; Base + 10%
Thermal efficiency, net CV basis	46.3	45.7	46.3
Delivered and prepared wood price (£/nGJ)	2.70	2.70	1.50 & 3.0
Delivered coal price. £/nGJ	1.30	1.30	---
Fossil fuel carbon dioxide emission abatement credit, £/tonne	---	5	Breakeven with coal
Coal CV, nGJ/tonne	26	26	---
Coal ash content, % a.r	10	10	---
Discount rate (real), %	15	15	20
Amortisation period, years	20	20	15
Load factor, %	80	80	80

The evaluation again shows (see Table 18) that the main contribution to increased generation costs comes from the increased fuel cost and the higher capital charges.

Table 18.
Results of assessment of 10% wood co-fired IGCC plant - differential cost components
(10% wood co-firing minus 100% coal reference), p/kWh

Component	**Differential costs, p/kWh**
Capital	0.14
O & M	0.02
Fuel	0.12
Total	0.29
Carbon dioxide abatement credit	-0.04
Diff gen cost with CO_2 credit of £5/tonne	0.25

Sensitivities are shown in Table 19.

Table 19. Results of assessment of 10% wood co-fired IGCC plant – sensitivities

Changed input	**Effect on differential costs excluding capital repayments (p/kWh)**	**Effect on total differential (p/kWh)**
Specific capital cost 10% higher than coal only plant (twice differential)	+0.02	+0.16
Specific capital cost made equal to that of coal only plant	-0.02	-0.17
DCF increased to 20%; amortisation period decreased to 15 years	0.00	+0.06
Thermal efficiency of co-fired plant raised to equal that of coal only plant	-0.01	-0.02
Wood price reduced by 44% to £1.5/nGJ	-0.09	-0.10
Wood price increased by 11% to £3/nGJ	+0.03	+0.02

Thus, sensitivities were greatest to wood price, capital cost, and capital repayment conditions. Carbon dioxide abatement credit for breakeven was £41/tonne for the base economic assumptions used. This increased to about £50/tonne for the more tight economic assumptions in the DCF/plant life step-out case.

In confirmation of this, IEA Coal Research found from reviewing various economic evaluations of co-firing that some form of subsidy was ultimately required to achieve viable projects.

4.10.3 Maintenance and Performance Issues

Biomass feeds often have higher chlorine and potassium concentrations than coal. Co-firing of coal-fired boilers can therefore be expected to increase corrosion rates by the enhancement of normal sulphate corrosion. However, to date, tests in utility boilers have been encouraging, in that serious corrosion enhancement has not occurred. Slagging and fouling increases have also been only small-moderate. Based on these findings, it therefore appears that the additional cost of co-firing from these boiler effects could well be only minor.

A further issue to be considered in conversion to co-utilisation of biomass is the possible decrease in boiler efficiency as a result of reduced carbon burnout and increased latent heat losses. The former will usually be insignificant in FBC systems and has been shown to be only a minor factor even in wall-fired pulverised coal systems, at ~<0.5%. The latter are easy to predict and should also be minor (e.g. 0.25% increase). 0.8% was used in the short evaluations for this review.

Many pulverised coal-fired power stations sell a significant quantity of their furnace and fly ash to the construction industry. The quality of these by-products must remain within the constraints set by the market or revenue from these sales will be lost and additional disposal costs incurred. Of particular importance are the carbon concentration in the ash for use in cement (e.g. not >5% in UK specifications) and the leachability of heavy metals from the ash. When co-firing, the ash carbon content can rise, reflecting the slightly lower fuel burnout, and the co-firing ratio may be limited if this is to be kept within bounds. The concentrations of heavy metals can also rise, as referenced earlier, although leachability has not usually been affected. The accumulation of undesirable species in FGD plant, not currently an issue, could affect by-product gypsum marketability, hence further trials to establish the situation would be required. The consequences of limitations noted would probably be the imposition of an upper limit for co-firing ratios adopted.

Since, for wood co-firing in pulverised coal boilers, all primary air fans and mills will generally be needed to maintain output, there is no room for the normal margin of redundancy (usually 1 mill in

6), with a consequent impact on maintenance and availability. Airflow rates could also affect pipe wear.

The costs associated with many of these issues were investigated for ETSU in the UK, using the EPRI *Coal Quality Impact Model*. An examination of these results shows that the differential maintenance cost from co-firing wood fuel would depend on the coal analysis but is likely to be only minor (up to £0.06 million/y for a 500 MW_e unit at 51% load factor, equating to <0.003 p/kWh). Dwarfing these effects, at around £2.8 million/y was the effect of the delivered fuel cost (£2.93/GJ after drying and handling for wood, coal only £1.5/nGJ excluding transport). Auxiliary power requirements were actually predicted to fall with co-firing, hence the net cost increase was ~£2.7 million/y, or 0.12 p/kWh, before capital charges, i.e. virtually all coming from the higher fuel cost. This is in agreement with the present analysis.

4.10.4 Summary of Economics Issues

Published cost data on processes and on the costs of biomass vary widely. Moreover, the economics of co-utilisation are very dependent on assumptions. The main reason for this is the much higher cost of biomass. Dried sewage sludge currently does not have a selling price, since it is normally disposed of at a cost. It is therefore potentially more attractive economically as a gate fee could be charged. However, if there are to be large numbers of commercial-scale co-utilisation projects, many will probably need to rely on energy crops grown for the purpose. It is by no means certain that the selling price of such materials will fall. Support mechanisms are therefore necessary so that governments shoulder part of the risk. A possible form of guaranteed support mechanism could be a credit for replacement of fossil fuel-derived carbon dioxide, since carbon dioxide abatement is often one of the major aims of many biomass projects. An alternative mechanism could be in the form of guaranteed power selling prices similar to the NFFO scheme in the UK. In the absence of such measures, the uptake of biomass and wastes for co-firing applications may remain limited, as a consequence of the increased costs compared with firing coal alone.

Most economic analyses have been carried out on wood or straw co-utilisation for power generation applications. The commercial-scale tests appear to be indicating that technical risks are not unduly high. New plant (eg. based on gasification for combined cycle power generation) will need to be constructed with sufficient coal supply systems to ensure that 100% use of coal at full rating is possible, as there must inevitably be a degree of risk attached to the certainty of the biomass/waste feedstock being available in adequate quantities over the station’s lifetime.

5.0 MARKET POTENTIAL FOR CO-FIRING

In 1985, biomass was estimated to supply some 12% of global energy requirements and by the 1990s, this had reached ~26% (50). Most of this is was in the form of wood, used in open fires or crude ovens.

According to the IEA/OECD(51), indigenous total energy production from renewables and wastes was 6,300 PJ in 1993. However, the potential is far greater. Patterson(52) gives a table of the energy content of selected biomass residues from another source(53) that suggests significantly greater amounts; these are summarised in Table 20 below.

Table 20. Energy content of selected biomass residues, world-wide, PJ/year

Maize	Wheat	Rice	Sugarcane baggase	Dung	Roundwood	Fuelwood/charcoal
6,700	10,909	9,700	7,700	40,800	22,300	13,300

In Europe, there is considerable potential for the increased use of biomass and waste feedstocks for energy production purposes. However, it is very difficult to arrive at an overall total of such materials as a result of the number of countries involved, a universal definition of what materials can be classified in this manner, differences in the compilation of statistics between countries, and the diverse range of biomass/wastes involved. Predicting the extent of future uptake of biomass/wastes for co-firing duties is further complicated by many factors such as the uncertainties in how national electricity industries will be structured in the future, governmental attitudes and policies, environmental requirements, etc. For instance, the extent of land potentially available for growing biomass fuels as energy crops within Europe will be dependent on all of the above factor. However, in this case, an estimated 10 million hectares (<10% of EU agricultural land) could be devoted to growing biomass, in the form of short rotation coppice and rapeseed(54). This could yield approximately 3360 PJ of primary energy, or approximately 20% of total European energy needs.

A number of studies have addressed the potential for the utilisation of biomass/wastes, usually on a national basis. For instance, in the UK, consumption of wood for total energy purposes is ~1 Mta. Much of this wood consists of arisings from thinnings generated during woodland management(55). It is estimated that the harvestable yield of UK forest residues will amount to 0.7 Mt of coal equivalent (i.e. 20 PT) annually by the year 2000(56). There are several small plants that will be wood-fired under development in the UK. These include facilities fired on short rotation coppiced wood that will use 36 kta to generation ~5.5 MW_e each. In addition, Border Biofuels is building a 20 MW_e biomass-fired power plant in Cumbria. This will require some 450 kta biomass from local forestry operations, energy crops and primary wood processing activities. The utilisation of wood is also being pursued in the 8 MW_e gasification-based ARBRE plant being built at Eggborough.

Even where indigenous wood resources are not large, significant amounts of wood can be retrieved from demolition, etc. and utilised for energy production. For instance, recent estimates suggest that 250,000 tonnes of waste wood (i.e. about 3 - 4 PJ) are produced in the Netherlands annually(57). Much is currently dumped.

Some biomass feedstocks are currently used in relatively sizeable amounts within the EU although the rate of utilisation is not uniform between Member States. As noted earlier, considerable amounts of straw are already utilised for power generation purposes in Scandinavia. In other countries, there is considerable potential for similar usage although currently, application in this way may be minimal. For instance, in the UK, annual production of straw was 13.6 Mta in the late 1980s, and is now estimated to have risen to ~15 Mta. Currently, ~50% of this straw is used in animal feed and bedding, leaving approximately 7 Mt (about 105 PJ) potentially available for energy use(58). To date, use of straw for power generation purposes has been small; however, a 36 MWe straw-fired plant is currently being constructed by EPR, a joint venture between Energy Power Resources and Cinergy Global Power; the plant will use 200 kta straw.

In the UK, an assessment by ETSU of renewable energy for the UK showed that accessible resources, assuming no constraints (eg. on public acceptance) of energy crops could be equivalent to the generation of about 200 TWh/year. Application of practical and economic constraints modified this to the 'Maximum Practicable Resource' of 90 TWh per year by 2005. This would imply a biomass input of around 900 PJ per year, assuming a 35% generation efficiency. The Maximum Practicable Resource for landfill gas and municipal wastes together were assessed at <10 TWh per year (equivalent to an annual input of about 100 PJ). Their use in industrial heat production would give additional market.

Almost 60 Mta waste could be used in energy-from-waste schemes, according to a study for ETSU by MEL(60). Total energy available would be 663 PJ/year. Two thirds comprises general industrial waste, one quarter is household waste. Waste wood amounts to 21 PJ. Another study for ETSU found that annually 3.4 Mt of green forest wastes and 1.5 Mt of processing wastes were not used at present in the UK, equivalent to about 50 PJ per year.

The UK Government intends that 1500 MWe of renewables electric power generation capacity will be in place in the UK by ~2000, driven by the NFFO. Biomass and wastes account for around half of the current NFFO capacity. If the proportion remains of this order, the implied biomass usage for the NFFO could rise to 30-35 PJ per year, assuming a 35% generation efficiency and 50% load factor. Co-utilisation projects are not currently within the NFFO mechanism, although one project was supported in the first NFFO round.

Another widespread source of material potentially applicable to power generation application in large quantities is sewage sludge. Although estimates vary, the quantity of sewage sludge produced in the EU has been estimated as between 320 and 430 million cubic metres. The UK produces over 1 Mta of sewage sludge (dry solids). Several studies have been carried assessing this material as a potential power station feedstock, both for direct co-utilisation and co-gasification with coal and/or other materials. These studies have confirmed that there is considerable potential for application in these ways.

Thus, overall, although the different sources of statistics on biomass and waste potential reserves tend to be rather ill-defined because of the variability of these materials, the data given in the above examples do illustrate the enormous potential reserve of biomass and wastes. To put the data in perspective, they are compared with the consumption of coal below.

3.5 billion tonnes of hard coal, plus 1.25 billion tonnes of lignite/brown coal are produced across the world each year. Of these, half of the hard coal and two thirds of the lignite/brown coal are used in power generation applications. This huge installed capacity of coal-fired power plant consumes some 50,000 PJ of coal each year; if all of this capacity was co-fired at a rate of 10% (thermal input, as used successfully in a number of US-based initiatives), this would require 5,000 PJ of biomass/wastes per year. Clearly, a number of assumptions need to be made, such as local availability of biomass/waste feedstocks to power stations or other potential co-utilisation sites, as such factors would impact on the size of the potential market. On this basis, and the potential biomass/waste fuel production potential analysed above, it is conceivable that significant growth in co-firing, perhaps to 500 PJ per year, in existing coal-fired generating capacity, could be achieved in the future. This would be equivalent to 10% of existing capacity being modified to take 10% thermal input of biomass/wastes. The construction of new capacity, specifically designed to utilise higher rates of co-utilisation could increase this further.

Apart from power generation applications, there are also potentially large markets for industrial and commercial applications. These market areas account for significant coal use (e.g. 8% of OECD coal use and 30% of China's coal use, excluding iron and steel production(62). Thus, the industrial sector is large: even a conservative estimate of industry's proportion of world coal consumption of 10% leads to a figure for industrial world coal use of about 10,000 PJ per year. If 10% co-fuelling could be achieved on 5-10% of existing installations, this equates to a global market of 50-100 PJ for biomass/waste fuels in this sector. Biomass and waste therefore have the potential, *via* co-firing industrial boilers, to make an important contribution to raising the proportion of these “renewable fuels” usefully employed in the world energy supply mix.

An important factor in driving forward the various technologies will be the impact resulting from changes in various forms of legislation in place or introduced in the future.

5.1 Legislative Drivers Influencing Uptake of Biomass/Waste Feedstocks

Environmental

There are a number of international environmental initiatives that impact on the use of biomass/waste fuels as a means of reducing global dependency on the use of fossil fuels for energy production, either through the use of co-utilisation or in purpose-designed stand-alone renewable energy plant. These initiatives include:

- The Conference on the Human Environment (1972) led to the establishment of the United Nations Environment Programme (UNEP). The UNEP was formed as a result of increasing concern over the deteriorating environment. The UNEP has taken a major role in framing future global environmental legislation.

- The United Nations Conference on Environment and Development (Earth Summit) was held in Rio in 1992. The main aim of the conference was to reverse environmental degradation and to promote sustainable and environmentally sound development in all countries. During the conference, the Framework Convention on Climate Change was endorsed.

- Framework Convention on Climate Change. Developed countries are required to take measures aimed at returning emissions of greenhouse gases, in particular carbon dioxide, to 1990 levels by 2000 and to provide assistance to developing countries. Other obligations include compiling inventories of emissions, producing and publishing national programmes of measures to limit emissions and to promote research and public education about climate change. The convention came into force on 21 March 1994 following ratification by 50 countries. By mid-decade, the Convention had been ratified by 135 countries, including the European Community.

In addition to these measures, there are further international agreements developed by the United Nations Economic Commission for Europe (UNECE) that cover a range of environmental issues, some of which include the exchange of research information, starting a monitoring protocol, and agreeing to reduce certain emissions by a stated date. These protocols include:

- The Helsinki Protocol, adopted in 1985, came into force in 1987 requiring signatories to reduce national sulphur emissions, or their trans-boundary fluxes by 30% based on 1980 levels, to be achieved by 1993. This protocol was not ratified by the European Community, although a number of individual member states did ratify it. This protocol has now been renegotiated using data based on critical load assessments and countries are required to reduce, by the year 2000, their sulphur emissions to meet a target of 60% of the gap between sulphur emissions and the critical load. Individual countries’ target reductions are based on their contribution to acid deposition over the areas included in the calculations. The new protocol was officially signed in June 1994, and has been signed by the EU.

- The 1988 Sofia Protocol freezes nitrogen oxide emissions, or their trans-boundary fluxes, by 1994 using a 1987 baseline. Critical load maps have been drawn up covering the whole of Europe, by the European Evaluation and Monitoring Programme under the LRTAP Convention.

The European Community have ratified this protocol.

- A further Pro LRTAP under the LRTAP convention signed in Geneva in 1991 aims to control emissions of volatile organic or their trans-boundary fluxes. The new Protocol obliges most parties to secure a 30% overall reduction in their VOC emissions by 1999, using 1988 as a base.

The European Community (EC) is an important international innovator on environmental issues. The need to reduce emissions from all sources is a major thrust of the EC's policy to improve air quality and health. The EC legislation can be summarised as follows:

Air Quality - In 1995 the Environment Ministers agreed the draft a framework directive on ambient air quality. The directive set up monitoring programmes to assess and improve air quality. The directive was administered in a series of "Acts" which set ambient air quality levels in accordance with World Health Organisation (WHO) guidelines. The earlier SO_2, NOx, lead and particulate levels are now being reconsidered and strengthened. Levels for other species such as cadmium, arsenic, fluoride and nickel were in place by 1999. The directive also allows all levels to be reconsidered as new scientific evidence on health effects becomes available.

Carbon Dioxide - The member states agreed that CO_2 emissions should be stabilised at 1990 levels by the year 2000 to reduce global warming. Methods proposed for stabilising emissions included a SAVE programme to improve energy efficiency and a proposal for a carbon tax due for implementation by 2000.

Industrial Emissions - In 1988, the Large Combustion Plant Directive was set which specifies reductions in sulphur dioxide and nitrogen oxides and suspended particulates from fossil fuel power plant greater than 50 MW. In 1994, the Directive was amended to include plant in the range 50-100 MW. In the Fifth Action Programme, the EC set a target of reducing emissions of acid gases to ensure that no critical loads or levels are exceeded. In addition, the EC proposed a Community-wide 30% reduction of NOx by 2000. For sulphur dioxide, a reduction of 35% by 2000 from 1985 levels has been set.

The environmental legislation has tightened considerably in the last decade and will continue to become increasingly stricter. As more former Eastern European states become part of the EC, the reductions in emissions have spread eastwards. Similarly, as Western technology is increasingly transferred to the developing countries and as their awareness of the importance of air quality on health increases, there will be pressure to reduce emissions globally. Substantial reductions in the production of greenhouse and acid gases could be achieved by reducing the proportion of fossil fuels utilised for energy production. The reduction can be achieved by the greater use of natural gas or nuclear power, although both have associated disadvantages. Another method is the use of renewable energy, including the utilisation of biomass and waste. The utilisation of these energy streams can take place in purpose-designed plant, for which many countries have subsidised support programmes, such as NFFO in the UK. Alternatively it can take place in existing coal-fired plant in a co-fired application.

Unlike the emissions legislation, there are no similar international statutes for waste disposal. In the Western Industrialised nations there are rapidly developing protocols and initiatives to reduce the amount of waste disposed of, with recycling and energy recovery taking higher precedence. The beneficial utilisation of non-recyclable waste in existing coal-fired plant should be a major consideration. Since not only is a high value product produced from a low value material, but also the need for land-based disposal of waste will be significantly reduced. In the developing countries, at this stage, there is relatively little such legislative practise, although in some areas, these are being developed.

5.2 Market Stimulation

In addition to the legislative drivers, there are a number of market stimulation exercises that warrant consideration. For instance, within the EU, there are R&D programmes promoting the development of co-fired technology, initially for use within the EU, but ultimately for export to developing countries. These programmes include JOULE and THERMIE.

The JOULE research and development programme had a total Phase One budget of £94 million, of which over £9 million supported forty-four biomass projects. The European Commission's energy technology programme, THERMIE, awarded some 144 Renewable Energy Source projects a total of £59 million between 1990 and 1992. Another £25 million was allocated to fifty Renewable Energy Projects. Later THERMIE rounds included specific proposal calls for co-fired demonstration projects, both inside and outside the EU.

In addition, the EU has budget areas for international co-operation with other countries. Inco-Copernicus involves research co-operation with the former Eastern European and CIS countries. The SYNERGY programme allows for co-operative research with countries outside the EU boundaries such as India, China, and South Africa. The PHARE and TACIS programmes promote the development of energy efficient western technology in Eastern Europe and former CIS countries.

The 1993 joint European-ASEAN (Association of South East Asian Nations) co-generation programme aimed at promoting technology transfer from the European Community to Asia in the field of heat and power generation from biomass.

The international aid agencies are also active in stimulating markets for biomass and waste utilisation. The Global Environment Facility (GEF), administered by the World Bank, was a three year programme providing grants for investment projects, technical assistance and research concerning global pollution and biological diversity. The programme was funded by twenty-four countries, agreements within the Montreal Protocol, and co-financing arrangements. Only projects in countries with a per capita income of less than $4,000 (US) a year, in October 1989, were eligible.

Action to give greater attention to environmental issues is also under way in the regional development banks. For example, the Asian Development Bank (ADB) has upgraded its environmental unit to full division status.

In addition to those programmes listed, the US AID programme and country aid programmes such as the UK ODA and Know How Fund, and Swiss Aid also promote the introduction of new advanced technology into developing countries.

5.3 Market Opportunities and Technology Transfer Issues

The largest market for co-utilisation of biomass and wastes clearly lies in the retrofitting of existing power station boilers and large industrial boilers and furnaces. The feasibility of the concept has been established for both pulverised coal systems and CFBCs. There is an estimated potential of ~500 PJ of biomass/wastes additions per year, even assuming only ~1% of coal is displaced globally in these two sectors; most of this would be in power generation applications. Additionally, it appears likely that the co-gasification of sewage sludge in combined cycle power generation systems may be considered sufficiently attractive in some locations.

Construction of new biomass/waste co-utilisation capacity, as opposed to application in existing plants, would be most attractive in situations where there was the political will to use biomass/wastes as environmentally friendly fuels, but where their reliability of supply could be in question over the installation's lifetime. It would then be possible to fall back on fuelling with 100% coal at periods of shortfall in the biomass/waste resource. It would clearly be essential to design the installation such that full output could be attained on coal only. Co-utilisation may be preferred even where the biomass/waste fuel is assured, where greater output is required than could be achieved on the local crop alone. An example would be where export of power was attractive.

Notwithstanding the above, it is difficult in other situations to envisage significant interest in co-utilisation in new large installations: smaller, 100% biomass/waste utilisation plant appear more likely as new plant constructions, as the capital outlay would be smaller. Co-utilisation seems more likely to be regarded as a compromise between 100% fossil fuel utilisation and the 'ideal' of an almost CO_2-neutral biomass/waste-dedicated facility.

New biomass co-utilisation installations would probably be combined with establishment of plantations of energy crops specifically designated for that capacity. This could either involve the introduction on a wide scale of short rotation coppice in wetter climates or the planting of fast growing grassy crops, such as miscanthus, in drier regions. Naturally, the utilisation system would need to be near to both the plantations and a suitable coal supply source and the option of 100% fuelling on coal would be a wise precaution.

The suggested potential market for co-firing in the industrial sector of 50-100 PJ/year and power generation sector of 500 PJ/year (*via* retrofits), with potential for significantly more in new gasification combined cycle technology, will result in market opportunities over the short-medium and longer terms. In the short and medium term, most co-firing activity will lie in the retrofitting of pulverised coal power station boilers with biomass/waste feed handling and preparation systems and in adding systems to CFBC feed handling trains to cope with biomass/waste addition. In the longer term, the market will be less discrete in that the manufacturers of biomass/waste handling and feeding systems will need to be more involved in the total plant design-and-build strategy. The greatest interest in co-utilisation, and so greatest demand for technology to achieve it, will tend to be in retrofits over the short to medium term.

In order that the development of co-utilisation can come about, transfer of the know-how gained by the researchers and engineers at the test facilities and commercial combustion plant will be needed. For pulverised coal systems, there should be no difficulty in achieving this, especially on wood feedstocks. CFBC systems are now widespread and many burn low grade fuels, such as lignite.

Finally, development of an economic policy framework for energy crops will be needed if biomass fuel costs are to be regarded as sufficiently predictable for major new investments in co-utilisation (or dedicated biomass) capacity to be regarded as less than high-risk; macroeconomic studies will be required. In the meantime, in order that co-utilisation projects are identified and developed, except at particularly favoured locations, financial incentives and legislative drivers will be necessary instruments.

6.0 BARRIERS TO CO-FIRING MARKET TAKE-UP IN THE EU

6.1 Direct co-utilisation

In all of the co-utilisation technologies considered, there are technical problems and limitations that have not yet been fully resolved. These include the following:

Bubbling fluidised bed combustion (BFBC)

Although commercially proven, in some instances such as co-combustion of paper mill wastes with coal, other fuels have shown potentially significant problem areas. For instance, work carried out to assess the feasibility of co-firing straw and sewage sludge with coal in a bubbling bed resulted in bed agglomeration under some operating conditions. In addition, significantly increased levels of chlorine in the fuel gas, from both straw and sewage sludge, suggested that increased corrosion rates of downstream components was a real possibility. Thus, further materials development may prove necessary where particular fuel types are used.

Circulating fluidised bed combustion (CFBC)

Co-utilisation in circulating fluidised bed combustors has also revealed a number of potential problem areas. Depending on the particular installation, the use of some biomass fuels (such as straw) can lead to a combination of increased fouling of boiler internal surfaces, plus higher rates of plant component corrosion. Where straw and coal have been regularly co-fired, such as in Danish cogeneration plants, this increased corrosion has required careful monitoring and quantifying in order to be accommodated at the plant's design stage. Both wood and straw-fired plants have experienced higher levels of maintenance compared to units fired on coal alone. Thus, the high levels of alkalis and chlorides in some biomass fuels can lead to long-term plant reliability problems although when co-fired with coal in the appropriate proportions, problems such as corrosion can be significantly reduced. Problems associated with increased fouling and corrosion are not limited to one particular type of CFBC and range from the widely used Foster Wheeler/Ahlstrom Pyropower-type unit to the multi-solid circulating fluidised bed system (MSCFB). For instance, co-firing straw in the 20 MW_e MSCFB unit of a Midkraft power station in Denmark resulted in increased fouling and corrosion in the superheater section, a problem that has also been reported in several other plants.

Other considerations when co-firing wastes and biomass-derived fuels in CFBC units centre on the collection, blending and feeding systems required. By their very nature, biomass and waste fuels are generally inhomogeneous and this can cause difficulties in ensuring that the fuel feed to the combustor is of a consistent quality. In particular, these fuels are characterised by low heating values, high moisture contents, low bulk densities, high fibrosity and variable particle size, and these properties impinge on the size and nature of the blending and feeding systems required; the costs associated with this can be significant and for some biomass/waste-derived fuels, suitable preparation and feeding systems await full development.

Pulverised Coal Co-firing

Despite some success in the USA and Europe, the co-firing of biomass and waste fuels in conventional pulverised coal boilers can also be problematical. Apart from the necessary preparation and feeding systems, and possibly special burners, the co-utilisation of a biomass/waste-derived fuels with a high chlorine content could lead to both corrosion and emission problems when used with a high chlorine coal. Therefore, both biomass, waste and coal selection is an important factor in determining the optimum fuel blend. In addition, the reduction of biomass/waste fuels to a suitably small size can be energy-intensive, impacting in overall plant economics. Further complications can arise with the plant's waste products. For instance, work carried out by Vestkraft in a 125 MW_e pulverised coal-fired boiler confirmed that when coal was co-fired with >10% straw, the ash was no longer suitable for cement manufacture. In addition, when co-firing this level of straw, indications were that plant corrosion rates could be as much as ~50% higher than when firing coal alone. Other problems have occurred with the handling of such fuels and EPON in the Netherlands found difficulty in handling some wood chips supplied to the plant.

For both fluidised bed and pulverised coal systems, the inhomogeneous nature of biomass and waste fuels can lead to plant problems. Some biomass/waste-derived fuels are more acceptable than others in this respect; however, the properties of some materials can fluctuate significantly. In several Scandinavian countries, as a result of climatic variations, both the quality and quantity of straw can vary. In Denmark, straw is fired or co-fired in some 60 district heating plants and 7 cogeneration units. In some years, harvests have been affected to the degree that not only have straw properties been affected, an overall deficit has occurred, an important consideration where biomass supplies a significant proportion of a co-utilisation scheme.

Co-gasification systems are generally at the point where several have been proved to be technically feasible although further developments are needed in a number of areas. Clearly, similar problems of fuel collection, preparation and blending remain common to other technologies; however, especially for biomass fuels, feeding options generally require further research and development. Feeding systems for pressurised gasifiers are not yet fully developed or commercially available.

Thus, in a number of areas of co-utilisation, there has been rapid progress. However, research and development and demonstrations are required before widespread deployment of the technologies becomes a reality.

As noted, there remains a need for R&D on biomass/waste fuel handling and preparation systems to achieve predictable feed comminution at even and predictable feed rates, particularly for feeding to co-utilisation systems that require a comparatively finely divided fuel (eg. pulverised coal boilers and furnaces) and for feeding into pressurised systems such as gasifiers. The difficulties are more severe with handling and preparing softer biomass, such as straw and miscanthus, than with wood, which is generally easier to handle. Straw has proved to be very difficult to process, and handling systems have had to be modified in many cases to avoid plant outages. The unpredictability of the behaviour of straw in what are relatively simple handling and comminution processes, still requires complete resolution.

Moisture content is acknowledged as one of the main influences on the handleability of materials. Establishing a means of ensuring greater consistency in the water content of materials that may be stored for varying periods will present a challenge. Substantial initial reduction of moisture contents of green material such as wood chips, without the need for heat addition, has been achieved by careful construction of piles but more trials of natural drying without the risk of spontaneous ignition on greater quantities of material are required.

Development of satisfactory means of storage of soft biomass, especially miscanthus, would be valuable since these materials tend to become unusable if stored at high moisture contents. The handling and preparation of dried sewage sludge is, in contrast, comparatively straightforward, provided that experience of prior work is taken into account.

Co-firing of biomass/wastes in utility boilers is the furthest advanced of the co-utilisation technologies. Test firings in commercial boilers have been very encouraging in that adverse effects have been minor or even beneficial. It is encouraging that a number of power plant owners have considered the various technologies worthy of assessment. Further utility-scale testing of wood in US pulverised coal boilers, and straw and wood co-firing in pulverised coal boilers in Europe would be beneficial in increasing the attractiveness of the technologies.

Pulverised coal mill capacities are decreased by co-grinding of wood with coal. This has the effect of limiting the degree of co-firing that is possible in retrofits and removes the normal margin of mill redundancy. Wood has apparently often required surprisingly fine grinding for such a reactive fuel to achieve satisfactory burnout (<1 mm). There is recent evidence from Holland that this may be on the conservative side and investigations of the combustion of larger size particles would be valuable in confirming this. If less milling were needed, there may be the possibility of avoiding the availability penalty of lost mill redundancy.

The issues that could arise in co-firing of pulverised coal boilers include possible corrosion and deposition as a result of the higher chlorine and/or potassium concentrations in many biomass/wastes. Similar boiler degradation effects are, in principle, applicable to other types of boiler. Although straw-burning boilers are becoming established in parts of Europe, co-firing introduces the possibility of greater materials problems as the high chlorine content of some straws can act as a promoter of sulphate (from the coal) degradation mechanisms. Long-term tests of these effects are therefore necessary before co-firing is applied to relatively new boilers. Another possible technical issue that is probably readily resolvable, concerns, in pulverised coal systems, achieving a consistently low carbon-in-ash level by maintaining high combustion efficiency, without the need to increase excess air levels, which themselves reduce boiler efficiency and increase auxiliary power requirements.

There have been only limited tests with co-firing in pulverised coal boilers fitted with flue gas desulphurisation and selective catalytic reduction equipment. There is some evidence from these tests of a possible FGD performance fall-off due to contaminating materials from the biomass affecting limestone reactivity and the catalytic activity of deNOx SCR catalysts. Both of these aspects require further research and plant trials since any doubt here, unless resolved, could tend to restrict further uptake of co-firing.

To date, environmental performance of biomass/waste co-utilisation systems appears to be good, from the indications. NOx and SO_2 emissions are often lower than levels generated by firing 100% coal. However, sewage sludge may increase emissions, especially SO_2 levels. Optimum firing systems for NOx minimisation need to be confirmed from further large-scale combustion trials.

The fate of certain trace elements in biomass and wastes has not been fully established. Confirmation of the fate of dioxins from straw co-firing in pulverised coal boilers and of the non-leachability of residues that contain higher levels of heavy metals is required before more commercial uptake occurs. The dioxins that would be expected to be produced appear to be destroyed in the high temperatures within the furnace and the heavy metals appear to be trapped within the ash. Further leaching tests will be needed to confirm first indications that the heavy metals do not escape. The ash carbon content from pulverised coal boilers has generally been found to increase slightly as noted above. This could probably be avoided through optimisation of individual burner systems. In may transpire that there are minimal problems with ash generated from co-firing applications; generally, such ashes have been found to meet the specifications for use in construction products.

6.2 Indirect Utilisation Technologies

Biomass/waste/coal conversion (indirect) technologies are not yet a mature technology and further R&D and demonstrations are required before they can be regarded as commercially-proven. However, experience already gained with the first large demonstration coal-based IGCCs is highly relevant and these installations could be adapted to incorporate biomass with feed coal as a rapid route to proving the co-utilisation technology.

The corrosion of combustion turbines fired on fuel gas from co-gasification of biomass/wastes and coal is unlikely to be a problem where cold gas cleaning is employed. However, thermal efficiency improvements could be achieved by firing the product gas while it is still hot. This requires the use of hot gas cleaning to remove not only particulates, but also the alkali metal aerosols that are harmful to turbine blades. Hot gas cleaning is still being developed for 100% coal-fired IGCC systems and more development is needed to ensure that the gases from co-utilisation can be cleaned sufficiently well in order for them to be used in such systems without turbine damage.

6.3 Risks and Barriers to Technology Deployment

From the test programmes carried out on co-firing in power station boilers, it is considered that there is only a relatively small risk that one or more of the technical issues noted could emerge as a major obstacle in, for example, causing excessive plant degradation, poor environmental performance or unsalable ash. However, the introduction of any form of new technology can be affected by political and public misperceptions. Thus, waste incineration plants have been the focus of much public attention regarding possible emissions of heavy metals and, especially, dioxins. Similar fears could also impact on the perceived environmental impact of co-utilisation schemes, and could potentially impede their deployment. However, it seems likely that the use of a “green” biomass feedstock would meet with greater acceptance.

There may also be public concerns regarding the acceptability of wastes generated. These may include concerns over the leaching of heavy metals into watercourses from concrete or other materials prepared using co-utilisation ash, or the use of ashes as soil improvers. As always with issues of perception, even small technical uncertainties must be clarified so that the public can be presented with a credible argument regarding the safety of using the material or process.

Experience already gained with coal-fired IGCC is encouraging and there are no significantly greater risks in progressing to biomass/waste co-utilisation. Initial installations could use cold gas cleaning. If hot gas cleaning is selected, some additional risk will arise from the enhancement of volatile species due to the higher chlorine content of many biomass feedstocks. However, hot gas clean-up development programmes, in tandem with those on 100% coal feeds, should be able to reduce this risk to an acceptable level.

Achieving satisfactory fuel quality will be vital and will require the establishment of mechanisms for safeguarding co-utilisation equipment. For example, potassium concentrations, resulting from fertiliser additions to biomass crops, may require monitoring and controlling.

The establishment of reliable supplies of biomass/waste fuels to co-fuel a utilisation system is important. New coal utilisation systems, perhaps based on gasification of biomass/coal mixtures followed by combined cycle power generation, will involve the expenditure of large capital sums that will require repaying from income generated by power sales. Even retrofits of biomass or dried sewage sludge handling systems to existing power stations will require significant investments. This means that the first consideration of the plant owner, after establishing the existence of a market for the installation’s prime product, will concern biomass/waste availability over sufficient time to cover repaying the loan. This may be relatively easy to guarantee at certain locations, eg. in parts of the United States where vast quantities of forest and wood processing wastes are produced each year, but dependence on a regular surplus in a straw harvesting may be less certain. This degree of risk can be mitigated through ensuring that plant could also accommodate 100% coal firing. As with all risk reduction strategies, this necessarily incurs additional cost.

Where energy farms producing non-woody biomass for co-utilisation are established in the future, it may prove necessary for high loadings of fertilisers to be used in order to ensure high crop yields. There are two complications that could arise. On the environmental front, there is the potential of watercourse contamination with nitrate runoff, requiring remedial measures to be taken by water supply companies. An additional issue is that fertiliser production is generally energy intensive. Thus, arguments for substituting biomass for some of the coal on the grounds of CO_2 reduction would be weakened. Short rotation coppice production would be preferable, as it requires less fertilising although more watering may be needed.

At present, it appears likely that initiatives to establish co-utilisation schemes, as for 100% biomass utilisation systems, will be driven by commitments of governments who have taken on international obligations to relieve environmental pressures such as pumping of sewage to sea, the excessive use of landfill, and the emission of fossil fuel-based CO_2. These environmental objectives will probably need to be backed initially by subsidies, power selling price support mechanisms, or tax credits in order to encourage projects to proceed. From a technical standpoint, there are several co-utilisation options currently proven and the associated risks are deemed to be acceptable. However, the availability of public funds as an aid in establishing such technologies could be a constraint on their deployment. OECD economies may consider it worthwhile encouraging co-firing in the form of assistance in financing of projects in less developed countries.

7.0 CONCLUSIONS

1. Co-firing has emerged from niche applications to a broader commercial availability, often as a low-cost means for using biofuels in existing generation systems. Although co-firing does not generally add generating capacity to an installation, co-firing can be implemented in a manner that does not reduce overall capacity and, simultaneously, can be employed where appropriate to achieve both economic and environmental benefits.

2. The different sources of statistics on potential reserves of biomass/wastes are frequently ill-defined, largely as a consequence of the variability of such materials. However, the data confirm that, potentially, there are enormous reserves that could be utilised for energy production applications.

3. Three and a half billion tonnes of hard coal, plus 1.25 billion tonnes of lignite/brown coal are produced globally each year. Of these, half of the hard coal and two thirds of the lignite/brown coal are used for power generation The huge installed capacity of coal-fired power plant consumes 50,000 PJ of coal annually; if this capacity was co-fired at a rate of 10% (thermal) input, this would require 5,000 PJ of biomass/wastes per year. In order to achieve this level, there are obvious criteria that would need to be met. For instance, the proximity of biomass/wastes supplies to power stations or other potential co-utilisation sites would influence the scope for market size. On the basis of this and the potential biomass/waste fuel production potential analysed above, it is considered that significant growth in the co-utilisation markets could occur; co-firing levels could reach ~500 PJ/year in existing coal-fired generating installations, equivalent to 10% of existing capacity being modified to take 10% thermal input of biomass/wastes. New plant could increase this further.

   Industrial and commercial applications also account for significant current coal use (eg. 8% of OECD coal use and 30% of China's coal use, excluding iron and steel production). Introduction of a co-utilisation element could create significant additional markets, perhaps ~50 PJ or more per year.

4. Significant expansion in biomass/waste use *via* co-utilisation therefore appears realistic, provided the costs of biomass are not too high and that workable mechanisms can be developed for adopting accounting systems that address the environmental costs of generation.

5. There is various international environmental legislation that requires substantial reduction in the production of greenhouse and acid gases; part of their mitigation could be achieved through the reduction in the proportion of fossil fuels utilised for energy production. The utilisation of these energy streams could take place in purpose-designed plant, for which many countries have subsidised support programmes, such as NFFO in the UK. Alternatively, it could take place in existing coal-fired plant in a co-fired application. The advantages of the latter route include:

   - There is an established market for the heat and power produced.
   - A relatively small capital investment would be required, compared to those for new plant dedicated solely to biomass processing.
   - There are generally favourable impacts on overall emissions from the coal-fired plant.

6. The technology review indicates that there are a number of industrial and utility coal technologies that have the potential to co-fire coal and biomass and waste. These technologies include:

- Pulverised coal plant
- CFBC
- BFBC
- Cyclone combustors
- stokers
- advanced coal gasification-based plant,
- carbonisation plant.

For some of the technologies (BFBC, CFBC and cyclone burners) co-fired plant can be regarded as commercially-proven, with off-the-shelf designs available.

7. Pulverised fuel plant comprises the largest installed capacity for coal use in the world. The technology is suitable, with limited modification, for co-firing. Therefore, pulverised coal installations represent the single largest potential market for co-firing. The near-term market potential is for retrofitting existing pulverised coal installations in order to accommodate new biomass/waste handling plant and burner systems.

8. Published cost data on processes and on the costs of biomass vary widely. Moreover, the economics of co-utilisation are heavily dependent on various assumptions. A significant factor can be the higher cost of biomass feedstocks. Currently, dried sewage sludge does not have a selling price, since it is normally disposed of at a cost. Therefore, economically, it is potentially more attractive as a gate fee could be charged. Other wastes such as MSW, tyres etc, are also of zero/negative cost. However, if there are to be large numbers of commercial-scale co-utilisation projects, many are likely to be reliant on energy crops, specifically grown for the purpose. It is by no means certain that the selling price of such materials will fall. Support mechanisms are therefore necessary so that governments shoulder part of the risk. A possible form of guaranteed support mechanism could be a credit for replacement of fossil fuel-derived carbon dioxide, since carbon dioxide abatement is the ultimate aim of many biomass projects. An alternative mechanism could be in the form of guaranteed power selling prices similar to the NFFO in the UK. In the absence of such measures, the uptake of biomass-based co-firing is likely to be restricted as costs can be greater than for 100% coal firing.

9. Most economic analyses have been carried out on wood or straw co-utilisation for power generation. The commercial-scale tests have indicated that technical risks are not unduly high. New plant, eg. based on gasification for combined cycle power generation, will need to be constructed with sufficient coal supply systems to ensure that 100% use of coal at full rating is possible, as there must be a degree of risk attached to the certainty of the biomass feedstock being available over the station's lifetime.

10. In all of the co-utilisation technologies considered, there are technical problems and limitations that have not yet been fully resolved. However, it is considered that none of the perceived technical issues are unresolveable and that with continued R&D these technical risks can be overcome.

11. A number of barriers to the deployment of co-firing technology have been identified that include:

- Public perception of the plant in question as a consequence of the stigma associated with the use of waste-derived feedstocks; this could compromise planning procedures.
- Additional gas cleaning equipment could be required if environmental legislation is tightened; this will add to capital and operating costs.
- The need for secure long-term quality controlled biomass/waste supply schemes, otherwise

plants will simply burn coal alone.

- Pricing arrangements for biomass/waste streams need to be agreed and fixed for long periods (10 to 15 years).

8.0 Recommendations

5. The area of biomass and waste co-utilisation is one undergoing rapid development, with many potential fuels being investigated by the utility operators. Unfortunately, many of these trials are being undertaken under rules of commercial confidentiality, and it has not been possible to include them in this study. It is recommended that an update to this review is undertaken in approximately six to twelve months time to incorporate the results of the most recent trials where information has passed into the public domain (e.g. through Member States' environmental monitoring and control agencies)

6. A considerable body of expertise has been developed across the European Union in techniques for the co-utilisation of biomass and waste, and equipment for dealing with the specific problems that these fuels pose. It is considered that this expertise represents an opportunity for EU companies and organisations to market their skills and capabilities in the developing markets (e.g. China, India) where co-utilisation has yet to become firmly established. It is recommended that a first step to exploiting this opportunity might be through a series of workshops or seminars presenting the results of EU experience to invited potential customers and policy makers in appropriate locations within the developing world.

7. The largest market for the co-utilisation of biomass and waste lies in exploiting the huge installed capacity for power generation from pulverised coal. Despite the significant work that has already been undertaken on co-combustion of coal and biomass/waste, a number of technical issues require further work (e.g. reliable handling systems for biomass and waste fuels). It is recommended that these issues remain a priority for support within EU research programmes.

8. This review has concentrated largely on the technical issues associated with the co-utilisation of biomass and waste. However, the economic viability of a successful co-utilisation process is highly dependant upon local conditions, such as the availability of fuel without incurring excessive transportation costs, and EU and Member State legislative and taxation policy (e.g. landfill tax levels, recent and forthcoming EU Directives). It is recommended that this study is complimented with a comprehensive review of these legislative and taxation drivers.

9.0 REFERENCES

1 *EU Focus on Waste Management*. EC Publication. ISBN 92-828-4826-6. 1999. p7.

2 I Rasmussen et al. CFB Grenaa demo-*testing at enhanced straw input*. APAS Clean Coal Technology Programme. v2. ISBN 3-928123-16-5.

3 J van Doorn et al. *Combined Combustion of Biomass, Municipal Sewage Sludge and Coal in an Atmospheric Fluidised Bed Installation*. APAS Clean Coal Technology Programme. v2. ISBN 3-928123-16-5).

4 T Saksa. *Large scale production of wood chips from forest for energy*. Proc. 9th European Bioenergy Conference. Copenhagen. 1996. pp873-877.

5 M J T Laihanen et al. *A model for wood-fuel supply and production costs in the forest industry*. Proc. 9th European Bioenergy Conference. Copenhagen. 1996. pp992-997.

6 H B Probst. *Co-combustion of sewage sludge and coals*. APAS Clean Coal Technology Programme. v2. ISBN 3-928123-16-5.

7 W Adloch et al. *Use of sewage sludge in the HTW process*. APAS Clean Coal Technology Programme. v III. ISBN 3-928123-15-7.

8 Data abstracted from *EU Focus on Waste Management*. EC Publication. ISBN 92-828-4826-6. 1999. p9.

9 L Hietanen et al. *Processing of energy-rich packaging wastes for thermal recover*y. Proc. 9th European Bioenergy Conference. Copenhagen. 1999. pp948-953.

10 European Energy to 2020. A Scenario Approach. DG XVII Publication. ISBN 92-827-5226-7. 1996.

11 F Bauer. *Combined Combustion of Biomass/Sewage Sludge and Coals of High and Low Rank in Different Systems of Semi-industrial and Industrial Scal*e. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste. APAS Contract COAL-CT92-0002. Volume II:Final Reports. 1995.

12 Kelsall, G J and Laughlin, K. *The Development of Co-Gasification for Coal/Biomass and for other Coal/Waste Mixtures*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002. Volume III. Final reports. 1995.

13 Hey, W., Pelz, W., Romey, I. and Sowa, F. *Combined Combustion of Biomass/Sewage Sludge andCoals of High and Low Rank in Different Systems of Semi-Technical Scale*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

14 Morgan, D J. and van de Kamp, W L. *The Co-firing of Pulversied Bituminous Coals with Biomass and Municipal Sewage Sludge for Application to the Power Generation Industry*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

15 Meschgbiz, A. and Krumbeck, M. *Combined Combustion of Biomass and Brown Coal in a Pulverised Fuel and Fluidised Bed Combustion Plant*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

16 Kierkegaard Petersen, S C K and Hansen, K I. *Co-firing of Straw and Design Study and Test Cofiring of Wood in Pulverised Coal Fired Boiler I/S Vestkdraft, Unit 1*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Report, 1995.

17 Andries J, Vegelin R J and Verloop C M. *Co-combustion of Biomass and Coal in a Pressurised Fluidised Bed Combustor.* Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002. Final Reports. 1995.

18 Rasmussen, I and Overgaard, P. *Recent Results Concerning Co-combustion of Biomass and Coal*. Proceedings of the 9th European Bioenergy Conference, Vol. I. Copenhagen, Denmark, June 1996, Pergamon Press.

19 Tumbull, J H. Co-combustion of Solid Biomass. Paper presented at NOVEM/IA Symposium Cocombustion of Biomass, Nijmege, The Netherlands, 8 November, 1995.

20 Boylan, D M. *Southern Company Tests of Wood/Coal Co-firing in Pulverised Coal Units*. Biomass and Bioenergy, Vol 10, Nos2-3, page 139, 1996.

21 Gast, C H and Visser J G.*The Co-combustion of Waste Wood with Coal. Effects on Emissions and Fly-Ash Compositio*n. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

22 Kicherer, A., Gerhardt, Th., Spliethoff, H. and Hein, K. R. G. *Co-Combustion of Biomass/Sewage Sludge with Hard Coal in a Pulverised Fuel Semi-Industrial Test R*ig. Final Report, page 5: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Report, 1995.

23 Abbas, T., Costen, P., Glaser, K., Hassan, S., Lockwood, F. and On, J-J. *Combined Combustion of Biomass, Municipal Sewage Sludge and Coal in a Pulverised Fuel Plant*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

24 Probst, H H and Wehland, P. *Combined Combustion of Biomass/Sewage Sludge and Coals.* Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

25 Adlhoch, W, Hoffinann, H, Klossek, K and Schiffer, H-P. *Use of Sewage Sludge in the HTW Process*. Final Report: European Commission APAS Clean Coal Technology Programme on Coutilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume III: Final Reports 1995.

26 Kelsall, G J and Laughlin, K. *The Development of Co-Gasification for Coal/Biomass and for other Coal/Waste Mixtures*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002. Volume III. Final reports. 1995.

27 Anon. *Experience base grows for co-firing waste fuels*. Power. October 1993. 45-47.

28 Barnes J E and Jauhiainen E. *Managing Pulp and Paper Mill Wastes Using Bubbling Fluidised Bed Technology*. Power-Gen America Conference. Orlando. December 7-9. 1994.

29 Patterson, W. Power from Plants. The Global Implications of New Technologies for Electricity from Biomass. Earthscan Publications and Royal Institute of International Affairs, London. 1994. Johansson, T B et al: Renewable Energy: Sources for Fuel and Electricity. Island Press/Earthscan, 1993.

30 Tillman, D., Hughes, E., Gold, B.A. *Co-firing of Biomass in Coal Fired Boilers: Results of Case Study Analysis*. Paper presented to First Biomass Conference of the Americas, Burlington, USA, 1993.

31 Ibid

32 Berge, N., Carlsson, M., Kaliner, P and Stromberg, B. *Reburning of a Pulverised Coal Flame with a LCV Gas*. Final Report: European Commission APAS Clean Coal Technology Programme on Coutilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume III: Final Reports, 1995.

33 Meschgbiz, A. and Krumbeck, M. *Combined Combustion of Biomass and Brown Coal in a Pulverised Fuel and Fluidised Bed Combustion Plant*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

34 Morgan, D J. and van de Kamp, W L. *The Co-firing of Pulversied Bituminous Coals with Biomass and Municipal Sewage Sludge for Application to the Power Generation Industry*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

35 Abbas, T., Costen, P., Glaser, K., Hassan, S., Lockwood, F. and On, J-J. *Combined Combustion of Biomass, Municipal Sewage Sludge and Coal in a Pulverised Fuel Plant*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

36 Lutge C et al. *New applications for High Temperature Winkler Gasification (HTW) for thermal treatment of municipal solid waste and sewage sludge in combination with Catalytic Extraction Process (CEP).* Gasification Technologies Conference. October 1996.

37 Tilman, D A, Hughes, E and Gold, B A: Co-firing of Biomass in Coal Fired Boilers: Results of Case Study Analysis. Tillman, D., Hughes, E., Gold, B.A. *Co-firing of Biomass in Coal Fired Boilers. Results of Case Study Analysis*. Paper presented to First Biomass Conference of the Americas, Burlington, USA, 1993.

38 Swanekamp, R. *Biomass co-firing technology debuts in recent test burn*. Power. February, 1995, page 51.

39 McGowin, C R and Hughes, E. E. Efficient and Economical Energy Recovery from Waste by Cofiring with Coal. ACS Symposium Series No 515: Clean Energy from Waste and Coal, edited by Kahn, MR, 1992. Power/Internet, 1996.

40 McGowin, C R and Wiltsee, G A. *Strategic Analysis of Biomass and Waste Fuels for Electric Power Generation.* Biomass and Bioenergy, Vol 10, Nos 2-3, page 167, 1996.

41 Beekes, M L. *Test Facilities and Trials for Pre-treatment and Co-combustion*. Paper presented at NOVEM and TEA International Symposium on Co-combustion of Bio-fuels, Nijmegen, Netherlands, November, 1995.

42 Bestebroer, S I, Smakman, G J J and Kwant, K W. *Biomass to energy looks promising for the Netherlands*. Power Engineering International, November/December, 1996, page 30.

43 Sundermann, B., Rubach, T and Rensch, H P. *Feasibility Study on the Co-Combustion of Coal/Biomass/Sewage Sludge and Municipal Solid Waste for Plants with 5 and 20 MW Thermal Power Using Fluidised Bed Technology*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

44 Bauer, F. *Combined Combustion of Biomass/Sewage Sludge and Coals of High and Low Rank in Different Systems of Semi-industrial and Industrial Scale*. Final Report: European Commission APAS Clean Coal Technology Programme on Co-utilisation of Coal, Biomass and Waste, APAS Contract COAL-CT92-0002, Volume II: Final Reports, 1995.

45 Mosbech, H. *Biomass Use in Large Power Plants. Point of View of a Utility*. Paper presented to Final Conference of European Commission APAS Clean Coal Technology Programme on Coutilisation of Coal, Biomass and Waste, Lisbon, November, 1994.

46 Department of Energy: Review of Thermochemical Biomass Conversion. Contractor Report. ETSU.B 1202.

47 Exelby, D R and Davison, J E. *A Technical and Economic Assessment of Co-Gasification of Straw or Sewage Sludge with Coal in Conceptual Commercial Plants*. Confidential CRE Report. Assessment Report No. 94/10.

48 EPRI Journal. May/June 1996.

49 Ekmann, J M., Smouse, S M., Winslow, J C., Ramezan M and Harding, N S. edited by Morrison, G F. *Cofiring of coal and waste*. IEA Coal Research, London. IEACRI9O, August, 1996.

50 Krebs, K.H. *A prospective Assessment on the Role of Renewables energies in Response to the* CO_2 *Problem*. Report to the Forward Studies Unit of the CEC, Institute for Prospective Technological Studies, Seville, 1995.

51 Ekmann, J M, Smouse, S M, Winslow, J C, Ramezan M and Harding, N S, edited by Morrison, G F. *Co-firing of coal and waste*. IEA Coal Research, London. IEACRI9O, August, 1996.

52 Patterson, W. *Power from Plants. The Global Implications of New Technologies for Electricity from Biomass*. Earthscan Publications and Royal Institute of International Affairs, London. 1994.

53 Johansson, T B et al. *Renewable Energy: Sources for Fuel and Electricity*. Island Press/Earthscan, 1993.

54 Trebbi, G, ENEL. *Power Production Options from Biomass*. ENEL: Final Seminar of the JALO Programme, Espoo, Finland, December, 1992.

55 W S Atkins and Partners and International Forest Science Consultants: *Wood Utilisation Systems -Combustion Strategies*. ETSU-B-1 122, 1984.

56 FEC Consultants Ltd: *Forestry Waste Firing of Industrial Boilers*. ETSU-B-1 178, March, 1990.

57 Anon, EPON Project Summary Brochure: *Co-combustion of Pulverised Wood in the Netherlands*, 1995.

58 FEC Consultants Ltd: *Straw Firing of Industrial Boilers*. ETSU-B- *1158,* April, 1988.

59 *Assessment of Solid Waste Arisings and Potential for Use in Energy-From-Waste Schemes*:

60 Estimates for UK Electricity Company Areas. Study by MEL Research, Birmingham, for ETSU, 1996.

61. L' Hennite, P and Ott, H: Recycling International, Freitag Verlag Berlin, page 342, 1982.

62. Harrison, J S. *A UK and World Overview*. Paper to Combustion Engineering Association Conference: Coal, New Standards, New Challenges, UK, 1992.