ENERGY FROM BIOMASS

Summaries of the Biomass Projects carried out as part of the Department of Trade and Industry's New and Renewable Energy Programme

VOLUME 3: CONVERTING WOOD FUEL TO ENERGY

ETSU BM/04/00056/REP/1

Edited by
Scribe Writing and Editing Service

Published December 1998

INTRODUCTION

These volumes of Summaries provide easy access to the many projects carried out in the Energy from Biomass programme area as part of the Department of Trade and Industry's New and Renewable Energy Programme.

The Summaries in this volume cover contractor reports on the subject published up to December 1997.

REPORTS SUMMARISED IN VOLUME 3[1]

Report No	Title	Contractor	Publ. date	Page No
1. COMBUSTION				
1.1 Potential and Costs				
ETSU L/3	Energy from the combustion of wastes	Dr A Brown, ETSU	1984	5
ETSU B 1178	Forestry waste firing of industrial boilers	FEC Consultants Ltd	1990	8
ETSU B/M5/00488/04/REP	Wood as a domestic heating fuel	CRE	1995	11
ETSU B/M5/00488/22/REP	Wood fuelled boiler operating costs	LRZ Ltd	1995	14
ETSU B/M5/00533/27/REP	Review of biomass-fired space heating/domestic hot water boilers' application, operation and design parameters	Energy and Environmental Software Support Services	1997	17
1.2 Emissions Issues				
ETSU B 1313-P4	An emissions audit of a biomass combustor burning treated wood waste	Warren Spring Laboratory	1993	21
ETSU B/MS/00192/05/REP	Economic assessment of emissions abatement for small-scale waste combustion	ECOTEC Research and Consulting Ltd	1993	24
ETSU B/M3/00388/25/REP	Smoke emissions from a catalytic wood stove	CRE	1994	28
1.3 Relevant Case Studies				
ETSU B/1171 - P1	Monitoring of a commercial demonstration of harvesting and combustion of forestry wastes	Ove Arup & Partners	1989	31
ETSU B/M5/00488/05/REP	The West Dean wood-fuelled district heating scheme	The Edward James Foundation FEC	1995	34
ETSU B/U1/00531/REP	The commercial prospects for wood-fired combined district heat and power in Newcastleton in the Scottish Borders	Border Biofuels Ltd	1997	37
2. THE CO-FIRING OPTION				
ETSU B/M5/00488/26/REP	Options for the co-processing of coal and biomass in power generation	CRE Group Ltd	1995	41
ETSU B/U1/00417/REP	Co-firing wood with coal in utility boilers	International Combustion Ltd	1996	44
ETSU B/U1/00535/REP	Co-firing biomass with coal - power plant case study	PowerGen plc	1997	48

[1] Items in italics are archived

Report No	Title	Contractor	Publ. date	Page No
3. THERMAL CONVERSION				
3.1 The Technologies				
ETSU B 3118 B	*Conversion of biomass to fuels by thermal processes. Phase 1: Review and preliminary assessment*	*Ader Associates*	*1978*	*51*
ETSU B 1042 A [FR]	*Conversion of biomass to fuels by thermal processes. Phase 2A: Optimisation studies for conversion to methanol*	*Ader Associates*	*1980*	*54*
ETSU B 1042 B [FR]	*Conversion of biomass to fuels by thermal processes. Phase 2B: Optimisation studies for conversion to methane*	*Ader Associates*	*1980*	*57*
ETSU B 1042 C [FR]	*Conversion of biomass to fuels by thermal processes. Phase 2C: Optimisation studies for conversion to liquid hydrocarbons*	*Ader Associates*	*1980*	*59*
ETSU B 1202	Review of thermochemical biomass conversion	Energy Research Group, Chemical Engineering and Applied Chemistry Department, Aston University	1991	62
ETSU B/T1/00207/REP	An assessment of thermochemical conversion systems for processing biomass and refuse	Aston University DK Teknik (Denmark)	1993	66
ETSU B/T1/00208/REP/1	Fundamental research on the thermal treatment of wastes and biomass: Literature review of past research on thermal treatment of biomass and waste	Warren Spring Laboratory	1993	69
ETSU B/T1/00208/REP/2	Fundamental research on the thermal treatment of wastes and biomass: Thermal treatment characteristics of biomass	Warren Spring Laboratory	1993	72
3.2 The Potential for Gasification				
ETSU B 1167	*Technical and market assessment of biomass gasification in the UK*	*Aston University*	*1986*	*75*
ETSU B/M3/00388/04/REP	Downdraft gasifiers under 200kW$_e$	LRZ Ltd	1993	79
ETSU B/T1/00351/REP	Decentralised production of electricity from biomass	Natural Resources Institute	1996	82
ETSU B/M5/00533/09/REP	Small-scale biomass CHP using gas turbines: a scoping study	James Engineering (Turbines) Ltd LRZ Ltd	1996	85

1. COMBUSTION

1.1 Potential and Costs

Report No: ETSU L/3 Publication date: 1984

ENERGY FROM THE COMBUSTION OF WASTES

Dr A Brown, ETSU

Background

Although wastes and other biological materials have been used as fuel for many years, a renewed UK interest in this technology has arisen with the increase in fuel prices and the problems of disposing of wastes in an economic and environmentally acceptable way.

Waste combustion could generate energy savings equivalent to as much as five million tonnes of coal per year. However, lack of experience of waste preparation and combustion has made industry reluctant to invest in what are seen as technically and commercially risky projects. The Department of Energy has therefore been supporting work to identify, develop and demonstrate effective ways of using waste as fuel.

Report Objective

- To examine the types and quantities of suitable wastes available in the UK and their properties in relation to combustion.

Findings

Most dry wastes in the UK fall into one of three categies:

- industrial and commercial wastes handled by private disposal contractors
- domestic, municipal and some commercial wastes handled by waste disposal authorities
- agricultural residues such as straw and wood.

These wastes differ from conventional fuels in several ways:

- lower calorific value
- high volatile content and lower fixed carbon content than coal
- lower bulk density
- irregular shape and often awkward size
- less consistent.

There is therefore a need for specialist combustion equipment or modified coal-burning systems. The option selected will depend on the scale of operation required, but capital costs will tend to be up to more than twice the cost of an equivalent coal system. Nevertheless,

with many wastes available at zero or negative cost, the return on investment can still be attractive.

Industrial and commercial wastes

The on-site use of many general industrial wastes - broken pallets, used stationery, packaging plastics etc - is often appropriate, and most projects are likely to have a payback of between two and four years. However, the combination of efficient operation, an adequate rate of return and environmentally acceptable performance requires a scale of operation of more than 10 tonnes of waste per week.

Domestic waste

Most domestic and some commercial waste is collected by local district councils and disposed of to local landfill sites (the cheapest option). However, in most metropolitan areas there is a shortage of appropriate sites, and wastes have to be transported considerable distances, greatly increasing the cost of disposal. Using the energy content of the material is therefore an attractive alternative option.

Mass burn incineration, although well established in Europe and the US, has acquired a poor reputation in the UK, and there are only four incinerators in the UK from which heat is successfully recovered. Work is now in progress that aims to use refuse after pre-treatment, a route that seems to be more economically attractive.

Coarsely prepared waste is already being used to replace around 30% of the coal in two adapted coal-fired chain grate stokers, each providing 70,000 lb/hour of steam for industrial use. Plant combustion efficiency does not appear to be adversely affected, nor is there any evidence of increased rates of boiler fouling or corrosion.

Work in progress is designed to produce a refined refuse-derived fuel (rdf) that is suitable for use in much smaller boilers. The hard, stable pellets produced have a calorific value about 60% that of coal, and trials have shown that the fuel can be burnt in a satisfactory way. As rdf becomes more routinely available, further trials are planned covering a range of boiler types. The production and sale of rdf would appear to be economic for local authorities whose alternative waste disposal route costs £11/tonne or more. Around 20% of the refuse handled in the UK already incurs costs greater than this. A plant designed to produce steam at the rate of 25,000 lb/hour from rdf, and supplied with rdf at a cost of £22/tonne, would repay the £600,000 investment in three years if it replaced a gas-fired plant purchasing gas at 27p/therm.

Agricultural wastes

Considerable quantities of agricultural residues that are sufficiently dry to burn (eg straw and waste wood) are generated in the UK. The technical problems of using these more consistent, low-ash products are less serious than those encountered with refuse, and a wide range of technology is already available to encourage their use.

Around half of the 13 million tonnes of *straw* produced each year is burnt in the fields. It has an energy content equivalent to some 3.5 million tonnes of coal per year and could, in principle, be collected and used for fuel. Straw is already widely used for farm heating, and its use for steam-raising in rural industry would appear to be a viable option.

Even baled, straw is a bulky commodity with high transport costs that needs to be used locally. Nevertheless, a feasibility study carried out recently showed that, despite the higher capital costs of straw-burning plant, the installation of a 15,000 lb/hour straw-fired steam boiler offered a payback period comparable to that for a coal-fired system.

By treating the straw further to produce densified pellets or briquettes, it should be possible to reduce transport costs and open up wider markets for straw as fuel. At present, only the production of briquettes for use on domestic fires is likely to be viable, although certain technical problems remain to be resolved.

There are three main sources of *wood residues* that can be used as fuel: forestry wastes, bark and other sawmilling wastes, and sawdust and off-cuts from the processing (eg furniture) sector (secondary residues). The use of dry secondary residues as fuel is already well established for space and process heating. Forestry wastes are a less attractive proposition because they are wetter, more variable and often in a form that is not easy to handle. Nevertheless it is estimated that 500,000 tonnes of forestry wastes and 40,000 tonnes of sawmill waste could be recovered for fuel, although use is likely to be limited geographically.

Conclusions

It is clear that the use of waste offers considerable potential as a means of reducing energy costs and minimising waste disposal problems. While the technology is attractive, there are still technical lessons to be learnt, and the Department of Energy's programmes in this area are designed to assist in identifying, developing and demonstrating worthwhile opportunities.

Report No: ETSU B 1178 Publication date: 1990

FORESTRY WASTE FIRING OF INDUSTRIAL BOILERS

FEC Consultants Ltd

Background

Normal forestry practice generates residues during harvesting, some of which (tops and branches) can be recovered. It is also feasible to plant and manage forestry with the aim of producing both conventional forest products and energy products. Forecasts suggest that the harvestable yield of forestry residues in the UK will amount to 2.17 million tonnes/year by 2000.

Project Objectives

- To identify the most appropriate technologies for the commercial/industrial-scale combustion of forestry waste fuels.

- To investigate the use of forestry wastes as a partial or total replacement for coal in existing coal-fired combustion plants.

Methodology

The project was carried out in several phases:

1. A review of current technology.

2. Laboratory trials to determine the physical, chemical and combustion characteristics of forestry residues. This involved assessing numerous samples of forestry waste for carbon, volatile matter, moisture, ash and sulphur content; calorific value; ash properties etc. The samples came from various tree species and were obtained using a range of harvesting techniques. A laboratory investigation into the combustion mechanism of forestry waste and forestry waste/coal mixtures was also carried out.

3. Boiler plant trials. Initial trials were undertaken using systems designed specifically for use with biofuels such as forestry waste and conventional combustion equipment. Fully monitored combustion trials were then undertaken on the most promising systems to assess handling and combustion under normal plant operating conditions.

The project also incorporated an assessment of the economics of forestry waste as a fuel.

Findings

State of the art

Forestry and wood wastes have been used as a fuel for many years. The increase in their use for this purpose since 1960, particularly in Sweden and Canada, has been encouraged by improvements in forestry practice and by the rise in oil prices that has taken place.

Forestry waste, usually in chipped form, now makes a significant contribution to Sweden's energy requirements and is the main fuel in many district heating boiler plants. Government aid and grants have supported the installation of purpose-designed equipment which tends to be more costly than conventional fossil-fuel-fired plant. As a result, boiler designs have been developed to suit the particular properties of locally available wood fuel, and options exist for burning both dry and wet fuels. These purpose-designed combustion systems are available for use in the UK.

Wood fuel characteristics

Laboratory trials have shown that forestry waste is a low-grade fuel when compared with coal. It has a high volatile content and a low gross calorific value - typically 19.8 MJ/kg (dry ash free). The ash content is low when compared with coal - typically 0.4-2.0% by weight, although higher values do arise and tend to be associated with soil contamination during harvesting. The sulphur content of wood is very low (0.1% on average): sulphur emissions for a given plant output would be less than 20% of those for a coal-fired plant, and back-end corrosion as a result of high acid dew points is unlikely to occur.

The moisture content of forestry waste is high, ranging from around 30% to 60% by weight. A typical moisture content for fuel delivered to a commercial heating plant is around 40%. This means that considerable drying takes place in the boiler plant prior to ignition, and this has a significant effect on the heating value of the fuel.

The trials have also shown that ignition of forestry wastes takes place at a lower temperature than for coal. This is followed by the rapid evolution of volatiles and complete burnout, again at lower temperatures than for coal. The correct provision of secondary air is necessary for complete combustion.

The low bulk density and low calorific value of forestry waste means that between 9.5 and 12 times as much wood as coal is required (by volume) to generate the same net energy content. This has implications for fuel storage, handling and combustion system design.

Combustion systems

The most successful of the purpose-designed combustion systems for use with high moisture content forestry waste employ refractory-lined pre-combustion furnaces for the effective drying and ignition of the wet fuel. Secondary air systems are also used to ensure effective combustion of the high volatile content of the fuel.

Two conventional combustion systems, the underfeed stoker and the chain grate stoker, were found to be unsuitable for use without extensive modifications. Such modifications would entail either stoker replacement or excessive boiler derating.

Of the other conventional systems tested, only the low ram coking stoker was found to be suitable for use with forestry wastes without excessive modifications. This was primarily because the fuel feed system had been designed with low bulk density fuels in mind and was therefore not typical of coal-fired installations. The "overfeed" fuel supply to the grate promoted high ignition rates, although a supplementary premium-grade fuel such as coal is needed to maintain adequate combustion where forestry waste moisture contents are high.

Static grate combustion systems, such as the Towler water-tube boiler or the Vekos boiler, employ overfeed fuel supply techniques and are a potentially promising option for forestry waste combustion. However, fuel feed problems were encountered during the trials, and these need to be resolved.

Shallow fluidised bed combustion systems also appear to be suitable, although supplementary premium grade fuel firing is required where the forestry wastes used have a high moisture content. Switching from coal firing to forestry waste firing would require the removal of most or all of the in-bed heat transfer area to ensure the maintenance of adequate bed temperatures. This would result in derating of the boiler.

The economics of forestry waste as fuel

Forestry waste can, under certain circumstances, be an economically attractive alternative to conventional fossil fuels, even where fossil fuel prices are relatively low.

Low-cost modifications, which allow forestry wastes to be used in industrial boiler plant with conventional coal combustion systems such as the low ram coking stoker, could give a payback on capital expenditure of less than four years.

Comprehensive purpose-designed combustion systems, such as the boiler plant at Tormore (see Section 1.3, Report No: ETSU B/1171 - P1), are uneconomic because of their high capital cost and the relatively small delivered price differential between forestry waste and conventional fuels. However, the retrofitting of purpose-designed pre-combustors to suitable existing boiler plant is an economically attractive option, provided payback periods in excess of four years can be accommodated.

Recommendations for Further Work

- Further evaluation of the low ram coking stoker to optimise coal/wood mixtures.
- The development of a suitable wood and coal feed system for the Vekos boiler.
- Analyses to determine the effect of soil type on ash composition.
- The development of low-cost purpose designed plant.

Report No: ETSU B/M5/00488/04/REP Publication date: 1995

WOOD AS A DOMESTIC HEATING FUEL

CRE

Background

Around 900,000 tonnes of wood are used for fuel in the UK, and wood fuel availability could increase if set-aside land is used for forestry. A wide range of wood-burning appliances is already available, and these fall into one of two broad categories: open and closed. There are three main types of open fire: the simple dog grate, a convector unit and an open fire with a hot water boiler. Closed stoves include conventional dry wood/multifuel stoves, units with boilers, cookers (sometimes with associated boiler units) and smoke-reducing stoves. The popularity of these appliances, particularly in rural and semi-rural areas, is evidenced in the sale of 50,000 new wood or multifuel units each year.

Project Objectives

- To summarise the basic types of appliance available, with their performance characteristics.
- To review the findings of earlier work on the thermal performance of and emissions from wood-burning stoves.
- To undertake experimental work using one of each category of wood-burner to compare the performance of seasoned and unseasoned wood.

Methodology

The correct preparation (seasoning) of wood once a tree has been felled has always been an important component of good combustion. This programme has assessed the performance of two types of appliance, an open fire and a closed stove.

The open fire incorporated a double-skinned convector fire-back. Wood was burned on a layer of wood ash in a metal tray, and heat entered the room by direct radiation from the fire-bed and via the air which was warmed as it passed over the hot metal surfaces forming the inner and outer skins of the fire-back. Air flow control was limited to a slide damper at the entrance to the chimney.

The closed stove used was typical of the range of wood-burning stoves on the market. Wood was burned on a hearth of heat-resisting bricks, and air control was achieved via air slides at high and low level in the doors and via a damper at the appliance outlet.

The wood used in the tests came from a single source. Some of it was seasoned for at least one year after cutting and prior to use: the remainder was cut and collected for almost immediate use. The species burnt were beech, oak and elm, sized to comply with BS 7256, ie

a mixture of three nominal lengths (150, 200 and 250mm), with an even diameter range of 75-150mm, and with each piece split at least once.

Wood cut for almost immediate use had a moisture content of 55% and could not be burnt on either appliance. It was then partially dried in an oven to reduce the moisture content to around 40%, and the tests were repeated.

High and low output tests were carried out on the closed stove. Only high output tests were possible on the open fire. Measurements were taken of fuel charged, fuel gas composition, smoke emissions and appliance output and efficiency.

Findings

Review of earlier work

The findings of earlier work on closed stoves and a central heating cooker showed a significant variation in overall efficiency at high output (34.6-59.5%), although this variation related more to refuelling methods than to inherent stove performance. Limited testing using unseasoned wood showed that appliance output falls and smoke emissions increase with unseasoned fuel.

Volatile organic compound (VOC) emissions from the combustion of wood were more than twice those from coal briquettes, while oxide of nitrogen (NO_x) emissions were slightly higher (80 g/GJ compared with 50 g/GJ for coal, oil and gas). The negligible sulphur content of wood means that it does not contribute significantly to oxide of sulphur (SO_x) emissions.

Current tests

Appliance output

The output of the closed stove when burning correctly seasoned wood with a moisture content of 23% was 8.9kW compared with only 5.4kW when burning unseasoned logs with a 37.3% moisture content. Appliance efficiency, assessed by measuring heat losses up the chimney, were 58.1% and 47.4%, respectively.

Although the extra air drawn into the chimney by the open fire made it impossible to measure appliance efficiency accurately, average radiation output into the room was 1.36kW using seasoned logs, falling to 0.63kW using unseasoned logs.

Smoke emissions

Measurements of smoke emissions from the closed stove showed that, at high output, emission levels using unseasoned wood were almost three times those measured using seasoned logs (4.6 g/kg compared with 1.67 g/kg). However, at low burning rates, emissions were similar for both fuels, ranging between 10.14 and 13.87 g/kg.

On the open fire, the difference in smoke emission between seasoned and unseasoned wood at high output levels was even more pronounced: 2.67 g/kg for the seasoned wood and 20.15 g/kg for the unseasoned fuel.

Only the closed stove operating at high output gave smoke emissions substantially below the permitted levels in smoke control areas. Under all other conditions, emissions were either close to or above the permitted levels, the worst case being experienced with the open fire and unseasoned fuel, where an emission level of 21.2 g/kg considerably exceeded the permitted level of 5.5 g/kg.

Optical smoke levels for the high output tests were below 5% for both appliances. However, for the closed stove low output test levels averaged 30% for both seasoned and unseasoned fuels and would have been easily visible from street level, particularly during the first three hours when actual obscuration levels approached 100%.

Other findings

The visual impact of the fire was very poor for both appliances when burning unseasoned wood. The unseasoned wood was also very difficult to keep alight, and the lower combustion intensities would result in lower comfort levels during normal domestic use.

Report No: ETSU B/M5/00488/22/REP Publication date: 1995

WOOD FUELLED BOILER OPERATING COSTS

LRZ Ltd

Background

Wood fuel heating systems are both technologically and economically feasible in the UK. They are also very attractive on environmental and social grounds because of their ability to reduce carbon dioxide emissions from non-renewable and fossil fuels, and to provide jobs in the rural economy.

Despite these advantages, the potential of sustainable wood fuel energy systems is not being fully realised. There are perceived risks and uncertainties, as a result of which most systems are overspecified, making both capital and operating costs appear prohibitively expensive.

Project Objectives

- To identify the main components that comprise the annual fixed and variable operating costs of a wood fuel heating system.

- To assess the relative importance of each component based on case study analyses.

Findings

Fixed operating costs

Plant life and depreciation

Plant life can vary significantly, and the Chartered Institute of Building Services Engineers (CIBSE) suggests an average life of 15-25 years for boilers, 5-10 years for boiler electrodes, and 10-15 years for solid fuel (coal) handling plant. Electric motors can have a life of 24,000-30,000 hours. However, plant life will also depend on the degree of utilisation. Heating plant, for instance, is typically operated at part-load for much of the time, and it is important to calculate equivalent full-load hours for all types of equipment to provide a common basis for calculations.

Shelter

Where plant benefits from the provision of shelter, an allowance should be made under two circumstances:

- where the plant uses an existing building, displacing other activities in consequence (appropriate charge: 0.15-0.2% of plant purchase price per year)

- where lack of shelter is associated with corrosion and increased repair costs (appropriate charge: 0.5-1.0% of plant purchase price per year).

NB: The cost of buildings specifically constructed for the plant is already included in the capital cost of the installation.

Insurance

Two types of insurance apply to heating systems:

- Apart from the fire risks associated with fuel storage, wood-fired boilers are no more inherently risky than oil-fired boilers, and a reasonable guide for essential boiler *third party and fire risk insurance* is estimated at 0.22-0.34% of boiler purchase price per year. This allows for replacement/rebuild in the event of fire.

- The cost of *engineering insurance* against mechanical failure is much greater for wood boilers than for oil-fired units because of the greater number of moving parts. Furthermore, it is likely to represent a significant cost where wood size-reduction plant is used, as chippers and shredders are particularly vulnerable to damage from tramp materials such as metal or stone. A value of 0.14-1.4% of plant purchase price should provide a basic level of cover, although numerous optional extensions exist.

Variable operating costs

Fuel

Once equivalent full-load hours have been calculated, an estimate of fuel consumption can be made on the basis of boiler size, the type of wood fuel used and its net calorific value, and seasonal boiler efficiency.

Labour

A wood-fired plant requires labour for handling the fuel and ash, regulating the boiler system, cleaning the boiler, repairs, annual overhauls, and recording and processing plant operating data.

Most UK experience in this field involves dry woodchip fuel, usually joinery waste and other waste timber that arises in a form unsuited to mechanical handling. Labour requirements for the pre-treatment of this fuel are considerable.

Experience of wet woodchip-fired plant is more limited in the UK. Where this fuel is used, it may arrive in pre-chipped form, minimising labour requirements. However, the capital costs of automated handling are high.

From the foregoing, it is clear that the labour *requirement* per kW of installed capacity will vary, although it falls as installation size increases, benefiting from economies of scale, more efficient plant design etc.

Labour *costs* are both the most significant and the most variable of the operating costs. They can be allocated on a full or marginal cost basis. Furthermore, where other activities are competing for the labour, an opportunity cost needs to be allocated. Typically, the opportunity cost of boiler attendance can be taken as the cost of not using the labour on the next best alternative activity. If the opportunity cost of using existing labour exceeds the cost of employing labour, then it is cheaper to expand the staff or use contractors, particularly as, after installation, most of the staffing requirements can be met from low/semi-skilled sources. There may, however, be a need to bring in highly skilled external staff for certain overhaul and repair jobs.

Maintenance and repair

Maintenance and repair costs usually fall into one of four categories:

- routine replacement of wearing parts, where cost as a percentage of purchase price increases over time

- repair of the accidental damage that is quite likely to occur because of plant complexity and the need for greater human intervention, and the lack, in most plants, of specialist operators

- repair of damage associated with plant neglect (neglecting system maintenance and overloading the plant can double repair costs)

- routine maintenance, which includes regular planned activities such as refuelling/fuel handling, de-ashing, flue-way cleaning, lubrication/adjustment and inspection/servicing, and the specialist cleaning, inspection and servicing of plant on an annual basis.

Overall, costs associated with the routine replacement of wearing parts and with scheduled maintenance are small in relation to the plant's capital cost. However, as the level of automation increases, so does the proportion of moving (wearing) to static parts, and cost estimates need to be reviewed. The costs associated with neglect are essentially a management issue and should, again, be small. The costs associated with accidental damage can be significant.

Consumables

Consumables include items such as lubricants as well as electricity for motors, pumps, control systems, wood chipper operation etc. Wood fuel chippers and other wood size-reduction plants are major users of electricity, consuming an average of around 25 kWh per oven dry tonne. Furthermore, this type of plant often has to be run during the day to allow for labour availability and to limit night-time noise. This has important cost implications. Prices for the electricity used at different periods of the day is readily available from the electricity supply companies.

Report No: ETSU B/M5/00533/27/REP Publication date: 1997

REVIEW OF BIOMASS FIRED SPACE HEATING/DOMESTIC HOT WATER BOILERS' APPLICATION, OPERATION AND DESIGN PARAMETERS

Energy and Environmental Software Support Services

Background

A number of wood-fired heating schemes have been installed and monitored in the UK, and feasibility studies have been/are being carried out on several others. Potential project developers would now benefit from the provision of early guidance on project viability.

Project Objective

- To review existing and proposed wood-fired schemes, including an assessment of the suitability, fitness for purpose and economic viability of the various types of plant and equipment used (or proposed) for different applications.

Methodology

Sixteen schemes were reviewed, half already operational and the remainder the subject of feasibility studies. In each case, efforts were made to obtain information and data in the following main areas:

- application
- installed capacity and actual heat demands
- type of boiler plant and combustion equipment
- fuel storage and handling
- fuel quality
- plant performance - output, efficiency, emissions
- scheme economics - fuel, O&M and capital costs.

Comparative data on equivalent gas-fired plant were also sought.

Findings

Application

All but one of the schemes were for space heating or for a combination of space and domestic hot water heating. A proposed leisure centre project sought to heat swimming pool water as well. In most cases there was only a daytime demand, and this results in marked diurnal and, in the case of space heating, seasonal heat demands. The lowest demand may be only one-tenth of the maximum, and this has a major impact on system design.

Operating hours varied substantially, ranging from 860-1400 hours/year in school premises to 1750-2250 hours/year in day-occupancy commercial and industrial premises, and to more

than 8000 hours/year in large residential premises. However, in the latter cases, the plant operated at low load/idling for more than half the total number of hours. In the proposed leisure centre project, 2700 of the 8600 operating hours involved a low overnight heat demand.

Installations

Plant capacity was normally based on maximum heat demand plus distribution losses. Maximum demand for space heating was based on an outside temperature of -1°C or -2°C, although two systems were based on lower external temperatures. Domestic hot water and distribution losses would normally be <10% and <5% of total heat demand, respectively. To total heat demand calculated under steady state conditions must be added an allowance for heating up the premises from cold.

Plant is most efficient when it operates continuously at or near its maximum continuous rating (MCR). In all the cases examined, average heat demand was significantly less than installed capacity: in about half the cases it was 50-60% of MCR and in the remaining cases it was below 30% of MCR.

System options

Nine of the 16 schemes reviewed consisted of single wood boilers, one had two wood boilers and six were hybrid wood/gas oil systems. Various types of integral combustion equipment had been selected: these included underfeed stokers, stepped and fixed grates, a water-cooled burner tube and a horseshoe trough burner. Use was made in some instances of external combustion equipment, including a cyclone furnace and a pre-combustor gasifier.

Fuel storage and handling

Most of the schemes reviewed required wood chips with a moisture content of 35% (wet basis) or less. As the moisture content of freshly harvested woodchips is 50-60%, some drying is needed prior to combustion. This can be done off-site by the supplier or on-site by the user. In the latter case, drying is usually achieved in covered, well ventilated stores in which the fuel can be regularly turned to minimise thermal degradation and fungal decay. Nearly every site had some fuel storage, although the volume available varied substantially, depending on the need for fuel supply security and the availability of alternative fuel firing systems. Most subsequent fuel handling involved a moving floor with, in some cases, screw elevators or inclined conveyors.

Fuel quality

The calorific value of wood fuels varies with moisture content. For instance, a fuel with a 20% moisture content will have a gross calorific value of 15.79 MJ/kg and a net calorific value of 14.26 MJ/kg. Equivalent values for a fuel with a moisture content of 55% would be only half these values at 8.95 and 7.08 MJ/kg, respectively. Where moisture content is above the value specified for a specific plant, there will be an adverse effect on output and efficiency. There will also be an increase in emissions of the products of incomplete combustion.

The plants reviewed used fuels with moisture contents in the 13-50% range. Net calorific values varied from 8% for fuels with a high moisture content to nearly 16% for those with a moisture content of around 20%.

Fuel particle size is also important. Oversize material is normally the main problem: it can cause bridging and hang-up in silos, and it can block conveyor systems and combustion equipment feeders. The conventional stoker-fired plant reviewed required a nominal fuel size of 15-25mm, as did the two pyrolitic pre-burner units and the pre-combustor. However, the cyclone furnace required fuel hogged to less than 6mm.

Performance

Plant efficiency, based on net calorific value, ranged from less than 40% to more than 80%, with most operational plants achieving net efficiencies of 60-65%. Low thermal efficiencies were attributed to the simplicity of the fuel:air control systems and the wide range of heating demand. Well established wood-fired systems showed the highest efficiencies, and it is clear that fuel moisture content has an important effect. Efficiency assumptions for the feasibility studies reviewed (normally 80% on a net calorific value basis) could be optimistic.

In relation to emissions, the best performers were two plants with pre-burner units, where emissions fell well within the limits set by Guidance Note PG1/12(95). The other installations should be able to comply with particulate emission limits, although carbon monoxide and volatile organic compound limits are likely to be exceeded at some time, except under ideal conditions of continuous high heat demand and when burning a fuel with a low moisture content.

Financial appraisal

Fuel costs varied widely, from £7.00/green tonne (£0.48/GJ) for urban tree prunings to £72.00/green tonne (£5.48/GJ) for logs. Both these values are perceived to be extremes, and the predominant cost range was £2.00-2.40/GJ. Although gas oil is more expensive (net input cost £4.62/GJ at 17p/litre and £5.43/GJ at 20p/litre), gas oil appliances are much more efficient than wood fuel appliances, and this significantly reduces the apparent price differential in favour of wood fuel.

Fuel consumption also varied, from 4.2 oven dry tonnes per year (odt/year) for a 17kW installation to 1287 odt/year for the 3MW cyclone furnace plant. Most of the installations consumed less than 100 odt/year. Total wood fuel costs ranged from less than £1000/year to £55,000/year.

Labour and maintenance costs for wood-fired plant can be up to five times more than equivalent costs for a comparable oil-fired plant. Actual costs were only available for one plant, and these were high because of the inclusion of upstream equipment such as the splitter and chipper. A more typical cost would be £8.00/year/kW installed. This is more than three times the equivalent cost for an oil-fired plant.

Overall, those sites burning low-cost wood and/or having comparatively long on-load hours had proportionately higher operating cost advantages.

Capital costs varied with plant size, ranging in most cases from £120-£130/kW for the largest plants to more than £300/kW for plants of less than 50kW. Equivalent figures for gas oil fired plant were £20-£30 for large-scale plant and £50-£80 for small units. Small-scale wood-burning plant is up to six times more expensive than equivalent oil-fired plant.

Just over 30% of the schemes and feasibility studies reviewed achieved a reasonable return on the incremental capital cost over gas oil fired plant. These schemes had low wood fuel costs and/or long operating hours and/or a relatively low incremental capital cost over gas oil plant. Small systems with limited operating hours, relatively high incremental operating and maintenance costs and capital costs showed no advantage over equivalent fossil-fuel-fired plant.

The review has shown that wood fuel can be competitive if fuel costs are less than £2.5/GJ of net thermal input, operating hours are in excess of 2000/year, and the average plant load is more than 50% of installed capacity.

1.2 Emissions Issues

Report No: ETSU B 1313-P4 Publication date: 1993

AN EMISSIONS AUDIT OF A BIOMASS COMBUSTOR BURNING TREATED WOOD WASTE

Warren Spring Laboratory

Background

Legislation associated with the Environmental Protection Act 1990 is to regulate the combustion of waste and of fuels derived from waste. Schedule A combustion units are subject to integrated pollution control by Her Majesty's Inspectorate of Pollution (HMIP), while Schedule B (or smaller units) are subject to local authority air pollution control. The operators of such processes must demonstrate that they are using the best available techniques not entailing excessive costs (BATNEEC) to eliminate or minimise the discharge of pollutants to the environment. They must also show that the process represents the best practical environmental option (BPEO).

Project Objectives

- To provide information on the combustion performance of a biomass combustor burning wood waste.
- To provide full emissions data so that the unit can be assessed in relation to current legislation.
- To provide background information for future BATNEEC process guidance notes.
- To provide design data for gas cleaning equipment.
- To provide information for assessing the performance of a dust density meter.

Methodology

Tests were carried out on a Nordfab NL incinerator installed by a furniture company to dispose of about 30 tonnes/week of treated wood waste - chipboard shavings, dust and hoggings. The incinerator is linked to a 2.8 MW, three-pass shell boiler which produces hot water at 115°C and 3.4 bar pressure. The unit is classified as a Schedule A process.

The combustor was tested in two firing modes: continuous (Test 1) and modulating (Test 2). The emissions audit involved measuring combustion gas, acid gas and particulate concentrations in the exit stack. Boiler efficiency was measured using meters and thermocouples installed for the period of the trial.

Findings

Boiler efficiency

Boiler efficiencies achieved were greater than 75% in both tests. Although this is acceptable, analysis of the flue gases indicated that improved efficiencies are possible.

Combustion gases

Average concentrations of carbon monoxide (CO) and total hydrocarbons during Test 1 were high (512 mg/m^3 and 34 mg/m^3, respectively), indicating poor combustion. The combustor clearly does not meet the requirements set out in the Guidance Note for the combustion of wood waste. Carbon dioxide and oxygen concentrations were variable - an indication of unstable combustion conditions. The conclusion drawn is that improved combustion control should give rise to acceptable emission concentrations.

Although the results from Test 2 were inappropriate for compliance testing, they indicated that combustion control is likely to be worse when the unit is operated in modulating mode.

Further work will be required to show that the unit can comply with the guidelines, although pre-trial tests indicated that significantly lower CO levels are possible, depending on the nature of the waste being burnt.

Acid gases

Acid gas concentrations in the stack were variable throughout the tests, indicating a direct relationship with the composition of the waste. The test average of 504 mg/m^3 for hydrogen chloride (HCl) was well in excess of the guidance value. Although not yet subject to guidance values, concentrations of oxides of nitrogen (NO_x) and sulphur dioxide (SO_2) were measured, with values of 383 mg/m^3 and 79 mg/m^3, respectively. It may be necessary to install scrubbing equipment to control acid gas emissions.

Average test concentrations for hydrogen cyanide (HCN) and formaldehyde (HCHO) were both below the level of detection in Test 1 and so within the guidelines for wood waste.

Particulates

The particulate concentration for Test 1 (210 mg/m^3) was in excess of the guidance value. Improved combustion control should reduce the high (> 15% by weight) carbon content of the particulates. Analysis also showed that more than 21% of the particulates by weight comprised alkali metals. Boiler tube fouling is therefore a potential problem for this unit.

The particulate concentration for Test 2 was about twice that for Test 1, and the overall conclusion drawn is that particulate abatement equipment may be needed to ensure acceptable emission levels.

An assessment of particle size distribution showed that more than 39% of particles by weight were less than 1.0 μm in size.

The dust meter, although uncalibrated, showed trends that reflected unstable combustion.

Heavy metals

Although no guidance levels exist for concentrations of heavy metals, the emission concentration for Test 1 was clearly very high (14.5 mg/m^3). Comparison of particulate and vapour phase concentrations indicated that the installation of particulate abatement equipment should greatly reduce these emissions. With chemical analysis showing that lead accounted for more than 75% of heavy metals by weight, it is equally clear that significant reductions could be achieved by eliminating from the production processes those reagents that contain lead.

Ash

Solids from the combustor (grate ash, grit ash and particulates) showed very high carbon contents (15-50% by weight), with a fairly even spread between the different types of solid. Heavy metals were also fairly evenly distributed. The high carbon content, combined with the possibility that some of the heavy metals are available in soluble form, means that care should be taken when handling and disposing of this material.

Dioxins

Although no guidance levels have been set for dioxin emissions from the combustion of wood waste, concentrations were measured for comparison purposes. The toxic equivalent (TEQ) dioxin concentration in the flue gas for Test 1 was 2.3 ng/m^3, an order of magnitude greater than the proposed guideline for the combustion of municipal solid waste (MSW). Although the high concentrations of HCl, CO and heavy metals in the flue gas were expected to encourage dioxin reformation in the boiler, there was little evidence of this, perhaps because the predominant heavy metal was lead.

TEQ dioxin concentrations in the grate and grit ashes were similar and relatively low (< 1.0 ng/g). Low mass flow rates meant that their contribution to total dioxin emissions was relatively low.

Polychlorinated biphenyls (PCBs)

The concentration of PCBs in the flue gases was higher than the equivalent dioxin concentrations, while concentrations in the ashes were very much lower. It is possible that the chemicals used to treat the wood during the manufacturing process were the source of the PCBs.

Start-up and shut-down

Start-up and shut-down tests indicated short-lived problems with a visible dark plume when the unit was firing in modulating fire mode. The improvements needed to control combustion and emissions of acid gases will probably minimise this problem.

Report No: ETSU B/MS/00192/05/REP Publication date: 1993

ECONOMIC ASSESSMENT OF EMISSIONS ABATEMENT FOR SMALL-SCALE WASTE COMBUSTION

ECOTEC Research and Consulting Ltd

Background

A 1990 desk study of the technologies available for emissions abatement from waste combustion identified a lack of pollution abatement equipment applicable to small-scale combustion units (units handling less than three tonnes/hour). The reasons were found to be the absence of relevant legislation at this level, high capital costs for equipment, and a lack of interest on the part of potential suppliers. The study also found that there was a lack of detailed information on pollution abatement system costs.

Project Objectives

- To establish baseline costs for pollution abatement equipment currently available from UK manufacturers and appropriate to small-scale combustion systems.
- To ascertain the scope for reducing both capital and operating costs through improved design or strategic R&D.
- To identify UK manufacturers with an active or potential interest in this field.

Methodology

Plant costs and information have been obtained from UK manufacturers against specifications for three plants at different scales.

Findings

Legal requirements and market conditions

Although the legal requirements relating to emissions abatement for waste combustion systems are still uncertain, most small-scale applications will need to use some form of scrubbing in addition to conventional particulate controls.

Most manufacturers guarantee systems to meet specified emission limits within a range of inlet conditions. However, because operators do not normally take a long-term view of likely changes in emission limits, manufacturers are forced to be conservative in their choice of technology and cannot risk development costs for a market that is only interested in cheap solutions to a current problem. This thinking also means that project operators are likely to pay significantly more in the long run.

There is already evidence of an upturn in the market for abatement systems for waste combustion plant.

Available systems

Various systems are capable of meeting the emission limits currently proposed in Her Majesty's Inspectorate of Pollution (HMIP) Guidance Notes:

Wet systems vary in terms of plant configuration and capital/operating costs, depending on the design of the scrubber vessel and heat exchanger and the nature of the effluent treatment system. Greater scope for cost savings is therefore likely to be associated with system design rather than with changes in individual items.

Wet systems use reagents efficiently, although the reagents themselves are relatively costly. However, the waste arisings generated are sludges that are problematic to dispose of, and this may result in a sharp rise in disposal costs in the medium term.

Spray dryer systems are expensive to install and there is little scope for varying plant configuration. Compared with wet systems, the reagent costs are lower. Waste disposal, although simpler, is more expensive because of the larger volume of residues.

Dry injection systems vary widely in terms of plant configuration, operating parameters and cost. A "full" dry injection system, with a reaction tower for efficient mixing, a heat exchanger for pre-heating dilution air, and a filter by-pass and pre-heat system costs about the same as a wet system or a spray dryer. However, operating costs are higher because of the high fan power and inefficient use of reagent. A "budget" dry injection system, with no heat exchanger or reaction tower, is one of the cheapest options in capital terms for a given size. However, it is unlikely to achieve removal efficiencies higher than 90%.

Dry injection using bag filters has several operational disadvantages: dilution air is needed to cool the gas stream, there is a risk of acid condensation as dilution air enters the system, and there is a danger of the gas reaching acid dewpoint as its temperature is reduced.

Work is currently in the early stages on a system that combines dry injection with ceramic elements. The potential advantages include operation at higher temperatures and filtration velocities, lower fan power, resistance to acid dewpoint, and a longer life for the filter material.

Factors influencing costs

The three most important factors that determine *capital costs* are:

- the scrubber vessel - a requirement in most systems - which accounts for at least 30% of capital costs

- the heat exchanger, which accounts for at least 10% of the cost in those systems that require such a unit

- the filter - in all dry waste systems - which accounts for at least 25% of the costs, and significantly more in ceramic systems.

“Capital intensity” increases with decreasing scale.

The main factors influencing *operating costs* are:

- reagent consumption (needs to be considered in relation to waste disposal)
- inputs of dilution air - the use of dilution air requires a high fan power input
- pressure drop
- effluent treatment
- sorbent recycling and handling.

Operating costs increase with reduced plant availability, particularly for spray dryers but also for dry injection and wet systems.

Best technology options

The most important conclusion is the competitiveness of spray dryers. At the 10,000 Nm^3/hour level, spray dryers are 25% cheaper in annualised terms than conventional dry injection (see Table 1 below). Even at 4000 Nm^3/hour, the costs are comparable. Spray dryers are therefore worth serious investigation as an abatement option at this scale.

Recommendations

- Further desk and economic modelling studies for those technologies for which insufficient information was available.

- Verification of the findings of this report using cost data from operational plant.

- Technical assessment in areas where there is a lack of consensus in the supply industry, or where there is no independent evidence to verify manufacturers’ claims.

- A series of design studies and/or demonstration projects for the collection of detailed data regarding emission abatement plant costs and performance.

Table 1 Relative costs of main technology sub-types

System	Annualised cost £	Unit annualised cost £/tonne		
		Refuse-derived fuel	Mixed hospital waste	Wood waste
10,000 Nm^3/hour				
Spray dryer	60,000	5.5	13.2	-
Venturi-impingement scrubber	70,000	6.2	14.9	-
Dry injection/ceramic elements	80,00	7.1	17.0	-
Dry injection with reaction tower	84,000	7.5	17.9	-
4000 Nm^3/hour				
Dry injection, no reaction tower	39,200	-	20.9	-
Dry injection/ceramic elements	39,400	-	21.0	-
Spray dryer	39,400	-	21.0	-
Ionised packed scrubber	48,000	-	25.9	-
3000 Nm^3/hour				
Ceramic filter	17,900	-	-	4.1
Variable-throat venturi scrubber	24,400	-	-	5.4
Venturi-impingement plate scrubber	24,700	-	-	5.5

Report No: ETSU B/M3/00388/25/REP Publication date: 1994

SMOKE EMISSIONS FROM A CATALYTIC WOOD STOVE

CRE

Background

Wood-burning stoves are widely used around the world. However, the environmental and thermal performance requirements for such stoves vary from one nation to another, as do the testing procedures by which performance is determined. To allow comparisons and relationships to be established at the international level, the International Energy Agency (IEA) has put in hand a programme in which a catalytic wood-burning stove is tested for emissions in different countries according to the individual procedures of those countries. The UK tests form the subject of this report.

Project Objective

- To test a JOTUL 3TDIC-2 wood-burning stove for emissions, using procedures appropriate to the UK.

Methodology

There is no single standard regarding the determination of emissions from wood-burning stoves. The following procedure was therefore adopted:

- An electrostatic precipitator was used to collect the smoke emitted from the appliance. Its design and use was in accordance with BS3841.

- Both the precipitator and an optical smoke meter were used, and smoke emissions were measured at high, medium and low outputs as laid down in British Standards document PD6434.

- The appliance was set up as a free-standing unit, and its heat output was determined using an adapted version of the flue loss method described in BS3250: Part 1. (The setting prescribed in BS3250: Part 2 was not used, as this is concerned primarily with satisfying heat output measurements and uses a convection hood method.)

- The refuelling procedures and fuel specifications (size and moisture content) adopted were those suggested in BS7256, although some investigation was required to determine an appropriate refuelling datum for this 120 $\pm$ 1 minute interval.

- Each test was preceded by a period of operation at high output.

Parameters measured included:

- average dry burning rate

- carbon dioxide and carbon monoxide levels in the flue gas
- flue gas and ambient temperatures
- flue losses
- heat output (determined using heat input and efficiency)
- gravimetric smoke collection rates and optical smoke density.

Findings

The measured and calculated results are shown in Table 1 below. When assessed for compliance with UK Clean Air Act 1956 smoke emissions limits for smoke control areas, the stove proved satisfactory at medium and high burning rates, but smoke emissions were unacceptably high at low burning rates.

The findings were found to differ from those obtained in other countries only at low burning rates, where UK smoke emissions were seen to be much higher than those found elsewhere.

Smoke emissions were found to be similar to those obtained following the UK method for other smoke-reducing wood-burning stoves, except at the low burning rate, where the result were similar to those for a conventional (not smoke-reducing) wood-burning appliance.

The unexpected low burning rate results may be explained in several ways, including:

- catalyst damage or contamination;

- design flaws in the stove that were highlighted by UK test procedures;

- test procedures in other countries that may be more suited to the operation of catalytic stoves at low burning rates;

- a combustion gas temperature at low burning rates that might be below that at which the catalyst is most efficient.

In addition, the effect of moisture content was determined using wood at both 15% and 30% moisture content, at medium and high burning rates. The wetter wood resulted in smoke emissions approximately double those determined for the dry wood.

Table 1 Results summary (fuel moisture content around 15%)

Date	Burning rate (dry)	Fuel moisture	Carbon dioxide	Carbon monoxide	Flue gas temperature	Overall efficiency (by losses)	Heat output (calculated)	Gravimetric smoke		Average optical smoke (obscuration)
	kg/hour	%	%	%	°C	%	kW	g/hour	g/kg dry wood	%
High output										
24/2/94	2.59	13.0	11.1	0.72	289	74.1	10.9	7.18	2.77	16
25/2/94	2.44	15.5	9.1	0.36	258	73.9	10.2	4.22	1.73	11
01/3/94	2.64	12.3	12.0	0.66	296	75.3	11.2	5.08	1.92	12
Medium output										
02/3/94	1.78	12.3	9.86	0.51	232	76.9	7.7	2.72	1.52	10
03/3/94	1.61	15.6	10.47	0.27	225	76.3	6.5	2.67	1.66	10
04/3/94	1.69	15.2	9.28	0.24	219	75.3	6.7	3.43	2.04	11
Low output										
10/3/94	0.62	15.6	6.3	1.56	66	75.5	2.5	9.83	15.98	31
11/3/94	0.71	15.6	7.5	1.19	82	78.4	2.9	7.41	10.50	34
16/3/94	1.03	15.6	7.5	0.87	127	77.8	4.3	12.78	12.38	35
17/3/94	1.25	15.5	8.56	0.74	154	76.7	5.1	11.38	9.10	62

1.3 Relevant Case Studies

Report No: ETSU B/1171 - P1 Publication date: 1989

MONITORING OF A COMMERCIAL DEMONSTRATION OF HARVESTING AND COMBUSTION OF FORESTRY WASTES

Ove Arup & Partners

Background

Large quantities of forestry residues are available in the UK in areas with a sizeable forestry industry. These can be harvested and used as a fuel, and represent a potentially valuable renewable energy resource.

In 1985, Fibroheat set up a commercial operation in the Grantown on Spey area. The operation comprised an integrated forestry residue harvesting and combustion project, with the steam generated being sold to the Tormore Distillery of Long John International under a utility contract. The project was monitored for the entire 1986/87 season, and the findings are summarised below.

Project Objective

- To harvest and chip forest residues, burn these plus chipped sawmill residues in a boiler plant, and generate sufficient steam to meet Tormore Distillery's steam requirements.

Findings

Woodchip harvesting

Fibroheat own and operate the woodchip harvesting plant. This comprises a Bruks 800 CT terrain chipper mounted on a Kockums forwarder. This can travel into the forest to harvest the residues, producing woodchips that are then transported to the combustion plant site at the distillery by a haulage contractor.

During the monitoring season, the chipper produced 3452 tonnes of fuel from forestry wastes and another 870 tonnes from sawmill residues. A further 907 tonnes of chips were purchased from sawmills. These figures compare with a predicted residue availability in the area of approximately 15,000 tonnes, and a boilerhouse demand of nearly 7000 tonnes.

The sites on which harvesting took place varied widely in terms of size, species of residue and distance from Tormore. The average amount of residue harvested was 34 tonnes/ha swept by the harvester, with spruce residues giving up to 88 tonnes/ha. However, because not all the sites were completely cleared, average recovered density measured against total site areas visited was only 20 tonnes/ha.

Time studies undertaken at all the sites visited gave the following results:

- Machine availability was 59%, with 65% of that time actually spent chipping.
- Chipping windrowed forest residues took 30% less time than terrain chipping.
- The static chipping of pre-harvested residues took 53% less time than terrain chipping.
- Chipping at a sawmill took 58% less time than terrain chipping.

The fuel consumption of the chipper and forwarder combined was found to be 6.7 litres/tonne of chips (approximately 3% of the net energy content of the fuel produced).

The average cost of hauling the chips to Tormore was approximately £4.00/tonne over a road distance of 40km.

The total cost of harvesting and delivering chips to the boilerhouse averaged £24.00/tonne (£2.72/GJ - net basis). Of this, the chipper unit (largely the amortisation of capital) accounted for 64%, haulage for 17%, labour for 14% and fuel for 5%. The cost of forest chips varied widely, from £19.00/tonne to £40.00/tonne. There was also a significant variation in cost/GJ (between £1.80/GJ and £4.90/GJ), with the adverse effect of chip moisture content being very significant.

Combustion operation

Fibroheat own and operate the woodchip handling and combustion plant, which is located at the Tormore Distillery.

Between October 1986 and June 1987, the boiler plant operated at an average load factor of 35% and produced 21,115 tonnes of steam, 70% from 5040 tonnes of woodchips, and the remainder from gas oil (because of the shortage of chips).

Monitoring showed that, despite the variable quality of the fuel, with chips ranging in moisture content from 30% to 60%, the plant achieved a high level of overall efficiency (67.5% gross CV basis and 82.8% net CV basis). Apart from a few minor problems, plant reliability was good, and average availability over the season was 98%. Furthermore, the environmental impact of the plant is likely to be minimal, particularly in relation to flue emissions: emissions of oxides of nitrogen and sulphur, unburnt hydrocarbons and smoke were negligible, as was the production of ash.

The boiler readily achieved its rated output of 15,000 lb/hour of steam from fuel with a 50% moisture content, although output did fall with moisture contents nearer 60%. Increases in fuel moisture content have a significant effect, increasing the bulk density of the chips, and reducing calorific values, boiler efficiency and available output.

Costs

The costs of the project are dominated by capital charges. Assuming normal financial criteria, fixed costs (80% of them associated with capital) account for 50% of the combustion operation cost.

The cost of producing steam during the monitoring period averaged £16.72/tonne, which is not competitive with production using heavy fuel oil or coal. This could be reduced to £14/tonne given a favourable fuel supply and improvements to the harvesting regime. The

harvesting operation would benefit in particular from stronger management control and operator training. This would result in better site selection, improved liaison with felling contractors, and improved availability, machine utilisation and work load factor. Consideration should also be given to static chipping at a forest landing instead of terrain chipping. A further reduction in steam costs, to £10/tonne, could be achieved by increasing the steam load factor from 35% to 70%.

Future projects should be able to achieve steam costs of about £9/tonne by reducing capital costs through the design optimisation process. A steam cost of this order would be comparable with that achieved when producing steam from conventional plant burning oil at around 10p/litre or coal at around £60/tonne.

Report No: ETSU B/M5/00488/05/REP Publication date: 1995

THE WEST DEAN WOOD-FUELLED DISTRICT HEATING SCHEME

The Edward James Foundation
FEC

Background

The West Dean Estate in West Sussex consists of a mansion house, now used as a College, and around 2430ha of land, some 800ha of which are commercial woodland. Beech is the predominant woodland species, usually mixed with a conifer nurse crop. The Estate is owned by a registered charitable Trust and is managed by a board of Trustees.

The coke-fired boilers of the College were converted to oil in the 1950s but only operated at 40-45% efficiency. By the late 1970s, the system was unable to cope with the increasing demands of student accommodation and the growing use of the buildings, and expensive electric night storage heaters were being introduced to make up the heat deficit.

Careful consideration of the alternative fuel options for a new system made it clear that only oil and wood systems were appropriate. Gas was not available in the vicinity; uncertainties about mining and haulage, combined with environmental factors, eliminated coal as an option; while storage issues and the likelihood of a fluctuating supply reduced the viability of using locally produced straw. The decision to opt for wood rather than oil was based on the wild fluctuations in oil prices that were currently occurring, combined with concerns about future oil supplies.

Project Objectives

- To install an effective new boiler system that would make use of thinnings etc from the estate's extensive woodlands.

Findings

Fuel supplies

Assessment of the timber resource showed that the annual fuelwood demand (initially estimated at around 1000 tonnes/year) could readily be met without compromising the principle of sustainability on which the Estate's forestry management was based. Anticipated yields were 2240 tonnes/year from broadleaf sources and 462 tonnes/year from coniferous sources. However, in 1987, the Great Storm destroyed more than 300ha of productive woodland overnight and, although fuelwood supplies have so far been maintained internally, alternative sources of supply on neighbouring estates have been identified in case the need arises.

Cut timber is extracted to the rideside using a forwarder, and a load is brought to the boilerhouse wood yard by forwarder at the end of the operator's working day. Typically, 4-5

loads are brought in each week in winter and one load/week in summer. The timber is chipped and conveyed to the boiler using an automated moving-floor feed system.

West Dean College pays for its fuel on the basis of timber delivered to the boilerhouse. In 1995, this was at £46.00/tonne, a figure made up of £26.00/tonne for the wood (the commercial rate for delivered cordwood), an assessed labour cost for chipping, a depreciation charge for the chipper and a part depreciation charge for the forwarder.

Heat generation

A new boilerhouse, 18.5m long by 12.5m wide, was constructed in part of the walled garden. The design was selected to match surrounding buildings. Half of the boilerhouse contains the furnaces, boilers and ancillary equipment: the remainder is used for chip storage. The compound in front of the chip store is used to accommodate the log splitter, moving deck and chipper. Hardwood logs, two metres long and up to 300mm in diameter can be chipped without difficulty. Chip size is uniform, typically 25mm nominal.

The two furnaces are designed to burn green wood chips with a moisture content of up to 60% (wet wood basis). Each has an Argusfyre grate and a Volund boiler. The larger (770kW) furnace is used to meet the winter heating and domestic load: the smaller (465kW) furnace is used for the smaller summer load. Both boilers are designed to run in tandem, giving a maximum output of 1.235MW.

Four powerful hydraulic rams extract the chips from the fuel store and transfer them to a primary auger. This transports them through an underground trench into a sump in the boilerhouse. A sloping auger lifts the chips into the stoker bin of the chip firing equipment, and a feed auger delivers the chips to the furnace grate at a rate that can be adjusted to suit heating requirements. An automatic water dousing system prevents the chips burning back into the auger. Hot gases from the furnace pass into the base of a conventional steel boiler to provide heat in the usual way.

The ash is raked manually into pits built in the furnace. This takes less than one hour per day. The ash is then extracted by auger and, despite its high pH level and limited fertiliser value, is eventually returned to the woods. Approximately one tonne of ash is produced for every 100 tonnes of wood burnt.

The system incorporates a flue gas cleaner with multiple cyclones to minimise atmospheric pollution and allow compliance with the Clean Air Act.

Oil is available for immediate use as a back-up fuel.

Heat distribution

Heat is distributed from the boilerhouse to the College, approximately 200m away, via a buried pipeline system. From the College, underground spurs feed the Orangery, Church, Church Lane student blocks, Dower House, Vicarage and swimming pool, and four estate cottages. There are long-term plans to extend heating to the recently restored walled garden and its range of 13 glasshouses, and to neighbouring houses.

The system is a closed one, which is pressurised to 2.25 atmospheres. It incorporates two circulating pumps, one of which is on permanent standby.

No major faults have been experienced during 15 years of operation. All elements of the system are regularly serviced and maintained, and major and unforeseen equipment breakdowns are covered by insurance.

Advantages of the system

Cost is a major advantage of the heating system. The Trust does not have to make large payments to a third party for its fuel, and estimates for the mid-1990s were that around £34,000/year has to be paid out to cover repairs and maintenance, depreciation, insurance and standby oil. This compares with towards £50,000/year that would have been paid to an oil supplier had heating oil been selected as the system's fuel. This differential will increase as oil prices rise.

Security of fuel supply is a second important advantage. The fuel source is directly owned by the Trust, and the Trustees' stated policy is to retain the management of the Estate's commercial woodland in hand.

There are also woodland management benefits, including:

- thinning at the optimum time silviculturally, thereby potentially improving the quality of the final crop;

- better management of otherwise non-viable crops such as coppice and areas of natural regeneration, improving the variety of habitats for flora and fauna;

- appropriate replanting and the encouragement of natural regeneration;

- a regular income from the provision of low-grade timber for fuel, which eases the Woods Department's cash flow, particularly in lean years when little mature timber is available.

Labour costs for chipping are absorbed entirely within existing manpower levels. No extra staffing has proved necessary.

Report No: ETSU B/U1/00531/REP Publication date: 1997

THE COMMERCIAL PROSPECTS FOR WOOD-FIRED COMBINED DISTRICT HEAT AND POWER IN NEWCASTLETON IN THE SCOTTISH BORDERS

Border Biofuels Ltd

Background

The Borders Renewable Energy Study identified wood fuel as a viable renewable energy source for the Scottish Borders. The construction and operation of wood-fuelled plant was shown to have a significant positive local impact in terms of employment and income. These benefits could, potentially, be increased if the facility were communally owned.

Newcastleton, a community of 1000 people, is situated on the outskirts of Kielder Forest. It is remote, at the end of the electrical network and suffers from high cost primary fuel and electricity, with frequent interruptions in supply. The local community expressed a desire to investigate the potential for combined district heating and power production using wood as a primary fuel. The intention would be to offset the costs of electricity generation by selling heat to local consumers, and the location appears to be ideally suited to this type of development.

Project Objectives

- To assess the commercial prospects for combined district heating and power for Newcastleton, using wood as a primary fuel.

- To assess the local environmental impact that such a development may have.

Methodology and Findings

Energy demand survey

The energy demand for Newcastleton was determined using two methods:

- a community-wide survey using a questionnaire to provide appropriate information about occupancy, types of heating and weekly energy use for subsequent analysis;

- monitoring five different premises - three domestic and two commercial - for a four-week period to establish their electrical demand.

Total energy use was estimated at 15,700 MWh, of which by far the majority was for heating purposes (fuel and electrical heating), particularly in winter.

Technical and commercial analysis

Three commercial organisations were involved in the project's technical and commercial assessment. Between them they provided the relevant technical input, analysed operating and maintenance options, undertook financial modelling, and managed the project on behalf of the local Community Council.

Four options were considered:

- wood-fuelled heat only system, with power being provided by the existing supplier
- wood-fuelled CHP (steam cycle) system
- wood-fuelled heat and gas oil CHP system
- heavy fuel oil CHP system.

All schemes would involve the installation of a district heating system to distribute the thermal energy generated. This would be based on pre-insulated pipe systems developed in Denmark. A primary steel pipe network would deliver energy to the boundary of each dwelling, while a flexible pipe system would be used to connect each property. The flexible pipe system has two advantages:

- it minimises disruption to consumers during the installation period
- it can be installed using automatic burrowing equipment.

The main distribution network will include a leak-detection system linked to a computer in the central plant control room.

Each system was designed to meet a heat requirement of 5800MWh, and an oil-fired boiler with a heat output of 2800kW and a heat efficiency of 90% was common to all options for stand-by purposes and, where appropriate, for peak lopping.

Wood-fuelled heat only option

Low-cost renewable energy forestry residues are combusted in a specially designed boiler system, with the heat output (1250kW) being recovered as hot water at 90-95°C. The exhaust gases from the boiler are cleaned to remove particulate material and then passed through a condenser to obtain an additional heat output of 150kW and ensure that system efficiency approaches 100%.

The plant incorporates sufficient storage for five days' operation, together with an automatic handling and boiler feed system.

Scottish Power continues to provide electricity via the National Grid system.

Wood-fuelled CHP (steam cycle) option

This option uses forestry residues to generate steam for electricity production and hot water for district heating. The plant used is similar to that used for the heat only option, but has a steam-generating boiler instead of a hot water boiler. The heat output of this unit is a

maximum of 6000kW, with a heating efficiency of around 96%. Additional items include a small steam-turbine alternator, giving an electrical output of 1MW at an efficiency of around 22%, and electrical grid connection equipment.

Wood-fuelled heat and gas oil CHP option

This system combines the wood-fuelled heat only plant (see above) with an oil-fired CHP plant. The CHP plant consists of an oil-fired engine coupled to an alternator, with a waste heat recovery boiler providing additional heat to the district heating system. The electrical output of the CHP plant is 300kW$_e$ at an efficiency of around 41%. The heat output of the heat recovery unit is 420kW at an efficiency of around 48%. The combined heat output from the wood-fired unit and the CHP unit is 1820kW.

Heavy fuel oil CHP system

This option involves the installation of two heavy fuel oil CHP engines, giving an electrical output of 1MW$_e$ at around 42% efficiency and a total thermal output in CHP mode of 1.5MW at around 47% efficiency. The provision of two engines provides system flexibility at periods of low electrical load.

Costs and sales

The costs and projected sales for each option are summarised in Table 1 below.

Table 1 System costs and sales

	Option 1	**Option 2**	**Option 3**	**Option 4**
System capital costs (£000)				
Central plant	905	3220	1059	773
Community heating system	955	955	955	955
Consumer and internal connections	1409	1409	1409	1409
Total	***3269***	***5584***	***3423***	***3137***
Operation and maintenance costs (£000/year)				
Fuel	44	257	89	111
Labour, electricity, maintenance, administration	62	76	73	72
Total	***106***	***333***	***162***	***183***
Sales (MWh/year)				
Heat	5800	5800	5800	5800
Electricity (captive sales)	-	3575	1963	4375
Electricity (spill sales to National Grid)	-	3871	491	375

Financial analysis

An initial financial analysis clearly showed Option 3 to be the preferred option, and this was the subject of further detailed analysis. The relevant financial projections are summarised in Table 2 below. These assume a 90% take-up by the local population and a 50% grant for project implementation.

Table 2 Financial projections for Option 3

Revenues		£426,000/year
Costs		£417,000/year
Net operating revenue		£9,000/year
Capex.		(£1,712,000)
IRR	15 yrs	7%
	20 yrs	9%
NPV @ 12%	15 yrs	£52,000
	20 yrs	£58,000

Environmental impact

If a community heating and power plant were to be developed at Newcastleton, the three most significant environmental changes would be:

- the traffic and storage requirements of biomass-fuelled systems
- a net reduction in carbon dioxide and other gas emissions from biomass-fuelled systems
- the positive impact of biomass procurement and processing on employment and local economic activity.

The way forward

If the community decides to proceed with the project, there are several development procedures that must be completed prior to implementation:

- a promotional campaign to secure the participation of at least 75% of households
- detailed project design
- full financial analysis
- the preparation of draft contracts.

These development procedures are likely to take around three months to complete.

2. THE CO-FIRING OPTION

Report No: ETSU B/M5/00488/26/REP Publication date: 1995

OPTIONS FOR THE CO-PROCESSING OF COAL AND BIOMASS IN POWER GENERATION

CRE Group Ltd

Background

From an environmental standpoint, existing pulverised coal (PC) power plant requires the addition of oxides of nitrogen (NO_x) and sulphur dioxide (SO_2) reduction systems to meet increasingly stringent emissions legislation. Although the most widely adopted low-cost retrofits are currently low-NO_x burners and flue gas desulphurisation plant, there is growing world-wide interest in the co-firing of biomass with coal in PC plant. Displacing a small amount of coal with biomass (eg wood) would reduce NO_x, SO_2 and carbon dioxide (CO_2) emissions. However, the local availability of biomass supplies limits the extent to which co-firing can be achieved in large PC plant to, typically, 5% of the energy input.

A similar level of co-firing is also a potential option for the new generation of advanced clean coal power generation technologies now entering the market. Furthermore, the inherent advantages that these advanced power plants offer in terms of greater efficiency and reduced emissions can be improved still further by using biomass alone as the fuel - although the local availability of the biomass tends to limit plant size to less than $100MW_e$.

Co-firing may also be an option for the new biomass gasification cycle power generation plant that is currently under development. Although giving significantly lower emissions than coal-fired plant, the viability of these units is adversely affected by seasonal fluctuations in biomass availability, the need to dry the biomass prior to gasification, and high capital costs. Co-firing with small quantities of coal may be a more attractive option.

Project Objective

- To identify and assess the options for co-processing coal and biomass in conventional and advanced power generation plant, including plant designed specifically for biomass gasification.

Methodology

The work was divided into three separate tasks dealing, respectively, with conventional power generation cycles, advanced clean coal power generation cycles, and biomass gasification cycles. An initial review identified the co-processing options to be considered within each task, and study teams then sought to identify the potential advantages and disadvantages of each option to determine the most practicable approach.

Findings

Conventional cycles

Eight possible co-firing options were identified for PC and circulating fluidised bed combustion (CFBC) plant. The findings can be summarised as follows:

- The main near-term option in the UK is the co-firing of biomass in conventional PC-fired generating plant, some 25,000MW_e of which already exist in the UK. Commercial-scale co-firing trials have already been conducted in Denmark and the USA, but consideration needs to be given to the biomass feed system to the boiler and to the impact of co-firing on combustion performance.

- The use of a separate gasification plant to provide a fuel gas for reburning in a PC plant to reduce NO_x emissions was not considered practicable for the UK. The size of boiler plant in use (typically 4 x 500MW_e) would require up to 20 gasifier units, and these would be costly to install and operate. Using natural gas would be both easier and more cost-effective in this application.

- The separate gasification of biomass to provide a fuel gas for firing in a gas turbine, followed by use of the vitiated air as the combustion gas for the PC boiler, appears to be a promising option. A fully integrated unit, although achieving an efficiency gain of up to 7%, would require a 100MW_e gasifier. However, the use of smaller gasifier units could significantly increase the efficiency of existing PC plant, and this represents a relatively low-risk integration option, the technology for which has already been demonstrated successfully in Germany using a gas-fired turbine.

- It was not considered economically viable to integrate small (5MW_e) gasifier units into PC plant.

- Only three CFBC boiler plants exist in the UK, thereby limiting the potential for using large amounts of biomass in this type of application. Of the three CFBC co-processing options considered, the co-firing of coal and biomass proved most attractive, as is also the case in the European Union and the USA where large numbers of CFBC plant are operational.

Advanced clean coal technology cycles

Advanced clean coal technology is now at the introductory commercial scale and represents the future technology for large-scale coal use both in the UK and internationally. Of the six potential co-processing options identified for pressurised fluidised bed combustion (PFBC) and integrated combined cycle gasification (IGCC) plant, the most promising was co-firing. However, it was noted that considerable development of pressurised biomass feed systems is required before this option can be realised in practice.

Biomass gasification cycles

Biomass gasification cycles incorporate a dryer to reduce the wood moisture content prior to gasification. This improves fuel gas quality and also reduces downstream gas cleaning costs. If the dryer could be reduced in size by using some coal in the system, plant capital costs could be reduced. However, the study has shown that reducing the capital cost of the dryer would be partly offset by increased capital costs elsewhere, notably:

- the addition of a coal feed system

- uprated ash discharge and gas cleaning systems to meet the higher ash, nitrogen, sulphur and chlorine contents of the coal.

Furthermore, in an unmodified biomass gasification unit, the dryer is sized to match the low temperature heat produced at the back end of the process. This heat is recycled for drying, making the process thermally efficient. Any reduction in dryer size would necessitate the disposal of excess waste heat and represent a loss of thermal efficiency. A steam stack or cooling tower would also be required, again adding to plant capital costs.

Overall, co-firing in biomass gasification cycle plant is not regarded as a promising option.

Recommendations

Further studies should be carried out for two options: co-firing biomass and coal in PC plant, and the use of a separate gasifier and gas turbine with vitiated air recycle to the PC plant. Specific requirements are as follows:

Co-firing

Practical studies to assess:

- the impact of fuel blending on milling costs
- the design of the injection system into the boiler
- combustion performance.

Gasifier and vitiated air recycle

Flow sheet modelling to examine the economics of the option before any practical work is considered.

Report No: ETSU B/U1/00417/REP Publication date: 1996

CO-FIRING WOOD WITH COAL IN UTILITY BOILERS

International Combustion Ltd

Background

Two main factors limit the large-scale generation of electricity from wood fuel in the UK:

- the difficulty of providing sufficient quantity of wood from existing and potential future resources;
- the variable moisture content of the fuel (20-60%).

The co-firing of wood with coal, however, offers certain benefits, including a lower capital cost and higher conversion efficiencies than for dedicated wood fuel plant, and reduced carbon dioxide (CO_2), sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) emissions compared with coal-fired plant.

A review of existing technology undertaken as part of this project has identified wood- or co-firing schemes in various countries, including the USA, the Netherlands, Germany and Sweden.

Project Objectives

- To identify the most appropriate retrofit option for co-firing up to 10% wood in a UK large-scale pulverised-coal-fired power plant.
- To review the technical impacts on plant operation for the most promising option.
- To carry out a risk/uncertainty review.
- To carry out an analysis of plant economics.

Findings

Co-firing options

The project considered five possible co-firing options.

- *Scheme 1* involved mixing wood chips with coal upstream of the existing coal-preparation plant, co-preparing the resulting mixture, and firing that mixture through existing burners. However, milling trials have shown that existing coal milling equipment is not necessarily capable of processing wood chips into a sufficiently fine powder for efficient combustion. The wood chips should therefore be reduced to powder before they are blended with the coal. There are also other mill plant limitations:

- Separating and transporting wood particles needs more air than is required for coal. The fixed capacity of the primary air fan would therefore limit mill throughput.

- More power is needed to mill wood because of its fibrous nature. Mill motor size would therefore be a limiting factor.

- Controlling the quality of the fuel blend to the burners might be difficult.

- *Scheme 2* mixes pre-prepared wood and coal upstream of some or all of the burners and fires the mixture through those burners. The most logical approach is probably to inject the prepared wood after the coal mills. This would avoid the problems associated with Scheme 1 and, in a tangentially fired arrangement, would not cause blending problems. However, ductwork alterations and the addition of local fans would be costly.

- *Scheme 3* fires pre-prepared wood through dedicated burner(s) using separate wood forwarding and preparation systems. It requires a fuel preparation system designed specifically for wood, and a burner optimised for wood fuel.

The Gelderland power station in the Netherlands has been converted for the co-combustion of ground wood from demolished buildings with pulverised coal. Wood chips entering the site pass first through a grinder and then through a MicroMill unit. On entering the latter, the wood is entrained in an airstream and dried while being conveyed into the mill Provided the timber has an initial moisture content of less than 15%, no further energy is required to reduce it to the 8% moisture level that allows stable flames to develop at all levels of air staging. The wood particles leaving the MicroMill are less than 1mm in size. They are trapped in a dust collector and pneumatically conveyed to a storage silo adjacent to the boiler. A metering system feeds the powder into four separate burner injection lines, each linked to a $20MW_{th}$ wood burner.

In the Dutch project, wood accounts for only 3.7% of the total fuel to the boilers. To achieve a 5% or 10% wood throughput in the UK would require an increased fuel supply, with a further increase if the moisture content exceeded 8%.

- *Scheme 4* involves partially combusting the wood in a pre-combustor and burning the resulting gas in the existing boiler combustion chamber. It is unlikely to be adopted because of the cost of the modifications required, the lack of physical space, and the negative impact on system efficiency.

- *Scheme 5* involves the preparation and combustion of wood slurries. Although coal-water mixtures have been used successfully in several countries, wood slurries are unlikely to be viable because of their very low calorific value, the difficulty of achieving a stable flame, and the additional moisture, which would increase flue gas volume and associated fan duty.

Scheme 3 was identified as the most practical engineering option.

Scheme 3: Technical considerations

Fuel supply, storage, drying and handling

The proposed scheme assumes a supply of short rotation coppice (SRC) willow wood chips with an average moisture content of 43.5%. It may also be possible to use other clean wood wastes and construction/demolition waste wood. Drying at the forest edge would reduce the moisture content to 30-35%. Further drying to 20% would take place at the power plant before milling, possibly using low-grade waste heat. Some mechanical agitation of the chips is required to prevent sticking, particularly when the chips are wet.

Level of co-firing

The most viable option is likely to involve co-firing at several stations using a wood input of 5% or less.

Combustion behaviour

The Gelderland plant has opted for a high level of fuel upgrading. A UK scheme might reduce its costs by upgrading only to the level that will ensure efficient combustion. Indications are that a maximum wood particle size of 2-3mm might be appropriate. Better mills and milling options are needed.

Boiler performance and efficiency

Boiler performance and efficiency is determined by fuel specification and by the losses associated with fuel moisture content and excess air levels.

Ash deposition and corrosion

Co-firing with up to 10% wood is unlikely to cause slagging and fouling problems. High temperature corrosion will only occur if the coal contains significant quantities of chlorine. The higher proportion of abrasive silica may marginally increase erosion.

Emissions and solid residues

Co-firing with 10% wood (which is CO_2 neutral) would reduce SO_2 emissions by 10%. Overall NO_x levels should also be significantly lower, provided combustion is controlled to prevent the formation of thermal NO_x. Co-firing with wood is unlikely to affect the performance of electrostatic precipitators, nor should it create ash sale/disposal problems.

Risks and uncertainties

Risks and uncertainties associated with co-firing include:

- the potential health hazards associated with fungal spores
- the increased risk of fire and explosion
- the implications of using a different fuel specification than that used in the Netherlands
- the operational performance of the untested on-site drying system

- quantifying emissions performance
- public acceptability
- the possible impact on pollution limits.

Economic analysis

Capital costs of the Scheme 3 co-firing option are around £42.5 million, and the cost of fuel after transportation, drying and milling is £2.93/GJ. Computer modelling has shown that co-firing with 5% wood would increase the overall cost by £0.60-0.63/MWh (excluding capital costs and risk assessments, and with an assumed load factor of 51%). For a 10% wood input, the increase in costs would be £1.19-1.23/MWh. Non Fossil Fuel Obligation (NFFO) support would be needed to encourage the development of co-firing.

Recommendations

- Modelling and testing to determine the appropriate fuel specification.

- Trials of alternative milling equipment and the scaling up of existing fluid energy mills.

- The development of testing procedures to assess the likelihood of slagging and fouling using wood.

- A detailed review of the practical availability of clean wood and wood wastes, and more accurate assessments of delivered wood fuel costs.

- Identification of a demonstration location.

- Development of the power plant drying house concept.

- Detailed design of a burner scheme.

Report No: ETSU B/U1/00535/REP Publication date: 1997

CO-FIRING BIOMASS WITH COAL - POWER PLANT CASE STUDY

PowerGen Ltd

Background

The high cost of power generation in biomass-specific power plants has encouraged consideration of co-firing biomass with coal in existing power plants. This offers a number of benefits, including a reduction in emissions, the provision of some fuel flexibility, and the generation of a substantial market for biomass, particularly surplus cereal straws, poultry litter, forestry residues and urban wood wastes, total availability of which is around 12 million tonnes/year. A 1995 study has concluded that, although co-firing is believed to be technically viable, there are a number of areas of concern, including fuel supply issues, operational issues, health and safety issues and cost. This project has investigated the feasibility of co-firing biomass in two hypothetical UK coal-fired utility boilers, one co-fired with straw and one with wood.

Project Objectives

The overall objective was to investigate the feasibility of co-firing biomass, particularly wood and straw, with coal in two hypothetical UK power station designs. Specific objectives were:

- To review UK straw and wood supplies.
- To review key straw and wood co-firing technologies.
- To define the main technical issues.
- To identify the key UK regional areas appropriate for biomass co-firing.
- To undertake a preliminary cost/risk analysis.
- To assess strategic considerations.
- To define the associated health and safety issues.
- To recommend necessary further investigative work.

Findings

The main findings can be summarised as follows:

Fuel supply issues

The establishment of cost-effective fuel supplies is essential for competitive power generation. At present there is an inadequate fuel production infrastructure to meet the needs of co-firing in a 500MW_e coal-fired boiler.

In the case of straw, the fuel supply industry is limited. However, both wheat and rape straw are suitable for co-firing and the combined resource in the East Midlands Region, and in the South East, may be sufficient to supply two 500MW units at the 5% co-firing level or one unit at the 10% level.

In the case of wood, the fuel supply industry is virtually non-existent. There is no wood fuel element in current forestry management because the value of the product is too low to make recovery profitable. In the case of short rotation coppice (SRC) it would be difficult to arrange supplies of more than 100,000 green tonnes/year, and 10% co-firing in a typical $500MW_e$ unit would require about 245,000 green tonnes/year. Although an estimated 600,000 tonnes of construction and demolition waste wood are currently landfilled and therefore potentially available, there are likely to be emissions issues where timber has been treated with preservatives etc.

Issues associated with the transportation, storage and handling of biofuels are more site-specific in terms of local planning and environmental restrictions. The geographical location of the plant in relation to these fuels is also an important factor. These issues would help to determine which specific plants could be adapted for co-firing. They would also have a bearing on the cost of electricity production.

The overall conclusion is that an effective fuel management strategy and supply network would need to be established to meet the needs of the power generation industry.

Operational flexibility of existing coal-fired plant

Operational flexibility depends on the fuel preparation and combustion technologies adopted. The system most likely to maintain operational flexibility is that associated with separate fuel milling and combustion. Any operational difficulties experienced with the biomass system would then be less likely to jeopardise the operational integrity of the existing coal-fired combustion system.

The preferred on-site handling, processing, feeding and combustion system will have to be customised to the requirements of each individual site and will depend on fuel type and quality.

Effect on emissions

Co-firing biofuels with coal will reduce gaseous emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2) and oxides of nitrogen (NO_x). However straw co-firing may increase hydrogen chloride (HCl) emissions and may adversely affect the resale of fly ash, particularly at co-firing levels of more than 10%.

Effects on boiler slagging and fouling

Co-firing up to 10% wood with coal is unlikely to adversely affect boiler slagging and fouling characteristics, although performance will depend on wood fineness and fuel injection characteristics.

Straw co-firing can cause increased ash deposition and higher corrosion rates for high-temperature boiler components.

Effect on operating costs and non-productive time

Operational costs will increase because of the capital and maintenance costs associated with the biomass handling and combustion system. There may also be cost penalties that arise in relation to existing fuel supply contracts if power plant availability deteriorates unexpectedly. Some level of subsidy would therefore be needed to maintain competitive power generation, and this project has calculated levels in the 0.5-7.1p/kWh range.

Health and safety issues

There are health and safety issues associated with wood and straw storage, handling and combustion. These may necessitate revision of the Health and Safety policy of a particular site in relation to fire hazards, microbial development and the associated air-borne hazards.

Project costs and scale

Project costs associated with straw or wood co-firing are likely to be of the order of £8-12 million and £15-43 million, respectively. Actual figures will depend on the rate of co-firing and the level of any operating penalty.

Conclusions

- The co-firing of biofuels such as wood or straw in a coal-fired utility boiler is considered technically achievable.

- Significant fuel supplies are already available or potentially available, depending on the management of land and fuel resources.

- Issues that need to be addressed before co-combustion can be considered on a specific power plant include:

  - further development and validation of the relevant combustion technologies
  - an appropriate power station location
  - compliance with local planning and environmental restrictions
  - the development of an effective biofuel supply infrastructure
  - optimisation of particle size for both wood and straw combustion systems
  - suitable subsidies
  - the implications for plant operating cost
  - health and safety.

3. THERMAL CONVERSION

3.1 The Technologies

Report No: ETSU B 3118 B Publication date: 1978

CONVERSION OF BIOMASS TO FUELS BY THERMAL PROCESSES PHASE 1: REVIEW AND PRELIMINARY ASSESSMENT

Ader Associates

Background

The thermal processing of organic feedstocks is not new. Examples include the destructive distillation of wood to provide source materials for chemicals prior to the development of the oil industry; the gasification of coal; and the gasification of biomass to produce gas for transportation in certain countries during the Second World War.

During thermal processing (which can be based on numerous different feedstocks), a wide and complex range of parallel chemical reactions can take place either simultaneously or consecutively as a result of further reaction. The nature and sequence of these reactions depends on feedstock temperature, on reactor environment, on the initial products formed and on other process variables.

This preliminary assessment focuses on the thermal processing of biomass and is in two volumes, a Management Summary and a detailed technical overview.

Project Objectives

- To appraise and analyse the state of the art of thermal processing by a world-wide survey of the literature and of work currently being undertaken.
- To identify processes and plants that offer the best potential, and to establish optimum design and processing parameters and the most likely product compositions and yields.
- To evaluate selected processes for their technical and economic viability.
- To identify further research and development requirements.

Findings

Technical appraisal

There are six main types of thermal processing:

- pyrolysis - the breakdown of organic compounds by heat without oxygen;
- carbonisation - pyrolysis optimised to produce char or charcoal;

- gasification - the simultaneous combustion and pyrolysis of organic compounds in insufficient oxygen, producing a mixture of flammable gases;

- steam reforming - reaction of organic compounds with steam to give carbon monoxide and hydrogen;

- hydrogasification - pyrolysis in a hydrogen atmosphere to produce gas with a high methane content;

- hydrogenation - pyrolysis in a hydrogen atmosphere to produce liquid hydrocarbon.

The reactor environment is influenced by the present of water/oxygen/recycled gases; by the way in which the feedstock is heated; and by the arrangement of the gas flow. All these have an important bearing on the temperature profile in the reactor.

The primary products of thermal processing include:

- a solid char - can be sold as a solid fuel or gasified to provide an in-plant heat source;

- pyroligneous acids - liquid products resulting from the pyrolysis of cellulose-containing biomass, which are highly acidic, unstable, corrosive and difficult to handle, and are preferably recycled as an in-plant fuel source;

- pyrolytic/combustion gases - the most valuable primary products, which can be used as a fuel in their own right or as chemical feedstocks for the production of upgraded fuels such as methane, methanol, liquid hydrocarbons or gasoline.

Work to date has focused principally on certain biomass feedstocks (municipal refuse, forestry and agriculture residues and, to a lesser extent, sewage sludge and manure) plastics and rubber. The process used for one feedstock is usually appropriate to others.

The most popular type of reactor is the vertical shaft reactor. This is simple to construct and has a minimum of moving parts. The feed is introduced at the top, and char, ash or slag is removed at the bottom. Two processes are commercially available for the pyrolyis of refuse using a slagging type vertical shaft reactor. In the UK, Warren Spring Laboratory and Foster Wheeler Power Products Ltd have developed a modified version of the reactor that uses a cross-flow arrangement for recycling reaction gases.

Rotary kilns are popular and have been used for projects in the USA, Japan and Germany. Fluidised bed reactors are being used for several projects in the USA and Canada.

Current work is open to criticism because of the lack of account that has been taken of the many process variables. However, the thermal processing of biomass does offer considerable flexibility in terms of feedstock and end product and provides potentially viable routes for the production of usable fuels.

Economic appraisal

The economic appraisal has been based on conceptual process routes for producing gas, methane and methanol by pyrolysis or oxygen gasification. Assumptions made:

- the design of the thermal reactor is relatively unimportant and is not specified
- the mechanism of heat transfer to the biomass is relatively unimportant
- maximum conversion to gas occurs
- all liquid products and char are recycled to provide an energy input to the process
- feedstock requires no on-site pre-treatment or drying
- gas conversion to methane or methanol is by well established process routes.

The availability of unused forestry, wood residues and straw would give many locations access to 100,000 dry tonnes/year of relatively low-cost feedstock, the input needed for a 300 tonne/day plant producing gas for local consumption. Assuming £10/tonne for feedstock collection and transportation, gas could be supplied at around £2/GJ and could possibly become competitive with natural gas within the next decade.

The most economic feedstock for local gas production would probably be domestic and industrial refuse. About 250,000 tonnes/year would be required to feed a 300 tonne/day plant, and it is possible that such plants could supply gas at £1.50/GJ, thereby being competitive with natural gas even at current prices.

Methane derived from the further processing of primary gas could be supplied directly to the gas grid. The cost would be around £3/GJ for methane from a 300 tonne/day wood or straw plant and about £2.25/GJ for methane from a refuse-fed plant of the same capacity.

Conversion of the primary gas to methanol is likely to incur costs of around £90/tonne for a 300 tonne/day wood- or straw-fed plant, and £65/tonne for a refuse-fed plant.

Capital-related charges account for more than 80% of total product cost.

Conclusion

Thermal processes offer good prospects for eventual development into economically viable methods of converting biomass to fuel.

Recommendations

- Identification of the best processes for each feedstock, with detailed costings.
- Laboratory experimental work - effect of process variables on product composition.
- Pilot-scale experimental work.
- Research into catalytic pyrolysis.

Report No: ETSU B 1042 A [FR] Publication date: 1980

CONVERSION OF BIOMASS TO FUELS BY THERMAL PROCESSES PHASE 2A: OPTIMISATION STUDIES FOR CONVERSION TO METHANOL

Ader Associates

Background

Biomass is a renewable source that can potentially be converted into energy. Thermal processing is one of the methods that can be used to convert biomass into fuel and is the subject of detailed investigation. Report No: ETSU B 3118 B, published in 1978 and summarised above, provided a review and preliminary assessment of the thermal processing of biomass. This report examines the production of methanol from biomass. Report No: ETSU B 1042 B looks at conversion to methane, while Report No: ETSU B 1042 C examines conversion to liquid hydrocarbons.

The overall biomass-to-methanol process has three main stages:

- the thermal processing of biomass;
- methanol synthesis and purification;
- the "matching" operations which ensure that the thermal process products match the requirements of the methanol loop.

Project Objectives

- To identify the process routes from biomass to methanol.
- To develop outline flowsheets.
- To evaluate selected case studies in terms of overall mass and energy balances.
- To derive approximate capital and processing costs.

Methodology

Mass balance and energy balance calculations were completed for the production of methanol by three thermal routes, pyrolysis at 900°C, oxygen gasification and steam gasification.

Evaluation of mass and energy flowsheets for processes starting with pyrolysis were based on the composition of products published by Knight for the medium- and high-temperature pyrolysis of wood. Those for oxygen gasification routes were based on the "Purox" gasification data for urban refuse. For the steam gasification route, evaluation was based on the work of Wright-Malta on the gasification of wood in rotary kilns.

The data used for the conceptual conversion of thermal decomposition products to synthesis gas, for the "matching" operations, and for the final conversion to methanol were derived mainly from existing information on the production of methanol from natural gas or naptha.

Capital cost estimates were developed for a plant with an assumed capacity of 250 tonnes of methanol per day. Calculations were based on specified cost models for process units where historical costs are available. For other items, a functional unit step costing method was adopted.

Production costs were computed from operating costs given by the formula:

$$1.1R + 2.64L + 0.18I$$

where R = raw material cost (assumed to be £20/dry tonne);
L = direct labour cost;
I = investment cost;

and from financial charges based on ten-year amortisation at 10% interest.

All energy costs are assumed to be met in house, so there are no fuel and power costs.

Findings

Steam gasification gave the highest overall yield in terms of both net energy recovered and weight of methanol per unit of dry biomass feedstock (Table 1 below).

Table 1 Methanol yields from different processes

Thermal route	Net energy yield	Weight yield
Pyrolysis (900°C)	41%	34%
Oxygen gasification	48%	35%
Steam gasification	55%	51%

Table 2 below summarises the inputs, outputs and costs of the three different process routes for a 250 tonne/day plant. Pyrolysis gave the highest costs, with even the more efficient high-temperature process showing costs as high as £209/tonne of methanol produced. The costs for oxygen gasification were slightly lower, but were derived solely from data on the processing of urban refuse. Although no reliable data exist for the oxygen gasification of wood, it is not unreasonable to presume that using wood as a feedstock might increase the net energy yield to more than 50% and reduce costs to around £167/tonne of methanol.

The steam gasification route gave the lowest methanol cost (£149/tonne). If plant capacity were to be doubled to 500 tonnes/day, a capital cost increase of around 50% could be anticipated, giving a methanol production cost of around £120/tonne. The current (early 1980) world price for contract supplies of methanol is £110/tonne and the spot price is around £130/tonne.

Table 2 The production of methanol from biomass: inputs, outputs and costs

	Pyrolysis		Gasification	
	Medium temp.	**High temp.**	**Oxygen**	**Steam**
Raw material input (tonnes/day)	1250	1000	1000	700
Methanol output (tonnes/day)	250	250	250	250
Capital cost estimates (£ million)	39	31	28	23
Production cost breakdown				
Raw materials (%)	31	29	33	29
Labour (%)	4	4	4	5
Capital-related (%)	65	67	63	66
Methanol production cost (£/tonne)	253	209	193	149

Conclusion

In terms of both yield and cost, thermal processing by steam gasification is likely to prove the optimum route for producing methanol from biomass. However, because the technology is at a relatively early stage in its development, any direct comparison with alternatives might be misleading. Using currently available technology, methanol production via oxygen gasification may give comparable costs at a reasonable throughput.

Report No: ETSU B 1042 B [FR] Publication date: 1980

CONVERSION OF BIOMASS TO FUELS BY THERMAL PROCESSES PHASE 2B: OPTIMISATION STUDIES FOR CONVERSION TO METHANE

Ader Associates

Background

Biomass is a renewable source that can potentially be converted into energy. Thermal processing is one of the methods that can be used to convert biomass into fuel and is the subject of detailed investigation. Report No: ETSU B 3118 B, published in 1978 and summarised above, provided a review and preliminary assessment of the thermal processing of biomass. This report examines the production of methane from biomass. Report No: ETSU B 1042 A looks at conversion to methanol, while Report No: ETSU B 1042 C examines conversion to liquid hydrocarbons.

The biomass-to-methane process is a sequence of operations that begins with thermal processing of the biomass and continues with whatever treatment of the thermal products is required prior to methanation of the gases. Several processes are at an advanced stage of development, although none is yet an established commercial process.

Project Objectives

- To identify the process routes from biomass to methane.
- To develop outline flowsheets.
- To evaluate selected case studies in terms of overall mass and energy balances.
- To derive approximate capital and processing costs.

Methodology

Mass and energy flowsheets have been evaluated for pyrolysis at 870°C, as described by Knight for wood; for oxygen gasification according to the “Purox” process for urban refuse; and for steam gasification according to the work of Wright-Malta for wood.

The methanation stage has been assumed to proceed according to the steam-moderated multi-bed process that is currently being developed for coal-to-methane processing. This is assumed to operate satisfactorily on the clean gaseous products of thermal processing.

Capital cost estimates were developed for a plant with an assumed capacity of 250 tonnes of methanol per day. Calculations were based on specified cost models for process units where historical costs are available. For other items, a functional unit step costing method was adopted.

Production costs were computed from operating costs given by the formula:

$$1.1R + 2.64L + 0.18I$$

where R = raw material cost (assumed to be £20/dry tonne);
L = direct labour cost;
I = investment cost;

and from financial charges based on ten-year amortisation at 10% interest.

All energy costs are assumed to be met in house, so there are no fuel and power costs.

Findings

Mass and energy balance calculations for the production of methane by each of the three thermal routes showed weight yields to be low but net energy yields to be relatively high, particularly for steam gasification (Table 1 below).

Table 1 Methane yields from different processes

Thermal route	Net energy yield	Weight yield
Pyrolysis	39%	13%
Oxygen gasification	48%	10%
Steam gasification	85%	29%

Estimates of capital and production costs are summarised in Table 2 below.

Table 2 The production of methane from biomass: inputs, outputs and costs

	Pyrolysis	Oxygen gasification	Steam gasification
Raw material input (tonnes/day)	1850	2620	865
Methane output (tonnes/day)	250	250	250
Capital cost estimates (£ million)	58	46	29
Production cost breakdown			
Raw materials (%)	38	44	37
Labour (%)	2	2	4
Capital-related (%)	60	54	59
Methane production costs			
£/tonne	428	378	209
£/GJ	7.7	6.8	3.8

With current natural gas prices at £1.50-2.00/GJ, methane production from biomass is unlikely to economically viable, although steam gasification may offer long-term prospects.

Report No: ETSU B 1042 C [FR] Publication date: 1980

CONVERSION OF BIOMASS TO FUELS BY THERMAL PROCESSES PHASE 2C: OPTIMISATION STUDIES FOR CONVERSION TO LIQUID HYDROCARBONS

Ader Associates

Background

Biomass is a renewable source that can potentially be converted into energy. Thermal processing is one of the methods that can be used to convert biomass into fuel and is the subject of detailed investigation. Report No: ETSU B 3118 B, published in 1978 and summarised above, provided a review and preliminary assessment of the thermal processing of biomass. This report examines the production of liquid hydrocarbons from biomass. Report No: ETSU B 1042 A looks at conversion to methanol, while Report No: ETSU B 1042 B examines conversion to methane.

Current technology indicates that there are two possible approaches to the production of liquid hydrocarbons from biomass:

- Thermal processing can be used to produce a syngas that is converted into a crude liquid hydrocarbon by a Fischer-Tropsch synthesis. This liquid hydrocarbon is comparable to a high-grade petroleum crude and requires further refining.

- The syngas produced can be converted to crude methanol and, subsequently, to a motor fuel using the M-gasoline process.

The direct liquefaction of biomass to crude oil is excluded from this study.

Project Objectives

- To identify the process routes from biomass to methane.
- To develop outline flowsheets.
- To evaluate selected case studies in terms of overall mass and energy balances.
- To derive approximate capital and processing costs.

Methodology

Mass and energy flowsheets have been evaluated for oxygen gasification according to the "Purox" process for urban refuse; and for steam gasification according to the work of Wright-Malta for wood. The Fischer-Tropsch reaction has been assumed to proceed according to data available for the coal-to-oil plant known as SASOL 1.

Several conceptual flowsheets were constructed in which the thermal product gases were assumed to have been variously adjusted to correspond to the $CO/CO_2/H_2$ molar ratios of the

syngas feed to the Fischer-Tropsch reactor. Furthermore, theoretically feasible conversions, not yet achieved in practice, have been considered as a means of exploring future potential.

Capital and production cost estimates were computed for plants assumed to have an output of 100 tonnes/day of liquid hydrocarbon. Calculations were based on specified cost models for process units where historical costs are available. For other items, a functional unit step costing method was adopted.

Production costs were computed from operating costs given by the formula:

$$1.1R + 2.64L + 0.18I$$

where R = raw material cost (assumed to be £20/dry tonne);
L = direct labour cost;
I = investment cost;

and from financial charges based on ten-year amortisation at 10% interest.

All energy costs are assumed to be met in house, so there are no fuel and power costs.

Findings

Table 1 below summarises mass and energy yields and production costs.

It is evident that, compared with high-grade petroleum crudes (current price around £100/tonne), liquid hydrocarbon produced from biomass via Fischer-Tropsch reaction is unlikely to be economically viable. Even at the largest practical scale of operation (biomass feedstock at 2200 tonnes/day), and assuming further improvements will achieve the ultimate yields that are theoretically feasible, costs would still be some three times the price petroleum crudes are likely to reach by 1990.

Conversion via the M-gasoline route has been visualised as an add-on process (Table 2 below). Biomass is converted first to methanol and then to gasoline by the process, which has recently been developed by the Mobil Oil Company. Data published so far indicate that the process will yield about 38 tonnes of stabilised gasoline for every 100 tonnes of methanol processed. Production costs for a plant with a methanol input of 250 tonnes/day are around £22/tonne of methanol processed.

Given a current price for gasoline of around £210/tonne, the estimated cost of £450/tonne from the steam gasification route has some prospect of becoming economically viable as the price of fossil fuels continues to escalate in the future. Furthermore, based on currently available technology, steam gasification and the M-gasoline process show better prospects of viability than conversion via the Fischer-Tropsch reaction.

Table 1 The production of liquid hydrocarbon from biomass via Fischer-Tropsch synthesis: inputs, outputs and costs

	Via thermal process route		
	Oxygen gasification	Steam gasification	
		A	B
Raw materials (wet basis: tonnes/day)	3000	1100	2200
Liquid hydrocarbon output (tonnes/day)	100	100	300
Other hydrocarbon output (tonnes/day)	360	130	(?)
Capital cost estimates (£ million)	86	55	40
Production costs/tonne of liquid hydrocarbons (£)	1400	770	400
Net weight yield (dry basis: %)			
Liquid hydrocarbons	4	15	18
Total hydrocarbons	21	29	-
Net energy yield (%)			
Liquid hydrocarbons	15	39	48
Total hydrocarbons		74	-

Table 2 The production of liquid hydrocarbon from biomass via M-Gasoline process: inputs, outputs and costs

	Via thermal process route		
	High temperature pyrolysis	Oxygen gasification	Steam gasification
Feedstock (wet basis: tonnes/day)	1000	1000	700
Methanol production (tonnes/day)	250	250	250
Gasoline output (tonnes/day)	95	95	95
Overall yields (gasoline on feedstock: %)			
Weight	13	13	19
Net energy	38	46	52
Total capital cost (£ million)	36	33	28
Production costs/tonne methanol (£)			
For biomass/methanol	209	193	149
For methanol/gasoline	22	22	22
Total production costs/tonne **gasoline** (£)	608	566	450

Report No: ETSU B 1202 Publication date: 1991

REVIEW OF THERMOCHEMICAL BIOMASS CONVERSION

Energy Research Group, Chemical Engineering and Applied Chemistry Department,
Aston University

Background

Biomass and solid wastes offer considerable potential for solving some of the world's energy problems. The energy in biomass can be realised through direct combustion or through upgrading into a more valuable and usable product such as fuel gas or fuel oil, or into a higher value product for the chemical industry. Upgrading may be physical, biological, chemical or thermal. This report is concerned with thermochemical conversion - gasification, pyrolysis and liquefaction.

Project Objectives

- To identify the range of feedstocks available.
- To assess the main technology alternatives.
- To identify the various products and their characteristics.
- To consider applications and constraints.
- To examine the economics of thermochemical conversion technologies.
- To identify opportunities for the future.

Findings

Feedstocks

The main feedstocks considered for thermochemical conversion are wood and wood waste, agricultural wastes and refuse. Sewage sludge is also under investigation for this purpose.

Wood and wood waste consists of timber produced specifically as an energy crop, for example short rotation coppice (SRC), and forestry and wood processing residues.

Agricultural waste is a particularly attractive feedstock for thermoconversion. It is often available in quantity at a single site that also has storage and handling facilities; it may already have been subjected to size reduction and drying; and the costs of its disposal may actually incur a credit when the waste is considered for thermoconversion.

The cost of disposing of the significant quantities of domestic and commercial refuse produced in many societies is considerable. Thermoconversion can help to reduce this cost.

Thermoconversion technologies and products

The *gasification* of biomass and solid waste has been developed to the commercial level very rapidly and has been widely implemented throughout the world. However, there have been many failures, and these can be attributed to the complex interaction of technological, economic, socio-economic, environmental, political and public awareness factors. Few systems are currently available commercially, and few are operating successfully.

Wood has been the main feedstock to date, producing a low-quality fuel gas with a lower heating value than natural gas and a higher level of contaminants. Relatively little attention has been given to refuse, which is potentially a much more attractive feedstock from an economic point of view.

The technology still needs a robust R&D programme to develop a reliable gasification system that can meet performance specifications. Well engineered and operating pilot plants are also essential to prove the technology.

Pyrolysis has been the subject of greater research effort but less development to demonstration and commercial scale. The main exception is carbonisation in developing countries, where the technology is important in meeting domestic fuel needs.

Recently developed high-efficiency flash pyrolysis processes produce substantial yields of liquids with zero or minimal char, and allow in-house use of the pyrolysis gas. The liquid can be used directly as a fuel-oil substitute. Alternatively, it can be upgraded to a conventional hydrocarbon fuel, although the upgrading technologies are at an early stage of development. Several flash pyrolysis demonstration plants are being implemented, eg in Belgium, Canada, Italy, Spain and the USA.

Pyrolysis is also the mechanism in twin fluid bed gasification processes, in which a medium-heating-value gas is produced at temperatures that are higher than those used for liquids production. High-temperature flash pyrolysis has been used for research into the production of chemicals such as olefins. Furthermore, chemicals have been produced under low-temperature slow pyrolysis conditions from specific feedstocks such as sewage sludge. They have also been recovered from flash pyrolysis liquids.

In North America, attention is focusing on the commercial production of chemicals by pyrolysis. In Europe, the emphasis is on liquid fuels for fossil fuel substitution and commercial power generation. More research is needed if industry is to become more actively involved.

Liquefaction is a low-temperature, high-pressure process that is carried out in a reducing environment, usually with hydrogen but sometimes also with carbon monoxide. The liquid product has a much lower oxygen content and is more physically and chemically stable than the products of pyrolysis. Furthermore, less upgrading is required to produce a marketable hydrocarbon product. However, the product is very viscous and thus more difficult to use than flash pyrolysis oil.

High costs, combined with unresolved problems of feeding biomass slurries at high pressure, and of product separation, have limited activity mainly to batch-scale operations. Attention

has focused on the reaction step, and little effort has been put into process design. Liquefaction must therefore be seen as the most long-term option, but the potential processing and reaction advantages should not be ignored.

Comparison with alternatives

Thermoconversion technologies produce a fuel that can be stored and transported, and that can be combusted more efficiently than the original solid fuel. They therefore offer certain advantages over combustion, which gives a thermal output that has to be used immediately. Small-scale power generation systems of up to 5MW based on gasification or pyrolysis could offer significant cost savings over combustion routes. However, a consistent and thorough comparison of the alternative technologies is needed to define preferences and RD&D needs.

The competing feedstock is coal, and the capital and operating costs of coal conversion processes are similar to biomass and waste processing costs. However, although coal costs are comparable to energy crop costs on an energy content basis, sulphur and other environmental problems arise with coal, and coal does not attract the credits associated with waste disposal. Furthermore, the net production of carbon dioxide with coal is likely to become an increasingly important consideration.

Economics

The estimated cost of producing energy products via biomass and waste gasification and pyrolysis is such that both technologies can be viable in a European context as long as the scale of operation is sufficiently large and the feedstock is available in sufficient quantities at an acceptable cost. Fuel gas, power and liquid fuels can be produced competitively from refuse in many locations even in quite small plants, and there are limited opportunities for using straw and wood. Most opportunities are likely to be site-specific in the short term.

Opportunities

The most likely industrial markets for fuel gas and liquids from biomass and wastes occur where fuel oil quality specifications are undemanding - in boiler retrofitting, in the direct firing of products such as lime, cement, bricks and unglazed pottery, and, for liquid fuels, in the gas turbine field. The technologies will be affected by technical and economic changes in the waste and its availability, and by changes in environmental legislation.

Research and development is still required in certain areas:

- the resolution of feedstock feeding problems
- fuel gas clean-up
- the production of higher value liquid fuels and chemicals
- improvements in pyrolysis and liquefaction technologies - for better yield and quality
- demonstrations of promising technologies
- process optimisation.

Present oil and gas prices, and the high level of UK fossil fuel reserves, mitigate against the rapid development of alternative feedstocks and technologies. However, there are short-term

opportunities in alternative waste management practices which should be realised for both energy and environmental reasons.

Report No: ETSU B/T1/00207/REP Publication date: 1993

AN ASSESSMENT OF THERMOCHEMICAL CONVERSION SYSTEMS FOR PROCESSING BIOMASS AND REFUSE

Aston University
DK Teknik (Denmark)

Background

The thermochemical processing of biomass and wastes offers a means of energy production from renewable sources. It may also be a potentially attractive method of waste disposal. Apart from combustion, which is considered to be a well established technology, there are three main approaches to conversion: gasification, pyrolysis and liquefaction.

Project Objectives

- To survey biomass and solid waste gasification, pyrolysis and liquefaction processes, their history and their current technical and economic status.

- To assess the applicability of these thermochemical conversion systems to opportunities in the UK and Denmark.

Methodology

Relevant processes were selected for this study using a database set up at Aston University under the IEA Bioenergy Agreement. Fifty-seven processes were identified, and 22 of these were subsequently selected for more detailed investigation on the basis of satisfying at least one of the following criteria:

- at or near commercial availability
- contain innovations
- operate at a significant scale
- involve ongoing development or research work.

Eighteen of the 22 processes were visited. Of these, 13 were gasification processes and five involved pyrolysis for the production of liquid fuels. Each process was assessed for:

- status
- product quality requirements
- environmental impact
- capital cost
- application to opportunities in the UK and Denmark.

Findings

Feedstocks

Table 1 below summarises the main types and quantities of biomass available for thermoconversion in the UK and Denmark.

Table 1 Biomass available for energy conversion and its potential

UK		Denmark	
Type of waste	**Energy potential[1]**	**Type of waste**	**Energy potential [1]**
Straw	7.000	Straw	2.983-3.483
General industrial and trade waste	25.000	Wet municipal solid waste	0.330
Municipal solid waste (MSW)	25.000	Dry municipal solid waste	0.430
Refuse derived fuel (RDF)	0.100	Wet organic waste from industry	0.560
Sewage sludge (dry material)	1.500	Dry organic waste from industry	0.870
Tyres	0.466	Waste tyres	0.016
Demolition wood waste	0.100	Forestry surplus wood	0.340
Forestry wastes	0.400	Industrial wood waste	0.400
		Waste wood from parks	0.320
		Other wood	0.110

[1] Maximum potential resource for energy, million tonnes dry basis

Technologies

Gasification has been developed to a larger scale of operation than flash pyrolysis for the production of liquids. Almost every gasifier configuration was studied and of these, circulating fluid beds are the most developed and have been the most widely commercialised. The product is usually a low-heating-value gas.

The product of flash or fast pyrolysis is a medium-heating-value liquid, referred to as bio-crude or bio-oil. The production of a liquid rather than a gas allows the fuel production process to be decoupled from the power generation system. This has certain advantages such as more economic peak power generation and opportunities for transporting the fuel product to a central power station, thereby encouraging economies of scale.

Applications

The use of the gas and liquid fuels produced has been widely tested in both steam/hot water boiler and kiln firing applications. However, only TPS (Studsvik) in Sweden has tested the use of low-heating-value gas for fuelling an internal combustion engine and, typically, an engine derating of 30% can be expected. No systems have yet been built for producing

electricity via a gas turbine using gas or liquid fuels. However, several are under development, based on both pressurised and atmospheric gasification systems.

Gas and liquid clean-up

Most of the gasification systems produce a raw gas that is suitable for direct firing in kilns or boilers. Minimal raw gas cleaning is required, and systems are very efficient. Engines for power generation are more demanding in their requirements. They involve upper limits for tars and particulates in the gas, and require the injection of gas at as low a temperature as possible to maximise the energy density of fuel to the engine. Water scrubbing is the preferred gas clean-up system, although this approach creates a waste water problem. Gas turbines are the most demanding in terms of gas quality requirements, and considerable development work has been and is being undertaken on both hot gas filtration and catalytic tar cracking to provide gas of the necessary quality.

The liquids generated by pyrolysis can be directly fired in boilers, kilns and furnaces. Furthermore, recent tests have demonstrated that combustion in a dual-fuel diesel engine is feasible. No problems have been identified, although longer-term testing is required. On the other hand, gas turbine applications are still unresolved, with potential problems resulting from the alkaline ash content of the fuel.

Environmental impacts

Thermochemical processes for biomass and waste conversion will generate a solid residue, the composition and flow-rate of which will depend on the type of feedstock involved. The installation of water scrubbing in a gasification process will generate waste water, and pyrolysis systems incorporating upgrading may also produce a waste water stream. Other environmental issues include oxide of nitrogen (NO_x) emissions; the possible management of sulphur in gas turbines; hydrocarbon and carbon monoxide emissions as a result of incomplete combustion; and potential accidental emissions of gases, liquids and solids.

Costs

There is no perceptible difference in capital cost between atmospheric gasification and pyrolysis systems. Pressurised gasification systems are inherently more costly but offer potential cost savings at the power generation stage because of the lack of gas compression required and the higher system efficiency.

Opportunities

Thermochemical conversion opportunities for the UK involve feedstocks such as short rotation forestry crops, MSW, RDF, general and industrial trade waste, wood waste, straw and sewage sludge. The most likely size range for power generation, taking into account both economics and fuel resource availability, is 5-30MW_e.

In Denmark, the main opportunities lie in the conversion of MSW, RDF, general and industrial trade waste, and straw. The most likely size range for power generation, taking into account both economics and fuel resource availability, is 5-20MW_e.

Report No: ETSU B/T1/00208/REP/1 Publication date: 1993

FUNDAMENTAL RESEARCH ON THE THERMAL TREATMENT OF WASTES AND BIOMASS: LITERATURE REVIEW OF PAST RESEARCH ON THERMAL TREATMENT OF BIOMASS AND WASTE

Warren Spring Laboratory

Background

Thermal conversion processes, most of them originally developed for coal, can be expected to have a major impact on the future use of biomass fuels. These processes employ elevated temperatures to convert 85-90% of the organic content of biomass - and waste materials - into more useful forms of energy - steam, electricity/power, liquid and gaseous fuels, charcoal and chemicals such as methanol, other alcohols and ammonia. Wood and crop residues make up most of the feedstock available for conversion: the fuels produced have a relatively low heating value because of the high oxygen content of biomass.

Objectives

- To investigate past research on the gasification, pyrolysis and liquefaction of biomass/waste, assess the merits of each technology and identify those with the greatest potential for future use in waste disposal.

- To determine the most suitable mode of the identified technologies for application to specific wastes.

- To compare the experimental techniques used previously to identify the most practicable data-producing technique.

- To review experimental data to avoid unnecessary duplication in subsequent experimental work.

Findings

Apart from orthodox combustion, there are four relevant thermochemical conversion technologies: gasification, pyrolysis, liquefaction, and the upgrading of the liquid hydrocarbons produced by pyrolysis and liquefaction.

Gasification competes satisfactorily with normal combustion, converting the biomass into gaseous fuels which can then be combusted in conventional boilers, gas turbines or internal combustion engines. It offers several potential advantages over combustion:

- The volume of the product gas is only one third of the volume of combustion flue gas. The associated downstream cleaning equipment can therefore be smaller and cheaper.

- Gasification allows a high proportion of acid gas components to be retained in the ash, again substantially reducing the demand on downstream gas-cleaning plant.

- Gasification is very versatile in respect of the wastes that can be treated.

The gasification process involves a combination of drying, pyrolysis and oxidation/reduction reactions. The reactors themselves vary in type and include fixed/moving bed (updraft and downdraft) units, various fluidised bed systems and entrained bed reactors. Of these, the fixed/moving bed is the simplest to construct, control and operate, and the downdraft system can produce a gas that requires only limited clean-up in relation to tar and particulates to make it suitable for combustion in internal combustion engines and gas turbines. Another important feature of this unit is that, with the assistance of additives such as limestone and dolomite, large amounts of acid gas (hydrogen chloride and hydrogen sulphide) can be retained in the ash.

Fluidised bed and entrained bed systems, on the other hand, although versatile in their operation, are generally more difficult to design, build and operate, are more expensive, and are currently considered inappropriate for small-scale applications of less than 1MW.

Gasification can be used to produce low-, medium- and high-energy gas:

- Low-energy gas is produced by gasification with air and competes effectively with combustion. As well as being used in boilers and gas turbines, there are proposals for its use in the internal combustion engine. However, past work has shown that low-energy gas contains 15-18% hydrogen by volume and virtually zero methane at low-pressure operation.

The low-energy gasification of biomass has been commercially proven at capacities up to a few MW_e. However, in the UK, no gasification units have been fully demonstrated as capable of converting the more contaminated forms of waste such as refuse derived fuel and sewage sludge into more usable forms of energy.

- Medium-energy gas is the result of using steam or a steam/oxygen mix in the gasification process in place of air. This gas can be converted to more complex chemical compounds such as alcohols.

- High-energy gas contains a high proportion of methane and other gaseous hydrocarbons and can be used as a substitute natural gas.

Both the pyrolysis and liquefaction of biomass/wastes generate liquid fuels, although both processes require supplementary catalytic upgrading to produce fuels that are compatible with conventional fossil fuels. Maximum yields from pyrolysis are obtained at low pressure and rapid heating rates in entrained flow or fluidised bed reactors at temperatures of less than 650°C (low). Liquefaction involves high-pressure operation (up to 200 bar) in an inorganic or organic solvent. It is a complex process and, although the products contain less oxygen and have a higher calorific value, yields tend to be lower and production costs higher than for pyrolysis. Furthermore, the products of pyrolysis are much easier to pump. For these reasons, interest in liquefaction has faded during the past five years.

The review has shown that further effort is needed at the laboratory and pilot scale, particularly in the case of biomass/waste materials such as sewage sludge where, despite the disposal problems currently being experienced, there is a lack of fundamental technological data. There is also a need for long-term demonstrations of the feasibility and technical soundness of the various technologies being explored.

Recommendations

- Bench-scale pyrolysis, gasification and combustion studies on a range of wastes, particularly those such as sewage sludge, scrap tyres and straw which face growing disposal problems.

- The application of downdraft gasification to the chain grate stoker process (the most appropriate technique for refuse derived fuel combustion).

- Kinetics studies of the gasification reactions on some of the waste chars to provide information for the design and operation of the gasification unit.

- Leach tests on ash products.

- The development of large-scale waste treatment units, specifically:

  – the design and development of a pilot-scale continuous feed fixed/moving bed downdraft gasifier to investigate the gasification of a wide variety of biomass and waste

  – the design and development of a pilot-scale pyrolysis test rig for the production of oil, together with the development of a process for upgrading the crude oil so that it is compatible with conventional fuel oils.

Report No: ETSU B/T1/00208/REP/2 Publication date: 1993

FUNDAMENTAL RESEARCH ON THE THERMAL TREATMENT OF WASTES AND BIOMASS: THERMAL TREATMENT CHARACTERISTICS OF BIOMASS

Warren Spring Laboratory

Background

Biomass is ranked as a promising renewable energy source that contains immense potential for supplementing fossil fuels in the immediate future. Over the past decade, interest in the thermal treatment of biomass and waste for power generation as well as for waste disposal has increased. Of the thermal treatment options available, combustion/incineration and gasification are the most practicable. However, nearly all the energy/power generated from biomass and wastes has been by conventional direct combustion/incineration, and little information is available on gasification, particularly of wastes.

Project Objective

- To determine the thermal characteristics of various types of biomass/waste that are suitable for disposal by gasification or combustion, the characteristics to provide indicators to their performance in full-scale plant.

Methodology

Tests were carried out on refuse derived fuel (RDF), digested sewage sludge, wood, straw and scrap tyres. The work was carried out in a cylindrical pot furnace, 400mm in diameter and 420mm high, internally lined with refractory and externally insulated. Each waste was tested individually under two conditions:

- primary air flow rate of 1250 kg/h/m^2 (normal combustion conditions)
- primary air flow rate of 150 kg/h/m^2 (sub-stoichiometric/gasification conditions)

The tests sought to determine fuel bed temperature, combustion/ignition rates, ignition temperature, thermal loading, potential clinker formation and product gas composition.

Findings

Fuel bed temperature

Under normal combustion conditions, the maximum bed temperature was around 1200-1300°C for all fuels tested. Under gasification conditions there were two clear reaction stages, ignition and burn-out. Ignition stage temperatures were around 800°C for all fuels tested. In the burn-out stage, maximum fuel bed temperatures varied from fuel to fuel:

- RDF 1200°C
- sewage sludge 1050°C

- wood blocks 1125°C
- straw 1000°C
- scrap tyres 1300°C.

Ignition rates

Individual rates of ignition for RDF, wood and digested sewage sludge remained reasonably similar for both gasification and combustion conditions. However, for straw and scrap tyres the rate of ignition under gasification conditions was only one-third that for normal combustion. Overall, the highest rates of ignition were for straw and scrap tyres under normal combustion conditions and for straw and wood under gasification conditions.

Thermal loading

Under normal combustion conditions, the average rate of combustion/thermal loading for complete combustion was 0.8-1.0 MW/m^2 for all the wastes except sewage sludge. The latter is less reactive and the loading was only 0.35 MW/m^2.

Average thermal loading under gasification conditions was much lower, 0.30 MW/m^2 overall, and 0.18 MW/m^2 for sewage sludge

The rates of reaction were shown for wood blocks to be 270 $kg/h/m^2$ for combustion and 115 $kg/h/m^2$ for gasification.

Volatile content

The studies have shown that most forms of biomass/waste have an extremely high volatile matter content (80-90% wt, dry ash free (daf)). Full-scale tests have shown that combustion is incomplete under conventional single-stage conditions, giving rise to severe smoke emissions. Full combustion should therefore be carried out in a two-stage system. The initial stage must be sub-stoichiometric gasification, and the product gas from this could be burnt in a boiler as in normal combustion, or in a reciprocating engine/gas turbine for electricity generation.

Fixed carbon content

For all the wastes tested, except scrap tyres, the fixed carbon content was very low (10-20% wt, daf). Furthermore the reactivities of the charcoals produced by these fuels was extremely high. The reactivity of scrap tyre charcoal (33% wt, daf), on the other hand, was much lower, comparable with the charcoal from bituminous coal.

Fuel moisture content

The moisture content of most forms of biomass/waste must not be more than 15% by weight if the fuels are to be pelletised. Higher moisture levels could adversely affect the pelletisation/densification process, causing disintegration during subsequent handling, transportation and combustion. A high moisture content will also reduce the thermal efficiency of normal combustion, removing high-grade energy as latent as well as sensible heat. It follows from this that the drying requirements for certain fuels, including RDF,

sewage sludge and many others, can be substantial. However, it may be possible to make use of the cheap low-grade energy associated with the thermochemical process, ie sensible heat in the gasification product gas or in the flue exhaust gas from internal combustion engines and turbines. Although wood does not need to be pelletised, thermal efficiency can be improved by ensuring that it is dry since wood that is freshly felled has a moisture content of 30-50% by weight.

Ash residue

The ash content and the ash fusion temperature of a fuel both have an important role to play in combustion and gasification. For wood and straw, there was no distinct clinker formation under either combustion or gasification conditions. However, for RDF and sewage sludge, although only small amounts of clinker were formed under gasification conditions, normal combustion caused the formation of hard lumps of clinker, posing potential operating problems.

Acid gas emissions

The tests suggest that there should be no acid gas emission problems from the combustion or gasification of wood, which contains only 0.1% by weight of sulphur and no chlorine.

However, both the combustion and the gasification of scrap tyres and sewage sludge will give severe sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) emission problems, the SO_2 concentration for the combustion of sewage sludge being around 2000 parts per million by volume (ppmv).

Hydrogen chloride (HCl) emissions arise from both RDF and straw, the flue gas levels under normal combustion conditions being around 1000ppmv and 400ppmv, respectively.

However, it is clear that the lower temperatures associated with gasification provide conditions that are conducive to in-situ acid gas retention using chemical additives. Tests carried out on RDF have shown that 60-70% of the fuel's chlorine content was retained in situ when 3.5% by weight of limestone was added. Dolomite is reputed to be the most effective chemical for sulphur retention, and tests need to be carried out to investigate this.

Recommendations

Investigations into chlorine retention with limestone using full-scale thermal treatment processes.

Further investigations into in-situ sulphur retention in the pot furnace gasification of sewage sludge.

The application of pilot plant downdraft gasification to coppice wood and straw.

3.2 The Potential for Gasification

Report No: ETSU B 1167 Publication date: 1986

TECHNICAL AND MARKET ASSESSMENT OF BIOMASS GASIFICATION IN THE UK

Aston University

Project Objectives

- To identify and characterise UK and relevant overseas biomass gasification systems.
- To assess the capital and operating costs in each case.
- To derive fuel gas and electricity production costs.
- To identify markets and opportunities for the various technologies.

Methodology

A database of gasification activities has been generated both from the literature and from responses to a survey questionnaire. This allowed the main characteristics and costs of gasifiers to be derived.

The fuels considered were wood and wood waste, straw and other agricultural wastes, refuse and sewage sludge.

Findings

Capital costs

The difference in capital cost between gasification and combustion is typically within $\pm$ 10%, taking into account both feed rate and energy output. For any given size of basic gasifier, there appears to be a minimum capital cost that is independent of gasifier type and that benefits from the conventional economies of scale.

Two levels of gasifier technology have been deduced:

- Basic systems include fixed beds and single fluid beds based on air gasification. These give a low-heating-value (LHV) gas (4-7 MJ/Nm^3), and are currently the most widely used. Fluidised bed systems offer greater versatility than fixed beds and with no cost penalty. They are readily scaled up and are not as feed-specific as fixed-bed reactors.

- More sophisticated technologies include oxygen gasification and twin (circulating) fluid beds. These generate a medium-heating-value (MHV) gas (12-18 MJ/Nm^3) but are up to three times as costly as the basic systems. Similar in cost to coal gasifiers, these systems are unlikely to be economically attractive in the short term, although there are, potentially, substantial advantages at larger plant sizes. Normally, where an application requires MHV gas, it is more economic to generate this using pyrolysis techniques.

Gas production costs

Production costs for hot raw fuel gas and cold clean fuel gas are summarised in Table 1 below for different sizes of plant and different feedstocks. These costs agree well with those estimated by various plant contractors. The likely attainable selling price for the gas produced is £2.40-£2.60, about 75-80% of the current interruptible natural gas price. Although MHV gas is potentially more valuable than LHV gas, the premium could not be established and is unlikely to be significant. The £2.40 level was adopted for economic analysis.

The main conclusions to be drawn are summarised below for current feedstock and equipment costs and for the production of a cold clean fuel gas:

- Refuse can be economically converted to a fuel gas at plant capacities of more than 1 tonne/hour if there is a disposal credit of £5/tonne of raw refuse, and at plant capacities of about 0.75 tonnes/hour if the disposal credit is £10/tonne of raw refuse. Refuse is the only feedstock giving payback times of less than three years at reasonable scales of operation.

- In the case of straw, fuel gas can only be economically produced on-farm at plant capacities of 2 tonnes/hour and above. In the case of delivered straw, the technology does not become viable until plant capacity rises to 9 tonnes/hour or more.

- Wood wastes cannot economically be converted to fuel gas or power at current fuel costs. The break-even point for wood with a 50% water content is estimated at £7.50/tonne (£15/tonne dry ash free(daf)) or less.

An assumption that the requirement is for hot raw gas rather than cold clean gas does not significantly affect these conclusions, except that production from straw becomes viable at a realistic scale of operation.

It is clear that the most sensitive cost element in gas production cost is the feedstock cost, and that using wastes on site offers economic advantages because of the relatively high costs of off-site handling and transportation.

Market potential

The current total potential feed supply for gasification has been estimated at 44 PJ/year, based on current economically realisable wastes and residues, and assuming no changes in the quantity or availability of waste. In the “most likely” scenario, the number of new gasifiers (2.5 tonne/hour daf units) installed will increase to six/year over the next ten years, with a capital value of £3.6 million at 1985 prices. This will bring the total number of gasifiers to 37, supplying about 8.3 PJ/year and representing a total investment over the time period of £22.2 million at 1985 prices.

Table 1 Cold clean and hot raw gas production costs (£/GJ)

Fuel	Assumed conversion efficiency	Plant capacity			
		1 t/h	2.5 t/h	5 t/h	10 t/h
Cold clean gas					
Straw					
£22/tonne delivered	78%	3.2	2.7	2.4	**2.3**
£17/tonne on farm	78%	2.8	**2.3**	**2.0**[1]	**1.9**[1]
Refuse (wet)					
£10/tonne disposal credit	71%	**2.0**	**1.4**	**1.2**	**0.9**
£5/tonne disposal credit	71%	2.7	**2.1**	**1.9**	**1.7**
Refuse (dry)					
£10/tonne disposal credit	78%	2.5	**2.0**	**1.7**	**1.6**
Wood					
£17/tonne delivered	62%	4.6	3.9	3.6	3.4
£13/tonne on site	62%	4.0	3.3	3.0[1]	2.8[1]
£7.50/tonne	62%	3.1	**2.4**	**2.1**	**1.9**
Hot raw gas					
Straw					
£22/tonne delivered	90%	2.7	**2.3**	**2.1**	**2.0**
£17/tonne on farm	90%	**2.4**	**1.9**	**1.8**[1]	**1.6**[1]
Refuse (wet)					
£10/tonne disposal credit	83%	**1.7**	**1.2**	**1.0**	**0.8**
£5/tonne disposal credit	83%	**2.3**	**1.8**	**1.6**	**1.5**
Refuse (dry)					
£10/tonne disposal credit	90%	**2.1**	**1.7**	**1.5**	**1.4**
Wood					
£17/tonne delivered	72%	3.8	3.?	3.1	2.9
£13/tonne on site	72%	3.3	2.7	2.1[1]	**2.3**[1]
£7.50/tonne	72%	.5	**2.0**	**1.8**	**1.6**

[1] Feedstock unlikely to be available on site in sufficient quantities.

The steady state market is about 20 gasifiers per year with a market value of £12 million at 1985 prices. However, changes in the quantity of waste and increases in its economic availability will alter this market potential, almost certainly resulting in an increase in the figures quoted.

The most likely industrial markets for fuel gas from biomass and wastes are where gas quality specifications are undemanding, for instance in direct firing and boiler retrofitting. LHV gas is suitable for most applications, and any difficulties achieving the highest flame temperatures can usually be overcome by mixing LHV gas with natural gas.

Direct firing in process industries is likely to be the main application, particularly in the lime, cement, brick and unglazed pottery sectors. Other potential applications are in the non-ferrous metal and glass sectors, although quality requirements are likely to be more stringent.

Gas quality requirements in boiler retrofitting applications are not generally onerous. No specific industrial sector is likely to benefit more than any other, and location in relation to feedstock quantities and costs is likely to be a more important factor. The economic attraction of this application involves both the lower initial cost of retrofitting and the lower running costs associated with the fuel gas generated.

In terms of power generation, refuse is likely to be the only feedstock that can compete effectively with current average power costs to industry of about 3.8p/kWh.

Report No: ETSU B/M3/00388/04/REP Publication date: 1993

DOWNDRAFT GASIFIERS UNDER 200kW$_e$

LRZ Ltd

Background

Concern for the environment, fears over dwindling fossil fuel resources, and the desire to use agricultural land for non-food uses have stimulated an interest in farm- and forest-produced biomass fuels. However, fuels such as wood and straw have low energy densities and are both bulky and expensive to transport. This limits economic haulage distances and leads to the conclusion that biomass fuels are best converted near the point of production either to a form in which they can meet the requirements of the limited domestic heating market or into electricity.

Electricity is, in many ways, the highest grade of energy. It is readily convertible, at high efficiencies, into other energy forms; it is readily transported; and it can now be produced by private generators and sold into the national distribution system. Furthermore, the Non-Fossil Fuel Obligation (NFFO) provides a mechanism for the payment of premium prices for electricity generated from renewable fuel sources.

Most of the UK's electricity is generated using large-scale steam plant, mainly fuelled by coal. Fuel availability significantly restricts the size of biomass-fuelled plant, and generating electricity using small-scale steam plant is both capital intensive and inefficient. For example, the efficiency of a small, on-farm, steam-cycle plant would be well below 10% in most cases.

The alternative is to use a readily available generator set based on an automotive-derived engine. Although most such units operate using conventional distillates and gaseous fuels, it is possible to produce an appropriate combustible gas from biomass using a downdraft gasifier.

Project Objective

- To provide agricultural or plant engineers with details of the background, equipment, processes and economics of power plant based on the downdraft gasification of wood.

Gasifiers and Their Operation

Downdraft gasifiers have been in existence since the early 20th century. Although significant operational problems remain, several designs are manufactured commercially, and some of these appear to work given a uniform feedstock of the correct quality.

Thermochemical gasification transforms solid feedstock into combustible gas by partial oxidation at elevated temperatures. Different types of gasifier suit particular scales of operation, with the downdraft fixed-bed gasifier being the most appropriate for 0-200kW$_e$ (possibly up to 500kW$_e$) applications.

The downdraft gasifier consists of a cylindrical reaction vessel, usually with a constriction near the base. Fuel enters the top of the vessel and moves under gravity down through the unit, gradually rising in temperature as it does so. Drying takes place in the upper layers of the vessel, and this is followed first by pyrolysis, then by oxidation and finally by reduction.

Pyrolysis drives off the volatile constituents of the fuel. The main products of pyrolysis are carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), formic acid, acetic acid, hydrocarbons and char. Of these, the CO and H_2 are combustible, but the hydrocarbon fractions contain very large tar molecules that must be reduced in size before they enter the combustion engine.

Oxidation of the char takes place with added air in the lower part of the gasifier, producing CO_2 and methane (CH_4). The large tar molecules in the gas phase also burn to form CO_2 and H_2O. Further combustible gases are generated in the subsequent reduction zone. Some unburnt carbon remains in the final ash. High temperatures in the oxidation zone can also cause some slagging of the ash. To ensure efficient ash removal, and to promote an even flow of fuel down through the gasifier, an automatically operating riddling grate, often of the semi-rotary type, is fitted.

The quality of the initial fuel is critical to the successful operation of any gasifier plant. The most important variables are:

- moisture content - normally less than 25%
- particle size - fairly even, 1-2" cubes or similar, no fines
- ash content - maximum of around 5% usually quoted.

To achieve these fuel characteristics, it may be necessary to install some on-site fuel preparation facilities for:

- drying - making use of engine waste heat
- screening and rechipping to deal with outsize material
- the removal of fines and tramp material.

Gas Clean-up

Gross particulate contamination is normally removed in a hot cyclone. The gas is then cooled - either by bubbling the gas through water or by using a dry cooling system - and filtered to remove any remaining tars.

Engine and Generator Plant

Either spark ignition or compression ignition reciprocating engines can be used with a downdraft gasifier. The former has particular attractions in that it does not incorporate a costly fuel-injection system, nor does it need a second fuel. However, it is less tolerant of gas quality variations than compression ignition engines and requires air:fuel ratio control, sometimes automatic, to achieve the necessary compensation. Sets with an induction generator will operate at constant load.

Compression ignition engines are dual-fuel systems that incorporate a diesel fuel-injection system and require diesel as well as a gas/air mixture to operate. They can even operate during a total disruption of gas supply.

Power generation systems of this type can operate either as stand-alone (islanded) units or in parallel with the mains. Stand-alone systems may operate permanently or temporarily in this mode. Permanent islanding may exist in remote locations. Where the generator operates as a standby set in the event of mains failure, islanding is temporary.

Operation in parallel with the mains can occur under several conditions:

- the site plant provides the base load, with the regional electricity company (REC) supplying power at a reduced rate to meet the remaining demand

- site plant output fluctuates, sometimes providing more than the site requires and sometimes less

- the site plant always produces more than the site requires, eg acts as a small power station.

Operation in this mode requires the installation of protective equipment to ensure no adverse reactions between the public supply and the private generator.

Economics

The economics of a gasification plant are determined by a number of factors, including:

- capital cost, particularly the cost/kW of capacity
- value of electricity generated
- value of heat recoverable from the engine coolant and from the exhaust
- fuel cost
- plant availability (hours/year).

If the plant can be procured for an attractive price and operated reliably on the fuel available, then gasification holds much potential. However, the onus remains on the project developer to ensure that all the necessary technical and economic conditions can be satisfactorily met. It is therefore strongly recommended that advice is sought from both existing users and from qualified professionals at the earliest possible project stage.

Report No: ETSU B/T1/00351/REP Publication date: 1996

DECENTRALISED PRODUCTION OF ELECTRICITY FROM BIOMASS

Natural Resources Institute

Background

Approximately 18% of the European Union's most productive arable land could be taken out of production under Common Agricultural Policy Rules. Some of this land could be permanently set aside for energy crop production. Other biomass fuels are available from agriculture and forestry-related residues/wastes, and under-exploited traditional coppice.

Although larger-scale electricity generating plant is more likely to be economic, farmers and rural industries in the UK and Europe are very interested in smaller-scale technologies that can be implemented on individual farms or in a locally centralised location. There is a need for a broad examination of the whole system - from fuel supply/cropping activity through preparation of the fuel to conversion to electricity.

Project Objectives

The overall objective was to research the conversion of energy crops into electricity. Specific objectives were:

- To determine the production potential and economics of growing selected energy crops in a representative area of the UK.

- To carry out a technical and economic evaluation of available equipment for the generation of electricity through the thermal conversion of energy crops.

- To review the routes for power generation using biomass feedstocks and to define systems for field testing based on technical, economic and environmental criteria.

Methodology

The project examined the production of electricity from solid biomass for power outputs of $100kW_e$-$2MW_e$. It considered both commercially available technologies and those under development, and it carried out a detailed analysis of selected options at or near the commercialisation stage.

A regional mapping approach was used in the East Midlands region to indicate potential areas for the supply of energy crops grown on set-aside land. This involved:

- collating data on the magnitude of various agricultural activities and on concentrations of large agricultural electricity users

- identifying the locations and routes of regional and national power lines in the area

- obtaining additional data - roads, motorways, built-up areas etc - from Ordnance Survey maps.

The information was digitised and plotted. Potential generation sites were identified and the connection costs investigated.

Electricity production costs were assessed using two models:

- the integrated farm model, which minimised costs by allowing farm labour inputs to be allocated to electricity production

- a modified International Energy Agency model which assumed that feedstock was bought in.

Sensitivity and environmental analyses were also carried out.

Findings

Suitable energy crops

Short rotation coppice (SRC) using either willow or poplar is a favoured option in the UK, with yields of 12 tonnes/ha/year. The East Midlands could produce around 1.25 million tonnes of dry wood chips if half the set-aside land were to be planted with SRC. This represents a continuous generating capacity of about 150MW_e assuming an 18% conversion efficiency. A similar tonnage is already available from cereal straw.

Short rotation willow and poplar coppice is being grown in demonstration plots. However, production is unlikely to be sufficient by the time a biomass power plant comes onstream, and agricultural and forest residues would be needed to supplement energy crop fuel during the initial years of power production.

System specification

Updraft gasification systems are the most practicable non-traditional route for power generation from biomass, provided improvements in gas clean-up systems are made. Neither gasification nor conventional steam systems are recommended at the 100kW_e scale.

Site selection

For the 2MW_e plant, the most convenient sites from the point of view of transport and power network connection were disused mine or power station sites in the area and the Bardon 22 Industrial Estate. Although the potential biomass fuel resource was not as concentrated as in more agricultural centres, ample fuel could be sourced within a 40km radius and potentially, given a high degree of SRC take-up by farmers, within an 8km radius.

Fuel for a 100kW_e system could be supplied from one large farm of the size that typically exists in the East Midlands region. Maintaining operation of the generator for 5000 hours/year would require 55ha of SRC.

Economics

Including financing, the gasification route could generate power at the following costs:

- $2MW_e$ output: 0.105 ECU/kWh
- $100kW_e$ output: 0.132 ECU/kWh.

A sensitivity analysis for the gasifier and engine system showed that availability is the single most important issue affecting the price of the electricity generated. It is therefore essential that such a plant is designed and operated for reliability. Other issues identified as having considerable importance in this respect are efficiency, feedstock costs and discount rate, the latter directly linked to the capital cost.

The study has shown that, capital costs of around 1000 ECU/kW of installed capacity are required for small-scale systems to be economic. For larger systems ($2MW_e$ in this study) capital costs up to 2500 ECU/kW of installed capacity can be tolerated.

Environmental issues

Although the burning or decay of plant material releases carbon to the atmosphere, this can be effectively "recycled" through photosynthesis as new energy crops are grown. This means that, if the energy crops are managed sustainably, a biomass fuel cycle contributes little or no net carbon to the earth's atmosphere. Furthermore, as a renewable energy source, biomass may displace carbon emissions from fossil fuel combustion.

At the local level the environmental issues are less clear cut and are best addressed by the Environmental Impact Assessment (EIA) to which most power-from-biomass projects will be subject under European Law. However, the impact of the project can be mitigated to a large degree by careful implementation, and the EIA is a useful tool for identifying measures that will make the system more environmentally acceptable.

Recommendations

- Consideration to be given to issues associated with the use of a range of biomass fuels - SRC, wood residues, agricultural and industrial wastes.

- A 2-$5MW_e$ biomass-fuelled power station using updraft gasification to be designed, developed and assessed in relation to feedstock requirements and market potential.

- Alternative technologies, eg the indirectly fired gas turbine at 200-$500kW_e$, to be developed for smaller-scale applications.

Report No: ETSU B/M5/00533/09/REP Publication date: 1996

SMALL-SCALE BIOMASS CHP USING GAS TURBINES: A SCOPING STUDY

James Engineering (Turbines) Ltd
LRZ Ltd

Background

If the conversion of biomass to energy is to be undertaken on a large scale, it will need to be commercially attractive without subsidies. However, at present, both the cost of the biomass fuel and the costs of conversion are high, and it is clear that the best option is to convert the fuels close to their point of production into higher value commodities that are cheaper to transport (essentially electricity).

Project Objectives

The purpose of this study is to evaluate various options for small-scale (up to 250kW$_e$), self-contained CHP plants that can be located close to the fuel source, that can be moved when necessary, and that can supply electricity and heat to wherever they are required. Because this limits the technology to the small gas turbine, specific objectives were:

- To identify and describe the range of system options by which gas turbine technology could be used in small biomass CHP plant.
- To identify the technical and financial risks that need to be addressed before the technology can be commercialised.
- To establish the size and character of the UK market for this type of equipment.

Methodology

The study has considered both combustion and gasification options:

- Direct firing - the exhaust gases from a pressurised combustor form the working fluid in a gas turbine.
- Indirect firing - the exhaust gases from a biomass combustor are used to heat air (via a heat exchanger). The air is then used as the working fluid in a gas turbine.
- Direct gasification - gas produced in a gasifier is cleaned, burned and used as the working fluid in a gas turbine. Gas from a conventional downdraft gasifier will be compressed first. Gas from a pressurised downdraft gasifier will be used directly.
- Indirect gasification - gas produced in a downdraft gasifier is cleaned and burned to heat air (via a heat exchanger). The heated air is used as the working fluid in a gas turbine.

A simple BASIC computer program was developed to calculate thermodynamic parameters for each option from data input by the user. The following constraints were applied:

- two plant sizes - a unit generating 15-25kW$_e$ and a unit generating 150-200kW$_e$
- a turbine inlet stagnation temperature of 850°C
- other parameters identical for all calculations.

The results were fed into an overall economic analysis that also takes into account relevant capital and operating costs.

The market for small-scale biomass CHP was identified in terms of who the potential customers are and the extent to which they can justify investing in the necessary plant. Three detailed case studies are used to quantify the circumstances under which specific technical options can be used to satisfy customer requirements.

Findings

The main technical performance characteristics are summarised in Table 1 below.

An economic case can be supported for the commercial development of biomass-fired CHP units incorporating gas turbines, depending on the cost of the fuel and the continued operation of Non-Fossil Fuel Obligation incentive schemes. However, the minimum size of plant that can be justified commercially is unlikely to be less than 200kW$_e$ because of the fixed nature of the costs for operation and maintenance and for electrical connection.

The potential market for small-scale biomass CHP can be divided into three:

1. Those whose interest is motivated by the availability of fuel:

   a) those with a waste stream to dispose of, perhaps at some cost, eg joinery waste or wood waste from industry

   b) those with the potential for producing fuel, at a cost, and wishing to add value to it, eg owners of undermanaged woodland, short rotation coppice (SRC) or forest residues.

2. Those whose interest is motivated by a need for heat and/or power:

   a) existing CHP users, or those in with similar requirements
   b) potential users of biomass for space heating
   c) potential users of biomass for process heat
   d) those wishing to generate electricity for their own use or for sale under NFFO.

3. Sites where conditions 1 and 2 above coincide:

   a) country estates with fuel resources and large buildings
   b) larger operations producing waste and having significant heat/power loads
   c) Type 2 sites where fuel-producer-led contract energy management is applied.

Table 1 Leading technical performance characteristics

Cycle	Recuperator	Size	Electrical output (kW)	Electrical efficiency	Heat:power	Unresolved technical issues
Combustion - direct	No	Small	25.0	10.1%	8.8	Clean-up/turbine fouling/corrosion/ pressurised feeding/pressurised combustor
Combustion - direct	Yes	Small	18.1	17.5%	4.7	
Combustion - direct	Yes	Large	178.0	30.7%	2.3	
Combustion - indirect[1]	No	Small	18.1	13.5%	6.0	High temperature heat exchanger fouling
Combustion - indirect[1]	No	Large	178.0	25.4%	2.9	
Combustion - indirect[2]	Yes	Small	15.0	4.4%	4.7	
Gasification - external	Yes	Small	22.0	20.1%	3.8	Gas compressor/fuel tolerance of gasifier
Gasification - external	Yes	Large	186.0	31.6%	2.2	
Gasification - direct	Yes	Small	18.1	16.6%	4.7	Fuel tolerance of gasifier/pressurised feeding
Gasification - direct	Yes	Large	178.0	29.2%	2.3	
Gasification - indirect	No	Small	18.1	12.8%	6.0	High temperature heat exchanger
Gasification - indirect	No	Large	178.0	24.1%	2.9	

[1] Waste heat recovery unit located in combustor exhaust
[2] Waste heat recovery unit located in turbine exhaust

Type 3 sites offer the best potential in the short term.

Anticipated user requirements can be summarised as follows:

Type 1a	Maximum reliability Minimum intervention As convenient and cost-effective as alternative waste disposal options Payback of less than three years
Type 1b	Efficiency vs capital cost optimised Low levels of intervention - regular visit acceptable 15% return on capital
Type 2	Dependable for major output of heat or power Tidy, quiet, no mess As convenient and cost-effective as alternative heat/power sources Payback of less than four years
Type 3	Efficiency vs capital cost optimised Low levels of intervention - regular visit acceptable Dependable for major output of heat or power Tidy, quiet, no mess As convenient as alternative heat/power sources
(Type 3a/3c)	15% return on capital
(Type 3b)	Payback of less than three years.

Conclusions

1. Although there is no adequate operational or experimental evidence, two options appear to merit further investigation:

   - direct biomass firing incorporating two-stage combustion in cyclone burners
   - indirect biomass firing incorporating two-stage combustion.

1. Direct firing combines high efficiency with high technical risk. Indirect firing offers lower efficiencies but the risk is also reduced. Indeed, on sites with free fuel, indirect firing suffers relatively few disadvantages compared with direct firing, as long as there is sufficient demand for the extra heat.

Recommendation

A small (about 40kW$_e$) experimental facility should be constructed to determine the levels of technical risk and the potential commercial attributes of both options.

3.3 Gasification: Specific Technical Issues

Report No: ETSU B/M3/00388/08/REP Publication date: 1994

COPPICE WOOD DRYING IN A GASIFICATION POWER PLANT

Stamford Consulting Group

Background

The presence of too much moisture in the wood chip feedstock to a gasification power plant would significantly reduce the efficiency of the generation cycle and, in the extreme, would interfere with the operation of the gas engine by reducing the calorific value of the fuel.

Project Objectives

- To assess the heat flows and thermodynamic demands involved in drying coppice wood from 35% to 15% moisture content.
- To assess the waste heat flows provided in terms of both their ability to remove moisture without becoming saturated and their economical use in the process.
- To evaluate available drying methods and recommend the best option for this purpose.

Findings

The drying process

When a natural cellulosic material is cut down (eg when a tree is felled), its initial moisture level is easily reduced. Under natural conditions, this reduction takes place slowly. If the process is accelerated by forced drying at elevated temperatures, the adjacent air quickly becomes saturated during the early stages of drying (the psychrometric drying period). As the moisture content of the material falls, so does the rate of drying. Eventually a point is reached when the evaporation of moisture is determined not by the ability of the air to take up water vapour but by the rate at which the water molecules diffuse through the mass of solid material. At this stage the drying process is known as the thin film or diffusion process.

The waste heat potential

A preliminary process flow sheet for the drying process gave the following information:

Wood flow rate @ 35% moisture: 2.148 kg/second
Wood flow rate @ 15% moisture: 1.6426 kg/second
Moisture evaporation rate in dryer: 0.5054 kg/second

Waste heat at 80°C from the engine cooling water: 2.24MW thermal
Waste heat at 80°C from engine oil cooling: 1.34MW thermal
Waste heat at 120°C from engine exhaust: 1.42MW thermal

The heat required to dry the wood chips is 1.3MW. The low grade heat available is 5MW. However, because the low grade heat is quoted above a datum of 0°C, not all the energy is available in practice.

Calculations show that, assuming an ambient temperature of 15°C, the total heat required to dry wood chips to a final temperature of 55°C is 1490 kj/second.

If the waste heat from the engine cooling water and oil cooling were to be captured in a heat exchanger, it would be possible to generate an air flow rate at 70°C of 64.87 kg/second. However, the final air temperature would fall to 47°C and, while drying at these temperatures is certainly feasible, the power consumption of fans and the size of the equipment needed suggests that heat from the engine exhaust should be used. This has a higher temperature, and the quantity of heat is unlikely to decline.

Combining the exhaust gas with air from the water and oil heat exchangers would give a combined air flow of 76.18 kg/second at 77°C and a dew point of 23°C. However, the exhaust gas contains contaminants such as carbon monoxide (CO) and oxides of nitrogen (NO_x). Any build-up of the latter could cause corrosion in the dryer. Furthermore, reducing the absolute humidity level in the system improves the rate of mass transfer in the drying process. The recommended option is therefore to install a heat exchanger between the exhaust gas and clean dry air.

Using a heat wheel of the type now being applied to large gas-fired boilers would produce 9.61 kg/second of clean air at 115°C.

Adding the mass flows of low grade heat gives 74.48 kg/second at 76°C.

Dryers and dryer operation

The average rate of feedstock at 35% into the dryer is assumed to be 35.8 m^3/hour or 10.6 litres/second.

The overall drying time is assumed to be one hour.

The air flow through the dryer would be 73.5 m^3/second, and air would leave the plant at an estimated relative humidity of 18% at 56°C.

Many types of dryer are unsuited to wood chip drying: the rotary kiln dryer is only applicable to relatively high temperatures; drying floors and tray drying tend to be labour-intensive; fluidised bed drying is unlikely to be successful because of the difficulty of maintaining the fluidisation of irregular particles; wood chips do not flow freely and are therefore unsuited to drying silos.

The best type of dryer for wood chips is one comprising mass flow drying beds in which the material to be dried is spread out on a travelling belt in a uniform layer. The required rate of evaporation (0.5054 kg/second) can be achieved given the following parameters:

Volume of wood chips: 25.8 m^3/hour
Thickness of chip bed: 300mm
Length of bed of chips: 28.6m or three layers each 9.6m long
Width of bed of chips: 3m
Area of bed exposed to chips: 86m^2

Air flow entering dryer at 76°C: 73 m^3/second
Air velocity through bed: 0.85 m/second
Air exhausted at 56°C and 18% relative humidity

The travelling belt can be woven or perforated material. If designed in three layers, the wood chips can be arranged to cascade under gravity from layer to layer, disturbing the material during the drying process and presenting fresh surfaces to the incoming air. The air is normally passed downwards through the bed to prevent air pollution.

An alternative novel configuration that might be considered is a double flow inclined bed dryer in which the wood chips move by gravity over inclined, louvered surfaces and are collected at the bottom by a travelling screw discharger.

Power consumption

Assuming travelling belt beds and an overall pressure drop of the drying air of 1500 N/m^2, the power requirements of the plant would be 146kW at a fan efficiency of 75%.

Implications of initial moisture content

An increase in initial moisture content above the 35% envisaged for this project would have two significant effects:

- it would increase the drying time substantially (to ten hours at 60%)
- in a dryer of fixed size, it would increase the final moisture content of the wood chips.

Conclusions

It is feasible to use the waste heat from the proposed gas engine to dry the wood chips from 35% to 15% moisture content. An economic design would involve harnessing heat from water and oil cooling and from the exhaust gases, in the latter case via a heat wheel. The recommended dryer design is a multi-pass travelling belt dryer. Chip residence time is one hour.

Report No: ETSU B/T1/00358/REP Publication date: 1997

STUDIES ON THE THERMAL PROCESSING OF BIOMASS AND WASTE MATERIALS

Mitsui Babcock Energy Ltd

Background

There is an increasing interest, world-wide, in the development of technologies for the thermochemical processing of biomass and waste materials. Of particular interest are the gasification processes which produce a low/medium calorific value gas, a solid residue and some liquid/condensable products. However, the successful development of gasification technologies will require a detailed knowledge of the characteristics and behaviour of the feedstock constituents. This project is designed to provide this knowledge for cereal straw, Danish pine roundwood, short rotation coppice (SRC) willow and poplar from two sites, scrap vehicle tyres, sewage sludges, refuse derived fuels (RDF) and poultry litter.

Project Objectives

- To provide data on the basic characteristics of a range of biomass and waste materials, relevant to their use in energy conversion processes.
- To provide data on the reactivity of these materials and their chars in gasification processes.
- To provide information about the characteristics of the inorganic constituents of biomass and waste materials and their behaviour at high temperatures.

Findings

Biomass materials

The cereal straw had an ash content of around 4%, which is fairly typical for this material. Sulphur and nitrogen contents were relatively low: the chlorine content was rather higher at 0.83%, although high chlorine contents are not untypical of some cereal straws.

The wood materials all had low ash, sulphur, nitrogen and chlorine contents. However, there was some variation in the ash content of the different wood fractions, with bark material yielding a significantly higher ash content (3.5-4.0%) than the sap and heartwood materials (<1%).

All the biomass ashes tended to be rich in SiO_2, CaO, K_2O and P_2O_5, although concentrations varied from sample to sample. X-ray diffraction analysis of low-temperature wood ashes indicated that the crystalline phases were calcium oxalate, calcite, sygenite, potassium amidophosphate and quartz.

Fusion within the biomass ash specimens first occurred in the 600-950°C temperature range, with complete fusion occurring between 1380°C and 1500°C. The measured fusion temperatures generally reflected the CaO and SiO_2 contents of the ashes - the more refractory ash components.

Char yields for all the biomass materials were in the 22-29% range. Bark material gave the highest yields, but this char had the lowest carbon and nitrogen contents and the highest hydrogen content. There is a very good correlation between char yields and carbon and nitrogen contents.

At temperatures below 590K, char reaction rates for all materials were very low: above 700K, reaction rates were too high to measure conveniently. Reaction rates at 613K and 633K increased with increasing char yield and decreasing char carbon content. Bark char was therefore significantly more reactive than char from sapwood.

Mineral matter was found to have no influence on char yield but a significant effect on char reactivity. There was a remarkably good linear correlation between char reactivity and the CaO content of the char.

Wastes

Scrap vehicle tyres

The combustible materials in scrap vehicle tyres consist of rubber hydrocarbon at around 43%, carbon black at around 22% and mineral oils at around 11%. The rubber hydrocarbon and mineral oils have high volatile matter contents and are highly reactive in combustion and gasification processes. The carbon black is significantly less reactive.

The inorganic fraction comprises steel wire and a mineral fraction rich in CaO, ZnO and, sometimes, Al_2O_3. X-ray diffraction of high-temperature ash showed the main crystalline phases to be ZnO and $CaCO_3$.

The formation of ash deposits on heat exchanger surfaces has been a major operational problem in tyre combustion and other thermal processing plant. Samples from the Elm Energy plant showed an inner deposit adjacent to the boiler tubes and around 1mm thick that was very rich in ZnO. The bulk of the deposit, up to several cm in thickness, consisted of glassy alumino-silicate particles bonded by condensed layers of $ZnO/ZnSO_4$. The same mechanisms are also likely to occur in gasification systems, if temperatures are sufficiently high.

Sewage sludge

Dried sewage sludge is a high volatile, highly reactive material with an ash content of 20-40% and a gross calorific value of 15-20MJ kg^{-1}. The sulphur content is 0.5-1.0%, and the chlorine content can be up to 1%. The nitrogen content, as would be expected for a material with a significant protein content, is relatively high (3-4% dry basis).

Sewage sludge ash is alumino-silicate based, with significant levels of free quartz, CaO and P_2O_5. It has a relatively short fusion range and is in the high slagging and medium fouling category, mainly because of the relatively high phosphate levels. Quartz is the major crystalline phase, with calcite and kaolin as less abundant phases.

Pelletised RDF

Pelletised RDF is a highly reactive fuel with a gross calorific value of 15-17MJ kg^{-1}. These fuels have a medium ash content, low sulphur and nitrogen contents, and a chlorine content that can be significant at around 1%.

Char yields at 1173K in nitrogen were 20-21% and reflect the relatively high reactivity of the paper/board constituents. The ash analysis indicated an alumino-silicate system with a high lime content. This was confirmed by the X-ray diffraction analysis of low temperature ash which gave the major crystalline phases as quartz, kaolinite, calcite and rutile, most of them derived from fillers and additives to the paper/board and plastic constituents. The ash is considered to be in the high slagging and high fouling categories.

Poultry litter

Poultry litter consists of either wood shavings or straw with significant quantities of poultry excrement. Nitrogen content is high, commonly in the 2.5-4.0% range, while sulphur and chlorine contents are low. The ashes, in common with most biomass materials, are rich in CaO, K_2O, P_2O_5 and SO_3. X-ray diffraction of low-temperature ashes indicated that the major crystalline phase is hydroxyapatite [Ca_5 $(PO_4)_3$ (OH)], with minor quantities of K_2SO_4 and NaCl. Fusion first occurred in the ash at around 800°C, with complete fusion occurring at around 1100°C. The ash analysis data and the fusion behaviour indicate that poultry litter is a high slagging and high fouling fuel. These observations are borne out by operational experience at Eye Power Station.

Conclusions

- Biomass materials are highly reactive in thermochemical processes. They generate small quantities of char that is highly reactive, even at relatively low temperatures. There is also compelling evidence of the influence of mineral components, particularly CaO, in increasing char reactivity to oxygen at low temperatures.

- The chemistry of the ash and its behaviour at elevated temperatures indicates that this material will present significant problems to the designers and operators of thermal processing plants. The formation of sintered ash deposits in existing gasifier reactors and of fouling deposits in the ash clean-up equipment represents a real problem area in which further work is required.

Report No: ETSU B/M5/00533/07/REP Publication date: 1996

TARRY LIQUOR PRODUCTION IN A DOWNDRAFT GASIFIER

Power Gasifiers International Ltd

Background

The downdraft gasification of biomass can result in the production of various by-products. None of these is particularly useful, but all have to be disposed of. The two main liquid waste streams from the gasifier are liquor from the fuel compartment and condensate from the gas.

The liquor is a mixture of the water given off as the fuel dries, and the wood tar that evaporates at the same time. The condensate is initially present as steam in the gas. As the gas passes through the coolers, the steam changes to a mixture of water vapour and fine droplets. The droplets are removed via a coalescer unit that is periodically drained. Both liquid wastes are currently collected in drums.

Project Objectives

- To examine the two main liquid waste streams from the gasifier and determine their constituents.
- To examine the costs of disposing of these materials by conventional means.
- To ascertain whether the liquor has any commercial uses and whether alternative, more cost-effective forms of disposal will become available in the near future.

Methodology

The gasifier was operated using Shimada briquettes as fuel. Samples of liquor and gas condensate were collected.

The costs of disposal were examined by obtaining quotations from four leading waste disposal contractors.

The Environment Agency and Anglian Water were contacted to determine whether the material could be treated in any way that would allow discharge to sewer or similar.

Several companies were contacted about more advanced disposal methods and for advice as to whether the material could be used in any way.

Findings

The tarry liquor and gas condensate produced from downdraft gasifiers present significant disposal problems that must be solved.

If off-site disposal by a specialist contractor is chosen, then bulk transport is likely to prove the least costly option, even though this will involve the installation of a bulk holding tank. The company offering this option provided a quote for the bulk disposal of up to 5000 gallons of waste. The disposal cost is quoted as £30/tonne for the liquor and £35/tonne for the gas condensate. A minimum of five tonnes is required in each case, with transport costing £320/load. A maximum phenol content of 500 mg/litre has also been set.

The cost/litre for this option is estimated at 4.41 pence, and the cost per kWh for a 200kW_e unit with a combined output of condensate and liquor of 0.2 litres/kWh is 0.882 pence.

The other options examined were:

- removal of the material in 205-litre drums (two companies)
- removal of consignments from a rented 100-litre tank (one company).

Costs ranged from 17.6p/litre (3.52p/kWh) to 18.5p/litre (3.72p/kWh), and these options were not considered to be commercially viable for a continuously operating power plant.

The Environment Agency suggested various treatment methods, with oxidation (burning) in a specialist treatment plant being the preferred option. Disposal of material to the foul sewer was discouraged, even if it were possible to meet the relevant conditions.

Anglian Water suggested that the material could probably be discharged to sewer but might fall foul of effluent limits. The concentration of phenol in the gas condensate gave cause for concern, although it was thought that sufficient dilution might occur given the small quantities likely to be discharged. A consent to discharge would be needed, and this would necessitate further investigation.

Alternative methods of disposal are potentially available. These include:

- treating the material with some form of filter or catalyst
- concentrating the material
- separating the elements using a centrifuging or ultrasonic separation technique.

Some of these processes are relatively new and therefore still expensive. Furthermore there are problems that remain to be resolved:

- Conventional filters face the fundamental problem of tarry substances coating the filters, while catalysts would probably need to be used at high temperatures, with tar in the vapour phase, again to prevent coating.

- Concentrating the material could reduce disposal costs but would itself incur a cost. Further work is needed to ascertain whether this approach is feasible and what the costs would be.

- Separation would also require further work. Ultrasonic separation, although possible, was not perceived to be economic at this stage.

It is clear that off-site disposal or treatment will be expensive. A better option may be to avoid the pollution of waste water by designing and operating the gasifier and gas clean-up systems appropriately. Discharge of the liquid waste stream to sewer could then become a secure alternative.

Report No: ETSU B/T1/00418/REP Publication date: 1997

IDENTIFICATION AND PROCESSING OF BIOMASS GASIFICATION TARS

CRE Group Ltd

Background

The potential offered by biomass and solid wastes for solving some of the world's energy problems is widely recognised. However, while conventional power generation and combustion technology are not necessarily suited to the high process efficiencies required, new generation technology offers considerable potential in this field. Two particularly useful techniques are:

- pressurised biomass gasification and combined cycle applications
- atmospheric pressure biomass gasification.

Several issues need to be addressed before technologies of this type can operate at maximum efficiency. One such issue is the formation of tars during the biomass gasification process. These high molecular weight compounds can condense, resulting in severe operational problems and reduced gas yields.

Project Objectives

The overall objective of this project was to identify and characterise process residues (primarily tars) from a range of biomass gasifiers. This would involve devising the most appropriate methods for their removal, thereby improving gas yield and avoiding the operational problems associated with tar formation. Specific objectives were:

- To obtain tars from biomass gasification plant.

- To analyse the tars, thereby determining the influence of operation and process type on tar characteristics.

- To assess the influence of tar characteristics on thermal cracking behaviour, including the composition of the product gas.

- To evaluate the catalytic cracking behaviour of these tars using a variety of catalysts to determine their influence on product gas compositions.

Methodology

Sufficient quantities of representative tars (and scrubber/condensate liquors if appropriate) were collected from four types of biomass gasification plant, a fluidised bed reactor, updraft and downdraft fixed-bed reactors and an entrained phase reactor, thereby covering a range of operating temperatures. "In-situ" sampling was also carried out on the two fixed-bed gasifiers with the aim of slowing down or precluding the free radical reactions by collecting

the tar vapour in acetone cooled to approximately -55°C. The objective in this case was that analyses should reflect more closely the tar composition present in the gasifier.

Each sample was analysed using conventional techniques to determine its elemental analysis. It was also subjected to previously developed separation methods involving solvent fractionation and adsorption chromatography to separate the material into aliphatic, aromatic and polar constituents. Both the prepared fractions and the whole tar were analysed using gas chromatography - mass spectroscopy (GC-MS) to determine their composition in detail. Probe mass spectroscopy techniques were also used to provide molecular profiles of the original tar and the aromatic and polar fractions.

The thermal cracking work programme first investigated the thermal stability of a series of neutral aromatics and oxygen-, nitrogen- and sulphur-containing compounds, model compounds that are known to be predominant species found in biomass tars. The thermal cracking pattern of the fixed-bed gasifier tar was then investigated using the Pyrojector furnace at 800°C, an inert helium pyrolysis atmosphere and 2-10mg of the tar sample.

The catalytic cracking work programme first conducting experiments to assess the potential of two catalysts, nickel/molybdenum (Ni/Mo) and dolomite on two oxygen-containing compounds and two polynuclear aromatic hydrocarbons (PAHs). The catalytic cracking behaviour of the fixed-bed gasifier tar was then evaluated using the same quantities (0.25mg) of the same two catalysts. For both experiments the Pyrojector was operated at 800°C, with a pyrolysis atmosphere containing approximately 10% H_2 and 2-10mg of the tar sample. Cracking patterns using the Ni/Mo catalyst were also investigated at pyrolysis temperatures of 400°C and 600°C.

Finally, two Pyrojectors were used in series to simulate a combined thermal and catalytic hot gas clean-up facility. The thermal Pyrojector was maintained at 950°C and the catalytic Pyrojector at 800°C.

Findings

Tar characterisation

Characterisation of the updraft gasifier tar using GC-MS showed that the tar was highly polar, consisting essentially of phenol and methoxy-type compounds and, to a lesser extent, PAHs. Post-polymerisation reactions meant that this sample contained 58% high-molecular-weight material and was not wholly representative of the tar droplets/mist in the gasifier. The sample taken using an in-situ sampling procedure gave a similar analysis but with no high-molecular-weight material.

The chemical composition of the tar present in the downdraft gasifier, taken using in-situ sampling, was comparable with the composition of the tar in the updraft gasifier. The main difference was that the downdraft gasifier tar had a lower concentration of compounds with a molecular weight of >150, and no PAHs with a high molecular weight of >200.

The major components of the tar and condensate samples taken from the fluidised bed reactor were essentially parent PAHs containing a small proportion of oxygenated (polar)

components. Interpretation of the analyses showed that, during pyrolysis at around 950°C and 12 bar pressure, the cleavage of alkyl groups from aromatic rings takes place. This results in the formation of thermally stable benzene and PAHs, with a resultant increase in the gaseous hydrocarbon content of the product gas.

The major components of tars from the entrained phase reactor again showed the major components to be essentially parent PAHs. Minor quantities of nitrogen-containing compounds were also identified.

Size exclusion chromatography confirmed that the fluidised bed and entrained phase tars are similar in chemical composition.

Thermal/catalytic cracking

The thermal stability of the selected model compounds were investigated and gave the following trend in stability: S>C>N>O. This study also confirmed that, during pyrolysis, bond-breaking of $-CH_3$, $-CH_2$ and $-CH_2-O-$ bridges between aromatic structures takes place. The high thermal stability of unsubstituted aromatic compounds accounts for the increasing aromatic character of the tar.

Thermal cracking of the updraft gasifier tar produced a range of parent aromatics, with benzene the most frequently occurring and pyrene (four-membered ring) the least frequently occurring. This reflects on the composition of the tar, which consists mainly of one- and two-ring systems.

The catalytic studies using the dolomitic and Ni/Mo catalysts found the Ni/Mo catalyst to be the more effective at lower temperatures (650°C), decomposing both oxygen-containing aromatics and PAHs. The studies also showed that both dolomite and Ni/Mo have the potential to crack biomass tar, with the main products being CH_4, C_2H_6, C_3H_8, BTX and CO_2. However, the dolomitic catalyst appears to produce a more favourable cracking pattern, yielding greater quantities of CH_4, benzene and toluene, with no carbon deposition. Further experiments using the Ni/Mo catalyst showed that cracking can also be achieved at lower temperatures (400°C and 600°C) with no carbon deposition.

The overall conclusion is that catalytic cracking offers significant benefits over thermal cracking, especially in terms of the severity of the cracking conditions and the more favourable cracking patterns.

The two-stage experiments simulating a combined thermal and catalytic hot gas clean-up facility demonstrated the advantages of a combined configuration. There was a marked increase in the proportion of hydrocarbons C_1-C_4, benzene and toluene for both the dolomitic and the Ni/Mo catalysts.

3.4 Relevant Case Study

Report No: ETSU B/M4/00532/10/REP Publication date: 1996

RENEWABLE ENERGY PILOT PROJECTS

West Wales Task Force

Background

The West Wales Task Force was set up by the Secretary of State for Wales in 1992. Its purpose was to combat the downturn in the economy resulting from the closure of local defence establishments. Its specific objectives were to strengthen and support existing businesses and business opportunities in the area; to develop skills for existing and emerging businesses; to encourage self-reliance; to secure effective land-use and infrastructure improvements; and to promote partnerships between Government departments, agencies and local businesses and organisations.

In spring 1995, a renewable energy audit was carried out in the West Wales Task Force area. This examined:

- the current extent of research into the conversion of biomass and natural elements into usable energy
- the working technology already in existence
- the financial, environmental and physical considerations essential to the establishment of actual projects
- the potential for new projects within the West Wales Task Force area.

The audit identified gaps in the knowledge and understanding of renewable energy and showed that this lack of understanding was affecting the possible take-up of renewable energy resources.

In 1996 a study of three separate pilot projects designed to bridge these gaps in the understanding of renewable energy systems was completed. This focused on three areas:

- wood fuel storage, handling and usage
- the composting of fibre from the anaerobic digestion of farm waste
- the establishment of an anaerobic digester kit.

This summary focuses on the first of these projects. The other two are discussed in a later volume in this series.

Project Objectives

- To assess the handling, storage and drying of wood fuel on a representative working farm.

- To examine the maintenance and operating requirements of the boiler unit installed.

Findings to Date

The project has identified a farming business prepared to participate in the project. The farm is a 230-acre dairy farm with approximately 33 acres of woodland. It is located a few miles north of the A40.

Marick International, a company specialising in the design and installation of gasification boiler units linked to electrical generators, believe the site to be appropriate for the installation of a 30kW gasification unit fired by forest waste, firewood and short rotation coppice. Electricity will be generated through a coupled generator set and fed into the milking parlour through the existing emergency generator switch gear.

The unit will require five tonnes of wood per week, and this will be bought in and tipped into a 30 x 15 foot bay of an existing shed. It will, if appropriate, be further cut to size and stored. A hopper adjacent to the boiler will be filled with wood every three/four days. This wood will be dried using surplus heat from the boiler and exhaust system, and will then be fed directly into the boiler.

The boiler will operate during the working day. The electricity generated will be stored:

- in ice banks in the dairy unit (required for cooling the milk)
- in existing conventional electric storage radiators in the farmhouse.

The project will be closely monitored and reported on until June 1998. The unit will then be decommissioned and returned to the installers from whom it will be hired.

Total costs are estimated to be just over £140,000, 85% of which are capital, hire and installation costs. Operating the unit is expected to cost more than £6000 over the two years; fuel will cost around £6750; and monitoring and reporting a further £6400.

4. HYDROLYSIS

Report No: ETSU-R-55 Publication date: 1900

AN ASSESSMENT OF BIO-ETHANOL AS A TRANSPORT FUEL IN THE UK
Volume 2

Chief Scientist's Group, ETSU
CPL Scientific Ltd

Background

This report is part of a technical and economic assessment of the manufacture of ethanol from biomass (bio-ethanol) for use as a road transport fuel. The first volume examined the manufacture of bio-ethanol from readily available agricultural feedstocks such as wheat or sugar beet, using established technology. It also considered the use of ethanol-petrol blends for use in existing petrol engines. The main conclusions were that, at current prices, the costs of bio-ethanol production are several times its value as a fuel, and that future R&D should focus on reducing feedstock costs, the dominant component of the overall production cost.

Project Objective

- To assess the technical feasibility and likely costs of using lignocellulosic feedstocks, such as wood and straw, for the production of bio-ethanol.

Findings

Purpose-grown biomass as feedstock

From a technical point of view, wheat is the preferred feedstock for manufacturing ethanol in the UK. Yields of wheat are likely to rise, but prices are likely to fall. As a result, the real cost of producing ethanol from wheat, which is dominated by feedstock cost, is expected to fall by about 20% in the long term, and possibly by 25% if there are improvements in the production process and in energy efficiency.

It is unlikely that new arable crops such as artichoke, chicory or sorghum could be used to generate cheaper raw materials. There is a need for novel crops with characteristics and production technologies that are designed to give a high total biomass yield. Examples might include coppiced trees, reeds and rushes, and algae. Although energy forestry is being evaluated and developed as part of the UK Department of Energy's Biofuels Programme, the trials of coppice species are still at an early stage. Large areas of the UK could, in principle, be devoted to energy forestry, but actual areas are likely to be limited by economic and other constraints. At a delivered price of £24/fresh tonne, the annual supply of wood from conventional forestry could exceed six million tonnes, and this could be used to produce up to about one million tonnes of ethanol. However, at this price, coppiced wood for ethanol production is not an economic proposition.

Lignocellulose wastes and residues as feedstock

Various lignocellulosic wastes and residues - straw, animal wastes, forest wastes, wood processing wastes, waste paper, municipal waste etc - are potential raw materials for ethanol manufacture. Of these, straw represents one of the largest resources in the UK. By 2000, about eight million tonnes is likely to be available as surplus at a real cost of around £23/tonne delivered to large-scale users. This resource could supply around 1.9 million tonnes/year of ethanol. However, demand for straw as an industrial feedstock or for combustion may cause its price to rise.

The annual sustainable supply of surplus wood and forest wastes could amount to about 2.4 million tonnes/year by 2000. This would supply up to 0.4 million tonnes/year of ethanol. However, the real price of fresh wood chips delivered to large-scale users is likely to exceed £26/tonne.

The other wastes listed above are less suitable as feedstock.

Conversion technology for lignocellulosic materials

Producing ethanol from lignocellulosic materials is technically more complex and difficult than production from sugar or starch feedstocks. All the components of the lignocellulose must therefore be used if this route is to be competitive.

The cellulose may be hydrolysed to glucose by either acid or enzymatic catalysis, and the glucose fermented to ethanol using commercial yeasts. Several countries are operating modern pilot and demonstration plants based on acid hydrolysis technology and, in the UK, ICI has developed a process based on concentrated hydrochloric acid. Pilot-scale plants for enzymatic catalysis are operating outside the UK, and these are being used to investigate several critical aspects of the technology, including pre-treatment, which is required to allow enzymes access to the cellulose.

The costs of producing ethanol from wood or straw using current designs for dilute acid hydrolysis technology are expected to be comparable with the current cost of producing ethanol from wheat. Feedstock costs represent 40-55% of the total production cost (70% in the case of wheat), and the capital cost of the plant is likely to be two to three times that of a wheat-based plant of similar size.

Improvements in acid hydrolysis technology may have the potential to reduce ethanol production costs by up to about 40%, but production would still not be cost-effective at current values. Dilute acid rather than concentrated acid processes appear to offer greater scope for cost reductions. Although the latter give higher yields and operate at much lower temperatures, capital costs are high and the processes consume large quantities of expensive acid.

Best available estimates suggest that the costs of producing ethanol from wood or straw using enzymatic hydrolysis are at least 60% higher than those using acid hydrolysis. Reasons include the need for feedstock pre-treatment, inefficient enzyme production, and the need for large quantities of enzymes with low specific activity. To realise the considerable scope for cost reduction that exists, there is a need for breakthroughs at the basic research level,

particularly the development of cost-effective enzyme production and improved enzymes, and the fermentation of hemicellulose sugars. Although improvements in the basic process plus better process design could reduce costs by about 60%, overall costs are still likely to be greater than those achieved using acid hydrolysis.

In most proposed hydrolysis schemes the hemicellulose and lignin fractions, together with any unconverted cellulose, are used as boiler fuel, with the excess electricity generated being sold. Process economics could be improved by developing commercial technology for fermenting sugars derived from hemicellulose, thereby increasing ethanol yield. Alternatively the sugars might be converted to furfural. Furfural has a greater potential for reducing costs, but market development opportunities are likely to be limited. Lignin may be recovered in a potentially valuable form, although the markets are neither established nor potentially large enough or valuable enough to reduce sufficiently the price of the ethanol produced.

There is some ongoing research into fundamental aspects of the biological conversion of lignocellulose. Activities include maximising the production of sugars from cellulose and hemicellulose; increasing the efficiency of xylose fermentation; direct conversion of cellulose to ethanol; and developing enzyme systems that can convert the whole lignocellulose complex into useful products. Other groups are working to understand the nature and action of ligninase in the biodegradation of lignin. Much of the work has applications in other technology areas such as the production of paper pulp.

Conclusions

- The cost of producing ethanol from lignocellulose is high compared with its current value as a motor fuel, even if the scope for cost reductions is fully realised.

- If electricity is the principal by-product, the required selling price of ethanol derived from wood or straw using improved technology is expected to be 2.5-4.0 times its current fuel value of around £80/tonne. This route would only be competitive if oil prices were at 1973/74 and 1979/80 levels, and the oil industry suggests that such prices are unlikely to be reached or sustained until well into the next century. Furthermore, a rise in oil prices would tend to increase feedstock costs (transport typically represents more than 25% of the raw material price).

- It may be cost-effective to remove lignin as the main processing step and to use the remainder of the feedstock as fuel or for further processing to other by-products, which might include ethanol.

- A large programme of work directed towards bio-ethanol production cannot be recommended. There should be continued support for fundamental research and a watching brief should be kept on overseas developments.