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 5: STRAW, POULTRY LITTER AND ENERGY CROPS AS ENERGY SOURCES

ETSU BM/04/00056/REP/3

Edited by
Scribe Writing and Editing Service

Published January 1999

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 5[1]

Report No	Title	Contractor	Publ. date	Page No
1. FARM WASTE AND ITS MANAGEMENT				
ETSU-B-1055	*Resource mapping of agricultural wastes and residues*	*National College of Agricultural Engineering* *The Open University*	*1981*	*6*
ETSU B/FW/00224	Appraisal of farm waste management options	ADAS, Silsoe	1993	10
ETSU B/FW/00140/REP	Regulations relating to management and disposal of agricultural waste - effect on energy recovery	P J Scott, Consulting Engineers	1994	14
ETSU B/W2/00399/REP/1	Transport and supply logistics of biomass fuels. Volume 1 - Supply chain options for biomass fuels	Transport Studies Group, University of Westminster Scottish Agricultural College	1996	17
ETSU B/W2/00399/REP/2	Transport and supply logistics of biomass fuels. Volume 2 - Biomass and strategic modelling	Transport Studies Group, University of Westminster Scottish Agricultural College	1996	21
2. STRAW AS AN ENERGY SOURCE				
2.1 The Potential				
ETSU B 1115	*The acquisition and utilisation of straw as a fuel*	*Silsoe College, Silsoe, Bedford*	*1985*	*24*
ETSU-L-21	Straw as a fuel in the UK	P M Hare, ETSU	1987	27
ETSU B/M4/00487/01/REP	Energy and carbon analysis of using straw as a fuel	Resources Research Unit, School of Urban and Regional Studies, Sheffield Hallam University	1995	30
2.2 Straw Processing and Storage				
ETSU B 1189	The development of compacted straw fuel	Sir William Halcrow and Partners Limited	1992	34
ETSU B 1195	Design and development of an in-field straw-wafering machine	AFRC Institute of Engineering Research, Silsoe, Bedford	1992	37
ETSU B/SF/00196/REP	Development and evaluation of straw slicing equipment	Silsoe Research Institute	1993	40
ETSU B/SF/00202/REP	Advances in wafering technology	Stamford Consulting Group	1993	43

---

[1] Items in italics are archived

Report No	Title	Contractor	Publ. date	Page No
ETSU B/SF/00422/REP	Straw for electricity generation: an assessment of straw storage systems appropriate to a year-round supply requirement	LRZ Ltd	1996	46
2.3 Straw Combustion				
ETSU B 1158	Straw firing of industrial boilers	FEC Consultants Ltd	1988	49
ETSU B 1261	Straw firing demonstration trials: axial swirl burner and fluidised bed combustion	Babcock Energy Ltd	1991	52
ETSU B 1257	High capacity whole bale straw combustor	Henley Burrowes	1993	55
ETSU B/SF/00244/REP	Straw firing in a bubbling fluidised bed	Babcock Technology Ltd	1993	58
ETSU B/M5/00533/06/REP	Report on a survey of small-scale straw-burning boilers	Reading Agricultural Consultants	1996	61
ETSU B/U1/00535/REP	Co-firing biomass with coal - power plant case study	PowerGen plc	1997	65
2.4 The By-products of Combustion				
ETSU B 1242	Straw ash characteristics	Babcock Energy Ltd	1993	68
ETSU B 1313 - P5	An emissions audit of a purpose built whole bale straw combustor	Warren Spring Laboratory	1993	71
2.5 The Thermal Conversion of Straw				
ETSU B 1167	*Technical and market assessment of biomass gasification in the UK*	*Aston University*	*1986*	*74*
ETSU B/T1/00207/REP	An assessment of thermochemical conversion systems for processing biomass and refuse	Aston University DK Teknik (Denmark)	1993	78
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	81
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	84
ETSU B/T1/00358/REP	Studies on the thermal processing of biomass and waste materials	Mitsui Babcock Energy Ltd	1997	87
2.6 Straw Hydrolysis				
ETSU-R-55	An assessment of bio-ethanol as a transport fuel in the UK: Volume 2	Chief Scientist’s Group, ETSU CPL Scientific Ltd	1990	90

Report No	Title	Contractor	Publ. date	Page No

3. POULTRY LITTER AS AN ENERGY SOURCE

3.1 The Technology and its Potential

Report No	Title	Contractor	Publ. date	Page No
ETSU E/GS/00124/REP 1	A review of current and impending legislation and its implications for the future disposal of poultry manure	Agricultural Development and Advisory Service (ADAS)	1993	93
ETSU E/GS/00124/REP 2	Poultry manure (litter & excreta) in England and Wales in relation to the Regional Electricity Companies	Agricultural Development and Advisory Service (ADAS)	1993	97
ETSU E/GS/00124/REP 3	The potential for a blend of broiler litter ash and processed ruminant livestock manure or poultry manure	Agricultural Development and Advisory Service (ADAS)	1993	101
ETSU B/M3/00388/32/REP	Evaluation of used poultry litter ash as a fertiliser	Agrigen Ltd and ADAS	1994	104

3.2 Relevant Case Studies

Report No	Title	Contractor	Publ. date	Page No
ETSU B/M3/00388/27/REP	Technical monitoring of a mesophilic anaerobic digester fed with poultry manure - Bitterley Court Farm, Shropshire	Enertech (1983) Ltd	1994	107
ETSU B/M3/00388/18/REP	Poultry litter boiler plant at A J Woodward & Sons - development programme for EPA compliance	Automated Process Controls Ltd	1994	110
ETSU B/FW/00236/REP	Monitoring of the demonstration of the small scale use of poultry litter for CHP at A J Woodward and Sons	FEC Consultants	1995	112
ETSU B/U1/00549/03/REP	Review of medium scale energy recovery from poultry litter	Peter J Scott	1997	115
ETSU B/FW/00235/REP	Use of poultry litter for power generation - monitoring of Eye Power Station	FEC Ltd	1995	118
ETSU B/M1/00412/REP	Use of poultry litter for power generation - monitoring of Glanford Power Station	FEC Ltd	1995	122

4. ENERGY CROPS

4.1 Miscanthus

Report No	Title	Contractor	Publ. date	Page No
ETSU B 1354	The potential of Miscanthus as a fuel crop	ADAS	1992	126
ETSU B/M5/00488/16/REP	Analysis of Miscanthus as a fuel	FEC Consultants Ltd	1995	130

Report No	**Title**	**Contractor**	**Publ. date**	**Page No**
4.2 Oil-seed Rape				
ETSU-R-71	A review of the potential of biodiesel as a transport fuel	Faith Culshaw and Clare Butler, ETSU	1992	134
ETSU B/M3/00388/40/REP	Glycerine combustion	FEC Consultants Ltd	1994	137
ETSU B/M5/00533/16/REP	The fast pyrolysis of oilseed rape	Aston University	1996	141

1. FARM WASTE MANAGEMENT AND ITS MANAGEMENT

Report No: ETSU-B-1055 Publication date: 1981

RESOURCE MAPPING OF AGRICULTURAL WASTES AND RESIDUES

National College of Agricultural Engineering
The Open University

Background

Agriculture produces many by-products that are currently under-used but have to be disposed of. Disposal may incur some expenditure: it may also create problems associated with pollution.

Although most residues are returned to the soil to provide nutrients for future crops, they could be used either as fuels or, in some cases, for energy production, with the final residue being returned to the soil. However, the distribution of agricultural wastes and residues throughout the UK is uneven and reflects the variations in climate, soils, terrain and agriculture. There is also some seasonal variation in waste and residue arisings. A detailed knowledge of these variations is essential to determine the most appropriate location for plants converting wastes and residues to energy.

Project Objective

- To summarise and map the agricultural wastes and residues generated in each region of the UK, thereby providing the information necessary for the efficient and economic use of these wastes and residues as an energy source.

The report is in five volumes. Volume 1 examines the generation of wastes and residues in England and Wales as a whole, while Volumes 2 and 3 contain the relevant regional tables and distribution maps. Volume 4 summarises the information for Scotland and Northern Ireland. Volume 5 consists of Appendices.

Methodology

The production of residues and/or wastes was estimated for each major crop and each class of animal. The estimates for England and Wales were based on information drawn from the Ministry of Agriculture, Fisheries and Food (MAFF) Agricultural Census for June 1976. The parish data obtained were converted to data for 5km x 5km grid squares based on the Ordnance Survey National Grid. Some reallocation of information was necessary to minimise inaccuracies. Tables were generated for each waste or residue in each region, and the data files were also used to produce computerised regional maps.

A similar approach to the measurement of wastes and residues was adopted for Scotland and Northern Ireland. Estimates were based on the 1976 Agricultural Censuses carried out by the Department of Agriculture and Fisheries for Scotland (DAFS) and the Department of

Agriculture for Northern Ireland (DANI). However, both censuses are less comprehensive than the annual MAFF censuses.

Findings

England and Wales

Table 1 below summarises the production and availability of agricultural wastes and residues in England and Wales in 1976. Some of these wastes and residues are already being used for various purposes. For instance, about 95% of the waste from housed farm animals is ultimately spread on the land after various periods of storage. However, this material could generate energy using the anaerobic digestion process, with the residue being returned to the land. Straw, on the other hand, is either left in the field and burnt, or returned to the soil during cultivation, or baled and removed for feeding stock (particularly barley straw) or for animal bedding (mainly wheat straw). The straw that is currently burnt or ploughed in represents a significant potential energy source either on or off the farm, and the manure/straw mixture produced by housing livestock could be used to generate energy by anaerobic digestion.

Although nearly all animal wastes are potentially available for energy, crop waste/residue availability ranges from only about 10% for dried pea straw to 100% for items such as brassica residues, hop prunings and rye straw. Overall, 85% of the 17 million tonnes dry weight of wastes and residues produced in England and Wales is potentially available for energy production. The gross energy content is nearly 264PJ.

Estimates suggest that there will be significant increases in the production of certain crops and therefore in the wastes generated. Residues and wastes from wheat, barley, potatoes and sugar beet are expected to increase by 18-30% between 1976 and 2000, while the residues from oil-seed rape are likely to increase by 740% over the same period. Dairying, on the other hand is expected to decline, with a 25% reduction in total waste produced in the period 1976-2000. Waste generated by poultry, however, is expected to increase by 3-6%.

Scotland

Table 2 below summarises the production and availability of agricultural wastes and residues in Scotland in 1976. Because little information exists on availability, the values have been determined using the same approach as in Table 1.

Table 1 Production and availability of agricultural wastes and residues in England and Wales, 1976

	Total production		Available production	
	Dry weight	**Gross energy content**	**Dry weight**	**Gross energy content**
	000 tonnes	**TJ**	**000 tonnes**	**TJ**
Livestock				
Dairy cattle wastes	2,176	38,087	2,176	38,087
Beef cattle wastes	1,242	21,743	1,242	21,743
Pig wastes	832	15,810	825	15,652
Poultry wastes	1,265	18,756	1,246	18,509
Crops				
Straw	9,276	177,511	7,224	140,078
Sugar beet tops	1,084	16,690	810	12,471
Potato haulm/waste	290	5,042	285	4,932
Oil-seed rape straw	109	1,967	109	1,967
Pea and bean wastes	460	8,251	367	6,599
Brassica wastes	123	2,076	116	1,964
Root vegetables	63	1,028	55	895
Hop residues	10	181	10	181
Orchard prunings	14	276	14	276
Orchard grubbings	23	465	21	418
Total	**16,967**	**307,883**	**14,500**	**263,772**

Northern Ireland

Table 3 below summarises the production and availability of agricultural wastes and residues in Northern Ireland in 1977. Because little information exists on availability, the values have been determined using the same approach as in Table 1.

Table 2 Production and availability of agricultural wastes and residues in Scotland, 1976

	Total production		Available production	
	Dry weight	**Gross energy content**	**Dry weight**	**Gross energy content**
	000 tonnes	**TJ**	**000 tonnes**	**TJ**
Livestock				
Dairy cattle wastes	308	5,382	308	5,382
Beef cattle wastes	513	8,983	513	8,983
Pig wastes	72	1,364	72	1,364
Poultry wastes	156	2,326	154	2,300
Crops				
Straw	1,318	23,568	840	15,023
Potato haulm/waste	52	895	51	885
Pea and bean wastes	17	297	16	282
Brassica wastes	3	40	3	39
Root vegetables	4	62	4	49
Raspberry residues	9	152	9	152
Total	**2,449**	**43,069**	**1,967**	**34,459**

Table 3 Production and availability of agricultural wastes and residues in Northern Ireland, 1977

	Total production		Available production	
	Dry weight	**Gross energy content**	**Dry weight**	**Gross energy content**
	000 tonnes	**TJ**	**000 tonnes**	**TJ**
Livestock				
Dairy cattle wastes	169	2,955	169	2,955
Beef cattle wastes	229	4,009	229	4,009
Pig wastes	80	1,530	80	1,530
Poultry wastes	122	1,778	122	1,778
Crops				
Straw	145	2,597	91	1,637
Potato haulm/waste	26	445	26	445
Brassica wastes	<2	13	<1	10
Root vegetables	<2	33	<1	24
Total	**774**	**13,360**	**719**	**12,388**

Report No: ETSU B/FW/00224 Publication date: 1993

APPRAISAL OF FARM WASTE MANAGEMENT OPTIONS

ADAS, Silsoe

Background

Four main factors are currently affecting agriculture in Europe:

- Common Agricultural Policy reform
- world trade agreements under the General Agreement for Tariffs and Trade
- environmental considerations
- the contribution of the recently democratised Eastern European countries.

As a result, food and farming industries will need to adjust to lower internal market support, less protection from external trade and increased pressure for environmental protection.

From an environmental point of view, UK agriculture will need to respond to the Water Act 1989, the Water Resources Act 1991, the Environmental Protection Act 1990 and the EC Drinking Water directives. Considerable changes to current practice will be required in areas affected by the Nitrate Directive.

Project Objectives

- To review and appraise UK farm waste management options for all types of livestock.

- To provide a computer economic model that will enable an economic comparison and a sensitivity analysis of the options to be undertaken.

Findings

Sources of waste

Livestock in the UK produce some 170 million tonnes of excreta each year. Of this, some 60 million tonnes is voided in buildings: the remainder is returned directly to the land by grazing animals. In 1990 cattle were responsible for two-thirds of total excreta output and for more than 80% of that generated in buildings. The remainder was generated by sheep and by pigs and poultry. Intensification is characteristic of the pig and poultry sector, with small numbers of units containing a high proportion of the total stock. For example, some 1200 finishing-pig units (7% of the total number) house 59% of finishing pigs, while less than 1% of laying-hen holdings have more than 72% of the total number of laying birds.

Counties with large numbers of livestock (high livestock unit values) and large areas of agricultural land include Cumbria, North Yorkshire, Devon, Dyfed and Powys, and occur mainly in the west. Several eastern counties have large land areas with small livestock unit values, although localised areas of intensive livestock production do occur - mainly pig and poultry units associated with the production of cereals for feed. Pig slurries and manures, for instance, are significant in Humberside, North Yorkshire, Norfolk and Suffolk. Areas with high concentrations of poultry waste include Norfolk, Lincolnshire, Hereford and Worcester, and Suffolk. Humberside, North Yorkshire and Hampshire also have significant quantities. Poultry waste contains a much higher concentration of dry matter, nutrients and polluting potential to both air and water than other livestock wastes.

Waste occurs in three main forms:

- As slurry and farmyard manure from cattle and pigs, and as slurry and litter from poultry units.

- As dirty water (dilute slurry) from rainwater run-off from fouled open concrete yards, and from the cleaning of dairy facilities and pig and poultry houses. Many of these dirty water sources contain residues of manure, animal feed, milk and a whole cocktail of detergents and disinfectants with, at times, silage effluent.

- As silage effluent, which consists of a mixture of rainwater and plant juices. These drain from the store during and after silage making.

Waste management systems

All animal manures are valuable sources of crop nutrients, but there is concern about the large number of livestock farmers who do not fully utilise the nutrient values of their manures.

Each farm’s waste management system has to be tailored to meet the constraints imposed on it by local conditions. The more important factors that need to be taken into consideration are the location and sensitivity of the farm site in relation to neighbours, water courses, water catchment areas and aquifers.

Most livestock farmers will continue to use standard, straightforward approaches to the handling, storage and field spreading of slurries, but will increase their management input during the land application stage. However, some sectors of agriculture will need to change their systems to reduce the risks of direct water pollution and smell nuisance, and to comply with forthcoming nitrate-related regulations. This will probably involve storing wastes for longer periods and either treating them or providing specialist land-application equipment to improve access and reduce risk.

Where some form of treatment is required, there are various options (see Table 1 below). Slurries can be enhanced by removing the gross solids. This, in turn, facilitates pumping, improves liquid absorption into the soil and reduces emissions. Options for reducing odour include aerobic treatment (easier and less costly if slurries are dilute and have a low dry matter content), and anaerobic digestion (particularly useful for slurries with a dry matter content of 8-15%). Compared with aeration, anaerobic digestion normally results in a more intensive degradation of the organic content, with lower associated losses of gaseous nitrogen.

Of the feedstocks available, slurries will usually be more appropriate for anaerobic digestion than farmyard manure and poultry litter, both of which have a much higher dry matter content. The power and gross thermal energy potential of slurries is estimated at 980MW continuous, or 30,912 TJ/year.

The most environmentally friendly and effective method of using poultry manure is probably to burn it as a fuel. The result is a dry, sterile ash, which has a concentration of nutrients that can be re-used. However, strict guidelines to combustion apply, and these are outlined in the Secretary of State's Guidance Notes. Authorisation will be required.

Satisfactory solutions are still required in the sphere of land application. The removal of slurry from store and its subsequent application to the land can be achieved in several ways, the choice of system depending on factors such as slurry quality or consistency, quantities involved, travel distances and cropping patterns. Tanker systems are heavy and cause damage to land and crops. One useful alternative is a lightweight umbilical system with a special applicator, operating from static tanks. On sandy or loamy soils, modern slurry injectors can perform without technical problems and with little damage to the turf. However, on clay soils with backfill over drains, there is the danger that slurry will be released directly into the drains and water courses.

Table 1 Summary of waste management system options

Technique	Advantages	Disadvantages
Waste spread directly to land - still an option in some cases	Carried out as part of routine work Saves on storage/treatment costs Avoids peak activity	Damage to land Poor use of nutrient potential Danger of pollution
Slurry storage - most appropriate in majority of cases	Better timing of land applications Convenient at cleaning-out times Better use of nutrient potential	High capital cost Siltation and capping of store Requires powerful mixer Potential odour problems
Manure storage - appropriate and recommended in all cases	Better timing of land applications Convenient at cleaning-out times Better use of nutrient potential	High capital cost Rainfall causes effluent run-off Potential odour problems
Weeping wall store on dairy farm - excellent practical option for cow slurry	Convenient at cleaning-out times Passive separation of effluent Effluent use on land	Cost of compound and effluent store Two types of spreader needed Potential odour problems
Mechanical slurry separation - increasingly popular for new stores	Reduces store size required Reduces siltation/capping of store Easier pumping, less odour, saleable fibre Enhanced use of liquid on crops	Requires pit, chopper pump and mixer Requires management High power input High capital and operational costs
Aeration for odour control - best option for thin slurry	Mixing and aeration carried out simultaneously Various stabilisation strategies available Reduces biological oxygen demand and odour	Management is critical High capital and operational costs Not applicable to slurries with a high dry matter content
Anaerobic digestion - comprehensive option	Good odour control Several valuable by-products Continuous flow process Alleviates problems in store Eases pumping	High capital cost for full system Specialist management required More complex business decisions needed
Composting of fibrous solids - separate enterprise selling raw fibre	Can alleviate nuisance odours Markets likely to grow Option for diversification Many organic wastes can be composted	Can cause emissions if badly managed Very high marketing costs High capital, management and operational costs
Sale of dry poultry manure as fuel - appropriate where farm has no land	Reduces storage requirement Maintains a cash flow Little management required	Applies only to dry poultry litter Low prices paid to farmer Nutrients removed from the farm
Removal of manure from farm by contractor - appropriate where farm has no land	Limited farm facilities required Little management required	Very high continuous charges Nutrients removed from the farm

Report No: ETSU B/FW/00140/REP Publication date: 1994

REGULATIONS RELATING TO MANAGEMENT AND DISPOSAL OF AGRICULTURAL WASTE - EFFECT ON ENERGY RECOVERY

P J Scott, Consulting Engineers

Background

Recent years have seen considerable changes in farming techniques, combined with greater specialisation and intensity of production. Intensified crop production requires more fertiliser than is available from traditional sources of farm manure, and few large arable farms now carry livestock. More intensive rearing and farming systems have also been introduced for certain classes of livestock, eg poultry, and, because such units rarely have large areas of land, disposal of the associated wastes has become increasingly difficult.

Because farming is a low-cost industry, farmers have tended to dispose of these wastes in ways that may now be perceived as environmentally and ecologically undesirable. Many previously acceptable practices have now been questioned, and appropriate controls have been introduced.

Controlled disposal methods are more costly than the previous ad hoc methods, and consideration has therefore been given to how some benefit might be obtained from use of the waste materials. While small-scale energy recovery projects do exist, the money necessary for investment in such projects is limited by falling agricultural incomes. A more attractive alternative could be the development of independent facilities to which large quantities of waste might be delivered by a number of producers.

Project Objectives

- To summarise the legislation and controls that currently relate to the handling and disposal of agricultural wastes.

- To outline the effects of the regulatory system on farming.

Current Legislation and Controls

Town and Country Planning Acts

The *General Development Order 1988* increased the requirement for farmers to obtain planning permission before constructing buildings, stock yards, slurry stores etc. This allows planners to examine the siting, design, access and appearance of the proposed structures. Where livestock facilities are concerned, the planning authority requires details of the arrangements to be made for the control of noise and smell and for the disposal of waste. Local environmental health officers and the National Rivers Authority (NRA) are likely to be involved, and planning is unlikely to be granted for proposals that do not meet the expressed requirements of these agencies. A 1992 amendment requires outline notice to be given to the local planning authority for all proposals related to farming.

The *Town and Country Planning (Assessment of Environmental Effects) Regulations* of 1988 also applies to “major” agricultural developments - 5000 fattening pigs, 100,000 broilers or 50,000 laying hens. The purpose of the order is to ensure that developers are adopting best environmental practice so that pollution/nuisance is avoided at source. Applications must be accompanied by an “environmental assessment”, which examines how the proposal might affect local flora and fauna, the soil, water resources, climate and landscape, together with any possible interaction with the local cultural heritage.

Water pollution control

The legislative framework that exists to prevent the pollution of water courses and underground aquifers, and which applies as much to agriculture as to other areas of activity, consists of:

- the Water Act 1989
- the Environmental Protection Act 1990.

Under the terms of the Water Act, which set up the National Rivers Authority (NRA), the disposal of liquid wastes from farms may take place:

- after treatment to reach a quality standard set by the NRA, by discharge to a suitable water course

- by spreading untreated or partially treated liquid on to the land in a way that prevents the discharge of polluted material to a water course.

The NRA also requires, under the terms of The Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) Regulations 1991, facilities for the storage of liquid wastes and slurries to be of specific minimum capacities, properly constructed and fully water retaining.

The Environmental Protection Act introduces the principle of creating a “Duty of Care”, whereby those producing wastes have a duty to ensure their safe - and legal - disposal. The legislative requirements are contained in a document prepared by the Ministry of Agriculture, Fisheries and Food (MAFF) entitled *Code of Good Agricultural Practice for the Protection of Water*. This comprehensive document provides practical guidance on the handling of most types of farm waste. Failure to follow the Code may be taken into account in any prosecution arising from the pollution of water courses.

Air pollution control

The provisions of the *Public Health Act 1936* in relation to nuisance (offensive smells, particularly in built-up areas) have now been superseded by those of the Environmental Protection Act 1990. These provisions represent a significant problem for farmers in the operation of their activities, especially as there are no accepted methods for evaluating the extent and intensity of smells.

The control of odour is, to some extent, a matter of following the MAFF *Code of Good Agricultural Practice for the Protection of Air*.

If a farmer wishes to install a process for the treatment or disposal of waste that gives rise to smoke (eg incineration), the gaseous emissions will be subject to control, the process will require planning permission and the process may also require the preparation of an Environmental Statement and other documentation. Such procedures are complex and can only be justified for reasonably substantial projects.

Ground contamination

Spreading farm and other wastes in liquid and sludge form provides plant nutrients but may also contaminate the land with undesirable materials. In 1993, MAFF issued a *Code of Practice for the Protection of Soil* which summarises the relevant legal framework and provides useful practical guidance. However, the contamination of agricultural land is not believed to be widespread, except where the application of nitrate-based fertilisers results in high nitrate levels.

Effect of the Regulatory System

The disposal and handling of farm waste has, because of recent legislation, become a more exacting administrative task. As a result, there is little likelihood of an individual farmer wishing to be involved in the complexities of setting up and operating any system for on-site energy recovery from the waste produced.

A more rational and attractive option would be the transfer of waste to some central disposal unit on a “no fee” or limited fee basis. Existing examples are the disposal of poultry litter to the Eye and Glanford power stations. Centralised facilities for the anaerobic digestion of farm slurries could be an option for the future, with the scale of operation providing both economies of scale and the chance of more successful economic operation than a farm-scale facility.

Report No: ETSU B/W2/00399/REP/1 Publication date: 1996

TRANSPORT AND SUPPLY LOGISTICS OF BIOMASS FUELS
VOLUME 1 - SUPPLY CHAIN OPTIONS FOR BIOMASS FUELS

Transport Studies Group, University of Westminster
Scottish Agricultural College

Background

Biomass offers certain advantages as a fuel: it is sustainable; its use will help to reduce pollutant gas emissions, ensure the security of UK fuel supplies and contribute to employment creation; and it can offer visual and wildlife benefits in the form of coppice crops and forestry.

The production and use of biomass also faces certain problems, notably the economic cost of supply and environmental issues relating to transportation and power stations. Some of these problems will need to be addressed by managing the operational logistics (transport, storage, handling) in an integrated way.

Transport is the key link in the biomass fuel supply chain, linking discrete activities such as harvesting, storage, handling and delivery to the power station. Transport arrangements will be determined by storage facilities at the power station, while factors such as vehicle size, transport distance and time spent loading and unloading vehicles will have a significant effect on transport cost. Road transport will nearly always predominate, accounting for up to 70% of total delivered fuel costs, depending on the biomass type under discussion.

Project Objective

- To present the options for supplying biomass-fuelled electricity generating stations with fuel of the right specification, in the right quantities at the right time from resources that are typically diverse and often seasonally dependent.

The report examines forest fuels, short rotation coppice (SRC) crops, straw, *Miscanthus* and animal slurries. This summary focuses on the findings as they relate to straw and miscanthus.

Methodology

To help investigate the supply chain as a whole, the project has developed a series of spreadsheet-based supply chain option models. These are designed to incorporate and cost in detail all the activities involved in the supply of fuel from harvesting to final delivery to a power station. The models have been developed for a range of different biomass fuels and provide details of:

- total delivered cost to power station

- the constituent components of total delivered costs and an assessment of how they accumulate along the supply system

- activity costs for each supply system - ie the contribution of each cost category to the total delivered cost.

Findings

Delivered costs

Straw

Modelling has shown that straw supply systems producing large Hesston bales have substantially lower delivered costs than systems involving the production of small rectangular bales or roll bales. Furthermore, the intermediate storage of Hesston bales, ie two road transport movements and double handling, will have delivered costs that are approximately 10% higher than systems involving on-farm storage and then direct road transport to the power station.

Miscanthus

The modelling indicates that a supply system producing baled miscanthus is likely to have delivered costs per tonne of dry matter that are approximately 20% lower than equivalent costs for a direct cut and chop system.

Comparison with other biomass fuels

When the costs of different biomass fuels are compared, certain straw delivery systems prove to be the cheapest (around £28.00/tonne of dry matter for Hesston bales). This is due to the fact that straw is a by-product and incurs no growing costs. In addition, commercial straw supply systems already exist, meeting the needs of farmers for animal feed and bedding, and of the mushroom composting industry. These supply systems have already been subject to a long period of supply chain planning and machinery development to make them as efficient as possible. The same is not true for other biomass fuels.

Forest fuel systems provide the next lowest delivered costs (£32-£37/tonne of dry matter), followed by SRC (£47-£54/tonne of dry matter). Forest fuel, like straw, is a waste by-product: the cost of growing this material is not borne by the biomass industry and so delivered costs are relatively low. Delivered costs for SRC on the other hand are about 50% higher because growing costs are included.

The miscanthus systems modelled indicate that delivered costs are likely to be as high as, if not higher than, those for SRC. A major cost component is likely to be the money that will have been paid to farmers to encourage them to grow miscanthus on their land.

It is not realistic to compare the delivered costs of animal slurry with those outlined above.

In all cases, the use of intermediate storage facilities with double handling and transportation adds 10-20% to delivered costs. However, the use of such stores is likely to be essential to the provision of a year-round supply of fuel - a fuel supplier supplying straw, for instance, will probably have to make use of an intermediate store supply system as well as a farm store supply system.

The effect of road transport distance on delivered costs

Delivered costs are relatively insensitive to transport distance for most of the biomass fuels studied, including straw and miscanthus. Modelling has shown that doubling the transport distance from an 80km round trip to one of 160km adds only 5-15% to the delivered costs. There are three main reasons for this:

- transport already accounts for 15-40% of delivered costs
- average trip speed is likely to increase as distances increase
- terminal costs remain the same, irrespective of transport distance.

Nevertheless, cost savings can be achieved by sourcing fuel from closer rather than more distant locations, and such savings may be crucial to the financial viability of the electricity generation scheme.

Transport systems

Factors influencing transport distance

The catchment area for the biomass, and hence the transport distance over which biomass will have to be moved, will depend on several key factors:

- the size of power station and the conversion technology used

- the crop yield achieved

- the proportion of land adjacent to the power station that is forested, or that is planted with biomass energy crops (SRC and miscanthus) or with crops that have biomass as a by-product (straw)

- the degree of competition for the crop or by-product.

Modelling the transport systems to meet power station requirements

Transport system requirements for biomass power stations have been modelled in terms of the number of vehicle deliveries (per day and per year); the maximum number of round trips per vehicle per day; the number of vehicles and drivers required; and vehicle kilometres travelled (per day and per year).

A 20MW straw-fired power station would, for instance, require ten vehicles and 40 vehicle deliveries/day, giving a total of 800,000 vehicle kilometres/year.

Environmental implications of biomass schemes

Although biomass offers a number of environmental benefits, there are negative environmental impacts that need to be considered. As well as the negative impacts of constructing and operating a biomass power station, these include the fuel consumed during harvesting, transportation, processing and handling; possible effluent run-off from stores; the fire risks associated with storage; the health risks associated with mould growth during storage; and the environmental impact of transportation - emissions, noise, traffic levels etc.

The significance of these environmental impacts will depend on the specific location and the physical and human geography of the surrounding area. Public perception is also an important factor in the development of energy from biomass.

Conclusions

All the supply systems modelled in the report are plausible and have the potential to be used to provide fuel for power stations. It is critical that a balanced fuel supply strategy is adopted that is capable of meeting power station requirements in terms of quantity, timing and quality. In practice, minimising costs is not the only issue, and several supply systems are likely to be operated to ensure security of supply.

Report No: ETSU B/W2/00399/REP/2 Publication date: 1996

TRANSPORT AND SUPPLY LOGISTICS OF BIOMASS FUELS
VOLUME 2 - BIOMASS AND STRATEGIC MODELLING

Transport Studies Group, University of Westminster
Scottish Agricultural College

Background

This report is the second of two reports examining the transport and supply logistics of biomass fuels. It contains the biomass resource analysis and the strategic modelling of power stations in relation to resources.

Project Objectives

- To examine existing and potential biomass resources in terms of the total quantities available and their geographical distribution throughout Britain, and to consider seasonality of supply.

- To use strategic modelling to describe the distribution of the biomass resource in terms of its supply potential for power stations.

The report examines forest fuels, short rotation coppice (SRC) crops, various types of straw, and animal slurry. This summary focuses on the findings as they relate to straw.

Findings

Resource distribution and availability

About 1.75 million ha of *winter wheat* are grown in the UK, the highest density planting being in the eastern counties of Humberside, Lincolnshire and western East Anglia. The estimated production of wheat straw is 6.12 million wet tonnes. It is used less than barley straw for animal feed or bedding and therefore has a significant energy potential.

The production of *winter barley* is more widely dispersed, covering about 680,000 ha, mainly in eastern and central England. Less *spring barley* is grown (481,000 ha), but it is a highly valued crop in Scotland if it reaches malting quality. The total output of winter and spring barley straw is about 4.48 million wet tonnes.

The most concentrated areas of *oat* production are the mid-west of England, north-east Scotland and north-east England. Although production is low, straw output per ha is relatively high and the total is assessed at around 0.4 million wet tonnes.

Oil-seed rape is grown on 450,000 ha, mainly in Eastern Scotland, Bedfordshire, Hertfordshire, Cambridgeshire and Essex. Although straw production per ha is low, there is little alternative use for the 0.68 million wet tonnes except as a potential energy source.

Strategic modelling

The project has involved the development of a strategic modelling program that allows various factors affecting the number and location of potential power stations to be examined. The program can:

- alter the biomass resource data set to reflect different scenarios for resource availability

- change the catchment area around the power station from which the biomass can be sourced

- alter the size (MW capacity) of power stations to explore the effect on power station numbers and location.

The model assumes that each power station lies in the middle of a catchment area from which the biomass is sourced. Implied in this is that, once a catchment size has been defined, the power station constructed would be sized to consume all the resource available in that catchment, thereby avoiding transportation between catchments.

Calculating a “total tonnes/km” value for each catchment provides an indication of the “goodness of supply” and allows decisions to be made as to the order in which catchments should be allocated power stations.

Results of strategic modelling

Using all the wheat straw resource in the country, it would be possible to fuel approximately 800MW of electricity-generating power stations. However, wheat straw has many other competing uses, which are likely to be prepared to pay as much, if not more, for the straw than the biomass industry. It is therefore reasonable to assume that only a relatively small proportion of wheat straw will be available for use as biomass.

The strategic model was run assuming that only 30% of the wheat straw produced in the top 20% of 10km x 10km squares would be available for use as biomass fuel. Taking a power station catchment area of 90km x 90km, the model produced six 10MW power stations and two 20MW stations.

Conclusions

Significant quantities of several biomass resources, including straw, already exist in Britain. There is a marked variation in the geographical distribution and degree of concentration of these resources, which means that different solutions in terms of power station location and size will be needed for each resource.

The work has also demonstrated that there is sufficient biomass resource to achieve relatively low transport distances in supplying the fuel to biomass power stations in the capacity range currently being considered by power station developers. For example, in areas with a high concentration of wheat straw production in Britain, a 20MW power station could be built that would be able to source sufficient fuel from within a 90 x 90km catchment area, ie a maximum transport distance of 64km.

Finally, the transport distance over which biomass resources would have to be transported depends on resource availability. This, in turn, is determined by demand from non-biomass users and the price they are prepared to pay, by annual production, and by other factors such as the willingness of farmers and forest owners to grow and/or supply biomass. Further work is required in these areas.

Although the project has achieved its objectives and contributed to the understanding of power station size and location in relation to the resource base, the findings do have their limitations because of the simplifying assumptions that have been necessary for the strategic modelling.

2. STRAW AS AN ENERGY SOURCE

2.1 The Potential

Report No: ETSU B 1115 Publication date: 1985

THE ACQUISITION AND UTILISATION OF STRAW AS A FUEL

Silsoe College, Silsoe, Bedford

Background

Estimates suggest that only about half (6.7 million tonnes) of all the straw produced is baled and used - mainly for animal feed and bedding. The remaining 6.9 million tonnes represents an unwanted surplus, most of which is disposed of by in-field burning, although a small proportion is incorporated into the soil.

Farmers burn straw in the field for several reasons. Burning is easy, convenient and cheap, and it represents the most economic disposal method. It is believed to help in weed and disease control, and it allows easier, cheaper cultivations. However, there is growing public concern about the environmental implications of in-field burning - air pollution, damage to the countryside and the risk of accidents - and this has led to a consideration of alternatives, notably the potential for using straw as a competitively priced fuel.

Project Objectives

- To examine the current production of wheat, barley, oat and oil-seed rape straw.
- To determine the potential availability of straw for fuel, and identify feasible straw-for-fuel systems.
- To estimate the likely degree of market penetration of straw as a fuel.
- To identify the most cost-effective areas of research and development.
- To make appropriate policy recommendations.

The resulting report is in two volumes, the second of which contains the Appendices.

Findings

The costs associated with straw removal from the field

The costs associated with removing straw from the field fall into two categories: costs associated with subsequent cultivation, and the costs of straw removal.

Farmers are believed to incur several costs from not burning straw. These include:

- a reduction in yield of the subsequent crop
- the removal of nutrients in the straw
- the addition of extra nitrogen to promote stubble decomposition
- additional cultivations
- timeliness penalties
- the costs of weed, disease and pest control.

There are also costs associated with baling, handling, storage and transportation. These range from £13/tonne for on-farm use to £20-22 where transport distances are around 40 km. To this must be added the value of straw in the swath to the farmer, and the profit of those involved in the procurement chain. These figures assume maximum annual utilisation of straw baling and carting machinery, storage in a building and transportation on an articulated vehicle with a low-loader trailer. Large round bales have higher transport and storage costs than conventional or Hesston bales because of their shape and low density.

Increasing bale density

Baled straw is relatively costly to store under cover, and to transport, because of its low bulk density. However, the compaction of straw bales is expensive because of the double handling involved, and this option can only be justified for transportation over long distances. Work is now in progress on new, high-density bales designed to fit on lorries.

Briquetting is another possible option. The cost of this procedure, using currently available equipment, ranges from a theoretical minimum of £22/tonne to the £45/tonne being attained by operational briquette presses. When the costs of straw procurement are added to these figures, together with a profit component, it is clear that straw briquettes cannot compete economically with coal.

Combustion issues

Straw has a gross calorific value (at 15% moisture content) of 14.8 MJ/kg, approximately half the value for coal and one-third that for oil.

On an industrial scale, straw can already compete with coal at a delivered price of more than £30/tonne for small boilers, eg 0.6MW and 1.5MW units. It cannot compete for large boilers, eg units with an output of 15MW or, to a lesser extent, those with an output of 4.5MW. This conclusion holds even if the delivered price of straw were to fall to as low as £10/tonne. At these scales of combustion, coal prices would need to rise to £90/tonne for straw to be a competitive fuel. However, the capital costs of straw-fired plant are likely to fall, while fossil fuel prices are expected to rise. Both factors will help to improve the economic case for straw as a fuel.

Farm-scale combustion systems are assumed to consist of units of up to 300kW. At this scale, straw can compete with oil at straw prices of up to £42-£53/tonne and with coal provided its price does not exceed £15/tonne for manual systems and £0-£10/tonne for automatic systems. Again, increases in coal prices will increase the maximum permissible price for straw.

Potential markets

The likely markets for straw as a fuel include:

- agriculture - for farmhouse domestic heating, glasshouse heating, pig housing and grain drying

- industry - parts of the food and drink, textile and engineering industries (for steam raising or water heating): there is also some potential for mixing straw with coal in the cement and brick industries

- institutions - large schools, colleges (especially agricultural), local and regional government offices.

The commercial and domestic sectors are likely to provide much less market potential.

The future

Straw production is unlikely to decrease or increase significantly. A ban on straw burning might increase the willingness of farmers to supply straw to the market, but this is unlikely in the immediate future. There may be an increase in competing uses for straw.

Recommendations

- The development of new baler technology producing higher density bales with better dimensions for transport.

- Improvements in the information available on straw losses during storage, and the development of a low-cost storage system with minimum wastage.

- Improved briquetting machinery, particularly the development of in-field equipment.

- Research into the combustion properties of straw in different forms.

- A more detailed market assessment of straw.

Policy Proposals

- Continued research, development and demonstration.
- Grants for straw use on the same basis as for coal.
- The co-ordination of policy between Government departments.
- The announcement of a ban on straw burning in the field in five years’ time.

Report No: ETSU-L-21 Publication date: 1987

STRAW AS A FUEL IN THE UK

P M Hare, ETSU

Background

Straw is produced in large quantities every year in the UK. About half of this is used for a variety of agricultural purposes, but the remainder is predominantly burned in the field. The most likely way in which this wasted surplus can be used is as a fuel, and the Department of Energy is carrying out a programme of research and development to encourage its use in this way.

Report Objective

- To examine the production and use of straw, its potential as a fuel, likely markets, and developments in the associated technology.

Findings

Straw production and use

Each year 13.7 million tonnes of straw are produced in the UK, mainly in Eastern England and parts of Central and Southern England. The main straw-producing crops are barley, wheat and oil-seed rape, and output is increasing as a result of both higher yields and extended acreages. If these trends were to continue, production in 2000 would be about 18 million tonnes/year, but Common Market policies are likely to result in a levelling out at around 15 million tonnes/year.

About half the straw produced is baled for subsequent use. Some 5.8 million tonnes are used for animal bedding and feed, with a further 0.3 million tonnes being chemically treated to provide higher-grade cattle fodder. Around 0.5 million tonnes is used in vegetable production both for storage and to protect crops from frost damage and weeds, while around 170,000 tonnes are already used as a fuel to heat farmhouses and farm buildings such as glasshouses and animal raising units.

As well as its potential use as a fuel, surplus straw could become an industrial feedstock. Processes are already being developed to pulp straw for use in papermaking or to shred it for making hardboard.

Combustion technology

Straw has a relatively low energy content. Its calorific value is 14.7 GJ/tonne (at 17% moisture content), roughly the same as well seasoned wood, one half that of coal and one-third that of oil. However, the low energy content is further compounded by the very low density of straw. As a result, its “energy density” is only about one quarter that of coal.

Straw contains around 70% volatiles. Combustion involves the distillation of these volatiles, which then burn in the gas phase leaving a mixture of ash and char. Higher temperatures and quantities of air are required to burn out the char. The ash produced is quite unlike coal ash. It is quite bulky and may require special handling equipment. It also has a low fusion temperature, usually melting at around 1050°C (compared with 1200-1300°C for coal ash), but with melting temperatures as low as 820°C having been recorded.

Straw can be burned in a variety of combustors. While specially designed custom-built units are required for the combustion of whole bales, compacted straw can be substituted directly for coal in most standard coal-fired stoking boilers. In between these two ends of the spectrum lie the options of burning chopped straw in a modified coal-fired boiler or of using a straw-fired boiler that can also burn other fuels. Chopped straw also readily lends itself to cyclone-type furnaces in which straw is conveyed in the air stream. Such furnaces have long path lengths which allow a very high combustion efficiency.

Economics

Straw is not free. A typical cost to the farmer, including baling, handling, on-farm transport and on-farm storage (including losses), is £18/tonne. When off-farm transport is added to this, the costs rise further. For instance, delivering straw to a local industry within 10km of the farm would increase the delivered cost to £22/tonne, while delivering straw over longer distances would increase the cost to £24-£28/tonne.

There are also significant cost implications associated with the form in which straw is made available. Estimates suggest that the cost in energy terms for baled straw (excluding transport) is around £1.49/GJ. For straw wafers, the equivalent figure is £3.06/GJ, while for briquettes, including transport to the distribution agency, the cost is £5.78/GJ, well above the value of competing fuels (£3.43/GJ for natural gas, £3.26/GJ for heavy fuel oil, £2.35/GJ for singles coal and £2.19/GJ for smalls coal).

Even though the cost of baled straw is relatively low, this is counterbalanced by the relatively high cost of straw-burning boilers, which cost considerably more than comparable coal-fired systems.

Markets

The potential market for straw as a fuel has four components:

- Farm-site use continues to grow through the development of low-technology, whole-bale-burning boilers that are manually stoked. The straw burnt is often produced on the farm.

- Rural industry (cement, brick, minerals) offers a high potential for the use of straw as fuel. Certain classes of commercial user in rural areas may also be well suited in this respect.

- Hospitals, schools and Government offices in rural areas are likely to find straw attractive for reasons that include high boiler utilisation, longer acceptable payback periods and low transport costs.

- The domestic sector is a potentially large market, but development is likely to be limited for technical reasons and because of the high cost of processing straw for home use.

Department of Energy programme

Efforts are currently directed towards enhancing the prospects for straw-fired furnaces and boilers by reducing costs through research and development.

In one demonstration, at Needham Chalks near Ipswich, 2000 tonnes of chopped straw are burnt each year in a cyclone furnace, and the hot gases generated are used to dry chalk from 26% to 6% moisture content. Another demonstration at Woburn Abbey uses 400 tonnes/year of chopped straw in a 0.8MW chopped-straw-burning boiler to provide heat to all the central buildings. Other projects are planned, for instance the development of a whole-bale-burning boiler capable of producing 3-5MW, and the modification of existing coal-fired boilers to take shredded straw.

Combustion trials have shown that, provided boilers are modified to permit overbed firing of straw (in effect blowing the straw in an air stream directly at a bed of hot coals), straw can be substituted for coal to a level of up to 30%, without either significant power losses or excessive emissions. On the most promising types of boiler, substitutions of up to 50% straw were satisfactorily achieved.

Considerable attention has been paid to ash fusion as this occurs at lower temperatures with straw than with coal. However, it proved not to be a problem with coal/straw mixes, and the addition of straw may well improve the caking characteristics of some coals. There was also a substantial reduction in acid emissions.

Monitored combustion trials gave the following results:

- Sprinkler stokers require the most modification because of the need for a second, larger cyclone and for baffles to improve turbulence.

- Chain grate stokers and low ram coking stokers only require an air conveyancing system to blow the straw directly at the incandescent coal bed and cause turbulence.

Attention has also been given to straw compression. High costs mean that briquettes are only likely to be competitive with the highest quality coals, such as those often used in domestic stoves. However, there is scope for developing a low-cost medium-density form of straw called a “wafer”. By compressing straw using a rolling mill, it is possible to achieve densities of up to 300 kg/m^3 without the high energy input that conventional pelleting mills require. A machine is being developed for in-field use that will produce wafers at rates of up to five tonnes/hour. Although the wafers will required dry storage, they are expected to be competitive with industrial coal, thereby extending the potential market for straw into rural industry and, possibly, the domestic market.

A dual strategy of combustion research and fuel improvement could result in up to one million tonnes of straw per year being used as fuel by 2000.

ETSU B/M4/00487/01/REP Publication date: 1995

ENERGY AND CARBON ANALYSIS OF USING STRAW AS A FUEL

Resources Research Unit, School of Urban and Regional Studies,
Sheffield Hallam University

Background

Two factors are encouraging the use of straw as a fuel in the UK:

- regulations preventing the burning of most crop residues in the field
- financial encouragement for generating electricity from straw (the Non-Fossil Fuel Obligation).

Several proposals have been formulated for the construction and operation of straw-burning power plants, and interest is increasing in the use of straw for heating purposes in commercial, industrial and other large-scale applications.

Project Objective

- To calculate preliminary estimates of the primary energy input and carbon dioxide (CO_2) output of using straw as a fuel and to compare these with equivalent figures for various methods of disposal or alternative use.

The resulting report is in two volumes, the second of which contains the Appendices.

Methodology and Findings

Basic energy and carbon analyses

The study applied energy and carbon analysis techniques to each method of straw disposal or use to determine the total primary energy requirement for each activity and the associated CO_2 output. Table 1 below summarises the main findings in each case.

Straw burning in the field requires the lowest primary energy input and gives the lowest CO_2 output of all the options considered. The fuel used for clearing and spreading the straw and for ploughing the firebreak is responsible for energy inputs and CO_2 outputs during both its manufacture and its use. The equipment used - tractor, tedder, plough - is responsible for energy inputs and CO_2 outputs during its manufacture and during maintenance and repair.

Similar principles are applied to each method of straw disposal or use, with heat-only straw-burning plant incurring the highest values per ha: in this case the high primary energy input and CO_2 output of plant manufacture and installation must be apportioned over a relatively limited field area because of the plant’s low straw consumption.

Table 1 Primary energy input and carbon dioxide output for straw disposal/use

Method of disposal/use	**Primary energy input MJ/ha**	**Carbon dioxide output gCO_2/ha**
Straw burning in the field	709.2	41,924
Straw incorporation in the field	1208.2	71,599
Straw used as a material:		
Hesston bales	1256.2	71,222
Round bales	1308.8	76,744
Small standard bales	1664.6	98,821
Straw used as a fuel:		
Power-only plant	3458.2	194,564
Heat-only plant	6494.4	352,649
Combined heat and power plant	3472.6	196,990

The study demonstrated that the most significant contributions to primary energy inputs and CO_2 outputs of using straw as a fuel are associated with:

- the manufacture and installation of the straw-burning plant
- the fuel consumption of agricultural equipment used to collect the straw and of trucks and trailers used to transport the straw
- the production of weatherproof protective material for straw at storage sites
- the manufacture of specific types of agricultural machinery and equipment, especially the Hesston baler.

Comparison of straw-fired plants with other electricity and heat generating technologies

The primary energy inputs and CO_2 outputs of straw-fired plants were compared with equivalent values for alternative heat and power generation units.

Straw-fired power-only plants were compared with:

- a new combined cycle gas turbine power plant with an assumed thermal efficiency of 50% and an emission factor of 145.8 gCO_2/MJ_e
- an existing coal-fired power plant with an annual assumed average thermal efficiency of 33% and an assumed average emission factor of 298.5 gCO_2/MJ_e.

Straw-fired heat-only plants were compared with:

- a new natural-gas-fired condensing heat plant with an assumed thermal efficiency of 85% and a natural gas emission factor of 49.0 gCO_2/MJ_t

- an existing oil-fired heating plant with an assumed thermal efficiency of 60% and a petroleum product emission factor of 64.0 gCO_2/MJ_t.

Straw-fired combined heat and power (CHP) plants were compared with:

- the new combined cycle gas turbine power plant and the new natural-gas-fired condensing heat plant identified above, assuming a heat-to-power ratio of 2.6:1

- the existing coal-fired power plant and the existing oil-fired heating plant identified above, assuming a heat-to-power ratio of 2.6:1.

In each case, using a straw-fired plant in place of the alternatives substantially reduced the primary energy inputs and CO_2 outputs. The net effect is that using straw as a fuel is a much more energy- and CO_2-efficient option than either burning or incorporating straw in the field or using it as a material. Although all straw-burning plants are profitable in energy terms, the most appropriate option for using straw as a fuel is in CHP plant. The second most appropriate option is using straw in heat-only plant. These conclusions are confirmed by the findings on carbon coefficients (gCO_2/MJ).

Sensitivity analyses

A preliminary sensitivity analysis considered the effect on primary energy input and CO_2 output, when using straw as a fuel, of straw losses during storage, straw recovery rate, straw production density, the rating of the straw-burning plant and average transport distances.

Both primary energy input and CO_2 output proved relatively insensitive to straw losses during storage, provided these did not exceed 30%. Straw recovery rates, provided these remain above 5% of what is available, have little impact, and the results are similarly relatively insensitive either to straw production density over the 15-165 tonne/km^2 range or to the selected rate of assumed plant ratings.

The most influential parameter was found to be average transport distance, and quite a strong linear correlation was observed between distance and primary energy input/CO_2 output. However, it was clear that the use of straw as a fuel continued to be economic in terms of primary energy and CO_2 savings within a realistic transport range.

Recommendations

Further work could usefully be carried out in two areas:

- more detailed assessment of the primary energy input and CO_2 output of manufacturing and installing straw-burning plant

- further comparison of results with those for other energy generating technologies, particularly those using other forms of biomass.

2.2 Straw Processing and Storage

Report No: ETSU B 1189 Publication date: 1992

THE DEVELOPMENT OF COMPACTED STRAW FUEL

Sir William Halcrow and Partners Limited

Background

Each year about 14 million tonnes of straw are produced in the UK. Half of this total is disposed of as waste, mainly by burning it in the fields. For most farmers straw burning is the easiest, cheapest and most convenient method of waste straw disposal. However, the public regards burning as an environmental nuisance. The smoke generated can cause road accidents and the fires themselves can cause damage.

One possible alternative to burning in the field is to use waste straw as a fuel for generating heat. Two studies on the availability and use of straw as a fuel, which were carried out in 1983 and 1986, concluded that there are reasonable prospects for the use of compacted straw as a fuel. Furthermore, about 170,000 tonnes is already used for this purpose on farms, either to provide domestic heating or to generate heat for agricultural or horticultural use. Experience to date shows that straw can be burned satisfactorily in appropriate combustion equipment and with no evidence of any damaging effect.

Project Objective

- To provide a concise and up-to-date review of the technology, the markets and the economics of using compacted straw as a fuel.

The resulting report is in two volumes, the second of which contains the Appendices.

Findings

The technology

Optimising bulk density

Loose straw has a bulk density of 30 kg/m^3 and, although this can be increased to 100-150 kg/m^3 by baling, this is still low by comparison with other fuels. This makes baled straw relatively expensive to store and transport. It is also unsuitable for handling by conventional fuel-handling plant.

For ease of handling and combustion in conventional solid fuel plant, the desirable form for compacted straw fuel is small (less than 75mm), uniform, fairly rounded packages with a good durability. Machines exist that can produce a product of this type in the form of briquettes, pellets or cobs. Although these products have a density of 800-1200 kg/m^3, they are expensive to purchase and energy intensive in operation.

For efficient bulk transport, straw should have a bulk density of 400-600 kg/m^3. Experimental work has shown that straw wafers of this density form a durable combustible product, although further experience of mechanical handling is still required. However, there are no insurmountable technical reasons why compacted straw fuel cannot be produced in a suitable form.

Two projects currently under way in the UK are seeking to develop a machine for making straw wafers while minimising the input of energy. It is thought feasible to operate such a machine either travelling through a field of straw or in static mode. A machine with an output of 5 tonnes/hour would be adequate, although a ten tonne/hour machine would be much more cost effective.

Combustion

Combustion tests have shown that compacted straw can be burnt in an environmentally acceptable manner, although suitably designed combustion equipment is needed to deal with the high proportion of volatile matter and the risk of clinker formation on the fuel bed or grate.

The most suitable types of boiler for this purpose are water tube boilers, low pressure horseshoe boilers, cyclone burners and incinerators of the types already used for the combustion of waste products and biomass, and circulating fluidised bed combustors. Solid-fuel-fired shell boilers are unsuitable for compacted straw combustion, as are oil- and gas-fired units, although it may be possible to retrofit additional combustion chambers.

The high volatile matter content of straw makes it unsuitable for use as a domestic fuel, except where it is burnt in specially designed equipment.

Markets

Straw has not been widely adopted as a fuel for three main reasons:

- the lack of a reliable fuel supply chain
- inadequate development of combustion plant
- high costs.

The maximum potential demand for straw fuel in Eastern England, within a short distance of the areas where straw is in surplus, is estimated at 6.1 million tonnes/year. Of this, 2.7 million tonnes (44%) comprises potential domestic use, while the remainder is divided between agriculture (15%), industry (25%) and commercial and institutional users (16%).

For *compacted* straw fuel the total potential market is estimated to be 2.8 million tonnes/year, with domestic use accounting for 50% of the total, commercial and institutional users for 21%, industry for 16% and agriculture for 13%.

The potential market for straw as fuel will only be achieved with the introduction of specially designed new boiler plant and retrofit equipment for existing boilers. The replacement of existing plant and the installation of new units during the 1990s is expected to generate a market for several thousand new boilers or retrofit units. If straw is used to fuel even a small proportion of these units, this could represent a significant proportion of the potential take-up. In the case of the substantial domestic market, where the price paid for fuel is normally significantly higher than that paid by non-domestic users, consideration needs to be given to the safety of compacted straw use and, possibly, to the development of special appliances.

Economics

The production and delivery of compacted straw to the customer involves processing, transportation and storage, and optimisation of the total procedure is important. After considering the range of costs for each operation, the study has concluded that, once adequate compaction machinery has been developed, compacted straw can be delivered in bulk to the end user at between £29.60 and £52.20 per tonne (£1.87-£3.30/GJ).

The study has also compared the costs of using compacted straw fuel in industrial sized boilers rated at 5, 10 and 15 GJ/hour with equivalent costs using coal, oil and gas.

For all *new boiler installations*, compacted straw is more expensive than conventional fuels at 1986 prices. At the higher fuel prices assumed for 1996, when appropriate compaction and combustion plant might be commercially available, compacted straw is likely to be a competitive fuel except when compared with gas in the smallest size of boiler considered.

The competitiveness of compacted straw proved to be not very sensitive to the capital cost of the boiler, but sensitive to boiler utilisation factors and to the price of competing fuels. Competitiveness would improve if the value of straw in the field were to decline as a result of further restrictions on in-field burning.

The study has considered the *conversion of existing coal plant* to compacted straw fuel for boilers of the same size as those assessed above. Again, such a change is not attractive at 1986 prices. At 1996 prices, assuming straw prices at the lower end of the band, it would be possible to achieve a payback of 5-10 years. Again the findings are very sensitive to boiler utilisation and to coal prices, but not to a 30% reduction in the capital cost of conversion.

Conversion from oil and gas to straw at 1996 prices is more attractive than conversion from coal, although there is insufficient information to establish whether conversion to straw or to coal would be the preferred option.

Recommendations

- More detailed supply chain studies/costings based on machine costs and production data.
- Better data on the capital costs of straw-burning plant and conversion costs.
- Support for the development of improved compaction machinery.
- Support for a study into the use of compacted straw fuel in domestic appliances.
- Support for more detailed studies of non-domestic boiler markets.

ETSU B 1195 Publication date: 1992

DESIGN AND DEVELOPMENT OF AN IN-FIELD STRAW-WAFERING MACHINE

AFRC Institute of Engineering Research, Silsoe, Bedford

Background

Most conventional straw bales have densities in the 80-170 kg/m^3 range. However, even at this density, it is not possible to maximise the weight loading on a transport vehicle within the permitted limits on dimensions. To achieve this, it would be necessary to increase the bulk density to more than 350 kg/m^3, a process that would also improve the economics of storage.

The pelleting or cubing of milled straw has been well established for many years. However, the processes involve extrusion through dies, and specific energy consumption is in the 100-300 MJ/tonne range. Laboratory-scale work at AFRC showed that it was possible to produce 100g wafers with a density of 300-600 kg/m^3 using closed-end cylindrical dies. The specific energy requirement was only 11-25 MJ/tonne. Later work with a rectangular die achieved wafer densities of 650-750 kg/m^3 at pressures up to 100MPa and specific energy requirements of 24-50 MJ/tonne.

Project Objectives

- To study the process of making straw wafers in a laboratory-scale rotary waferer.
- To design and build an in-field wafering machine.

Methodology and Findings

Laboratory testing

A rotary laboratory wafering machine was made to study the differences between wafering in linear compression dies and the rolling action of cells on the periphery of rollers. The machine had two rollers 900mm in diameter.

Cell shape is critical in wafer making, but initial experiments found that a suitable cell shape could be made by fitting different elements to the faces of the opposing wafering rolls. The elements forming the cell were blunt knives having an included angle of 80° at the tip so that the wafer was tri-axially compressed to a thickness of 16mm. The cells on one roller consisted of the axial elements needed to separate one wafer from the next. These were spaced at 60mm intervals. The other roller contained the circumferential elements needed to compress the ends of the wafers. Half-height axial elements were later added to the latter roller, and both rollers were geared, to ensure that each wafer was retained for long enough to prevent extrusion and subsequent loss of integrity as the nip opened.

Each wafer was nominally 100mm high, 60mm long and 16mm thick at maximum compression in the roller nip point, and weighed about 100g.

The rotary wafering machine and a hydraulic linear compression tester were used to make wafers from straws of a wide range of varieties of wheat and from straw that had been subjected to various fertiliser treatments. Although the tests were not repeated on an annual basis, the results showed that the wafering energy required varied very little with either straw variety or fertiliser application. However, some varieties of straw were shown to make better wafers than others.

Wafer quality was found to vary with two other factors:

- Straw moisture content. The most acceptable level is 10-17%, although this is not readily attainable in either very wet or very dry harvesting seasons.

- Speed of manufacture. Increasing the speed to more than two wafers per second (<0.5 seconds per wafer) caused a reduction in wafer quality. The laboratory machine produced wafers at the rate of three per second. An effective field machine would need to produce 27 wafers per second to have a throughput of ten tonnes/hour, and this indicates a need for multi-row dies.

An interrelationship was also established between the age of the straw and its moisture content. Wafers made directly behind the combine were found not to hold together, while two-day-old straw, at a suitable moisture content, made good wafers.

The field machine

The field machine was designed to collect straw from a field swath and increase its density to about 80 kg/m^3 in a primary compactor. This procedure ensured adequate entanglement of the straw. Further compaction of the straw to more than 300 kg/m^3 was undertaken in a secondary compactor. The straw then passed between a pair of vertical axis wafering rolls where density at the nip approached 1800 kg/m^3.

Control signals from density monitoring rollers mounted in the secondary compactor were conditioned by a microprocessor to vary the speed of the wafering rollers and maintain a sufficiently constant density of straw in each cell.

The finished wafers dropped from between the rollers onto conveyors before being elevated into a trailer towed beside the waferer. Power for the pick-up and the primary compactor came from the towing tractor. The remaining power was provided by an on-board engine and delivered through hydraulic drives.

The machine was first tested in the field at the end of the 1988 harvest. Further static tests were carried out during the spring of 1989, with field tests during the 1989 harvest.

Although the rotary laboratory machine with its single row of waferers had a specific energy consumption of 50 MJ/tonne, double that of the four-row in-field machine (25 MJ/tonne), the field machine proved less satisfactory in several ways:

- The field machine did less work on the straw than the laboratory machine, producing 75mm x 75mm wafers instead of 50mm x 100mm wafers. The approach to the nip proved less severe with 1200mm diameter rollers than with the 900mm diameter rollers of the laboratory unit.

- The straw feed was not sufficiently constant to ensure full-weight wafers all of the time.

The wafering process as developed did not achieve the expectations of the linear press laboratory experiments. This was due to the rotary action of the machine and the need to cut the straw column on four sides of the wafer. This in turn resulted in a less than acceptable wafer being produced. Wafers up to 115g were measured with unit densities of up to 514 kg/m^3. Selected wafers gave a bulk density of 330 kg/m^3, but a more typical output in the trials was 245 kg/m^3.

Minor improvements to the machine, as built, should ensure the desired crop flow-in and wafer flow-out. However, major improvements to the actual wafering process are needed, and this will require further investigation into some of the fundamental principles.

Recommendations

Further work is need to establish why straw that has been compressed to 1800 kg/m^3 relaxes to less than 600 kg/m^3, and whether straw can be treated, or an additive incorporated, to prevent this.

It would also be appropriate to devise a cell shape that will cause separation of the crop column into individual wafer-sized packages before maximum density is reached and then compress it. This would allow entanglement at the edges to take place. It was apparent from laboratory tests in cylindrical dies that a die charge separated before being compressed produced a much more durable wafer.

Report No: ETSU B/SF/00196/REP Publication date: 1993

DEVELOPMENT AND EVALUATION OF STRAW SLICING EQUIPMENT

Silsoe Research Institute

Background

Straw for combustion as a fuel can be used as whole bales, as shredded bales or in finely chopped form, depending on the particular combustion technology employed. Past work on the combustion of straw in a bubbling fluidised bed and in a modified power station burner for pulverised coal has shown that both technologies require straw in a chopped form. For power station use, the rate of straw provision would need to be up to ten tonnes/hour.

Existing bale-breaking and straw-chopping machines have high power requirements and a limited throughput. Tub choppers, for instance, combine bale breaking and comminution operations. Their maximum, although intermittent, feed rate is 10-15 tonnes/hour but, to achieve this, they need an installed power capacity of, typically, 100-150kW.

Research on forage harvesters has shown that slicing requires only 50% of the power input of conventional cylinder choppers for comminuting grass: it also affords an increased throughput capacity and reduced vulnerability to damage by foreign objects. The slicing process uses a draw cutting action rather than conventional chopping. A bank of slowly rotating circular knives engages with two slotted rollers that force the crop against the knives. The cut crop then passes into the interdisc spaces and is removed by stationary extractors.

It may be possible to achieve similar advantages with straw by using slicing rather than chopping techniques.

Project Objectives

- To set up a pilot rotary slicing test facility to give median particle lengths of 25-35mm at rates of 1-10 tonnes/hour.
- To evaluate the performance of the equipment under standard conditions in terms of energy consumption per unit of measured throughput and for different particle length characteristics.
- To evaluate the performance of alternative machines for chopping straw and to compare the findings with those for slicing equipment.

Work on the first objective was carried out in collaboration with an EC (ECLAIR) project.

Methodology

An optimising experiment was conducted with existing grass slicing equipment to determine an appropriate design specification for the processing of straw. The next stage was to design, construct, commission and evaluate the equipment prior to siting it in a pilot straw pulping plant for ongoing EC-supported work.

The performance evaluations of alternative machines involved a multi-purpose chopper fan, an agricultural cylinder chopper and a hammer mill. Tub choppers were not included in the trials as consultations with manufacturers and existing users showed evidence of erratic throughput characteristics and very large fluctuations in power demand.

The trials were all conducted under controlled conditions to achieve uniform and repeatable throughput rates. Power requirements were monitored and straw samples were taken to determine particle length distributions. Fully replicated experimental runs were carried out with each machine up to its maximum operating throughput rate.

Findings

The results for throughput and chop length are summarised below:

- The slicing equipment was capable of operating at throughput rates of up to ten tonnes/hour. However, it could not be adjusted to give a range of different nominal straw output lengths, but consistently produced material with a median length of 28-30mm.

- The chopper fan achieved a maximum throughput of eight tonnes/hour. Although it could handle and process whole straw pieces, it was found to be unsuitable for straw comminution because the output material ranged in length from 78mm to 103mm.

- The cylinder chopper achieved a maximum throughput of six tonnes/hour. Because the machine is designed for forage chopping, it could be adjusted to give a range of theoretical output lengths. Three settings were evaluated: nominal chop lengths of 6mm, 19mm and 29mm. The machine proved appropriate for handling whole straw pieces, but produced median output lengths of 20mm at the 6mm setting, and typically 30mm for the 19mm and 29mm settings.

- The maximum throughput of the hammer mill was four tonnes/hour, but it was operating under different straw length conditions. It could not handle the long input material of the other three, but did produce a much shorter output straw length. Three different screen sizes were used, with hole diameters measuring 10mm, 15mm and 20mm respectively. The associated median output lengths were 12.6mm, 14.1mm and 15.2mm.

The power output of the four machines can be summarised in terms of the specific power requirement, ie the power required to process one tonne of straw per hour. This was calculated from data at the maximum operating throughput rate. A measure of the degree of fluctuation in power demand is given by taking twice the standard deviation value and expressing it as a percentage of the mean. The values generated are shown in Table 1 below.

Table 1 Comparison of specific power requirements

Equipment	Specific power requirement kWh/tonne	Fluctuation
Slicing machine	1.56	40%
Chopper fan	4.19	30%
Cylinder chopper	1.63	108%
Hammer mill	8.15	25%

It is clear from the above that the slicer has a similar mean power requirement to the cylinder chopper, although its power demand is much smoother which means that smaller motors can be used. The comparison between these two machines has been made at a common particle output length of approximately 30mm median.

The chopper fan was much less efficient, requiring more power for an inferior chop performance, although this machine did have the capability of conveying the chopped material.

Direct comparison is not appropriate for the hammer mill as it was the only device capable of reducing already comminuted straw to very short lengths.

Conclusions

Overall, the slicing machine was found to be the most suitable equipment for preparing straw to a median length of 30mm. As well as having the lowest power requirement, it provided protection against damage by foreign objects, together with ease of maintenance - knife sharpening and setting. When combined with efficient bale-breaking and feed metering equipment, the slicer has been demonstrated to require only 19-28% of the installed power capacity of existing tub choppers. Cost savings arise in relation to both capital and operating costs.

If further length reduction is required, it will be necessary to use a hammer mill, and the overall power demand will increase.

Report No: B/SF/00202/REP Publication date: 1993

ADVANCES IN WAFERING TECHNOLOGY

Stamford Consulting Group

Background

Two prototype straw wafering machines were constructed during the 1980s and early 1990s, one by Silsoe Research Institute and the other, independently, by British Sugar plc. These machines revealed a number of fundamental problems, which this research has sought to resolve.

Project Objectives

- To clarify some of the important issues associated with the production of straw wafers and their long-term stability, specifically:

  - properties of the bonds between fibres
  - high power use during the operation of rotary closed-end die mechanisms
  - problems in field performance due to lack of crop uniformity.

- To review and update commercial aspects of using straw a fuel.

- To review technical progress to date.

Findings

Properties of the bonds between fibres

Experimental work carried out at the BioComposites Centre, Bangor produced the following results:

- *Bonding* - Mechanical interlocking rather than chemical bonding is the most significant mechanism in the formation of straw wafers. If straw is uniformly aligned before wafering, planes of weakness occur.

- *Gas pressure* - The build-up of gas pressure during the formation of wafers suggests that the faster the process is carried out, the more wafers are likely to fall to pieces and the less stable they are likely to be, especially if the permeability of the material is low.

High power use during the operation of rotary closed-end die mechanisms

Experimental work carried out at the University of Loughborough produced the following results:

- *The effects of die overcharge* - The overcharging of dies is the single most important factor affecting power consumption. An increase in input mass of 15% in a given die volume corresponds to an energy increase of about 54%. The equipment also risks destruction from stresses of the same order as the strength of the materials used.

- *The effects of straw traps* - Traps, which occur whenever two equipment surfaces approach one another, are significant causes of wasted energy. Flat traps consume 100-200% extra energy; chamfered traps consume 50-100% extra energy.

- *Friction losses* - Frictional losses occur at the peripheral surfaces of the dies and, although they vary widely, with some modification of the straw surface taking place and reducing the coefficient of friction, these losses are estimated to waste around 30 MJ/tonne. However, improved die design would reduce frictional die loss by less than 50%.

- *Rotational losses* - Rotational losses during die formation are inevitable but relatively limited.

- *Overall* - Straw traps and friction against the static components of the equipment are very significant causes of energy loss during the wafering process. Even feed of the straw swath reduces the risk of very high energy demand peaks within the machine. The development of a die system that could accommodate variable swath feed would be a great advantage.

Problems in field performance due to lack of crop uniformity

Experimental work carried out by Silsoe Research Institute produced the following results:

- *Straw swath variation* - Average straw weight per metre was 2.5 kg and the average variation was 16.9%, although the largest variation measured was 139%. A wafering die design that will accommodate density variations of its input feed of +/- 15% is available. However, considerable smoothing or speed variation will be needed before typical combine swaths can be fed into a wafer-making process.

- *Feed regulation* - Various systems for reducing the variation in an uneven straw swath were investigated. Combining a high-speed pick-up rotor with an inclined conveyor belt moving at half the machine's forward speed smoothed an irregular swath density to less than +/- 20%. Another possible option is to supply a static wafering device from a large bale feeding mechanism.

- *Control algorithm* - Hydrostatic forward speed control would appear to be a solution to the degree of forward speed change necessary for in-field wafering. A feed forward control system was incorporated on the Silsoe machine, whereby the speed of the wafering rollers was adjusted according to the density of the approaching column of straw. A density sensor that will provide a continuous and sufficiently accurate measure of crop density for effective control is very desirable.

- *Straw presentation* - A test rig investigated a mechanism involving straw walkers with a uniform stroke of 40mm and converging to increase crop density as it is transported. Four pairs of elements, mounted at 90° to each other around the direction of motion, conveyed the crop at 83 mm/revolution and compressed the straws together with some degree of folding.

- *Mechanical bonding* - Any form of alignment in the feed material weakens the wafer produced. Any separation or layering in the wafer causes structural weakness. The longer the length of material crushed in random orientation within the wafer, the more stable the final product. Straw chopped into 4-5cm lengths fails to make stable wafers, even when mixed randomly.

Commercial changes

The industrial power generation market has changed substantially since the early 1980s. The costs of industrial and power generation coal are now much lower, and straw wafers cannot compete. High density bales are well established technology and their delivered cost to plants is lower than for wafers. Furthermore, unlike wafers, they can be stored in the open without significant losses.

The mobile wafering machine would be costly to develop and produce, and the immediate UK market for wafers is too small to encourage such development. However, the wafering process may provide the ideal solution when preparing biomass for gasification, where large volumes of material must be fed into high-pressure reactors. Under these circumstances, wafering is best integrated as a static process that prepares baled straw for transfer into the reactor. Furthermore, the wafering process is suitable for other materials such as rape straw, linseed straw, bean stalks, mixed waste paper and mixed wood wastes. The process can also be applied to other bulk-handling applications such as animal feed and certain forms of paper pulp.

Development of a new machine

A new wafering machine design has been produced, which incorporates the main findings of research and development work to date. Once modifications to the pre-compactor mechanism have been completed, it should be possible to build a demonstration machine with an output potential of an estimated 6-7 tonnes/hour of wafers. The target price for a pre-production prototype has been estimated at between £70,000 and £100,000. A static machine with its associated drive and handling gear is likely to cost more than its mobile counterpart - perhaps £80,000-£120,000.

Report No: ETSU B/SF/00422/REP Publication date: 1996

STRAW FOR ELECTRICITY GENERATION: AN ASSESSMENT OF STRAW STORAGE SYSTEMS APPROPRIATE TO A YEAR-ROUND SUPPLY REQUIREMENT

LRZ Ltd

Background

The UK straw surplus is currently around 6 million tonnes/year. It occurs mainly in the cereal growing areas of the south and east of the country, and this makes it the most widely available biofuel in the UK at the present time.

At least one of the plants that obtained funding in the *Energy crops and agricultural and forestry wastes* category of the third round of Non-Fossil Fuel Obligation bids is planning to use straw as a primary fuel. Others are examining its potential as a secondary fuel. All plants using straw as fuel will require large quantities of a high and consistent quality throughout a year-round operating period. At the same time there are tight limitations on delivered fuel price.

The key variable determining straw quality is its moisture content. The Volund "cigar burner" unit, which is currently pre-eminent where 100% straw combustion is used for electricity generation, is designed for a straw moisture content of 15-17%. Higher moisture levels reduce the straw's calorific value, and combustion plant efficiency falls. Similar constraints apply to other straw combustion systems. It follows from this that, if suppliers are to receive the maximum price for their straw, they will need to deliver it at the lowest possible moisture content.

Project Objectives

- To assess the main options for storing straw prior to its use as a fuel.
- To evolve an optimal storage strategy based on cost effectiveness.

Methodology

A combination of field trials and economic modelling was used in the project. Key elements were:

- measurement of the moisture content of baled straw stored in unsheeted stacks, November 1994 to May 1995

- field evaluation of the 410 sheet tensioning system developed for sheeting straw stacks

- economic evaluation of the main storage options.

All the work was based on the bale produced by the Hesston 4900 baler, as most fuel handling systems are designed for this size of bale.

Findings

Unsheeted stacks

Where straw was stored in unsheeted stacks, the findings were as follows:

- Absolute wastage is almost entirely confined to those bales where the top of the bale is directly exposed to the elements (top and "shoulder" bales). These bales are at or near saturation point by October/November.

- From January onwards, moisture penetrates the second layer, devaluing it in an energy market and, possibly, resulting in total wastage.

- Beyond the second layer, moisture ingress is unlikely to have a significant effect on straw quality for electricity generation purposes during the first year.

- Moisture ingress into the sides of stacks affects mainly those bales below directly exposed top and shoulder bales. Both are likely to be devalued in an energy market from April onwards. The former may even be wasted. Moisture ingress into the side of the stack is unlikely to have a significant impact on straw quality for electricity generation purposes below the bale directly under the shoulder bale.

- Long-term straw storage in unsheeted stacks results in considerable water penetration and very high wastage levels.

Overall, in some instances, wastage may account for 25% or more of the total straw in storage.

The 410 sheet tensioning system

Although current practice is to leave large stacks uncovered, some sheeting does take place. However, conventional sheeting is awkward and cumbersome to put in place, difficult to maintain once in place and, over long periods, highly prone to failure.

The 410 system has been designed to overcome these problems. The sheet is anchored by a straw claw that is driven into a lower bale. As the sheet comes under stress, the claw is pulled further into the bale. The webbing straps between the claw and the sheet incorporate an elasticated section that provides some flexibility, thereby reducing stress on the sheeting itself. The webbing is attached to a ratchet that is used to bring the whole system under tension.

Field trials indicated that further development is required before the 410 system represents a viable storage option. The main problem is the link between the tensioning straps and the sheet itself. Some modifications have since been introduced (not as part of this project), including stronger sheets, with webbing straps stitched directly into the sheet across its whole width plus, in some instances, a combination of hook and eye attachments at the edge of the sheet. A watching brief should be maintained on these and any further developments of the system.

Economic evaluation of straw storage systems

This part of the study involved an economic evaluation of three storage options:

- unsheeted stacks
- sheeted stacks using the 410 system
- storage in a permanent building.

For unsheeted stacks, the effective costs/tonne, ie the cost of wasted straw, ranged from £0.17/tonne for straw stored from July until September to £5.03/tonne for straw stored from July until the following April-June.

If the 410 or a similar sheeting system can be made to work correctly, it is highly cost effective. Indeed, at £1.60/tonne it is cheaper than all unsheeted systems except where the straw is stored for less than three months.

At £9.60, assuming a build cost of £70/m^2 and a stack height of six bales, inside storage is not an economically viable option under UK conditions.

The aggregate cost per tonne over the year shows that sheeted storage systems from October onwards are the cheapest option at £1.29/tonne. Unsheeted storage has an overall cost/tonne of £3.54 and a combination of sheeted storage between October and December and inside storage from January until June gives an overall cost of £5.54/tonne.

2.3 Straw Combustion

Report No: ETSU B 1158 Publication date: 1988

STRAW FIRING OF INDUSTRIAL BOILERS

FEC Consultants Ltd

Background

Annual UK straw production is around 13.6 million tonnes, of which about 6.7 million tonnes is baled for use. The remaining 6.9 million tonnes, equivalent to 3.5 million tonnes of coal or 1% of UK energy requirements, is either burnt in the field or ploughed in. By 2000, the annual production of straw is likely to be about 15 million tonnes, but no significant expansion in existing straw markets is anticipated. The potential for using straw as a fuel is apparently considerable.

Project Objectives

- To determine the economic viability of using straw as an industrial fuel.
- To characterise straw as a fuel for industrial boiler plant.
- To determine the suitability of existing combustion systems for straw and straw/coal burning.
- To establish a body of operational experience of straw as fuel using different combustion technologies.
- To establish size-reduction and handling techniques appropriate to the different combustion technologies.

Findings

Potential for straw as fuel

Straw surpluses are found in most of the eastern half of the country, particularly in East Anglia. In these areas the potential energy markets exceed the surplus supply of straw by a factor of about two.

Most commercial straw burning takes place in purpose-designed low-thermal-output boilers that burn whole bales. The process is slow and relatively inefficient. Whole-bale-burning boilers for industrial use, with high efficiencies and high thermal ratings, have been developed abroad, but are very expensive.

Straw is, to some extent, already being used as a cost-effective fuel in the UK, particularly on farms, where 166,000 tonnes/year are currently being burnt for heating farmhouses and buildings. Whole-bale burners predominate, although automatically stoked boilers that use shredded straw are increasingly being used for more critical applications such as greenhouse heating. At Woburn Abbey, a chopped-straw-fired boiler with a capacity of 0.8MW provides space heating, while Needham Chalks Ltd uses straw to fire a 7.3MW cyclone burner for chalk drying.

A study visit to Denmark concluded that straw makes a significant contribution to that country's energy requirements and is the main fuel in numerous district heating boiler plants. Although Danish straw combustion technology is well advanced, the equipment is expensive when compared with boiler plant fired using more conventional fuels. However, Government incentives have encouraged the use of straw as a fuel in Denmark.

In the UK, farm use is expected to increase to up to 1 million tonnes by 2000. The domestic market, even for processed straw as pellets or briquettes, is limited, so it is the industrial market that has the potential to take up the residue of more than 5.75 million tonnes/year. This will only happen quickly if existing plant and combustion technology can be shown to be potentially capable of burning straw efficiently and cost effectively.

Straw fuel characteristics

Laboratory trials have confirmed that straw is a low-grade fuel compared with coal. It has a high volatile content (typically 65%) and a low calorific value (typically 15 MJ/kg). The ash content of straw is comparable to coal, but the sulphur content is much lower - 40% of that for coal for an equivalent plant output.

The low bulk density and calorific value of straw means that ten times the volume of baled straw is required to match the energy content of coal, and 27 times the volume of chopped straw. This has implications for fuel storage, handling and combustion system design.

Loose straw is difficult to handle, and serious bridging problems occur in positively sided hoppers. These problems are compounded if compaction takes place. Generally, the magnitude of the handling problems diminishes with straw length.

Compared with coal, straw ignition and complete combustion occur at lower temperatures. Straw combustion also takes place more rapidly than with coal, and the high volatile content of straw means that much of the combustion takes place in the gas phase. The correct provision of secondary combustion air is essential for efficient combustion.

Combustion systems

The use of straw was found to be impractical for conventional stoker systems - chain grates, coking stokers, underfeed stokers etc - on coal-fired boilers, largely because of feeding difficulties. The high volumes of straw, compared with coal, and the combustion air provisions on these systems proved incompatible. For on-grate combustion, only purpose-designed systems are likely to be suitable for straw firing.

Suspension firing systems, such as cyclone burners, have demonstrated a good capability for burning chopped straw efficiently. The highly turbulent mixing of the air and fuel produces ideal conditions for complete straw burn-out in the short space of time available, while volumetric fuel feed rates pose no restrictions because of the low residence times involved.

Cyclone burners could be retrofitted to existing boiler plant in place of conventional fuel-firing equipment.

Deep or recirculating fluid bed combustors are potentially suited to straw utilisation. Shallow fluidised bed systems, however, are much less suitable. The high volatile content of the straw means that most or all of the combustion takes place above the fluid bed and supplementary fuel is needed to maintain bed operating temperatures.

During the course of this project, a supplementary straw-firing system was developed that allows straw to be burnt with coal in conventional coal-fired boiler plant. The straw is fed to the boiler by a pneumatic transport system and is then burnt, in suspension, above the existing coal-fired bed. This lean phase air conveyance system has been demonstrated using high levels (up to 50%) of straw substitution in conventional boiler plant, while allowing normal coal firing at any time. High efficiencies were achieved. The only restriction on straw substitution is that a threshold minimum coal-firing rate is required to provide an adequate ignition source for complete straw combustion. Fouling has been experienced with this system in dry back boilers, but either on-line or off-line cleaning methods should be able to overcome the problem. Overall, further work is required before the system can be used commercially.

Economics of straw as fuel

Straw can, under certain circumstances, be economically attractive as an alternative to more conventional fuels, not only on the farm but also in local industrial installations.

On-farm combustion of whole bales for space heating purposes produces a simple payback of about two years on a capital expenditure of £5000. In a commercial premises requiring a purpose-designed straw boiler with a capacity of 0.75MW, the simple payback is more than nine years. However, on larger installations of the shell type, and using the conversion technique developed during this project and summarised above, the simple payback on capital expenditure could be reduced to 2-3 years.

The relative economics are greatly affected by three factors:

- the price of the alternative fuel - coal, oil etc
- the delivered price of straw - determined by the haulage distance from the straw source
- the annual load factor of the plant
- the investment capital required to convert the system to straw firing.

Each potential site therefore needs to be individually evaluated.

Existing, purpose-designed automatic straw handling/preparation plant is costly, and this has a detrimental effect on the economics of straw firing. A more simplified approach to straw handling could reduce capital costs.

Report No: ETSU B 1261 Publication date: 1991

STRAW FIRING DEMONSTRATION TRIALS: AXIAL SWIRL BURNER AND FLUIDISED BED COMBUSTION

Babcock Energy Ltd

Background

A series of short trials involving the firing of straw in a range of small industrial boilers and furnaces was carried out by FEC Consultants Ltd (see above, Report No: ETSU B 1158), and the results showed that four types of straw combustion system were worthy of further study:

- cyclone burners used alone or as a replacement for gas-, oil- or coal-firing systems
- fluidised bed combustors
- lean phase air conveyance systems for suspension firing of straw
- whole-bale combustors with a higher thermal output.

It would appear that the development of straw combustion systems, whether custom-built units or low-cost retrofits to existing industrial boiler equipment, is feasible. It also seems likely that, provided boiler operators have an economic incentive to fire straw, the use of straw as a fuel will increase.

Project Objectives

- To determine whether it is possible to fire chopped straw through an unmodified pulverised fuel burner without oil support and, if oil support is necessary, to determine the minimum ratio of oil to straw required for stable combustion.

- To determine whether it is possible to fire straw, either baled or chopped, in a fluidised bed without coal support and, if coal support is necessary, the maximum ratio of straw to coal that will give stable combustion conditions.

Methodology and Findings

Straw burning through a low-NO_x axial swirl burner

The burner used for the trials was a Babcock 12MW low-NO_x axial swirl burner. It was fitted into the top burner position of the test facility.

The straw-handling rig operated satisfactorily at full load with chopped straw screened at 12.5mm. No problems occurred with material building up at 90° bends or dropping out in horizontal sections. However, while the rig was suitable for short-term testing, it is not appropriate for long-term, 24-hour testing for two reasons:

- the labour-intensive nature of feeding chopped straw into a small-capacity hopper.

- The need for a feeder capacity that is three times its present value of 1000 kg/hour to give the full burner load associated with stable flames.

The low-NO_x axial swirl burner proved prone to blockage at straw feed rates of 1000 kg/hour. Removal of the internals alleviated the problem, but it will be necessary to test any tendency to block at higher feed rates.

Air velocities are likely to need optimising for straw combustion at increased burner loads.

A stable flame was obtained at approximately 50:50 straw:oil heat input. It was not possible to test performance at a lower oil input because of the turndown limitations of the existing oil firing system.

The straw burned well with a long thin flame. The large quantities of burning material floating around the furnace, impinging on the rear wall and being carried up towards the furnace exit, were probably due to some of the straw particles being too large and the residence time in the furnace being too short for complete combustion. Reducing the top size of the particles could alleviate the problem.

Overall, the combustion of chopped straw was encouraging, despite the requirement for oil support. It is not inconceivable that, if the burner could operate at full load using purpose-designed feeding equipment rather than modified existing equipment, it could fire unsupported on straw or with a low level of oil support.

Straw firing in a fluidised bed

The straw-handling rig operated satisfactorily at the lower end of its capacity. The major problem with the rig is that the system is labour intensive and requires chopped straw rather than long, baled straw which is cheaper.

Attempts to fire baled straw through the side of the rig were unsuccessful as the ignition temperature of straw is too low. Radiation and conduction from surrounding hot surfaces caused the straw to ignite. Burnback of the bales into the feed chute is a possibility and would be very difficult to prevent. Overall, the technical and safety problems associated with feeding baled straw may be too difficult to overcome.

Under solid circulating conditions, chopped straw had a degree of success. Most of the combustion took place above the bed, and coal support was required to heat the bed as straw penetration proved poor. Compressed air may have been responsible for blasting some straw into the bed.

Bed temperature increased significantly as the straw proportion increased, and this resulted in high exit temperatures - a possible cause for concern, particularly where items such as bag filters are used.

Stable operation proved easy to maintain. This is encouraging as it indicates that chopped straw can be fed at constant rates and there is no change in quality that would affect combustion. Stable operation appears to be possible at both low and high straw feed rates.

Similar results were obtained firing chopped straw under hot gas generator conditions.

The overall conclusion is that straw could be a viable fuel for fluidised beds if more straw could penetrate the bed. Underbed feeding is an acceptable feeding system for fluidised beds and, as straw is easily transported in chopped form, underfeed conditions might provide the bed with a greater straw heat input, eliminating the need to maintain bed temperature using coal.

Recommendations

- The design of an appropriate burner for straw.
- The design of a straw feeding system that matches burner throughputs.
- Modification of underbed feeding systems for straw to allow more straw to enter the bed.

Report No: ETSU B 1257 Publication date: 1993

HIGH CAPACITY WHOLE BALE STRAW COMBUSTOR

Henley Burrowes

Background

Straw is an important renewable biofuel that has considerable unexploited potential as an energy source. Most UK straw combustion systems have been installed on farms for heating dwellings, ancillary buildings etc. They use mainly small bales, one or two of which are batch loaded into a boiler and left to burn through. Some large-bale boilers are also being built, and there is some small-scale use of chopped or guillotined small straw bales.

Most of the industrial capacity straw combustion systems available in the UK are of Scandinavian origin and are 3-5 times the cost of equivalent coal-fired plant. However, proven incinerators for the combustion of municipal and other solid wastes do exist, such as the Henley Burrowes rocking grate, and it should be possible to combine this with a simple feed system for unbroken half-tonne Hesston bales, around 800,000 tonnes of which are produced in the UK each year.

Project Objectives

- To design, build, install and test a system capable of burning whole Hesston-type bales at a throughput of 500 kg/hour (2MW thermal input).
- To monitor and evaluate the performance of the whole system and of its individual components.
- To establish commercial viability.

Methodology and Findings

The unit

The combustor unit was built and tested at Secondary Resources plc, a facility at the Castle Bromwich refuse derived fuels plant in Birmingham. It consists of a refractory lined steel case with a moving grate (the combustor) plus a dump grate, separate primary and secondary air fans, burners, access doors and ash and clinker handling systems.

The grate has nominal dimensions of 1200mm x 2500mm and incorporates specially shaped grate teeth hooked on to rocker bars. Rotation of the rocker bars and teeth serves to break up, and distribute the burning mass of straw, and transport it up the grate towards the dump grate at the discharge end.

The primary air fan provides underfire air via the ash chute below the grate: the secondary fan supplies overfire air via a series of ports positioned above the firebed. Normally, about 75%

of the total requirement will be secondary air, and the balance of undergrate to overfire air is crucial to the system's effective performance.

Four oil burners ensure initial ignition and complete combustion of the straw. There are two ash-handling conveyors, a dry operated drag bar unit immediately under the firebed and a quench conveyor partly filled with water. The quenched ash is transferred to a chain and slat conveyor and discharged to a suitable receptacle for disposal.

The bale charger was designed to accommodate three Hesston bales, 1200mm x 1200mm x 2500mm. It comprises a powered roller conveyor, a bale loading pusher and tilting transfer table that pushes the bale sideways to position it directly in front of the combustor, and a bale feed pusher. The bale is fed into the combustion chamber in 100mm increments on a timed basis that can be varied to suit the combustor retention time required. Water sprays installed round the feed door prevent burn-back along the outside of the bale, while sprung plackets positioned around the feed opening act as a seal and cater for any variations in bale cross-section.

The whole plant is controlled using a positive location and detection system and a programmable logic controller.

Performance testing

Initial monitoring over a one-month period was designed to test systems and equipment prior to performance testing. Some 70 new wheat straw bales with a 12.14% moisture content and eight old wheat straw bales with a 25.3% moisture content were burnt during this period at an average rate of one bale/hour. During the final test periods, throughput was increased to determine the maximum limits obtainable.

Performance tests were carried out over two separate three-day periods.

Equipment performance

The bale handling system proved to be a simple, cost-effective device for feeding whole bales into the combustor. The only significant problems related to the large variation in bale dimensions and, initially, to the difficulty handling badly distorted bales.

The combustor itself operated excellently and showed no signs of deterioration. However, difficulty was experienced in destroying old bales with a moisture content above 20% because the control parameters could not be adjusted sufficiently. When burning straw with a moisture content of 13-18%, excellent results were obtained with very low carbon monoxide and carbon-in-ash levels.

The small waste heat boiler installed to convert the thermal energy produced into hot water proved adequate except at combustion rates above the 500 kg/hour originally designated.

At the optimum design throughput of 500 kg/hour (2.2MW), the system achieved an efficiency of fuel to hot water at 70°C of 64%.

While operating at design capacity, ash levels were 5.833% (dry) and carbon-in-ash (dry) levels were 8.7%. Where tests were carried out at combustion rates higher than design capacity (750 kg/hour), the carbon-in-ash content increased, indicating that complete combustion was not being achieved.

Solid emission rates were well in excess of the 200 mg/Nm^3 laid down in the Environmental Protection Act 1990 best available technique not entailing excessive cost (BATNEEC) guidance notes. A wet gas scrubber was added to the system, which put a high demand on the existing induced draught fan. A high-temperature filter between the combustor exit and the boiler inlet should minimise fouling while complying with legislation.

Manpower requirements under commercial conditions are likely to be three per day shift and two per late or night shift. This would be adequate from a health and safety point of view, although additional cover for illness etc would be required.

Estimated costs for the unit, including bale handling, combustor, ash removal, chimney, induced draught fan and ducting were £80,000, with a further £25,000 for hot water boiler plant, £45,000 for gas scrubbing equipment and £60,000 for building and civil work.

Conclusions

- Combustor development has reached the level where a commercial application can be contemplated with confidence.

- Apart from the need to reduce particulate levels in the gas emissions, the products of combustion are well within levels demanded by relevant legislation.

- The whole-bale straw combustor offers a proven method of using a valuable renewable resource while providing an environmentally acceptable alternative for waste straw disposal.

Recommendations

- Minor modifications to the combustor feed aperture.
- Further monitoring of boiler fouling.
- The incorporation of a high-temperature filter in future designs.
- Tests using barley and rape straw.
- Assessments of the technical and commercial potential of the ash produced.
- Modifications to the bale handling section to accommodate the full size range.
- Minor modifications to the ash quench conveyor.
- Greater flexibility for the induced draught fan.

Report No: ETSU B/SF/00244/REP Publication date: 1993

STRAW FIRING IN A BUBBLING FLUIDISED BED

Babcock Technology Ltd

Background

About 6-7 million tonnes of surplus straw is currently available in the UK, most of it in East Anglia, the East Midlands and the South Yorkshire/Lincolnshire area. A small proportion of this is used for space heating, mainly on farms, but the industrial use of straw as a fuel in the UK is very limited.

Several factors are changing the prospects for energy recovery from straw:

- On-field straw burning will be banned from the 1993 harvest onwards, and farmers will need to seek environmentally acceptable alternative disposal routes.

- The Non-Fossil Fuel Obligation has provided a short-term protected market for the production of energy from renewable resources.

- Privatisation of the UK electricity supply industry has encouraged generators and Regional Electricity Companies to take an interest in small-scale generation schemes, particularly those that are CO_2 neutral.

- The fall in farm profits is encouraging farmers to explore new activities, particularly those that do not involve food production.

Combustion in a fluidised bed has a number of important attractions for straw. Combustion efficiencies are high, while relatively low combustion temperatures reduce fouling of the combustion chamber and boiler surfaces. Earlier work (see above Report No: ETSU B 1261) showed that, while straw burned very well in a fluidised bed test facility, there was insufficient combustion within the bed to maintain bed temperatures and allow withdrawal of the coal support fuel. It was concluded that the underbed introduction of fuel might be more appropriate.

Project Objectives

- To test the feasibility of firing chopped straw of various lengths in a bubbling fluidised bed by underbed feeding at a rate of combustion above 0.5MW, and to design and develop an appropriate feeding system.

- To move towards the elimination of coal as a support fuel.

- To experiment with different straw chop lengths to determine the minimum amount of chopping compatible with good combustion and handling.

Methodology and Findings

Main plant characteristics

The straw feeding rig used for the tests consisted of a feed hopper and two screw feeders in series. Chopped cereal straws of three different chop lengths were purchased in bags and were fed manually into the hopper of the rig during the tests.

A straw conveying and distribution system was also designed and installed. This consisted of a new pneumatic conveying fan, installed downstream of the straw feeding rig, a new straw conveying line and two purpose-designed, inverted-cone straw distribution devices.

The tests were carried out on a solids circulation fluidised bed test facility using half-inch, three-inch and six-inch chopped straw. The facility comprises a 1m x 1m refractory-lined furnace into which coal is fed, above bed, through a 0.18m diameter variable speed screw feeder. An overbed oil burner provides start-up. Combustion air is supplied from the forced draught fan, and the hot gases from the combustion chamber pass through a series of heat exchangers, a high-efficiency cyclone and a bag filter and induced draught fan before exhausting to atmosphere. The unit can be operated in solids circulating or hot gas generator mode.

Combustion using half-inch straw

The straw feeding system operated reasonably well with the half-inch straw, and it proved possible to carry out combustion test work in both hot gas generator mode at $1MW_{th}$ and solids circulating mode at around $2MW_{th}$, firing straw alone for long periods. Although the variability in straw feed rate proved higher than desirable, the main rig operational targets were met, and some good quality combustion and gaseous emissions data were collected.

Bed temperature profiles proved fairly uniform, indicating that the straw conveying system and the distribution devices were operating well. Measured carbon monoxide (CO) emissions were low and well within the maximum permitted limits for straw combustion plant, which are currently 250 mg/Nm^3 (dry, 11% oxygen). This indicates that the combustion conditions, over a wide range of excess air levels, were reasonably good. Measured emissions of oxides of nitrogen (NO_x) exhibited a strong positive correlation with the level of excess air, while sulphur dioxide (SO_2) levels were low, as expected for a low-sulphur fuel.

Combustion using longer straw

The system proved only partially successful with three-inch straw and could not be operated at all with the six-inch straw. The longer straws tended to wrap around the shaft of the screw feeder and block the rig, with the result that feeding was inconsistent or did not take place at all.

In the case of the three-inch straw, straw feed rates had to be limited to a maximum of 150-175 kg/hour to prevent blocking of the rig. This meant that relatively high levels of coal support were required to meet the target heat input to the combustor in both hot gas generator and solids circulating mode. However, bed temperature profiles were again reasonably uniform, which indicates that the straw conveying system and the distribution devices were operating well. Measured CO emissions were low, indicative of reasonably good combustion conditions. The NO_x emission levels exhibited a positive trend with increasing excess air levels, while SO_2 levels were higher than with straw combustion alone because of the higher sulphur content of the coal.

No combustion tests were carried out using six-inch straw.

Ash component

Although samples of ash were collected from the rig's bag filter, it was found to be heavily contaminated with elutriated bed material. Although this was not surprising, given the very low ash content of straw, it made it impossible to establish specific information about the nature of the straw ash from the combustor.

Conclusions

The results of the tests with the half-inch straw, and to a lesser extent with the three-inch straw, are sufficiently encouraging to suggest that, if a suitable straw-feeding rig were available, the conveying system and the straw distribution devices would operate well, even with the longer straws for which they were initially designed. Recent experience of industrial scale units in Denmark indicates that a rotary valve feeder rather than a screw feeder may be more suitable for straw with a longer chop length.

The principle of the underbed feeding of chopped straw into a bubbling fluidised bed furnace has thus been demonstrated at the pilot scale, and there is justification for further work. The principle of underbed feeding is well suited to the larger scale, with the findings of this test work suggesting that, at the industrial scale, a minimum of two straw distribution devices per m^2 would be required to achieve a sufficiently uniform fuel distribution across the bed.

Recommendations

- Investigations into suitable feeding systems for longer straw chop lengths.

- Preparation of a detailed system design for the underbed feeding of chopped straw in a fluidised bed combustor at industrial scale - either as a retrofit for existing coal-fired plant or for a purpose-built unit - and the completion of relevant combustion test work.

Report No: ETSU B/M5/00533/06/REP Publication date: 1996

REPORT ON A SURVEY OF SMALL-SCALE STRAW-BURNING BOILERS

Reading Agricultural Consultants

Background

It is estimated that there are probably around 2000 straw-burning or partly straw burning boilers in use in the UK, despite the fact that the prices of straw and oil have changed since the early 1980s (straw - in pence per MJ - has gone up in price, while oil has come down), and straw is no longer quite as attractive as a fuel.

Project Objective

- To carry out a survey of farmers and growers with straw-burning installations in the Oxford area in order to determine why and how the installations are used and to assess the technical aspects and economics in each case.

Methodology

An appropriate questionnaire was designed and tested. It was then used to elicit information from 24 farmers and growers in the Oxford area. Most of the information was obtained by telephone, although some sites were visited.

Most of the farmers and growers contacted were known to the surveyor. Although the survey was not random, it was considered to give reasonably representative information and to include examples of the main types of burner currently available.

Findings

Boilers and their installation costs

Of the 24 burners, six were installed 15-18 years ago, nine 10-14 years ago and the remainder between one and ten years ago. Scanfield boilers imported from Denmark were the first to be installed. They accounted for five of the early installations, but none have been imported recently. Farm 2000 units accounted for the majority (11), with Dragon boilers in two installations and various others in the remaining six. The boilers ranged from 150,000 Btu/hour when burning straw to 1,000,000 Btu/hour. Most were in the 200,000-500,000 Btu/hour range.

Accurate information on costs was difficult to obtain. However, the highest figure quoted was £52,000 for a 1 million Btu/hour unit at Ditchingham Hall, which included the cost of housing, straw chopper, store for chopped straw, automated stoking, a considerable length of imported insulated piping and an expensive “one-off” boiler. One other large installation was quoted as costing £30,000. At the other end of the scale, was a small, second-hand Scanfield boiler attached to an existing central heating system, which was estimated to have cost about

£1000. Twelve of the installations were reckoned to have cost £1000-£4000, with ten costing between £5000 and £13,000.

Reasons for installation

The universal reason for installing the units was to save on fuel costs, with independence of supply often given as a related reason. Several users recalled that they had considered it good policy to burn straw in a boiler rather than in the field, even though the quantity burned was usually much less than their total production. A few respondents installed straw-burners when building a new house or installing a new central heating system. In two cases where the heat produced was used to dry grain, the cost was offset against tax.

Current boiler use

Nineteen of the boilers were still in full use, including four that had replaced earlier models. One was used only in the summer for grain drying. Another was used to heat a swimming pool. Three units had been scrapped, reasons including the need for continual hand-stoking, mechanical difficulties with automatic stoking systems and, in one case, serious trouble with neighbours because of excess smoke.

Fuels and stoking

Eight respondents used cereal straw mainly or exclusively. A similar number were currently using mainly oil-seed rape or linseed straw. Estimates of straw use varied: 80-125 tonnes per year in large installations to as little as ten tonnes for the burner used only for the winter heating of a potato pack-house. Eight units used 30-70 tonnes per year and six used less than 30 tonnes per year. Four users now burned waste wood mainly or exclusively. One burned mainly waste from a tree and shrub nursery. All, or almost all, used the boilers as incinerators for various types of waste.

Twelve of the remaining users relied solely on the twice-daily (at least) hand stoking of conventional bales (or wood when used). Six of the larger burners used big bales and were stoked by tractor with hydraulic grab. Of the five examples of automatic stoking, only one system proved consistently reliable. Several installations are now using “accumulators”, or insulated tanks, to store very hot water and act as a buffer, thereby providing some elasticity in the stoking regime.

Heat use

All the units that are still in use incorporate a heat exchange system for the supply of hot water. Twenty-two of the 24 used their boilers for central heating, and all but three used them to provide domestic hot water. In 14 cases only one house was involved - often a large farmhouse. There were seven instances of two houses being heated, one in which six self-catering flats and an NFU office were provided with central heating and hot water. In one case, a farmhouse had been converted into a conference hotel. In two instances the energy was used to heat commercial glasshouses and, in one case, polytunnels. There were four examples of swimming pool heating and two of grain drying. In one instance the burner had been used to heat only a potato pack-house, and in another the hot water was used in a dairy and for calves.

Sixteen of the boilers were used only during the winter. Seven were used all year round and one was used in summer to heat the swimming pool.

Fuel and operating costs

The quoted cost of straw at the burner ranged from £7/tonne to £30/tonne, the latter figure including double handling of the material and chopping for automatic stoking. Most costs were in the £10-£15 range. In most cases, no charge was made for storage, own-machinery use (other than the cost of twine, diesel and labour) or the value of the soil nutrients removed in the straw. In the latter instance, a charge of perhaps £2/tonne of straw used for fuel would be reasonable to take account of its fertiliser value.

It was difficult to establish costs for stoking and ash removal: some farmers made light of stoking while others considered it a chore. A reasonable cost may be £2-£4/tonne. Stoking big-bale boilers requires more time and some fuel. In this instance, a reasonable estimate may be around £4/tonne. The cost of automatic stoking has been even more difficult to establish on the basis of the small number of examples in this survey, but probably amounts to at least £5/tonne of straw.

Service, maintenance and repair costs varied greatly from site to site. Items replaced included chimneys, grates, underground piping, thermostats and fans. One farm had modified the system to include a large accumulator. However, taken over the lifetime of the equipment, repairs and maintenance costs had been relatively limited - £100-£200/year on several farms, with the largest installations spending £300-£400/year.

Fifteen of the 24 users said they would install a similar system today. Seven said they would not and two were undecided, reasons cited including smoke problems, automatic stoking difficulties and the labour and inconvenience of stoking straw. All agreed that the current low cost of oil made straw boilers less attractive.

Overall

Experience with straw burners has emphasised a number of points:

- Really dry straw (15% moisture or less) burns better and more cleanly than damp straw.

- Better fan arrangements and multi-pass boilers give more efficient combustion.

- Accumulators combined with faster combustion may improve efficiency.

- Putting some wood in the burner at night can simplify stoking.

- Stoking is an inconvenience and a serious disadvantage. Big-bale stoking using tractors can ease the work. “Automatic” augered stoking using pre-chopped straw is a satisfactory alternative.

Recommendation

It would be useful to carry out a small, in-depth enquiry among a limited number of co-operating users to provide precise data on issues such as:

- the cost of biomass-burning boilers, including installation and maintenance/repair costs
- actual and notional fuel-procurement costs - straw, baling, transport, storage
- actual and notional costs of stoking by various methods
- detailed information about energy use - eg the area heated, the amount of hot water supplied, the value of a grain-drying operation
- comparative information for an oil-burning installation that would provide a similar energy output.

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$_e$ 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.

2.4 The By-products of Combustion

Report No: ETSU B 1242 Publication date: 1993

STRAW ASH CHARACTERISTICS

Babcock Energy Ltd

Background

If suitable collection, handling and combustion techniques can be developed and the economic climate is favourable, significant quantities of straw could be used as fuel on farms (900,000 tonnes/year), in industrial, rural commerce and institutional establishments (2.5 million tonnes/year) and, if the fuel can be made available in an appropriate form and at the right price, in the domestic sector (2.8 million tonnes/year).

Trials involving the firing of straw on a range of small industrial boilers and furnaces (see above, Report No: ETSU 1158) showed that the simple substitution of straw for coal on conventional stoker-fired boiler plant is not feasible without major plant modifications. However, results with a cyclone burner, and the findings of demonstration projects at Needham Chalks and Woburn Abbey, which successfully used chopped straw, showed that the development of straw use as fuel is a feasible option given the right equipment and an appropriate economic environment. It is therefore relevant to characterise straw in more detail and to examine the nature and behaviour of straw ash under industrial boiler conditions.

Project Objective

- To study the nature and high-temperature behaviour of straw ashes, thereby providing the boiler engineer with sufficient information to make the appropriate boiler design decisions and to respond to ash-related problems that may occur on plant.

Methodology

Test work was based on a number of different straw samples:

- oil-seed rape straw collected directly from the field
- small bales of oil-seed rape straw from a farm
- one Hesston bale each of barley and wheat straw from a straw merchant
- one Hesston bale each of wheat and barley straw from a farmer/straw merchant.

The samples were used for straw characterisation, straw ash characterisation, straw-coal co-firing experiments, sulphur retention studies and sodium and potassium volatilisation.

Findings

Straw characterisation

Basic fuel data for the six straw samples indicated that straw is a typical high volatile, cellulose based fuel with moderate moisture and low ash content. Volatile matter contents varied between 62% and 72% as received, and between 79.5% and 82% on a dry, ash free basis. Moisture contents ranged from 6.2% to 15.1% as received, reflecting differences in the original moisture contents of the straws and their history prior to sampling and analysis. The sulphur and nitrogen contents are low compared with most coals, and the chlorine content (0.04-0.36%) is similar to that of British industrial coals.

Overall, the fuel properties of the three types of straw were very similar, although there was evidence that rape straw had a lower ash content (3.5-4.0%) than cereal straw (5-6%).

The pot furnace tests clearly indicated another characteristic of straw that will have a major impact on its use as a fuel - its very low bulk and energy density. The tests showed that serious difficulties will arise when firing straw or coal/straw mixtures on stoker-fired boilers that were designed for coal.

Straw ash characterisation

The chemical and mineralogical analyses showed that straw ashes differ from coal ash. Straw ashes are not alumino-silicate systems but consist of silica (mainly amorphous) and simple inorganic salts, principally calcium and magnesium carbonates and potassium orthophosphates. The oil-seed rape straw ashes are particularly rich in calcium carbonate, but have significant levels of amorphous silica and the potassium phosphates. The cereal straws are rich in amorphous silica and the potassium phosphates, with the carbonates present in lower concentrations.

The high temperature microscopy and ash fusion test work showed that the oil-seed rape and cereal straw ashes have very different fusion properties, and that these reflect the major differences in their chemical and mineralogical composition. Initial deformation temperatures measured under reducing conditions (IDT (red.)) are often used as boiler design parameters, and recommended values are as follows:

- oil-seed rape straw ash: IDT (red.) = 1250°C; relatively short fusion range
- oil-seed rape straw/coal ash mixtures: IDT (red.) = 1100-1200°C
- cereal straws: IDT (red.) = around 900°C
- cereal straw/coal ash mixtures: IDT (red.) = 900-1200°C.

For most straw ash/coal ash mixtures the ash fusion temperatures are lower than or intermediate between those of the pure ashes. The figures given above clearly show that cereal straws are particularly prone to clinker and slag deposit formation, and this will present serious difficulties to boiler designers and operators.

Sulphur retention studies

The sulphur retention studies showed that the uptake of sulphur dioxide (SO_2) by straw ashes is controlled by the reaction of SO_2 with calcium oxide (CaO) in the ash and occurs over the 400-1050°C temperature range. The oil-seed rape straw ashes, which have a relatively high CaO content, showed a strong affinity for SO_2, whereas with cereal straw ashes the level of uptake was very low.

In practice, the level of SO_2 retention by the fuel ash will depend on the details of the combustion system and boiler design. Overall, the scope for a reduction in emission levels of oxides of sulphur by retention in the ash is likely to be both limited and unreliable. The only likely exception would appear to be the firing of oil-seed rape straw in fluidised bed systems with bed temperatures below about 1000°C.

Sodium and potassium volatilisation

The relatively high potassium content and the high availability of alkali metals in straw ash at temperatures above 800°C suggests that fouling by a volatilisation and condensation reaction will be significant. This is likely to result in serious problems with the formation of fouling deposits on the boiler surfaces of conventional steam-raising plant. The problem is likely to be reduced by burning straw in a fluidised bed combustor.

Report No: ETSU B 1313 - P5 Publication date: 1993

AN EMISSIONS AUDIT OF A PURPOSE BUILT WHOLE BALE STRAW COMBUSTOR

Warren Spring Laboratory

Background

Henley Burrowes & Co Ltd has developed and installed a whole bale straw combustion unit on the former Birmingham City Reclamation Site at Castle Bromwich (see above, Report No: ETSU B 1257). The unit has a design throughput of about 600 kg/hour of straw, with the flue gases passing through a waste heat boiler producing hot water.

Under legislation associated with the Environmental Protection Act 1990, the combustion of wastes and of fuels derived from waste is to be regulated. Operators of such processes must demonstrate that they are using the best available technique not entailing excessive cost (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). Her Majesty’s Inspectorate of Pollution (HMIP) is publishing a series of guidance notes which lists the emissions concentrations that should be achievable using BATNEEC.

Project Objective

- The overall objective was to assess the environmental impact of recovering energy from a Heenan Nichols rocking grate burning straw bales and, more specifically:
    - to provide information on combustion performance
    - to provide design data for gas cleaning equipment
    - to provide full emissions data for assessment of the unit with respect to current legislation
    - to provide information for the drafting of future BATNEEC process guidance notes
    - to provide information about emissions during unit start-up and shut-down
    - to provide information for assessing the performance of a dust density meter.

Methodology

The emissions audit involved measuring combustion gas, acid gas and particulate concentrations in the flue duct. Flue gas and grate ash concentrations of toxic organic micropollutants were also measured. Boiler efficiency was measured using an energy meter and thermocouples.

The trial consisted of a series of tests, the core of the trial being two tests carried out on consecutive days (13 and 14 November 1991) at one operating condition. Tests were conducted with the installed emissions abatement equipment not operational.

Findings

All concentrations are given at standard conditions - 273K, 101.3kPa, 11% O_2 dry gas - unless otherwise stated.

The unit was classified as a Schedule B process, ie it was regulated by the Local Authority using the Secretary of State's Guidance Note PG 1/7(91).

The two tests carried out on consecutive days indicated good reproducibility of operation.

Gas phase temperatures of 1100°C and 960°C were measured in the primary and secondary combustion chambers respectively. Gas residence times in these chambers were not measured.

Boiler efficiency was measured using two methods, both giving a value of 67%. This efficiency was quite low but can be explained by the fact that the boiler had been downgraded to produce hot water instead of steam.

Combustion gas concentrations were good, with test averages for carbon monoxide (CO) and total hydrocarbons of 54 mg/m^3 and 4 mg/m^3 respectively. Carbon dioxide and oxygen concentrations varied during the test, but this was related to the burnout of the straw bale. Combustion gas concentrations were well within guidelines for the combustion of straw.

There are no guidelines for *acid gas emissions* from the combustion of straw. Acid gas concentrations measured in the flue duct were generally steady and relatively low at less than 200 mg/m^3. However, the HCl concentration was greater than the 100 mg/m^3 guideline for many wastes.

Particulate emissions were very high at more than 1100 mg/m^3, well in excess of the guideline value of 200 mg/m^3. Particulate abatement equipment will clearly be necessary for this unit. Chemical analysis showed that 40% by weight of the particulates was chlorine, indicating that boiler tube deposition may be a problem with straw combustion. The particle size distribution indicated that more than 70% of particulates by weight were <1.4µm. Although the dust meter was not calibrated, it did indicate periods of unstable combustion associated with events such as bale collapse.

There are no guidelines for *heavy metal emissions* from the combustion of straw. However, the concentrations measured (1.1 mg/m^3) are well within the guidelines for many other types of waste. The dominant heavy metal in this case was lead at more than 60% of the total.

Ash accounted for more than 85% by weight of the solids emitted by the combustor and for 75% by weight of the heavy metal discharge.

Toxic equivalent (TEQ) dioxin emissions in the grate ash were very low, and the combustion conditions measured indicate a high level of destruction of any dioxins in the fuel. However, dioxin flue gas emissions were high at 17.8 ng/m^3 - similar to emissions from wastes such as refuse derived fuels (dRDF). Given the high potassium, sodium and chlorine content in the flue gas, it seems likely that dioxin reformation is occurring in the boiler and the flue duct. Although particulate abatement should reduce these high concentrations, it is unlikely to achieve the 0.1 ng/m^3 guideline target given for many types of waste (no guidelines are given for straw combustion).

Polychlorinated biphenyl (PCB) concentrations in the flue gas were much lower than dioxin concentrations. While PCB concentrations in the grate ash were higher than dioxin concentrations, they were still at a low level and constituted less than 10% of the total PCB concentration. There is currently no guidance for PCB emissions from either existing or new combustion units of any size in the UK.

Polynuclear aromatic hydrocarbon (PAH) concentrations in both the flue gas and the grate ash were several orders of magnitude greater than concentrations of either dioxins or PCBs. Although there are no limits for emissions to atmosphere from stacks for either incineration or combustion processes, and only limited work has been carried out on PAH toxicity, some PAHs are known to be carcinogenic.

The *start-up and shut-down tests* indicated that high concentrations of CO and dust are likely to occur, especially during start-up, but that these are short lived. Particulate abatement equipment should limit emissions of dark smoke.

2.5 Thermal Conversion of Straw

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 ± 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/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 (updraught and downdraught) 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.

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.

2.6 Straw Hydrolysis

Report No: ETSU-R-55 Publication date: 1990

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 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 cost represents 40-55% of the total production cost (70% in the case of wheat), and the capital cost of the plant is likely to be 2-3 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 amounts of enzymes with low specific activity. Breakthroughs at the basic research level are required to realise the considerable scope for cost reduction that exists, particularly the development of cost-effective enzyme production and of improved enzymes, and fermentation of the 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 any unconverted cellulose together with the hemicellulose and lignin fractions 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 greater potential for reducing costs, but the potential for market development is 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 the price of the ethanol produced sufficiently.

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 this 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.

3. POULTRY LITTER AS AN ENERGY SOURCE

3.1 The Technology and its Potential

In addition to the reports summarised below and in Section 1 above, reference should be made to two reports summarised in Section 2 of this volume:

- Report No: ETSU B/U1/00535/REP Co-firing biomass with coal - power plant case study
- Report No: ETSU B/T1/00358/REP Studies on the thermal processing of biomass and waste materials.

Report No: ETSU E/GS/00124/REP 1 Publication date: 1993

A REVIEW OF CURRENT AND IMPENDING LEGISLATION AND ITS IMPLICATIONS FOR THE FUTURE DISPOSAL OF POULTRY MANURE

Agricultural Development and Advisory Service (ADAS)

Background

Environmental pollution caused by agriculture, particularly livestock farming, has increased over the past two decades. The attendant publicity has caused considerable public concern.

The total UK production of used poultry litter and excreta is estimated at 1.4 million tonnes/year and 0.4 million tonnes/year respectively. Its direct disposal as a fertiliser or by landfill can, in some cases, have an adverse environmental impact.

The pressure for improvement has caused governments in all EEC countries to review and update their legislation to achieve radical changes in farming practice. In the UK there have been major changes in the laws covering environmental pollution, and these will affect the disposal of poultry and broiler litter by agricultural methods.

Review Objectives

- To review current and impending legislation relating to the disposal of poultry manures.
- To assess the implications of the legislation for schemes involving poultry wastes as fuel.

Findings

Water pollution restrictions

The Water Act 1989 sets out the basis for controlling and prohibiting discharges into controlled waters - ditches, streams, rivers and estuaries, coastal waters, ponds, lakes and aquifers - in England and Wales. Similar legislation covers Scotland and Northern Ireland.

The Act set up the National Rivers Authority to provide uniform procedures and standards for the control of water pollution. It has also set up procedures for the provision of Nitrate Sensitive Areas in response to the EC Directive on drinking water quality. This could reduce the application of poultry manure to 10-15 tonnes/ha as poultry farms are, by tradition, on light, well drained soil and poultry manure has a high nitrogen concentration.

The Act sets out the basis for a Code of Good Agricultural Practice for the Protection of Water. The main effects of this practical guide are recommendations on the storage of manure, the storage and disposal of dirty water from cleaning buildings, and the spreading of manure and litter on to farm land. In the latter instance, poultry farmers with limited areas of land will need to seek agreements with neighbours for the use of additional land for spreading manure.

The Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) Regulations 1991 have also been introduced under the Water Act 1989. This requires new installations to have a design life of 20 years and to be constructed according the British Standard 5502 Part 50. The National Rivers Authority can require existing facilities to be brought up to the same standards if they present a significant pollution risk. Farmers receiving poultry manure for spreading need to treat the run-off from solid manure as slurry. This must be collected and stored either independently or in the main slurry disposal systems.

Soil pollution restrictions

There are no specific conditions in the Water Act 1989 for the control of soil pollution from livestock farming. It is implicit in the Act that applications of solid or liquid wastes that are likely to cause water pollution by leaching or run-off must be applied according to the Code of Good Agricultural Practice for the Protection of Water.

In addition, the Environmental Protection Act 1990 Part II requires producers of waste to ensure its safe disposal. A “duty of care” is applicable to every person (except private householders) who has control of waste at any stage from production to disposal. Plans are in hand for a Code of Good Agricultural Practice for the Protection of Soil - expected to be available by late 1992.

Air pollution restrictions

The poultry industry is responsible for 20% of all odour nuisance complaints by the public, and will be affected by recent legislation under the Environmental Protection Act 1990. The most important causes of justifiable complaint were smell from poultry houses and manure spreading, and the Act includes provisions which strengthen procedures for dealing with statutory nuisance, including odours.

The Environmental Protection Act also provides control over activities such as combustion and incineration. Schedule A processes, which include gasification and carbonisation, general combustion where the net thermal output is 50MW or more, and animal incineration at the rate of more than one tonne/hour, are subject to integrated pollution control by Her Majesty's Inspectorate of Pollution. Combustion processes with a net thermal input of 20-50MW and animal incineration at the rate of less than one tonne/hour class as Schedule B processes, which come under local authority control.

Various Guidance Notes may also affect poultry farming activities, notably:

- the combustion of solid fuel manufactured from or consisting of poultry litter in appliances with a net rated thermal input of 3MW or more
- poultry litter combustion processes with a net rated thermal input of 0.4-3MW
- animal carcass incineration.

A Code of Good Agricultural Practice for the Protection of Air is also being prepared. This deals with odour and ammonia emissions and also the emission of dark smoke, all issues of importance to the poultry industry.

Planning restrictions

Several aspects of the Town and Country Planning General Development Order 1988 affect livestock buildings and poultry farming, including changes to the limit of the ground area of a development; distance from a "protected building"; change of use of recently erected farm buildings; amenity protection for occupants of protected buildings; control of temporary structures; and new housing close to existing livestock units. A 1992 amendment means that all outline plans for agricultural building should be submitted to the planning authority for them to consider whether full planning permission needs to be applied for.

Planning authorities vary in their attitude to requirements to control noise and smell. However, all large developments and certain major developments are also subject to the Town and Country Planning (Assessment of Environmental Effects) Regulations 1988. This ensures that the best environmental policy has been applied to prevent pollution or nuisance at source.

Many local authorities have their own development plans to control livestock building and structures. None of these has yet been approved by the Department of the Environment and cannot be enforced.

Impending regulations, controls etc

Further EC directives on the application of livestock manures to the land are likely in relation to nitrate vulnerable zones. There may also be changes to the keeping of hens in cages, which could increase the amount of poultry litter requiring disposal.

Report No: ETSU E/GS/00124/REP 2 Publication date: 1993

POULTRY MANURE (LITTER & EXCRETA) IN ENGLAND AND WALES IN RELATION TO THE REGIONAL ELECTRICITY COMPANIES

Agricultural Development and Advisory Service (ADAS)

Background

Environmental pollution by agriculture and, in particular, livestock farming, has increased over the past decade. As a result, new and future legislation is likely to impose much greater control on the amount, timing and applications of manure, especially broiler litter, to the land. At the same time, Government is encouraging identification of sources of renewable energy.

Total UK production of poultry litter and excreta is estimated at 1.4 million tonnes/year and 0.4 million tonnes/year respectively. Direct disposal as fertiliser or to landfill can have an adverse environmental impact. An environmentally acceptable alternative is a waste to energy scheme that generates revenue from the energy produced and provides a valuable fertiliser by-product.

Project Objective

- To identify the quantities of poultry litter that may be available as an alternative fuel for the production of electrical or heat energy.

Findings

Number of birds

The June 1989 census showed that there were some 96 million poultry in England and Wales. Of these, more than half were broilers for eating and the remainder laying hens, one fifth of them young stock. In addition, there were more than two million ducks and geese, 1.85 million of them ducks. About 21 million turkeys are processed each year, with a further 6% in the breeding flock. Given a 20-week life, there could be more than nine million in existence at any one time.

Poultry litter production

Calculation of the quantities of manure and litter produced were based on actual annual production, taking into account the types of manure, the residence time of each crop of birds, and the small percentage from free-range poultry that is not collectable. Table 1 below summarises the quantities of poultry excreta and litter produced by different types of bird, together with the dry matter content.

Table 1 Production of poultry excreta and litter per bird

Poultry type	**Output kg/bird/day**	**Dry matter content**	**Notes**
Growing pullets	0.024	85%	Air dried manure
Growing pullets	0.036	70%	Litter
Laying hens	0.036	85%	Air dried manure
Breeding fowl	0.036	70%	Litter
Broilers	0.036	70%	Litter
Ducks	0.017	70%	Litter
Geese	0.197	70%	Litter
Turkeys	0.124	70%	Litter

Considerable drying is anticipated in these figures, when compared with both raw excreta and spent litter.

The depth of litter at the start of the crop has a substantial effect on the output quantities at the end of each cycle of broilers or other birds on litter. While there is experimental evidence to suggest that increasing litter depth improves bird performance (depths of 100-150mm are considered optimal), commercial producers tend to limit the depth of wood shavings to about 50mm. The unavailability and cost of wood shavings in some parts of the country is increasing the use of straw.

Poultry wastes arising

Table 2 below summarises the quantities of poultry manure and litter produced by Regional Electricity Company (REC) area. The data have been derived from county data on the assumption that production is evenly spread across each county.

Spent litter

Most of the waste arising is from spent litter. Of the total of 1.24 million tonnes of litter, one third is from ducks, geese and turkeys and the remainder from other fowl, including broilers. The Eastern REC has the greatest potential for poultry litter as a fuel, followed by the East Midland, Southern and Midlands RECs.

A further 375,653 tonnes of manure is produced from laying hens and growing pullets. Although there are cases where the manure produced is stored as slurry, there is a general move towards conveyor belt systems and air drying or composting of the manure below the house. As a result, a major proportion of this waste can be regarded as a potential fuel source. The Southern REC offers the greatest potential, followed by the East Midland, Eastern and Midlands RECs.

Table 2 Summary of poultry manure and litter production by REC

Regional Electricity Company area	Laying hens, pullets, breeders and broilers		Ducks, geese and turkeys
	Manure (85% dry matter)	Litter (70% dry matter)	Litter (70% dry matter)
North Western	31,056	56,676	9,656
Northern	15,567	58,082	2,253
Yorkshire	28,623	44,650	81,895
MANWEB	21,383	65,581	12,511
Midlands	46,814	91,273	44,157
East Midlands	55,944	108,843	73,322
South Wales	10,165	25,198	2,484
Eastern	51,609	175,901	177,188
South Western	32,285	59,000	3,339
Southern	58,000	106,435	6,170
London	540	972	581
South Eastern	23,663	29,836	3,981

Utilisation of poultry manures

Poultry manure can be used as a fertiliser or as a fuel. Use as a fuel may involve direct combustion to produce heat, or digestion for the production of biogas, or gasification by pyrolysis. Each technique has its merits, but there are also practical difficulties associated with both the processes and the form of waste generated.

Poultry litter with a dry matter content of 84% has a gross calorific value of about 13.5 GJ/tonne - half that for coal. It gives about 50% more ash than coal and has about twice the volatiles content. The combustion of poultry litter comes under the control of the Environmental Protection Act and strict guidelines apply.

The ash retains many of its original nutrients and could be used as a fertiliser. There are also opportunities for blending the ash with other forms of organic fertiliser. Most ruminant manure, for instance, is spread on the land as fertiliser, but cannot meet all the nutrient requirements because of its excess of potash. This excess can be balanced by the concentrated form of phosphate supplied by broiler litter ash.

Recommendations

Future investigations should focus on:

- the drying of poultry wastes using waste heat from combustion
- the detailed composition of ash from the combustion of poultry litter and manure
- the nutritional or toxic effects of using the ash as a fertiliser
- an economic appraisal to determine the value of litter and manure as a fuel.

Report No: E/GS/00124/REP 3 Publication date: 1993

THE POTENTIAL FOR A BLEND OF BROILER LITTER ASH AND PROCESSED RUMINANT LIVESTOCK MANURE OR POULTRY MANURE

Agricultural Development and Advisory Service (ADAS)

Background

Environmental pollution by agriculture and, in particular, livestock farming, is of increasing public concern, and the new and future legislation is likely to impose much greater control on land applications of the associated manure.

The pressure for improvement has caused EEC governments to review their legislation and update their laws in relation to farming practice. During the last three years, there have been major changes in the UK's laws covering environmental pollution, and consideration is now being given to the ways in which poultry and other manures are used. There are two main options: to spread the manure directly on the land or to use it as a fuel. The latter option, however, generates by-products that have to be dealt with appropriately. In some cases, the by-products may be useful as fertilisers, provided the right balance of nutrients can be achieved overall.

Project Objectives

- To consider the potential for blending ash produced by the combustion of poultry litter and manure with other organic manures.

- To assess the market for the resulting organic fertilisers.

Findings

Plant nutrient requirements and their sources

There are three principal nutrients that affect plant growth: nitrogen (N), phosphorus in the form of phosphate (P_2O_5) and potassium in the form of potash (K_2O). The relative quantities of these nutrients that are required for optimum growth vary with plant type and soil fertility, and fertiliser manufacturers produce a range of products to provide for the needs of a wide range of cropping conditions. Highly concentrated compound or straight fertilisers are used in commercial agriculture and horticulture where accurate application equipment exists.

Organic materials used in their raw state to supply plant nutrients are much less concentrated in their contents than mineral fertilisers and a greater bulk has therefore to be used. Organic fertilisers include livestock wastes that are applied in large volumes to the land. They also include some composted ruminant wastes. These retain their original potash and phosphate levels but may be low in nitrogen because of loss through volatilisation.

The potential for using broiler litter ash

The properties of broiler litter give it a high fertiliser value, while burning the litter concentrates the nutrients in the ash, which accounts for 9.0-13.6% of the original waste. The relative concentration of nutrients is:

- P_2O_5 30%
- K_2O 17%
- Mg 4%.

This very closely matches a commercial fertiliser product containing 0% nitrogen, 30% phosphate and 15% potash. The conclusion is that, for certain areas of use such as potato production, the ashed broiler litter would be directly saleable as a fertiliser.

Ruminant livestock slurries and manures are extremely objectionable to most people in their raw forms. They have a low dry matter content, and contain volatile fats and odorous compounds. They therefore require conditioning and treatment to improve their stability.

There would be considerable merit in combining the combustion of dry waste (eg broiler litter) to produce energy and ash with the drying of slurries using waste heat. The dried slurry could then be used as a fuel, or mixed with ash or other residues to produce organically based crop growth products.

The main potential for using broiler litter fuel ash lies in its phosphate and potash content, which can be used to complement other forms of manure. Most ruminant manures, for instance, have an excess of potash which can be balanced by the concentrated form of phosphate supplied by the ashed broiler litter. The combined product can then be used for effective crop nutrition.

The equipment is already available for undertaking the mixing process. Where slurry is concerned, the broiler litter fuel ash could be mixed in either in the mixing/agitation tank adjacent to the main storage tank, or in a spreader tank. In the case of farmyard manure, the ash could be mixed with the manure in muck spreaders, either before or during the spreading process.

There is also considerable interest is processing slurry and farmyard manure with other agricultural residues to produce a soil conditioner, growing medium or organic fertiliser.

- *Soil conditioner*

Composted manure from ruminants is suitable for use as an organic soil conditioner. The levels of phosphate and potash found in the compost are adequate and there is no need for additional nutrients in concentrated form.

- *Growing medium*

The levels of phosphate and potash in composted ruminant manures are too high to allow them to be used as a growing medium in place of peat for horticultural use. The compost must be diluted several times over with a filler material such as soil.

- *Organic fertiliser*

As an organic fertiliser, composted cattle waste is very low in nutrients when compared with established compound fertilisers. There is therefore considerable scope for adding broiler litter ash to upgrade the nutrient status of the composted product. As indicated above, ashed broiler litter gives a 0-30-17 fertiliser that is similar to several commercial products. The demand for these phosphate-potash fertilisers in England and Wales in 1989 was around 475,000 tonnes - more than 600,000 tonnes if other variants are considered. Further analysis would be required to determine the relative proportions of soluble and insoluble phosphate and potash in the litter ash. However, if the use of phosphate and potash can be viewed as part of an overall long-term fertility strategy, and if this is properly planned, then there is the potential for a substantial proportion of this large market to be filled using ashed poultry litter fertiliser.

Logistical considerations

A typical broiler-litter-fuelled power station with a capacity of $14MW_e$ would produce 13,500 tonnes of ash per year. A mix ratio of 3:1 would require a total of 40,500 tonnes of farmyard manure/separated slurry. This could be generated with a 25-mile radius.

The relative bulk and quantities of ruminant waste as a composted product suggest that the ash should be transported to the site where the waste is produced and treated.

Special precautions will need to be taken during the handling, transfer and additional processing procedures to avoid health hazards.

Conclusions

- Most ruminant manures have an excess of potash that can be balanced by the concentration of phosphates supplied by ashed broiler litter. At the same time, it would further unbalance the proportion of other nutrients to nitrogen - for which the demand is greater.

- Perhaps the greatest potential for marketing ruminant wastes as organic fertilisers is to sell them in their composted form.

Report No: ETSU B/M3/00388/32/REP Publication date: 1994

EVALUATION OF USED POULTRY LITTER ASH AS A FERTILISER

Agrigen Ltd and ADAS

Background

Litter produced by broiler poultry housed on wood shavings or straw can be used as a fuel to generate electricity. Typically this litter has a 60-65% dry matter content and contains 0.3% nitrogen, 0.25% phosphate and 0.18% potash on a fresh weight basis. During the combustion process, nitrogen is lost to the atmosphere as a gas. This leaves a residual ash that is rich in phosphate and potash and has potential for use as a crop fertiliser.

Project Objective

- To investigate the availability to ryegrass of phosphate and potash by comparing poultry litter ash with established fertilisers.

Methodology

The poultry litter ash was produced from combustion trials carried out on a FinaFire fluidised bed combustor where the temperature of combustion was controlled to a maximum of 975°C to prevent the ash from melting.

To determine the availability of phosphorus, two soils with a very low phosphorus content were obtained, one with a pH of 8.2 and the other with a pH of 6.4. Three replicates of each of the following were prepared in pots for both soils:

- no fertiliser
- triple superphosphate at rates of 40, 80, 120, 160 and 200kg of phosphate per ha
- poultry litter ash at rates of 80 and 160kg of phosphate per ha
- basic slag at rates of 80 and 160kg of phosphate per ha
- rock phosphate at rates of 80 and 160kg of phosphate per ha.

Potassium was added at 150 kg/ha of potash. Magnesium was also added at 50 kg/ha to the high pH soil.

Ryegrass Melle was sown at about 316 kg/ha and nitrogen was added at 100 kg/ha after seedling emergence, with two further additions later in the growing season.

Six grass cuts were taken whenever the most advanced plants reached 10-12cm in height.

To determine the availability of potassium, a single soil of very low potassium content was selected. Four replicates of each of the following were prepared as above:

- no fertiliser
- muriate of potash at rates of 40, 80, 120, 160 and 200kg of potash per ha

- poultry litter ash at rates of 80 and 160kg of potash per ha.

Phosphorus was added at a rate of 300kg of phosphate per ha. Magnesium was added at a rate of 50 kg/ha. Nitrogen was added after seedling emergence.

Ryegrass Melle was sown at about 316 kg/ha, and crop management was similar to that for the phosphorus experiment.

Findings

Phosphorus

Low phosphorus, high pH soil

Initially there was little difference in yield between the various treatments, with the grass surviving on the small amount of phosphorus already present in the soil. However, by Cut 4, three months after sowing, yield was restricted on the nil treatment, whereas all fertiliser treatments except rock phosphate increased markedly in yield. The results showed that the phosphorus in the ash was at least as readily available - possibly more so - as that in basic slag, and more readily available than that in rock phosphate.

By Cut 6, both yield and phosphorus take-up showed the poultry litter ash to be superior to basic slag and rock phosphate as a phosphate fertiliser, and fully as effective as triple superphosphate, the indication being that it is 100% efficient within months of application.

Low phosphorus, normal pH soil

Yields were more variable on the normal pH soils. Whereas all the fertiliser additions appeared to increase yield by Cut 6 when compared with the nil treatment, the results were not significant and so are inconclusive.

This soil had come from a field where a long-term field trial had given marked responses to phosphate fertilisers over the years. Foliage phosphorus content was greater at Cut 6 than at Cut 4 - the reverse of findings on the high pH soil - and it is likely that the much larger clay fraction in the normal pH soil continued to release phosphorus at a low but sufficient rate to support crop growth for longer in the absence of added phosphorus. Additions of phosphorus served to boost foliage phosphorus content. Foliage analysis after both Cut 4 and Cut 6 indicated that phosphorus was similarly available from all fertilisers.

Potassium

Response to potassium was rapid and significant from Cut 1 onwards. At Cut 4, both yield and leaf potassium content showed potassium in the poultry litter ash to be very largely available. Foliage potassium content was markedly lower at Cut 6 than at Cut 4, except for the nil potassium treatment. It is possible that growth had been so vigorous where potassium was added that the crop had largely depleted the soil of potassium, whereas the much lower grass production in the nil treatment continued to concentrate potassium at a higher level while total potassium take-up remained lower.

The overall evidence indicates that the potassium in the poultry litter ash is 90-100% available within a few months of application.

Conclusions

The results indicate that phosphorus in poultry litter ash is 90-100% as available as that in triple superphosphate within the first growing season after application. At high soil pH it is as effective as basic slag and superior to rock phosphate. Similarly the potassium content of the ash is very quickly available, and it appears to be 90-100% as effective as that in muriate of potash.

It is likely that any residual phosphorus and potassium unused in the first season will remain or become available to plants in the longer term. Thus poultry litter ash is a very effective fertiliser for grass, and it can be assumed with confidence that it would be equally valuable on cereals, oil-seed rape, peas, beans, linseed and many other crops. It would be appropriate to apply the ash either annually or in larger dressings every three years for nutrient maintenance purposes.

3.2 Relevant Case Studies

Report No: ETSU B/M3/00388/27/REP Publication date: 1994

TECHNICAL MONITORING OF A MESOPHILIC ANAEROBIC DIGESTER FED WITH POULTRY MANURE - BITTERLEY COURT FARM, SHROPSHIRE

Enertech (1983) Ltd

Project Objectives

- To establish the viability of using the anaerobic digestion of hen excreta to produce biogas for the generation of heat and, possibly, electricity.
- To assess the technical performance of the Bitterley Court Farm digester and confirm whether ammonia inhibition drastically reduces biogas yield under current operating conditions.

Methodology

The methane and hydrogen sulphide contents of the gas are continuously displayed on appropriate equipment. The methane values were confirmed by on-site readings using a Gascoseeker of checked calibration and by bag samples analysed at a British Gas laboratory. The hydrogen sulphide content was confirmed using Draeger tubes as indicators and also by the analysis of gas samples. Samples were taken to determine the presence of oxygen and nitrogen.

A datalogger was used to record the heating water flow and return temperatures for the digester and other temperatures. It also recorded electrical consumption. Appropriate instrumentation was installed to measure gas, sludge and water flows.

Findings

The system installed

Bitterley Court Farm has 22,000 laying birds arranged in nine lanes and housed in a single building. The manure is collected automatically from three lanes and manually from the other lanes. The total collected is fed, via a conveying system, to an anaerobic digester with a capacity of $150m^3$. A gas circulation system operates for 12 hours/day to mix and agitate the digester contents. Gas generated is retained in the domed portion of the digester, and this is connected to a small floating roof gas holder from which excess gas is vented to atmosphere.

The sludge extracted from the digester is drawn off using a variable speed pump. It then passes to a separator/belt press where the fibre and liquor components are separated. The fibre is stored in $1.4m^3$ containers and then removed from site for composting before being used as a peat substitute. The liquor is piped to an open-air lagoon from which it is periodically removed and spread on an adjacent field to encourage growth.

The gas produced by the digester is used first for digester heating, secondly for fuelling two greenhouse heaters and finally, if available, for a swimming pool heating system and the house central heating. A small gas-fired boiler produces hot water for heating the digester so that it maintains its operating temperature of 35°C. Two hydrogen sulphide gas scrubbers, connected in parallel, are installed in the gas pipework serving the greenhouse, house and swimming pool.

Feedstock quantities and characteristics

Digester feedstock quantities were estimated using published data from reputable sources. Estimates indicate that the quantity of excreta produced by 22,000 laying birds is likely to be between 2.332 and 3.143 tonnes (m^3) per day. The equivalent retention time in a digester with a capacity of 150m^3, assuming no water dilution, would be between 63.8 and 47.7 days.

Assuming a daily input to the digester of 3.143 m^3/day of excreta with a moisture content of 70%, plus 6.287m^3 of water to reduce the solids content to 10%, the total input is 9.430 m^3/day, giving a digester retention time of 15-16 days.

Gas production and quality

A laboratory analysis of the excreta gave the following values:

moisture content (by loss on drying): 65.2% w/w
dry matter (by difference): 34.8% w/w
residue on ignition at 700°C: 9.5% w/w
organic matter (by difference): 25.3% w/w

Assuming that, typically, 30-40% of the organic and volatile matter is destroyed in the formation of biogas, gas production is estimated to be of the order of 10-13 m^3/hour. This figure was partly confirmed by the gas flow measurements taken during gas use. These varied from 8.6 m^3/hour early in the programme, with the digester heating boiler and one greenhouse heater in operation, to 10 m^3/hour for one 24-hour period during which the digester heating boiler, both greenhouse heaters and the house central heating system were operating. These values do not include any gas vented to atmosphere.

Gas production is inhibited by the ammonia content in the digester. An increase in ammonia levels first destabilises the digestion process, then reduces gas generation and results, ultimately, in the cessation of the process. Ammonia concentrations can be reduced by introducing additional animal wastes or suitable industrial wastes into the system. The addition of extra water appears to have a similar effect.

The methane content of the biogas produced was found to vary, initially, between 30% and 40% by volume, and the presence of oxygen and nitrogen in two of the readings indicated some degree of air ingress. Better quality gas was produced during the later stages of monitoring, when more stable digester operation had been achieved. The methane content increased to around 50%, the latest analyses giving a value of 55.2% with no oxygen present.

The hydrogen sulphide content of the gas, which can inhibit gas production, was generally in the 3200-3800ppm range, although levels as high as 4400ppm were observed.

Sludge characteristics

The sludge removed from the digester had a typical solids content of 8-9%, a pH of 7.9 and an ammonium salts content (as NH_4) of 0.32% w/v.

The subsequent separation process generated approximately 20 tonnes/month of recovered fibre with a moisture content of 74%.

Analysis of the fluids entering the digester and the belt press showed that the efficiency of pathogen kill varied - around 90% for faecal *coliforms* and rather lower for faecal *streptococci*. Pasteurisation of the excreta before it is fed to the digester would probably be necessary to ensure a higher level of pathogen kill.

Efficiency of digester heating system

The heat required to raise the temperature of the sludge input to the digester from 20°C to 40°C and maintain the required temperature over a 24-hour period has been estimated at approximately 9.15kW. Digester heat losses were estimated at 3.408kW.

Conclusion

Although some problems were experienced with the plant, the indications are that consistent operation could be achieved, with an associated improvement in gas quality.

Report No: ETSU B/M3/00388/18/REP Publication date: 1994

POULTRY LITTER BOILER PLANT AT A J WOODWARD & SONS DEVELOPMENT PROGRAMME FOR EPA COMPLIANCE

Automated Process Controls Ltd

Background

In 1986, a project was set up with A J Woodward & Sons Ltd to carry out a technical and economic assessment of using poultry litter as a fuel to heat broiler houses. Following the successful conclusion of the project, the company installed a steam engine to generate electricity. Work to date under the programme showed that combustion met the requirements of the then Clean Air Act. With the implementation of the Environmental Protection Act 1990 (EPA), some improvement work was needed with respect to particulate and carbon monoxide (CO) control to allow the plant to comply first with interim standards and ultimately with full Schedule B process requirements for poultry litter combustion.

Project Objective

- To develop a control regime enabling the combustion plant to meet the PG1/10 (91) Guidance Notes.

Methodology and Findings

The problem

The existing plant is a pre-combustor designed to burn wet and dry wood waste. It has been equipped with superheaters and a reciprocating steam engine/generator set. The generator has a maximum rating of 160kVA.

The plant’s initial operating performance was well outside the limits for EPA compliance. Carbon monoxide emissions were 3-11 times the maximum permitted, while particulates were 1.2-2.0 times greater than the maximum permitted. There was also a need for close-loop control of the fuel/air ratio. Some of the deficiencies resulting in high CO emissions were easily rectified.

The improvements

Instrumentation was installed so that the current combustion performance of the existing boiler plant could be determined.

Initially, underlying design flaws combined with unusually wet litter prevented CO emissions being reduced to EPA limits. The problem was resolved by designing a combined concurrent and countercurrent turbulator jet assembly and installing it in the pre-combustor. The system now has a stability that it previously lacked, and CO can now be reliably held at below 60 mg/Nm^3, even when litter conditions are poor. This is below the 100 mg/Nm^3 required for EPA compliance. There is a crucial point at which increased output has a significant adverse effect on CO, but there is only a gradual increase to around 180 kg/Nm^3, much lower than the values of 1200 mg/Nm^3 previously experienced.

Operating conditions were also analysed, and environmental performance, thermal output and electrical generating capability were characterised.

Plant output is partly constrained by the varying litter quality and by tube fouling of the second and third passes of the waste heat boiler. The former is now improving, and on-line soot blowers have been installed to control the latter.

The furnace is at its practical output limit, which is below the output ideally required by the steam generating set, and superheat quality is critical to maintaining the desired minimum 80kVA output. Output has now been optimised, even under wet litter conditions, by separate control of the two combustion air (forced draught) fans coupled with precise control of the negative pressure. A 6% oxygen level has been established as the optimum flue gas concentration.

Performance and emission data are stored on a microprocessor for analysis and proof of compliance. A computer programme ensures intelligent control of the furnace.

To minimise dust emissions and eliminate the visible “plume” of water vapour condensing on micro-particulate material, consideration is now being given to the installation of novel ceramic filter technology.

Conclusions

The project has improved the combustion performance of the plant, allowing it to meet the interim standards for Schedule B processes under the EPA. Instrumentation procedures have been thoroughly tested and rectification procedures established where necessary. The fundamental design deficiencies of the original combustion system have been resolved and design work on dust emission abatement is proceeding. Maintaining the plant’s emissions within compliance limits will be a management challenge, particularly given the difficulties in ensuring fuel consistency and moisture content.

Report No: ETSU B/FW/00236/REP Publication date: 1995

MONITORING OF THE DEMONSTRATION OF THE SMALL SCALE USE OF POULTRY LITTER FOR CHP AT A J WOODWARD AND SONS

FEC Consultants

Background

The success of the initial demonstration of the small-scale use of poultry litter as fuel encouraged A J Woodward & Sons of Beckford, near Tewkesbury, to make further use of the steam generated by installing a single-cylinder steam engine and alternator. The intention was to supply all or part of the site electrical demand and to export the surplus to the Midlands Electricity board.

Project Objective

- To monitor and report on steam engine and alternator performance at A J Woodward & Sons.

Findings

Installation

The "Spilling" type 1KO H1Z steam engine and type D6-200 alternator were installed in 1990, together with an oil/condensate separator. The steam mains within the boilerhouse were renewed at the same time. This involved constructing a 150mm nb steam main from the engine inlet along the length of the boilerhouse. The feeders from the oil- and poultry-litter-fired boilers were branched into the main and a "Gilflo" full-bore variable orifice steam meter was installed for measurement purposes.

Although the engine was installed to run on the saturated steam that was currently available, operational experience and economics identified a need for superheated steam. A wraparound superheater designed to give 7 bar, 300°C steam was attached to the boiler's dry back section. To ensure steam quality, a full bore steam/water separator was installed between the boiler crown valve and the superheater inlet.

Operational experience

Generally, the engine and alternator have worked well with minimal problems. The engine has been subject to a few minor faults that have been repaired by site maintenance staff. In each case a 24-hour shutdown was needed to allow the engine to cool, to effect the repair and to bring the engine slowly back on line. A major breakdown occurred in March 1994 that required replacement of a cylinder liner, piston and rings. The repair took 11 weeks and included the stripping down and cleaning of the engine to remove any trace of metal debris.

Problems were also experienced with the steam meter. Inspection by the manufacturers revealed severe wear of the shaft and cone assembly, probably caused by pulsations in the system emanating from the engine. The meter was eventually converted to a calibrated fixed orifice unit providing a 10:1 turndown. Since conversion, stable and acceptable meter readings have been obtained.

Electricity generation

Records show that the generator has, over the last two years, produced 55.5% of the site's electrical requirement, worth around £32,000 at 1994 prices. The equipment was off-line for 38 weeks - 19 weeks for maintenance, cleaning and sterilisation, and 19 weeks for major repairs (see above) and for plant modifications required to satisfy Her Majesty's Inspectorate of Pollution (HMIP) requirements. The repairs and plant modifications reduced electricity output by 151,000kWh or 16.9% of the site's electrical requirement. This reduction was worth £10,120 at 1994 prices. As well as having to import electricity during these periods, A J Woodward had to dispose of 1000 tons of poultry litter and also lost 100 tons of ash worth £4300.

Engine efficiency

Engine efficiency was determined from data collected manually over a six-day period. Average engine isentropic efficiency (ratio of actual heat drop through the engine to isentropic heat drop) was 65.4%. Heat drop to power output conversion efficiency averaged 89.7%.

CHP plant efficiency

CHP plant efficiency has been calculated using the following averaged data:

Steam flow	1616 kg/hour
Power output	97.8kW
Enthalpy of steam at inlet	2.9796 MJ/kg
Enthalpy of steam at outlet	2.7609 MJ/kg
Boiler efficiency (GCV basis)	78%

The following have then been calculated:

Heat input	1715kW
Heat output	72.24%
Power output	5.66%
Overall CHP efficiency	77.9% (GCV basis) 86.6% (NCV basis)

Financial assessment

The financial assessment is based on the period from October 1992 to October 1994. This period is considered to be representative of normal operation, although due allowance must be made for the major breakdown and the modifications required by HMIP.

The unit cost £63,000 to install, including civils and electrical connection costs.

Income from the sale of electricity at around 6.7p/kWh totalled £32,000 over the two years. Against this must be set the cost of maintenance over the same period at around £2000. Net savings averaged £15,000/year, giving a simple payback period of 4.2 years.

These figures compare with anticipated electricity sales of £42,120 over the two-year period (assuming no excessive downtime associated with teething problems), and an expected payback period of 3.14 years.

Conclusions

- The decision by A J Woodward & Sons to install a “Spilling” steam engine and alternator proved to be well founded.

- The subsequent decision to install a wraparound superheater to the boiler enhanced electrical generation by about 100%.

- Problems with the variable orifice steam meter suggest that future installations should use fixed orifice meters.

- Phased poultry production cycles should be considered to eliminate the costly periods of downtime between flocks and the associated dependence on imported electricity.

Report No: ETSU B/U1/00549/03/REP Publication date: 1997

REVIEW OF MEDIUM SCALE ENERGY RECOVERY FROM POULTRY LITTER

Peter J Scott

Background

Poultry litter, which consists of wood shavings, straw or paper plus the excrement and urine produced by the birds, has traditionally been spread on the land as a fertiliser. Although this is an acceptable practice, it can result in excessive concentrations of some of the nutrients contained in the litter.

In the early 1980s, waste poultry litter was identified as a potential fuel. Using it in this way offers two main advantages:

- The litter itself is a worthwhile source of renewable energy with a net calorific value of about 13.5 GJ/tonne.

- The resulting ash is rich in chemicals and can be used as a fertiliser, enabling a reduction in the excessive concentrations that can arise when fresh litter is spread on the land.

The then Department of Energy took steps to encourage the use of poultry litter as a fuel, seeking first to demonstrate success on a small scale before supporting a larger, centralised initiative.

Report Objective

- To review progress made to date in the medium-scale recovery of energy from poultry litter.

Findings

The Beckford project

An initial demonstration project was supported at the premises of A J Woodward & Sons, Beckford, near Tewkesbury. The company had a holding of 230 acres in 1986 and was engaged in fruit and flower growing and in the production of broiler chickens. The market gardening component of the enterprise involved a number of glasshouses. Initially these were heated by a dry back boiler that consumed about 675 tonnes of coal per year. However, over time, the heat was switched from the glasshouses to the poultry unit. The seven poultry houses contained a total of 210,000 birds and, with six crops of birds per year, the total annual production of poultry litter was about 2000 tonnes.

The first stage of the project involved converting the coal-fired boiler by adding a pre-combustor appropriate for the burning of poultry litter. Independent monitoring showed that the plant was meeting the requirements of the Clean Air Act. Analysis of the ash showed that it contained 14.3% potassium, 13% phosphates and 4.5% magnesium, and that it could readily be used as a valuable fertiliser.

The change to poultry litter firing reduced boiler operating costs by 45% and gave an operating cost benefit of £20,800/year. Adding the value of the ash (£11,800/year) and the improved value of the poultry produced (estimated at £60,000/year) increased the total benefits to £92,400/year and gave a simple payback of 1.04 years on the £96,500 investment. The project successfully demonstrated both the suitability of poultry litter as a fuel and the viability of the conversion with the heat being used for heating the poultry houses.

The second stage of the project came about as a result of a decision to install two further poultry houses, thereby increasing the amount of poultry litter available by 30%. It was clear that the heating needs of the expanded poultry unit could be met with the boiler using only part of its capacity. It was also clear that sufficient poultry litter was available to make use of the spare capacity if there was a suitable application. The system was therefore converted for operation as a combined heat and power (CHP) scheme by adding an alternator driven by a reciprocating steam engine. The modified installation met all of the environmental conditions of the first stage of the project. It also proved to be both a practical and a viable method of generating heat and electricity. Details are given in Report No: ETSU B/FW/00236/REP, summarised above.

Legislation and regulatory changes and associated upgrading of the plant

Introduction of the Environmental Protection Act in 1990 led to a requirement for the “authorisation” of the plant by the local authority. That authorisation placed conditions on plant operation and required that it be modified to meet stringent emission standards, set under the Act, by 1 October 1995.

A J Woodward & Sons put in hand an upgrading programme that was both financially demanding and absorbed much of the time of directly employed farm staff, particularly that of one of the directors. All the work directed towards upgrading had to be undertaken on site as no similar plant existed elsewhere.

Work on the improvement of combustion efficiency was relatively successful, but the installation and commissioning of improved flue gas cleaning equipment gave rise to serious and ongoing problems. At the same time, relations with the local authority and with local residents deteriorated, causing unexpected stresses and unpleasantness for the resident directors. During 1995 it became apparent that the flue gas cleaning system chosen would either need costly redesign and reconstruction or need to be replaced with an alternative system. At this point, the directors of A J Woodward decided that the project was hindering proper operation of the farming enterprise because of the costs and managerial time involved. The project was closed down; the litter combustion equipment was removed; and the boiler was re-equipped for coal firing. Coal firing has been in progress since the end of 1995.

The abandonment of the project was a disappointment to all concerned. The introduction of the Environmental Protection Act meant that the focus shifted to a single aspect of environmental control, and this effectively resulted in the closure of the plant with the loss of other important benefits. Furthermore, the switch back to coal meant that there was no gain in air quality as the limits for particulates are more than twice those set for the poultry litter and the carbon monoxide content is not subject to control.

The potential for replication

Although it had been hoped that the demonstration project would be replicated on other poultry farms, this did not occur. However, the success of litter combustion at the medium scale provided confidence for the development of much larger litter-fired projects at Eye and Glanford power stations. These projects further demonstrated the suitability of poultry litter as a fuel.

Further major power projects using poultry litter are currently under construction or development in Northampton, Thetford, Wellington (Somerset), Corby and Fife. These, together with the Eye and Glanford stations, could result, within the next two or three years, in the use of more than one million tonnes/year of poultry litter in energy from waste projects - more than 75% of the total annual arising of the material in the UK. Hence, although the hoped for replication of farm-scale plants did not take place, the take-up of the technology, over a period of only 5-7 years, has been much greater than was foreseen. Furthermore, in areas where the quantities of litter arising, although substantial, are insufficient to justify the construction of major centralised plant, there may still be opportunities for medium-scale plant, particularly where new plant incorporating appropriate features and technologies from the outset can be made available.

The potential for energy recovery from similar wastes

The study has also considered the possibility of using the system and techniques associated with poultry litter combustion for energy recovery from certain other wastes, notably, race horse bedding, spent mushroom compost and straw used to cover crops. The evidence available suggests that these materials are unlikely to have any potential as a fuel on any significant scale in facilities that are likely to be viable.

Report No: ETSU B/FW/00235/REP Publication date: 1995

USE OF POULTRY LITTER FOR POWER GENERATION - MONITORING OF EYE POWER STATION

FEC Ltd

Background

Environmental concerns over conventional ways of disposing of waste poultry litter, together with a proposed EC Nitrates Directive, encouraged a search for alternative disposal routes. At the same time, a series of studies carried out by ETSU on behalf of the then Department of Energy identified waste poultry litter as a potential source of energy. The litter, with annual arisings of around 1.4 million tonnes/year, has a calorific value of 10-12 GJ/tonne on an as-received basis, although this depends on moisture content.

The Department of Energy developed a two-stage strategy to encourage the use of poultry litter as fuel. A series of combustion trials was followed by a small-scale pilot project at the premises of A J Woodward & Sons at Beckford, near Tewkesbury. The success of this demonstration led to the decision to proceed to a larger-scale project, provided a suitable host company could be found.

A heat service company, Fibroheat, made its own assessment of the market, decided to go forward with a project provided a demonstration grant was available, and approached ETSU/DTI for information and assistance. A project company, Fibropower Ltd, was formed, and a power station was built on a disused airfield at Eye in Suffolk. The electricity generated was sold under the Non-Fossil Fuel Obligation (NFFO) to Eastern Electricity.

Project Objectives

- The aim of the monitoring exercise that is the subject of this report was to evaluate all aspects of the project. Specific objectives were:

  - to determine the combustion efficiency of the furnace and boiler system
  - to carry out an energy balance for the operation of the facility
  - to determine the normal operational labour requirement
  - to review the extent and cost of maintenance over a reasonable period of time
  - to analyse typical waste poultry litter and ash samples
  - to test and analyse the flue gases
  - to examine the potential of the ash produced for use as a fertiliser
  - to evaluate the economics of operation
  - to undertake environmental monitoring at three-month intervals
  - to undertake dioxin and furan monitoring of the food chain at three-month intervals.

Findings

Project description

Poultry litter is collected from about 100 farms, generally within a 50km radius of the site. It is transported in enclosed vehicles and, after weighing and sampling for moisture content, is tipped into a reception pit. The litter is then transferred by grab cranes into reinforced concrete pits with a total storage capacity of 15,000m^3 - equivalent to approximately a ten-day supply. The storage hall environment is maintained under negative pressure to avoid the release to atmosphere of noxious odours.

A stockpile of litter has been built off-site to alleviate any possible shortfalls in supply.

The litter is transferred to the boiler fuel feed system and spread on to a reciprocating hearth. This hearth is split into four zones, each with a variable air supply. The heat produced is transferred to a 56MW$_{th}$ Aalborg Ciserv AT-23 three-pass boiler. This has a large water-wall combustion chamber above the firebed followed by a long radiant section that allows the gases to be substantially cooled before they come into contact with the convection surfaces and superheater. The boiler produces 50 tonnes/hour of steam at 65 bar and 450°C which goes forward to a condensing turbine.

The combustion products pass through a three-stage electrostatic precipitator before being discharged to atmosphere via a 41.5 metre high chimney.

The power plant consists of an Allen twin cylinder steam turbine coupled to a Brush 17MVA generator giving a peak electrical power output of 15.6MW$_e$. The generator supplies the in-house load and makes 12.6MW$_e$ available for export.

Commissioning problems

Some commissioning problems arose because of the higher than expected fuel moisture content. These included:

- electric drive motor failures caused by equipment working at the top end of its design range

- high moisture content of flue gases requiring modifications to emissions monitoring equipment

- compaction and densification of the stored fuel necessitating the reprogramming of the grab cranes to ensure a worthwhile payload

- bridging in the fuel hoppers necessitating modifications

- difficulty optimising the performance of the electrostatic precipitator.

Plant performance

Combustion efficiency

The oxygen content of the flue gases (6.9%) indicated an excess air level of just under 48%. The low carbon monoxide (CO) level (31 mg/Nm^3) and small carbon-in-ash content showed that combustion conditions were good. However, the high moisture content (45.5%) and high ash figure (almost 11%) adversely affected the fuel's heating value and resulted in high flue gas heat losses.

Boiler efficiency was calculated at 64.6% based on the gross calorific value (GCV) of the fuel and 81.4% based on net CV.

Efficiency of electrical generation

Gross power output was 13.5MW$_e$. Parasitic load was measured at 1MW$_e$ and net output at 12.5MW$_e$. Turbine isentropic efficiency was calculated at just under 84%, which is good for the size of the plant.

The firing rate was calculated at just over 28 tonnes/hour, and the overall power generation efficiency was 24%. This could be improved using a better quality fuel with a lower moisture content.

Environmental impact

Emissions to air

Dioxins and furans have an I-TEQ of 0.22 ng/Nm^3, below any limits imposed by Her Majesty's Inspectorate of Pollution (HMIP) on other prescribed processes.

Volatile organic compounds (VOCs) were generally below the 20 mg/Nm^3 limits set by HMIP:

- 0-0.24 mg/Nm3 burning poultry litter only
- 0.95-3.21 mg/Nm^3 burning poultry litter and gas oil (burners on minimum setting)
- 3.21-615.30 mg/Nm^3 burning poultry litter and gas oil (burners on maximum setting).

The heavy metal contents of two samples were 28.49 mg/Nm^3 and 28.41 mg/Nm^3. Of the total metal quantity, 45.5% was in the form of nickel and 36.5% was in the form of chromium in the vapour phase. Cadmium, lead and mercury levels were small.

Average quantities of the main acid gases were:

- SO_2 109 mg/Nm^3 compared with the HMIP limit of 300 mg/Nm^3
- NO_2 172 mg/Nm^3 compared with the HMIP limit of 435 mg/Nm^3
- HCl 181 mg/Nm^3 compared with the HMIP limit of 250 mg/Nm^3.

Carbon monoxide levels were 31 mg/Nm^3 compared with the HMIP limit of 250 mg/Nm^3.

Particulate emission levels were improved to 155 mg/Nm^3 following optimisation of the electrostatic precipitator, within the 200 mg/Nm^3 allowed for the first year of operation. Discussions are under way to reduce levels to below the 100 mg/Nm^3 set for Year 2.

Impact on water quality

All rain, surface and wash water is ducted to a common tank for settlement and treatment before being discharged to drain. Boiler water blowdown is discharged through a conventional blowdown vessel into a holding tank for attemporation and pH correction before discharge to drain. Although National Rivers Authority consent limits were initially exceeded, modifications have rectified the situation.

Emissions to land

Analysis of soil and foliage samples for heavy metals showed that, although these are generally above average concentrations, they are within the normal range and there is no evidence of additional accumulations.

Analysis of milk samples from two farms, approximately 1km and 2km downwind, showed that the power station had no measurable effect on the level of dioxins in the milk.

Financial statement

The main financial components can be summarised as follows:

- The capital cost of the project was £22 million.
- The average cost of the used litter for fuel is £7.00/tonne.
- Operating costs (excluding fuel) are estimated at £1,480,000/year.
- The electricity generated is sold at 6.24p/kWh.
- The ash is sold for £15.00/tonne for use as a fertiliser.

Conclusions

- The decision to proceed with the project at Eye has proved to be well founded.

- Most initial operating problems were eliminated as operator experience improved.

- Emissions monitoring has shown that poultry litter at these volumes can be burnt cleanly and efficiently, and there has been no adverse impact on soil and vegetation or on the food chain.

- The environment has benefited from the reduction in methane, noxious odours and nitrate leaching that would have occurred using conventional disposal procedures.

- The economic assessment has shown that the project is viable.

Report No: ETSU B/M1/00412/REP Publication date: 1995

USE OF POULTRY LITTER FOR POWER GENERATION - MONITORING OF GLANFORD POWER STATION

FEC Ltd

Background

Two large-scale poultry-litter-fired power stations were accepted under the first Non-Fossil Fuel Obligation tranche of renewable energy projects. The first to be commissioned was Fibropower's plant at Eye in Suffolk, which is operating successfully (see Report No: ETSU B/FW/00235/REP, summarised above). Fibrogen's Glanford Plant was next on-line and was handed over in November 1993.

The Glanford plant is similar to that at Eye with the exception of its combustion system. At Eye, the poultry litter falls on to a stepped grate. At Glanford, spreader stokers are employed, where the fuel is pneumatically thrown on to reverse travelling, slatted grates. The Glanford combustion system was designed to improve combustion efficiency and increase furnace release rates.

Project Objectives

- To monitor the performance of the Glanford plant and particularly:

  - to determine the combustion efficiency of the furnace and boiler
  - to carry out a heat and power balance for the plant
  - to test and analyse flue gases
  - to determine the efficacy of particulate arrestment equipment
  - to provide a general overview of plant operation.

- To confirm whether or not the alternative combustion system achieved its design objectives.

Findings

Feedstock and plant

Poultry litter is collected from farms that are usually within a 50km radius of the site. It is transported in enclosed vehicles and, after weighing and sampling for moisture content, is tipped into a reception pit. The litter is then transferred by grab cranes into reinforced concrete pits with a total storage capacity of 15,000m^3 - equivalent to approximately a ten-day supply. The storage hall environment is maintained under negative pressure to avoid the release to atmosphere of noxious odours.

The Aalborg Ciserv boiler is a conventional three-pass, natural circulation, single drum water tube boiler of integral construction. Combustion equipment consists of three Detroit Air Jet Spreader stokers. Fuel is fed automatically from the fuel chute into air-swept distributors and thrown via a specially designed trajectory plate into the furnace. Primary (under-grate) air is pre-heated and evenly distributed across the active grate area. Secondary (over-fire) air provides turbulence and intimate mixing of air and fuel to ensure complete combustion.

The power plant consists of a W H Allen 1.2/BP.3 machine coupled to a GEC Alsthom alternator rated at 17,400 kVA. Design output at the generator terminals is 15.13MW_e. Design net output, allowing for plant load and cable and transformer losses, is 13.5MW_e.

Careful combustion control limits gaseous pollutants, while particulate emissions are minimised using a three-stage electrostatic precipitator. Ash is collected and transferred to enclosed containers and is sold as fertiliser. Liquid effluent is treated before discharge.

Plant performance

Combustion efficiency

Two tests were carried out to determine combustion efficiency. The low carbon monoxide and carbon-in-ash figures indicated that combustion conditions were good. Boiler efficiencies in the two tests were as follows:

Test 1: Boiler efficiency (gross calorific value (GCV) basis) 70.2%
Boiler efficiency (net calorific value (NCV) basis) 84.7%

Test 2: Boiler efficiency (GCV basis) 70.6%
Boiler efficiency (NCV basis) 85.1%

These efficiencies are considered to be good for the quality of fuel being used at the time.

Excess air levels in both tests were lower than those experienced at Eye, as were exit flue gas temperatures. As a result efficiencies were higher. The efficiency advantage of Glanford over Eye represents a fuel saving of around 3.5%.

Power generation

Net power outputs measured in two tests were slightly above design net output at 13.54MW_e and 13.67MW_e. The average for the month in which the tests were carried out was 13.2MW_e, equivalent to 97.8% of design. Maximum output in the same month was 13.8MW_e.

Isentropic efficiencies during the two tests were 76.8% and 75.8%, respectively, ie very close to those calculated for design conditions.

Firing rates were calculated at 23.78 tonnes/hour and 23.67 tonnes/hour. Overall power generation efficiencies were 27.6% and 27.4%.

Pollutant emissions

Her Majesty's Inspectorate of Pollution (HMIP) emission limits and test measurements are summarised in Table 1 below for specified substances.

Table 1 HMIP emission limits and test measurements

Substance	HMIP limits (mg/Nm^3)		Test measurements (mg/Nm^3)	
	First year	Second year	Test 1	Test 2
NO_x	600	435	127	143
HCl	300	250	126	103
HF	-	-	0.6	-
SO_2	600	300	431	377
CO	-	250	53	53
Organics	-	20	4	3
Particulates	100	100	52	62

This shows that, with the exception of SO_2, actual emissions are well within HMIP compliance limits. The SO_2 limits compare very favourably with those set for large, solid-fuel-fired boilers with a net thermal input of 50-100MW (2000 mg/Nm^3). Discussions are under way with interested parties to determine how the SO_2 emissions can be reduced. This should be possible with existing technology.

Total heavy metals were also well below any HMIP limits imposed on other prescribed processes. This is also the case with dioxins and furans emissions.

General overview

Glanford has not experienced the commissioning, operational and maintenance problems initially experienced at Eye because of the latter's higher than expected fuel moisture content. This is in spite of the fact that the fuel at Glanford normally has not only a high moisture content but also a higher ash content than the fuel at Eye. There have been no major operational or maintenance problems since plant handover.

The spreader stoker system at Glanford appears to work effectively and to have a combustion efficiency advantage of 2-3% over the stepped grate system at Eye. The combination of suspension and grate combustion allows higher furnace heat release rates and enables the required furnace temperature to be attained more easily than with stoker firing alone. Furnace temperatures have been consistently above 850°C since the plant commenced operation.

There are two plant operators per shift on a five-shift rota. Operating personnel total 15, which is not excessive for the capacity and complexity of the power plant.

Conclusions

- The technical performance of the poultry-litter-fired power station at Glanford has lived up to expectations. Lessons learnt from the first installation at Eye have resulted in improvements at Glanford and the avoidance of the problems that occurred initially at Eye.

- Although no financial details are available, the plant has performed better than the Eye plant, which was economically viable. This indicates that the economics of the Glanford plant are favourable.

- The environment has benefited from the replacement of fossil fuel with a renewable fuel, and from the reduction in methane emissions, noxious odours and nitrate leaching, all of which would have arisen had the poultry litter been used directly as a fertiliser or disposed of to landfill.

4. ENERGY CROPS

4.1 Miscanthus

ETSU B 1354 Publication date: 1992

THE POTENTIAL OF MISCANTHUS AS A FUEL CROP

ADAS

Background

British agriculture is facing a period of uncertainty and change. Farmers are facing rising costs and static or falling prices. There is increasing pressure for more balanced, sustainable farming systems. There is also a growing awareness of the damage caused by excessive use of fossil fuels. Faced with set-aside and the perception by Brussels that renewable energy systems are one of the most likely alternatives to set-aside, farmers are now considering both short rotation forestry and annually harvested energy crops.

The ideal fuel crop is a perennial that can be harvested dry for efficient combustion. It should also have a sufficiently high dry matter yield. Plant species with a C4 photosynthetic pathway provide a significantly higher dry matter yield potential than those with the C3 pathway. All UK crops except maize have the C3 pathway and their dry matter content is limited. However, research programmes in Germany, Holland and Denmark have identified *Miscanthus*, a perennial woody grass that is related to sugar cane, as a potentially promising energy crop that can be harvested on an annual basis once established. This crop not only has a C4 photosynthetic pathway, it is also relatively easy to grow and harvest.

Project Objectives

- To identify the potential of *Miscanthus* as an energy crop for the UK.
- To assess the availability of suitable *Miscanthus* species and cultivars for the UK.
- To determine the likely effect of soil, water, nutrients and climate on growth and yield.
- To consider mechanisation requirements.
- To quantify the crop's likely economic performance and any production risks.

Findings

Land suitability

High yields have been reported on the continent for a wide range of arable soils. However, light soils only yield well with adequate rainfall, while heavy soils may give compaction and harvesting problems. The crop tolerates a wide pH range. Dark-coloured soils are preferred to light-coloured soils because they warm up more quickly. A southerly aspect is also preferable.

The crop has a high moisture requirement because of its high yield. However, water availability is unlikely to be limiting factor in the UK on medium available water capacity soils with a rooting depth of at least 750mm. Yields are likely to be lower on lighter or shallower soils in the east, although shallower soils should yield satisfactorily in the wetter west.

Areas experiencing temperatures suitable for maize (another C4 crop) are likely to be suited to *Miscanthus*. The crop is more frost-tolerant than maize. Although leaf-growth is killed at temperatures below -5°C, and this determines the growing season, the below-ground parts of the plant are well adapted to survival over the winter. Wind reduces growth because of its cooling effect. It may also cause the crop to lodge. However, mature canes are very wind resistant.

Arable expertise is suitable for growing *Miscanthus*, and the availability of contractor services for planting and harvesting would help to introduce the crop in livestock areas.

Propagation and crop establishment

Although no fertile seed is available for the most productive cultivars of *Miscanthus* currently grown in northern Europe, seed offers the greatest long-term potential, both for cheapness and for ensuring high-yielding, disease-resistant plant material. Mass selected cultivars would contain a range of genotypes, allowing further selection of improved types. However, the taxonomy of *Miscanthus* spp is confused and needs further investigation to determine whether other species would be more productive.

In the short term, rhizomes and division are the most suitable propagation method, although these techniques need refining. Micropropagation is likely to be economic for new cultivars, especially for those that do not breed or breed true from seed.

Although very little work has been done in the UK on techniques for establishing rhizome pieces and young plants, existing farm machinery appears, from work in Denmark and Germany, to be suitable. Optimum planting dates need to be determined.

Crop husbandry

Work in Denmark and Germany has shown an optimum plant population of 8000-10,000/ha, although higher populations gave higher yields in the first two or three years. Different optimum conditions may be determined for different cultivars and different climatic conditions such as the more maritime UK.

In theory, plants should be planted in a square spatial arrangement to optimise access to light and nutrients. Machinery requirements and problems may alter this. In Denmark, a strip system of double rows, 75cm apart with 175cm gaps between the double rows, is commended. In mature plantations, plants overgrow rows.

Weeds, pests and diseases

Weed control is vital to crop establishment, but less important after the second year provided perennial weeds have been eradicated before planting. There has been no critical evaluation of crop safety when herbicides are used, and field trials are needed to screen glyphosate, propyzamide, fluroxypyr, phenoxy compounds and sulfonyl ureas.

Diseases are, at present, negligible in Europe. Rhizome cuttings occasionally become infected with *Fusarium* spp, but they could be protected by dipping in fungicide approved for nursery stock. There have been no European reports of foliar diseases, although in the Far East, the crop can be infected by rusts and other diseases associated with sugar cane. Disease could become a problem if the crop is cultivated widely.

No insect pests have been reported on the foliage, either in the UK or elsewhere in Europe. In Denmark, there have been occasional below-ground attacks from wasp and owlet moth caterpillars. Leatherjackets have been found in the UK. None of these have had major harmful effects on the tough, fibrous rhizomes. Rabbits and hares have damaged young shoots and dug up newly transplanted rhizomes. Damage was only significant in one UK location where the rabbit population was very dense and uncontrolled. The effect of rabbits on established *Miscanthus* plantations needs to be monitored under UK conditions.

Plant nutrient requirements

Preliminary evaluations of nutrient requirements have been undertaken in Germany and Denmark and have shown that the requirement in established crops is unlikely to exceed 75 kg/ha of nitrogen, 20 kg/ha of phosphate and 100 kg/ha of potassium on soils with nutrient reserves that are normal for arable crops. The crop may be suitable for the disposal of sewage effluent and farm manures, although little is yet known about the crop’s susceptibility to and absorptive capacity for heavy metals.

Mechanisation

Although the physical dimension of *Miscanthus* plants is similar to that of maize and so, theoretically, appropriate machinery already exists, there is some concern because the expected volume and weight of material will be higher than the equivalent for maize harvested for forage. This poses questions of machinery scale and durability. Harvesting, handling, transport and storage systems will all require careful analysis and development for a range of utilisation scenarios.

Yield and quality

In Germany and Denmark, yields from the third to the tenth year of the crop have ranged from 13 tonnes/ha to 30 tonnes/ha. Data from experimental UK plots suggest that similar yields may be achieved in this country, but further research in necessary. Nevertheless, the crop is perceived to be the most promising crop for biomass production, with a high dry matter yield potential, a higher dry matter content on harvesting than coppiced willow or poplar, good combustion characteristics and a low sulphur and nitrogen content. *Miscanthus* yielding 20 tonnes/ha would give a gross energy yield equivalent to seven tonnes of oil per ha.

Economic appraisal

The value of 20 tonne/ha *Miscanthus* was calculated at £617/ha. This compares with £399/ha for 7 tonne/ha wheat. As a fuel, on a dry matter weight basis, the crop is valued at one-third the price of oil and more than half the value of coal. Production costs, assuming a *Miscanthus* yield of more than 20 tonne/ha, compare favourably with wood chips from short rotation forestry and with whole crop cereals.

There may also be benefits to the rural community such as improved employment prospects, reductions in edible crop surpluses and associated Common Agricultural Policy support.

ETSU B/M5/00488/16/REP Publication date: 1995

ANALYSIS OF MISCANTHUS AS A FUEL

FEC Consultants Ltd

Background

There is increasing interest in the growing of *Miscanthus* for use as a fuel in the UK. This is because of its relatively high yield potential and its relatively low moisture content on harvesting.

Project Objective

- To analyse samples taken from a bale of *Miscanthus* and assess the use of *Miscanthus* as a fuel.

Methodology and Findings

Analyses

Two 50kg samples (A and B) were taken from a bale of *Miscanthus* after stripping off the outer layer to minimise the risk of sample contamination. The samples were taken to Eurolab and the following analyses were carried out on each sample:

- proximate analysis
- ultimate analysis
- calorific value
- ash fusion temperatures
- dioxins and furans
- PCBs.

Proximate analysis

The proximate analysis showed an average moisture content of 11.5%, a volatile matter content of 66.8% and a fixed carbon content of 15.9%. The variation in the readings was limited in each case. However, for ash, the readings were 2.8% for Sample A and 6.9% for Sample B, a very significant difference that can probably be explained in terms of soil contamination. Data from samples analysed in 1992 showed that the ash content of leaves is higher than that of stem material. This means that, as plants get older and the ratio of stem to leaf increases, the ash content falls.

Calorific value

Gross calorific values for *Miscanthus*, taking data from various sources and comparing them on a dry basis, is in the 18-19 MJ/kg range, with corresponding net calorific values of 17-18 MJ/kg. The range variance is only 5-6%.

Ultimate analysis

Elemental analyses of Samples A and B were compared with equivalent values for samples from Austria. The results were as follows:

- The carbon content figures proved very similar in all cases at 47.67- 48.80% w/w dry basis.
- There was a significant difference in hydrogen content between Samples A and B (6.6% and 6.4%) and the Austrian samples (5.18-5.46, depending on age), the former being more representative of woody biomass data.
- The nitrogen content of mature whole-plant *Miscanthus* is relatively constant at around 0.5%, with a higher figure for leaves (0.99%).
- With the exception of two Austrian samples (one-year and leaves), the sulphur content is 0.1% or less.
- The chlorine content of the mature Austrian *Miscanthus* samples was high and could give cause for concern regarding HCl and halogenated hydrocarbon emissions and the greater potential for fouling.

Ash analyses

The variation in ash chemistry between Samples A and B and the Austrian samples was quite wide, particularly in relation to the main constituents of oxides of silicon and potassium. Ash from Samples A and B has much higher Fe_2O_3, Al_2O_3 and Na_2O contents than ash from the Austrian samples.

Data from the Austrian samples suggest that heavy metal emissions from the combustion of *Miscanthus* will be insignificant, although the values given do not account for materials lost in the vapour phase.

Ash fusion temperatures

Ash fusion temperatures give a measure of the likelihood of deposition on and fouling of heat exchanger surfaces. The data provided for Samples A and B and the Austrian samples showed that fusion temperatures are better than those for straw, but worse than those for wood.

Dioxins and furans

Levels of inherent dioxins and furans and their precursors in *Miscanthus* proved to be very low.

Combustion characteristics

Calorific value

The gross and net CVs for *Miscanthus*, on a dry basis, are similar to those for straw and slightly less than those for wood. The crop's big advantage over wood is that its moisture content, when harvested, is much lower, and the current aim is to provide *Miscanthus* at the point of use with a moisture content of 20% or less, without pre-drying. The effective heating value of the fuel will therefore be significantly higher than that of forest residues or short rotation coppice. Furthermore, ignition will not be a problem, and combustion chambers that are fully water cooled can be employed.

Fixed carbon and volatile matter

The high volatile matter content of *Miscanthus* means that a large proportion of the combustion process will be in the gaseous phase. The provision of secondary air and sufficient freeboard in the combustion space will be needed to ensure complete combustion of the volatiles.

Fouling potential

The ash content, its constituent components and its fusion temperature will have a significant effect on the fuel's potential for fouling heat exchanger surfaces. Alkali metals in the ash are believed to be the main constituents that result in fouling, and these tend to coincide with low ash fusion temperatures. Further research is needed on *Miscanthus* ash chemistry and fusion temperatures to establish the relationships more clearly. Nevertheless, it is already clear that fouling is more likely to occur with *Miscanthus* than with solid fossil fuels, and combustion system and boiler heating surface design must take this into account.

Pollutant emissions

Particulate carryover is likely to be higher than with wood, but emissions can be minimised by good combustion design and control. On small *Miscanthus* combustion systems, eg farm boilers and rural heating schemes, multi-cell cyclone particulate arrestors should be adequate. On large plant, bag filters will be needed.

No significant problems are expected with sulphur dioxide or chlorine emissions as the calcium in the fuel neutralises them as they form. Combustion temperatures are too low for thermal NO_x formation, but with fuel nitrogen contents ranging from 0.3% to 1.5%, fuel NO_x emissions could be a problem, depending on the emission limits set. The problem can be significantly reduced by using a two-stage combustion system.

No greenhouse gas problems are envisaged. *Miscanthus* is carbon dioxide neutral and could be used to replace fossil fuels.

The very low levels of inherent dioxins and furans and their precursors in *Miscanthus* mean that the fuel is unlikely to be the source of any dioxin of furan emissions.

Although heavy metal contents were shown to be low, consideration should be given to the findings of research into the take-up of heavy metals by SRC when fertilised with sewage sludge, if sewage sludge is to be considered for *Miscanthus*.

Combustion systems

The information to hand suggests that existing wood/straw combustion technology, with minor modifications, would be satisfactory for *Miscanthus*, except for screw-type underfeed stokers. In Denmark, small batches of *Miscanthus* have been successfully burned on a “cigar” burner (in Hesston bale form) and on a stepped grate (in comminuted form).

Recommendations for Further Work

Further work should be carried out on:

- ash chemistry and ash fusion temperatures to ensure easier prediction of fouling propensity
- harvesting and pre-combustion treatment options
- combustion, including fully monitored combustion trials using a range of combustion systems.

4.2 Oil-seed Rape

Report No: ETSU-R-71 Publication date: 1992

A REVIEW OF THE POTENTIAL OF BIODIESEL AS A TRANSPORT FUEL

Faith Culshaw and Clare Butler, ETSU

Background

There is considerable interest in non-food markets for agricultural produce, and the production of biodiesel (rape methyl ester) from rape seed has attracted much attention. There are several reasons for this:

- the success of biodiesel production and use in Austria, albeit heavily subsidised
- food overproduction and Common Agricultural Policy (CAP) reforms involving set-aside
- the experience of farmers in growing oil-seed rape.

Report Objectives

- To review the current status of biodiesel production.
- To outline the financial and energy budgets and the effects of CAP reform.
- To estimate the current value of energy production from rape oil and the possible direction for future R&D.

Findings

Biodiesel can be produced from oil-seed rape relatively simply and can be used in existing diesel engines. The harvested seed is crushed to extract the rape-seed oil which is then reacted with methanol in the presence of a catalyst at a temperature of about 50°C. The product is rape methyl ester. Apart from the straw, there are two main by-products from the process: high-value glycerine, and a 28-30% protein livestock meal from the crushed seed, which is used for animal feed.

Biodiesel is already being successfully produced and used in Austria in both the agricultural and the public sector, where it accounts for about 5% of the diesel market. Production is supported by area payments to farmers and tax relief on the fuel. France, Italy and Germany are also supporting biodiesel production by the introduction of tax incentives on the fuel, and there is considerable interest in the UK in following a similar course of action, particularly in view of the large areas of land due to be taken out of food production following CAP reforms. These reforms have now approved the use of set-aside land for industrial crops.

Economics

The existing market price for rape seed is approximately £110/tonne. This would give a cost for untaxed biodiesel of approximately 42 pence/litre without by-product credits, 32 pence/litre with a credit for the livestock meal and 26 pence/litre with livestock meal and glycerine credits. This compares with around 11 pence/litre for untaxed post-refinery mineral diesel and suggests that a subsidy of approximately 15 pence/litre is necessary to make biodiesel competitive. The environmental benefits might justify such a subsidy. Alternatively the cost of post-refinery diesel would have to increase by a factor of 2.4.

There is evidence that farmers are prepared to grow oil-seed rape for non-food uses on set-aside land with rape-seed prices as low as £83.50/tonne. This would reduce the price of biodiesel to 19.5 pence/litre with by-product credits and 36 pence/litre without.

It is clear from the above that a major factor affecting the economics of biodiesel production is the ability to market the by-products. The rape-seed meal is worth approximately £80/tonne and can now be used in most livestock feeds, although the elasticity of this market needs further clarification. Glycerine is a high-value product with applications in the pharmaceuticals, cosmetics and explosives industries. Current prices are approximately £600/tonne but, although the UK currently imports around 9000 tonnes/year, the world market is at or approaching saturation point. The price elasticity of this market also warrants further study. Rape-seed straw is usually ploughed into the soil. Although it could be used as a combustible fuel, its low energy density makes collection and transportation costly, while pelleting or briquetting the straw is very energy-intensive.

Energy ratio and environmental benefits

The energy ratio for biodiesel production (output:input) is between 1.3 and 3.8, depending on the use of the by-products. The optimum energy ratio is achieved where both the meal and the straw are used as fuel. However, the livestock feed market is more lucrative for the meal, while the costs of delivering the straw to its point of use might prove prohibitive. Other ways of improving the energy ratio, eg reducing inputs, need to be investigated.

Because biodiesel is a renewable fuel, it is often claimed to be carbon dioxide (CO_2) neutral. However, some fossil fuel inputs are needed at the agricultural and processing stages, thereby reducing this benefit. This is reflected in the energy ratio.

The amount of CO_2 saved for each litre of biodiesel used (ie CO_2 emitted from the substituted fossil fuel minus CO_2 emitted during biodiesel production) has been calculated at 1.5kg. If all the estimated 630,000ha of set-aside land (1992 figures) were to be used for biodiesel production, the fuel produced would replace approximately 6% of the diesel market and there would be a 3.5% reduction in CO_2 emissions from diesel fuel. The use of set-aside land for biodiesel production would thus give some benefit in terms of reducing carbon emissions compared with leaving the land fallow. However, it is unlikely that the impact would be as significant as if the land were used for growing lower input, higher yielding energy crops that can be directly combusted, eg arable coppice or woody grasses such as *Miscanthus*. A greater reduction in carbon emissions could be achieved from biodiesel by using the straw and meal by-products as fuel.

The use of pure rape-seed oil in low-volume diesel blends would appear to offer some advantages. It would eliminate the capital investment required for biodiesel production and reduce the financial and energy inputs into processing. There would be no long-term commitment to fuel production. Problems associated with selling glycerine would be avoided. However, this approach would require the support of the oil companies, which would be difficult to obtain. Furthermore, some reports suggest that certain emissions, notably carbon monoxide, are higher with this fuel than with diesel.

Most sources describe fewer emissions from biodiesel than from mineral diesel. This applies particularly to emissions of sulphur dioxide, unburnt hydrocarbons, particulates and smoke. However, some reports suggest a slight increase in the production of nitrous oxides and, as indicated above, carbon monoxide. More work is needed to quantify the environmental impacts.

Conclusions

There is currently no greater incentive to find replacements for liquid fossil fuels than for solid ones. There would therefore need to be compelling environmental and socio-economic benefits from the conversion of oil-seed rape to biodiesel to warrant subsidies of 15 pence/litre.

The most likely market for biodiesel is likely to be where the fuel's environmental advantages, eg its biodegradability or emissions quality, can be exploited for specific niche markets such as inland water transport or inner city vehicles. If such markets could be identified, the crop could be grown as a rotational set-aside option, preferably ensuring an optimum energy balance by reducing inputs and using all the by-products as fuel.

Recommendations

Further research is needed in several areas:

- emission comparisons for biodiesel, diesel and, possibly, blends of diesel with rape-seed oil or biodiesel
- identification of niche markets for biodiesel or rape-seed oil in diesel blends
- the economics of large-scale biodiesel production, including evaluation of by-product markets
- improving the energy equation (eg by reducing inputs and using all the by-products)
- assessing the environmental effects of large-scale production, including comparisons with other potential energy crops.

Report No: ETSU B/M3/00388/40/REP Publication date: 1994

GLYCERINE COMBUSTION

FEC Consultants Ltd

Background

Most countries in the European Union are investigating the use of arable land for industrial rather than food crops. One crop being investigated is oil-seed rape for the production of biodiesel. However, the economic viability of biodiesel production is influenced by the feasibility of earning revenue from the sale and use (including combustion) of by-products, one of which is glycerine.

Project Objective

- To assess, from the basic chemical and physical properties of glycerine, the requirements for storing, handling and burning this biodiesel by-product in combustion systems.

Findings

Properties of glycerine

Glycerine is composed, on a weight for weight basis, of carbon (39.12%), hydrogen (8.75%) and oxygen (52.12%). The high oxygen and low carbon contents mean that its calorific value is relatively low - an estimated 16.5 MJ/kg gross (14.7 MJ/kg net). These values compare unfavourably with fossil fuels. Gross calorific values for the latter range from 42.4 MJ/kg for heavy fuel oil to 53.4 MJ/kg for natural gas. Corresponding net calorific values are 40.2 MJ/kg and 48.2 MJ/kg.

Because of the high inherent oxygen content of glycerine, the air requirements for its stoichiometric combustion are low (5.269 kg/kg of glycerine or 4.095 Nm^3/kg) compared with conventional liquid fuels.

Adiabatic flame temperature is around 1700°C when operating with an excess air level of 20%. This is 100-250°C lower than for conventional liquid fuels.

The main physical properties of glycerine are summarised below:

Melting point	17.8°C+ (solidifies after prolonged cooling at 0°C)
Boiling point	290°C (decomposition takes place)
Density	1.261 kg/litre @ 20°C
Dynamic viscosity	12,700cP @ 0°C
	1480cP @ 20°C
	180cP @ 50°C
Kinematic viscosity	1174cSt @ 20°C
	145cSt @ 50°C
Open cup flash point	176°C

In addition, it has a neutral pH, is totally miscible with water and alcohol, absorbs moisture from air and also absorbs H_2S, HCN and SO_2.

Storage and handling

The temperatures at which a liquid fuel is stored and pumped depends mainly on its viscosity. The viscosity of glycerine is such that it must be heated during storage to ensure a satisfactory flow at the storage tank outlet and to prevent solidification during prolonged periods of low ambient temperatures. At the same time, to keep heating costs down, the storage temperature should be held at the minimum commensurate with these requirements.

The probable heating requirements can be summarised as follows:

- a heating coil in the base of the tank

- a tank outflow heater to increase the temperature for pumping from the tank to the combustion system

- trace heating of the distribution lines and fittings to maintain transfer temperature and prevent an unacceptable viscosity increase (or solidification) when there is no flow

- a trim heater on the burner block.

An in-line heater between storage tank and burner is unlikely to be required.

In large, multiple burner installations, a ring main distribution system with duplex pumps and filters would be needed.

It is not yet clear what effect moisture absorption from the atmosphere (via the storage tank vent pipe) would have on the fuel properties of glycerine. Some form of inert gas blanket or pressurisation system may be required.

Glycerine might cause corrosion problems with stainless steel at atomising temperatures (towards 80°C). This could have implications for pipelines and burner nozzles, but not for storage.

Glycerine is unlikely to require storage and handling temperatures that are higher than those quoted in BS 2869: Part 2: 1988 for a Class F fuel oil:

- Maximum viscosity at 100°C: 20cSt
- Minimum storage temperature: 25°C
- Minimum temperature for outflow from storage and for handling: 30°C.

Combustion systems

The successful combustion of any liquid fuel requires it to be effectively atomised and then intimately mixed with the combustion air. Three main types of burner are considered applicable for glycerine firing:

- pressure jet
- rotary cup
- steam or air assisted atomisers.

Although each will have its own pressure and temperature/viscosity requirements, the pre-heating requirements to achieve them will not be too great.

Preliminary discussions with two burner manufacturers suggest that there should be no insurmountable problems burning glycerine with their equipment, although test firing trials would be necessary. Flame stability is the main concern. To overcome this, one company suggested that the glycerine should be fired with an auxiliary fuel (80% glycerine to 20% pilot fuel) via a dual-fuel nozzle burner.

The low calorific value of glycerine means that more than twice the mass flow is required to achieve an output equivalent to that from an oil-firing system. However, glycerine's high bulk density means that the increase in volume flow rate required is substantially less than for mass flow.

While it is believed that small amounts of water may help atomisation, any water present will further depress glycerine's calorific value and, if the water content varies, this could give rise to unstable combustion conditions.

Emissions

The products of glycerine combustion will comprise mainly carbon dioxide, water vapour, nitrogen and any excess combustion air. Good burner design combined with combustion control should minimise carbon monoxide, hydrocarbons and oxides of nitrogen. The fuel is therefore more environmentally friendly that distillate and residual fuel oils.

Glycerine's value as a fuel

New combustion systems will probably be needed for retrofitting to existing boilers.

In small-scale plant (<600kW), glycerine will compete with gas oil (also firm natural gas and LPG in new installations) provided the delivered glycerine price is £48.10/tonne or less, below that currently obtainable for non-fuel glycerine use.

In large-scale plant it will compete with heavy fuel oil (also interruptible natural gas and coal in new installations). This would require a delivered glycerine price of 25.70/tonne, again well below that obtained for non-fuel use.

Overall, the market will be limited by the current depressed state of the fossil fuel market.

Conclusions

- There appears to be no reason why glycerine could not be used as a fuel with proprietary combustion equipment.

- Glycerine's current fuel value is low because of the depressed price of fossil fuels.

Recommendations

Further work should involve:

- proximate and ultimate analyses to confirm calorific value and physical properties
- tests to establish whether the glycerine by-product is contaminated and if so with what
- tests to determine the rate of moisture absorption from air
- investigations into potential corrosion problems downstream from glycerine storage
- glycerine combustion trials - both stand-alone and combination firing.

Report No: ETSU B/M5/00533/16/REP Publication date: 1996

THE FAST PYROLYSIS OF OILSEED RAPE

Aston University

Background

Fast pyrolysis for the production of liquids for use as fuel or as a source of speciality chemicals is becoming a more established and accepted technology. High yields can be obtained by controlling key process parameters - reactor temperature, gas/vapour product residence time and temperature, and feedstock size and moisture content. Yields and chemical composition can be altered by feedstock pre-treatment.

Project Objective

- To examine the possibility of pyrolysing oil-seed rape, either as whole crop or as constituent parts after conventional processing.

Methodology

Three feedstocks were used: rape meal, rape straw and rape seeds. The rape meal was screened and ground to <355µm and then oven-dried to overcome feeding problems that occurred because of the meal’s higher bulk density. The rape straw was screened and ground to <500µm. Both were successfully pyrolysed in a 150 gram/hour fluid bed reactor.

Five experimental runs were carried out on the rape meal within the 465-555°C temperature range. Four experimental runs were carried out on the rape straw within the 450-525°C temperature range.

The rape seeds were sieved to remove chaff and were found to be in the 1.7-2.4mm size range, too large for the 150 gram/hour reactor. As size reduction by grinding would have released the oil and created a feedstock that would have been difficult to feed, the seeds were fed whole to the 1 kg/hour fluid bed reactor for pyrolysis. Five experimental runs were completed within the 459 -535°C temperature range, and the liquid was collected in propan-2-ol (an inert quench).

Each feedstock was characterised by elemental analysis, moisture and ash analysis, and bulk and absolute density. The oil content of the rape seeds was also measured.

The water content of the liquids collected as a result of pyrolysis was measured using Karl Fischer titration. Analysis of the gaseous products of pyrolysis was carried out by gas chromatography.

Findings

The higher bulk density of the rape meal caused some feeding problems, together with some agglomeration in the bed. However, a fairly constant organic liquid yield of around 47wt%, dry feed basis, was achieved over the temperature range considered. This was expected from the high ash content (7.7wt%, moisture-free basis). The water content varied from just under 10wt% to just over 12wt%.

The temperature for maximising the liquid yield from rape straw was approximately 460°C. This gave an organic liquid yield of 49wt%, dry feed basis, of the order expected given the straw's fairly high ash content. The water content was just over 10wt%. Comparable organic liquid yields (53wt%) at similar temperatures have been achieved from *Miscanthus*.

The optimum temperature for maximising the liquid yield from rape seed was approximately 500°C. This gave an organic liquid yield of 51wt%, dry feed basis, which compares with a yield from pine of 60wt%. The water content was just over 11wt%. Rotary evaporation of the propan-2-ol gave a single-phase dark brown liquid.

Rape seed produced two types of char - fines (about 70% by weight) and whole particles that maintain the shape of the seed as fed. The latter had a specific surface area of around 30 m^2/gram and tended to accumulate in the fluid bed, although it was possible to remove them quite readily by increasing the fluidisation velocity. Char accumulation in the bed would have to be avoided in a large-scale continuous process.

Overall, the organic liquids produced by pyrolysis were typically dark brown and mobile, with a more distinctive smell than liquids from wood. This was particularly noticeable for the liquid derived from rape meal.

The gases detected by gas chromatography were primarily carbon monoxide and carbon dioxide, with some hydrocarbon gases in typical performance.

Conclusions

Rape meal may be difficult to pyrolyse at volumetric throughputs compared with other forms of biomass.

Rape straw is considered to be suitable as a fast pyrolysis feedstock. No unusual phenomena were observed during pyrolysis or product collection.

Whole rape seed pyrolysis is a potentially interesting alternative way of deriving liquid fuels from the seed. Although phase separation did not occur, this may have been due to the propan-2-ol residue, and further work is needed to establish whether large-scale processing might result in two phases or one. There is also evidence of significant cracking of the vaporised rape oil, possibly a combination of thermal and catalytic cracking, and further work needs to be done in this area.

Whole-crop pyrolysis might be achieved in three ways:

- seeds and straw pyrolysed in separate reactors

- seeds and straw combined and co-fed into one pyrolysis reactor
- seeds and straw pyrolysed in the same reactor at separate times.

The second of these might pose some difficulties because of the differing densities of seeds and straw. A possible option might be to use a deeper fluid bed and to feed the straw in at a lower point to ensure that it has sufficient reactor residence time for pyrolysis to occur. This would allow the higher flow rates necessary to entrain the char out of the reactor, while preventing the removal of straw prior to its pyrolysis.

Recommendations

Additional work needs to be carried out in three areas:

- detailed analysis of the organic liquids produced, particularly the potential miscibility or separation of the hydrocarbon rape oil from bio-oil

- the combined pyrolysis of rape straw and rape seed in the ratio that would be found in the harvested crop

- evaluation of the effect of typical pyrolysis temperatures and other reactive environments on the rape oil.