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Potential use of combinable crop biomass as fuel for small heating boilers

by

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ABSTRACT

This report presents the findings of a research project to investigate the potential of certain combinable crop products as biomass fuels for heat generation in small scale heating systems. Initially, a review of boiler technology and existing expertise was conducted. The five fuels studied were: oats, wheat, wheat with a limestone additive, straw pellets and oilseed rape. Wood pellets were included as a reference fuel, since wood is the most widely used form of biomass fuel for heating.

Tests were conducted in two stoker burner boilers at a test facility using a heat meter, flue gas analyser and photographic equipment with reference to existing British Standards for solid fuel boilers rated up to 300kW. Relative efficiency calculations, flue gas emissions, operational and observational data were collected for each fuel during combustion periods ranging from 4 – 48 hours. Observations were made on ten small biomass heating systems during studies in Sweden Denmark, Finland, Luxembourg and Germany.

The results demonstrated that oats and wheat are viable fuels for small scale biomass boilers but only when automatic and/or manual intervention is available to remove ash and clinker build up. Combustion efficiencies for oats and wheat were comparable with those achieved when burning wood pellets and the addition of limestone to wheat appeared to improve combustion efficiency further. Carbon monoxide emissions from the combustion of oats and wheat were below the British Standard limits for solid fuel boilers. Emissions of NOx were above the Austrian limits for solid fuel boilers but currently no equivalent standard limits exist in Britain. Few existing small biomass heating systems were found to be suitable for burning grain fuels and no systems were as efficient when burning grain as they were when burning wood fuel. A few manufacturers have developed heating systems to reduce combustion and ash removal difficulties.

Data from the experimental work were used to produce an economic evaluation for oats and wheat as a biomass fuel. It was found that grain was cost effective fuel when it was priced at £60, but at a price of £130/tonne it is unlikely to be cost effective. Industrial crop production of grain on set aside land is now not considered to be an option. The experimental data were also used in a life cycle analysis to compare energy consumption and greenhouse gas emissions from cereals with other forms of heating fuel. Using oats and wheat grain for heating achieves substantial reductions in primary energy consumption and total green house gas emissions compared with heating based on conventional fossil fuels or electricity.

1 SUMMARY

There is increasing interest in biomass as a heating fuel in the UK. This trend is due to government policies and incentives to promote the use of renewable energy and due to the perceived economies of this fuel compared to fossil fuels. Wood chips and wood pellets have been the main fuels to be used in the UK although there is considerable interest in utilising other low cost materials including cereal grain and straw. The purpose of this project was to explore the potential of combinable crop grains and straw as biomass fuels for heat generation both to expand the availability of different biomass fuel types and to develop non-food applications for grain in the UK. The objectives were to:

1. Provide recommendations on suitable heating systems, grain fuels and investment and operating economics to potential users of biomass heating systems.
2. Provide Life Cycle Analysis on the two most suitable biomass fuels and collect unique efficiency and emissions data for further LCA work.
3. Provide calorific and economic comparisons for the range of combinable crop fuels and compare with values for energy crops and fossil fuels.
4. Review the biomass technologies suitable for grain combustion.
5. Assess the potential for the use of set aside land to produce cereal biomass.

The strategy used to address these objectives included the following five elements:

i). An initial review of boiler technology and existing expertise in burning cereal grains. This was conducted in order to select test boilers for experimental work and resulted in two boilers being selected, a Thermia 20kw stoker burner and a TwinHeat 40kw stoker burner.

ii). Experimental work to investigate cereal grain combustion. This work was conducted by a Finish Research Organisation, VTT and Rural Energy Trust and involved a series of combustion tests carried out to British Standard BS EN 303-5. These tests involved fuel analysis, combustion efficiency testing, flue gas emission testing and ash deposit measurements.

iii) A study to review existing grain burning boilers in Europe. This included visiting seven boilers in Sweden, Luxemburg and Germany that were burning cereal grains

iv) An economic evaluation of cereal grain as a biomass heating fuel.

v) A selective life cycle assessment of using oat and wheat grain as heating fuels. Again this uses data from the experimental work to compare the primary energy consumption and total greenhouse gas emissions from oats and wheat burnt for heat compared with wood pellets from short rotation coppice, conventional fossil fuels and electricity. The work was conducted by North Energy Associates.

Five cereal based fuels were tested including; oats, wheat, wheat with a calcium additive, oilseed rape/rape meal pellets and straw pellets. Oilseed rape and straw pellets were not suitable for burning in either of the test boilers as they produced large quantities of ash and clinker that quickly caused the boiler to shut down. Combustion of oats, wheat and wheat with a calcium additive also produced ash and clinker but to a lesser extent. The ash content of cereal grains is significantly higher than for wood fuels and there are notable differences in elemental fuel composition with the percentage by weight of sulphur and nitrogen being considerably higher in the cereals.

Combustion efficiencies for oats, wheat and wheat/calcium were comparable with wood pellets and within the boiler manufacturers published efficiency range. In general short combustion periods (4 hours) were most efficient because build up of ash and clinker reduced efficiencies over longer combustion periods (24 hours). Manual raking of ash and clinker from the combustion chamber improved combustion efficiency over longer burn periods.

Flue gas emissions were tested with levels of O2, CO, CO2, NO, NOx and SO2 measured for each of the fuel types (oats, wheat and wheat/calcium). CO is the only gas that has published emission limits for small scale heating boilers and these limits were not exceeded during combustion of any of the fuels. Currently there are no equivalent limits for NOx or SO2 emissions but the Austrian limits of NOx emissions were exceeded during combustion tests with oats and wheat. NOx and SO2 emissions were greater from the cereal fuels compared to wood pellets which are probably a result of the different elemental compositions of each fuel.

Both of the boilers used for cereal grain combustion tests were stoker burners. Although some tests were conducted using the Thermia boiler it was found to be unsuitable for burning cereal grains. The TwinHeat boiler was adequate for this purpose although additional design features, such as automatic de-ashing, may improve performance.

The boilers visited during the study tour included some moving grate boilers and these were successfully burning cereal grains. Fuel quality was an issue with more dusty cereal fuels creating greater volumes of ash and dust and hence requiring more manual intervention to clean and maintain the boiler. Automatic ash removal was a feature of all but one of the boilers visited and this was an important feature in terms of successful combustion of cereal fuel.

Evidence from the study tour suggests that a moving grate may be a desirable feature for burning cereal grains. The motion of the grate increases gas turbulence in the fire bed which in turn lowers the combustion temperature. This almost certainly reduces clinker formation which forms when some of the components of ash melt in the combustion chamber. The moving grate also helps to break up the harder clinker formations whilst carrying the fully combusted fuel away from the fire-bed.

Cereal grain and straw biomass fuels create many challenges to the operator of a biomass heating system. The major challenge is to deal with the production of between four and time times the volume of ash that is produced by wood fuels. This ash also tends to form hard lumps of clinker. Some heating systems have developed system modifications to automatically remove this ash and to reduce clinker formation, but regular internal cleaning of the heating system is still a prerequisite. The addition of limestone flour and other additives may also reduce clinker formation. There is evidence that corrosion can result from the use of straw and grain fuels and that this can reduce the life of the boiler and flue system. Emissions from the system are within current legal limits but may not be considered satisfactory in the future.

There is no small scale heating system technology which can totally overcome all of the challenges of large quantity ash production, clinker production, and gradual combustion efficiency reduction over operating time, the need for regular cleaning, higher emission levels and risk of corrosion. There are, however a few systems which go some way to making these challenges reasonably tolerable for operators who are prepared to embark on quite regular maintenance and intervention.

The economics of grain as a biomass fuel has changed dramatically over the period 2006/7. Grain needs to be a very low cost fuel compared to wood fuel alternatives to justify the many challenges that it creates to the operators of biomass heating systems. Grain costing £60/tonne has an energy cost equivalent to that of heating oil at 17p/lit. It is therefore an attractive fuel option in this price scenario. At £130/tonne, grain has an energy cost equal to heating oil at 36p/lit and is unlikely to be economically attractive. Grain screenings which have a low opportunity cost may be attractive as a biomass fuel.

The selective life cycle assessment of using oat and wheat grain as heating fuels and comparison with heating based on wood pellets from short rotation coppice and conventional heating fuels and electricity was undertaken by North Energy Associates Ltd as part of this project. Basic data for this work was provided by the combustion tests conducted by the Rural Energy Trust Ltd and from the measurements conducted by VTT. The life cycle analysis is provided in a separate report with a summary of methods and results included here.

The essential principles of life cycle assessments were introduced, including definition of the functional unit, the specification of systems boundaries and the selection of allocation procedures. Process chains are established for heating with oat and wheat grain, with wood pellets from short rotation coppice and with conventional fuels (coal, liquefied petroleum gas, natural gas and oil) and electricity. The life cycle assessment undertaken focuses on the calculation of primary energy inputs, as an indicator of energy resource depletion, and the evaluation of carbon dioxide, methane and nitrous oxide as prominent greenhouse gases implicated in global climate change. Details of subsequent calculations are recorded, with complete transparency, in standard Excel workbooks, which document all data assumptions and sources. Results show that primary energy inputs, and carbon dioxide and methane emissions are similar for heating with oat and wheat grain, and wood pellets from short rotation coppice. However, nitrous oxide emissions associated with oat and wheat grain heating fuels are significantly higher than those for short rotation coppice wood pellets. This is due to the manufacture of nitrogen fertiliser and subsequent nitrous oxide emissions from the soil. Together, such emissions account for 53% and 69% of the total greenhouse gas emissions associated with oat and wheat grain heating. Despite this, using oat and wheat grain for heating achieves substantial reductions in primary energy consumption and total greenhouse gas emissions compared with heating based on conventional fuels and electricity. If wheat and oat grain is used to displace natural gas for heating, total greenhouse gas emissions savings of 54% and 63%, respectively, can be achieved. Total greenhouse gas savings of 76% and 81% can be realised if heating with wheat and oat grain, respectively, replaces conventional electric heating.

2 INTRODUCTION

Evidence for the link between climate change and human activity has become increasingly recognised by global scientific organisations and government bodies [1]. As a result, government policies are being developed to address the economic and environmental consequences of this change. The Stern Report, published in the UK in October 2006 [2], confirms the important role that renewable energy sources can play in reducing harmful emissions which contribute to global warming.

Biomass is a term used to describe combustion fuels of plant (and animal) origin. Such fuels have therefore adsorbed carbon dioxide and solar energy to photosynthesise organic compounds. When a biomass fuel is burnt it releases the carbon dioxide that was fixed during growth. Biomass is a renewable fuel since its production and use is carbon neutral, apart from the small amount of fossil fuel used to process and transport the fuel.

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Biomass fuels, particularly wood chip and wood pellets are widely used for heat generation in Scandinavia and other parts of Europe. As a result, the technologies available for burning biomass are well developed. In these countries, the widespread availability and understanding of many biomass fuels means that this form of renewable energy has made a significant contribution to heat generation, reducing greenhouse gas emissions and the reliance on fossil fuels.

In the UK, the adoption of biomass as a source of heat energy has been slow to develop because of lack of cohesive government support and rewards from the market place. However the increases in fossil fuel prices over the last 2 years and recent grant schemes and renewable fuel incentives, has initiated a significant growth in biomass heating installations and the market is expanding rapidly from a low base. Furthermore, the Biomass Task Force report [3] and the Royal Commission on Environmental Pollution report [4] have recommended a number of market incentives and Government interventions to increase the uptake of biomass heating technologies.

Wood chips and wood pellets have become the most widely used biomass fuel in the UK but there is interest in the use of cereal grains and agricultural by-products as a source of sustainable fuel. Farmer led interest has developed following a decade of historically low grain prices. This farmer interest has been encouraged by verbal reports of use of grain as a fuel in Scandinavia and the apparent cost effectiveness of such use when grain market prices are very low. This is reinforced by a more formal visit and report by a Global Watch Mission in 2006 [5]. Existing supply chains make cereal grains a readily available biomass fuel. The low opportunity costs of poor quality and unmarketable grain at the farm gate, provides a particular attractive opportunity. Some documented research has been conducted [6] and boiler system modifications have been made but in general there is limited knowledge dissemination regarding the combustion characteristics of cereal grains or practical implications of using this fuel in boilers with a small heat output.

The main aim of this project was to explore the potential of cereal grains as a biomass fuel for heat generation in order to expand the availability of different biomass fuel types and to develop non-food applications for grain in the UK. The detailed objectives of the project are follows:

1. To provide recommendations on suitable heating systems, grain fuels and investment and operating economics to potential users of biomass heating systems
2. To provide Life Cycle Analysis on the two most suitable biomass fuels and collect unique efficiency and emissions date for further LCA work
3. To provide calorific and economic comparisons of the range of combinable crop fuels and compare with values for energy crops and fossil fuels
4. To review the biomass technologies suitable for grain combustion
5. To assess the potential for the use of set aside land to produce cereal biomass

During the lifetime of this project there have been some very significant changes in the market place for combinable crop products and by products. These have impacted greatly on the potential use of grains for biomass and bio fuels and also on the future for set aside in the EU.

3 MATERIALS AND METHODS

3.1 Review of relevant biomass heating technology

Questionnaires (Appendix 1) were distributed to 34 UK and European biomass boiler manufacturers /suppliers. The companies were identified from an Internet search. The questionnaires, along with follow-up telephone calls, were used to gather the following information:

1. Potential grain burning capabilities of various biomass boilers.
2. Any experience/research in burning grain in biomass boilers, including testing equipment, fuels, gas emissions and life cycle studies.

A review of published reports and tests relevant to this study was conducted

On the basis of data accumulated from this review and within the resources of this research and those offered by heating system manufacturers, two biomass boilers were selected for the combustion test studies.

3.2 Biomass fuel types

Five biomass fuel types were selected for testing; this choice was made in consultation with the HGCA. The fuel types were wheat, wheat & calcium, oats, oilseed rape and straw pellets. Wood pellets were used a reference fuel. At an early stage of observation, rape meal pellets were used as a substitute fuel for rape seed.

3.3 Test boiler installation and operation

Two boilers were selected for combustion testing work, a Thermia 20kw stoker burner and a Twin Heat 40kw stoker burner. (Appendix 2) The boilers were installed at the Rural Energy Trust test facility in Owston, Oakham, Leicestershire. This rig consists of the boilers, chimney flues and boiler pipe work arranged in a closed loop. A circulating pump creates the flow of water through the system and the heat generated in the boiler is vented to the ambient temperature outside of the building through two external fans. This arrangement allows the heating systems to be operated at constant output for test periods over which fuels can be evaluated and boiler operation observed. During the boiler tests, one fan ran continuously and the second fan was thermostatically controlled to start when the temperature exceeded 80 °C ensuring that the boiler in operation maintained continuous and steady combustion.

Measurement of heat produced by the heating system was recorded at the point of hot water exit from the system. Thermocouple probes which were located on the water flow and return to the boiler (Fig. 1&2) measured the temperature differential produced by the boiler. These were connected to a Metrima F4 Energy Meter (EN 60870-5) (Fig. 3) which calculated the power output in kW and total energy generated in MWh from the measured flow rates and temperatures. These data were used to calculate boiler efficiency rates for the different fuels.

Figure1: Hot water flow from boiler

Figure 2: Cold water return to boiler

Figure 3: Metrima F4 Energy Meter

3.4 Initial fuel suitability tests

Initially the five selected fuel types, along with the reference fuel (wood pellets), were appraised to determine their suitability as a biomass fuel in the two test heating systems. At this stage, the observations focused on the 'practicality' of the material as a fuel and the optimisation of the combustion settings of the heating systems for each particular fuel.

Each fuel was subjected to a series of combustion tests over short periods, in each boiler. These lasted up to 6 hours each. Where possible, a 'setting' to achieve optimum combustion efficiency was determined for each fuel and heating system combination. The parameters and indicators to achieve this optimum are shown in Table 1

Table 1: Parmeters and indicators relevant to achieving efficient combustion

Oxygen	**Carbon Monoxide**	**Carbon Dioxide**	**Nitrogen Oxide**	**Exhaust Gas Temperature**	**Fuel**
Ideally the level of O_2 in exhaust gases should be **5-8%.** Too low oxygen increases CO formation: too high risks creation of thermal NO_x and reduced combustion efficiency	Presence of CO indicates uncombusted gas. The goal is high CO_2 and **zero CO**; in practice they'll always be some CO present, this must remain below 100 ppm	This value should be as close to the theoretical maximum as possible, **20.4%.** In practice O_2 levels of 5-8% will clearly lead to reduced CO_2 **(13-16%)**.	Dependant on combustion temperature and the level of surplus air. High temperatures create thermal NO_x, whilst too low leads to incomplete combustion. Ideal temperatures will be in the range 850- 1200°C	Ideally **below 150°C** (prior to an exhaust gas fan). Slightly higher temperatures are permitted when using dry fuels.	Uniform particle size and moisture content. Enables steady combustion and reduces emission variations

Observations that were recorded at this stage were as follows:

- Fuel characteristics, including particle size, density and dust content and the flow characteristics of the fuel in the feed systems.
- Ash, slag and clinker (ash which first melts and then solidifies into large lumps) formation, including burner tube and air hole blocking and the impact of these on combustion performance.
- Combustion observations
- Notable emission characteristics

3.5 Detailed combustion tests

3.5.1 *General*

Two of the initial five fuels types were chosen for further investigation (wheat and oats). This work on the two test fuels and control fuel was principally conducted over a two week period on the same heating system test equipment but with the extra resource of VTT staff and more sophisticated heat production and flue gas analyser testing equipment. Following the difficulties experienced with configuring the 20kW Thermia heating system at the initial fuel suitability test stage, further time was spent by VTT technical staff, in conjunction with the manufacturer Thermia Oy, and a working configuration was achieved. Although the core data was obtained during this testing period, further extensive combustion testing was conducted over the following months by Rural Energy Trust technical staff. These data were collected using the more limited analytical equipment. However combustion tests over longer periods up to 72 hours were examined as were levels of limestone flour additions to wheat fuel between 1-5%.

3.5.2 *Fuel assessments*

Fuels were analysed to determine the basic fuel characteristics including moisture content, ash content, amount of volatiles, calorific value and elemental composition (C, H, N, S, Cl & O). Fuel weight and bulk density was measured for each combustion cycle.

3.5.3 *Combustion tests*

Tests were conducted with reference to the existing guidelines, detailed in the British Standards for Solid Fuel Biomass Boilers up to 300kW[7].

For each fuel the same boiler start procedure was followed. The fuel hopper was filled with suitable quantities of the selected fuel and a quantity of this fuel was fed into the burner tube using the electronic control panel (Figure 1). Once the burner tube was half filled with the fuel, three handfuls of wood pellets were added on top of the fuel pile. A blow-torch was used to manually ignite the pellets. Once the pellets were burning, the boiler cycled through a start up phase, pulsing air and fuel into the chamber. Following a successful start, the control panel automatically selected the normal running phase, calibrated for the specific fuel being burnt (wood pellets, grain or a customised setting). Typically the boiler required 1-2 hours from ignition before reaching steady state running. Testing periods of 4 hours were used during the VTT testing stage, but were extended up to 72 hours, where possible, during the later testing conducted by Rural Energy Trust testing stage. The target hot water output temperature for each combustion period was set to the boiler manufacturers recommended temperature of 85°C.

During start up, the boiler's heat exchanger was bypassed allowing the flue gases to rapidly heat the main chimney flue, increasing the draught and enabling good combustion. As the boiler water temperature steadily increased, any excess air trapped in the system was bled using a manual bleed valve above the water outlet thermocouple (Figure 1) and an automatic bleed system.

Each combustion test consisted of a test period (4 to 72 hours) during which the following data was recorded:

- Weight of fuel burned
- Weight of ash produced and elemental analysis of ash sample
- Heat produced
- Flue gas emissions (O2, CO, CO2, NO, NOx and SO2)
- Observation of nature of ash formed, including photographs

Flue gas emission values were recorded during steady state combustion. The tests that were conducted by VTT involved measuring the composition (O2, CO, CO2, NO, NOx and SO2) of the moist flue gas, collected from the flue gas fan using a KM9106CO Quintox flue gas analyser. Emissions were recorded over the entire duration of the combustion period at 5 second intervals. A mean figure was calculated for each gas and each combustion test.

Tests were conducted by Rural Energy Trust using a Testo 335 flue gas analyser. This equipment does not provide measurements that comply with BS EN 303-5 standards, however it is sufficiently accurate to provide comparative data (NO, NOx derived, CO and CO2) for different fuels. Dust content and organic compounds (OGC) were not recorded.

NOx levels were derived using the following equation (1)

$$NO_x = NO + (NO_{2ADD} \times NO) \qquad (1)$$

Where NO_{2ADD} is the Nitrogen dioxide addition factor [8]

Elemental composition of an ash sample was determined for each fuel type using a Philips PW2404 X-ray fluorescence spectrometer (XRF) and the semi-quantitive SemiQ program. Photographs were taken of the boiler and burner tube after each test and other relevant observations recorded.

3.5.4 *Combustion efficiency*

Boiler efficiency calculations are based on the method outlined in Equation (2) taken from BS 303-5, where Q_B is the calorific value of the fuel burned during the test period and Q is the total energy generated in kWh over the test period. This method does not included losses in the system as these can only be recorded in laboratory conditions.

$$\text{Efficiency, } \eta_K = \frac{Q}{Q_B} \qquad (2)$$

3.6 Review of a sample of working grain fuelled heating systems in Europe

Following the inadequacy of the review of relevant biomass heating technologies, described in section 3.1, to provide clear information, an extra work package was conducted towards the end of the data collection stage of the project. Site visits were made to observe eleven biomass heating systems in operation on the owner's premises in Sweden, Luxembourg, Denmark, Finland and Germany. Observations were made and the comments of the operators were collected. Eight site visits in Denmark, Sweden, Luxembourg and Germany were conducted by a Rural Energy Trust research technician and three visits in Finland were conducted by the VTT partner.

The objectives for the study tour were to:

- obtain observational data from each operational boiler
- investigate fuel types used in boilers
- discuss operational requirements with boiler operators and installers
- ascertain more clearly which biomass heating technologies are relevant for UK conditions

4 RESULTS

4.1 Review of relevant biomass heating technology

4.1.1 *General*

Thirteen responses were received to the questionnaires. Where possible these responses were followed by telephone conversations and in some cases by further email communications. Five further manufacturers, who did not initially respond or who were not originally identified on the questionnaire circulation list, made contributions during the progress of the project

The information collected was almost entirely subjective with very little test report data available. The UK based distributors had been importers and distributors for a short period and had only installed a few systems, if any at all, and none of these had been operating long enough to be able to give useful experience. It proved impossible to identify a single working installation which was available or suitable for some observational tests to be conducted.

Manufacturers of biomass systems offered in many cases very cautious information and advice on the applicability of their systems to utilise grain as a fuel. In all cases they indicated that there were a number of issues to be addressed by clients choosing to use grain as a fuel: ash production was likely to be 5-10 times greater than for wood, the ash is subject to clinker formation (forming large lumps), the fuel tends to extinguish more easily on low flame and the whole combustion system requires regular internal cleaning of ait injection holes and heat exchangers. The point was clearly made that wood, in all its forms, was certainly the ideal biomass fuel.

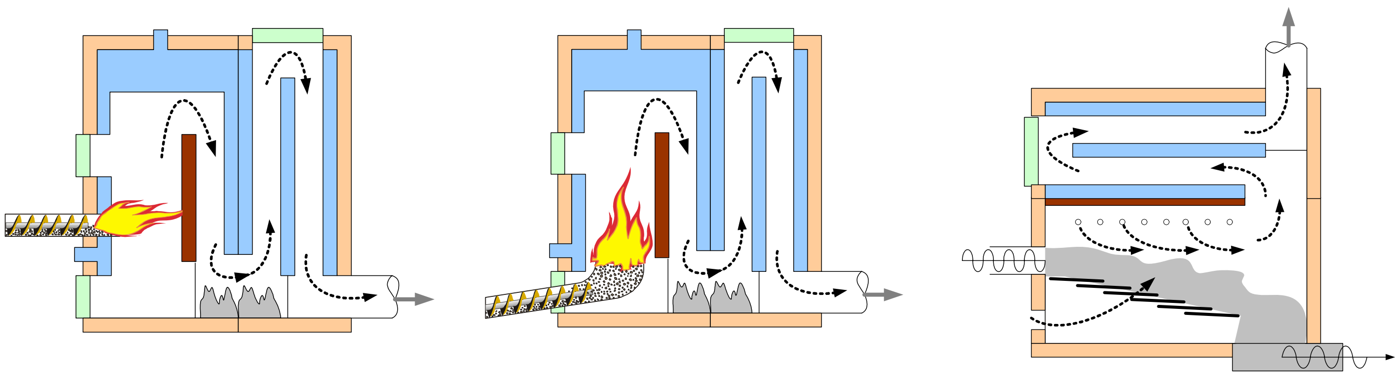
The choice of heating systems to use for the fuel testing was therefore made from a limited information base and from the limited resources available to fund this aspect of the project. Thermai Oy (now called Ariterm), Finland, made available a newly developed grain stoker-burner head and 20kW boiler. Rural Energy Ltd in conjunction with Twin Heat, Denmark, made available a 40kW composite stoker burner, boiler and hopper heating system. Photographs of these systems appear in Appendix 2.

4.1.2 *Types of burner systems and suitability*

There are three broad types of fuel stoker systems in use for small scale (under 200Kw) biomass heating systems: under stoker, stoker burner and moving grate. Schematics of the systems are shown in Figure 2.

The under stoker system pushes fuel in an upwards direction into the base of the boiler. Combustion air is blown from below and from the sides, above the stoker. It is clear that the under stoker system is very unlikely to be suitable for burning grain, straw and other high ash fuels. Ash tends to be push upwards, during the combustion process, and out over the edge of the stoker. When clinker is formed, this cannot escape and blocks the under stoker in a very short time.

Figure 4: Stoker types in small scale biomass systems



Stoker Burner | Under Stoker | Moving Grate

The stoker burner system consists of burn chamber external to the boiler. Fuel is fed into this burner in a lateral direction with combustion air blown into the chamber, usually along the length of the cylinder. The system is very simple and tends to be the least expensive of the three systems. The stoker burner system was found to be the most widely used type of system for grain burning. Ash is pushed horizontally out of the stoker burner and falls into the boiler base. The horizontal movement is much less likely to cause ash clogging and blocking than the upward movement

The moving grate system is usually associated with larger output systems and tends to be the most expensive to buy and to maintain. Fuel enters the boiler onto the higher level of the grate and is moved progressively down by the movement of the individual steps. Most biomass moving grate systems would be unsuitable for burning grain since the grain would fall through the grate. However in at least one case a small scale system has been developed with modifications to allow grain to be used as fuel satisfactorily. In another case, a small step grate has been incorporated into a stoker burner to achieve the same end.

4.1.3 *Manufacturer and Installer Comments*

Many of the larger manufacturers of biomass heating systems stated categorically that their equipment was unsuitable for use where grain or very high ash products were to be used as fuels. Some of these manufacturers also expressed serious doubts about the ability of any biomass systems to perform this function satisfactorily. Unsatisfactory operation of the heating system, reduction in life of the boiler and unsatisfactory levels of emissions were all mentioned as potential difficulties. There was also an undercurrent of doubt concerning the social acceptability of grain being used as a combustion fuel, when it is perceived to be a food product.

Most of the manufacturers who condoned the use of their equipment for burning grain were small and medium size businesses. These manufacturers gave the impression that the practice of using grain as a fuel was farmer motivated and that they had responded to requests for advice rather than being proactive in making such recommendations. In some cases, manufacturers had made modifications to heating systems to facilitate better performance, but still made clear to clients that operation would be less problematic when wood chip or wood pellets were used as a fuel.

Lars Hansen, director of Faust (Maskinfabrikken) ApS, Denmark [9] that there were 50 of his company's clients who were using grain as a fuel, using systems in the 40kW- 260kW range. The company had three years experience of grain fuel use and had identified a number of issues. Much larger quantities of ash (2-4% of fuel dry weight) results from grain fuels compared to wood (0.5%). Also clinker formation, blocking of air inlets and heat exchangers were a feature of these fuels. The build up of ash and clinker and blocking of airways led to reduction in boiler output and efficiency. Correct boiler function could only be maintained by very regular cleaning of all parts. The company has encountered far more problems with heating systems over 60Kw output and this was thought to be due to the higher combustion temperatures generated. His company had developed a stoker burner, which incorporated a three step feature, with a central moving section and also a system to reduce clinker formation and dust accumulation in the convection areas. These features increased the operational period before efficiency and output drops significantly and the boiler has to be cleaned.

Jean-Luc Schmitt, a biomass heating system installer and agent [10] in Luxembourg has installed ten grain burning systems in Germany, Luxembourg and Belgium. These systems ranged from 10-45kW in output and included four different products sourced from Germany, Denmark and the Czech Republic. All the systems were working to the reasonable satisfaction of their owners and were largely using oats and barley as a fuel. Wheat is only used occasionally as a fuel and in this case limestone flour is often used to reduce clinker formation (by raising the melting point of the ash). The limestone flour is mixed with the grain at a rate of 1% by weight. Problems are experienced with separation of the limestone flour from the wheat in the fuel hopper and some system needs to be devised to reduce this problem.

Lars Brusgaard, director of REKA Maskinfabrikken A/S, Denmark [11] has developed a range of boilers with multi fuel capabilities including grain and possibly straw. The main feature that has been developed in this system is a small step grate. The fuel moves down the steps of the grate, as it burns, and is assisted by independent movement of alternate steps. This action is helpful in moving the large quantities of ash away from the combustion zone and also the movement tends to reduce clinker formation from molten ash. The grate is manufactured in such a way that grain does not fall through the air vents or gaps in the grate. The manufacturer reports that clinker formation is further reduced by the ability of this boiler to combust grain and straw at lower temperatures. This is achieved by the reduction of primary air flow, which is blown up through the grate and the balance of secondary air, introduced higher up the combustion chamber. Large amounts of ash are produced in the combustion of straw and grain and the optional addition of an ash removal screw facilitates longer burn runs before the system requires manual attention. The advantages of a this step grate system is endorsed by research at the Danish Energy Agency [6]

Thomas Hvid, Technical Manager of Thomas Hvid, Twin Heat, Denmark [12] reported that their 10-80kW output heating systems were approved for use with grain as a fuel, in addition to conventional use of wood chop and wood pellet fuels. The systems had been in use for burning grain and grain residues for up to twelve years. The company was still uncertain about recommending their larger range of heating systems for use with grain. The systems have been developed to accommodate the special requirements of grain combustion in a number of ways: firstly the horizontal stoker burner design has been developed to minimise ash build up and clinker formation; secondly the stoker burner is fitted with a replaceable stainless steel liner to increase stoker longevity due to corrosion; thirdly an ash removal screw is available as an option to reduce ash build up and a reduction in boiler performance; and fourthly the control system is pre-set with a range of oxygen and fuel flow parameters which can be reset with the ‘flick of a switch’ when fuels are changed.

Heikki Oraveinen, Senior Research Officer at VTT in Finland [13] reported unpublished observations and fuel evaluation work that show the combustion of cereal grains and straw is more difficult than wood combustion and causes more emissions. The calorific values of cereal grains and straw tend to be about 10% less than for wood. Ash content, however, is between and 3-7% higher and the melting point of this ash is significantly lower. The result of this combination is that clinker formation is likely during the combustion process. Nitrogen and sulphur contents of cereal grains are several times higher than wood and therefore emissions of NOx and SO2 emissions are also likely to be higher, also. Chlorine content of cereal grain is also much higher than wood and there is therefore a risk that more rapid corrosion in the boiler and flue could take place. The challenges for boiler manufacturers, if cereal grain is to be a widespread biomass fuel, are to design systems with effective grate and ash removal systems for large ash quantities, technologies which can remove the higher NOx, SO2 and particulate emissions and boiler linings and flues which can resist the impact of corrosion

Although a number of other contributors provided information on heating systems, with which they were associated, some of this was conflicting and difficult to interpret. Since some of these contributors clearly had a short association with the heating systems of which they spoke, this information is not specifically reported.

4.1.4 *Test reports and literature*

Official test reports on the performance of biomass heating systems, when using grain as a fuel were generally unavailable and unpublished. In most European countries biomass heating systems are required to pass standard tests at approved testing laboratories. A common standard of attainment is the standard EN 303-5, in which the definition of parameters varies slightly between countries. Under this test protocol, grain is not recognised as a biomass fuel and therefore heating systems cannot formally be accredited to burn specifically such fuels.

Some unpublished [15] [16] [17] and published reports [6] [14] by the Danish Technological Institute describe testing of some small biomass heating systems on a range of non wood fuels. These include wheat (plus 1% limestone flour) and a range of specially prepared pelleted fuels which includes straw (plus 1% CaO) and grain screenings (plus 5% limestone flour). The tests are conducted on a number of heating systems but notably a 20kW Twin Heat stoker burner system and a Reka 30kW step grate systems; both manufactured by Danish companies.

Selected data from two published reports and three unpublished test reports are summarised in Table 2

Table 2: Selected data from tests on grain, straw and wood pellet fuels (Danish Technological Institute)

Test /fuel/specification	**Stoker type**	**Efficiency %**	**CO mg/m^3**	**NOx mg/m^3**	**SO_2 mg/m^3**	**OGC (CH_4) mg/m^3**	**Dust mg/m^3**
Twin Heat M20i *Wheat +1% LSF*	Stoker burner	87.0	337	662	No data	3	337
Twin Heat M80i *Grain*	Stoker burner	90.2	59	582	No data	9	338
Twin Heat M80i *Wood pellets*	Stoker Burner	89.6	102	207	No data	0	35
Reka 30 *Straw pellets +1% AlO*	Step grate	No data	2355	343	219	No data	No data
Reka 30 *Grain screening pellets + 5% LSF*	Step grate	85	224	548	210	No data	338
Reka 30 *Wood pellets*	Step grate	88	25	191	8	No data	15
EN303-3 (Denmark) *Wood pellets*	Standard	78	2500	n/a	n/a	150	150
EN303-5(Austria) *Wood pellets*	Standard	83	890	260	n/a	75	120

[6][14][15][16][17]

Notes: All emission values mg/m^{3} ^{data} for CO, NOx, SO_2, OGC, and Dust at 10% O_2

The main points that emerge from this data and the observations made during the tests are:

- Straw combustion is initially good but rapidly deteriorates as serious ash and clinker formation develops. Even the use of a step grate and automatic ash removal system could not clear the clinker and reduced efficiency and flame failure resulted before tests could be completed. The combustion chamber and heat exchanger tubes became heavily fouled with dist and air inlets became rapidly obstructed.

- Grain fuels, with added limestone flour performed reasonably well by comparison with straw. Small quantities of clinker formed, but did not cause obstruction problems in either of the test heating systems, over 18 hour test periods. However clinker did form in the air nozzles of the step grate boiler and removal was recommended every second day. Efficiency levels over the tests compared to those for wood pellet fuel and were well in excess of standard biomass test levels.
- Emission levels during the combustion of grain are considerable and in excess of levels for wood pellets and in most cases in excess of standards set for biomass fuels. Nitrogen oxides (NOx), sulphur dioxide (SO_2) and dust (particulate) emission levels for grain combustion were several times higher than for wood pellets and in most cases were in excess of national standards where applicable for that emission type. The emission of the most serious greenhouse gas, methane, however was very low in the heating system for which this parameter was recorded.

4.2 Initial fuel suitability tests

The Thermia 20kW heating system was satisfactorily configured for the combustion of wood pellets during this observational stage, but could not be configured to achieve any satisfactory combustion runs for the test fuels. The Twin Heat system was relatively easy to configure at this testing stage, with programmed controller settings for grain combustion and guidance being readily available from the manufacturers. The fuels and combustion characteristic results are therefore based on observed data from the Twin Heat system alone.

It was found to be completely impractical to use oilseed rape seed as a fuel. Because of the very light weight of rape seeds, they were blown out of the combustion zone, by the primary air system, before combustion could be satisfactorily started, let alone completed. It was decided to use rape expeller meal pellets as a substitute fuel for the remainder of the project.

Satisfactory boiler control system configurations were achieved for all test fuels. Short period test runs (3 and 6 hours) were completed for all fuels. Long period tests (24 hours) were completed for wood pellets and oats, but not for any of the other fuels.

Observational results for the five test fuels and control fuel are summarised in Table 3. The comments represent the observed characteristics over short and long combustion tests for each fuel burned in the TwinHeat boiler.

Table 3: Fuel and combustion characteristics.

Fuel	Feed & flow characteristics	Ash formation	Combustion observation	Gas Emissions
Wood Pellets	Flows well in the auger and burner tube. Low dust levels	No clinkering, small quantities of fine grey ash. Blown and pushed from stoker tube.	Strong flame established after 1 hour. Clean and sustainable flow of fuel and ash	Very low CO and NO values, both below 10 ppm
Oats	Flows very well in the auger system, moderate dust levels	High ash volume, easily broken apart, but tending to cake together. Ash tending to half fill stoker but pushed out into ash pan	Strong flame, initially. Slightly reduced flame as stoker tube reduced in available diameter	Low levels of CO concentration, ~30pmm. Higher NO emissions than all other tested fuels, ~ 350 ppm. ppm
Wheat	Flows very well in the auger system, moderate dust levels	High ash volume. Clinker build up, leading to fire being gradually extinguished,	Moderate to good flame strength	Very low CO values during steady state combustion – below 50 ppm
Wheat & Calcium	Flows well but some loss of calcium powder coating pre-combustion through deposits on the internal surfaces. Moderate to high dust levels	High ash volume but low clinkering and ash build up. Additional calcium deposits on walls of combustion room and heat exchanger surfaces	Good Flame	Low CO values with all mixes of calcium – typically ranging between 10- 70 ppm
Rape meal Pellets	Brittle pellets – rapid breakdown of pellet structure after transportation through auger system – leading to high dust levels	Very large amounts of hard white ash. Clinker formed in burner tube, which is pushed out during combustion, but was problematic for longer combustion periods	Very strong flame, tending to spit: possible result of high oil content	Low CO levels – below 30 ppm and NO levels below 300 ppm
Straw Pellets	Flows well in fuel delivery system - limited pellet disintegration- low dust levels	Extremely high levels of ash formation and high levels of clinker formation in burner tube, rapidly leading to blocking	Good initial flame, however significant clinker inhibiting combustion to a few hours	Medium to high levels of CO, approximately 250 ppm. NO levels were low approx. 50 ppm

The normal operation of the biomass heating system can be observed during the combustion of wood pellets. (Appendix 3.1) The small quantity of light and powdery ash is part blown and part pushed out of the stoker burner and falls into the ash area at the base of the boiler. The stoker tube remains clear and clean and normal efficient combustion continues indefinitely.

This operation is compromised, to varying extents, during the combustion of the test fuels by the accumulation of the considerably larger quantities of ash. Ash builds up in the stoker tube, causing blockage of primary and secondary air holes which eventually prevents the entry of fuel. The formation of ash as clinker inhibits normal operation of the stoker burner much more rapidly since it cannot be pushed forward and down into the ash area. The accumulation of ash and clinker may eventually extinguish the flame. (Appendix 3.2 to 3.5) Normal boiler operation can be only be achieved by manual intervention to remove ash and clinker and to clean any obstructions to air and gas movement. The regularity of these required interventions varies for the different ash formation characteristics of the test fuels.

The expected and observed ash characteristics of the test fuels are shown in Table 4

Table 4: Ash characteristics for different fuel types

Fuel Type	**Standard Analysis Ash Volumes**	**Experimental Ash Volumes**	**Characteristics**
Wood Pellets	0.3 %	1-2%	Fine & light, grey ash, low volume
Oats	2.7 %	5%	White, low density ash, high volume
Wheat	1.4 %	3-5%	Grey, granular, brittle and contains some
Straw Pellets	*8-13.7%	6 – 10 %	Grey, Granular, hard ash and high clinker
Rape meal Pellts	**6%	6 %	White, hard clinker with some grey ash

*[18] [19] ** [20]

Straw pellets produced large quantities of ash which tended to form a continuous ‘tube’ of clinker. (Appendix 3.4). The impact of this accumulation in the stoker tube began to adversely impact on combustion efficiency in as little as 6 hours. This observation is confirmed by tests carried out by the Danish Technological Institute using a step grate boiler [12]

Oilseed rape cake pellets produces less ash than straw but tended to form the same continuous clinker formation (Appendix 3.5). Again this accumulation of solid ash rapidly reduced combustion efficiency and eventually extinguished the flame

Wheat produced approximately three times as much ash as wood pellets. This ash tended to form clinker, but it was found that the addition of 1% limestone flour to the fuel reduced this effect. (Appendix 3.3 and 3.4) Combustion continued at a satisfactory level of efficiency for a period of 24 hours.

Oats produced four times as much ash as wood pellets, by weight, but this tended to be less dense and therefore produced significantly more volume than wheat. However, there was virtually no clinker formed in the ash and so it was able to flow relatively freely out of the stoker tube and into the ash pan area. (Appendix 3.4)

Oats and Wheat (plus a limestone additive) grains were chosen as the two most promising fuels to progress to the more detailed combustion studies in this project. Straw pellets and oilseed rape meal pellets were discarded as potential fuel types in these types of biomass boilers due to the extreme levels of manual intervention which would be necessary to achieve a reasonable level of normal combustion.

4.3 Detailed Combustion Tests –VTT, Finland

4.3.1 *Fuel Analysis*

The two test fuels and control fuel were sampled before and during testing and were analysed at the Enas Oy laboratory in Finland. Results of these tests are shown in Table 5

Table 5: Characteristics of test fuels (ISO, DIN, ASTM and EN standards)

Fuel	**Unit**	**Wood Pellets**	**Oats**	**Wheat**
Bulk Density (loose)	kg/m^3	538	489	733
Energy Density (NCV), wet basis (25 degrees C)	MJ/m^3	2452	2063	2926
Energy Density (NCV), wet basis (25 degrees C)	MWh/m^3	0.68	0.57	0.81
Volatile matter	wt-%	84.5	82.0	82.5
Moisture	wt-%	10.8	14.4	13.6
Gross calorific value, dry	MJ/kg	20.04	19.58	18.41
Gross calorific value, dry	MWhr/t	5.57	5.44	5.11
Net calorific value (NCV), dry basis (25 degrees C)	MJ/kg	18.69	18.16	17.01
Net calorific value (NCV), dry basis (25 degrees C)	MWhr/t	5.19	5.05	4.73
Net calorific value (NCV), wet basis (25 degrees C)	MJ/kg	16.41	15.19	14.36
Net calorific value (NCV), wet basis (25 degrees C)	MWhr/t	4.56	4.22	3.99
Fuel Composition (Dry basis)				
Carbon (C)	wt-%	50.2	47.1	45.3
Hydrogen (H)	wt-%	6.2	6.5	6.4
Sulphur (S)	wt-%	<0.02	0.13	0.16
Oxygen (calculated)	wt-%	43.1	42.1	44.7
Nitrogen (N)	wt-%	0.15	1.45	1.95
Chlorine (Cl)	wt-%	0.011	0.057	0.067
Ash (550 degrees C)	wt-%	0.3	2.7	1.4
Total		100.0	100.0	100.0

The bulk density and the energy density of wheat are significantly greater than wood pellets and oats. Nevertheless all three fuels are relatively dense compared to other biomass fuels (e.g. wood chip). This parameter has considerable significance in terms of the fixed volume of a fuel storage hopper and consequent frequency of refilling.

The derived net calorific values for wood pellets and wheat are comparable to other results [21], but the figure for oats was much higher than expected.

The ash content of the cereal grains is very much higher than the wood pellets and the mineral composition of this ash shows sulphur, nitrogen and chlorine levels to be several times higher in the cereal grains

4.3.2 *Combustion Efficiency*

Combustion efficiency test results are detailed in Table 6 below. Mass and energy balances and combustion efficiencies were determined using the standard DIN 1942 [22]

Table 6: Boiler efficiency results for different fuel types over a 4 hour test period

Fuel	Thermia Wood pellets	Thermia Oats	Thermia Wheat	TwinHeat Wood Pellets	TwinHeat Wheat	TwinHeat Oats
Efficiency %	78	76	-	85	84	84
Heat produced (kWh)	56	49	-	150	134	134
Fuel weight (g)	15984	14544	-	50832	43488	48384
Ash weight (g)	1440	1440	-	2160	2448	2592
Flue gas temperature (˚C)	141	141	-	165	155	155

The efficiency levels vary only slightly for different fuels but there is a substantial difference between the two boiler types. No results are available for wheat burned in the Thermia boiler as a satisfactory combustion test was not achieved. The more satisfactory performance of the Twin Heat system, whilst burning oats, is shown by the much lower proportion of ash to fuel ratio (5.35%) than for the Thermia system (9.90%)

4.3.3 *Flue Gas Emissions*

Gas emission measurements taken during the combustion tests are given in Table 7 (See Appendix 4 for more detailed data). The figures are mean values for test duration of four hours. This is the test protocol for the standard test procedure BS EN 303-5.

During efficient combustion of biomass fuels the expected flue gas levels of oxygen (O_2) would be in the 7-10% range. The levels recorded for all fuels tested in the Twin Heat system fall in this range. Oxygen levels recorded in Thermia systems tests fall well out of this range and further reflect the inability of this system to perform satisfactorily.

Table 7: Flue gas emissions for different fuels in the two test boilers

Boiler	Fuel	O_2 [%]	CO [mg/m3]	CO_2 [%]	NO [mg/m3]	NO_x [mg/m3]	SO_2 [mg/m3]
Thermia	Wood Pellets	14.7	241	5.3	111	175	0
	Oats	14.7	123	4.9	393	628	15
	Wheat	-	-	-	-	-	-
Twin Heat	Wood Pellets	6.6	16	13.1	191	304	0
	Oats	10.9	0	8.3	451	720	100
	Wheat	8.0	21	11.4	749	1200	463

Carbon monoxide (CO) emission levels are all well within the BS EN 303-5 limits [7], although the levels from the operation of the Twin Heat system is much lower than the Thermia system, on all fuels.

NO_x and SO_2 emissions are very much higher for the oats fuel than for wood pellets and higher again for wheat. These levels probably reflect the relative levels of nitrogen and sulphur in the fuels (see Table 4). Although these levels do not exceed any UK emissions limits, there are clearly implications for the cereal grain fuels in terms of their extra NO_x and SO_2 emissions.

4.3.4 *Composition of Ash*

The elemental composition of the ash samples taken during these combustion tests are shown in Table 8. Oats and wheat grains contain levels of phosphorus and potassium many times greater than the levels in wood pellets. Oats contain levels of silicon which are many times higher than both wood pellets and wheat These relative mineral contents are confirmed elsewhere [6] [14] and the higher levels of these minerals in grains, straw and oat husk may be associated with the formation of clinker in the ash. [23]

Table 8: Elemental Composition of Bottom Ash

Boiler	Thermia			Twin Heat		
Fuel	**Wood Pellets**	**Oats**	**Wheat**	**Wood Pellets**	**Oats**	**Wheat**
Sodium, Na	0.32	0.1	-	0.55	0.22	0.05
Magnesium, Mg	0.64	2.1	-	2.5	4.2	2.5
Aluminium, Al	0.06	0.02	-	0.22	0.08	0.006
Silicon, Si	0.87	12.0	-	1.1	19	0.2
Phosphorous, P	0.65	7.4	-	1.2	12	7.4
Sulphur, S	0.10	0.2	-	.32	0.07	0.84
Chlorine, Cl	0.05	0.13	-	0.84	0.04	0.22
Potassium, K	3.00	9.8	-	4.6	14	13
Calcium, Ca	3.20	1.6	-	15.0	3.3	1.4
Titanium, Ti	<0.01	<0.01	-	0.02	<0.01	<0.01
Chromium, Ch	<0.01	<0.01	-	0.01	<0.01	<0.01
Manganese, Mn	0.39	0.11	-	2.1	0.2	0.12
Iron, Fe	0.43	0.13	-	1.5	0.25	0.17
Nickel, Ni	<0.01	0.01	-	0.008	0.01	<0.01
Copper, Cu	0.007	0.01	-	0.01	0.02	0.02
Zinc, Zn	0.007	0.03	-	0.02	0.03	0.03
Rubidium, Rb	0.008	0.008	-	0.01	0.01	0.006
Strontium, Sr	0.02	0.006	-	0.1	0.01	0.005
Zirconium, Zr	0.03	0.02	-	0.02	<0.01	<0.01
Barium, Ba	0.04	<0.01	-	0.2	<0.01	<0.01

4.4 Further Combustion Tests – Rural Energy Trust

4.4.1 *Introduction*

Following the boiler and fuel tests conducted by VTT, sufficient data was available for the LCA project to be conducted. However there was not considered to be sufficiently clear data to make recommendations in relation to the use of the tested fuels in small scale biomass heating systems. A series of further *ad hoc* tests were therefore conducted by Rural Energy Trust technical staff. Each test was designed to learn from the experience of previous tests. Tests were only conducted on the Twin Heat boiler system which was previously found to be better suited to burning grain fuels than the Thermia system.

It had become apparent that the main operational factor in determining the length of time that the heating system could operate, when using grain fuels, was the build up in the ash chamber and burner head of ash, and possibly clinker (solid ash), deposit. Grain fuels create such large quantities of ash and dust in the combustion area that the air flow gradually becomes impeded, reducing combustion efficiency and eventual loss of flame. The ash produced by grain and straw fuels tends to have a significantly lower melting point than that of wood fuels [19]. Molten ash forms clinker as it moves away from the combustion zone and cools.

In practice, the operators of biomass heating systems using grain and other combinable crop by-products as fuels are required to provide regular manual intervention to relieve the accumulation of ash and clinker. Alternatively an automatic ash removal system is available as an option on some systems (including the one used in these tests). The frequency of manual intervention that is required to maintain reasonable combustion function depends on the fuel used.

Heating systems are running at nominal output during test conditions. In practical applications, heating systems produce heat in response to demand and therefore modulate for the much of the time. At these times, fuel use and ash production fall dramatically. In practical use, therefore, manual intervention and ash removal will be required at much less frequently.

In order to examine the test fuels (wheat + limestone flour and oats) in this more practical mode, the combustion tests that were conducted at this later stage were all associated with longer test periods and, where necessary, with manual intervention to relieve the adverse effects of ash and clinker accumulation. In the case of wheat, varying levels of limestone flour were added to the fuel to examine the impact of this measure on clinker formation.

4.4.2 *Schedule of Tests*

The tests which reached worthwhile conclusions are listed in Table 9.

Table 9: Schedule of Combustion Tests and total ash formation

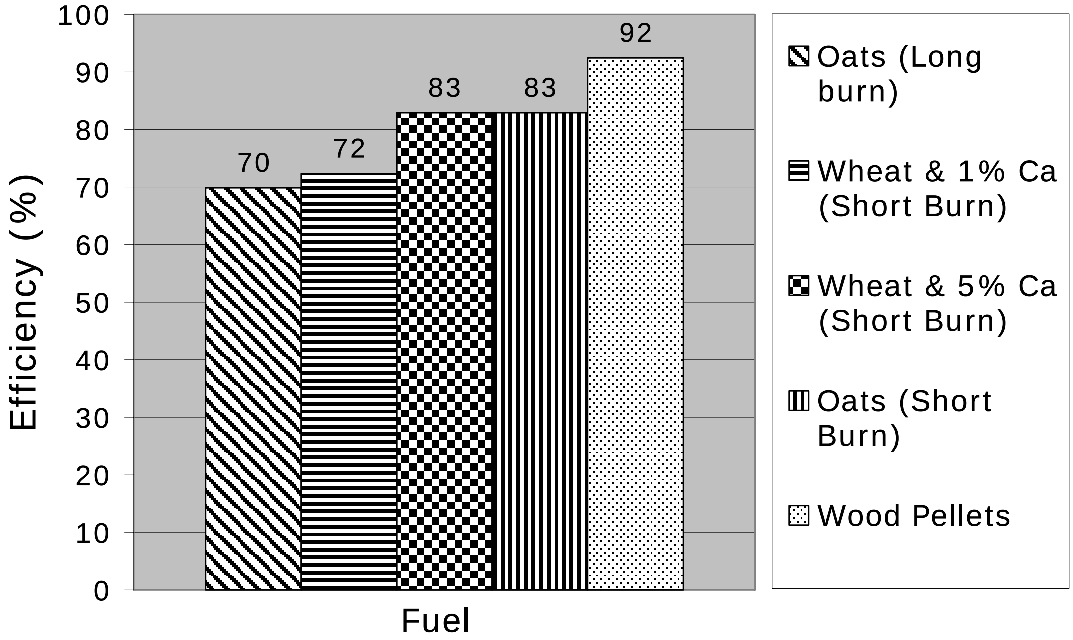
Fuel	**Test Duration (hh:mm)**	**Manual intervention to clear fuel from stoker and accumulation in boiler**	**Reason for Termination**	**Ash collected* %**
Oats (short burn)	09:00	None	End of test	3.15
Oats (long burn)	24:00	8 and 16 hours	End of test	3.36
Wheat (1% Ca)	48:00	8, 16, 24, 32 and 40 hours	End of test	4.27
Wheat (5% Ca)	37:15	8, 16, 24, 32 hours	Ran out of fuel	7.20
Wood Pellets	24:00	None	End of test	1.04

* Ash collected in the ash pan as a percentage of the dry matter weight of fuel

4.4.3 *Results*

Combustion efficiencies are shown in Figure 5

Figure 5: Boiler efficiencies for biomass test fuels



The test fuel, wood pellets were the most efficient fuel with a combustion efficiency of 92%. An indicator of this efficiency is the level of carbon monoxide (CO) produced during combustion. A low level of this emission shows complete oxidation of carbon, as in equation (3), and a high level shows incomplete combustion as in equation (4)

$$C + O_2 = CO_2 \qquad (3)$$

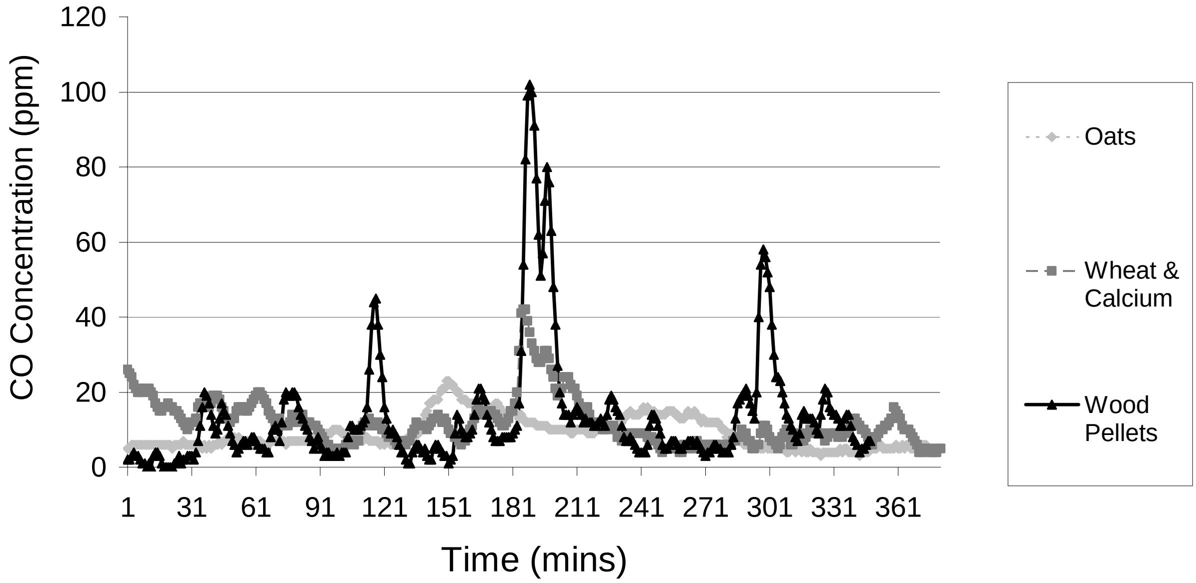
$$2C + O2 = 2CO \qquad (4)$$

The levels of CO recorded during the first 6 hours of the tests are shown in Figure 6. These data show the generally lower level of CO emission during wood pellet combustion, but there are a number of 'spikes' of higher CO production. The reasons for these spikes are unknown, but may be associated with momentary fuel variation, air flow variation or ash build up

Oats achieved a relatively high level of efficiency of 83% during the short burn period of 9 hours. This level of efficiency dropped to 70% for the long burn period of 24 hours. It is certain that combustion efficiency of oats would be even higher than 83% during the first few hours of a test, when the combustion system is clean and airflow is perfect. The operation of the heating system for this fuel therefore becomes increasingly unsatisfactory. Although manual intervention, whilst combustion continues, can alleviate this decline; eventually the system will need to be extinguished and thoroughly cleaned before a reasonable level of efficiency can be achieved

Wheat with the addition of 5%, by weight, of limestone flour, was able to achieve an efficiency of 83% over a long burn of 48 hours. Five separate manual interventions were necessary during this time to release ash accumulation in the stoker and to move ash to the back of the ash pan to prevent obstruction of the stoker.

Figure 6: Comparison of CO Emissions for different fuels over a 6 hour combustion period

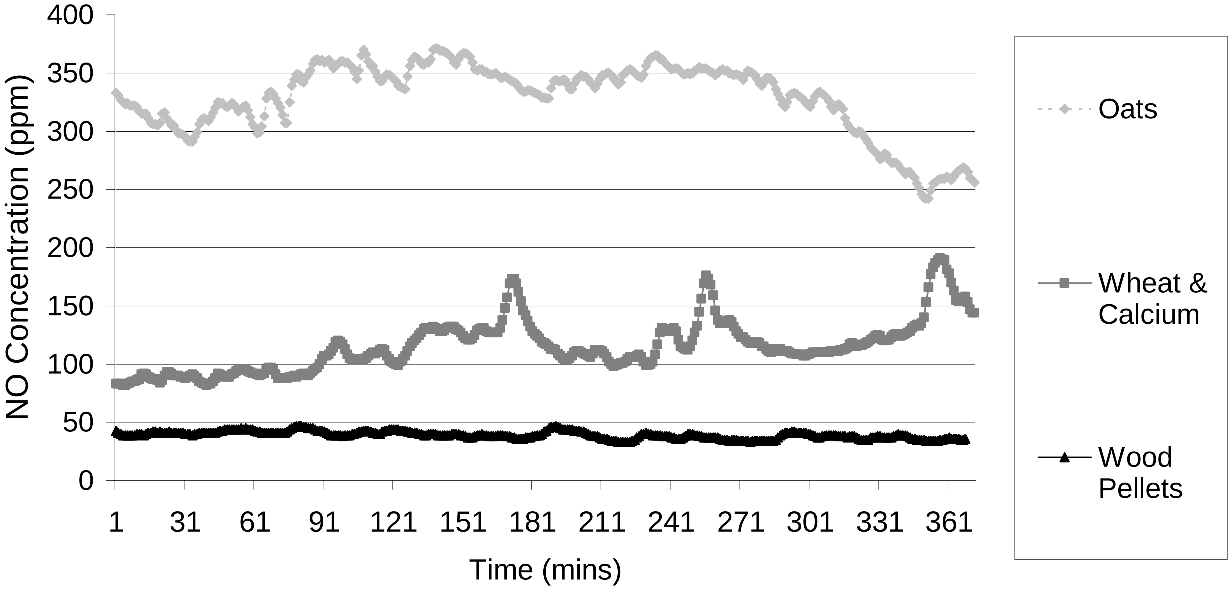


This 5% level of limestone addition resulted in free flowing ash characteristics and clearly allowed combustion to continue relatively unobstructed. However, the inside of the boiler and heat exchanger tubes became seriously coated with dust and ash, during this test.

Wheat fuel with the addition of 1% limestone flour was not able to maintain combustion efficiency at the same level over a similar period and fell to 72%, even with manual interventions. However this smaller level of limestone produced much improved results compared to the results of combustion of wheat alone as determined in the initial fuel suitability tests.

Figure 7 shows the recorded NO emissions during the first six hour period for the three fuels. NO emissions are clearly and consistently higher for wheat and oats than for wood pellets. These findings support the data

Figure 7: Comparison of NO Emissions for different fuels over a 6 hour combustion period



shown in Table 5. Since there are no statutory limits on NOx emissions for this equipment in the UK or under the test standard EN 305-3, this has limited immediate significance. However, since NOx emissions have a significantly impacts as a greenhouse gases, it is likely that this effect will become increasingly important.

4.4.4 *Ash residues*

The ash residues collected during these tests were shown in Table 7. The ash measured was confined to that quantity collected from the ash pan and did not include ash and dust deposited on the sides of the boiler and in the heat exchangers. The later deposits were observed to be significantly higher for cereal fuels than for wood pellets and even higher for wheat with limestone added. The quantity and the nature of ash produced by the cereal fuels is clearly a very significant challenge factor in the combustion of cereals in heating systems designed for wood fuels.

The elemental composition of the bottom ash, produced in these tests and also the ash produced in a test with rape meal pellets, is shown in Table 10

Table 10: Elemental Composition of Bottom Ash (TES Laboratory, Brentby using IPCASH Method

Composition % m/m as analysed

Elemental Oxide	Wheat Only	Wheat + Limestone Flour	Oats	Rape meal pellets (Used in earlier tests)	Wood Pellets (Results taken from Table 6)
SiO_2	10.1	2.0	39.3	2.2	1.1
Al_2O_3	0.3	0.1	0.3	0.5	0.2
Fe_2O_3	4.7	0.4	0.7	0.6	1.5
TiO_2	0.1	<0.1	<0.1	<0.1	<0.1
CaO	5.7	27.6	4.2	29.1	15.0
MgO	11.3	5.1	6.9	7.8	2.5
Na_2O	0.3	0.2	0.4	0.3	0.5
K_2O	27.4	22.4	21.3	19.9	4.6
Mn_3O_4	0.8	0.3	0.1	0.5	2.1
P_2O_5	38.7	39.9	27.0	33.2	1.2
SO_3	3.1	2.7	0.5	1.8	0.3
Total	**102.5**	**100.8**	**100.8**	**96.0**	**29.0**

The level of potash (K_2O) is 4 times greater in combusted oats and 6 times greater in wheat than in wood pellets. Similarly, the level of phosphate (P_2O_5) is 22 times greater in oats and 32 times greater in wheat than in wood pellets and it is thought that these high mineral levels in grains are part of reason for low ash meting point and consequent clinker formation [23].

Potash and phosphate levels in rape meal are similar to those in wheat and oats.

Sulphur ($S0_3$) levels in wheat ash are between 6 and 10 times greater than the levels in wood pellets and oats. This may be linked with the much higher sulphur dioxide emissions from wheat in the tests reported in Table 5.

4.5 Case Studies of some existing heating systems using grain fuels in Sweden, Finland, Denmark, Germany and Luxembourg.

Table 11 summarises the 11 biomass boiler systems that were visited during the case study visits in Sweden, Finland, Denmark, Germany and Luxembourg.

Table 11: **Observational data collected from case study grain fuelled boiler systems**

Location	Capacity (kW)	Heat Application	Fuel	Stoker or Grate type	Fuel storage and feed mechanism	Ash removal	Comments
Sweden Ormestad S1	20-30	Rural Domestic	Oats	Step grate	Large fuel store, intermediate hopper & inclined auger	Automatic de-ashing screw	Operated by owners living on site. Fuel type may vary depending on price and availability
Sweden Rosavei S2	20-30	Rural Domestic	Oats (fairly dusty)	Step grate	Large fuel store, intermediate hopper & inclined auger	Automatic de-ashing screw	Operated by owners living on site. Fuel type may vary. High ash deposition in boiler and chamber
Sweden Mosas S3	20-30	Rural Domestic & Barn Heating	Oats (& Wheat)	Step grate	Large fuel store, intermediate hopper & Inclined auger	Automatic de-ashing screw	Operated by owners living on site. Fuel type may vary depending on price and availability.
Sweden Ostansio S4	150	School - District Heating	Oats (low quality, very dusty)	Step grate	Removable container fuel store, horizontal auger then second inclined auger delivering fuel into a drop cell connected to boiler auger.	Large de-ashing screw and ash box	Cyclone fitted to flue to reduce particulate emissions. Operated by an engineer on a call-out basis. High ash deposition on internal boiler surfaces and in combustion chamber
Luxembourg L1	50	Farm House and Barn – 500m^2	Wheat husk pellets. Wheat had been used. Current fuel very dusty	Horizontal plate moving grate	Manually fed into a top loading hopper, located at the rear of the boiler. Fuel was delivered from the hopper via an auger into the combustion chamber, the pellets dropped directly onto the main combustion grate.	A de-ashing auger removed clinker and ash from the fire bed into an ash box	20m long flue. Primary air blown through air holes in fire bed floor. Secondary air in above fire bed to add turbulence. Moving grate, connected to fuel feed motor, moved ash out of fire bed. Large amounts of ash.
Luxembourg L2	20-30	Farm House, dairy heating equipment & 3 small barns	Waste straw & grain (high dust content)	Step moving grate	Externally sited metal hopper with capacity 2-3m^3 Filled from tractor and loader arrangement. Screw feed to boiler	De-ashing screw to a separate ash box	Primary air delivered under the grate and secondary air above the fire bed. There was an induced draught fan on the flue. Very heavy deposits (10-20mm thick) in flue.

Location	Capacity (kW)	Heat Application	Fuel	Stoker or Grate type	Fuel delivery	Ash removal	Comments
Germany G1	20	Rural domestic house and apartments	Triticale & 2-3% limestone powder	Triangular rotating cone in hearth to break clinker.	Large fuel store above boiler, intermediate boiler hopper and auger screw delivering fuel into combustion chamber.	Manual ash removal from combustion chamber twice a day with weekly clean of the heat exchanger.	Primary and secondary air blown by fans through air holes in chamber. Triangular rotating cone in the combustion chamber prevented build up of clinker and ash.
Denmark D1	35	Farm house and offices	Barley	Stoker burner	Large fuel store in loft above boiler; intermediate boiler hopper (700lit) filled by gravity feed through pipe. Auger screw delivering fuel into combustion chamber.	Manual ash removal from base of boiler, every few days	Operated by owner for 11 years. Stoker tube liner has been replaced at approximately 5 year intervals
Finland 1 Niinilahti	150	Grain dryer, farm house, and workshop	Waste grain and screenings from grain	Stoker with part moving gate and water cooled burner head	Fuel feed from an outside grain hopper	Auto ash removal with auger screw feed into ash box, which can be lifted mechanically for emptying	No issues with burn-back or loss of flame as result of low heat load. Water to air heat exchanger for grain dryer. Heating system equipment cost of €25,000
Finland 2 Lehtimäki	120/180	Shop, house and grain dryer at farm and farming retail business, producing seed and drying grain.	Screening fractions of oats, barley and rye produced by seed production enterprise	Stoker burner	Customised containerised heating system with integral fuel hopper. Lifting roof to allow filling with loading bucket.	Automatic ash removal by screw feed into 1m^3 ashbin	Ash spread on fields three times per annum. Heating system equipment cost of €32,000
Finland 3 Lapua	150	Grain dryer, house and workshop	Grain screenings and saleable grain at certain times	Stoker burner	External fuel hopper filled by tractor bucket. Auger screw feed to stoker	Automatic ash removal with auger screw to outside container	Heating system capital costs €40,000

There were a number of common features identified in the case studies:

1. The heating systems were relatively low nominal output (20-150 kW)

2. Ten out of eleven of the case studies involved heating systems on farms and produced heat for a combination of domestic, office and grain drying uses.

3. In all cases there was the expectancy that daily or very regular attention was required to operate the system and most of this attention involved manual and relatively dusty work.

4. The common ethos was that the systems could burn a range of fuels and usually waste or by-product materials available at low cost. Fuels were often used on an ‘as available’ basis.

5. Most of the systems involved automatic ash removal to a large receptacle and a grate technology which moved the ash as it cooled so as to reduce clinker formation. However, there was evidence of regular cleaning and maintenance; typically, the owner would perform a weekly clean of the combustion chamber and heat exchanger surfaces, taking 20-30 minutes, although in one of the boilers (G1) the ash was manually cleared out twice a day. Where lower quality cereal fuels were being burnt the cleaning requirements may have been greater. In addition to frequent cleaning there was evidence that settings on the boilers were adjusted regularly to take into account different fuel types or quality.

6. There was awareness that emissions levels were probably higher than with wood systems and that heating system and flue life expectancy may be reduced by the combustions of the high ash fuels.

7. Oats appeared to produce a significantly greater volume of ash than what. The ‘cereal waste’ fuels which were very dusty and contaminated with straw and other seeds, appeared to produce very large volumes of ash

8. There appeared to be a reasonable level of satisfaction amongst users and they believed that their heating systems provided a reasonable balance between low heating costs and the operational demands of system operation.

5 ECONOMICS AND SCOPE FOR COMBINABLE CROP BIOMASS FUELS

5.1 Fuel economics

The attraction of a heating fuel would depend on a number of factors:

- The potential energy contained in the fuel (calorific value)
- The percentage of this energy that can be extracted and reclaimed as heat (efficiency of the heating system)
- The unit cost of the fuel relative to other fuels
- The relative operating cost of the heating system in terms of depreciation and running costs.
- The ease and convenience factors associated with the operation of the system and its fuel

5.2 Calorific values and the cost of fuels

Calorific values from a number of sources [24][25][26][27][28][29][30] are summarised in Table 12 along with some current and anticipated fuel unit costs.

Table 12: Calorific values and costs of a range of heating fuels

	Gross Calorific Value (dry) MJ/kg	Typical Moisture Content	Net Calorific Value (GJ/tonne)	Net Calorific Value (MWh/tonne)	Unit price (£/tonne) Sept 2007	Unit price (£/tonne) Forward price Sept 2008	Energy Cost (pence/kWh)
Wheat	17	15%	14.1	3.92	185		4.73
Wheat	17	15%	14.1	3.92		130	3.32
Barley	17.5	15%	14.5	4.03	178		4.41
Barley	17.5	15%	14.5	4.03		125	3.10
Oats	18	15%	14.9	4.15	180		4.34
Oats	18	15%	14.9	4.15		125	3.01
OSR	26.5	8%	24.2	6.72	230		3.42
OSR	26.5	8%	24.2	6.72		180	2.68
Straw (Wheat/barley)	17.5	15%	14.5	4.03	40		0.99
Miscanthus	17	18%	13.5	3.75	50		1.33
Wood Chips	19	30%	12.6	3.49	60		1.72
Recycled Wood Chips	19	20%	14.7	4.09	30		0.73
Wood Pellets	19	10%	16.9	4.69	130		2.77
Heating Oil *	45.2	0%	45.2	12.1	408		3.38
Gas Oil**	45.6	0%	45.6	12.7	382		3.02

** Kerosene (28sec) oil; price based on 35p/litre*
***Red Diesel (35 sec) oil; price based on 37.5p/litre*

The net calorific values[1] (NCV) of cereals and straw are similar and have a value of around 4 MW/tonne. Wood pellets from white sawdust sources have a NCV 17% higher. Whole rape seed has a much higher NCV due to the high level of oil.

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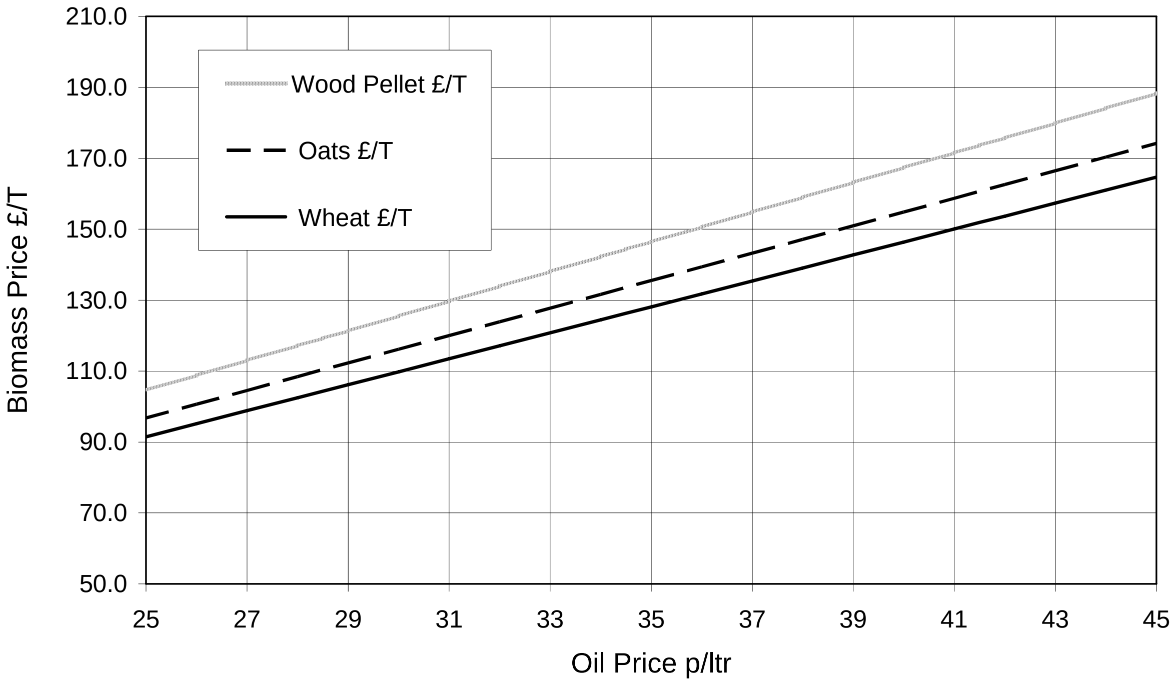
[1] Net calorific value is the quantity of heat liberated by complete combustion of a unit of fuel when the water vapour is assumed to remain as vapour and the heat is not recovered.

Table 12 also shows the computed energy cost of the fuels (p/kW hour) based on current fuel prices, and in the case of cereals, on current and forward prices. At current cereal prices, cereals fuels are 43-57% higher in cost, than gas oil. However, at the considerably lower prices for cereals, indicated by September 2008 forward prices, grain would compare favourably with oil on a unit cost basis.

Figure 8 shows the equivalent fuel value of wheat, oats and wood pellet fuels compared to the cost of heating oil.

Figure 8: Equivalent fuel value of oats and wheat in relation to heating oil



5.3 Efficiency of biomass heating systems

It is clear from data reported here and elsewhere [6] [14] [15] [16] [17] that heat conversion efficiencies of 90% can be consistently achieved by biomass heating systems when using both wood pellets and grain as a fuel. These levels of efficiency compare favourably with most modern oil and gas heating appliances. The efficiency levels for grain and straw fuels fall rapidly when ash deposits obstruct the efficient operation of heating systems. The time over which this occurs will depend on the ability of the heating system to satisfactorily remove ash deposits and the degree of manual intervention which the operator considers acceptable.

5.4 Capital costs of biomass heating systems

Biomass heating systems are more expensive to purchase and install than oil and gas heating systems. [31] [32] [33]. Biomass systems can be between three and six times more expensive than their fossil fuel counterparts, depending on size, level of sophistication and the building or hopper costs associated with fuel storage and handling.

Many of the farm located heating systems reported in Table 6 had been acquired and installed at low cost by their owners. Capital grants were also obtained in many cases to further reduce the costs. Capital grants are available to most purchasers of biomass heating systems in the UK, available from the Energy Savings Trust under the Low Carbon Building Programme [34] and from the Department for the Environment, Food and Rural Affairs under the Bio Energy Capital Grant Scheme [35]. It is uncertain, however if they are available in cases where grain is used as the fuel. These grants could reduce the capital cost by 10-35%

5.5 Fuel production on Set-aside land and the Energy Crop Aid Scheme

Under the current set-aside regulations [36], crops with no food or animal feed use can be grown on set-aside land. Cereals and oilseed rape can be grown on set-aside for non food and feed uses and growers must have a contractor with a collector or first processor or user. Combinable crops appear not to have been grown for biomass fuel use on set-aside, to date, but with the development of a significant user and therefore a relevant contract, such arrangements are possible, under set-aside regulations.

Growers may grow combinable crops on set-aside to produce fuel for heating purposes on their own holdings [37]. This can be achieved more simply by signing a declaration to Rural Payments Agency to use the crops covered by the declaration on the holding. Cereals and oilseeds for this use can be measured by weight, on a public weighbridge, or by volumetric assessment, on the farm. In any event the produce needs to be denatured, by application of a brightly coloured dye. Such arrangements need to be approved by RPA, and application needs to state the relevant technical information relation to the heating technology to be used on the farm.

It now seems almost certain that the European Commission will adjust the set-aside rate for crops planted in autumn 2007 and spring 2008 to 0%, following a recommendation by the Agricultural Commissioner [38]. Since this change seems likely to be effective for some years to come, due to supply deficits in the world combinable crop markets, it is unlikely that biomass production on set-aside land is a consideration for growers.

An Energy Crop Aid Premium was introduced in 2003 as part of the reforms of the Common Agricultural Policy. A €45/hectare aid for energy crops was applied for the first time in 2004 to provide an incentive for growers to produce the raw materials for biofuels and biomass. The area on which this payment can be paid was capped at 1.5m hectares and the amount claimed in 2006 was just below this limit at 1.2-1.3 m hectares [39]. This limit is to be raised to 2.0m hectares and also made available to the ten new member states. At the moment this aid scheme would provide a useful addition to the rewards of growing combinable crops for biomass fuels. However, approximately half of the €45/hectare aid would be unlikely to reach the grower since this is required by supply chain intermediaries to cover their costs.

6 LIFE CYCLE ASSESSMENT OF WHEAT AND OATS AS BIOMASS HEATING FUELS.

The Life Cycle Assessment of the two grain fuels Oats and Wheat was conducted by Northern Energy Associates Ltd and is reported separately (Appendix 5).

7 DISCUSSION

7.1 Biomass Heating Technology in Europe

The development of efficient biomass heating technology in Europe has taken place over the last 50 years and has been in response to the availability of a huge forestry by-product resource and the economic demand for low cost and alternative energy sources. The main features of biomass heating technology are therefore:

1. The technology design is based on the chemistry of wood combustion, with its clean and efficient burning characteristics. Most European countries have legislation to ensure that the technology has high performance efficiency standards and very low levels of harmful emissions. European test standards are based on wood as the fuel. It has not been possible to ascertain the regulatory response in Europe to the use of grain or other crop products in small heating systems.

2. Heating systems have been developed for a wide range of applications. These range from very small domestic to very large industrial and centralised energy generation. Systems are available in highly automated or basic manual forms and sometimes with some flexibility on the type of fuel which can be used.

3. There are several hundreds of manufacturer's of biomass heating systems across Europe. Many are quite small companies, perhaps manufacturing a few hundred units annually. There are a few large producers who manufacture many thousands of units annually. Most companies tend to specialise either in a sector of the market or in a type of application

The development of cereal grain as biomass fuel has been motivated by two factors: the low prices received by farmers for cereals over the last 10 years and the annual availability of small amounts of low value screenings or damaged grain. Since most farmers and remote rural residents in Denmark and Sweden have small biomass heating systems to heat their domestic and business premises, it has been a natural progression to attempt to use grain as a fuel.

The initial review of biomass heating technology and available expertise in burning grain clearly demonstrated that the practice is not widespread in Europe, apart from farm and some other rural applications. There was only limited information available about suitable biomass boilers and it was very difficult to get reliable information relating to burning grain. In general the biomass boiler suppliers in the UK were not particularly forthcoming with information and this must be assumed to be lack of experience. Boiler manufacturers and suppliers were more helpful in other European countries but it was clear that the practice of burning grain was limited. Most manufactures expressed the view that grain is an inappropriate fuel for their systems due to high ash, high emission levels and corrosive side effects. A few manufacturers have responded to farmer demand for guidance in this area and have developed their system designs to accommodate or partly accommodate the challenges of cereal grain as a biomass fuel.

Within the scope of this project it was possible to gather information on the products of three Danish biomass system manufacturers who have developed their products in response to the demand from farmers to use grain as a fuel. In each case the product development has enabled the system to cope much more adequately with combustion problems created by the grain fuel, but not to the extent that the problems are completely mitigated. Although these manufacturers may not be the only producers of adapted systems for grain, they serve to show some of the developments which have occurred:

- Twin Heat has manufactured biomass heating systems for 26 years and their systems have been used by some clients for burning grain for at least 12 years. Systems with outputs between 12-80kW are available. The systems all have a stoker burner combustion system. The stoker has been reduced in length to allow the large volume of ash to escape and fall into the ash pan more easily. In anticipation of some corrosion at the burner head, the stoker has a stainless steel liner that is replaceable at low cost. An automatic ash removal system is available to allow large amounts of ash to be cleared. The digital control system has a preset array of parameters suitable for the combustion of wood pellets, wood chip and grain. These include the fuel feed rate, air flow and the oxygen lambda control levels. The company believes that approximately 40% of their systems are used to burn grain for part of the year at least.

- Faust Maskinfabrikken ApS has manufactured biomass heating systems for 25 years and has developed a stoker burner head over recent years to deal with the large amounts of ash produced by grain and to eliminate the clinker that tends to form with high ash fuels. The base of the stoker consists of three steps, which move at set intervals. This movement moves the ash forward and into the ash box and also prevents the formation of clinker by constantly moving the ash as it solidifies from a molten state. Automatic ash removal is available to avoid regular manual removal from the ash pan.

- REKA Maskinfabrikken A/S has manufactured biomass heating systems for 29 years and has developed a system suitable for grain and other high ash biomass fuels. The boiler contains a moving step grate which both moves ash forward out of the combustion zone and avoids clinker formation by regular movement of the ash. An automatic ash removal system allows ash to be moved from the base of the grate, without manual intervention. Clinker production is further avoided by a reduced input of primary air that keeps the combustion temperature lower than the melting point of the ash. There is some evidence that this boiler supports a lower combustion temperature on the hearth, thus reducing clinker formation further. Operators of this equipment in Sweden reported that experience and skill was required to reset the heating system when the fuel quality changed significantly.

7.2 Combinable crop fuels

The immediate attractions of cereal grains as biomass fuels are their physical characteristics. Grain has excellent flow characteristics, a high bulk density and exists in small enough particles to burn without any processing. Grain has similar flow characteristics to wood pellets but has dramatically better characteristics than wood chip and the other range of cheaper biomass fuels. The density of cereal grains (See Table 5) is similar or greater than wood pellets and up to five times denser than wood chip [40]. Grain therefore requires relatively small fuel storage receptacles and can to flow into the combustion chamber by gravity, aided by simple feed screw systems.

Many small domestic biomass systems are configured with a small manual-fill fuel store. This fuel container may require daily filling when low density wood chips are used. The use of wood pellets or cereal may reduce filling frequency to once every 4-5 days; a considerable saving in time. Wood pellets are considerably more expensive than wood chip and recently have been more expensive than grain. Therefore cereal grain fuels have recently had the low cost advantages of wood chip fuel, whilst possessing all the handling and storage advantages of wood pellets.

Straw presents a somewhat less attractive immediate case as a biomass fuel, since it has none of the physical advantages of grain. Straw can be made into pellets, to overcome these difficulties, but at an increase in cost of approximately £30 per tonne [41] in fuel cost.

The combustion characteristics of grain and straw present considerable challenges to most if not all of the biomass heating systems that were designed for wood fuels. These can be summarised as follows:

- Grains and straws contain very much higher residual ash contents then wood fuel; this was found to be 3-6 times the weight and volume of wood pellet ash and in the case of straw up to 6-15 times the quantity. In the case of the 'cereal waste' fuels seen on the study tour, this level of ash production may well be even higher. The dispersion of this large ash volume from the combustion chamber and the removal of the ash from the ash pan area require automatic ash removal or very regular manual removal.
- Wheat, and more particularly straw, produces significant solid ash (clinker) which can block the combustion chamber and may be difficult to remove through an automatic ash removal system. Clinker formation is thought to be due to high levels of potassium chloride and silicon dioxide in the ash, which combine to form a group of compounds, which melt at the comparatively low temperature of 700˚C [19]. Clinker can also obstruct the air inlet jets and reduce combustion efficiency as a result. Clinker formation can be reduced or eliminated by adding limestone flour to the fuel. This measure, however, significantly increases the amount of ash produced

- All high ash fuels tend to form significantly more ash and dust in suspension in the combustion gases. This causes rapid coating of the boiler walls and heat exchanger surfaces. Cleaning of these areas needs to take place regularly if heating system efficiency is to be maintained.
- It is thought likely that the flue gases produced from grain and straw fuels are more corrosive than from wood due mainly to chlorine gas and its associated compounds [42]. This may cause corrosion in the boiler and flue systems with reduction in the life expectancy of the system.
- The NOx, SO_2 and dust emission levels resulting from grain and straw fuels were found to be many times higher than the levels from wood pellets. Other reports (See Table 2) confirm these findings. Although these levels may not infringe current UK regulations, at present, this is an area for serious concern should the use of these fuels expand significantly. NOx gases have been identified as serious greenhouse gases. Sulphur dioxide has long been associated with harmful impacts on the environment and high dust levels are associated with possible human health problems.

The extent to which biomass heating systems, designed to use wood chip or wood pellets can be satisfactorily used to burn cereal grains, will depend partly on the design of the system, but largely on the willingness of the owner/operator to provide manual intervention solutions for the problems created by these fuels.

In general the use of cereal grains may be practical in rural, farming and domestic situations where fuel and combustion residues can be managed on a day to day basis. However, the difficulties associated with burning grain will certainly hinder its use as a fuel in larger scale commercial applications.

7.3 Combustion efficiency

Combustion tests on the biomass heating systems observed in this project have shown that combustion efficiencies with grain fuels can be similar to those achieved with wood pellets. Results with similar heating systems, shown in Table 2, confirm these findings and show that combustion efficiencies approaching 90% are possible for both types of fuels. These efficiencies compare favourably with manufacturer's efficiency figures for oil boilers of similar outputs range. These are quoted at 85-92% [43]. Grain fuels can be efficiently used to produce heat.

The extent that biomass heating systems can maintain a high level of efficiency whilst burning high ash fuels depends on the continued removal of high ash and dust deposits from all parts of the system. Some heating systems are designed to achieve this automatically but even these may need a significant amount of manual cleaning at intervals of a few days [44].

Grain and straw biomass heating systems need to maintain efficiencies for long periods by accommodating the high ash production, clinker formation, higher flue gas emissions and possible corrosion issues of cereal and other high ash fuels. Design of such systems may be feasible but may not then be ideal for use with wood fuel. Further investment in such developments clearly would depend on the economic attraction of grain and straw as fuels.

7.4 Flue Gas Emissions

The accreditation standard in the UK, for biomass solid fuel boilers (BS EN 303-5) [45] indicate minimum emission levels for boilers of under 300kW output. Limits are indicated for CO, OGC, dust and NOx. Modern biomass systems achieve emission levels very much lower than these standards when burning wood pellets and wood chip.

Whilst the emission levels of CO and OGC produced from grain and straw fuels are well within these limits, NOx and dust emissions levels significantly exceed the standards. This must be a cause for some concern since NOx gases are potent greenhouse gases and dust emissions at high levels can be associated with human respiratory health problems.

7.5 Blending of fuels

It is not within the scope of this project to investigate the use of fuels resulting from blending two or more component fuels together. However, the blending of grain and other high ash fuels with fuels of lower ash, such as wood pellets or wood chip offers the opportunity of a fuel compromise; reduced combustion problems and an intermediate cost of fuel.

A report published by the Danish Energy Agency [14] examines the comparative combustion of a range of biomass fuel blends. The twelve fuels evaluated are standardised in physical presentation by grinding and then pelleting each of the blends. Anti clinkering agents, such as limestone flour, are also combined with the blends to further enhance the combustion performance.

The report indicates that by adding 33% sawdust and 5% limestone to grain screenings, there was little difference in performance compared to 100% screenings with 5% limestone. There was still the requirement to clean air nozzles every few days in order to maintain reasonable boiler efficiency. Flue dust levels were reduced significantly.

The addition of 33% sawdust to straw fuel resulted in the fuel becoming useable, by dramatically reducing very heavy clinker formation with straw alone. However, the straw/sawdust blend still resulted in very heavy fouling of air nozzles and heat exchanger tubes, as well as producing unacceptable amounts of flue gas ash.

The report noted that blends did not always result in the proportional increase in performance expected from that ratio of the two component parts. Blending did not appear to offer major improvements in solving the problems surrounding high ash fuels at the blending levels used.

7.6 Economics

The interest in using grain as a heating fuel developed when grain market prices were at all time low levels, 10 years ago. At the time when wheat was priced at £60/tonne, then it had a comparative value as a fuel, compared to heating oil, of 17p/litre. At £90/tonne, wheat has a comparative value of 25p/litre, at £130/tonne a value of 36p/lit and at £170/tonne a value of 47p/lit. During the summer of 2007, heating oil prices have ranged from 34-38p/lit.

Because of the high capital costs of biomass heating systems and the challenges surrounding the operation of these heating systems when burning grain, it would require a very significant fuel saving for the practice to be popular. It would seem that the economic advantages of the practice have vanished with the era of low cereal prices and with the forecast for cereal prices to remain strong, at least in part due to other none-food used such as liquid bio-fuel production, it is difficult to envisage the practice becoming widespread.

Grain screenings represent a significant by-product on some farms and in some agricultural and food businesses. The opportunity cost of this material may continue to make it attractive as a fuel in some locations.

Straw still remains a relatively low cost fuel, although the increasing shortage of all natural resources may contribute to a continuing increase in the price of this commodity. The problems caused by large amounts of ash and high emissions, associated with the use of straw as a fuel, are a serious challenge for small boilers. These issues are almost certain to confine its use to a few large systems that can more easily use specialist plant to obviate the problems.

7.7 Life Cycle Assessment

The Life Cycle Analysis gives a good indication of the overall environmental impact of biomass fuels. It achieves this by evaluating the energy resource depletion and greenhouse gas release from the process chain of each biomass fuel.

The primary energy inputs and the CO_2 and CH_4 emissions are all similar for heating with oats, wheat and wood from short rotation coppice willow. However, the N_2O emissions associated with both cereal fuels are significantly higher than those from willow coppice wood fuel. This results mainly from the manufacture of nitrogen fertilizer and the subsequent emissions from soils during the production process.

Although there is significant net greenhouse gas reduction benefits associated with the use of grains as biomass fuels, the higher NOx emission factor is likely to be one that is seized upon by the opponents of biofuels being produced from combinable crops.

8 CONCLUSIONS

Burning cereal grains for heat generation is a feasible option for small scale applications, especially where the boiler is being operated, fuelled and maintained by an ‘on site’ owner.

Oats and wheat with calcium additives were the most promising grain fuels. The addition of limestone flour to wheat reduces clinker formation and improves the practical use of this fuel. Oilseed rape, rape meal pellets and straw pellets were unsuitable biomass fuels although they may be suitable for burning in specially developed biomass heating systems.

Combustion efficiency for oats, wheat and wheat with calcium additives were all reasonably high and within the boiler manufacturers stated efficiency range. They also compared favourably to wood pellets which was used as a ‘reference’ fuel. Levels of combustion efficiency could only be maintained for the cereal grain fuels by regular cleaning of ash and clinker and in the case of wheat, by the addition of limestone flour.

The combustion of oats and wheat is unlikely to produce CO emissions that exceed the limits set by the British Standards for small scale boilers. Currently there are no equivalent limits for NOx or SO2 emission but the Austrian limits of NOx emissions were exceeded during combustion tests with oats and wheat.

The removal of ash and clinker and the regular cleaning of air inlets and heat exchangers are a constant requirement to operate heating systems burning grain. Some heating system products have been developed to reduce the frequency of this onerous work. Automatic ash removal, step grate systems, short stoker burners and fuel choice control system options all have been shown to improve performance.

There is some evidence to suggest that the use of grain fuels can cause corrosion in the boiler, heat exchanger and flues.

The use of grain as a fuel in small combustion systems is only likely to be attractive to farmers and other owner operators who are not averse to the frequent attendance that is required to maintain the systems.

The economic attraction of grain as a fuel was considerable when wheat and oats were being sold at £60/tonne ex farm. Following the increases in the market price of grain during 2006 and 2007 it seems that a more realistic ex farm price for the medium term future might be £130/tonne. At this price, it is unlikely that grain will be an attractive fuel, unless fossil fuel and other biomass fuel costs rise ahead of grain. Grain screenings may continue to be an attractive biomass fuel due to their lower opportunity cost.

Whilst the production of grain as an industrial crop for biomass fuel and grown on set aside area might have been attractive in the past, the change of set aside level to 0% effectively removes this as an option.

Grain as a fuel has considerable environmental advantages by reducing greenhouse gas emissions. However the higher level of NOx emissions may be an adverse factor in its social acceptability for this purpose.

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