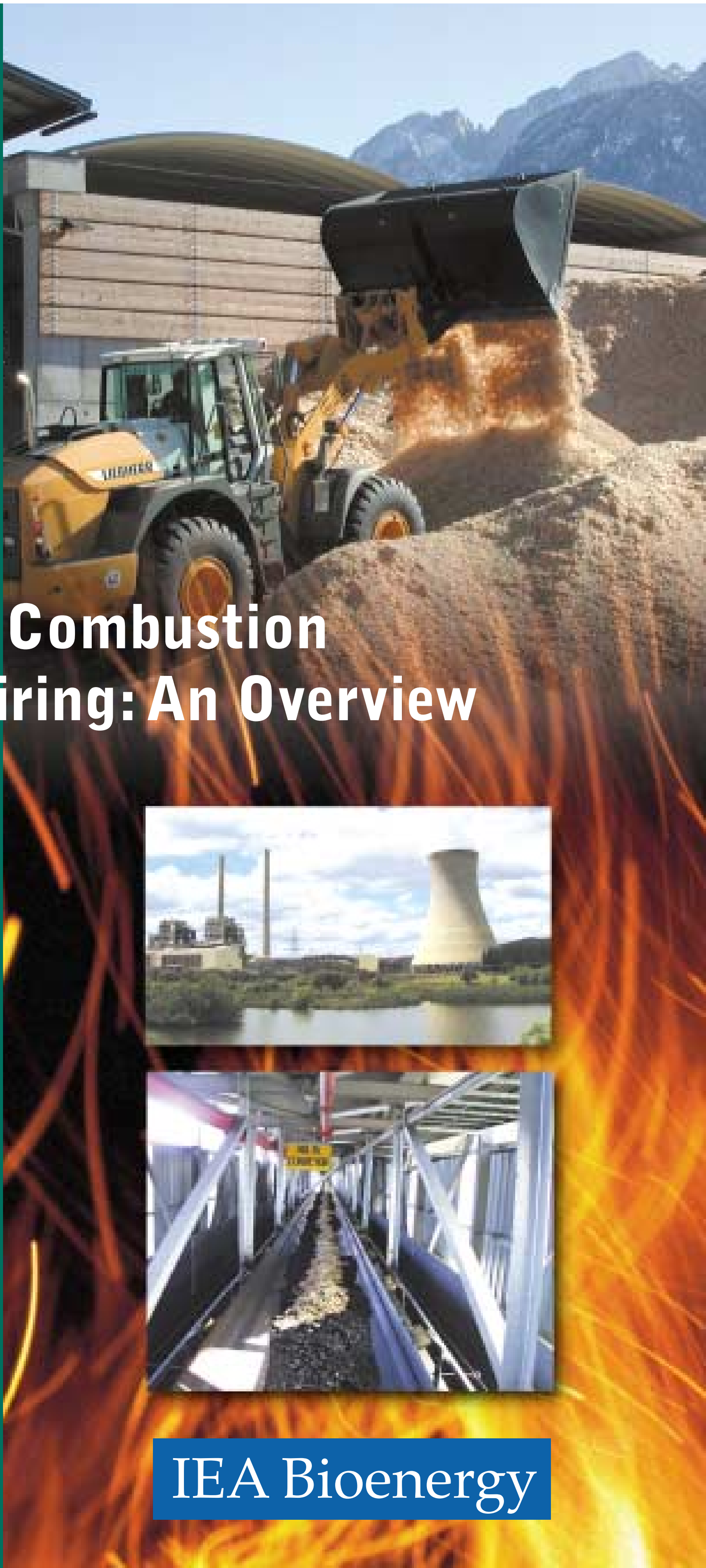
Biomass Combustion and Co-firing: An Overview



IEA Bioenergy

Biomass Combustion and Co-firing

This overview was prepared by Task 32 on the basis of the collective information and experience of members of the Task. It describes some of the major issues involved in biomass combustion and co-firing technologies for both domestic and industrial use.

Introduction

Worldwide, interest in using biomass for energy is increasing because of:

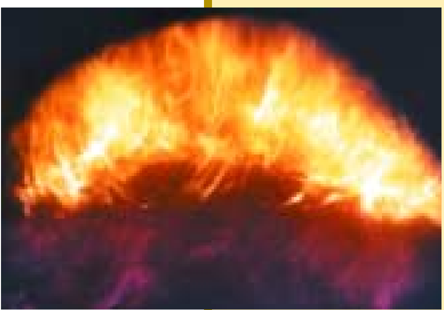
- Political benefits - e.g. reduced dependency on imported oil;
- Employment creation - biomass fuels create up to 20 times more employment than coal and oil;
- Environmental benefits such as mitigation of greenhouse gas emissions, reduction of acid rain, and soil improvement.

Many countries have abundant resources of unused biomass readily available, e.g. sawdust.

Already, around 12% of the global energy required is generated by combustion of biomass fuels, which vary from wood to animal by-products and black liquor. A wide variety of appliances is used to convert this biomass into useful energy.

In developing countries, around 35% of the energy used originates from biomass, but most of this is for non-commercial use in traditional applications (such as cooking). In a country such as Nepal, over 90% of the primary energy is produced from traditional biomass fuels.

A view inside a step grate boiler. (Courtesy of TNO, The Netherlands)



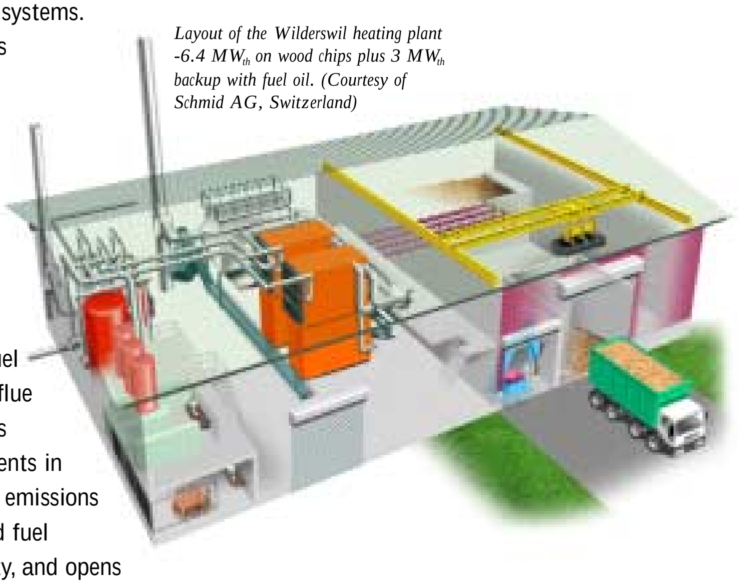
In industrialised countries, the total contribution of biomass to the primary energy mix is only 3%. This mainly involves the combustion of commercial biomass fuels in modern devices - for example, woodchip-fired co-generation plants for heat and power. Other applications are domestic space heating and cooking, industrial heat supply, and large-scale power generation in coal-fired plants.

Combustion is the most common way of converting solid biomass fuels to energy. It is well understood, relatively straightforward, and commercially available, and can be regarded as a proven technology. However, the desire to burn uncommon fuels, improve efficiencies, reduce costs, and decrease emission levels continuously results in improved technologies being developed.

Types of applications

The selection and design of any biomass combustion system are determined mainly by the characteristics of the fuel to be used, existing environmental legislation, the costs and performance of the equipment available, as well as the energy and capacity needed (heat, electricity). Due to economy of scale effects concerning the fuel feeding system, the combustion technology, and the flue gas cleaning system, usually large-scale systems use low-quality fuels, while high-quality fuels are typically used for small-scale systems. Therefore, large-scale biomass combustion technologies are often similar to waste combustion systems, but when clean biomass fuels are utilised, the flue gas cleaning technologies are less complex and therefore cheaper. Improvements are continuously being made in fuel preparation, combustion and flue gas cleaning technologies. This leads to significant improvements in efficiencies, and reductions in emissions and costs, as well as improved fuel flexibility and plant availability, and opens new opportunities for biomass combustion applications under conditions that were too expensive or inadequate before.

Layout of the Wilderswil heating plant -6.4 MW_{th} on wood chips plus 3 MW_{th} backup with fuel oil. (Courtesy of Schmid AG, Switzerland)

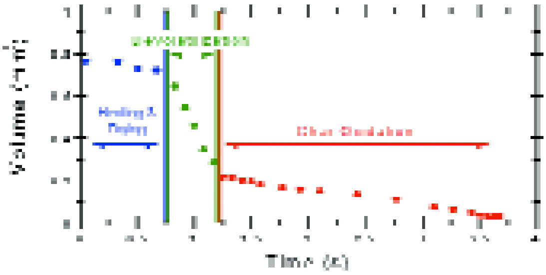


For any biomass combustion application, emission reduction and efficiency improvement are major goals. The results of research projects and experiences of demonstration plants in one country can have a strong impact on other countries as well, and here the IEA collaboration plays an important role in information exchange.

Basic principles of biomass combustion

Biomass can be converted into energy (heat or electricity) or energy carriers (charcoal, oil, or gas) using both thermochemical and biochemical conversion technologies. Combustion is the most developed and most frequently applied process used for solid biomass fuels because of its low costs and high reliability. However, combustion technologies deserve continuous attention from developers in order to remain competitive with the other options.

During combustion, the biomass first loses its moisture at temperatures up to 100°C, using heat from other particles that release their heat value. As the dried particle heats up, volatile gases containing hydrocarbons, CO, CH_4 and other gaseous components are released. In a combustion process, these gases contribute about 70% of the heating value of the biomass. Finally, char oxidises and ash remains.



Distinct stages in the process of combustion of a particle: heating and drying, devolatilization and char oxidation.

The combustion installation needs to be properly designed for a specific fuel type in order to guarantee adequate combustion quality and low emissions. Emissions caused by incomplete combustion are usually a result of either:

Wood chip combustion on a grate furnace. Fuel enters the furnace at the right hand side and devolatilizes as it is transported to the left. At the left hand side, remaining char burns out.

- poor mixing of combustion air and fuel in the combustion chamber, giving local fuel-rich combustion zones
- an overall lack of available oxygen
- combustion temperatures that are too low
- residence times that are too short
- radical concentrations that are too low

Through experiments and modelling, new boiler geometries and combustion concepts have been developed that result in significantly lower emissions. Examples of such developments are reburning of fuel, air staging, air preheating, radiation shields, advanced combustion control systems, application of novel materials, etc. Task 32 aims to be instrumental in the exchange of information in these areas.

Biomass fuels available

The characteristics and quality of biomass as a fuel depend on the kind of biomass and the pre-treatment technologies applied. For example, the moisture content of the fuel as fed into the furnace may vary from 25 - 55% (on a wet weight basis) for bark and sawmill by-products, and be less than 10% (on a wet weight basis) for pellets. Also, the ash sintering temperatures of biofuels used cover a wide range (800 to 1200°C), as do particle shapes and sizes. Fuel quality can be improved by suitable pre-treatment technologies, but this increases costs.

Different combustion technologies are available to deal with various fuel qualities - less homogeneous and low-quality fuels need more sophisticated combustion systems. Therefore, and for 'economy of scale' reasons, only medium and large-scale systems are suitable for low-quality and cheap biofuels. The smaller the combustion plant, the greater the need for fuel quality and homogeneity.

A mobile chipper with crane efficiently collects roadside thinnings for fuel. (Courtesy of Bruins and Kwast, Netherlands)

The chemical fuel composition has a direct influence on combustion characteristics, i.e. energy content, ash deposition, emissions, corrosion mechanisms, as well as ash behaviour inside a boiler. It is therefore important to know probable variations in chemical fuel composition. A database on the chemical compositions of fuels, ash and condensates has been prepared by Task 32. This can be accessed through the internet.

Clean and dry woodpellets are an ideal fuel for combustion in small-scale installations.

Supply and pre-treatment

Several types of pre-treatment are being applied in practice to lower handling, storage, and transportation costs, and to reduce the need to invest in very complex, robust, and expensive combustion installations. For example, wood waste from northern Sweden is first pelletised, before it is transported to combustion installations in the south of the country. Common pretreatment options are size reduction, compacting, drying, and washing.

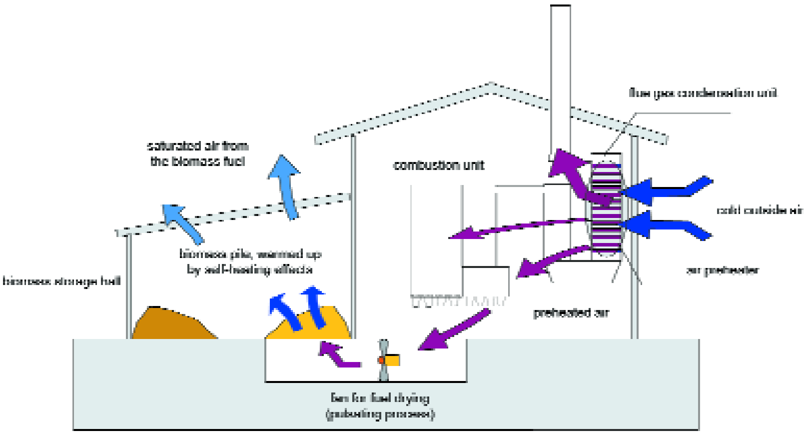
Wheel loaders are often used for transporting sawdust and bark from the long-term storage to the feeding system of the biomass heating plant. (Courtesy of Stadtwärme Lienz, Austria)

In order to reduce its moisture content, freshly harvested wood is often left outside for a number of weeks before it is chipped and fed to a combustion plant.

Herbaceous species such as grain straw are often left in the field and exposed to weather conditions to reduce the alkali and chlorine contents. In this way, combustion problems related to corrosion and sintering are reduced. Further fuel drying may be feasible if natural heating sources (e.g. solar energy) or waste heat from the combustion plant (e.g. from flue gas condensation units) are available.

Solid biofuels are increasingly 'tailored' to the respective application process, using new upgrading methods or technologies. These can either be applied during or immediately after field production (e.g. leaching by rainfall or irrigation), or in a preparatory process prior to use (e.g. stationary leaching, use of additives, compaction). The need for such pretreatment steps depends on transportation distances, fuel prices, size of the plant, fuel-feeding mechanism applied, combustion and heat recovery technology applied, materials used, etc.

With the growing market for bioenergy systems, analysing and improving fuel properties becomes increasingly important. This even extends to plant breeding and variety/clone selection. Genetic engineering, although still controversial could open up new opportunities for yield and quality improvement of biofuels.



Schematic diagram of the principle of a short-term biomass drying process based on pre-heated air from a flue gas condensation unit.

Small-scale appliances for space heating

Wood fires have been used as a local heat source for thousands of years, progressing from open pit to semi-open pit (a fireplace) to enclosed pit (a stove).

The interest in using wood for heating purposes is increasing. Besides heating, wood-burning appliances are also used for cooking, for producing a pleasant atmosphere, and for interior decoration. Domestic wood-burning appliances include fireplaces, fireplace inserts, heat storing stoves, pellet stoves and burners, central heating furnaces and boilers for wood logs and wood chips, and different kinds of automatic wood chip and pellet appliances.

Over-fire boilers are commonly used to burn logs and are relatively inexpensive. In such systems, a fuel batch is placed on a grate and the whole batch burns at the same time. The stove or boiler is normally equipped with a primary air inlet under the grate and a secondary air inlet above the fuel batch, into the gas combustion zone. Wood is fed from above and ashes are removed from a door below the grate. These boilers work on the principle of natural draught and, as the fuel bed is cooled by fresh fuel, the initial CO emissions can be relatively high.

A microprocessor controlled woodlog stove with downdraught combustion and separate chamber where secondary combustion takes place. (Courtesy of Fröling, Austria)

Very strict emission limits in some countries have made it necessary to introduce down-draught burners. Here, unburned wood gases released by wood placed on a ceramic grate are forced by a fan to flow downward through holes in the grate. Air is introduced below the grate in the secondary combustion chamber, where the gases flow along ceramic tunnels, and final combustion takes place at high temperatures. By using lambda control probes to measure and control flue gas oxygen concentration, staged air combustion, and even fuzzy-logic control, very low emissions are achieved. Naturally, down-draught boilers are much more expensive than conventional boilers.

A recent innovation in space heating is automatic pellet combustion. The excellent handling properties of pellets mean that the fuel is gaining popularity rapidly in Sweden, Denmark, and Austria. In other countries, the interest in pellet burners is starting to increase. Pellet burners are of special interest since they can replace an oil burner in an existing oil-fired boiler.

Two wood pellet boilers, used to heat a school in Denmark

If the burner-boiler combination is well designed, efficiencies over 90% can be achieved at nominal thermal output. At part load, and varying load, the efficiency decreases but for the best burners efficiencies over 86% have been obtained.

Large-scale combustion

Different biomass combustion systems are available for industrial purposes. Broadly, they can be defined as fixed-bed combustion, fluidised bed combustion, and dust combustion.

Fixed-bed combustion

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, where drying, gasification, and charcoal combustion take place in consecutive stages. The combustible gases are burned in a separate combustion zone using secondary air.

Two 3.2 MW_{th} grate furnaces for wood chips, used for disctrict heating in Interlaken, Switzerland. (Courtesy of Schmid AG, Switzerland)

Grate furnaces are appropriate for burning biomass fuels with high moisture content, different particle sizes, and high ash content. Usually, the capacity goes up to around 20 MW_{th}. Mixtures of wood fuels can be used but straw, cereals, and grasses may cause problems due to their different combustion behaviour, their low moisture content, and their low ash melting point. The grate and walls can be water-cooled to avoid slagging problems.

The design and control of the grate are aimed at guaranteeing smooth transportation and even distribution of the fuel and a homogeneous primary air supply over the whole grate surface. Irregular air supply may cause slagging, and higher amounts of fly ash, and may increase the oxygen needed for complete combustion.

Underfeed stokers represent a cheap safe technology for small- and medium-scale systems up to about 6 MW_{th}. The fuel is fed into the combustion chamber by screw conveyors from below and is transported upwards on a grate. Underfeed stokers are suitable for biomass fuels with low ash content (wood chips, sawdust, pellets) and small particle sizes (up to 50 mm). Underfeed stokers have a good partial load behaviour and simple load control. Load changes can be achieved more easily and quickly than in grate furnaces because there is better control of the fuel supply.

Fluidised bed combustion

In a fluidised bed, biomass fuel is burned in a self-mixing suspension of gas and solid bed material (usually silica sand and dolomite) in which air for combustion enters from below. Depending on the fluidisation velocity, bubbling and circulating fluidised bed combustion can be distinguished.

The intense heat transfer and mixing provide good conditions for complete combustion with low excess air demand. Using internal heat exchanger surfaces, flue gas re-circulation, or water injection, a relatively low combustion temperature is maintained in order to prevent ash sintering in the bed.

Due to the good mixing achieved, fuel flexibility is high, although attention must be paid to particle size and impurities contained in the fuel. Fluid bed combustion plants usually operate at full load.

A 25 MW_e woodchip fired power plant in Cujk, The Netherlands with Bubbling Fluidised Bed (BFB) boiler.

Low NO_x emissions can be achieved by good air-staging, good mixing, and a low requirement for excess air. Moreover, additives (e.g. limestone for sulphur removal) work well due to the good mixing conditions. The low excess air amounts required reduce the flue gas volume flow and increase combustion efficiency. Fluid bed combustion plants are of special interest for large-scale applications (normally exceeding 30 MW_{th}). For smaller plants, fixed bed systems are usually more cost-effective. One disadvantage is the high dust loads in the flue gas, which make efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new bed material.

Dust combustion

Dust combustion is suitable for fuels available as small, dry particles such as wood dust. A mixture of fuel and primary combustion air is injected into the combustion chamber. Combustion takes place while the fuel is in suspension; the transportation air is used as primary air. Gas burnout is achieved after secondary air addition. An auxiliary burner is used to start the furnace. When the combustion temperature reaches a certain value, biomass injection starts and the auxiliary burner is shut down. Due to the explosion-like gasification process of the biomass particles, careful fuel feeding is essential.

Fuel/air mixtures are usually injected tangentially into a cylindrical furnace to establish a rotational vortex flow. This motion can be supported by flue gas re-circulation in the combustion chamber. Due to the high energy density at the furnace walls and the high combustion temperature, the muffle (cylindrical furnace) should be water-cooled. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and efficient load control can be achieved. Since the fuel and air are well-mixed, only a small amount of excess air is required. This results in high combustion efficiencies.

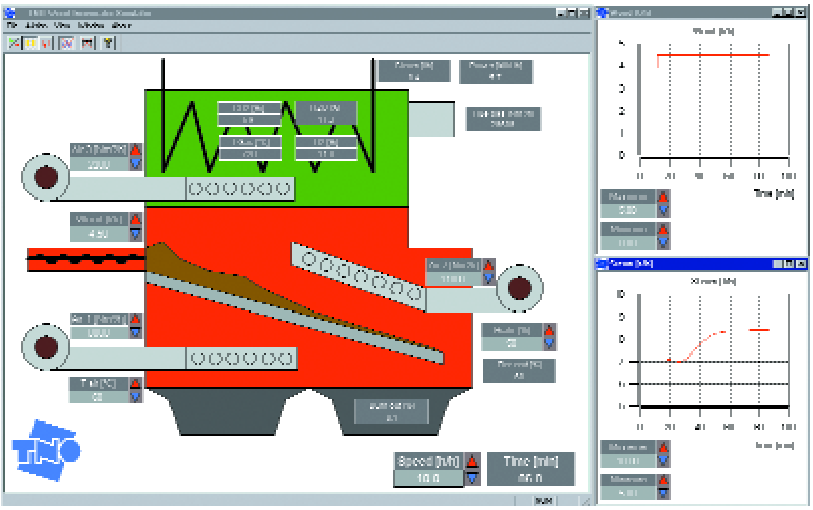
Need for research

Combustion technologies can be improved to further reduce the total costs of heat and/or power produced and to maximise safety and simplicity of operation. The need for innovation is also driven by the wish to burn new biomass fuels, such as energy crops, waste wood, and agricultural residues.

Instead of performing expensive and time-consuming test runs, Computational Fluid Dynamics modelling is increasingly used to calculate flow, temperature, and residence time distributions as well as two-phase flows (flue gas and ash particles) in biomass furnaces and boilers, and to evaluate the impact of design on combustion quality and emissions.

Ash-related technical problems such as particulate formation, deposit formation, and corrosion as well as slagging require ongoing R&D. To reduce maintenance and repair costs and to increase the availability of installations, the mechanisms responsible for problems as well as appropriate primary and secondary measures to prevent them have to be thoroughly understood.

There are still gaps in our knowledge about the thermodynamic and physical properties of certain elements, compounds, and multi-component/multi-phase systems, as well as the chemical reactions related to ash, NO_x and SO_x formation. Improvement of basic data and models is therefore necessary.



A computer simulation program used to evaluate the dynamic reaction of a step grate combustion system on sudden fluctuations in woodfuel properties.

Power generation and co-generation

For power production through biomass combustion, steam turbines and steam piston engines are available as proven technology. While steam engines are available in the power range from approximately 50 kW_e to 1 MW_e, steam turbines cover the range from 0.5 MW_e up to more than 500 MW_e with the largest biomass-fired, steam turbine plant around 50 MW_e.

Example of a small-scale biomass fired CHP system. In a rice drying and packaging plant in Malaysia, rice husk is burned in a water cooled step grate furnace to generate steam (17.5 Bar) for a single stage 225 kW_e backpressure turbine. Remaining heat is used for paddy drying. (Courtesy of TNO, The Netherlands)

Small-scale steam turbines are usually built with a single expansion stage or few expansion stages, and operated at quite low steam parameters as a result of the application of firetube boilers. Plants smaller than 1 MW_e are usually operated as backpressure CHP plants and aim for electricity net efficiencies of typically 10% - 12%. The backpressure heat can be used as process heat.

400 kW_e ORC plant fired by a biomass grate furnace using sawdust and woodchips as fuel in Admont, Austria; the remaining heat is used for drying purposes and for district heating. (Courtesy of Turboden Srl, Italy)

Steam piston engines can also be used for small-scale applications, enabling efficiencies of 6% - 10% in single-stage and 12% - 20% in multi-stage mode. Steam engines are relatively robust - even saturated steam can be used.

For large steam turbine plants, water tube boilers and superheaters are employed, thus enabling high steam parameters and the use of multi-stage turbines. Furthermore, process measures such as feed water preheating and intermediate tapping are implemented for efficiency improvement. This results in electricity efficiencies of around 25% in plants of 5 - 10 MW_e. In plants around 50 MW_e and larger, up to more than 30% is possible in cogeneration mode and up to more than 40% if operated as condensing plant.

As an alternative to conventional steam plants in the range 0.5 MW to 2 MW, Organic Rankine Cycles (ORC) using a thermal oil boiler instead of a costly steam boiler are also available, enabling operation at lower temperatures. A few plants are in operation with biomass combustion. ORC plants can be operated without a superheater due to the fact that the expansion of the saturated steam of the organic medium leads to dry steam.

35 kW_e Stirling engine for biomass combustion plants. (Courtesy of Henrik Carlsen, Denmark)

Another interesting development for small-scale biomass power production is the externally fired Stirling engine. A 30 kW_e prototype plant has reached approximately 20% electricity efficiency in CHP operation. Up to 28% efficiency is aimed at by improving the process and scaling up to 150 kW_e. It is expected that Stirling engines may enable economic small-scale power production by biomass combustion in the future.

In spite of the high complexity, closed gas turbine cycles or hot air turbines may become attractive for medium-scale applications. Before market introduction, however, development of process and component design (especially heat exchanger and/or hot gas particle separation) is needed.

Co-combustion

Co-firing biomass with coal in traditional coal-fired boilers is becoming increasingly popular, as it capitalises on the large investment and infrastructure associated with the existing fossil-fuel-based power systems while traditional pollutants (SO_x, NO_x, etc.) and net greenhouse gas (CO_2, CH_4, etc.) emissions are decreased.

The R&D demands for co-firing cover the proper selection and further development of appropriate co-combustion technologies for different fuels, possibilities of NO_x reduction by fuel staging, problems concerning the de-activation of catalysts, characterisation and possible utilisation of ashes from co-combustion plants, as well as corrosion and ash deposition problems.

Fuel Characteristics

The biomass fuels usually considered range from woody to grassy and straw-derived materials and include both residues and energy crops. The fuel properties differ significantly from those of coal and also show significantly greater variation as a class. For example, ash contents vary from less than 1% to over 20% and fuel nitrogen varies from around 0.1% to over 1%. Other properties of biomass which differ from those of coal are a generally high moisture content, potentially high chlorine content, relatively low heating value, and low bulk density. These properties affect design, operation, and performance of co-firing systems.

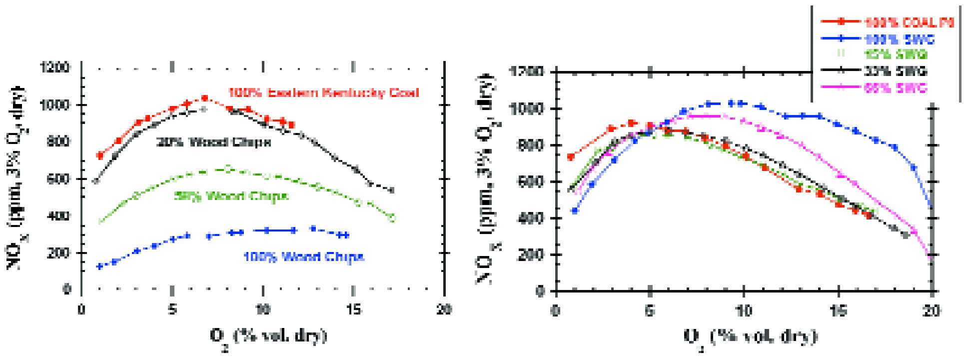
A biomass fuel handling facility which directly meters biomass onto the coal conveyor belts at the Wallerawang Power Station, Australia (Courtesy of Delta Electricity, Australia).

Fuel Preparation and Handling

Because biomass fuels are hygroscopic, have low densities, and have irregular shapes, they should generally be prepared and transported using equipment designed specifically for that purpose. In some cases, however, they can be directly metered on the coal belt conveyor. Care must be taken to prevent skidding, bridging, and plugging in pulverizers, hoppers, and pipe bends.

Emissions

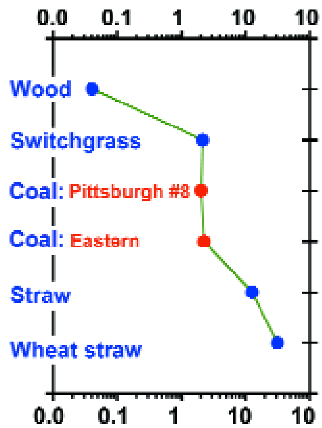
Co-firing biomass with coal can have a substantial impact on emissions of sulphur and nitrous oxides. SO_x emissions almost uniformly decrease when biomass is fired with coal, often in proportion to the biomass thermal load, because most biomass fuels contain far less sulphur than coal. An additional incremental reduction is sometimes observed due to sulphur retention by alkali and alkaline earth compounds in the biomass fuels. The effects of co-firing biomass with coal on NO_x emissions are more difficult to anticipate (see figure below).



Effect on NO_x emissions when cofiring wood (left) and switchgrass (SWG) with coal (right). NO_x emissions can both increase and decrease when cofiring biomass. Fuel nitrogen content: wood=0.18, switchgrass=0.77; coal=1..2.2lb N/MMbtu (Courtesy Larry Baxter, USA)

Ash Deposition

Rates of ash deposition from biomass fuels can greatly exceed or be considerably less than those from firing coal alone. This is attributable only partially to the total ash content of the fuels. Deposition rates from blends of coal and biomass are generally lower than indicated by a direct interpolation between the two rates. Experimental evidence supports the hypothesis that this reduction occurs primarily because of interactions between alkali (mainly potassium) from the biomass and sulphur from the coal.



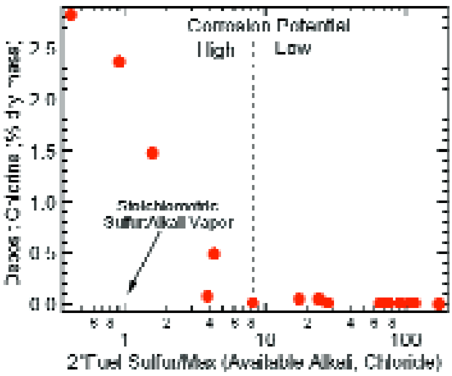
Ash deposition rate for various fuels in g deposit per kg fuel. (Courtesy Larry Baxter, USA)

Carbon Conversion

Experiments on carbon burnout of biomass fuels in coal power plants show that large, wet or high-density biomass particles may undergo incomplete combustion. However, this biomass-derived carbon does not always figure prominently in fly ash analyses because of the relatively low amount of carbon in biomass, the limited share of biomass usually co-fired, and the fact that large biomass particles are more likely to collect in the bottom ash than in the fly ash.

Chlorine-based Corrosion

High-temperature corrosion of superheaters is of great concern when burning high-chlorine or high-alkali fuels, such as herbaceous crops, since species containing chlorine (generally alkali chlorides) may deposit it on heat transfer surfaces and greatly increase surface chlorine concentration. However, research has indicated that the corrosion potential can be reduced if alkali chlorides (primarily from the biomass) can interact with sulphur (primarily from the coal) to form alkali sulphates. As a result, highly corrosive alkali chlorides on superheater tubes are converted to HCl and other gas-phase products that are less corrosive and that leave the surface relatively easily. The HCl may condense on lower-temperature surfaces such as air heaters. However, this problem is generally less serious and more manageable than superheater corrosion.



The molar ratio of sulpher to available alkali and chlorine is and indicator of the chlorine corrosion potential. (Courtesy Larry Baxter, USA)

Fly Ash Utilisation

The majority of the fly ash generated from coal combustion world-wide, is used as a concrete additive or for other purposes. However, current standards preclude the use of fly ash as a concrete additive from any source other than coal.

The technical case for precluding the use of fly ash from co-firing wood with coal appears to be unjustified. However, the less comprehensive data available for herbaceous biomass fuels suggest that alkali, chorine, and other properties may compromise several important concrete properties.

Strict interpretation of many standards that are the basis for regulations and policy for many institutions would preclude all fly ash from use in concrete if it contains any amount of non-coal-derived material, including co-fired fly ash. Though these standards are under active revision, this may take many years to complete.

Environmental aspects of biomass combustion

Emission reduction measures for biomass combustion are available for virtually all harmful emission components; whether the emission reduction measures are implemented or not is mainly a question of emission limits and cost-effectiveness. Though scale-effects ensure that large installations (such as coal power plants) can be equipped with flue gas cleaning more economically, local availability of the biomass fuel and transportation costs will usually be a limiting factor for size.

NO_X and SO_X emissions from biomass combustion applications are in general low compared to those from coal combustion, and secondary reduction measures are usually not required to meet emission limits. Emissions of NO_X from biomass combustion applications originate mainly from the nitrogen content in the fuel, in contrast to fossil fuel combustion applications where nitrogen in the air to some extent also contributes to the NO_X emission level. In most cases the NO_X emission level can be significantly lowered by the use of primary emission reduction measures, and can be further decreased by implementing secondary emission reduction measures.

The main disadvantage of small-scale applications that are based on natural draft and operated batchwise (such as wood stoves, fireplaces, and wood log boilers) are their high levels of emissions from incomplete combustion. For such small units, combustion process control systems are usually not cost-effective.

Limiting values for gaseous (especially NO_X) and particulate emissions are continuously reduced by the authorities, and this raises the need for major R&D efforts. This is particularly the case for biomass fuels rich in N and ash, such as waste wood and energy crops. Small-scale combustion units are of special concern, as they need simple and affordable solutions.

Solid ash and soot particles, emitted from biomass combustion installations, are important sources of aerosols. Therefore, mitigation of aerosols that result from biomass combustion deserves increased attention from research organizations, manufacturers of boilers, and particle removal technologies as well as policy makers. Equipment manufacturers therefore need to be encouraged to develop novel, low-cost, combustion installations and filtration techniques that result in low particulate emissions in small-scale applications as well as large ones.

Finally, questions remain regarding the most environmentally sound and affordable manner for processing ashes from clean and contaminated biomass sources.

For further information, readers are advised that Task 32 has prepared a 'Handbook on Biomass Combustion' which will be published in 2002. Details can be found on the Task 32 website: www.ieabioenergy-task32.com

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