

The status of large scale biomass firing

The milling and combustion of biomass materials
in large pulverised coal boilers



This publication reviews the current experiences and accepted practical approaches in biomass cofiring. It contains both an assessment of the potential impacts that biomass can have on plant integrity, and ways to minimise such impacts in terms of storage, transportation, milling and combustion behaviour. A number of practical case studies are included to illustrate how is dealt with the changes in fuel behaviour in practise.

IEA Bioenergy

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Biomass Combustion and Cofiring

The status of large scale biomass firing

The milling and combustion of biomass materials in large pulverised coal boilers

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Executive Summary

It is widely considered that biomass firing and co-firing in large coal-fired power boilers, both in existing and new build plant, is a very attractive option for the utilization of biomass materials for power production, and for the delivery of renewable energy, in terms of the capital investment requirement, the security of supply, the power generation efficiency and the generation cost. It is also apparent that, coupled with carbon dioxide capture and storage (CCS) technologies, biomass firing and co-firing provides one of the very few means of removing substantial quantities of carbon dioxide from the atmosphere.

There are three principal options for the utilization of biomass materials for power production in combustion-based conventional steam cycle plants:

- The installation of new, dedicated biomass power plants which, at industrial and utility scale, have normally been based on grate fired or fluidised bed combustion systems,
- The co-utilization or co-firing of biomass with a more conventional fuel, normally coal, in large pulverised coal boilers, and

The conversion of existing pulverised coal boilers to 100% biomass firing

Biomass types

The principal types of biomass materials employed as power plant boiler fuels have included:

- The solid waste materials from the olive oil, palm oil, sunflower oil, rape seed oil and other industries, which involve the processing of agricultural products in large volumes,
- Dried sawdust and cereal straw pellets,
- Dried sewage sludges,
- Wood materials in various forms, but principally as dry sawdust pellets or wood chips, and
- Cereal straws and other baled agricultural residue materials.

In general terms, the agricultural wastes and the faster growing biomass materials are relatively inexpensive, but tend to have higher ash contents, and ashes with higher levels of alkali metals and lower ash fusion temperatures than do the woody materials. These tend to give rise to significant ash deposition problems and can only be co-fired at fairly modest co-firing ratios in boiler plants originally designed for coal.

The clean wood materials tend to have lower ash contents and more benign ashes, and can be fired at higher co-firing ratios. For 100% biomass firing, only the higher grade wood materials are suitable. For handling, storage,

transportation and firing in very large quantities, dry materials in pelletised and other densified forms have been preferred.

The preferred fuel for large scale biomass firing in large pulverised coal-fired boilers is pelletised sawdust, which is traded in very large quantities worldwide. The total moisture content of wood pellets is normally less than 10%, with the average lying around 6-7%. This would appear to be perfectly acceptable for processing through modified vertical spindle coal mills and firing at most coal power plants.

For processing in hammer mills, a wider range of fuel types may be possible, i.e. biomass materials in granular and coarse dust forms, and with higher moisture contents, up to 15-20%, on a wet basis, can be processed using hammer mills to provide a suitable product.

There has been significant interest in recent years in the production and utilisation of biomass materials that have been thermally treated, principally to improve their storage and handling, and their milling properties, compared to those of conventional white pellets. The more important of these processes are:

- Torrefaction, a low temperature pyrolysis process, and
- Steam expansion, most commonly by a technology related to the Masonite process, which has historically been employed to make hardboard.

Impacts on milling and combustion

In general terms, the impacts of biomass co-firing on the operation and integrity of the boiler plant depend largely on the nature of the biomass material and on the co-firing ratio.

When a wide range of biomass materials have been co-fired with coal at co-firing ratios less than 10% on a heat input basis, the impacts on the performance and integrity of the installed coal milling and combustion system have been very modest.

When the biomass has been pre-milled and is co-fired in direct injection systems at up to 50% heat input to individual mill groups of burners, the impacts on the performance and integrity of the combustion system have mostly been modest. In this case, the biomass combustion is supported at all times by a stable pulverised coal flame. A relatively wide range of biomass ash and moisture contents can be accommodated without causing problems with the combustion system, provided that the biomass has been milled to an appropriate top size.

If there is oversize material in the biomass feed, this will result in an increase in the number of unburned particles or 'sparklers' at the end of the flame, and an increase in the unburned fuel levels in both the bottom ash and fly ash.

When milled biomass materials have been fired without coal support through unmodified low NO_x pulverised coal burners, there is a tendency for the flame

produced to have the ignition plane located further out into the quarl than in a well-anchored pulverised coal flame. The effect of this has been that the flame monitor signals obtained with the unmodified burners have been poorer than for a stable pulverised coal flame, particularly at reduced mill loads.

The response to this issue has been two-fold:

- In some cases, modifications have been made to the flame detection system to provide a focus on a position in the flame further out into the furnace, and
- In other cases, significant physical modifications have been made to the installed burners, designed to bring the ignition plane back into the burner quarl, and improve the flame monitor signals.

These modifications would in most cases tend to reduce the NO_x control capabilities of the burner. There has in recent years been significant development and demonstration work carried out by the combustion equipment suppliers to enable them to offer a purpose-designed burner for milled biomass materials, which provides rapid ignition and good flame monitor signals, good burnout of the biomass and minimum NO_x emissions.

Ash-related impacts

The key fuel related impacts on boiler performance and integrity, are associated with the inorganic components of the biomass. These include the deposition of the fuel ash on boiler surfaces, boiler tube corrosion and particle impact erosion.

The more important high temperature ash deposition occurrences within the furnace are associated with the following phenomena:

- The deposition of fused or partly-fused ash materials on burner components and divergent quarl surfaces, and the formation of 'eyebrow' deposits around burners and over-fire air ports, can result in interference with light-up and burner operation.
- The deposition of fused or partially-fused slag deposits on furnace heat exchange surfaces reduces furnace heat absorption.
- The accumulation and subsequent shedding of large ash deposits on upper furnace surfaces can lead to damage to furnace ash hoppers and other components of the lower furnace.

These are slag formation processes which occur at relatively high temperatures in excess of around 800-1000°C, on furnace refractory or water wall surfaces in direct receipt of radiation from the flame. These processes occur relatively rapidly, over a matter of minutes or hours, when conditions are favourable, and usually involve the sintering and fusion, or partial fusion, of fuel ash particles on the surfaces within the furnace.

The accumulation of ash deposits in the convective sections of boilers also occurs. These ash accumulations are normally termed fouling deposits, and

the more common occurrences include:

- The formation of ash deposits on the surfaces of superheater, reheater and evaporator banks occurs at flue gas temperatures less than around 1000°C. This is generally a much slower process than slag formation, with the tendency for significant ash deposits to grow over a period of a number of days and weeks. The process involves the formation of deposits in which the ash particles are bonded by specific low melting point constituents, principally the alkali metal species and, in some cases, the more volatile trace elements, such as lead and zinc,
- Convective section fouling is one of the most troublesome ash-related problems associated with the combustion and co-combustion of biomass materials, because of their relatively high alkali metal contents, and hence high fouling potential in many cases.
- Increased fouling also increases the gas-side pressure drop across the banks, and can eventually lead to ash bridging between the tubes.
- Ash deposits on economiser surfaces at low flue gas temperatures tend to be relatively weakly bonded.
- Low temperature fouling and corrosion of air heater surfaces are also common occurrences. These are fairly complex processes involving the condensation of acid species at temperatures below the dew points, and the chemical interaction of the ash particles with the condensed acid.

Uncontrolled ash deposition would very quickly result in operational problems in most boiler plants firing solid fuels. Most solid fuel furnaces and boilers are designed to minimise the extent of ash deposition in key locations. They are also fitted with on-line cleaning systems of various types to permit a level of control over the deposition rates, and hence to maintain heat absorption levels in the furnace and convective section.

The corrosion processes that occur on the gas-side surfaces of boiler tubes are very complex. They occur at high temperatures underneath ash deposits and in contact with combustion product gases, over extended periods of time during which the fuel diet and the operating conditions can change significantly.

The corrosion concerns are principally associated with the final stage superheaters and reheaters, with the leading elements and steam outlet legs being subject to the most aggressive attack.

The majority of biomass materials of industrial interest have the following key chemical characteristics, which have an influence on the high temperature corrosion processes:

- The biomass ashes tend to be relatively rich in alkali metals, which tend to form deposits on the tube surfaces via a volatilisation/condensation mechanism,

- Most biomass materials have relatively low total sulphur contents, generally less than 0.5%, and the chlorine contents of biomass materials vary significantly, but can be up to 1% or so in some cases. The result is that the S/Cl mass ratios for many biomass materials can be relatively low, compared to those for most coals.

This is very different from coal ash deposits, and in general, it is necessary to design dedicated biomass boilers with final steam temperatures that are significantly lower than those that apply in large coal-fired boilers. The general experience with the operation of boiler plants firing a wide range of clean biomass materials has been that, at final steam temperatures in excess of 500°C, unacceptably high rates of metal wastage of superheater elements can occur.

There are a number of potential remedial measures available to address the observed corrosion problems:

- The control of the final steam temperatures, at the boiler design stage, to levels at which the corrosion rates are acceptable, for the fuel being fired and the superheater materials employed, and the selection of more corrosion resistant alloys for construction of the final superheaters, if necessary,
- The protection of the surfaces of vulnerable high temperature tubing by the use of coatings, weld overlays and other measures, and
- The application of fireside additives to modify the flue gas and ash deposit chemistries and hence render them less aggressive.

The erosion and abrasion of boiler components and other equipment in solid fuel-fired plants are associated predominantly with the presence in the fuels and ashes of hard mineral particles. Clearly, high quartz biomass materials, and those which have been contaminated with significant levels of tramp materials, are expected to present significant problems with erosion and abrasion of metallic components of the fuel handling and firing equipment.

In general terms, however, the experience has been that, with one or two exceptions, the ash abrasion and erosion problems associated with the utilisation of the great majority of biomass materials are similar to or less important than those experienced when firing more conventional solid fuels.

Environmental impacts

In modern coal-fired and biomass boilers, the principal gaseous and gas-borne emissions control equipment is currently concerned with the control of the following prescribed pollutant species:

- Total particulate emissions control, principally using dry electrostatic precipitators or fabric filters,
- NO_x emissions control, by both primary and secondary measures, with low NO_x burners, two-stage combustion systems, selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) systems

being the most commonly applied measures, and

- The control of SO_x emissions, principally by limestone additions to fluidised bed boilers, particulate capture in fabric filters, and by limestone-gypsum, wet flue gas desulphurisation (FGD) techniques in large pulverised coal boilers.

When considering the effects of the firing and co-firing of biomass materials on the performance of the electrostatic precipitators, the principal technical concern is that the fly ash particles generated from biomass combustion tend to have significantly smaller particle size distributions than the fly ashes from coal firing, and there is a greater tendency towards the generation of sub-micron fumes and vapours. There may, therefore, be a tendency for the particle capture efficiency in electrostatic precipitators to decrease with increasing co-firing ratio. It should also be noted that the ash contents of most biomass materials are much lower than those of most steam coals, which means that compliance with a prescribed emission consent limits can be achieved at lower particle collection efficiency levels

There is a growing body of evidence that, at relatively low biomass co-firing ratios, that there have been very few incidents of significant increases in the total particulate emission levels due to the biomass co-firing activities. There is also a growing body of experience that indicates that there has not normally been a requirement for major upgrades to the electrostatic precipitator performance when pulverised coal boilers have been converted to 100% biomass. It is clear, however, that compliance with the particulate emissions consent limits is an issue which requires very careful consideration.

It is relevant to note that the nitrogen contents of most biomass materials are significantly lower than those of most coals. The result is that the uncontrolled NO_x emission levels from biomass firing and co-firing at elevated levels tend to be significantly lower than those for coal alone, everything else being equal.

A number of laboratory and plant tests of the impacts of biomass co-firing on the fouling and deactivation of SCR catalysts have also been performed over the past few years. Overall, it would appear that the increased deactivation rates of SCR catalysts due to alkali metal and phosphorus fouling is a significant technical issue when firing or co-firing biomass materials with high levels of these species. The suppliers of de-NO_x catalysts can provide estimates of catalyst lifetimes for particular fuels and specific biomass firing/co-firing operating regimes in particular plants. The addition of coal fly ash has been applied to reduce the catalyst deactivation rates in coal boilers that have been converted to fire 100% clean biomass pellets

The great majority of clean biomass materials of industrial importance have sulphur contents that are significantly lower than those in most coals and, in the great majority of cases, they also have similar or lower chlorine levels. Clean materials also have significantly lower levels of the key trace element species than most coals. The levels in the ash discards and the duties of the waste water treatment plants are generally reduced when firing and co-firing biomass.

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1 Introduction

Most current predictions indicate that the utilization of steam coal for power production worldwide will increase substantially over the next two decades, with the increase in demand occurring particularly in the developing countries in Asia. The market demand will increasingly be for high efficiency coal-fired power generation plants, operating to the highest environmental standards, with biomass co-firing capabilities and, in time, with the capability to capture and store carbon dioxide. In this context, it is widely considered that biomass firing and co-firing in large coal-fired power boilers is a very attractive option for the utilization of biomass materials for power production, and for the delivery of renewable energy, in terms of the capital investment requirement, the security of supply, the power generation efficiency and the generation cost.

This is recognised by IEA Bioenergy and in the EC Biomass Action Plan, and by EC member state and other governments, who have introduced specific policy instruments to encourage biomass firing and co-firing activities. It is also apparent that, coupled with carbon dioxide capture and storage (CCS) technologies, biomass firing and co-firing provides one of the very few means of removing substantial quantities of carbon dioxide from the atmosphere. The more conventional biomass-CCS combinations are close to the full scale demonstration stage, but these developments are currently hindered by the absence of a suitable financial support mechanism. There are three principal options for the utilization of biomass materials for power production:

- The installation of new, dedicated biomass power plants which, at industrial and utility scale, have normally been based on grate fired or fluidised bed based combustion systems,
- The co-utilization or co-firing of biomass with a more conventional fuel, normally coal, in large pulverised coal boilers, either as a retrofit to existing power plants or in new build applications, and
- The conversion of existing pulverised coal boilers to 100% biomass firing. This has been increasingly popular in Britain, and in some northern European and North American countries, in recent years.

There has been significant activity worldwide involving the first option, i.e. the installation of purpose-designed biomass power plants at commercial and industrial scale. The material in this document is concerned, however, with the second and third of these options, i.e. biomass utilisation at utility scale.

To date, biomass co-firing activities worldwide have almost exclusively been associated with retrofit projects to existing coal power plants, i.e. making use of the extensive existing infrastructure for the generation and distribution of renewable energy. Initially, of course, there were significant concerns about a number of the potential project risk areas:

- The availability of suitable biomass materials in large quantities, at acceptable and stable prices,

- The long term security of the subsidy incomes required to support biomass utilisation in most countries, and
- The impacts of the co-firing of the biomass materials on power plant performance and integrity.

In general terms, the options which involve the replacement of all or a fraction of the coal fired at existing power plants with biomass have tended to be more cost-effective and energy efficient than new build options. This type of retrofit project can, in most cases, be implemented relatively quickly and conveniently, and normally involves lower levels of technical and commercial risk, principally because significant use is being made of the existing infrastructure, operating permits and skilled staff.

This has particularly been the case in Britain and Northern Europe, where the utilization of biomass in the electricity supply industries has increased dramatically over the past 10 years. This trend is likely to continue in response to the EC and member state government policies on renewable energies.

This trend is also becoming more apparent on a worldwide basis as national governments are progressively introducing policy instruments aimed at the promotion of renewable energies to meet their international obligations to reduce CO₂ emission levels. In this document an attempt is made to summarise the key technical and other issues associated with these developments.

The key technical options for biomass firing and co-firing include:

- Option 1 involves the milling of 100% sawdust pellets through the existing coal mills, after modification, and the combustion of the milled biomass through the existing pulverised coal firing system, again with modification, if required.
- Option 2 is the simplest approach, and involves the pre-mixing of the biomass with coal, in the existing coal handling and conveying system, at modest co-firing ratios, and the milling and firing of the mixed fuel through the existing coal firing system. This has been by far the most popular approach to co-firing, principally because it can be implemented relatively quickly and with modest capital investment.
- Options 3, 4 and 5 involve the milling of the biomass to sizes suitable for suspension firing, and the direct injection of pre-milled biomass into the pulverised coal firing system, i.e. into the pulverised coal pipework, into modified burners or into new dedicated biomass burners. These options involve much higher levels of capital investment than Option 2, but significantly higher co-firing ratios can be achieved

Option 6 involves the gasification of the biomass in a dedicated unit, normally air-blown and at atmospheric pressure, and the co-combustion of the product gas in the pulverised coal boiler.

2 Biomass fuels available for large scale utilisation in power plants

2.1 GENERAL COMMENTS

The principal types of biomass materials employed as boiler fuels are listed in Table 2-1, below. To date, the solid biofuels that have been utilised in large volumes in Britain and Northern Europe for commercial co-firing projects at coal-fired power plants have included:

- The solid waste materials from the olive oil, palm oil, sunflower oil, rape seed oil and other industries, which involve the processing of agricultural products in large volumes,
- Dried sawdust and cereal straw pellets,
- Dried sewage sludges,
- Forestry residues, sawmill residues, short rotation coppice wood and other wood materials in various forms, and
- Cereal straws and other baled materials.

The power utility companies can normally procure their fossil fuel supplies from a number of well-established sources, and on a variety of different types of contract, to ensure security of supply and to minimise the delivered fuel costs. The fuel procurement departments of the large power utility companies generally purchase coal against a coal quality specification, which is supported by substantial operating experience at particular stations. Many of the companies have internal procedures for the technical assessment of fuels that may be out of specification. This allows the risks of adverse impacts on the performance and integrity of the power plant associated with the firing of an unfamiliar fuel to be assessed prior to making a decision to purchase the fuel in question. This is normally based on a program of laboratory analysis, and perhaps combustion rig or plant testing, of the fuel, and comparison of the results of this exercise, as far as is possible, with the known plant behaviour of a range of more familiar fuels.

A suite of fuel sampling, analysis and characterisation procedures for fossil fuels, comprising both standardised and in-house methods, are available to provide the technical basis for this type of exercise, and most power companies employ suitably qualified and experienced fuel technologists for this purpose. Despite these efforts, mistakes are made from time to time, and the consequences can be costly in terms of lost generation and of the repair of damaged plant.

The operators of pulverised coal-fired power station boilers would clearly prefer to procure biomass materials for firing or co-firing on a similar basis to that applied for fossil fuels. This may be possible, to some extent, for the large volume supplies of high quality biomass, such as wood pellets and chips.

In most cases, however, the power plant operators may be obliged to take a greater interest in, or even to invest directly, in the biomass fuel supply chains to meet their contractual commitments, and to protect their investment in on-site biofuel handling and firing equipment and their future income from biomass firing.

Table 2-1 *The major types of biomass material that may be available as boiler fuels.*

Agricultural products	Forestry products	Domestic and municipal wastes	Energy crops
Harvesting residues <ul style="list-style-type: none"> • Straws • Corn stalks 	Harvesting residues <ul style="list-style-type: none"> • Forestry residues 	Domestic/industrial <ul style="list-style-type: none"> • MSW/RDF/SRF • Scrap tyres • Wood wastes • Sewage sludges 	Wood <ul style="list-style-type: none"> • Willow • Poplar
Processing residues <ul style="list-style-type: none"> • Rice husks • Sugarcane bagasse • Olive/palm oil/sunflower husks and residues • Fruit residues • Cereal straws and residues 	Primary process residues <ul style="list-style-type: none"> • Bark • Sawdusts • Offcuts • Wood pellets 	Urban green wastes <ul style="list-style-type: none"> • Leaves • Grass and hedge cuttings 	Grasses etc. <ul style="list-style-type: none"> • Switch grass • Reed canary grass • Miscanthus
Animal wastes <ul style="list-style-type: none"> • Poultry litter • Tallow • Meat and bone meal 	Secondary process wastes <ul style="list-style-type: none"> • Sawdusts • Offcuts 		

In general terms, the waste materials and the faster growing biomass materials such as the olive, palm and the other agricultural residues and cereal straws are relatively inexpensive, but tend to have higher ash contents and ashes, with higher levels of alkali metals and lower ash fusion temperatures than do the woody materials. These tend to give rise to significant ash deposition problems and can only be co-fired at fairly modest co-firing ratios.

The clean wood materials tend to have lower ash contents and more benign ashes, and can be fired at higher co-firing ratios. For 100% biomass firing, only the higher grade wood materials are suitable. For handling, transportation and firing in very large quantities, dry materials in pelletised and other densities forms have been preferred.

As stated above, the supply of biomass materials as fuels in significant

volumes to power plants, i.e. either for small dedicated plants or for co-firing in large coal-fired power plants is a relatively novel activity, and it is fair to say that the infrastructure required for securing biofuel supplies is not always in place at the present time.

2.2 THE PROPERTIES OF WOOD PELLETS

As stated above, the preferred fuel for large scale biomass firing in large pulverised coal-fired boilers is pelletised wood, which is traded in large quantities worldwide. The total moisture content of wood pellets is normally less than 10%, with the average lying around 6-7%. This would appear to be perfectly acceptable for processing through modified vertical spindle coal mills and firing at most coal power plants. The processing of pelletised biomass fuels with higher moisture contents may result in problems with the heat balance across the modified coal mills.

For processing in hammer mills, a wider range of fuel types may be possible, i.e. biomass materials in granular and coarse dust forms, and with higher moisture contents, perhaps up to 15-20%, on a wet basis, can be processed using hammer mills to provide a suitable product.

Previous experience at a number of converted power plants has indicated that provided the particle size distribution of the dry sawdust particles being delivered to the burners is acceptable, and the fuel flow is steady, then the combustion conditions and burnout will also be acceptable. This has been achieved with both converted vertical spindle coal mills and hammer mills. To date, the processing of wood pellets through large ball and tube coal mills has not been successfully demonstrated.

Because of the much higher volatile matter content of biomass, the particle size distribution required for efficient combustion in a suspension flame is relatively coarse, i.e. with a top size of 1-3 mm, compared to the 300 µm top size required for bituminous coal. This means that the biomass particles can, in some cases, take longer to dry, heat up and ignite than do pulverised coal particles. The ignition plane can, therefore, be located further out into the furnace, and may not be so readily detected by the flame monitoring equipment, in some cases. This is discussed in more detail below.

Based on the previous experience at a number of plants, it is clear that provided that there are no major changes to the distribution and extent of ash deposition, no significant changes to the furnace heat absorption are anticipated when co-firing at high biomass ratios, and firing 100% biomass, compared to that which applies with coal. There should be no requirement for any significant boiler pressure part modifications when converting from coal to wood pellet firing.

In general terms, the concentrations of the minor acidic elements, i.e. nitrogen, sulphur and chlorine, in good quality wood pellets are significantly lower than those in most coals, viz:

N	<0.5%, as fired
S	<0.1% as fired

Cl <0.1% as fired.

For 100% biomass firing, the levels of sulphur and chlorine would help to minimise the uncontrolled acid gas emission levels, and to reduce the risks of high temperature corrosion of boiler surfaces.

The acceptable levels of nitrogen in fuel will depend on the specific emissions limits and the details of the installed combustion and emissions control equipment.

One of the principal concerns when considering the conversion of a coal boiler to 100% biomass firing is the risk of increased ash deposition on boiler and other surfaces. Many biomass materials have ashes with relatively low ash fusion temperatures and high slagging potentials compared to most bituminous coals. The principal concern is that the firing of the biomass would result in excessive slag formation on the final superheater elements, on the platen superheaters, around the burners and on other refractory surfaces in the furnace.

It is normal practice to carry out a thorough investigation of the slagging potentials of the fuels under consideration, i.e. to have the full ash analysis and ash fusion temperatures and other slagging parameters of the candidate fuels measured and to apply the appropriate slagging indices.

Experience elsewhere has indicated that the risks of excessive ash deposition on the boiler surfaces are controlled largely by the ash content of the fuel and the ash composition. In general terms, high grade wood pellet materials with ash contents less than 0.5%, and modest levels of the alkali metals should present relatively low risks in this regard. There is experience however that the firing of 100% wood in large pulverised fuel boilers does give rise to relatively thin white ash deposits on furnace wall surfaces, which can represent a radiative barrier to furnace heat absorption. This factor has to be taken into account in the assessment of the requirements for the on-line cleaning of furnace surfaces, when retrofitting pulverised coal boilers to 100% wood firing.

In general terms, however, the high quality wood fuels are significantly more forgiving in this regard than are the agricultural residue and other biomass materials that are available in pellet form.

The other principal concern is that there may be an increase in the ash fouling of the boiler convective pass when firing 100% biomass. This type of ash deposition is largely driven by the volatilization and subsequent condensation of alkali metals in the fuel ash. The most effective response is to restrict the alkali metal content of the fuel on a kg/GJ basis, to a level at which the fouling is controllable by the use of the on-line cleaning systems. It may also be wise to consider the upgrading of these systems, depending on the existing arrangements on the plant and the range of fuels to be fired.

In general terms, for 100% biomass firing in a pulverised fuel boiler, it is suggested that the following ash quality criteria should be applied:

- Ash content less than 0.5%,
- Ash Deformation Temperature (reducing) >1150°C,
- Total Na₂O + K₂O < 0.17 kg/GJ, and
- P₂O₅ < 5% in ash.

It would be wise to restrict the biomass fuels that are fired to those that pose an acceptable risk of excessive slagging and fouling, and to investigate the use of fuel additives as a remedial measure, should problems with particular fuels arise, or of a more flexible fuel purchasing policy is being considered.

The basic physical and chemical characteristics of the wood pellets that are traded in large quantities in the world market are described in a number of standard documents under EN14961. These standards cover the ash content of the pellets and some of the more important trace elements. The ash chemical composition is not covered by the standard, and it is only required that the supplier should state the ash fusion temperature of the fuel.

2.3 THE PROPERTIES OF NON-WOODY BIOMASS MATERIALS

As stated above, a number of other non-woody fuels are currently being utilised as fuels for co-firing in large coal power boilers. In general terms, these can be considered under two groupings, viz:

- Processed biomass from large volume agriculture, and related industries, and
- Grasses, reeds and straws.

In the first category, processed biomass, the principal materials employed as fuels have included:

- The residues from large scale vegetable oil production, including olive oil, palm oil, sunflower oil, shea meal, etc.,
- The residues for nut and fruit production, including citrus fruit, grape pits, almond shells, peanut husks, etc., and
- The residues from flour and grain production, including, wheat and oat husks, rice husks, etc.

These materials are available in large quantities in certain parts of the world and are generally delivered in dry meal, granular or pelletised forms. They have been utilised largely for co-firing at fairly modest co-firing ratios, partly because of the quantities available, and because of their relatively high ash contents and high alkali metal contents.

In general these materials have higher moisture and ash contents than wood pellets, i.e. they have generally <15% moisture and <10% ash, as received. The gross calorific value, as received, varies in the range 18-23 MJ/kg. The

residues from vegetable oil production can contain a significant residual oil content, which can increase the calorific value, but can also have an impact on the handling properties of the material.

The nitrogen, sulphur and chlorine contents of these fuels are also very variable, up to around 5-6%, 0.3% and 0.4% for nitrogen, sulphur and chlorine respectively. These values are significantly higher than those for wood pellets.

As stated above, these materials tend to have very much higher ash contents than woody biomass, and the ashes tend to be rich in silica, lime, potash and phosphate. The ash fusion temperatures also vary widely, depending on the chemical composition. In general terms, these materials are in the medium to high slagging category and in the severe fouling category.

They are generally not suitable for firing on their own in large boilers designed for firing coal, and are best employed as fuels for co-firing with coal at relatively low co-firing ratios.

The second general category of non-woody biomass fuels that have been employed for co-firing in large coal boilers are the grasses, reeds and straws. These materials are available in large quantities, most often on a seasonal basis, and are generally harvested and handled in baled form.

The straws and other residues are generally collected and handled in baled form, usually for use as animal feed and bedding. Suitable equipment for the bulk handling and transportation of grasses and straws in this form is commercially available. The baled straws generally have relatively low moisture contents, and can usually be stored for long periods without significant dry matter losses and deterioration in fuel quality. These materials are also available in dried and pelletised form, which will tend to be the preferred form for bulk transport and utilisation at power plants.

A small number of coal power plants have installed the handling and feeding systems to permit the co-firing of baled cereal straws, generally at low co-firing ratios.

The other materials in this category, i.e. miscanthus and the grasses are generally grown as energy crops, currently in fairly small quantities.

These materials have ash contents up to around 10-12% and relatively high ash contents, in the range 3-8%, as received. They have gross calorific values around 17-18 MJ/kg, as received. They can have high nitrogen contents, up to around 5%, and sulphur and chlorine contents up to around 0.2%.

The ashes produced by the combustion of these materials are rich in silica, up to 50% or so, with significant levels of lime, potash and phosphate. The ash fusion temperatures of these materials can be quite low, in some cases less than 1100°C. In general terms they tend to be in the high slagging category and the severe fouling category. Again these materials are generally not suitable for firing on their own in large boilers designed for firing coal, and are best employed as fuels for co-firing with coal at low co-firing ratios.

2.4 THERMALLY PROCESSED BIOMASS FUELS

There has been significant interest in recent years in the production and utilisation of biomass materials that have been thermally treated, principally to improve their storage and handling, and their milling properties compared to those of conventional white pellets. The more important of processes are:

- Torrefaction, a low temperature pyrolysis process, and
- Steam expansion, most commonly by a technology related to the Masonite process, which has historically been employed to make hardboard.

A short summary of the key features of these processes, as applied to biomass materials as fuels, is presented in this section.

Torrefaction is a mild thermal pre-treatment process which involves the drying and heating of the raw biomass in the absence of oxygen, at atmospheric pressure. In the torrefaction unit the pre-dried fuel is exposed to temperatures of 250-350°C, and a modest amount of combustible volatile matter is released. A char material, which is hydrophobic and brittle in nature, is produced.

Both the drying and torrefaction processes are endothermic, i.e. an external energy source is required. The volatile matter released in the torrefaction process is combustible, and can be collected and burned to provide some of this heat.

The energy content and mass yield of the torrefied product is dependent on several important factors, principally the temperature, the reaction time and the biomass type. The mass loss during torrefaction is greater than the energy loss, which results in a net energy densification in the product. High density pellets of bulk density up to 750-850 kg/m³ with a GCV higher than normal wood pellets can be produced from torrefied biomass.

The torrefaction of biomass is currently being commercialised in a number of countries, and two major technical developments are under way:

- The reduction of the additional energy input that is required in order to dry and pyrolyse the fuel, and hence of the delivered fuel cost, and
- The optimisation of degree of torrefaction and the production of a pellet with the required durability level in bulk handling, transportation and storage systems.

These, and other, issues are currently being investigated by the torrefaction technology developers, and efforts are being made to make it a fully commercial process in the biomass to energy production chain.

Steam explosion is a hydro-thermal pre-treatment process used for biomass materials. It involves the physical and chemical opening up of the wood fibres. The principal aim is to improve the pelletizing properties and the calorific value of the product. Steam explosion is normally associated with the pre-treatment

of biomass material for chemical and biochemical conversion, and its potential for use in the pre-treatment of boiler fuels is currently being explored.

In the first stage of the process, the biomass material contacted with steam at temperatures of between 180-220°C and pressures of between 1-3.5 MPa. This is followed by explosive decompression which partially destroys the fibrous nature of the cellulose.

The solid product has reduced moisture and volatile matter contents. The steam explosion process also causes degradation of hemicellulose within the wood cell walls which reduces the number of hydrogen bonding sites, and increases the hydrophobic properties of the particle surfaces. Steam explosion also makes the material more brittle in nature. This should render them easier to mill in large coal mills, although this has not been demonstrated clearly to date at industrial scale.

The torrefaction and steam explosion processes can be applied to any biomass material providing a more homogeneous product of higher bulk density and higher calorific value. There is little or no impact on the chemical composition or the mineral matter content of the biomass.

The most important technical challenges in the development of torrefaction and steam expansion technologies are related to the following issues:

- The process gas recovery and combustion, and the associated environmental control systems,
- The process scale-up,
- The improvement of the predictability and consistency of the product quality,
- The densification of processed biomass,
- The heat integration of the thermal treatment process, and
- The process flexibility in using different feed materials.

The objective has been to produce a hydrophobic material in the form of durable pellets or briquettes that can be more conveniently handled and stored, and which have improved milling properties compared to conventional sawdust pellets. The achievement of these objectives has not yet been fully demonstrated at commercial scale, however these fuels may well play a significant role in future as energy carriers, and fuels for firing and co-firing in large pulverised coal boilers.

Most solid fuel furnaces and boilers are designed to minimise the extent of ash deposition in key locations. They are also fitted with on-line cleaning systems of various types to permit a level of control over the deposition rates, and hence to maintain heat absorption levels in the furnace and convective section. There are also natural ash deposit shedding mechanisms and other processes which are responsible for the reduction in the extent of deposition.

3 The principal biomass firing and co-firing options

The principal technical options for the firing and co-firing of biomass materials in large pulverised coal-fired boilers are listed in Figure 3.1.

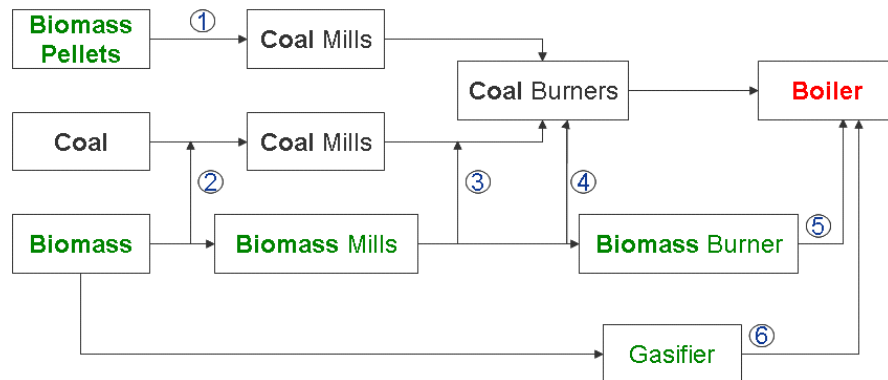


Figure 3.1 Biomass co-firing options at large pulverised coal-fired power plants (Livingston and Morris, 2009)

The key technical options for biomass firing and co-firing include:

- Option 1 involves the milling of 100% sawdust pellets through the existing coal mills, after modification, and the combustion of the milled biomass through the existing pulverised coal firing system, again with modification, if required. This approach has been achieved successfully in a small number of pulverised coal power plants in Northern Europe and North America.
- Option 2 is the simplest approach, and involves the pre-mixing of the biomass with coal, in the existing coal handling and conveying system, at modest co-firing ratios, and the milling and firing of the mixed fuel through the existing coal firing system. This has been by far the most popular approach to co-firing, principally because it can be implemented relatively quickly and with modest capital investment. As such, it has been particularly popular with power station operators embarking on co-firing activities for the first time, and where there are uncertainties associated with the security of the supply of suitable biomass materials, or with long term security of the government subsidies or other financial incentives that may be available for co-firing. Although the level of substitution of the coal is modest, generally less than 10-12% on a heat input basis, quite significant volumes of biomass have been co-fired in this way in Europe and elsewhere, over the past few years.
- Options 3, 4 and 5 involve the milling of the biomass to sizes suitable for suspension firing, and the direct injection of pre-milled biomass into the pulverised coal firing system, i.e. into the pulverised coal

pipework, into modified burners or into new dedicated biomass burners. These options involve much higher levels of capital investment than Option 2, but significantly higher co-firing ratios can be achieved. A number of coal-fired power plants in Northern Europe have installed direct injection systems of this type, over the past few years, and this is one of the more favoured options for the provision of biomass co-firing capabilities in new build pulverised coal power plant projects.

- Option 6 involves the gasification of the biomass in a dedicated unit, normally air-blown and at atmospheric pressure, and the co-combustion of the product gas in the pulverised coal boiler. The product gas may or may not be cleaned prior to firing into the coal boiler. This approach to biomass co-firing has been adopted in a small number of plants in Northern Europe.

Overall, therefore, it is clear that a number of co-firing options are available for biomass materials, for both retrofit and new build applications, depending on the fuels available for co-firing, and on the aspirations of the power plant operator or project developer.

The key options for biomass milling include:

- The use of the installed coal mills for the processing of pelletised biomass, as described above, and
- The installation of dedicated biomass milling facilities.

3.1 THE CONVERSION OF COAL MILLS FOR PROCESSING SAWDUST PELLETS

This refers to Option 1 in Figure 3.1.

The use of the installed coal milling plant and the associated auxiliary equipment, such as the coal feeders, the primary air fans and ductwork, and the pulverised coal pipework and burners, for biomass firing and co-firing, is a cost-effective and technically attractive option. The existing systems have high throughput and are familiar to the operating staff. They are robust, resistant to even sizeable items of tramp material, capable of continuous operation for prolonged periods of time, and require limited maintenance. The principal alternatives for biomass milling are hammer mills or roller mills, and these tend to have modest throughputs, compared to large coal mills, are relatively sensitive to the presence of ash and tramp material in the fuel and need regular hammer and screen changes, due to erosive and abrasive wear.

The general experience with this type of mill conversion projects in Europe has been that the converted coal mills can deliver a suitable mill product at 70-100% of the maximum heat input from coal when processing wood pellets. The reason for the reduced throughput in some cases is due to the lower energy density of the sawdust pellets compared to bituminous coal.

The practical application of this approach, i.e. Option 1 in Figure 3.1, has been

demonstrated in a small number of cases in Northern Europe. It has been shown that large, vertical spindle coal mills can be employed, with fairly modest modifications, to reduce dried and pelletised sawdust to provide a product material that can be fired successfully through the existing pulverised coal pipework systems and burners.

There have been a small number of recent attempts to modify large ball and tube coal mills to process wood pellets in this way. This work has, to date been unsuccessful in that it has proved difficult to get reasonable pellet throughput levels and there have been some significant safety issues.

In all cases, the vertical spindle coal mills have been modified in a number of ways to mill the wood pellets, principally to maximise the mill throughput and to optimise the mill product quality.

In general terms, the key milling plant modifications have included:

- In some cases, there may be a requirement for the modification or replacement of the coal feeding system, depending on the design and condition of the installed equipment,
- Most vertical spindle coal mills operate under positive pressure and the installation of a rotary valve in the fuel feed chute is commonly required to provide a better seal between the mill and the bunker. This helps to prevent blow back of fine particles of fuel into the bunker hall when the bunker level is insufficient to form an effective seal. The biomass materials in pelletised form do not form this type of seal as well as does coal,
- The installation of a fuel distributor at the bottom of the feed chute/classifier return cone, to direct the raw pellets towards the inside of the grinding elements, can be of value in some cases,
- The reduction of the mill throat gap and the installation of fixed baffles in the upper part of the mill body to maintain the primary air velocities within the desired range for milled biomass are commonly applied. In this context the reduction of the primary air inlet temperature is commonly done when processing biomass, for both safety and process reasons,
- The removal or opening out of the static classifier fixed vanes to reduce the level of classification within the mill, and hence to increase the pellet throughput, is commonly applied, and
- The installation of a dynamic classifier has also been applied, in some cases, to provide greater control over the product fineness.

When the pellets are processed in vertical spindle mills, after suitable modification, the particles are returned to the original sawdust size distribution, and a limited degree of further size reduction of the primary sawdust particles occurs. In practice, it has been found that the product particle size distribution can be suitable for combustion in pulverised fuel

furnaces, and the mill throughput can be acceptable, i.e. at the level described above.

Overall, this has proved to be an attractive option for the firing or co-firing of pelletised biomass and there is successful, long-term experience with this approach in Scandinavia and elsewhere in Northern Europe.

Despite these potential difficulties and limitations, the co-milling and co-firing of a number of chipped, granular and pelletised biomass materials through most of the more common designs of conventional coal mill has been achieved successfully on a fully commercial basis in a number of coal-fired power plants in the UK, and elsewhere in Northern Europe.

It is possible to install vertical spindle mill coal mills which have been specifically configured for the processing of biomass pellets that can also be reconfigured within a relatively short period of time to return to the milling of coal. This type of mill has recently been demonstrated successfully in a small number of biomass conversion projects in Northern Europe.

3.2 THE CO-FIRING OF BIOMASS BY PRE-MIXING WITH COAL AND CO-MILLING

This refers to Option 2 in Figure 3.1.

Initially, the great majority of the biomass co-firing activity in the UK, and in much of Northern Europe, was by pre-mixing the biomass with coal, normally in the existing coal handling and conveying system. The mixed fuel was then processed through the installed coal bunkers and mills, and through the installed pulverised coal firing equipment, with very little modification of the installed equipment.

This approach has been applied successfully in a large number of pulverised coal power stations, and with a fairly wide range of biomass materials in kernel, granular, pellet and dust forms. Relatively dry biomass materials, with moisture contents less than 20%, have been most popular for co-firing by this method, however, sawdust materials at moisture contents up to approximately 50-60% have been co-fired successfully in this way, albeit at low co-firing ratios.

The maximum achievable co-milling ratio, and hence the level of co-firing, without significant mill throughput constraints, is limited, and depends on the design of the coal mill, the nature of the biomass material and the plant operating regime. In most cases, the co-firing of biomass at up to around 10% heat input is possible, although co-firing ratios up to around 5-8% or so are more commonly applied on a commercial basis.

As an illustration of the simplicity of this approach, a photograph of granular olive residue material, which was imported from Spain, being dropped at a controlled mass flow rate from a chute on to the coal on the main coal conveyor at a large coal power station in the north of England is shown in Figure 3.2, below. The biomass co-firing ratio, in this case around 6-8% by mass, was controlled by continuously matching the mass flow rate of the

biomass on a belt feeder to the coal flow rate on the main coal conveyor belt, measured in a weigh belt section just upstream of the biomass introduction point. In most cases, the biomass is laid on top of the coal on the conveyor, and there is no attempt made to mix the two fuels.



Figure 3.2 Granular olive residue material being dropped on top of coal on the main coal conveyor at a large coal power plant.

In general terms, conventional coal mills operate by compressing the raw coal between two hard surfaces to break up the coal and ash particles by a brittle fracture mechanism. Most biomass materials tend to squash rather than fracture under compression, and the milling process largely reduces the pellets back to the size distribution of the parent sawdust. As a consequence the milled biomass product tends to be relatively coarse. There is also a tendency for the larger biomass particles to be returned by the classifier and retained within the mill. This can act to limit the mill throughput and the co-firing ratio that is achievable in this way.

For instance, in vertical spindle coal mills, there may be a tendency for the primary air differential pressure and the mill power consumption to increase with increasing biomass co-firing ratio, due to the increased inventory of material circulating within the mill. This can often represent a limiting factor since both of these parameters tend to have maximum limits. It is also the case when co-milling very wet biomass materials, that there is a significant impact on the mill heat balance, leading to low mill outlet temperatures, and

this can also be a limiting factor on the maximum biomass throughput.

There may also be an increase in the particle size of the mill product when co-milling biomass. This is a result of the relatively low particle density of most biomass materials, which means that larger particles of biomass can pass through the classifier, than is the case for coal.

There will clearly be mill safety issues when co-processing biomass in most conventional coal mills, where hot primary air is applied to dry the coal in the mill. The biomass materials tend to release combustible volatile matter into the mill body at temperatures significantly lower than those which apply when milling bituminous coals. It may be necessary, therefore, to modify the mill operating procedures to minimise the risks of overheating the coal-wood mixture, and thereby causing temperature and pressure excursions within the mill. The details of the modified mill operating practices depend on the type of mill and the station operating practice.

In general terms, it is relatively rare for coal mills in normal operation to have a problem, since there is a constant flow of wet coal into the mill, and the mill inlet and outlet temperatures are under control. Most mill incidents are associated with particular occurrences during the operation of a mill which can present higher risk levels. These include:

- Planned start-up and shutdown of the mill,
- Incidents involving the loss of feed or intermittent feeding to the mill, which can lead to increased mill outlet temperatures,
- Incidents involving a fire within the mill, and
- Emergency mill shut downs (trips), and restarts after mill trips.

The operating procedures for dealing with this type of mill occurrences require assessment, and may need modification in the light of the differences between the properties of biomass and coal. These actions have been successful in the main, and incidences of mill fires and pressure excursions have been relatively rare.

It is fair to say that the modifications to the mill operating practices have been demonstrated in a large number of power plants, and with all of the more common types of coal mill and a wide range of biomass materials.

Overall, it has been the general experience that a wide range of biomass materials can be successfully fired in this way, and that the impacts of co-firing on boiler plant operations are fairly modest. The environmental performance of the plant, when co-firing relatively clean biomass materials at co-firing ratios less than 10%, on a heat input basis, was similar or slightly better than when firing coal. The principal technical problems encountered by the power plant operators have been with the storage and handling of the biomass, and in particular with the tendency of some biomass materials to generate significant dust levels in the storage and handling facilities.

The basic arrangement of a very basic biomass co-firing system based on pre-

mixing the biomass with the coal and processing the mixed fuel through the existing fuel handling, bunkering, milling and firing system, is illustrated in Figure 3.3 and Figure 3.4 below.



Figure 3.3 The biomass store at a large British coal power station.

The biomass store is shown in Figure 3.3. The store is located in an area of hard standing with a turning circle for delivery trucks, and a front loader for moving the biomass around the store. The store was designed to take up to 1,000 tonnes of biomass, and the system was designed for the co-firing of 100,000 tonnes per annum of dry biomass materials, principally wood pellets.

Towards the rear, right hand side of the store there is a pile of biomass which sits over a ground hopper. This is shown on the top left hand side photograph in Figure 3.4. Under the ground hopper is an automatically controlled screw feeder. The feeder speed is controlled by a signal from a weigh belt on the main coal conveyor, and is set to provide a flow rate of biomass at a pre-determined ratio to the coal flow rate on the conveyor.

The biomass is then fed to the biomass conveyor, which is shown on the top right hand side photograph in Figure 3.4. The conveyor carries the biomass to the main coal conveyor, the housing of which can be seen running across the bottom of the bottom left hand side photograph in Figure 3.4.

There are two parallel coal conveyors, and there is a trouser leg with an automatic flap valve which directs the biomass to either of the two conveyors, depending on the signal from the coal weigh belt.



Figure 3.4 The biomass feeding system

Inside the housing, the biomass is dropped on top of the coal on the main coal conveyor, as illustrated in the bottom left hand side photograph on Figure 3.4 and is carried with the coal to the boiler. In this case, the biomass chute has a discharge hood to help control the fugitive dust emissions in that section of the coal conveyor.

The biomass is then carried along the coal conveyor on top of the coal stream towards the coal bunkers. No attempt is made to mix the two fuels positively, although a certain amount of mixing occurs at the transfer points on the conveyor system and in the drop from the conveyor into the coal bunkers. The biomass and coal particles are very well mixed within the coal mill, and the mixed fuel is sent to the coal burners.

As part of the conversion of a power plant to co-firing biomass, it is normally necessary, for health and safety reasons, to perform a series of trials to demonstrate the proposed procedures for the bunkering, feeding, milling and firing of the mixed fuel in a controlled and safe fashion. It is also a requirement that the technical and environmental performance of the plant when co-firing biomass is demonstrated both to the station management and to the environmental regulator.

The test programme, in most cases, involves the feeding of the coal-biomass mixture, at a low co-firing ratio, to a single bunker, normally overnight, with the testing of the processing of the mixed fuel through a single mill and the associated group of pulverised fuel burners being carried out over the day shift. The biomass co-firing ratio can then be increased progressively over a period of a few days.

The mill testing involves the performance of load range tests, with the

collection of the key mill performance data at a range of mill loads, and the performance of mill shutdown and restart tests.

This approach helps to minimise the technical risk, and to ensure that the modified mill operational practices can be demonstrated on a single mill, before rolling the biomass co-firing out to the other mills on the boiler unit. This is normally done at the preferred co-milling ratio, which is established during the single mill test work. By the end of a test programme of a week or two in duration, the boiler is operating with the preferred biomass co-firing ratio being fed to all mills.

The environmental performance of the boiler and the associated gas cleaning systems is normally also tested. It is normally necessary to demonstrate to the environmental regulator that there are no additional environmental impacts to air, land or water, associated with the biomass co-firing activities. The scope of the environmental tests has to be agreed in detail with the environmental regulator. Only on the basis of a successful trial programme can the co-firing of biomass be incorporated into the normal commercial operational practices at the stations, under any site-specific conditions imposed by the regulator.

Overall, this approach to biomass co-firing has been very popular, particularly with operators who have limited experience with the procurement and firing of biomass materials. The capital investment required is relatively modest and is associated principally with the reception, storage and handling of the biomass, and the risks of significant damage to the installed coal firing equipment and boiler are small.

As stated above, this approach generally allows operation at co-firing ratios up to around 10% on a heat input basis. This is modest compared to the output levels from large coal-fired power stations, but is very significant when compared to the output from most dedicated biomass boilers and other forms of renewable energy generation.

3.3 THE DIRECT INJECTION OF PRE-MILLED BIOMASS MATERIALS

This refers to Options 3-5 in Figure 3.1.

The direct injection approach to co-firing is described under Options 3, 4 and 5 in Figure 3.1, and involves the milling of the biomass to sizes suitable for suspension firing, and the direct injection of the pre-milled biomass into the pulverised coal firing system. These options involve much higher levels of capital investment than are associated with Option 2, but significantly higher co-firing ratios can be achieved.

In some locations, it is possible at times to purchase pre-milled biomass materials in modest quantities, but in most cases the biomass will be delivered in granular, pelletised or even baled forms and will be milled to a size distribution suitable for firing or co-firing using on-site milling facilities.

3.3.1 Hammer mills

The most popular type of mill employed for the milling of biomass materials, for use in pelletizing plants, for instance, and for co-firing, are hammer mills. A simplified diagram of a hammer mill is replicated in Figure 3.5.

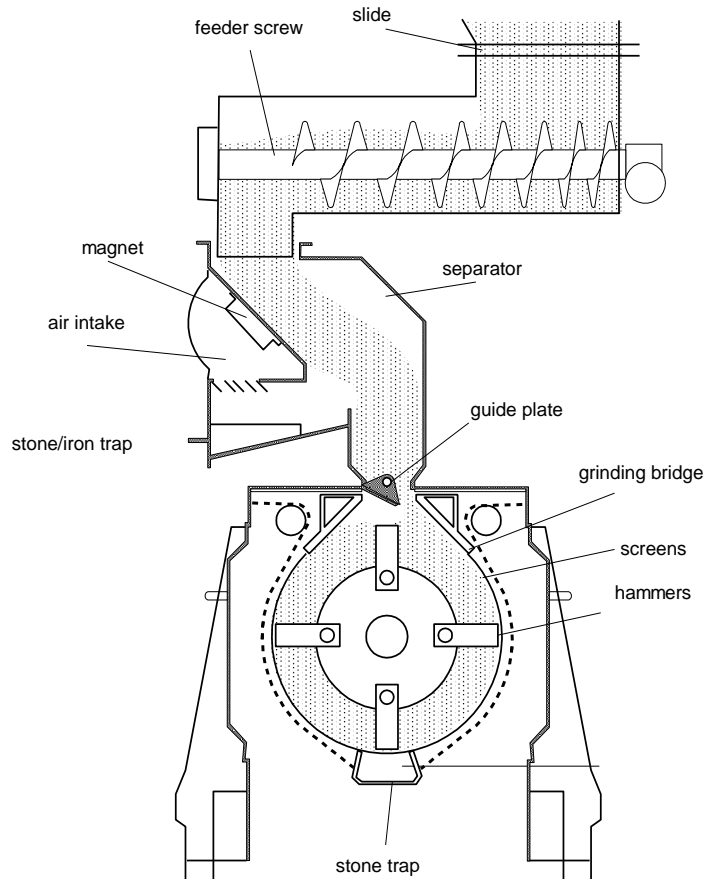


Figure 3.5 A schematic diagram of a horizontal hammer mill (after van Loo et al. 2008).

In almost all cases, the mill is fed by gravity from the top, normally using a screw feeder. In some cases, there is a stone trap and a magnetic separator at the mill entry to protect the mill from tramp material. The grinding elements in a hammer mill comprise a high speed rotor with plate-shaped hammers. The hammers drive the raw feed material towards the grinding bridge and through the screens which encase the grinding chamber. The product material falls into the outlet chute. The product size distribution is determined largely by the screen size.

Horizontal hammer mills have an aspirating air intake at the top of the mill through which air is drawn, to help cool the mill components and draw the milled material through the screens into the outlet hopper. The air and fine product particles are drawn to the air exhaust via a bag filter. The coarser product material drops to the bottom of the outlet hopper. The coarse and fine mill product materials are normally removed from the mill using screw feeders.

In vertical hammer mills there is no requirement for aspirating air, and the milled product is drawn through the screen and out of the bottom of the mill into the outlet hopper by gravity.

3.3.2 Experience with introduction of hammer mills in direct replacement of the coal mills

As stated above, large ball and tube coal mills have not, as yet, been converted successfully to the milling of 100% wood pellets, and it may be necessary in some cases to replace them with dedicated biomass mills, if it is desired to convert the boiler to 100% wood pellets.

One of the simplest and cheapest ways to achieve this, which makes maximum use of the existing fuel and air supply systems to the boiler, involves:

- The removal of the existing coal mills,
- The installation of the new hammer mills in the same location, and commonly two hammer mills would be required to replace one large coal mill,
- The modification of the existing fuel storage, conveying and feeding system to handle the wood pellets and to feed the pellets to the inlets to the new hammer mills,
- The modification of the installed primary air ductwork systems,
- The modification of the installed pulverised fuel pipework systems to receive the milled biomass, and deliver to the installed pulverised burners,
- The modification of the installed pulverised coal burners to fire the milled wood, if necessary,
- The modification of the mill, burner and boiler control systems to take account of the new systems and any modifications to plant operations, and
- In most cases it will be necessary to install a primary air cooling and heat recovery system, to cope with the reduced air heater duty associated with the firing of 100% wood pellets compared to coal.

This type of project has been successfully carried out in Northern Europe in a coal power plant comprising two large pulverised coal boilers, each generating in excess of 370 MW_e-

The general experience with hammer mills is that they can produce a milled material with a top size of less than 2-3 mm from wood pellets with a 4 or 6 mm outlet screen, at reasonable output levels, but that they are very sensitive to the presence of ash and tramp material in the fuel. Even relatively modest ash levels in the fuel can reduce the hammer and screen replacement cycle to a few days. Although these operations can be carried out relatively quickly, they do require the hammer mill to be taken out of service for a significant

period of time, and it is inevitable that the hammer mill systems are subject to a large number of shutdowns and start-up sequences. This is much more onerous than the maintenance requirements of a large coal mill.

The presence of significant pieces of tramp material, i.e. metal items or stones, can cause significant mechanical damage to hammer mills. This type of tramp material can also generate significant numbers of sparks, which can represent an ignition source. The risks of ignition of the biomass within the mill body are relatively low, because the biomass material within the mill is relatively coarse and difficult to ignite under normal operating conditions. Any sparks that can escape the mill by passing through the screens may ignite the mill product material, which, in the case of horizontal mills with aspiration air, may be in the form of a dispersion of fine biomass particles in air. The result can be a significant pressure excursion. In this case, any hoppers or ducts at the outlet to the mill should be fitted with appropriate explosion protection and suppression systems.

Any hot or smouldering material in the biomass feed to the hammer mills can also act as an ignition source within the mill or in the outlet hopper, and it is clear that the biomass fuel storage and handling systems should be designed very carefully to minimise the risks of both tramp material and hot or smouldering materials being carried forward into the hammer mill systems.

3.3.3 Introduction of milled biomass into the pulverised coal pipework

This refers to Option 3 in Figure 3.1.

The milled biomass, with a top size less than 3 mm or so, is normally pneumatically conveyed from the fuel handling and milling facility to the boiler, and injected directly into the coal firing system.

The following fuel injection points into this system are available:

- Into the pulverised coal pipework,
- Into the existing pulverised coal burners after suitable modification, and
- Into new, purpose-designed biomass burners, additional to the existing pulverised coal burners.

The simplest and cheapest approach to direct injection firing and co-firing is to introduce the milled biomass into the pulverised fuel pipework upstream of the coal burners. In this case, the milled biomass or pulverised coal/biomass mixture is carried forward along the pulverised coal pipework, and the mixed fuel then enters the combustor via the primary air annulus of the burner as normal. This type of approach is, in principle, applicable to all burner designs.

Two general potential locations for the introduction point of the biomass are apparent, namely:

- The introduction of the biomass into the pulverised coal pipework just upstream of the non-return valves and local to the furnace. This

location is downstream of the pulverised coal splitters, if any, and one biomass delivery system will be required for each coal burner, and

- The introduction of the biomass into the mill outlet pipework, just downstream of the mill product dampers, and upstream of the pulverised coal splitters, if any. In this case, there will be one biomass injection system for each mill outlet pipe, and it will be necessary for the biomass/coal mixture to pass through the coal splitters or riffle boxes, if there are any of these in the system.

The first of these options, i.e. injection of the biomass stream local to the burner inlet, has a number of potential attractions:

- In general, the point of introduction of the biomass and the associated shut-off valve, instrumentation, etc. will be readily accessible from the burner galleries, for inspection and maintenance,
- The potential process risks associated with the introduction of a significant quantity of pre-milled biomass into the pulverised coal pipework are minimised, by having the shortest possible length of pipework carrying the mixed fuel stream, and avoiding the splitters in the coal pipes, and
- The introduction point for the biomass is well away from the coal mill, and hence the potential impacts of mill incidents and of mill vibration on the integrity and performance of the biomass conveying and injection system is reduced.

In many cases, however, the routing of the biomass pipework through the normally congested region local to the boiler front, and the arrangements for supporting the biomass pipes, can become overly complex and expensive. It should be noted, in this context, that the pulverised coal pipework local to the coal burners will have to move with the burners as the furnace expands with increasing temperature. Sufficient flexibility must be introduced into the biomass conveying pipework to allow for this movement, which may be several inches between off-load and full load conditions.

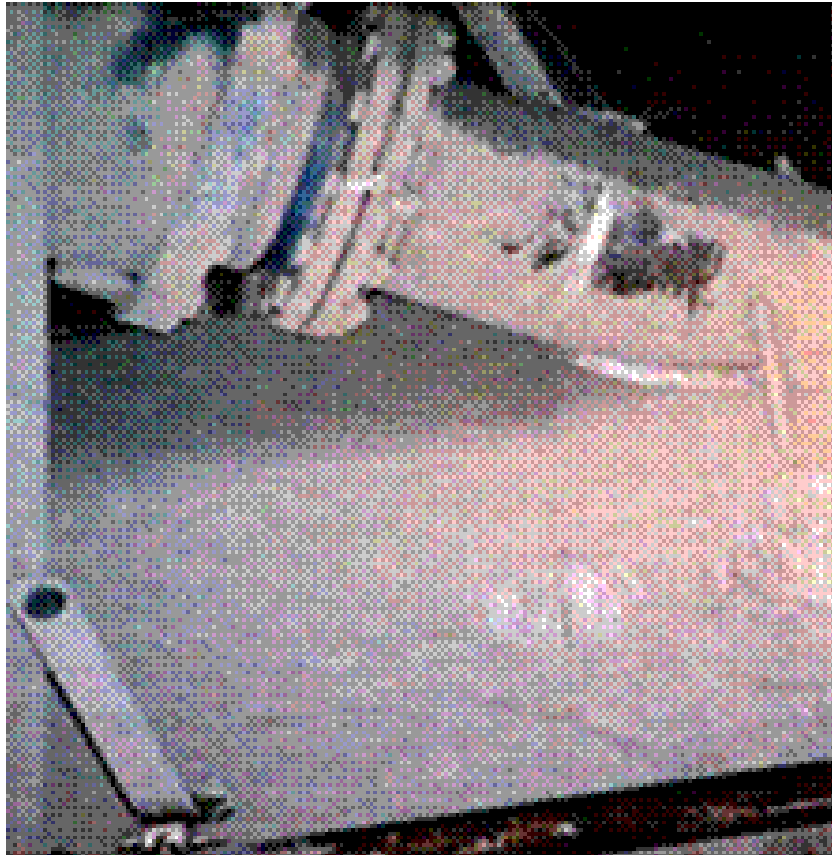


Figure 3.6 The biomass injection point to the mill outlet pipe in a direct injection co-firing system at a power station in England

For most applications, the second approach may be preferred, i.e. the introduction of the biomass stream into the mill outlet pipework just downstream of the mill product dampers and upstream of any pulverised coal splitters. The mixed biomass/pulverised coal stream is then carried forward to the burners, via any splitters in the pulverised coal pipework.

This approach is much easier to engineer and will be relatively cheap to install. In many cases, the number of biomass feeders and pneumatic conveying systems will be substantially lower than for biomass injection downstream of the splitters. The degree of movement of the pulverised coal pipework close to the mill is relatively small, which will make the biomass injection pipework simpler to engineer.

A photograph of the injection point of a biomass conveying pipe (200 mm dia.) into a mill outlet pipe (660 mm dia.) in a large pulverised coal boiler is presented in Figure 3.6.

In all cases, the introduction point of the biomass to the pulverised coal pipework is fitted with a fast-acting, actuated biomass shut-off valve which allows rapid isolation of the biomass system from the coal mill and firing system, during mill trips and at other occasions.

If the direct injection co-firing system is engineered appropriately, there are a

number of key advantages of the direct injection systems involving biomass injection into the pulverised coal pipework, i.e.:

- There are no requirements for significant modification of the boiler milling and firing systems, beyond the installation of the biomass injection point, or of the boiler draught plant, etc.
- The boiler and mills can be started up on coal as normal, and the biomass co-firing system brought into service when all of the combustion and boiler systems are functioning properly,
- If there are problems with the biomass system on one mill group, the biomass co-firing system can be turned off automatically and the boiler load can be picked up on coal firing on that mill automatically, as normal.
- If there are any significant problems with the coal mill, e.g. coal feeder problems, a fire in the mill, a mill trip, etc. the biomass co-firing system can be switched off rapidly, until the problem is resolved using normal procedures,
- The biomass feeder control system only communicates with the mill controls, i.e. it is an add-on to the normal boiler/mill/burner controls, and the appropriate safety interlocks are relatively simple,
- The biomass is co-fired with the coal through the unmodified coal burners at up to 50% heat input, i.e. there is much lower risk of problems associated with fuel feed instability and with combustion efficiency/burnout/flame shape/furnace heat transfer factors, etc. than for firing of the biomass through dedicated burners,
- The combustion of the biomass is always supported by a stable pulverised coal flame. This will help to optimise the combustion efficiency of the biomass, and can increase the fuel flexibility of the system to fuels with higher ash and moisture contents than could be fired successfully in suspension flames on their own, and
- Using this approach, the products of the combustion of the biomass are always well mixed with those from coal. This means that the risks associated with the striated flows in furnaces and boilers, and the tendency to produce localised deposition and corrosion effects, due to the concentration of the products of biomass combustion at particular locations, are minimised.

For both new build and retrofit applications, where the desire is to achieve elevated co-firing ratios, there will be a requirement to co-fire biomass through a number of mill groups. The potential impacts on the mills and the boiler will depend largely on the nature of the biomass and the target co-firing ratio, and this will generally need careful consideration. In principle, the co-firing of biomass up to a co-firing ratio of 50% or so, on a heat input basis, may be possible using this approach, although the range of biomass materials that can be co-fired at this ratio will be limited.

In most cases, the co-firing of biomass at up to 50% or so of the total heat input to the mill group is possible, depending on the turndown capabilities of the mill and burners. It is also possible, however, to install a double direct injection biomass firing system which will have the capability of firing 100% biomass into the mill group at up to the maximum heat input achievable on coal. In this case, the balance of the primary air, in addition to the biomass conveying air, is delivered through the empty coal mill. This can be achieved on a single mill group. It can also be done on all mill groups in the boiler to provide the unit with 100% biomass firing capability, while retaining the capability to return rapidly and automatically to coal firing as normal provided, of course, that the combustion system is capable of both 100% biomass and 100% coal firing.

3.3.4 Introduction of milled biomass into modified coal burners

This refers to Option 4 in Figure 3.1.

The direct injection co-firing of the pre-milled biomass into the existing pulverised coal burners in a wall-fired combustion system will normally involve significant modification of the burners. This approach may be relatively expensive to implement, and inevitably involves significant technical risk.

This approach may, however, be necessary for some biomass materials, where there is concern about the potential for the blockage of the pulverised coal pipework system, and particularly of splitters, riffle boxes, etc. and of the internals annular gaps within the pulverised coal burners themselves. One important example of a successful pulverised coal burner modification for this type of application is at Studstrupværket in Denmark, where chopped straw has been co-fired through the core air tubes of Doosan Babcock Mark III Low NO_x burners. The pulverised coal is fired through the primary air annulus, as normal. The modifications to the burner are illustrated in Figure 3.7, below.

In this case, the biomass material is cereal straw, which is delivered to the station in baled form, and is processed on-site to produce a fairly coarse chopped straw material. This is metered and blown along independent pneumatic conveying lines, at a rate of up to 5 tonnes per hour per line, from the straw handling plant and is co-fired with coal in four modified coal burners. Overall, the system is designed to co-fire more than 100,000 tonnes p.a. of biomass.

The biomass is injected directly through the back of the burners into the central core air tubes. Significant modification of the coal burners was required, including relocation of both the central oil lance and the flame detector to clear the core air tube for the biomass injection. This approach has the disadvantages that it inevitably involves some interference with the performance of the tertiary air swirlers, and their relocation means that both the oil lance and the flame detector are in non-ideal positions.

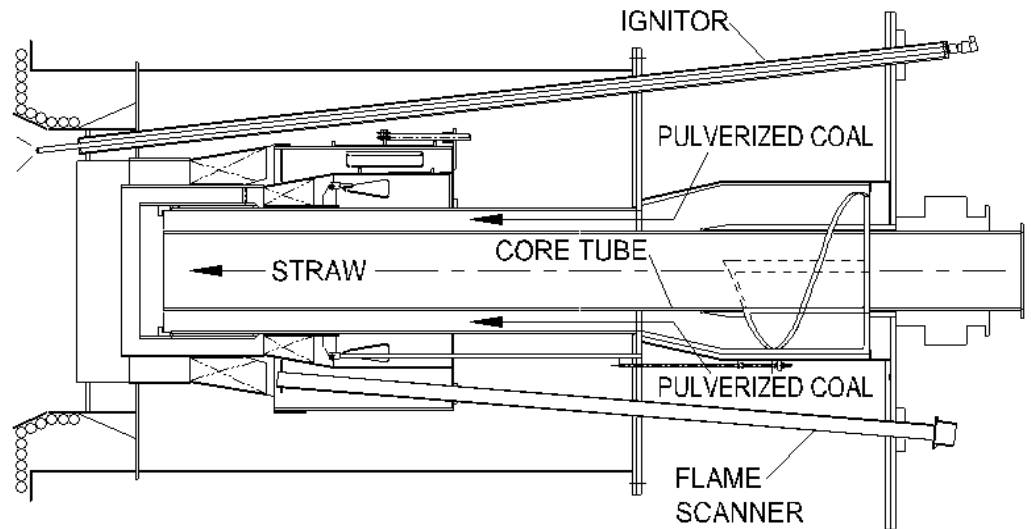


Figure 3.7 Doosan Babcock Mark III Low NO_x burners at Studstrup power station in Denmark, modified for straw co-firing (after Overgaard et al., 2004).

At Studstrup, the boiler engineers were forced down this particular route because of the requirement to provide a clear passage through the pulverised coal pipework and down the core air tube for the relatively large straw particles, to avoid blockages, particularly with wet straw. It was considered that trying to pass the chopped straw particles through the existing primary air annulus within the burner would lead to unacceptable risks of blockage, and that it was imperative that there should be no significant penetrations into the straw conveying pipework behind which the straw particles can accumulate.

A more detailed description of the experience with the straw co-firing system was given by Overgaard et al. (2004). In general terms, the experience at Studstrup has been positive, with some negative impacts on the combustion efficiency, due to drop out of the larger straw particles into the bottom ash hopper underneath the furnace. There was little negative impact on the NO_x emission levels, and on the boiler ash deposition.

There were significant initial difficulties with the handling and conveying of even relatively small quantities of very wet straw. This required significant improvement in the management of the quality and consistency of the delivered fuel, in co-operation with the fuel suppliers, to provide the level of control over the moisture content necessary for reliable operation of the system.

This type of approach may have some attractions, particularly for pre-milled biomass prepared from baled materials, which are difficult and expensive to mill to small particle sizes, and for materials that may have a tendency to blockage of the pneumatic conveying pipework and burner internals.

Although there are significant quantities of surplus cereal straws available in

many countries in Europe, this approach has not been widely replicated in other coal power plants in Northern Europe, principally because of the complication and relatively high cost of the fuel reception, storage and handling facilities that are required to permit the co-firing of biomass materials in baled form.

3.3.5 Direct injection through new dedicated biomass burners

This refers to Option 5 in Figure 3.1. In some applications, the installation of new, dedicated burners, in addition to the installed pulverised coal burners, for the co-firing of biomass materials, as a retrofit in existing boiler plants, may have some attractions. In these instances there will be a number of technical and commercial risk areas and significant practical problems to be resolved, namely:

- New burner locations, which will generally be within the existing burner belt, have to be identified, and significant new furnace penetrations are required. This is expensive and involves significant modification of the existing pressure parts,
- It can prove to be difficult to find suitable locations for new burners and for the associated fuel and air supply pipes and ducts, galleries etc. A secondary air supply to the biomass burners is required, i.e. there are significant modifications required to the existing boiler draft plant,
- The impacts of biomass co-firing on the performance of the existing pulverised coal combustion system and on the furnace and boiler performance may be significant, depending on the locations of the new burners. This is a significant potential risk area, and will need to be assessed in some detail,
- The dedicated biomass burners are based either on conventional pulverised coal burners or on cyclone burners, and these have not been extensively demonstrated commercially for this type of application. A large, multi-burner furnace, where the biomass burners will be operated in tandem with the conventional coal firing systems, represents a relatively challenging environment. There will be particular risks to the integrity of the new biomass burners when they are out of service and the pulverised coal burners are firing, again depending on the details of the locations of the new burners,
- This approach to the direct firing of biomass is complex, both in terms of the mechanical and control interfaces with the boiler, and
- The scope of the modifications to the furnace and the installed draft plant is substantial and it is clear that this approach to co-firing biomass will be relatively expensive.

There is a small number of co-firing systems in Europe based on the installation of dedicated biomass burners, although it is fair to say that the accumulated plant experience to date is not extensive, and all of the experience to date has not been successful.

3.3.6 General comments

Clearly, there are a number of viable technical options for the direct injection co-firing of pre-milled biomass materials as a retrofit to pulverised coal-fired power stations. The preferred technical option for any particular application will depend on a number of factors, namely:

- The types of biomass to be co-fired,
- The desired co-firing ratio,
- The site-specific factors, i.e. the types of coal mill, the arrangement of the installed coal firing systems, etc., and
- The proposed operating regime of the biomass co-firing system, and the aspirations of the station engineers.

A number of the more important direct injection biomass co-firing systems have been in successful commercial operation in Britain and Northern Europe for a number of years.

Overall, it is clear that direct injection co-firing is a technically reasonable and cost-effective approach to the co-firing of pre-milled biomass in a pulverised coal-fired boiler, for both retrofit and new build project applications. As stated above, this is based on successful commercial experience, albeit at a relatively small number of applications at power plants in Europe.

For new build applications, as with retrofit projects, the direct injection of the biomass to the pulverised coal pipework has significant additional attractions in that the technical risks associated with the combustion system and boiler design can be reduced significantly, i.e.

- The biomass co-firing system is additional to the coal milling and firing equipment, which can be designed for coal firing, applying normal design practices,
- This means that the coal firing capability of the boiler plant is not compromised in any significant way by the provision of the biomass co-firing capability,
- The co-firing of the biomass through one or more of the coal mills at up to 50% heat input will only have a very modest impact on the furnace heat absorption, i.e. the current combustion system and furnace design rules can be applied with only minor modifications, and
- The products of combustion of the biomass are always pre-mixed with at least the same amount of those of coal combustion, with reduced risks of localised ash deposition and corrosion effects due to the biomass firing. Because of the relatively low ash contents of most biomass materials compared to most coals, the mixed ash produced when co-firing is always dominated by the coal ash, even at 50% co-firing.

4 The impacts on plant operation

In general terms, the impacts of biomass co-firing on the operation and integrity of the boiler plant depend largely on the nature of the biomass material and on the co-firing ratio, as would be expected. At low co-firing ratios, say less than 10% on a heat input basis, i.e. the levels which are associated with co-firing by pre-mixing the biomass with coal and co-milling through the installed milling plant, a very wide range of biomass materials, with relatively high ash, moisture, sulphur and nitrogen contents, for instance, can be co-fired without significant problems.

With increasing co-firing ratio, the quality of the biomass will, of course, tend to be of more importance, and there will be significant limitations to the fuel flexibility of the system. At high co-firing ratios and when converting pulverised coal boilers to 100% biomass firing only the high grade sawdust pellet materials can be fired and it may be necessary to upgrade the on-line cleaning systems and apply fireside additives to control the risks of excessive ash deposition and high temperature corrosion.

4.1 COMBUSTION EQUIPMENT

When biomass materials have been co-fired with coal at low co-firing ratios less than 10% on a heat input basis, by pre-mixing the two fuels in the coal handling system and processing the mixed fuel through the installed bunkers mill and burners, the impacts on the performance and integrity of the installed coal combustion system have been very modest. Provided that the mill operational practice is modified to take the properties of the biomass properly into account and the co-firing ratio is controlled within the correct range, the impact on the performance of the mills is modest and the risks of increased incidence of mill fires and pressure excursions can be managed. The principal impacts of co-firing the biomass have been on the mills, as described in Section 3.2 above.

The properties and combustion behaviour of the mixed fuel are dominated by those of the coal, and the impacts of co-firing have been largely negligible, provided that the biomass material has been milled to an appropriate particle size distribution.

When the biomass has been pre-milled and is co-fired in direct injection systems at up to 50% heat input to individual mill groups of burners, the impacts on the performance and integrity of the combustion system have mostly been modest. In this case, the biomass combustion is supported at all times by a stable pulverised coal flame. A relatively wide range of biomass ash and moisture contents can be accommodated without problem, provided that the biomass has been milled to an appropriate top size.

If there is oversize material in the biomass feed, this will result in an increase in the number of unburned particles or 'sparklers' at the end of the flame, and an increase in the unburned fuel levels in both the bottom ash and fly ash. It will not normally be necessary to discontinue firing the biomass, but this may have an impact on the gaseous and gas-borne emissions from the plant and it

will represent a significant reduction in plant efficiency. There may also be problems associated with the disposal of high carbon ash discards from the plant. The installation of a dry bottom ash system with combustion and heat recovery from the unburned material can help to minimise these losses.

When milled biomass materials have been fired without coal support through unmodified low NO_x pulverised coal burners, there is a tendency for the flame produced to have the ignition plane located further out into the quarl than in a well-anchored pulverised coal flame. This is considered to be a result of the significantly longer heating times required for the larger, less dense biomass particles compared to pulverised coal particles.

The effect of this has been that the flame monitor signals obtained with the unmodified burners have been poorer than for a stable pulverised coal flame, particularly at reduced mill loads. There is no indication that the biomass flames are unstable, only that the ignition of the biomass particles is delayed.

This effect can be monitored by the insertion of a thermocouple through the core air tube of the burners out into the flame, and the measurement of the temperature profile at the centre-line of the flame with distance from the mouth of the burner. In the case of a well anchored coal flame, the temperatures will increase sharply to values in excess of 800°C within 500 mm of the end of the primary air annulus. In the case of the biomass flames in unmodified burners, the temperature increase was significantly slower.

The response to this issue has been two-fold:

- In some cases, modifications have been made to the flame detection system to provide a focus on a position in the flame further out into the furnace. This can provide acceptable signals from the biomass flames from unmodified pulverised coal burners, and
- In other cases, significant physical modifications have been made to the installed burners, designed to bring the ignition plane back into the burner quarl, and improve the flame monitor signals. These modifications normally involve a decrease in the primary air velocities at the mouth of the burner and an increase in the degree of swirl in the primary and secondary air streams.

These modifications would in most cases tend to reduce the NO_x control capabilities of the burner. There has in recent years been significant development and demonstration work carried out by the combustion equipment suppliers to enable them to offer a purpose-designed burner for milled biomass materials, which provides rapid ignition and good flame monitor signals, good burnout of the biomass and minimum NO_x emissions.

4.2 ASH DEPOSITION ON BOILER SURFACES

4.2.1 General comments

When converting pulverised coal boilers to biomass co-firing and 100% biomass firing, it should be recognised that the boiler has not been designed to reflect the properties and behaviour of biomass materials, and particularly

the biomass ash, and the range of biomass materials that can be fired successfully at higher co-firing ratios will be increasingly restricted, in most cases to include only the high grade wood pellet materials

The key fuel parameters that may be of importance in this context are:

- The ash content and ash composition, which will determine the risks of excessive ash deposition on boiler surfaces, and of high temperature corrosion of boiler components,
- The moisture content, which may affect the ignition rate of the fuel and the combustion conditions,
- The sulphur, nitrogen and chlorine contents, which will affect the uncontrolled gaseous emission levels, and may determine the risks of excessive high temperature corrosion rates, and
- The trace element contents, which may have an impact on the gas borne emissions and the ash discards from the plant.

Operational problems associated with the deposition and retention of ash materials can and do occur on all of the major gas-side components of combustors and boilers firing or co-firing biomass materials. The more important high temperature ash deposition occurrences within the combustion system and the furnace are associated with the following phenomena:

- The deposition of fused or partly-fused ash materials on burner components and divergent quartz surfaces, and the formation of 'eyebrow' deposits around burners and over-fire air ports, can result in interference with light-up and burner operation, and with combustion performance and NO_x emission control,
- The deposition of fused or partially-fused slag deposits on furnace heat exchange surfaces reduces furnace heat absorption, and leads to increased gas temperatures both within the furnace and at the furnace exit. This can lead to increased ash deposition and high metal temperatures in the convective sections of boilers, and if this becomes excessive, it may be necessary to reduce load or to come off load for manual cleaning,
- The accumulation and subsequent shedding of large ash deposits on upper furnace surfaces can lead to damage to furnace ash hoppers and other components of the lower furnace.

These are slag formation processes which occur at relatively high temperatures in excess of around 800-1000°C, on furnace refractory or water wall surfaces in direct receipt of radiation from the flame. These processes occur relatively rapidly, over a matter of minutes or hours, when conditions are favourable, and usually involve the sintering and fusion, or partial fusion, of fuel ash particles on the surfaces within the furnace.

The accumulation of ash deposits in the convective sections of boilers also occurs. These ash accumulations are normally termed fouling deposits, and

the more common occurrences include:

- The formation of ash deposits on the surfaces of superheater, reheater and evaporator banks occurs at flue gas temperatures less than around 1000°C. This is generally a much slower process than slag formation, with the tendency for significant ash deposits to grow over a period of a number of days and weeks. The process involves the formation of deposits in which the ash particles are bonded by specific low melting point constituents, principally the alkali metal species and, in some cases, the more volatile trace elements, such as lead and zinc,
- The flue gas temperatures are generally too low for significant sintering or fusion of the bulk of the ash particles to occur. In general terms, as the gas temperatures decrease through the boiler convective section, the deposits tend to be less extensive, and to be less well bonded and physically weaker. This is commonly reflected in the design of the boiler convective section, i.e. it is often possible to reduce the cross pitches of the tube banks progressively as the flue gas temperatures decrease, because of the reduced risk of uncontrollable ash deposition and of ash bridging across the tubes in the banks,
- Convective section fouling is one of the most troublesome ash-related problems associated with the combustion and co-combustion of biomass materials, because of their relatively high alkali metal contents, and hence high fouling potential in many cases,
- Increased fouling also increases the gas-side pressure drop across the banks, and can eventually lead to ash bridging between the tubes. This further increases the gas side pressure drop, and can result in the channelling of the flue gas, through a smaller number of open gas passes. This, in turn, can result in local overheating of the heat exchange tubes, and localised damage to boiler tubes and other components by particle impact erosion, due to the increased flue gas velocities,
- Ash deposits on economiser surfaces at low flue gas temperatures tend to be relatively weakly bonded. They are commonly initiated by the physical accumulation of ash, often by the gravitational settling of ash material which has been dislodged from primary deposition sites upstream of the economiser by the action of sootblowers.
- Low temperature fouling and corrosion of air heater surfaces are also common occurrences. These are fairly complex processes involving the condensation of acid species at temperatures below the dew points, and the chemical interaction of the ash particles with the condensed acid. These processes tend to be very specific to the design and operation of the air heater and the details of the chemistry of the flue gas and fly ash.

4.2.2 Ash fusion behaviour

One of the key properties of fuel ash materials, which has an impact on ash deposition, is their behaviour at elevated temperatures and, in particular, their fusion behaviour. In very general terms, three types of biomass ash system have been described by Bryers (1996), on the basis of their general ash chemical composition and their fusion behaviour:

- High silica/high potassium/low calcium ashes, with low-medium fusion temperatures, including many straws and agricultural residues,
- Low silica/low potassium/high calcium ashes, with relatively high fusion temperatures, including most woody materials, and
- High potassium/phosphorous ashes, with low fusion temperatures, including most manures, poultry litters and animal wastes.

The fusion behaviour of the ashes is an important factor in determining the propensities of the fuels to form fused or partly-fused slag deposits on furnace surfaces and may have an influence on the nature of the fouling deposits that can occur on the heat exchange and other surfaces.

The fusion behaviour of most fuel ashes is a fairly complex phenomenon, which is best described in terms of a melting curve, where the mass percentage of the ash, which is fused, is plotted against the temperature. An example of such a curve is reproduced in Figure 4.1. In this example, the melting curves of a model biomass ash system, comprising a mixture of simple alkali metal salts, have been calculated using a procedure based on experimental phase diagrams and thermodynamic data, (see, for instance Backman et al, 2005, and the references given therein).

On the ash melting curves, two key temperatures are commonly identified, and these can be used to help describe the behaviour of the ashes:

- The T15 temperature is the temperature at which 15% of the ash material by mass is molten. This is considered to be the temperature at which the surfaces of the ash particles or slag deposits begin to become sticky and receptive to the adhesion of solid ash particles arriving at the surface within the furnace, and
- The T70 temperature is the temperature at which 70% of the ash material by mass is molten. This is considered to be the temperature at which the outer surface of an ash deposit on a vertical surface will begin to flow, depending, of course, on the slag viscosity.

The standard Ash Fusion Test, which has been applied for the characterisation of the fusion behaviour of coal ashes for many decades, is based on the determination of three or four key temperatures on the melting curve. This procedure has been developed and applied specifically for alumina-silicate, coal ash systems, which have very variable and complex melting behaviour. Coal ash systems commonly melt over a fairly wide range of temperatures from around 1000-1500°C and, in most cases, tend to produce relatively viscous melts.

The results of the application of this test procedure to biomass ashes, most of which are not alumino-silicate systems, and many of which melt at temperatures less than 1,000°C, are of real technical interest, and can be used to compare the behaviours of different ashes. The results, however, should be treated with a good deal of caution.

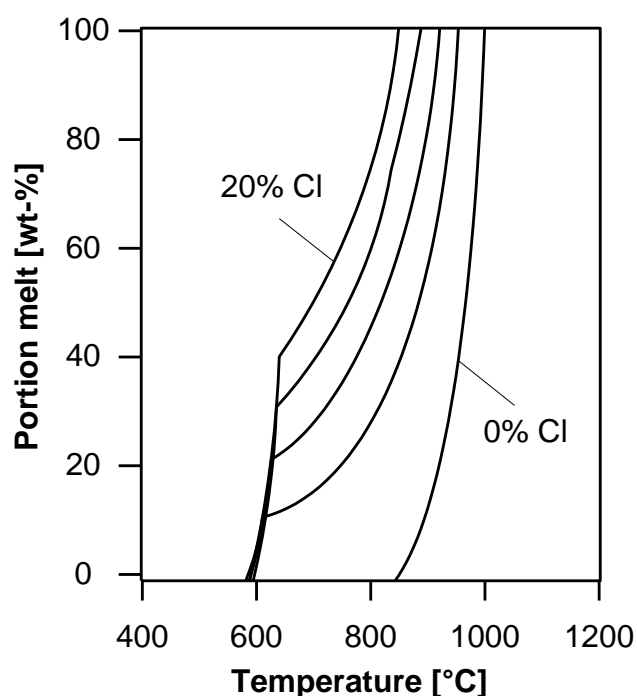


Figure 4.1 Calculated melting curves for salt mixtures with K/Na molar ratio 90/10, SO_4/CO_3 molar ratio 80/20 and Cl varying between 0 and 20% of the total alkali. (after Backman et al, 2005).

4.2.3 Slagging and fouling indices

A number of Slagging and Fouling Indices are available for the assessment of the propensity of fuel ashes to form boiler deposits. A detailed description of the technical basis and use of a number of the more traditional indices is presented in Raask (1985). These indices are based either on the fuel ash content and the ash chemical composition, or on the results of the Ash Fusion Test. In the main, these indices have been developed for the assessment of coal ashes. They have been applied, with appropriate modifications, to the ashes from other solid fuels, including wastes and biomass materials, and to the mixed ashes produced by the co-firing of biomass materials with coal.

The majority of the Slagging Indices are concerned with the assessment of the fusion behaviour of the ash and/or the viscosity of the melt. The traditional indices are based either on the results of Ash Fusion Test or on the chemical composition of the ash, and commonly on the mass ratio of the acidic metal oxides, (SiO_2 and Al_2O_3) to the basic oxides (Fe_2O_3 , CaO , MgO , Na_2O and K_2O). These indices provide a general assessment of the fusion behaviour of the ashes, which is then employed to rank the ash in terms of its propensity to form fused or partially-fused agglomerates and slag deposits. Despite the technical limitations of both of these approaches, they are still used widely in

the industry for fuel specification, furnace and heat exchanger design and for plant operational purposes to provide an assessment of the risks of excessive slag deposition for coal and for biomass firing.

A number of more sophisticated approaches to the assessment of the slagging propensity, for instance based on the use of phase diagrams of the appropriate alumina-silicate systems, or on the use of mineralogical analysis data derived from the characterisation of the fuel using scanning electron microscopes and other advanced techniques, have been developed, however these have enjoyed only relatively limited use within the industry.

Since the majority of the coal ash slagging indices are based on the assessment of the fusion behaviour of alumina-silicate coal ashes, their application to biomass ash systems, which are chemically very different, can be problematic. Great care should be applied when interpreting the conventional Slagging Index values for biomass ashes and to the ashes produced from the co-processing of biomass materials with coals. In general terms, the use of biomass ash melting curve data, if available and the results of the Ash Fusion Test, are preferable.

When considering the potential slagging behaviour of the mixed ashes from the co-processing of biomass with coal, it is clear that, apart from SiO_2 , all of the significant chemical constituents of most biomass ashes, and principally the alkali and alkaline earth metals, are powerful fluxes for alumina-silicate systems. It is expected, therefore, that the co-firing of biomass with coal will result in a reduction in the fusion temperatures, and hence an increase in the slagging potential. This will, of course, depend on the level of fluxing agents already present in the coal ash and on the co-firing ratio. It has been found that the effect is much more dramatic when biomass is co-fired with coals with high fusion temperature ashes. The effect of adding biomass ash to a coal ash with low levels of the fluxing elements tends to be much greater than that for a coal with lower ash fusion temperatures and higher levels of fluxing elements.

For the co-processing of biomass with coal at relatively low levels, the mixed ash is still predominantly an alumina-silicate system, and the normal coal slagging assessment methods based on the ash composition can generally be applied to the mixed ash with some confidence. At higher co-firing ratios, the mixed ash composition can be very different from that of most normal coal ashes, and this type of assessment can become more problematic. It may be preferable to base the assessment on ash fusion data, as discussed above.

The Fouling Indices for coal ashes are, in the main, based on the sodium content of the fuel. The deposition of the sodium compounds by a volatilisation/condensation mechanism is considered to be the principal driving force for the consolidation of heat exchanger fouling in coal plants. The potassium in coal ash is present predominantly as a constituent of the clay minerals, and is not considered to be available for release by volatilisation in the flame.

For most biomass materials, potassium tends to be the dominant alkali metal, and this is generally in a form that is available for release by volatilisation. The

fouling indices which have been developed specifically for the assessment of biomass materials tend, therefore, to be based on the total alkali metal content of the fuel on a mass or heat content basis (see for instance, Miles et al. 1995).

Overall, therefore, a practically useful suite of ash characterisation techniques and ranking methods are available for biomass materials and for the mixed ashes produced when co-firing. The majority of these techniques were originally developed and applied for the characterisation of coals and other conventional solid fuels, and for the study of their behaviour in combustion systems. Because they are already familiar within the energy industry, many of these methods have been adapted for use with biomass materials. As always, great caution should be exercised when applying these fuel assessment procedures and methodologies to materials and processes for which they were not originally developed.

4.2.4 Deposit formation and removal processes

In all practical situations, the long term accumulation pattern of deposits in furnaces and boilers involves competition between processes which tend to add to the mass of the deposits and those which remove material from deposits. These have been described by a number of authors in the technical literature for coal and biomass ashes (see, for instance, Raask, 1985, Baxter, 1993 and the references cited therein). The key deposit growth processes are as follows:

- Ash particle inertial impaction on the boiler surfaces is the dominant mass transfer process in high temperature slag formation, and for larger ash particles. The rate of deposition by impaction is a function of the fly ash particle flux to the surface, and of the deposition efficiency which, in turn, is dependent on the degree of fusion or stickiness of both the existing deposit surface and of the fly ash particles themselves,
- The condensation of volatile inorganic species, in vapour or fume form in the flue gases, on cooled surfaces, is one of the principal driving mechanisms for the initial slag formation process on clean furnace surfaces and is the key ash particle consolidation process in convective pass fouling. This is of particular importance for biomass materials because of the relatively high levels of volatile alkali metal and other species in these fuels,
- Chemical reactions occurring within the deposits, and particularly oxidation, sulphation and chlorination processes, can alter the nature of the deposit material and will tend to increase the deposit mass, and
- Thermophoresis, which involves the transport of small, gas-borne, ash particles to cooled surfaces by the effects of the local gas temperature gradients, is only important for very small, sub-micron particles. It may be relevant during deposit initiation when the local temperature gradients are at a maximum and when the rate of deposition by inertial impaction and other mechanisms is very low.

Uncontrolled ash deposition, with no deposit shedding or removal would very quickly result in operational problems in most boiler plants firing solid fuels. Most solid fuel furnaces and boilers are designed to minimise the extent of ash deposition in key locations. They are also fitted with on-line cleaning systems of various types to permit a level of control over the deposition rates, and hence to maintain heat absorption levels in the furnace and convective section. There are also natural ash deposit shedding mechanisms and other processes which are responsible for the reduction in the extent of deposition.

The key deposit removal processes are as follows:

- The principal means of on-line control of deposition in most furnaces and boilers is the use of the installed soot blowers or lances. These devices direct a high velocity jet of steam, water or compressed air at the ash deposits, and employ a combination of mechanical impact and thermal shock to break up and remove the deposited ash material.
- Sonic soot blowers can also be deployed, particularly for the dislodging of the relatively weak deposits in the cooler parts of the boiler convective section.
- In extreme circumstances, where very tenacious and troublesome ash deposits have formed, small explosive charges have been employed to break up the deposit material.
- The deposit material removed in this way may be carried forward through the boiler with the flue gases, but can also accumulate elsewhere on secondary sites within the furnace, in the convective pass of the boiler, at the hot end of the air heater, etc.
- The natural shedding or detachment of deposits also occurs. This can happen when deposits grow too large for the adhesive forces to support them, or due to the effect of thermal expansion differences between the ash deposit and the boiler tube, during shutdowns and boiler load changes. Rapid boiler/combustor load changes can be deliberately used for ash deposition control, particularly within the furnace.
- The detachment of large accumulations of slag in this way can, however, result in damage to boiler components or in the formation of troublesome accumulations of ash lower in the furnace, leading to the formation of deposits around the burners, or to the bridging of the ash hopper throat, for instance,
- Heavily fused ash deposits of low viscosity can run down the furnace walls or can drip on to surfaces lower down in the furnace or boiler, and
- In the boiler convective section, fly ash particle impact erosion wear can result in the reduction of the thickness of fouling deposits, particularly on the sides of tubes.

It is clear, therefore, that ash deposition control in biomass combustors and boilers is a fairly complex issue, involving fuel quality, boiler design and operational factors.

The key technical issues are:

- The careful design of the furnace and boiler convective section, which recognises properly the characteristics and behaviour of the fuel ash, is of prime importance. The equipment supplier obviously has the key role in this regard. The minimisation of refractory coverage within the furnace is essential. The incorporation of specific furnace and boiler design features, where appropriate, to minimise ash deposition, to aid the removal of ash, and to avoid ash accumulation within the system, is also of key importance,
- The correct design, operation and maintenance of the combustion equipment and of the on-line cleaning systems are important, and
- It is also often preferable to maintain the plants at a relatively low level of deposition, rather than to deploy the on-line cleaning systems only when there is evidence of significant deposition,
- Intensive cleaning of the furnace and boiler surfaces during outages can be very effective in reducing overall ash deposition rates and, in more severe cases, in increasing the operating times between forced boiler outages for manual cleaning.
- There are specialised on-line ash deposition monitoring and soot blowing control systems that are commercially available, and that can assist significantly with the optimisation of the soot blower operations and the control of ash deposition. These systems are designed principally for the control of deposition in the larger industrial and utility fossil fuel-fired boilers. Systems are available for the control of ash deposition in both the furnace and the convective sections, for optimisation of the boiler performance.

4.3 HIGH TEMPERATURE CORROSION OF BOILER SURFACES

The corrosion processes that occur on the gas-side surfaces of boiler tubes are very complex. They occur at high temperatures underneath ash deposits and in contact with combustion product gases, over extended periods of time during which the fuel diet and the operating conditions can change significantly.

As a consequence, these processes are very difficult to study and the metal loss rates are difficult to quantify. Nevertheless, because of their great importance to the designers and operators of large boiler plants, these processes have been the subject of a great deal of technical work, at laboratory, test rig and plant scale, over many decades.

There is a substantial technical literature on this subject, particularly for fossil

fuel-fired boilers, (Raask, 1988), and increasingly for biomass boilers and for boilers co-firing biomass with fossil fuels, as the industrial importance of biomass utilisation for power generation and combined heat and power applications has increased. Gas-side corrosion processes have generally been of less importance for domestic and small commercial/industrial biomass boilers, which tend to operate at much lower steam and metal temperatures.

In general terms, it has been found that the gas-side metal wastage rates of boiler tubes are controlled by a number of factors, viz:

- The tube material,
- The flue gas and metal temperatures,
- The chemical composition of the ash deposit material at the metal-deposit interface,
- The chemical composition of the flue gases, and
- The operating regime of the plant.

The concerns are principally associated with the final stage superheaters, with the leading elements and steam outlet legs being subject to the most aggressive attack, principally because of the relatively high metal temperatures.

The majority of biomass materials of industrial interest have the following key chemical characteristics, which have an influence on the high temperature corrosion processes:

- The biomass ashes tend to be relatively rich in alkali metals, and particularly potassium compounds, which tend to form deposits on the surfaces of the superheater tubes, via a volatilisation/condensation mechanism,
- Most biomass materials have relatively low total sulphur contents, generally less than 0.5%,
- The chlorine contents of biomass materials vary significantly, but can be up to 1% or so in some cases, and
- The result is that the S/Cl mass ratios for many biomass materials can be relatively low, compared to those for most coals.

The ash deposits that form on the boiler surfaces, therefore, tend to be relatively rich in potassium salts, principally sulphates and chlorides, depending on the fuel composition and the gas and metal temperatures. The chemistry of the biomass ash deposits tend, therefore, to be very different from that of most coal ash deposits, which tend to be dominated by sulphates. This can have a significant impact on the corrosion behaviour, particularly at high metal temperatures on superheater surfaces. In general, therefore, it is necessary to design dedicated biomass boilers with final steam temperatures that are significantly lower than those that apply in large coal-fired boilers.

The general experience with the operation of boiler plants firing a wide range of clean biomass materials has been that, at final steam temperatures in excess of 500°C, unacceptably high rates of metal wastage of superheater elements can occur. In boilers firing contaminated biomass materials and a wide variety of waste materials, with high alkali metal contents, significant trace element and chlorine contents, and low sulphur contents, significant corrosion of the superheater tubes can occur at even lower final steam temperatures.

There are a number of potential remedial measures available to address the observed corrosion problems:

- The control of the final steam temperatures, at the boiler design stage, to levels at which the corrosion rates are acceptable, for the fuel being fired and the superheater materials employed,
- The selection of more corrosion resistant alloys for construction of the final superheaters, if necessary,
- The protection of the surfaces of vulnerable high temperature tubing by the use of coatings, weld overlays and other measures, and
- The application of fireside additives to modify the flue gas and ash deposit chemistries and hence render them less aggressive.

The conventional approach to the control of superheater corrosion is by selection of the appropriate combination of tube materials and final steam temperatures for the fuel being fired. For instance, in modern mass burn incineration plants for municipal solid wastes, where the flue gases and ash deposits are extremely aggressive, it is common practice to limit the final steam temperatures to around 400°C, and to protect the furnace tubes and the leading tubes in the final superheater against corrosion and erosion processes with spray coatings and, in some cases, with SiC sleeving.

Modern biomass-fired boiler plants commonly have final steam temperatures in the range 450-540°C, depending principally on the characteristics of the fuel and the materials selected for the construction of the final superheater elements. These are design decisions taken by the boiler supplier, based on previous experience with the fuel and the best technical information available on the predicted corrosion rates of the proposed boiler tube materials.

A comprehensive description of the extensive laboratory and plant scale corrosion test work in this subject area is beyond the scope of this document. As an illustration, however, of some of the key work it is relevant to consider the early work of Montgomery et al. (2002). This provides a report of the results of a very significant programme of plant-based corrosion test work in small straw-fired power plants, i.e. Masnedo, Rudkøbing and Ensted, in Denmark, is relevant in this context.

In this case, the selected power stations were firing cereal straws, and both ferritic and austenitic superheater tube alloys were exposed to the flue gas atmosphere at metal temperatures in the range 450-620°C. It was found that

the measured corrosion rates for the test materials increased with increasing metal temperature, from values less than 0.05 mm over 1,000 hours at 470°C to values in excess of 1 mm over 1,000 hours at temperatures in excess of 600°C. These are clearly very aggressive conditions compared to those that apply when firing coal.

They also found that all of the alloys tested all gave fairly similar corrosion rates at any given temperature, although there appeared to be a shallow optimum in corrosion resistance for alloys with chromium contents in the range 15-18%. These results are not untypical for boilers firing biomass materials, where the corrosion process is driven by the presence of alkali metal chlorides at the metal/corrosion product/deposit interface.

The key results of the corrosion test in the flue gas stream of a straw combustion plant are summarised in Figure 4.2 (Henriksen et al. 2002).

This shows the measured corrosion rates in mm per 1,000 hours as a function of the metal temperature. The major trend is clear, with the corrosion rates increasing sharply with increasing metal temperature, as expected. All of the superheater materials tested, which had chromium contents in the range 11.7-18.4%, showed very similar trends with increasing metal temperature, particularly at temperatures in excess of 500°C. In very general terms, the authors were of the view that the corrosion resistance of the materials tested, with chromium contents in the range quoted above, were fairly similar.

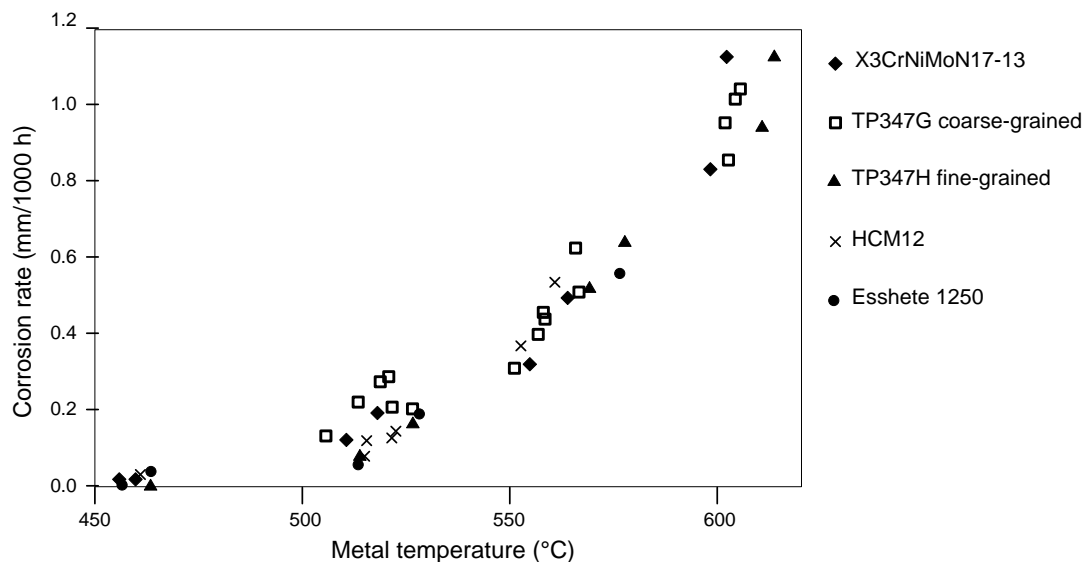


Figure 4.2 The corrosion rates of boiler tube material specimens exposed to the flue gases from straw combustion, plotted against the metal temperature. (After Henriksen et al. 2002)

Looking at the absolute corrosion rate values measured during these tests, it is clear that at metal temperatures around 460°C the measured corrosion rates for all of the materials were less than 0.05 mm/1000h, the equivalent of around 0.4 mm p.a.

At metal temperatures above about 500°C, the measured corrosion rates for all of the test materials were in the range 0.1-0.3 mm/1000h, or of the order of 0.8-2.4 mm p.a. These are very high corrosion rates, which would result in rapid failure if they were to apply to the boiler tubes.

At metal temperatures above 550°C, the corrosion rates were in the range 0.3-1.2 mm over 1,000 hours. This is a catastrophic corrosion rate for boiler tubes.

It should be noted that the solid and gaseous products of straw combustion tend to be particularly aggressive in this regard and that wood materials and other biomasses with lower sulphur and chlorine contents tend to be significantly less aggressive. The majority of boilers designed for the combustion of biomass materials have maximum metal temperatures less than 550°C, depending on the nature of the fuel.

A more comprehensive discussion of ash behaviour and boiler tube corrosion in biomass-fired boiler systems is presented by Frandsen (2011).

The use of fireside additives to modify the chemistry of the ash deposits may be of some benefit. This is common practice, for instance, in oil-fired boilers, where magnesia-based additives are employed to dry up the oil ash deposits on boiler surfaces, and to reduce the rates of metal wastage associated with the relatively aggressive vanadium oxides and sulphates in the oil ash deposits.

Vattenfall has been involved in the development of fireside additives, which have been of some value in reducing the active chloride concentration in biomass-fired boilers or possibly waste incineration plants, and which may have wider application (Henderson et al. 2006). They reported the use of a proprietary liquid fireside additive, ChlorOut, which was effective in removing KCl from the flue gases, but had only a modest effect on the SO₂ concentration and on the pH of the flue gas condensate. The results of 1,000 hour corrosion tests in a 100 MW_{th} bubbling fluidised bed boiler firing demolition wood, forestry residues and coal in Sweden indicated that there was a significant reduction in the measured corrosion rates when the additive was applied. Vattenfall have been actively applying the ChlorOut system, comprising the liquid additive and delivery system, with an in-furnace alkali chloride measurement system, specifically for use in biomass boilers and waste incineration plants.

There has also been some recent plant experience with the use of alumina-silicate additives, intended to react with the alkali metal species in biomass boilers and pulverised coal boilers converted to 100% biomass. This experience has involved the use of kaolinite or of coal fly ash as the source of the alumina-silicate, and has been applied principally in large pulverised coal boilers with relatively high final steam temperatures, which have been converted to biomass co-firing at high co-firing ratios or have been converted to 100% biomass firing.

Overall, therefore, it is clear from both laboratory and plants test work, and from plant experience, that the high temperature corrosion of superheater

tubes is a significant concern in biomass boilers, and particularly in boilers firing fuels with significant chlorine contents. There are also particular concerns in recent years about the risks of excessive rates of superheater and reheater corrosion in pulverised coal boilers which have been converted to 100% biomass firing, principally with wood pellets as the main fuel.

The key to the avoidance of excessive rates of metal wastage is the selection, at the design stage, of the correct combination of the final steam temperature and the tube material for the particular application.

It is also clear that the use of fuel additives can be of value in some cases, where problems arise on operating plants. This may be of particular interest in pulverised coal boilers with relatively high steam temperatures which are co-firing biomass at high co-firing ratios or have been converted to 100% biomass firing.

4.4 PARTICLE IMPACT EROSION OF BOILER TUBES

The erosion and abrasion of boiler components and other equipment in solid fuel-fired plants are associated predominantly with the presence in the fuels and ashes of hard mineral particles, and particularly those that are harder than the steels and refractory materials employed for the construction of the interior surfaces in the boiler. The only mineral species that is commonly found in clean biomass materials in significant levels in this category, is quartz.

Clearly, high quartz biomass materials, and those which have been contaminated with significant levels of tramp materials, are expected to present significant problems with erosion and abrasion of metallic components of the fuel handling and firing equipment. It is clear, however, from practical experience that, even for relatively low ash biomass materials, the risks of erosion damage in pneumatic conveying systems, are not negligible.

In general terms, the majority of the biomass materials under consideration have relatively low ash contents and, for this reason, erosion and abrasion processes tend, on the whole, to be similar to or less important than they are in coal-fired plants. There are, however, one or two specific areas where erosion and abrasion can be significant issues:

- The utilisation of some biomass materials, such as rice husks and sugar cane bagasse which have particularly high quartz contents can give rise to abrasion problems in the fuel and ash handling systems and to the erosive wear of pneumatic conveying systems and boiler components in the convective pass,
- In biomass boiler systems which suffer severe convective section fouling problems, excessive rates of particle impact erosive wear of boiler tubes and erosive wear associated with the overuse of convective pass soot blowers, in an attempt to control the impact of the fouling, are common occurrences, and with the high flue gas velocities that can be associated with ash bridging in the convective banks.

- The erosion rate of pneumatic conveying systems for biomass particles can be appreciable, again depending largely on the quartz content, the level of tramp material in the fuel and the conveying air velocity applied.

In general terms, however, the experience has been that the ash abrasion and erosion problems associated with the utilisation of the great majority of biomass materials are similar to or less important than those experienced when firing more conventional solid fuels.

4.5 FLUE GAS CLEANING SYSTEMS

The cleaning of the flue gases to a prescribed standard, prior to emission to the atmosphere, is a feature of all solid fuel boiler systems at industrial and utility scale in most countries. The larger combustors and boilers generally have fairly tight controls on emission levels, and the specific standards that are applied by regulators may depend on whether the biomass fuel being fired or co-fired is regarded as being a relatively clean fuel or as a waste material.

A range of appropriate flue gas cleaning systems, designed to comply with the relevant operating standards for most industrial biomass materials and combustion systems, are available commercially from experienced vendors, and are relatively well proven.

In modern coal-fired power plant boilers, the principal gaseous and gas-borne emissions control equipment is currently concerned with the control of the following prescribed pollutant species:

- Total particulate emissions control, principally using dry electrostatic precipitators or fabric filters,
- NO_x emissions control, by both primary and secondary measures, with low NO_x burners, two-stage combustion systems, selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) systems being the most commonly applied measures, and
- The control of SO_x emissions, principally by limestone additions to fluidised bed boilers, particulate capture in fabric filters, and by limestone-gypsum, wet flue gas desulphurisation (FGD) techniques in large pulverised coal boilers.

All of the flue gas clean-up technologies listed above are very well proven industrially for coal firing, over a wide range of coals. There are a number of experienced specialist vendors for all of the most commonly applied equipment. Generally speaking, the implementation of these emission control measures in large solid fuel-fired boilers has been very successful, and the emission levels of the key pollutant species have been reduced substantially over recent years.

4.5.1 Particulate emissions control

When considering the effects of the firing and co-firing of biomass materials on the performance of the electrostatic precipitators and on particulate emission

levels, the principal technical concern is that the fly ash particles generated from biomass combustion tend to be very different from those from coal firing, i.e.;

- The biomass fly ashes are very different chemically and mineralogically from pulverised coal fly ashes,
- They have significantly smaller particle size distributions than the fly ashes from coal firing, and
- With biomass, there is a greater tendency towards the generation of sub-micron fumes and vapours.

There may, therefore, be a tendency for the particle capture efficiency in electrostatic precipitators to decrease with increasing co-firing ratio. It should also be noted that the ash contents of most biomass materials are much lower than those of most steam coals, which means that compliance with a prescribed emission consent limits can be achieved at lower particle collection efficiency levels. Clearly, in the case of the particulate emissions there are two competing effects.

In most countries, it is necessary to demonstrate to the environmental regulators that the firing and co-firing of the biomass materials in large pulverised coal-fired boilers has no significant negative environmental impacts. There is a growing body of evidence that, at relatively low biomass co-firing ratios, i.e. less than 10% on a heat input basis, that there have been very few incidents of significant increases in the total particulate emission levels due to the biomass co-firing activities.

There is also a growing body of experience, albeit involving a much smaller number of cases, that indicates that there has not normally been a requirement for major upgrades to the electrostatic precipitator performance when pulverised coal boilers have been converted to 100% biomass. It is clear, however, that compliance with the particulate emissions consent limits is an issue which requires very careful consideration.

4.5.2 NO_x emissions control

Turning to NO_x emission control, it is relevant to note that the nitrogen contents of most biomass materials are significantly lower than those of most coals. The result is that the uncontrolled NO_x emission levels from biomass firing and co-firing at elevated levels tend to be significantly lower than those for coal alone, everything else being equal.

The performance of SCR catalysts, and particularly the effective catalyst lifetime, can be influenced by a number of factors, many of which are related to the ash chemistry of the fuel (Bill et al, 2005):

- Thermal degradation of the catalyst by pore sintering,
- Ammonia salt condensation inside the catalyst pores, commonly due to low temperature operation,

- The surface blocking of catalyst pores by small fly ash particles,
- The poisoning of catalyst surfaces by the condensation of volatile inorganic species, and
- Fly ash particle impact erosion of the catalyst material.

Early experiences of the use of SCR catalysts in wood chip and peat-fired boilers in Scandinavia, and of boilers firing animal manures and sludges, indicated that deactivation of the catalysts, chemical and physical, by sodium and potassium salts, and by phosphorus and silica compounds was a significant issue, which can result in markedly reduced catalyst lifetimes and increased operating costs (Ahonen, 1996, Beck et al, 2005).

A number of laboratory and plant tests of the impacts of biomass co-firing on the fouling and deactivation of catalysts have also been performed over the past few years. Baxter and Koppejan (2005), for instance, presented some of the results of experiments involving the exposure of SCR catalyst materials in a slip-stream reactor on a combustor firing alkali and alkaline earth metal rich fuel. These data have been reproduced in Figure 4.3. The data indicate clearly that there were significant increases in the concentrations of calcium, sulphur and sodium compounds on the surfaces of the catalyst material after prolonged exposure to the flue gas. The results of the test work also indicated that there was significant deactivation of the catalyst.

At Studstrup power station in Denmark where, since 2002, cereal straws and other baled biomass materials have been co-fired, at up to 10% on a heat input basis, with coal in a 350 MW_e boiler, the impact of the co-firing on a side stream SCR catalyst block has been studied over a period of up to 5,000 hours (Overgaard et al, 2004). The results of this test work have indicated that there was no significant difference in the performance of the catalyst between the straw co-firing test and coal firing alone. This indicates that the impact of low level co-firing, even of relatively high ash biomass materials, was modest.

The deactivation of SCR catalysts associated with the firing or co-firing of biomass materials is clearly of industrial importance, and this has been the subject of a major EC-funded R&D project, CATDEACT, which is co-ordinated by IVD at the University of Stuttgart. The details of the project partners, the work programme and test results are given in the project website, www.eu-projects.de.

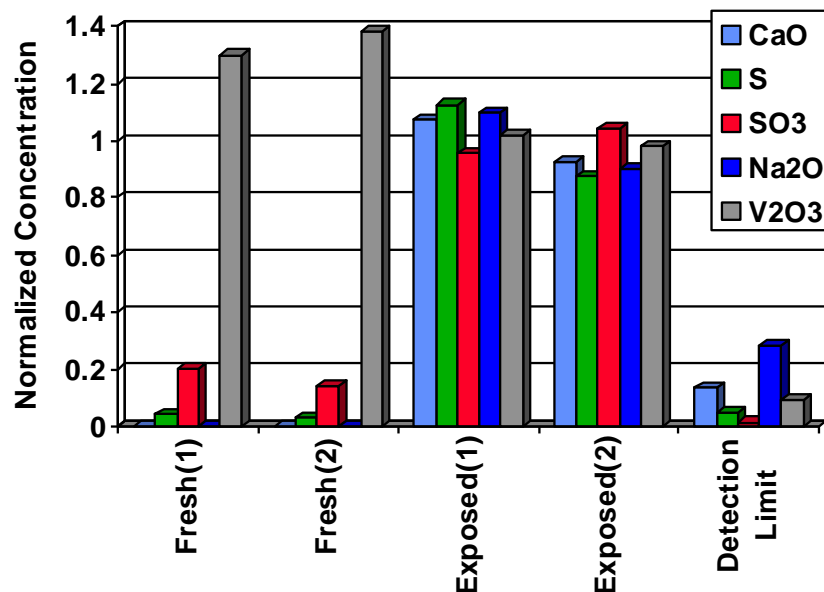


Figure 4.3 The results of surface compositional analysis showing the concentrations of key elements (as oxides) in pre- and post-exposure SCR catalyst from a slipstream reactor exposed to the flue gas from a combustor firing an alkali and alkaline earth metal-rich

At the biomass co-firing levels lower than 10% on a heat input basis, there have not, as yet, been any significant operational problems, and the results of a number of side stream tests at low co-firing ratios on operating plants have been relatively encouraging in this regard.

In the event of significant catalyst deactivation, it is possible to water wash the catalyst blocks to remove alkali metal and other salts and recover the catalyst activity. Avedøre power station in Denmark, where they have been involved in the co-firing of wood pellets with HFO and natural gas, has had such a system in commercial operation for a number of years (Ottosen, 2005).

Experience has shown that the co-firing of clean wood pellets does not have significant impact on DeNOx catalyst deactivation rates. However, full conversion from coal to 100% clean wood pellet firing does have considerable impact on catalyst deactivation rates. A proven method to mitigate this negative impact has been developed by DONG Energy and it consists of the addition of coal fly ash to the boiler. In this way, poisoning components originating from the wood are absorbed on the coal fly ash and their impact on catalyst deactivation is reduced.

Overall, it would appear that the increased deactivation rates of SCR catalysts due to alkali metal and phosphorus fouling is a significant technical issue when firing or co-firing biomass materials with high levels of these species. The suppliers of deNOx catalysts now have significant experience of these issues and can provide estimates of catalyst lifetimes for particular fuels and specific biomass firing/co-firing operating regimes in particular plants. The addition of coal fly ash can be applied to reduce the catalyst deactivation rates in coal boilers that have been converted to fire 100% clean biomass pellets.

4.5.3 SO_x emissions control

The great majority of clean biomass materials of industrial importance have sulphur contents that are significantly lower than those in most coals and, in the great majority of cases, they also have similar or lower chlorine levels. The impact of biomass co-firing, therefore, in the great majority of cases is to reduce the acid gas abatement duty of the installed FGD system, and hence reduce the limestone usage and plant operating costs.

The great majority of biomass materials also have significantly lower levels of most of the key trace element and heavy metal species than most coals, and the duties of the waste water treatment plants are reduced. This is not the case, of course, for a number of the biomass-based waste materials.

The evidence to date from coal-fired power plants which have been co-firing clean biomass materials, albeit at relatively low co-firing ratios, has been that co-firing has had no significant negative impacts on the operation and performance of the FGD plants.

5 Case studies co-firing and full coal to biomass conversions

A number of the key projects where biomass firing and co-firing in large pulverised coal boilers has been commercially practiced at large scale, and has operated over an extended period of time, are described briefly in this section.

5.1 DRAX POWER CASE STUDY

5.1.1 Introduction

Drax Power is part of Drax Group, a company that both sources biomass, generates electricity from coal and biomass, and delivers it to industrial customers. Drax power station was commissioned in the 1970s and 1980s, and comprises six pulverised bituminous coal boiler and turbine units, each of 660 MWe. The history of biomass utilisation at Drax is presented graphically in figure 6.1.

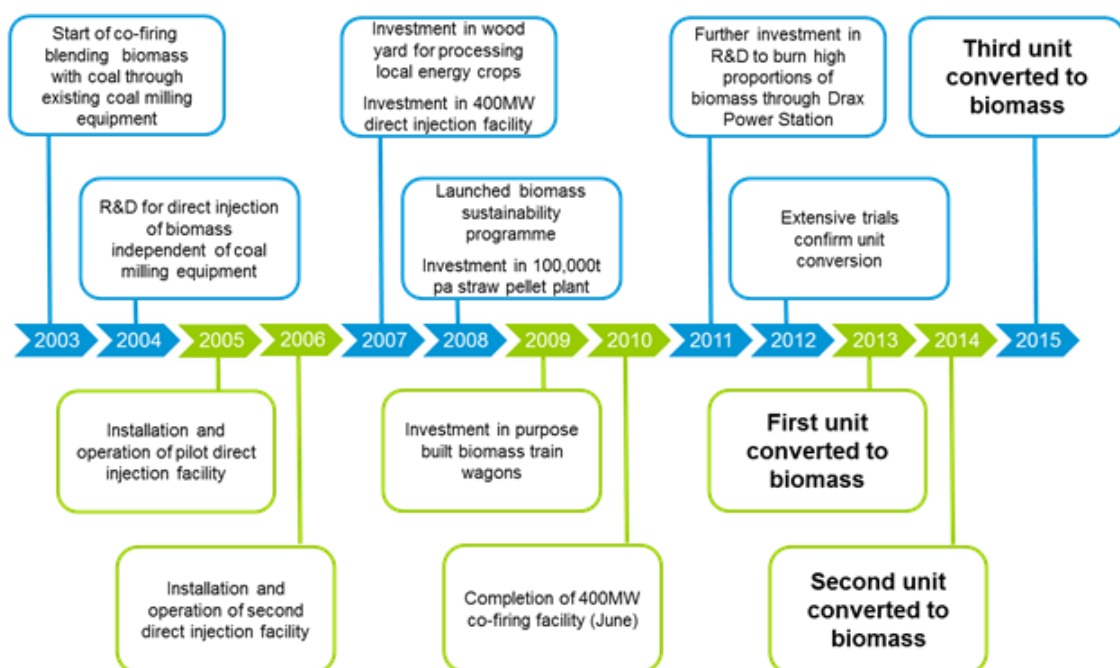


Figure 5.1 Timeline of Drax biomass firing and co-firing developments

5.1.2 Early days

In 2003, the first biomass co-firing trials were held. This led to commercial operation with biomass co-firing at a low percentage in all six boilers. The co-firing activities involved the pre-mixing of the biomass, principally in granular or pellet form, with the coal on the main coal conveyors, and processing the mixed fuel through the existing coal milling and firing system, with little or no modification. This approach allowed up to around 10% co-firing on individual mill groups. Commercially, around 3% biomass co-firing was achieved across the station, constrained mainly by the limitations of the biomass reception, handling and mixing systems.

In 2005-2006 a prototype direct injection co-firing system was installed. The biomass was milled in a hammer mill to a suitable size for firing in a pulverized coal flame, and was injected pneumatically at a controlled rate into the two mill outlet pipes on a single coal mill on Unit 3. This allowed up to 175,000 tonnes p.a. of a range of biomass materials to be co-fired. The system was extended by the addition of two further biomass pipes to allow co-firing on one of the coal mills on Unit 4.

From 2007-2010 a large scale direct injection facility, on the principle demonstrated by the prototype unit, was built. The project included road and rail receipt, storage, milling and delivery of biomass downstream of the coal mills. This system supplied all two mills on each of the 6 generating units and permitted the co-firing of around 1.5 million tonnes p.a. of biomass, equivalent to around 400 MWe or 10% of the generation capacity of the total station.

5.1.3 Full conversion

In 2010 two of the existing ten vertical spindle, ball and ring, coal mills on Unit 1 were successfully converted, initially on a trial basis, to the processing and firing of 100% wood pellets. This led, over the period 2012-15, to the conversion of all of the coal mills on three of the generating units to 100% biomass. This is equivalent to around 2,000 MWe, or around 50% of the generating capacity of the station, supplying the UK with approximately 4% sustainable, renewable energy.



Figure 5.2 Aerial view showing the coal stockpile and the four biomass silos.

To enable the conversion of three of its generating units to biomass, Drax commissioned a major upgrade of the biomass reception, storage and handling facilities, which are currently capable of handling up to 9 million tonnes of biomass p.a. This is by far the largest single wood pellet consumer in the

world.



Figure 5.3 One of the large dust extraction systems

The great majority of the biomass is in the form of imported white wood pellets, delivered by train, which is either fed straight to the generating units or stored in one of the four large storage domes, each of 75,000 tonne capacity. The domes are a UK first and include nitrogen purge systems and CO₂ extinguishing systems for fire prevention. The fuel is then conveyed mechanically to day silos then pneumatically to the boilers. All conveyor belts are enclosed and the transfer points on the conveyors are designed to minimize dust generation or extract dust where it is generated.

The biomass is then fed to the 10 converted coal mills and fired through up to 48 pulverised fuel burners on each unit. The principal physical modifications were to the mill classification system, to maximize the biomass throughput. There were no modifications to the mill grinding elements or the mill body. New biomass burners have also installed.

The maximum power output of the units has been maintained post-conversion

and the overall cycle efficiency of the power plant has not been adversely affected by firing biomass. The conversion has been Europe's single largest de-carbonisation project, reducing CO₂ emissions by 12m tonnes per annum (equivalent to 10% of UK motor cars).

The contribution of and review by Mr. Steven Tosney, Drax Power, is gratefully acknowledged by lead authors.

5.2 IRONBRIDGE CASE STUDY

Ironbridge Power Station is located in Shropshire, England and is owned and operated by E.ON. It has two 500 MW_e pulverised bituminous coal-fired boilers which were commissioned in 1969. The power station was due to close in 2013 under the EC Large Combustion Plant Directive.



Figure 5.4 Aerial view of Ironbridge Power Station

It was proposed to convert the two boilers to 100% wood pellet firing for the final 11,000 hours of operation, to assist E.ON and the British government to meet their CO₂ reduction targets. The project work on the Ironbridge site included a major upgrade to the fuel handling and storage facilities and the conversion of the boiler and associated plant to 100% biomass firing.



Figure 5.5 The covered storage facilities for the biomass

The scope of work on the fuel reception and handling facilities, included

- New fuel reception and covered fuel storage for the biomass, and
- Modification of the fuel conveyors and bunkers.

Each boiler had five large ball and tube coal mills. The results of a programme of test work in 2011 had established that this type of mill is unsuitable for the processing of wood pellets at the required throughput and product fineness, and it was decided to replace each of the large coal mills with two hammer mills. The primary air supply ductwork and the pulverised fuel pipework were modified to accommodate the new milling system.

In summary, the scope of the boiler conversion work, included:

- Modification of the installed fuel feeders,
- Removal and replacement of the coal mills with hammer mills,
- Redesign of the primary air supply system, to include primary air coolers, with heat recovery to the low pressure feed water system,
- Modification of the installed pulverised coal burners, and
- Modifications to the electrostatic precipitators.

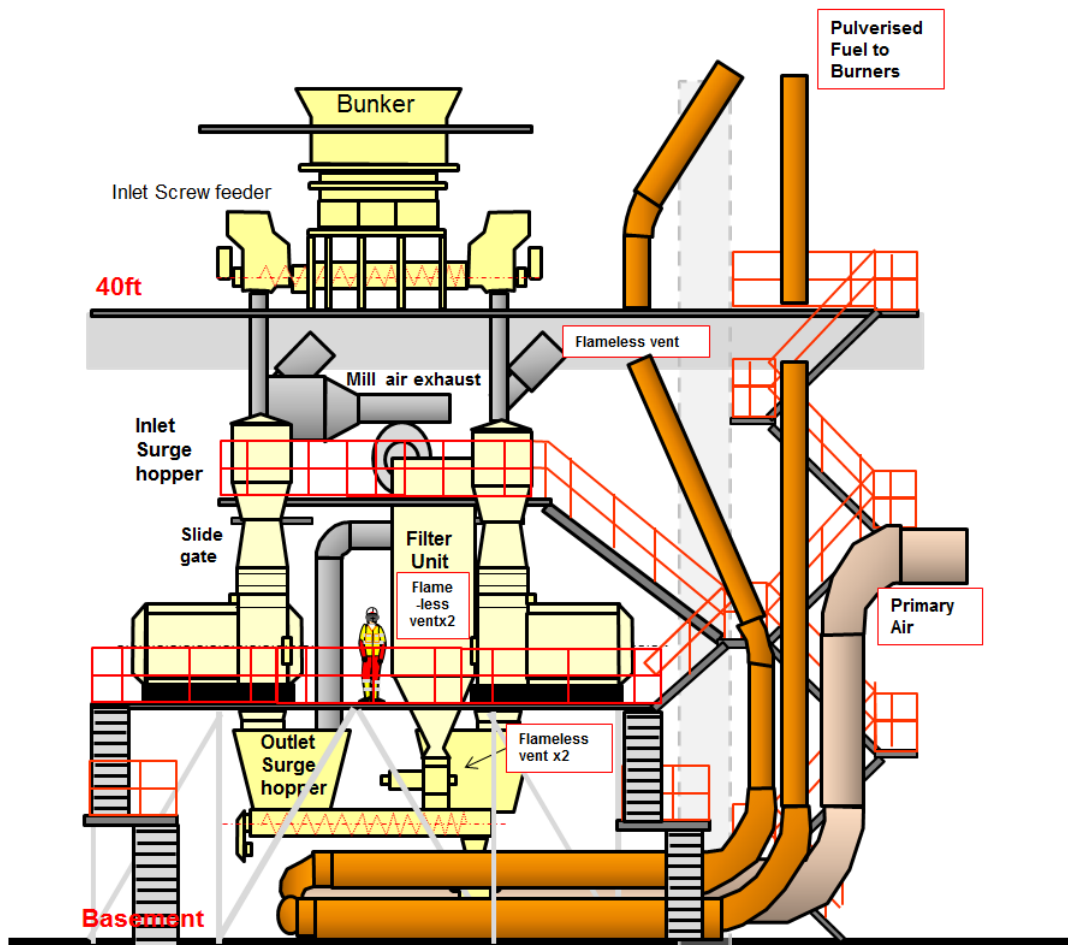


Figure 5.6 A sketch of the general layout of the biomass feeder, hammer mill and primary air/pulverised fuel pipework

No modification of the boiler pressure parts, the existing draft plant and air heaters was required, and there were no significant modifications to the balance of the power plant, including the steam turbines.

The converted plant performance tests were held in September/October 2013, and the two units were handed over in November 2013. Overall, the boiler efficiency was slightly improved when firing the biomass, due to the reduced flue gas losses and the lower unburned carbon levels compared to those when firing coal. The NO_x, SO_x and dust emission levels were all significantly lower than those achieved when firing coal.

5.3 AMER CASE STUDY

5.3.1 Background and history

Essent (an RWE company) commenced large scale biomass operations in 1999, with a stand-alone fluidised bed biomass combustion facility in Cuijk, generating 25 MWe. The plant has been operated using mainly fresh wood chips, park wood residues etc. Mixtures of different types of fuel including demolition wood, paper sludge, grass and RDF have been fired on a trial basis.

At that time Essent had also started to co-fire different types of biomass, including wood, palm kernel, rice/soya husks and coffee husks, by mixing biomass with coal at the 600 MWe pulverised coal boiler units at Amer 8 and 9 in Geertruidenberg. The biomass co-firing ratio was up to 5% on a mass basis. One of the conclusions of this early stage of co-firing was that the milling of biomass and coal should be done separately in order to reach the optimum particle size of each of these fuels.

In 2000 Essent started the operation of a 33 MWe biomass gasifier, which fed syngas to the Amer 9 boiler. The gasifier was initially equipped with an extensive syngas cleaning system, enabling the plant to gasify different types of biomass, including demolition wood.

In 2003, one of the existing coal mills at the Amer 9 power plant was converted to wood pellets to enable co-firing at up to 83 MWe in the 600MWe boiler. One year later, dedicated hammer mills were installed at the Amer 8 coal fired power plant, enabling the plant to generate 96 MWe (design) of green power. In 2005, at Amer 9, a second coal mill was converted to biomass, enabling the plant to generate another 83 MWe of green power.

By co-firing biomass at the Amer power station, as described above, Essent has reduced its annual CO₂ emissions by approximately 1 million tons per year. The incentives for the firing and co-firing biomass have been provided by the Dutch subsidy schemes MEP and SDE(+).

5.3.2 Technology applied at Amer power station

5.3.2.1 Direct biomass co-firing at AMER 8 and AMER 9

Amer 8 and Amer 9 receive most of their biomass fuel, mainly white wood pellets, by barge. These are unloaded using a pneumatic ship unloader. The material is either stored in four concrete silos with a capacity of 5000 m³ each or is directly transported to the day bunkers of the boiler units. The transport system consists closed belt conveyors and transfer points.

In Amer 9, the existing coal bunkers are used and in Amer 8 a new intermediate silo upstream of the hammer mills has been installed. In addition, the site has a small facility for truck unloading and fuel blending to mix biomass with coal upstream of the coal bunkers.

The Amer 8 power plant is equipped with two Christy hammer mills, with a total nominal capacity of 320,000 tonnes p.a. of white wood pellets. The pulverised biomass is transported pneumatically to dedicated biomass burners, which are at the position of two levels of the original oil burners in the corners of the tangentially-fired furnaces.

At Amer 9 power plant, two out of six MPS coal mills have been converted to mill biomass pellets. The original modifications to the mills included:

- reduced primary air inlet temperature,
- the installation of explosion suppression equipment,
- the construction of inner mill baffles and closure of inner holes to

minimise the primary recirculation within the mill and

- alteration of the orientation of mill rollers.

Additional measures, introduced after some years of operational experience include:

- discontinuing the use of the rotating classifiers,
- increasing the mill outlet temperature and
- increasing the mill capacity to the coal design value by improving the mill differential pressure control.

Each of the converted mills is capable of handling 18% by mass of the total fuel input of the boiler plant. The milled biomass is transported pneumatically to the unmodified pulverised coal burners.

5.3.2.2 Indirect cofiring at AMER 9

The Lurgi CFB gasifier has a capacity of 83 MWth and was designed to gasify about 150,000 tonnes p.a. of low quality demolition wood. The wood is delivered by truck and is chipped to a 50 mm top size upstream of the gasifier.

The gasifier was originally equipped with an extensive, low temperature gas cleaning system to effectively remove halogens, ammonia and tars from the fuel gas. There were severe problems during commissioning, principally associated with excessive fouling of the syngas cooler. It was decided to simplify the fuel gas cleaning system to include hot cyclones only, operating at approximately 450oC, to avoid condensation.

After these modifications, the gasifier has been operating for approximately 5000 hours p.a. This is limited by fuel feeding system issues and syngas cooler fouling due to tar deposition. At the end of 2013, the gasifier was taken out of operation, due to the expiry of the government subsidy scheme.

5.3.3 Lessons learned at Amer power station

Over the past 15 years Essent has experienced a number of operational issues related to co-firing of biomass at the Amer 8 and Amer 9 power plants.

Fuel handling problems have been experienced due to dust, fineness and poor pellet durability. Dust is the main safety concern in biomass application and dust formation and impact are to be minimised:

- Minimise the number of transfer points
- Prevent deposition on surfaces where possible
- Continuous cleaning is required
- Closed transport systems are to be preferred (tube conveyors, screws, pneumatic transport)
- Monitoring of surface temperatures, e.g. at bearings, is important

- Multi gas detection required in silo's for early recognition of self-heating
- Proper fuel logistics to reduce risk of fire and explosions

Fuel quality issues have included off spec biomass and impurities causing operational problems in transportation and milling equipment. High wear rates, mainly due to sand,

Milling capacity as a function of particle size of pulverised biomass. The hammer mills initially showed lower output than rated, when achieving adequate biomass particle size,

Boiler aspects:

The air-to-fuel ratio over the whole furnace is of great importance for good combustion behaviour

- Large biomass particles and inadequate air-to-fuel ratios lead to high carbon in fly ash and to unconverted biomass in the bottom ash system, ("green soup")
- The risk of furnace wall corrosion due to incorrect fuel to air ratios is significant. The air distribution needs to be adapted for each individual case, especially in low NO_x furnaces.
- The risk of overheating in superheaters due to changed reduced heat absorption in the furnace. This can lead to plant output limitations when not tackled adequately.

The contribution of and review by Dr. Wim Willeboer, Essent, is gratefully acknowledged by the authors.

5.4 DONG ENERGY CASE STUDY

5.4.1 Background and history

Denmark has a long history of the encouragement of the use of biomass in power and heat generation. In 1993 heat producers were obliged to increase the use of biomass, and in 1997 it became possible to use biomass in former natural gas areas enabling the growth of decentralised CHP. The high level of CHP application in Denmark is unique in Western Europe.

Avedøre power station is owned and operated by DONG Energy and it consists of two power plants:

- Avedøre 1 (commissioned 1990) and
- Avedøre 2 (commissioned 2001).

The power station is located close to Copenhagen and it is connected to the city's district heating system.

The Avedøre 1 unit is a coal and oil fired CHP plant, commissioned in 1990. In CHP mode the unit can generate up to 215 MWe of power and 330 MJ/s of heat. In power only mode the maximum output is 250 MWe at 540 °C and 250 bar. The overall efficiency is 91% when operating in CHP mode or 42% in condensation mode.

DONG Energy has recently announced that the unit will be fully converted to wood pellet firing and that it will be operational on biomass from autumn 2016 on. Based on a new agreement between DONG Energy and the district heating company VEKS the power plant will supply heat to VEKS' customers between 2016 and 2033. This agreement provides the basis for the investment in the converting and prolonging the lifetime of the CHP unit.

The Avedøre 2 plant was originally designed as a coal fired power plant, but coal has never been fired in the unit. Instead, the plant has been operated as a multi fuel plant, using natural gas, heavy fuel oil and straw. In 2000 DONG Energy had built a straw fired boiler (105 MWth), which has a steam-side connection to the main boiler of the Avedøre 2 power plant.

The multi-fuel concept at Avedøre 2 includes two 55 MWe gas turbines, of which the flue gases are directed to the main boiler of the power plant. Avedøre 2 is a CHP unit that can supply up to 495 MWe and 575 MJ/s. In power only mode the maximum output is 575 MWe.

In 2003 the main boiler of Avedøre 2 was converted to generate 80% of its nominal rating on wood pellets. Oil and gas burners were retained in case needed.

In 2014 the conversion of the main boiler enabling 100% wood pellets firing was realised.

The total wood pellet consumption at the Avedøre site is expected to reach more than 1.2 million tonnes p.a. by 2016.

5.4.2 Technology applied at Avedøre power plant

5.4.2.1 Straw firing at Avedøre 2

The straw fired boiler at Avedøre 2 is grate fired and it generates 105 MWth. The boiler was specifically designed to burn straw as a fuel.

The Hesston straw bales are stored dry in a large shed. Truck unloading as well as transportation of the bales to the shredders upstream of the boiler is fully automated. The strings that keep the bales together are removed automatically just upstream of the bale shredders.

The shredded straw is fed into the furnace by screw feeders onto a water-cooled vibrating grate where up to 80 percent of the energy content is released by pyrolysis and gasification. The remaining straw/carbon will burn out on the water-cooled vibrating grate.

The boiler generates steam at the parameters 300 bar and 540°C, which is added to the high pressure steam system of the main Avedøre 2 boiler, upstream of the HP steam turbine. The applied superheater alloy is TP347HFG.

The flue gas cleaning consists of a baghouse filter and the collected ashes are returned to the fields due to its fertilizer value.

5.4.2.2 Wood pellet firing at Avedøre 2

Avedøre 2 is a tangentially fired power plant with a design capacity of 800 MWth. The design steam parameters are 300 bar, 580/600 °C for coal and 540°C for gas/oil/wood. In 2006 this temperature was increased to 560°C after use of coal ash as an additive was introduced.

The boiler has 16 pulverised fuel burners in 4 levels, supplied by 4 Loesche coal mills. The flue gas cleaning system includes a high dust SCR, an electrostatic precipitator and a wet limestone FGD plant.

After commissioning in 2001 the main boiler of Avedøre 2 has been operated on natural gas and HFO. DONG Energy carried out the conversion to 80% wood pellet firing and commissioning took place in 2003.

Three of the "new" Loesche coal mills were adapted for biomass application. This included

- The introduction of holes in the milling table to provide good attachment between table and wood material,
- Primary inlet temperature reduction of primary air to 125°C.
- Just minor modifications to the classifiers were applied.
- Dust explosion protection/extinguishing containers on mills and pipework.

The mills are capable of reducing the wood particle size to approximately 85% < 1mm. This ensures good ignition and satisfying burnout of the particles, resulting in less than 5% carbon in ash.

The fuel specification as received include among <1.5% ash and 95% < 2mm. The modified coal mills have a high availability (98-99%) and the lifetime of wear parts is over 300,000 tons of pellets.

The burners at Avedøre 2 are modified coal burners, multi fuel burners that can handle natural gas, heavy fuel oil and wood dust. New swirlers have been installed in the primary air pipe to ensure a more attached flame.

From 2010, wood pellets have been stored in two silos with a capacity of 15,000 tonnes. The wood pellets are conveyed by covered conveyor belts to the coal bunkers. Coal feeders ensure transport of pellets from the bunkers into the modified coal mills.

In 2014, the fourth and last coal mill has been modified for wood pellet milling. This enables the plant to be operated at 100% of its rated capacity without any fossil fuels. Another wood pellet silo of 65,000 tonne capacity has been installed which brings the total storage capacity to 110,000 tonnes.

5.4.3 Lessons learned from biomass firing at Avedøre power plant

Over the past 14 years DONG Energy has experienced a number of operational issues related to wood pellet firing in the Avedøre 2 power plant, including:

- Fuel processing problems occur due to larger pieces of wood or other materials present in the wood pellets. These pieces cause blockages in the gate valve between feeder and mill. Adequate screening of the wood pellets upstream of the feeders is applied to solve this problem,
- Wear on pipes transporting the wood dust from the mills to the burners. Wood dust is known for its abrasive nature due to the inevitable presence of sand in the feedstock. Where required, DONG Energy has reinforced the pulverised fuel lines with composite steel plates. Bends on the dust pipes are reinforced with ceramic lining,
- DONG Energy has experienced deposits on burners due to operation at low air to fuel ratios at these burners. This has been caused by different fuel flow rates in the four pulverised fuel lines downstream of each mill. DONG Energy has installed trimming valves in each of the pulverised fuel lines to equilibrate the fuel mass flow,
- DONG Energy has experienced that higher ash contents in the wood pellets cause fluid slagging on the superheaters above the furnace. Stricter control on fuel quality (ash <1.5%) has been applied to prevent this as much as possible. Water cannons for cleaning of the furnace walls were installed in 2012. This prevents slagging on the furnace walls,
- High dust SCR systems suffer from severe catalyst degradation rates when plants are firing 100% biomass. The background for this is the high alkali metal content of most biomass types, causing poisoning of active sites and blockages of the micro pores of the SCR catalyst. DONG Energy has developed and applied a very effective method to

reduce catalyst deactivation rates: coal ash is injected at burner level 3 in the furnace. In this way, the alkali metals are absorbed on and eventually fixed in coal ash particles, thus preventing the alkalis from depositing on the downstream SCR catalyst surfaces,

- On August 12, 2012 DONG Energy had to close biomass operations at the Avedøre 2 plant due to a fire that started in the conveying system and quickly spread to the wood pellet silos. Rebuilding of the conveyor system has taken months. DONG Energy learnt that rubber is not an appropriate material for wood pellet conveying and they have changed to a heat resistant and inflammable material instead.

Much attention has been paid by DONG Energy to corrosion aspects of the 105 MW_{th} straw fired boiler at Avedøre 2. Extensive measuring and testing programs has been executed and a number of conclusions have been drawn regarding the application of alloy TP 347H FG for the superheaters:

- Corrosion rate increases with metal temperature and is accelerated above steam temperatures of 540°C,
- The highest corrosion rate is not necessarily in the flue gas direction. Local flue gas temperature governs the chemistry of the deposit while flue gas flow will affect the deposit morphology and thus govern the heat transfer and the corrosion rate around the tube,
- It is important to have plant data, i.e. both flue gas and steam temperature profiles coupled with tube thickness measurements, in order to calculate the corrosion rate and define a lifetime prediction.

The contribution of and review by Mr. Bo Sander, DONG Energy, is gratefully acknowledged by the authors.

6 Country reports

This chapter describes reports of countries that have significant experience with biomass co-firing and/or currently include power stations that practice co-firing at scale and over an extended period of time.

6.1 UNITED KINGDOM

One of the results of the introduction of the Renewables Obligation in Britain in April 2002, which provided an increased tariff for renewable power, was a dramatic increase in biomass co-firing, over the period 2002-2005, involving all of the large coal-fired power plants in the country. It is clear that, from a standing start, the electricity supply industry in Britain responded relatively rapidly to the financial incentives in the new legislation.

Co-firing by pre-mixing the biomass with coal

Initially, there was a clear preference for the pre-blending options for co-firing, i.e. the mixing of the biomass material with the coal at low co-firing ratio in the coal yard or on the main coal conveyors, and the processing of the blended fuel through the existing coal milling and firing system, with little or no modification to the installed plant.

This approach was demonstrated successfully in 2002 at Ferrybridge, a 2,000MWe pulverised coal power plant in Yorkshire in England. In this case, up to 8% by mass of olive residue material in granular form, imported from Spain, was co-fired into all four 500 MWe boilers, generating around 100MWe of renewable power. After the trial work, which involved both milling trials and extensive environmental monitoring to demonstrate that the co-firing of the biomass did not introduce any additional environmental burdens, the station continued to co-fire the biomass on a fully commercial basis.

When the level of additional income available from the co-firing activities at Ferrybridge became clear, all of the other operators of coal-fired plant initiated their own co-firing programmes. The degree of success differed greatly between stations, and it became clear over the next couple of years that two power plants, Ferrybridge and Drax, both in Yorkshire, were by far the most committed and successful in generating renewable energy by co-firing, and showed interest in expanding their activities.

Direct injection co-firing

The direct injection system at Drax has been described briefly in Section 6 above. The whole system comprises:

- The raw wood pellet silo which is supplied by mechanical conveyor from the biomass reception and handling facility
- The raw pellet feeder
- The hammer mill, with an outlet screw feeder

- The rotary valve
- The pneumatic conveying system, supplied by the Rootes type blower
- The pneumatic conveying pipework distributing the fuel across the boiler, and
- The injection point to the mill outlet pipes

Drax have installed twelve direct injection systems of this sort. The system is capable of co-firing 1.5 million tonnes p.a. of biomass. This system is still in operation.

At Ferrybridge, a biomass milling and direct injection biomass firing system was installed on two of the four boiler units, in the summer of 2007. A total of twelve Bioswirl burners, supplied by TPS Termiska Processer AB, a Swedish company, were installed through new penetrations on the rear walls of Units 2 and 3, for the co-firing of biomass at up to 10% on a heat input basis into each boiler.

The Bioswirl system comprised:

- A wood pellet silo,
- A pellet crusher,
- A crushed pellet bunker and rotary feeder, and
- The Bioswirl burner.

The Bioswirl system was based on a refractory-lined, cyclone burner concept. The thermal design capacity of the burner was in the range 0.5-25MWth. The burners at Ferrybridge were of 25 MWth capacity, and were provided with dedicated main fuel, light-up fuel and air supplies.

The TPS Bioswirl burner was developed for the combustion of crushed wood pellets for application in small district heating boilers in Sweden, usually as a replacement for oil firing, and this was the first application in a large multi-burner furnace. In the event, the Bioswirl burner did not prove to be robust enough for this type of application, and was particularly prone to thermal damage when the burner was out of service and exposed to hot furnace gases. Its use was discontinued after a few months operation.

Conversion of pulverised coal boilers to 100% biomass

In recent years the conversion of pulverised coal boilers to 100% biomass has been carried out successfully at three power plants in Britain, viz:

- At Tilbury power station near London, the installed vertical spindle roller mills and coal burners were modified to process 100% wood pellets in three 300MWe boilers. This system ran successfully for around two years before the station was closed down.

- At Ironbridge power station in Shropshire where two 500MWe pulverised coal boiler were converted to 100% wood pellets. In this case, the installed ball and tube mills were replaced with hammer mills and the installed primary air ductwork, pulverised fuel pipework and coal burners were modified for biomass firing. This system has been in successful operation for more than 10,000 hours.
- At Drax power station in Yorkshire where three 660 MWe boilers have been converted to fire 100% wood pellets. In this case, the installed vertical spindle ball and ring mills and coal burners have been modified to process and fire 100%. This system is currently in operation and it is planned that it will continue to fire biomass for several years.

6.2 NETHERLANDS

The Netherlands has a long history of biomass co-firing (KEMA, 2009). The first large scale co-firing project started as early as in 1995. At that time, 240,000 tons of waste and demolition wood was being sent for landfill disposal. It was decided to co-fire 60,000 tons per annum of processed waste wood with coal in Centrale Gelderland in Nijmegen.

Currently, the Netherlands has eleven coal-fired boilers units in eight locations. Seven of these were commissioned in the 1980s and 90s, and four more recently. Of the seven older units, six have been co-firing biomass on a commercial basis. These include boilers with both tangentially-fired and opposed wall-fired furnaces. Co-firing ratios up to 25% on a heat input basis are common, and higher levels have been achieved.

Trials have been performed with up to 5% co-firing by co-milling the biomass with coal. In other plants the biomass is milled separately and the pulverized biomass is either injected into the coal lines, or injected in separate feeding lines.

Table 6-1 The boilers in the Netherlands involved in biomass co-firing

Power station	Unit (year)	Owner	Plant output (MW _e)	Plant output (MW _{th})	Co-firing ratio (%)	Status
Maasvlakte	1 (1989)	E.ON	531	-	10%	Planned out-of-service: 1 July 2017
Maasvlakte	2 (1988)	E.ON	531	-	10%	Planned out-of-service: 1 July 2017
Amer Centrale	8 (1981)	Essent	600	250	10 - 12%	Planned out-of-service: 1 January 2016
Gelderland	13 (1981)	Electrabel	602	-	25%	Planned out-of-service: 1 January 2016
Borssele (1994)	12 (1988)	EPZ	403	-	10 - 15%	Planned out-of-service: 1 January 2016
Amer Centrale	9 (1994)	Essent	600	350	27 + 5% ¹⁾	-

1) On energy (LHV of fuel) basis

2) 27% direct co-firing and 5% indirect co-firing

A number of biomass materials fuels have been co-fired, including wood based materials as wood pellets and waste and demolition wood. Paper sludge pellets, meat and bone meal, and a variety of agricultural waste products have also been co-fired. This was especially the case until 2006.

Biomass co-firing has primarily been taken place in modified existing coal mills (such as at Amer Power Station) and by dedicated hammer mills (such as at Centrale Gelderland). At Amer Power Station there is also significant experience with a wood gasifier (for 5% co-firing). Maasvlakte power station has a dedicated installation (with e.g. dedicated mills) for processing a variety of alternative biomass types.

Trials with the co-firing of several thousand tonnes of torrefied biomass pellets have also been performed at Amer Power Station. Trials with torrefied and steam exploded biomass have also been performed at Buggenum's Willem Alexander Centrale (Padban, 2014).

The annual electricity generation (in GWh) by co-firing biomass in coal fired power stations in the Netherlands in the period of 1995-2013 is presented in Figure 1. Biomass co-firing played an increasing role in the total sustainable energy production, especially in the period from 2000 until 2006.

The electricity production from biomass as co-firing fuel has reduced significantly in 2007 (SenterNovem, 2007). This was due to a change in the subsidy programmes in July 2006. The subsidized co-combustion of bio-oil was

no longer allowed, and firing palm oil at Essent's Claus power station was discontinued. Also some units have been out of service for a longer period in 2007. The subsidies for the co-firing of certain types of solid biomass wastes were lowered significantly, which had an effect on co-firing.

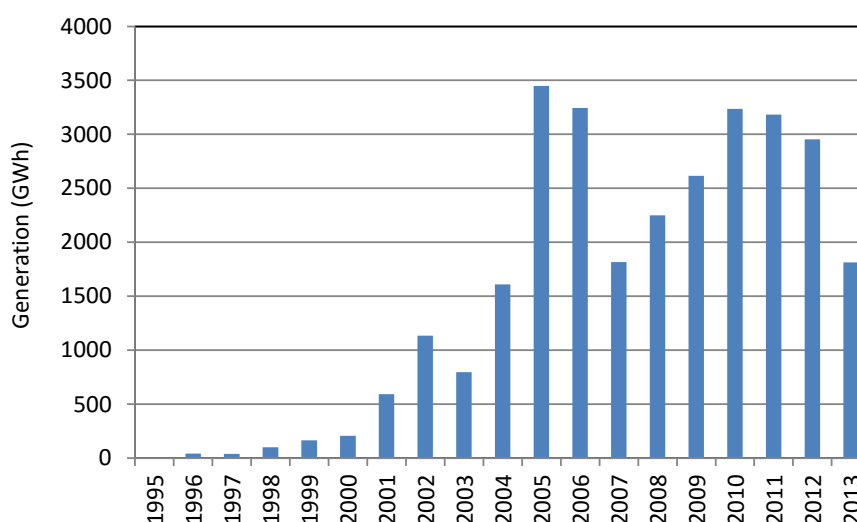


Figure 6.1 Electricity generation (in GWh, gross) for co-firing in coal fired power stations in the Netherlands (Data derived from CBS: cbs.nl, 15 Oct 2015).

The co-firing of biomass was subsidized by the Dutch MEP-subsidy programme. This programme was succeeded by the SDE subsidy programme in 2008. Co-firing was not included in the SDE programme, but the MEP programme was continued for the power stations involved in co-firing in the years after 2007. The MEP contracts have ended over the last few years, and this has resulted in a decline of biomass co-firing after 2012.

The five boilers that originate from the 80s will be taken out-of-service, as part of the Energy Agreement (SER, 2013). It was further agreed that promoting the use of biomass co-firing by coal-fired power stations will not exceed 25 PJ p.a. The biomass used for co-firing applications has to fulfil strict sustainability criteria.

The production of renewable energy in the Netherlands is currently encouraged by the SDE+ (Stimulerend Duurzame Energieproductie/Encouraging Sustainable Energy Production) operating grant (MINEZ, 2015). Biomass co-firing has been introduced in this scheme in 2015. The scheme includes separate categories for new and existing installations.

6.3 DENMARK

Biomass for power production was introduced in different sectors in Denmark since the 1980's. Co-firing is just one out of several technologies implemented; on a broad term these technologies include:

- co-firing wood or straw or alternative biofuels in medium to large scale power plants (large boilers, steam technology)
- dedicated biomass fired combined heat and power plants (wood or straw in smaller boilers, steam technology)
- dedicated biomass fired boilers coupled to the steam cycle of a larger coal-fired power plant (straw and/or wood in large boilers, steam technology)
- pilot and demonstration plants for indirect co-firing of biomass into coal-fired power plant (straw gasification into steam technology)
- pilot and demonstration plants for dedicated biomass power in small scale (small systems, gasification, ORC and other new technologies).

Table 6-2 Current status of co-firing in Denmark

Power station	Unit	Owner	Plant output (MW _e)	Plant output (MW _{th})	Direct co-firing percentage (heat)
Studstrupværket	4	DONG Energy	350	455	7
Studstrupværket	3	DONG Energy	350	455	0 to 100 ²⁾
Amager	1	HOFOR	80	250	0 to 100
Avedøre	1	DONG Energy	215	330	100 ³⁾
Avedøre main boiler	2	DONG Energy	365	480	100
Avedøre straw boiler	2	DONG Energy	¹⁾	¹⁾	100
Grenaa Co-Generation Plant	1	Verdo (from 2017 Grenaa Varmeværk)	19	60	50
Herningværket	1	DONG Energy	95	174	100
Randers Co-Generation Plant	1	Verdo	52	112	100
Ensted biomass boilers (closed)	3	DONG Energy	630 ⁴⁾	95 ⁴⁾	100
Skærbækværket	3	DONG Energy	392 ⁵⁾	444 ⁵⁾	100

1) Capacity is included in the figure for the main boiler

2) From 2017

3) Conversion to pellets decided in 2015

4) Biomass boilers supplied steam corresponding to 40 MW_e out of block unit total 630 MW_e

5) Biomass boilers to supply steam corresponding to 90 MW_e and 320 MW_{th} out of this from 2017

Studstrupværket are two identical coal-fired block units equipped with facilities to handle and co-fire 10% on energy basis straw. On an annual average, 7% is reached. Whole Hesston bales of straw each about 500 kg are received in the plant. The two units together use 100,000 to 150,000 ton/year of straw. Currently, unit 3 is being converted for 100 % biomass and will from 2017 be able operate at 100 % load on wood pellets and possibly a small percentage of straw.

The new Amager unit 1 is a new block unit retrofitted into the building of the old unit no.1. It is a suspension fired power boiler with very large fuel flexibility; among others solid biomass fuels, straw and wood can be co-fired from 35 to 100% of block unit capacity along with coal (only 90% percent capacity can be reached during straw-only operation). Also fuel flexibility exists to co-fire biomass with fuel oil. Wood and straw are both supplied as pellets. Annual consumption is between 300.000 and 400.000 tonnes pellets. In 2013 straw pellet production for the plant ceased and the unit has been using only wood pellets.

The plants Ensted 3 and the biomass boiler in Avedøre 2 are dedicated, grate fired biomass boilers supplying steam to the main block unit.

The Ensted plant is now closed, however, the straw boiler in Ensted 3 used about 150,000 ton/year of straw received in Hesston bales, while the wood chips consumption was about 30,000 ton/year in a boiler, which was super heating the steam from the straw boiler.

The straw boiler in Avedøre 2 uses about 150,000 ton/year of straw, received as Hesston bales. The Avedøre 2 main boiler can burn a mixture of wood in suspension firing along with natural gas and/or fuel oil. Typically wood has been supplying 70% of fuel on heat basis, but the unit can be operated very flexible from this point, up and down. In 2014 a fourth pellet mill was fitted enabling the plant to operate at full load on wood pellets.

The Avedøre unit 1 is currently being retrofitted from coal to 100% wood pellets and will from 2016 supply the district heating system of Copenhagen.

The Grenaa unit is a CFB boiler designed for a 50/50 (energy basis) mixture of straw and coal. Annual straw consumption is about 50,000 ton/year, received as Hesston bales.

Herningværket was recently retrofitted for 100% biomass operation, wood chips being the main fuel and wood pellets replacing the natural gas part. The annual consumption of wood chips is in the order of 230,000 ton/year.

The Randers co-generation plant has been retrofitted for 100 % biomass combustion but may still use co-firing with coal if feasible. The two traveling grate boilers are fed by spreader stokers supplemented with pneumatic feeding of biomass dust. Fuels are national and imported wood chips from forests and plantations as well as pits and dust from industry.

At Skærbækværket two wood chip boilers are currently being installed in order to feed steam into the existing steam system of the originally natural gas fired

plant. The natural gas possibility will be maintained. The biomass part is to come into operation from 2017.

Apart from these plants, decisions are being taken to close DONG Energy's Asnæsværket unit 2 (142 MWe) and to cover the local heat demand for district heating and industry by a new wood chip fired plant with a capacity of 25 MWe or a heat only capacity of 135 MWth. Unit 5 at Asnæsværket (640 MWe and 308 MWth) has for some time been out of operation with an ability to start up within 2.5 days.

Furthermore, it is considered to retrofit DONG Energy's Esbjergværket unit 3 (371 MWe) to some biomass solution, the challenge here also being the relatively limited heat demand in the local district heating system while the tax exemption for biomass relates to the biomass used for heating purposes.

Finally, during the last years, Vattenfall has succeeded in selling their thermal plants in Denmark for the respective municipal supply companies. Amagerværket has been acquired by HOFOR who has decided to invest in a new large wood chip fired CFB boiler (to be unit 4) instead of retrofitting unit 3 from coal to wood dust. Fynsværket in Odense has been acquired by Fjernvarme Fyn who considers how the coal can be abolished. Nordjyllandsværket in Aalborg has been acquired by the municipal supply company who is considering a retrofit for biomass.

The original driver for the majority - in terms of volume - of biomass power in Denmark was a specific scheme set up by the Folketinget (parliament) in the early 1990'ies. This scheme requires power plants to use a certain amount of biomass annually, totally 1.4 million ton/year.

In early 2008 this figure was increased with an additional 0.7 million ton/year as part of a political agreement that opens for increased coal use in power plants earlier restricted through legislation.

Added to the political pressure in this kind-of quota system, power companies also receive up to 3 different bonuses for using biomass for electricity production:

1. A fixed/guaranteed minimum tariff for renewable electricity, which includes the market value of electricity (the actual wholesale price) as well as a subsidy element up to the fixed minimum tariff in the case where market value is less than the fixed guaranteed tariff. Biomass electricity is eligible to this bonus for 100 % of the biomass based kWh determined through allocation of the total fuel consumption on an energy basis.
2. A Renewable Electricity bonus of 0.10 DKK/kWh (for newer plants 0.15 DKK/kWh). Biomass electricity is eligible to this bonus for 100% of the biomass based kWh determined through allocation of the total fuel consumption on an energy basis.
3. A subsidy per ton on biomass used, between 0 DKK and 100 DKK per ton, distributed to eligible power plants and calculated from a need-

principle based on the economic performance of the individual plant (biomass type and price, installation type, electric efficiency et cetera).

All costs associated with these schemes are part of the utilities' common Public Service Obligations, PSO. This way the costs are distributed to the electricity consumers in Denmark.

Further the EU carbon dioxide quota system adds value to electricity produced from renewables, further enhancing the incentives for power production in co-firing and dedicated biomass plants.

During the last couple of years a major driver for the biomass retrofitting development at the large CHP plants has been the large municipalities' desire for their district heating to become carbon neutral. In more cases the investment for retrofitting and life time extension has been shared between the supply companies and the utility companies

The contribution of and review by Mr. Morten Tony Hansen is gratefully acknowledged.

6.4 BELGIUM

In Belgium, the take off for co-firing and biomass utilization to produce electricity has started after the “green certificate” system implementation, which was decided by government decree in 2001 (KEMA, 2009)

In 2009, small scale cogeneration units and biogas production from waste were responsible for a total power output of around 10 MWe. Another 300 MWe was produced by 5 power plants. The Les Awirs power plant was fed by 100% biomass, and had an power output of 80 MWe. The other 4 power plants had 220 MWe power all together and used wood and olive residues as biomass fuels for co-firing. Today, Electrabel does not having co-fired power plants. For the time being, two of these power plants are running on 100% biomass: les Awirs (80MWel) close to Liège and the Max Green plant (250 MWel) close to Gent. Both are fuelled with pellets, and have hammer mills.

6.5 CANADA

Canada, with its large landmass and diversified geography, has substantial renewable resources that can be used to produce energy including hydro, wind, biomass, solar, geothermal, and ocean energy. Renewable energy sources currently provide about 16.9 per cent of Canada’s total primary energy supply. After hydro and wind, biomass is the third largest renewable source of Canada’s electricity generation. Its share in Canada’s electricity generation is 1.4 per cent (NRCAN).

At the end of 2010, Canada had 61 bioenergy power plants with a total installed capacity of 1,700 megawatts, and most of this capacity was built around the use of wood biomass and spent pulping liquor, as well as landfill gas. Most of the biomass-fired capacity was found in provinces with significant forestry activities: British Columbia, Ontario, Quebec, Alberta and New Brunswick.

In the utility sector, two Canadian power utility companies have been leading the biomass combustion and co-firing initiatives.

Ontario Power Generation

Ontario Power Generation is one of the largest producers of electricity and owns one of the most diversified, low-cost and low-emission portfolios in North America. Today 99.7 per cent of the electricity OPG produces is free of smog and greenhouse gas causing emissions. It operates/maintains 65 hydroelectric, 3 thermal, 2 nuclear stations and 1 wind power turbine. As of September 2015, OPG had just over 17,000 megawatts (MW) of in-service generating capacity. Thermal Fleet Generating Capacity is about 2,600 MW from 3 Stations. OPG currently owns two thermal electricity-generating stations operating on wood pellet fuel, Atikokan GS and Thunder Bay GS. Both stations have the flexibility to respond to changes in electricity demand and provide dispatchable power when it is most required.

Atikokan Generating Station is located near the Town of Atikokan in northwestern Ontario. The station stopped using coal as fuel in September

2012 and has been converted from coal to use biomass - wood pellets. It is now North America's largest capacity 100 per cent biomass-fuelled power plant generating renewable, dispatchable, peak power. After the conversion, Atikokan GS retains the ability to produce approximately 200 MW at full capacity. The total investment to repurpose the plant was about \$170 million and the conversion was completed on time and on budget. Wood pellets are used as fuel because the energy content is very similar to the lignite coal that Atikokan GS was designed to burn, so much of the existing equipment could be adapted for biomass. Wood pellet suppliers were selected through a competitive process requiring the wood-fibre to be sourced from sustainably managed forests. Aboriginal businesses are involved in the fuel supply chain.



Figure 6.2 Two new silos were constructed at Atikokan during the conversion to biomass. Each is 44 meters tall, and holds approximately 5,000 tonnes of wood pellets.

The **Thunder Bay Generating Station** is located in the City of Thunder Bay. First placed in service in 1963, it is the oldest of OPG's thermal electricity-generating stations. OPG stopped using coal as fuel in April 2014, and one of the station's two units has been converted to use advanced biomass. Conversion of Thunder Bay GS from coal to advanced biomass fuel was completed on time and budget in February 2015. Advanced biomass has emerged as a leading candidate for coal plant fuel conversions due to its favourable handling and storage properties. It is a solid biomass fuel, processed with advanced techniques. It has higher energy density and is hydrophobic (repels water) allowing it withstand the elements while being stored outside. It contains about 75 per cent less nitrogen oxide than coal emissions, and has virtually no sulphur dioxide. It can also be stored outdoors. The conversion project was completed under budget and ahead of schedule; the company documents previously stated the conversion was expected to cost about \$5 million.

Nova Scotia Power Inc.

Nova Scotia Power provides 95 per cent of the generation, transmission and distribution of electricity in Nova Scotia, and serve 500,000 residential,

commercial and industrial customers across the province. It produces more than 10,000 gigawatt hours of electricity each year using a mix including hydro, tidal, wind, coal, oil, biomass and natural gas to generate electricity. Its generation capacity is about 2,453 megawatts of electricity. It operates four coal power plants, another that runs on natural gas or oil plus a gas fired combined cycle, three oil-burning combustion turbine sites, one tidal and 33 hydro stations, two wind farms, two sites with single wind turbines, and a new biomass power plant.

Since 2009 NPSPI completed a preliminary engineering study for co-firing of biomass on one of its 150 MW units. This job however did not get approval to proceed. In addition NSPI has participated in collaborative studies with others on advanced biomass fuels and continues to monitor this field.

In 2013 Nova Scotia Power started up a 60 MW co-generation unit 100% biomass fired with natural gas burning capability in Port Hawkesbury. It's a facility helps reach renewable energy requirements in the province of Nova Scotia, and provides a source of firm renewable energy that can back up intermittent wind generation. This unit fires woody biomass with a combination of chips and bark. It has limited indoor storage for wood chips only.

Emera the parent company of Nova Scotia power operates a 23.4 MW biomass facility. It is a bubbling bed boiler firing wood chips.

Nova Scotia Power is an active participant in Canadian Clean Power Coalition. Leveraging of the original NSPI engineering study and with work from others, it continues to assess the economics of biomass co-firing in different Canadian regulatory regimes.

The contribution of and review by Ms. Sebnem Madrali is gratefully acknowledged by lead authors.

7 Conclusions

This report shows that the firing and co-firing of biomass as a replacement for coal in large pulverised coal boilers is a very attractive option for the utilisation of biomass materials for power production, and for the delivery of renewable energy. Biomass conversion projects offer a number of significant technical and commercial advantages, viz:

- The capital investment requirements of power plant conversion projects are very much lower than the investment costs of a new build power plant,
- The reliability and security of the supply of the power generated are higher than most other forms of renewable energy, and
- The power generation efficiency and the generation costs are much better than those associated with industrial scale biomass power plants.

The generation costs of the power from biomass are, of course, dependent on the delivered biomass fuel costs and, in most cases, these are higher than those associated with the coals normally fired at the stations. This means that in most instances the conversion of power plants to the firing or co-firing of biomass materials will require financial support. In most cases this is delivered in the form of an agreed power price under some government policy instrument aimed at the promotion of electricity from renewable sources.

It is clear from the material presented in Section 3 of this document that the key technical options for the conversion of large pulverised coal boilers to the firing and co-firing of biomass have been successfully demonstrated, principally in projects in Northern Europe, over the past 10-15 years or so. A number of the plants converted to biomass firing and co-firing are currently in operation, and there are a small number of further conversion projects currently in the proposal stage.

The storage and handling of the biomass materials, and particularly the tendency of the biomass to generate significant dust levels, have presented the most significant problems. It is fair to say, however, that the fuel suppliers and the materials handling equipment supply industry have learned many lessons over the past few years, and that the solutions currently being offered for biomass projects represent a significant improvement over previous practice.

The case studies and country reports show that through the years, a great experience has been gained with biomass cofiring in various types of power plants and with various types of biomass fuels. These projects show that the technical risk areas have been managed successfully and that the plant availability and efficiency levels after conversion have been acceptable.

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