Figure 7.13 gives a summary of the main effects of co-firing in a coal-fired boiler.
In many countries, the market for plantation-grown biofuels to be used for dedicated power generation is not yet mature because of a lack of confidence among entrepreneurs and financial institutions in its feasibility, the absence of realised dedicated biomass power plants or assured purchase contracts, the lack of market support institutions, etc. In such a situation it is as difficult to develop a mature fuel market as it is to establish a biomass power plant in the absence of assured fuel supply. As it provides a relatively cheap method of converting biomass into useful energy, co-firing can be a very effective strategy for large-scale infrastructure development for biomass fuels. It can then help create a full-fledged market for biomass fuels in which sellers and buyers can easily trade biofuels. This is particularly true if the combustion equipment used has a wide fuel acceptance range. Worldwide, much experience has been gained with co-combustion of various fuels. However, further research and development are being done to optimise co-firing applications and to reduce the negative effects of co-firing, such as boiler fouling and corrosion [183, 184, 185, 186, 187, 188].

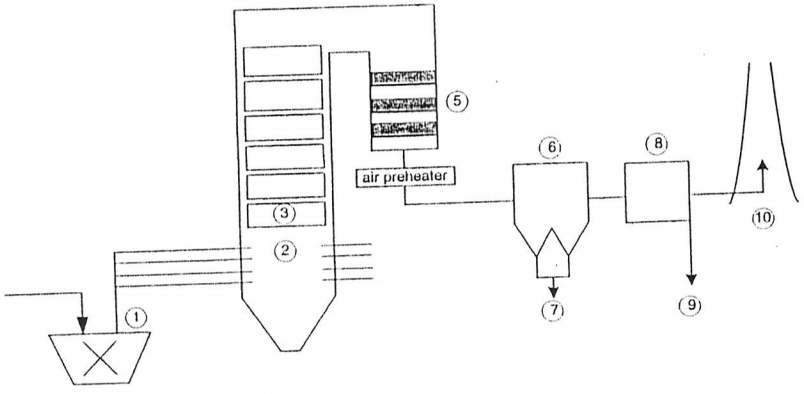

Figure 7.13: *Effects of biomass co-firing an a coal-fired power station [183]. 1: grinding equipment: reduced capacity and lifetime of, 2: combustion chamber: slagging, 3:superheater: high temperature corrosion, 4: heat exchanger: depositions and erosion, 5: De-NO_x installation: capacity, poisoning, 6: Electric precipitator: capacity, 7: ash: utilisation, 8 De-SO_x installation: capacity, 9: utilisation of residues from desulphurisation, 10: flue gas: emissions.*

7.6 Effects of biomass/coal ash on power plant operation

A great number of the key areas of concern about the impacts of biomass co-firing are associated with the behaviour of the mixed biomass/coal ashes. Although the ash contents of both wood and straw materials are significantly lower than those of most power station coals, the ash chemistry and mineralogy are very different and there are serious concerns that the behaviour of the mixed ashes from biomass-coal co-firing may give rise to significant problems. These potential problems can be listed under the following subject areas:

- increased ash deposition in the boiler furnace and convective tube banks;
- increased rates of metal wastage of boiler components due to gas-side corrosion;
- reduced collection efficiency of the particulate collection equipment and increased dust emissions;
- interference with the operation of SO_x and NO_x emission control equipment; and
- impacts on the utilisation/disposal of the solid discards from the power plant.

In this section, the nature of biomass ashes and of the mixed ashes from biomass/coal co-firing is described and the likely impact on boiler plant operation and integrity due to co-firing is discussed.

7.6.1 The nature of co-firing ash and the impact on ash deposition

Although the ash contents of both wood and straw materials are significantly lower than those of most power station coals, the ash chemistry and mineralogy are very different. The co-firing of biomass materials with coal produces a mixed ash, and it is important to understand the nature of both the individual ash components and the mixed ashes to allow prediction of the likely high temperature behaviour and the impact of co-firing on boiler performance. This is an important subject and it has been studied extensively over the past ten years or so.
The most important study of this subject was associated with the straw-coal co-firing demonstration trial at Unit 1 at Studstrup Power Station in Denmark during 1996. This trial involved the co-firing of cereal straws at up to 20%, on a heat input basis, in a 150 MW_e pulverised coal-fired boiler. An extensive programme of collection and characterisation of the ash materials and boiler deposits was performed using both conventional and advanced techniques, and the results of the work have been extensively reported. See for instance [189, 190, 191], and the references cited therein. The basic chemical analysis data for the coal and straw materials involved in the Studstrup trial are listed in Table 7.2.
The data presented in Table 7.2 are illustrative of the major differences between the coal and straw ashes, viz:

- The coal is a globally traded, highly volatile bituminous steam coal from South Africa, which is imported into Northern Europe in large volumes for power plants.
- The coal ash is an alumino-silicate system, with clay minerals (alumino-silicates) and quartz as the principal mineral species. The other major chemical constituents are the compounds of iron, calcium, magnesium, potassium, and sodium.
- The sulphur, chlorine and phosphorus contents of the coal ash are relatively low.
- This particular coal has relatively low levels of fluxing elements, i.e. iron, calcium, potassium, sodium, and magnesium, and the ash is relatively refractory in nature. It is regarded as being an ash with a low propensity to the formation of slagging and fouling deposits in pulverised coal-fired boilers.
- The straw ash, like most biomass ashes, is not an alumino-silicate system, but comprises quartz and the simple inorganic salts of potassium, calcium, magnesium, and sodium, principally phosphates, sulphates, and chlorides.
- The straw ash would be regarded as having relatively low fusion temperatures and a high propensity to the formation of slagging and fouling deposits in boiler plants.

Table 7.2: *Analysis data for the coal and straw ashes from the Studstrup Unit 1 Straw-coal co-firing trial in 1996 [191]. The analysis data for a typical wood ash have been included.*

Constituent (%, m/m)	Coal ash	Straw ash (min. levels)	Straw ash (max. levels)	Wood ash (typical)
SiO_2	59.8	19.7	38.9	10
Al_2O_3	19.1	0.24	0.52	2
Fe_2O_3	8.1	0.13	0.19	1
CaO	2.0	6.35	8.45	35
MgO	1.7	1.50	1.90	5
TiO_2	N.D.	N.D.	N.D.	-
Na_2O	0.6	0.29	1.00	3
K_2O	2.2	28.7	34.60	20
P_2O_5	0.2	2.45	3.00	12
SO_3	2.1	3.40	5.00	12
Cl	<0.1	4.55	7.06	-

Typical ash analysis data for a wood material have also been listed in Table 7.2. In general terms, the ash analysis of wood ash is similar in many ways to that of straw. However, it should be noted that the SiO_2, CaO, K_2O and P_2O_5 contents can vary widely. These data are not untypical of the ash chemistries of coals and biomass materials, although it should be noted that the chemistry of these materials does vary significantly. This is particularly true of the coal ashes. In general terms, the nature and behaviour of mixed coal-biomass ashes, at low to medium co-firing ratios, will be determined largely by the chemistry of the coal ash.

In the flame, where the mineral constituents of the fuel are subjected to very high temperatures, a number of mineral transformation reactions occur. For the major coal and biomass mineral constituents, the principal reactions are listed in Table 7.3. These reactions have a major impact on the nature of the ash deposits on boiler surfaces and on the nature of the mixed coal-biomass ash residues.

A key reaction, which is of particular importance when considering the combustion of biomass and waste materials, is the release of volatile inorganic species into the vapour phase at flame temperatures, and the subsequent condensation of these species on boiler surfaces and on the surfaces of ash particles and ash deposits. The species involved in these volatilisation-condensation reactions include:

- the free potassium and phosphate compounds in the biomass; and
- the free sodium and phosphate species in the coal.

It should also be noted that the sulphur and chlorine species in the fuels are also released into the gas phase at flame temperatures, principally as sulphur oxides and as HCl, and that these species can react with alkali and alkaline earth metal oxides in the ashes and deposits to form sulphates/sulphites and chlorides.

Table 7.3: *The major mineral transformations that occur in the flame when firing coal and biomass materials.*

a. Coal mineral transformations

Constituent	Mineral transformation
SiO_2	partial melting, cracking, rounding of edges
Clay minerals	dehydroxylation, melting in some cases
Pyrite (FeS_2)	decomposition to pyrrhotite (FeS) and iron oxides
Calcite/dolomite	decarboxylation to CaO and mixed Ca/Mg oxides
Na compounds	decomposition, release of Na species into the vapour phase

b. Biomass mineral transformations

Constituent	Mineral transformation
SiO_2	partial melting
K/Na salts	decomposition and release of K/Na species into the vapour phase
Ca salts	decomposition to CaO

The principal effect of the co-firing of cereal straw, at co-firing ratios up to 20% on a heat input basis, as found during the Studstrup trial, was associated with the release of potassium species into the vapour phase and the subsequent condensation of these species on the surfaces of the ash particles and deposits. Detailed mineralogical analysis of the fly ash and deposit specimens, collected during the Studstrup trial, was performed using advanced Computer Controlled Scanning Electron Microscopic (CCSEM) techniques. The most important change observed in the fly-ash mineralogy, due to the co-firing of straw, was a dramatic increase in the concentration of potassium alumino-silicates formed by interaction at high temperatures between the condensed potassium species and the alumino-silicate constituents of the coal ash. Enrichment in both potassium and sulphur was also observed on the surfaces of particles both in the fly-ash and deposit specimens. This enrichment was in the form of thin potassium sulphate rims on the particle surfaces, which were clearly visible in SEM X-ray maps.

The consequences of the co-firing of biomass materials with coal on ash deposition behaviour are two-fold, viz:

- The rate and extent of coal ash slag formation on surfaces in the boiler furnace tends to increase, due principally to the decrease in the fusion temperatures of the mixed biomass-coal ashes, since fused or partially fused slag deposits tend to be more receptive to oncoming particles and grow more rapidly. In general terms, biomass ashes have relatively low Ash Fusion Temperatures, with Deformation Temperatures commonly in the range of 750 to 1000°C, compared to values in excess of 1000°C for most coal ashes. The impact of co-firing on slag deposition depends largely on the chemistry and the fusion behaviour of the coal ash and the co-firing ratio. The most dramatic impact on the fusion behaviour of the mixed ashes is normally observed when biomass materials are co-fired with a coal, which has a relatively refractory ash, i.e. the ash has relatively high fusion temperatures. A refractory ash is generally rich in SiO_2 and Al_2O_3, and has low concentrations of the fluxing elements, i.e. Fe_2O_3,

CaO, MgO, K_2O, and Na_2O. This type of coal ash is dominated mineralogically by quartz and kaolin, with very low levels of other mineral species. The co-firing of biomass materials at even relatively modest co-firing ratios can have a major impact on the ash fusion behaviour. The introduction of significant levels of the alkali and alkaline earth metals into the mixed ash can act as a very effective flux on the coal ash, and the result can be a reduction in the ash fusion temperatures of 100-200°C. This can have a dramatic impact on the propensity of the mixed ash to form slag deposits in the boiler furnace.
Coal ashes which have lower ash fusion temperatures, and which have significant levels of the ash fluxing elements, are less dramatically affected by the co-firing of biomass materials. However, it should be noted that these ashes already have a significant slag formation propensity. In these cases, the co-firing of biomass materials will act to increase the slag formation propensity of the coal ash, but the effect will be less dramatic.

- The volatilisation and subsequent condensation of the alkali metal species and the phosphates during the co-firing of biomass materials with coal is a major mechanism responsible for the initiation and growth of fouling deposits on surfaces in the boiler convective section. Most biomass materials should be regarded as being high fouling fuels and the result of co-firing will, in almost all cases, result in a significant increase in the propensity to form fouling deposits.
  A simple index has been developed [192], which can be used to assess the fouling propensity of a fuel or mixed fuel ash. The index is based on the mass in kg of alkali metal oxides (K_2O + Na_2O) introduced into the system per GJ heat input to the furnace. At index values above 0.17 kg per GJ, significant fouling of the boiler convective section is probable. At index values in excess of 0.34 kg per GJ, severe fouling is to be anticipated. Most biomass materials, and particularly those from fast-growing plants, will have index values in excess of 1 kg per GJ, whereas most coals have relatively low values, generally less than 0.1 kg per GJ.

It is clear, therefore, that the co-firing of biomass materials with coal in large coal-fired power station boilers can introduce the risk of increased ash deposition on both furnace surfaces and on heat exchange surfaces in the convective section of the boiler. The level of risk depends on the nature of the biomass and coal ashes, and on the co-firing ratio. It should also be remembered that a number of site-specific factors are relevant in this context. Boiler plants vary significantly in their sensitivity to ash deposition, both in terms of the impact of reduced heat absorption in certain regions of the boiler, in the tendency for ash deposits to accumulate within the boiler and interfere with operation, and in the ability of the installed on-line cleaning systems to control ash deposition to acceptable levels.
In many instances, the most appropriate response to operational problems caused by excessive ash deposition will be to reduce the biomass co-firing ratio to a level where the deposition rate is more manageable and/or to increase the capabilities of the on-line cleaning systems. The limited experience to date in Europe indicates that co-firing ratios up to around 5-10% on a heat input basis can be achieved in most circumstances without significant difficulty, but that ratios in excess of 10% can be problematic.

7.6.2 Gas-side corrosion of boiler components

As indicated above, the co-firing of biomass materials with coal in large coal-fired boilers can introduce significant changes to the chemistry of the ash materials deposited on boiler surfaces, and this can have a significant impact on the chemical reactions that occur at the metal/oxide/ash deposit interface. Two important changes to the deposit chemistry are relevant in this context, viz:

- the introduction of increased levels of alkali metal species into the vapour phase and their subsequent condensation on boiler surfaces can lead to enrichment of particularly potassium compounds at the metal/oxide/ash deposit interface; and
- some biomass materials have relatively high chlorine contents and the release of significant HCl concentrations into the boiler flue gases can lead to enrichment of chloride at the metal/oxide/ash deposit interface.

The enrichment of alkali metal chlorides at the metal/oxide/ash deposit interface can lead to increased rates of metal wastage due to gas-side corrosion, particularly on high temperature surfaces in the superheater and reheater sections of the boiler. In a number of cases, rapid metal loss, leading to significant corrosion-related operational problems have resulted. This subject has been studied in some detail, particularly in Denmark, where there has been interest in the co-firing of cereal straws with coal in large power boilers for some time (see, for instance, [193, 194].
The experience derived from test work on the 80MW_{th} CFB boiler at Grenaa in Jutland, which fires a 50:50 mixture of coal and straw on a heat input basis, has indicated that the corrosion rates of superheater tubes when co-firing straw were 5-25 times greater than those measured when the boiler was firing coal alone. The history of the superheater fouling and corrosion at Grenaa is interesting as it may help to identify the key factors affecting the corrosion process. For the first six months of operation, the unit was never run above 80% load, and no particular problems with the formation of superheater fouling deposits were reported. Increasing the load to 100% resulted in significant increases in the cyclone temperatures from around 850°C to around 900-1000°C. Serious problems with excessive fouling on the surfaces in the cyclones and the superheaters were reported.
After 18 months' operation, it was found that corrosive damage to the superheater elements, which were operating at a final steam temperature of 505°C, was so serious that replacement of the final superheater elements was necessary. Selective chlorine corrosion was considered to be responsible for the accelerated metal loss. Examination of the superheater tubes and of test specimens suggested that the chromium had been selectively removed from the metal surface and along grain boundaries. The oxide layers were irregular, porous, cracked, and partly exfoliated. In many cases, significant enrichment of chlorine was detected at the corrosion front in the degraded metal zone.
Considerable efforts were made to provide a description of the key factors responsible for the accelerated superheater tube wastage. One of the most important observations was that the great majority of the potassium in the superheater tube fouling deposits, and particularly at the metal/oxide/ash deposit interface, was in the form of potassium chloride, and it was considered that this was the principal agent of the selective chlorine corrosion. A number of corrosion mechanisms have been suggested to describe the corrosion process in detail. The mechanism offered by Hansen et al [194] involves sulphation of the solid phase KCl followed by the release of chlorine gas, or possibly HCl,

adjacent to the metal surface. The evidence for this type of mechanism lies in the results of the detailed microstructural examination of the corroded metal specimens. The chlorine selective corrosion involves the removal of chromium and to some extent iron from the metal grains and particularly at the grain boundaries. The chromium and iron formed oxides that are found at the degraded metal surface and between the degraded metal grains. In many cases, the degraded metal layer is porous, with no included metal oxides. No solid or liquid ash or flue gas components have been found between the grains in the degraded metal except for chlorine, which is associated with the chromium and iron. Hansen et al. were of the view that this makes a liquid phase corrosion mechanism involving fused ash components unlikely, and that a mechanism involving a gas phase corrodent, probably chlorine gas or hydrogen chloride, is more plausible.
Significant modifications were made in response to the accelerated superheater corrosion and other operational problems at Grenaa. These included:

- the addition of heat transfer surface to reduce furnace temperatures;
- a switch to a coal of lower sulphur content; and
- a switch to a limestone of higher quality.

These modifications had the effect of providing significant reductions in the extent of fouling deposition in the boiler convective section and in the rate of superheater metal wastage.
The results of the corrosion test-work at Studstrup power station are also relevant in this context. The test-work was performed during the straw/coal co-firing trials, at up to 20% straw on a heat input basis, in a 150 MW_e pf boiler. The results were very different from those obtained from the CFB boiler at Grenaa. At Studstrup, the impact of co-firing straw, at a co-firing ratio of 10%, on the measured corrosion rates was modest, and the evidence indicated a very different corrosion mechanism from that observed at Grenaa.
Examination of the fly-ash material indicated that the great majority of the potassium was associated with the alumino-silicates in the coal ash. It was considered that the potassium species released into the vapour phase in the flame reacted with the other ash constituents, as described above, and that little or no KCl was present at the metal/oxide ash deposit interface. The chlorine released from combustion of the straw was present in the flue gases in the form of HCl, and possibly Cl_2. It was found that the dominant corrosion mechanism relevant to the superheater tubes, at straw co-firing levels up to 10%, was oxidation with perhaps some alkali sulphate melt corrosion, i.e. the normal corrosion mechanisms associated with coal-firing. It was considered that the key difference between CFB and pf combustion is that the flame temperatures in pf systems are considerably higher, and that this permits interaction between the released potassium species and the other ash components. Furnace gas temperatures in CFB systems are too low for substantial interaction to occur. It should also be noted that the straw/coal co-firing ratio at Grenaa was significantly higher than at Studstrup and that the differences observed in the behaviour of the potassium and chlorine may be related to this co-firing ratio.
It is clear, therefore, that the co-firing of biomass materials with coal introduces a risk of accelerated corrosion rates of high temperature boiler tubes, and that the risk is associated with the increased levels of available alkali metal species and chlorine released into the boiler flue gases. Under unfavourable circumstances, as for instance at Grenaa, the impact of the accelerated metal wastage can be dramatic and there can be significant impacts on the operation and integrity of the plant. These risks do appear to be lower in pf-fired

boilers with biomass fuels with lower ash, potassium and chlorine contents, and at low co-firing ratios.

7.6.3 The efficiency of particulate emissions abatement equipment

As has been described above, the characteristics of the solid products resulting from the combustion of biomass materials are very different from those resulting from the combustion of coal. The chemistries of the ashes are very different, as are the physical characteristics. The nature of the inorganic material in most biomass materials is such that a significant amount of submicron fume material can be generated in the flame.
The co-firing of biomass materials with coal will generally lead to a reduction in the total fly-ash dust burden, due to the lower ash content of the biomass. However, the mixed ash may contain significant levels of very fine aerosol material, which may present problems to conventional particulate emissions abatement equipment. When electrostatic precipitators are employed, the result may be an increase in the particulate emissions level from the chimney, compared to that measured when firing coal alone. This effect is likely to be highly site-specific and will be of particular interest in retrofit projects, where the existing electrostatic precipitators have been designed for coal-firing alone. When fabric filters are employed for particulate collection, there is a tendency for the very fine aerosol material to blind the fabric, resulting in cleaning difficulties and an increased pressure drop across the system.
The experience to date in the European demonstration projects and the straw/coal co-firing projects in Denmark has been that compliance with the relevant particulate emissions consent limits, normally 20 mg Nm^{-3}, dry at 6% O_2, has not presented any significant difficulties. This issue, however, is likely to be highly site-specific. There are reports from North America, for instance, of incidences of increased particulate emissions in biomass co-firing retrofit projects.

7.6.4 The performance of NO_x and SO_x emissions abatement equipment

Most biomass materials have relatively low nitrogen and sulphur fuels. The nitrogen contents of most biomass materials are less than 1%, with many less than 0.5%, on a dry basis. The sulphur contents are, in almost all cases, less than 0.5%, on a dry basis. In general, therefore the co-firing of biomass materials with coal will result in reduced uncontrolled NO_x and SO_x emissions, with the percentage reductions increasing with increasing co-firing ratios. Some biomass materials have relatively high chlorine contents, and the effect of co-firing can be an increase in the total chlorine input to the boiler, and a net increase in the uncontrolled HCl emissions levels.
A number of large coal-fired power boilers have installed NO_x emission abatement equipment, and these can be classified under four categories, viz:

- low NO_x burners;
- advanced primary NO_x reduction techniques, such as Two-Stage Combustion (TSC) and gas or coal reburn technologies;
- selective Non-Catalytic NO_x Reduction (SNCR) techniques; and
- selective Catalytic NO_x (SCR) techniques.

The co-firing of biomass materials is likely to have little or no impact on the performance of low NO_x coal burners, provided that the combustion equipment has been purpose-designed for co-firing. The only significant risk area is concerned with the possibility of increased ash deposition on the burner quarls due to co-firing, which may interfere with burner operation. This will be dependent on the co-firing ratio, the fusion behaviour of the mixed coal and biomass ashes, and on a number of site-specific factors. In general terms, operation at co-firing ratios less than 10% on a heat input basis is not likely to cause significant problems in this regard.

The advanced primary NO_x emission control techniques, and in particular the deeply staged TSC techniques, involve operation with a significant portion of the furnace volume under reducing conditions. Plant experience with the application of these techniques in both retrofit and new projects has indicated that there are significant risks of increased slag deposition and of accelerated corrosion of furnace wall tubes. The co-firing of biomass materials may act to increase these problems due to the relatively low fusion temperatures of biomass ashes. The risks of furnace wall corrosion may be increased by the co-firing of biomass materials, which have relatively high chlorine contents. The risks of operational problems due to increased ash deposition and furnace wall corrosion will be highly site-specific, and will depend on the co-firing ratio, the fusion behaviour of the mixed coal-biomass ashes, and the chlorine content of the biomass. This is a significant risk area, which will need to be examined carefully on a case-by-case basis.

The co-firing of biomass materials is not likely to have any significant impact on the operation of SNCR systems, but may interfere significantly with the performance of SCR systems. The performance of SCR systems is strongly dependent on the catalyst activity, and on the replacement rate of catalyst material necessary to maintain acceptable NO_x emission levels. SCR catalysts are susceptible to 'poisoning' due to the condensation of volatile inorganic species on the catalyst surfaces. The co-firing of biomass materials will generally lead to an increase in the concentration of these species, and particularly of the alkali metals, in the flue gases. There is a significant risk, therefore, that the rate of SCR catalyst poisoning will increase, and that it will be necessary to increase the rate of replacement of catalyst material in order to maintain the required NO_x emission levels. This will add significantly to the costs of operation of the SCR system. This is a subject of current interest within the industry, and one of the future challenges to the catalyst suppliers will be to develop catalyst systems, that are more tolerant to poisoning by alkali metal condensation. This is a significant area of uncertainty, which will require further development.

The conventional approach to the control of SO_x emissions has been the installation of wet limestone-gypsum flue gas desulphurisation (FGD) equipment. As has been stated above, most biomass materials have relatively low sulphur contents, and biomass co-firing will, in general, result in a reduction of the SO_x concentration at the inlet to the FGD plant, and reductions in both the limestone requirement and the gypsum production rate, depending on the co-firing ratio and the sulphur content of the biomass. Some biomass materials have relatively high chlorine contents and there may be an impact on the design and the performance of the FGD plant, depending on the co-firing ratio and the chlorine contents of the coal and the biomass. HCl is very reactive to the limestone slurry in an FGD plant and will be absorbed very efficiently. It may be necessary to modify the design of the FGD system and the wastewater treatment plant in situations where the total chlorine burden in the system is high.

7.6.5 Utilisation and disposal of solid residues from the power plant

A number of the more important environmental impacts of the operation of large coal-fired power plants are associated with the very large quantities of solid materials discarded from these processes. These are, principally:

- coal ash residues; and
- solid residues of flue gas desulphurisation processes.

In the main, these materials are produced and handled separately. However, there are a small number of plants, which produce a mixed coal ash/FGD residue discard material. Very large quantities of these materials are involved. It has been estimated [195, 196, 197] that the total quantity of coal-fired power plant solid residues produced in Europe in 2000 was 59 million tonnes, comprising around 48 million tonnes of ash materials and around 11 million tonnes of FGD residues. Annual statistics on this are collected by the European Association for Use of the By-Products of Coal-Fired Power Stations (ECOBA), in Essen, Germany, and a more detailed breakdown of the data is presented in Table 7.4.

Table 7.4: *European production of solid residues from coal-fired power plants - 2000 data [197].*

Material	European production in 2000 (million tonnes p.a.)
Coal fly ash	39.0
Bottom ash	5.6
Boiler slag	2.4
FBC residue	1.0
FGD residue	10.6
Other	0.7
Total	59.3

Ash discards are produced from a number of boiler ash outlets, including:

- fly ashes from the electrostatic precipitator or bag filter, and from the ash hoppers under the boiler economiser and air pre-heater; and
- bottom ashes and slags from the furnace ash hoppers and slag taps.

On average, around 80% of the total ash discard material from large pulverised fuel-fired boiler plants is in the form of *fly ashes* from the particle collection equipment, and the economiser and air pre-heater hoppers. This is a fine powder with the great majority of the particles being less than 50 microns in diameter. The pattern of utilisation/disposal of pulverised coal fly ashes (1997 data) is presented in Table 7.5.

The overall level of utilisation of fly ashes in Europe is around 57%. However, the rate in different countries varies markedly. In the Netherlands, Germany, Belgium, Italy, and Denmark, utilisation rates are in excess of 80%, and significant advances have been made in the reclamation of old fly-ash dumps. In other countries, utilisation rates are much

lower. In Britain, for instance, which produces around 10 million tonnes p.a., the utilisation level is less than 50%. Overall, there is a trend towards the increased utilisation of fly ashes, particularly for higher value uses, as a constituent of construction materials. For some of the higher value uses of boiler fly ashes, such as for cement and concrete applications, the quality of the fly ash is controlled by a standard specification or classification system, e.g. EN 450, DIN 1045 or BS3982, etc. These standards usually specify the Loss on Ignition, the SO_3 content, and the fineness. They sometimes also include a required level of pozzolanic behaviour for the ash, i.e. the tendency to set hard when mixed with lime and water and allowed to dry. In most countries, specialist commercial companies are involved in the treatment, storage, and sale of boiler fly ashes, principally to the manufacturers of construction materials and the civil engineering industry.

Table 7.5: *The utilisation/disposal of pulverised coal fly ashes in Europe (1997) [195].*

Utilisation/disposal	Quantity (million tonnes p.a.)
Cement raw material	4.0
Blended cement	2.3
Concrete addition	4.9
Aerated concrete blocks	0.7
Non-aerated concrete blocks	0.7
Lightweight aggregate	0.3
Bricks and ceramics	0.2
Subgrade stabilisation	2.1
Infill	1.0
Other uses	0.2
Reclamation/restoration	9.2
Temporary stockpile	0.6
Disposal	19.4
Total	45.6

On average, around 20% of the total ash discards from pulverised coal-fired boilers is in the form of *bottom ashes and slags*, collected from the furnace ash hopper. In the main, this material comprises fused furnace slags and dislodged ash deposit material. It is highly variable in nature, and can range in size from small particles less than 1 millimetre in diameter to large lumps of fused slag up to 1 metre or so in size. Chemically, the boiler bottom ashes tend to be similar to the fly ashes, however they tend to have relatively low unburnt carbon contents and low SO_3 contents. The pattern of utilisation and disposal of boiler bottom ashes and slags in Europe in 1997 is presented in Table 7.6.

Table 7.6: *The utilisation/disposal of pulverised coal bottom ashes and slags [195]*

Utilisation/Disposal	Quantity (million tonnes p.a.)
Concrete addition	0.2
Non-aerated concrete blocks	1.0
Lightweight aggregate	0.3
Grouting	0.2
Subgrade stabilisation	1.1
Pavement base course	1.2
Blasting grit	0.7
Other uses	0.3
Reclamation/restoration	2.0
Disposal	2.6
Total	9.6

The co-firing of biomass materials with coal will result in the production of mixed ashes, i.e. the fly ashes, and the bottom ashes will comprise components of both the coal and biomass ashes. The chemical and physical properties of the mixed ash discards will clearly depend on the ash contents and qualities of the coal and the biomass ashes, and on the co-firing ratio. The utilisation and disposal of these mixed ash discards will require careful consideration. For the higher value uses, particularly of the fly ashes, compliance with the standard specifications and classifications will be a requirement, and it should be noted that these standards were not prepared with biomass co-firing in mind. It is sometimes the case that the standards are poorly drafted and they may be over-prescriptive. This issue may represent a significant barrier to the implementation of biomass co-firing projects in some countries.

7.6.6 Summary of ash impacts

It is clear from the material presented above that the physical and chemical characteristics of biomass ashes are very different from those of coal ashes and that the co-firing of biomass materials with coal in large pulverised coal-fired boilers produces a mixed ash, which may have significant impact on the operation of the boiler. The key areas of concern are:

- The fusion temperatures of the mixed ash may be significantly lower than those of the coal ash and there are concerns about the increased risk of problems associated with slag deposition on furnace surfaces. These risks are dependent on the fusion behaviour and the chemistry of the coal ash, and on the co-firing ratio. There may be a significant impact on the heat absorption in the furnace and, if excessive slag formation occurs on the surfaces of burner quarls, there may be an impact on burner performance.
- The relatively high potassium contents of biomass materials will result in significant increases in the levels of alkali metal species released into the vapour phase at flame

temperatures, when co-firing biomass materials. There are concerns about the increased risks of excessive convective section fouling due to a volatilisation-condensation mechanism involving the potassium compounds to be released from the biomass.

- Some of the biomass materials have relatively high chlorine contents in addition to high potassium contents, and there are concerns about the increased risks of excessive high temperature corrosion rates of boiler tubes, particularly in the superheater and reheater sections, when co-firing biomass materials.
- The co-firing of biomass materials can have impacts on the environmental performance of the power plant and specifically on the operation and performance of the flue gas clean-up equipment and on the utilisation/disposal of the mixed ash discards from the plant.

The specific concerns surrounding ultra-supercritical (USC) boilers are associated with the impacts within the furnace and in the superheater and reheater sections. The major concerns have to do with the risks of increased ash deposition and of accelerated gas-side corrosion associated with biomass co-firing. These issues have been discussed by Henriksen and Larsen [198], specifically with regard to the combustion of cereal straws and with the co-firing of cereal straws with coal in large boilers. In this context, cereal straws can be regarded as representing one of the more difficult of the commonly used biomass materials. Concerning ash deposition in pulverised coal-fired boilers involved in the co-firing of straw, the authors concluded that design measures, particularly in the boiler convective section, can assist in reducing the extent of bridging between the heat transfer elements and avoiding excessive deposit buildup. On corrosion, the co-firing of straw with coal, at low co-firing ratios, is considered not to be particularly troublesome, because of the high flame temperatures and due to the presence of significant levels of SO_2 in the combustion gases. Limiting the biomass co-firing ratio to values less than 20% on a heat input basis could reduce the risks of fouling and corrosion. The authors also considered that one of the best ways to reduce the risks of both fouling and gas-side corrosion is fuel pre-treatment, by water or steam washing to reduce the alkali metal and chlorine contents of the fuel. Testwork has indicated that this approach can be reasonably effective, but is likely to be relatively expensive, increasing the fuel costs significantly. These specific conclusions for straw co-firing also apply on a wider basis to all biomass materials, i.e. that the risks of excessive fouling and gas-side corrosion can be reduced by specific boiler design measures and by limitation of the co-firing ratio. In some cases, it may be necessary to consider the pre-washing of the fuel.

7.7 Guidelines for co-firing biomass with coal

This paragraph presents guidelines for co-firing biomass with coal in coal-fired boilers. These guidelines are based on the results from pilot- and commercial-scale tests with a variety of biomass fuels and coals. Guidelines are offered in each of six general areas of major concern when co-firing biomass with coal: (1) fuel preparation and handling; (2) pollutant emissions; (3) ash deposition and deposit properties; (4) fuel burnout; (5) corrosion; and (6) fly-ash utilisation. For each of these areas, a brief statement of the issue and a brief guideline are summarised. More detailed information can be found in the

references. These guidelines are generally valid, but there are specific instances where each of them is not valid. Discussions in the literature provide the background to determine when such instances arise. This work is supported by DOE's Offices of Energy Efficiency and Renewable Energy (EE) and of Fossil Energy (FE). EE support is through the Biomass Power Program. FE support is from the National Energy Technology Laboratory (NETL). Major contributors to this research include Foster Wheeler Development Corp., the Electric Power Research Institute's Biomass Interest Group, NETL, the National Renewable Energy Laboratory, and Sandia National Laboratories.

7.7.1 Fuel characteristics

The biomass fuels considered here range from woody (ligneous) to grassy and straw-derived (herbaceous) materials and include both residues and energy crops. Woody residues are generally the fuels of choice for coal-fired boilers while energy crops and herbaceous residues represent future fuel resources and opportunity fuels, respectively. Biomass fuel properties differ significantly from those of coal and also show significantly greater variation as a class of fuels than does coal. For example (see Figure 7.14 and Figure 7.15), ash contents vary from less than 1% to over 20% and fuel nitrogen varies from around 0.1% to over 1%. Other notable properties of biomass relative to coal are a generally high moisture content (usually more than 25% and sometimes more than 50% as-fired, although there are exceptions), potentially high chlorine content (ranging from near 0 to 2.5%), relatively low heating value (typically about half that of hv bituminous coal), and low bulk density (as low as one tenth that of coal per unit heating value). Each of these properties affects design, operation, and performance of co-firing systems.

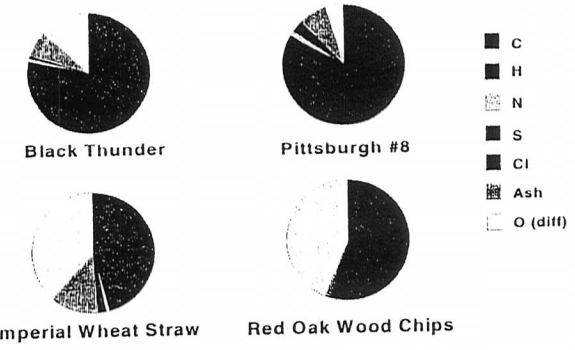

Figure 7.14: *Typical ultimate analyses of biomass and coal (courtesy Larry Baxter, USA). All of the components are presented clockwise, starting from the top with C.*

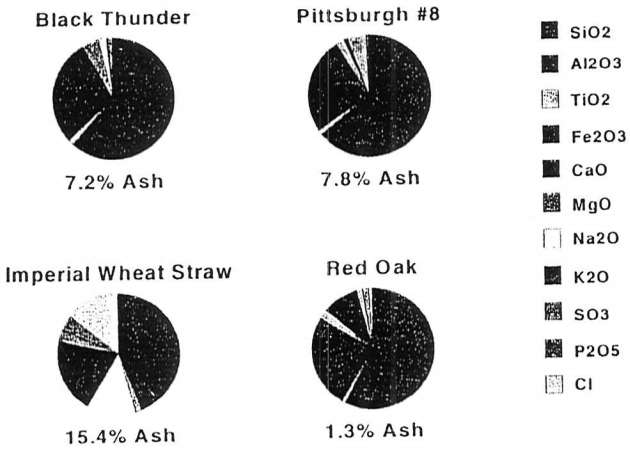

Figure 7.15: *Typical variation in inorganic composition of biomass and coal fuels (courtesy Larry Baxter, USA). All of the components are presented clockwise, starting from the top with SiO_2,.*

7.7.2 Fuel preparation and handling

Biomass is generally not as friable as coal, and comminution of biomass is best performed with other equipment that that used for coal and at higher energy cost. The most commonly used biomass comminution technologies include fuel hogs, tub grinders, and cutters of various types. It is possible to reduce biomass to arbitrarily small sizes by recycling material in a flow loop, but the cost of reducing biomass to sizes less than about ¼ inch increases substantially as the particle size decreases.

Because biomass fuels are hygroscopic, have low densities, and have irregular shapes, fuel handling is more difficult than for an equivalent coal system and is best done in a separate stream. Some exceptions to this general rule include biomass that has already been processed to an appropriate small size (sander dust and some types of sawdust) and very dense and relatively brittle biomass (some nut shells). Additionally, trivial amounts of biomass used for co-firing can often be directly mixed with coal (and generally produce a trivial impact on greenhouse gas emissions). When the biofuels are mixed with the coal, care must be taken to prevent skidding, bridging, and plugging in pulverisers, hoppers and pipe bends. Biomass characteristically is very heterogeneous in size, properties, and composition. Most co-firing biomass fuel preparation systems incorporate a screen after fuel comminution to prevent rogue particles from upsetting the process.

Fuel should generally be prepared and transported with equipment designed specifically for that purpose rather than mixed with coal and simultaneously processed.

7.7.3 Pollutant emissions

Co-firing biomass with coal can have a substantial impact on the emissions of sulphur and nitrous oxides (SO_x and NO_x). SO_x emissions almost uniformly decrease when firing biomass with coal, often in proportion to the biomass thermal load, because most biomass fuels contain far less sulphur than coal. An additional incremental reduction (beyond the amount anticipated on the basis of fuel sulphur content alone) is sometimes observed due to sulphur retention by alkali and alkaline earth compounds in the biomass fuels.

The effects of co-firing biomass with coal on NO_x emissions are more difficult to anticipate (see Figure 7.16).

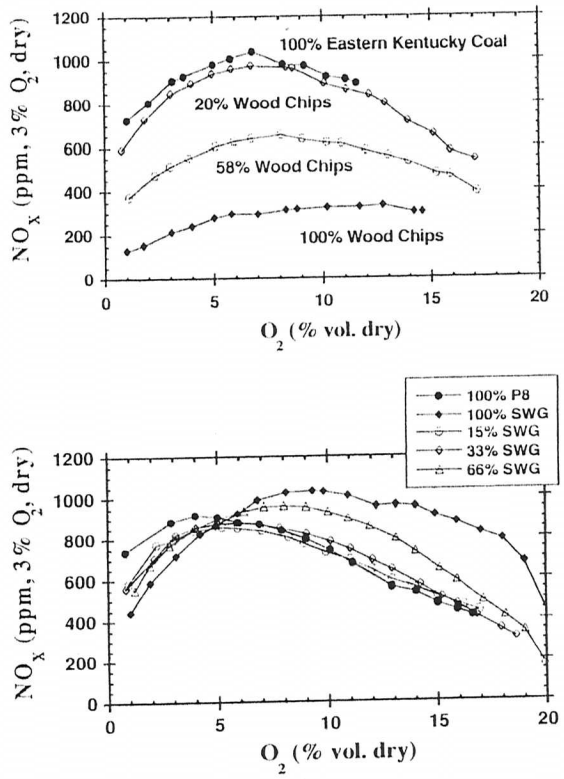

Figure 7.16: *Effect on NO_x emissions when co-firing wood (top) and switchgrass (bottom) with coal. NO_x emissions can both increase and decrease when co-firing biomass. Fuel nitrogen content: wood = 0.18, switchgrass = 0.77; coal = 1..1.2 lb N/MMBtu. (Courtesy of Larry Baxter, USA).*