

Co-combustion a summary of technology

Co-combustion of biomass or waste together with a base fuel in a boiler is a simple and economically suitable way to replace fossil fuels by biomass and to utilise waste. Co-combustion in a high-efficiency power station means utilisation of biomass and waste with a higher thermal efficiency than what otherwise had been possible. Due to transport limitations, the additional fuel will only supply a minor part (less than a few hundreds MW_{fuel}) of the energy in a plant. There are several options: Co-combustion with coal in pulverised or fluidised bed boilers, combustion on added grates inserted in pulverised coal boilers, combustors for added fuel coupled in parallel to the steam circuit of a power plant, external gas producers delivering its gas to replace an oil, gas or pulverised fuel burner. Furthermore biomass can be used for reburning in order to reduce NO emissions or for afterburning to reduce N₂O emissions in fluidised bed boilers. Combination of fuels can give rise to positive or negative synergy effects, of which the best known are the interactions between S, Cl, K, Al and Si that may give rise to or prevent deposits on tubes or on catalyst surfaces, or that may have an influence on the formation of dioxins. With better knowledge of these effects the positive ones can be utilised and the negative ones can be avoided.

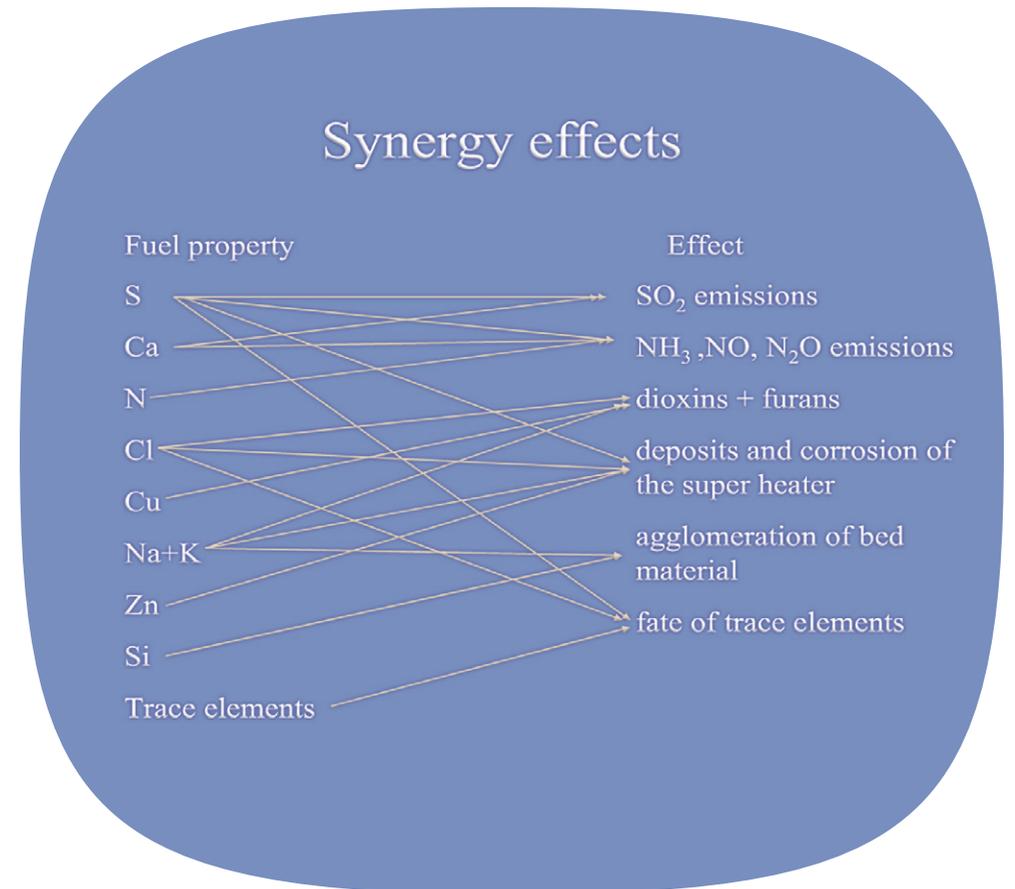
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The project has the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. Here the focus is on the stationary energy system (power and heat) in the European setting.

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a summary of technology

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PATHWAYS TO SUSTAINABLE EUROPEAN ENERGY SYSTEMS
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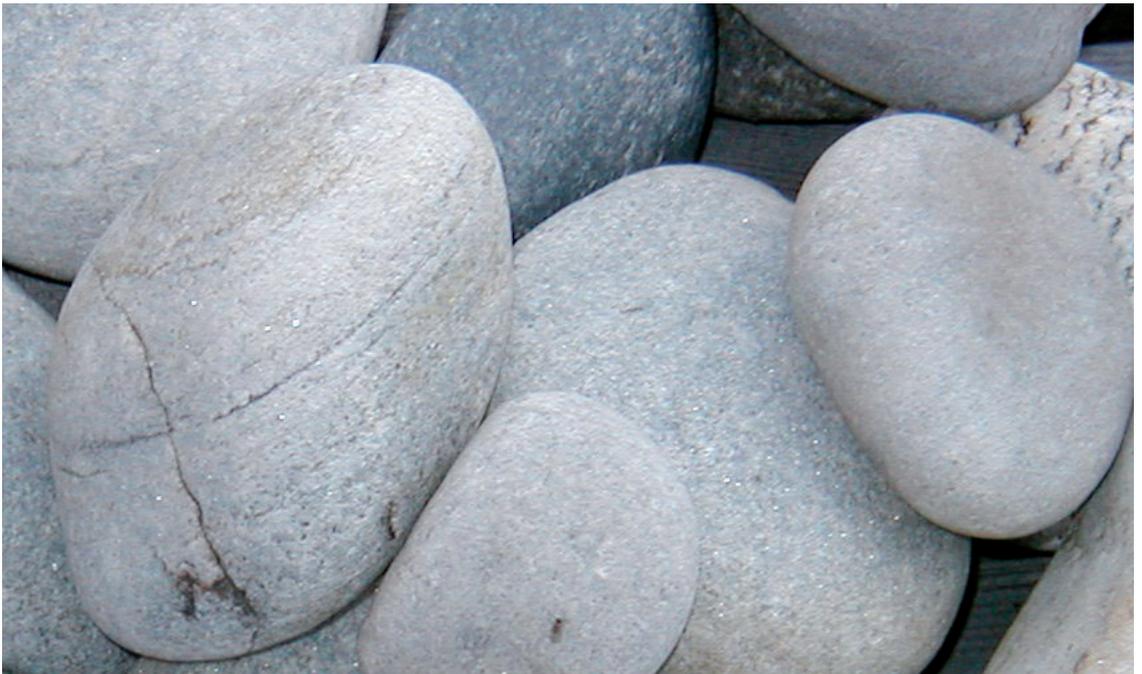
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Summary

Co-combustion of biomass or waste together with a base fuel in a boiler is a simple and economically suitable way to replace fossil fuels by biomass and to utilise waste. Co-combustion in a high efficiency power station means utilisation of biomass and waste with a higher thermal efficiency than what otherwise had been possible. Due to transport limitations, the additional fuel will only supply a minor part (less than a few hundreds MWfuel) of the energy in a plant. There are several options: Co-combustion with coal in pulverised or fluidised bed boilers, combustion on added grates inserted in pulverised coal boilers, combustors for added fuel coupled in parallel to the steam circuit of a

power plant, external gas producers delivering its gas to replace an oil, gas or pulverised fuel burner. Furthermore biomass can be used for reburning in order to reduce NO emissions or for afterburning to reduce N₂O emissions in fluidised bed boilers. Combination of fuels can give rise to positive or negative synergy effects, of which the best known are the interactions between S, Cl, K, Al and Si that may give rise to or prevent deposits on tubes or on catalyst surfaces, or that may have an influence on the formation of dioxins. With better knowledge of these effects the positive ones can be utilised and the negative ones can be avoided.





Introduction

Co-combustion is probably the least complicated and one of the most advantageous ways of utilising biomass and waste for replacement of fossil fuels for stationary energy conversion. It is therefore of interest to summarise its possibilities and limitations. This is the purpose of the present report that looks upon the topic from a general technical point of view, recognising that the reason to avoid CO₂ emissions from fossil fuels is not a national or a local issue but a global one. Economic and energy system aspects are important but outside of the scope of the present report that focuses on technical details.

Co-combustion means simultaneous combustion of two or more fuels in the same plant for energy production. Although this mode of combustion has been applied for many years, the interest has been enhanced recently, as seen from the rising number of scientific publications in Fig. 1, mentioning co-combustion in their headings.

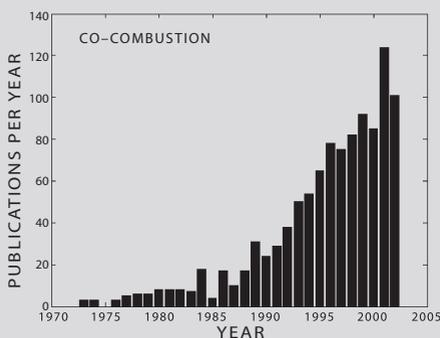


Figure 1. Number of scientific publications per year dealing with "co-combustion" or "co-firing" as extracted from the data bank of ScienceFinder, January 2003

The number of publications just indicates that co-combustion has been discovered as being promising for the use of biomass. When the first euphoria has declined, it is likely that the number of publications dealing with the phenomenon as such will fall, and interest will turn into more specific topics, like combustion phenomena and issues related to details of pollution and operation during co-combustion.

Co-combustion can be carried out in various ways for various purposes. A coarse classification could be as follows, covering new plants as well as existing ones converted for the purpose:

- 1) A small amount (a few percent of total fuel power) of biofuel or waste is fired together with coal in a boiler, originally designed for coal. The purpose is to get rid of waste or to replace coal by biomass utilisation.
- 2) A small amount of fuel with a high heating value is fired together with a fuel having a low heating value (such as sludge) that needs thermal support to attain a desired combustion temperature.
- 3) Spontaneous use of co-combustion with fuels in any ratio, depending on price, availability and local supply conditions.

The first type is of greatest significance due to its potential ability to reduce the consumption of coal, thereby decreasing the emissions of greenhouse gases. It is of interest to assess the possibility and reliability of such utilisation of biomass and waste in a plant designed for the base fuel (normally coal). Item two, addition of high-value fuel to a low-value one, or in general terms, combination of any fuels with different properties, may have

useful secondary consequences, such as reduction of emissions or improving reliability of operation. This could enhance the interest for combinations of fuels, because certain fuel constituents may influence each other, "synergy effects" may take place, leading to an improvement of operation of a boiler and to avoidance of inconveniences related to some fuels. This will be treated below, but first an account will be given on the technology of co-combustion. Item tree is more undetermined: it could include all kinds of combinations of available fuels, such as industrial residuals, sawdust, wood chips, peat, petcoke etc.,

used for energy conversion. It depends on local governmental restrictions (like taxes on coal in some Scandinavian countries) and on the local availability of waste fuels. The choice of fuels is related to economic and transport advantages. In this context, co-combustion has been greatly promoted by the introduction of fluidised bed combustion, a technique that facilitates the simultaneous combustion of different fuels. It is often related to waste disposal. Coal is not necessarily involved. Examples of this third type of co-combustion situation have been given by Järvinen and Alakangas (2001).

Advantages and disadvantages

Co-combustion has a number of potential advantages. A brief list could be as follows:

- Reduction of CO₂ emissions from fossil fuels.
- Increased use of local fuels.
- Conversion of biomass and waste fuels with high efficiency and under controlled environmental conditions.
- Seasonal variations that are inherent in some biofuels can be handled because the ratio of added to base fuel can easily be changed down from its maximum value.
- Less complicated than alternative conversion methods for biofuels and, hence, potentially economically advantageous.
- The amount of additional fuel employed can be adjusted to the availability of biofuels and wastes

within a reasonable transport distance from the conversion plant.

- Possible positive synergy effects between different fuels can be utilised.

Disadvantages can also be suspected to occur:

- The cost of some additional equipment or treatment processes has to be considered.
- The threat of harmful influence on the plant, caused by the additional fuel.
- Possible negative synergy effects if the additional fuel has extreme properties (some wastes) or if the combination of fuels is unfortunate.
- Lack of experience, as reflected from two of the above items.



Methods

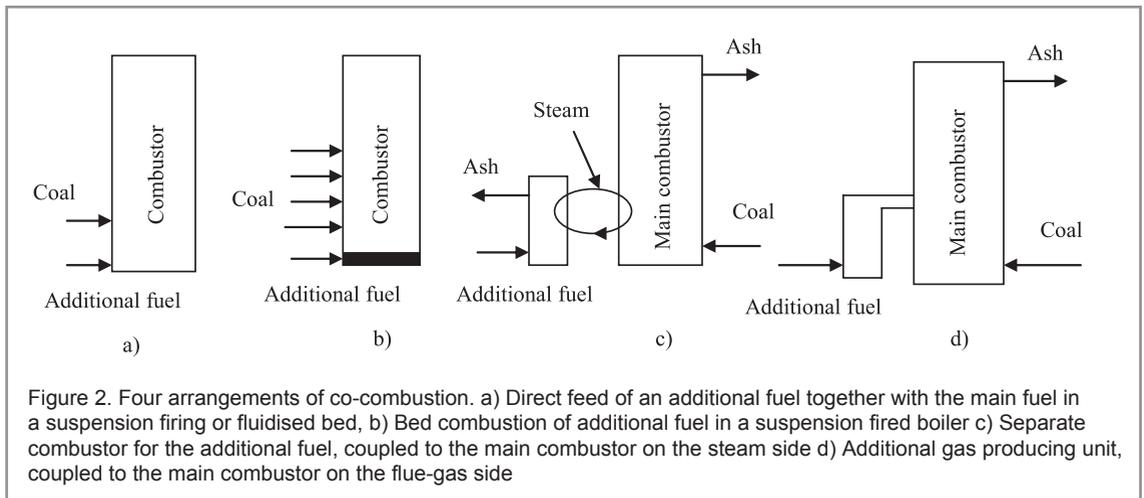
Any type of boiler may be used for co-combustion; boilers for pulverised fuel or for coarsely sized fuel in fluidised or fixed beds, probably firing coal as the main fuel. The boiler is the heat source in a utility plant for power production or an industrial or district heating plant. In a utility boiler, the minor amount of co-fuel added to the main fuel is treated in a highly efficient environment of a boiler with high steam data (such as typical for a utility boiler). In the third group mentioned above, co-combustion approaches waste incineration in small (less than a few hundreds MWth) boilers, and efficiency is optimised, emphasising the reliability of operation with difficult fuels and not necessarily the efficiency of electricity production. The boiler may even be a district-heating boiler; a hot-water boiler or a steam boiler for co-generation of electric power. In the latter one the steam data are important for the amount of power produced; the steam temperature is a critical parameter, since the surface of the superheater may become covered by deposits from the additional fuel and subsequently corroded. Thorson (2004) has classified steam data used in this group of application (the third case of co-combustion, mentioned above), Table 1.

The table shows a beneficial influence of peat on the propensity of deposit formation on tubes, as reflected by the experience of boiler designers. Coal, and probably also sulphur, would have a similar impact as peat. The data in Table 1 are lower than those aimed at in modern utility boilers fired with fossil fuels.

Figure 2 depicts four conceivable groups of arrangement for co-combustion. In arrangement a) the additional fuel is simply added to a boiler designed for the base fuel, usually coal. This is the most convenient method, which can be used in connection to both fluidised bed and pulverised fuel boilers. As mentioned, fluidised bed combustion (FBC) is quite suitable for the purpose because of its fuel flexibility, whereas the pulverised coal (PC) combustor requires a well defined fuel size distribution. The experience shows that only minor quantities of additional fuels (a few percent of the fuel power) can be handled directly together with the coal in the existing coal mills of a PC plant (Hughes and Tillman, 1998; Savolainen, 2003). If larger quantities are to be used, special mills and burners are desirable. There are no such limitations in FBC.

Table 1: Typical maximum recommended steam data for co-combustion boilers (Thorson 2004)

Type of combustible	Superheater located in flue gas path, °C	Superheater located in the return leg from cyclone in CFB, °C
Conventional waste fuels	405	465
"Problematic" fuels in co-combustion	460	520
Conventional bio fuels, such as wood waste	480-500	540
Conventional bio fuels, co-fired with peat	540	565



In fluidised beds larger pieces of fuel can be used, irrespective of the size restrictions imposed on the primary fuel. Only the heat balance of the bed sets a limit. The reason for the lack of size restrictions for the additional fuel in fluidised bed, in addition to the well known fuel flexibility of FBC, is the low ash content in most biofuels that makes the impact on the particle size distribution of the bed insignificant. Another advantage of FBC is noted in Table 1; allocation of the end superheater in the particle seal of the return leg from the cyclone (or in an extended particle seal) protects the superheater, allows high heat transfer and permits an increment of the steam temperature of about 60 degrees compared with a superheater located in the flue gas path. A grate-fired boiler also could have a reasonable fuel flexibility, provided that the additional fuel is mixed with the base fuel outside of the boiler before injection.

In arrangement b) the additional fuel is added on a grate, inserted in the bottom of a suspension-fired pulverised coal boiler. A large scale test has been

carried out on a commercial PC boiler where a 10 MW grate was installed in the bottom of the combustion chamber (Mory and Tauschitz, 1999). The result was positive, but the contribution of the additional fuel is always restricted, because the surface area of the cross section of the furnace determines the extension of the grate, and the surface power of such a device is low, less than 0.5 MWfuel/m^2 . Alternatively, the bottom part of a pulverised coal furnace may be rebuilt to a non-circulating fluidised bed, into which the additional solid fuel is introduced, while the original coal-firing of the boiler is partly maintained. The bottom part is added to the boiler and supplied with its own fuel and ash systems. It is likely that the amount of fly ash will increase compared with the original design and the boiler systems have to handle this ash and the increased flue-gas flow (if the additional fuel has high moisture content). This should be easier in a boiler originally designed for coal than in one for oil or gas. It is not clear if there are any such PC boilers, supplied with an additional FBC bottom, in operation. The Kaipola boiler

(Tekes) has a similar configuration. It was directly designed for co-combustion of coal powder and various biomass residues on an FB in the bottom of the furnace. It is operated with a combination of pulverised coal in suspension and wood wastes in a fluidised bed and could serve as an example on the design of a retrofit unit with PC-FBC.

Alternative c) is a combustion unit, separated from the main coal-fired boiler on the fuel side, but connected to it on the steam side. In this way, the additional furnace can provide heat to the steam cycle at a suitable level of steam temperature. Moreover, the ashes from the additional fuel are separated from those of the base fuel, which facilitates subsequent utilisation of the ashes. Such a plant, of a power of 100 MW_{fuel} for combustion of straw has been built in Denmark in a 600 MWe power block (Anonymous, 2000). The steam data of the additional boiler are identical to those of the main boiler (except for the reheat) and the steam joins the steam system of the main boiler before the turbine, as shown on Fig. 3. The advantage of connection only on the steam side is that any harmful substance, released in the additional boiler, will not affect the principal plant, and both ashes and flue gases can be treated separately. Even interruption of operation of the additional boiler can be handled by simply decoupling the boiler on the steam side. The choice of steam data in the additional boiler can be adapted to the properties of the additional fuels to be used (however, in Fig. 3 the steam data are the same as those of the main boiler). There are several such plants in operation.

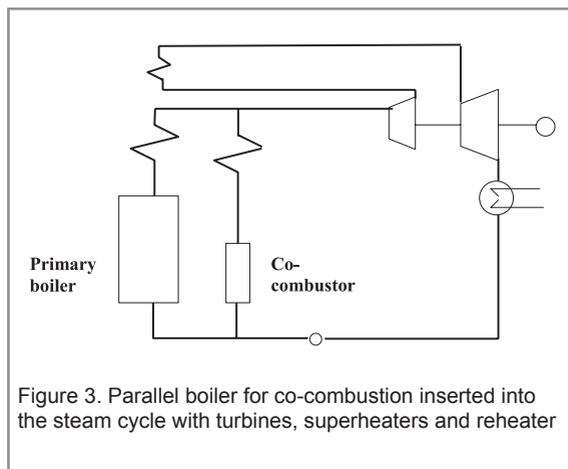


Figure 3. Parallel boiler for co-combustion inserted into the steam cycle with turbines, superheaters and reheater

The fourth arrangement d) consists of an additional combustor coupled to the main combustion chamber on the gas side to substitute the coal feed to a burner by gas. To reduce the volume flow of the hot gas produced in the additional combustor and, hence, to allow smaller dimensions of the hot gas-duct connecting the additional furnace and the main boiler, and to avoid heat removal by a steam system in the additional combustor, this furnace could be operated as a fluidised partial combustor or a devolatiliser with an air ratio of about 0.3, sufficient to raise the temperature of the bed to the desired level of 800-900 oC. If possible, the char residue should be gasified, but it is unclear if gasification is an efficient process at the low temperature level concerned. Such plants have been built in Finland and Austria (Raskin et al., 2000; Anderl et al., 2000). Combustible, low-calorific-value gas

is injected and burned in the main combustor, whereas most of the ashes remain in the gas generator and are removed from there, separated from those of the main boiler. Just as in Cases a) and b) also ammonia and volatile alkali compounds from the additional fuel enter the main combustor. Other arrangements of this type are conceivable but not investigated: the additional fuel could be devolatilised in the external converter on a grate or rotary kiln (to avoid dilution of the char by bed material as in a FBC) at a low temperature (500-600 °C); the gases are burned directly in the main combustion chamber, whereas the char, after sieving, is in a form that can easily be treated in the coal mills together with coal and injected through coal burners or used for other purposes if the impurities are prohibitive. In such a case impurities, like a considerable part of alkali and sulphur, remain in the char, and combustion of this product needs some consideration.

Many of these arrangements, especially Groups b) and d), are retrofits to existing coal-fired boilers. Arrangements a) and c) are the most likely ones for new designs, especially if the combustor is a fluidised bed. Plants conceived according to c) and d) have been called Indirect Cofiring. An account for several cases has been published by IEA, (Fernando, 2002).

There is a fifth mode of co-combustion: e) Employment of additional fuels for special purposes, such as "reburning" by means of pulverised biomass or gases produced by an external gas generator as in Method d) injected into a pulverised fuel boiler (Berge, 1993; Spliethoff and Hein, 1998) and "afterburning" in the cyclone (or its exit) of a circulating fluidised bed boiler to reduce N₂O (Gustavsson and Leckner, 1995).



Reburning and afterburning

Reburning, or fuel staging, as illustrated in Fig. 4, means injection of a secondary hydrocarbon fuel, gaseous, liquid or solid, downstream of the main combustion zone in order to establish a fuel-rich zone, where nitric oxide, NO, is reacted by hydrocarbons to mainly HCN. In the final combustion zone, the burnout zone, final combustion takes place and inevitably some new NO is produced by oxidation, but the overall result is reduction of NO by reaction with the nitrogen compounds formed (HCN) in the reburn zone. Reburning is a high-temperature (1300-1700 K) process, whose efficiency increases with temperature. The amount of fuel injected is in the order of 10 to 20 % of the boiler's total fuel power. An overview is given by Smoot et al. (1998). Originally, the secondary fuel (the co-fuel) was natural gas, whose task is to provide hydrocarbons. Later it was found that reburning also works well with solid fuels, for instance biomass, if the grinding is sufficient to produce fine fuel particles, together with sufficient residence time and temperature in the furnace for burnout of the char particles at the same time as ash deposition is avoided (Maly et al., 1999; Harding and Adams, 2000).

With solid fuels, not only hydrocarbons are introduced, but also various nitrogen compounds in volatiles and char particles. These compounds could be suspected to influence the reburning efficiency, but few systematic studies have been made to elucidate this effect. Spliethoff and Hein (1998) have compared various fuels and found that high-volatile fuels (biofuels) behave similar to gas and slightly better than coal. This result is similar to those of the other works referred to above. A relatively small quantity of sewage sludge with high nitrogen content did not perform as well as other fuels, but it was believed that this depended on other factors, such as a local temperature fall caused by the high ash content of the fuel. A modelling study by Vilas et al. (2004) showed that the effect of fuel nitrogen is rather small: positive (increased NO reduction) if the nitrogen is found in the volatiles and negative if it is in the char. In summary, the effect of fuel type seems not to be outstanding compared to other parameters influencing the efficiency of reburning: reburn zone temperature, residence time, reburn fuel percentage of total fuel, reburn zone stoichiometry, particle size, mixing conditions, etc.

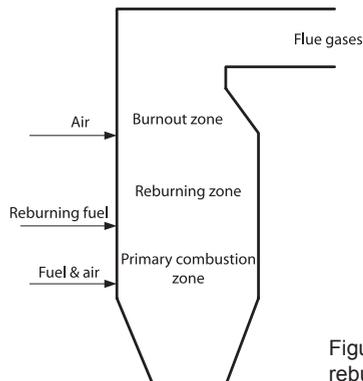


Figure 4. Schematic arrangement of fuel and air for reburning in a pulverised fuel boiler

Just like in the co-firing arrangement d), one can imagine an alternative reburning arrangement for difficult biomass fuels and wastes where gas is produced in an external pyrolyser at sufficiently low temperature to avoid devolatilisation of certain pollutants; the pyrolysis gas goes to reburning and the remaining char is utilised, after separation of external materials, to some suitable use (e.g. as an absorption agent in filters). Such an arrangement has been suggested by Fan et al. (2006). These authors showed the influence of the composition of the bio or waste gas on reburning: hydrocarbons

are favourable, whereas CO and H₂, not producing hydrocarbons, have even a negative effect on NO reduction. Hence, the pyrolysis conditions in an external reactor should be optimised to produce a biogas with high hydrocarbon content.

Afterburning means injection of additional fuel in the outlet of the cyclone of a CFB boiler to rise the gas temperature for reduction of the N₂O emission. This could be achieved with a few percent additional fuel. However, as long as there are no emission limits for N₂O this method has little interest.

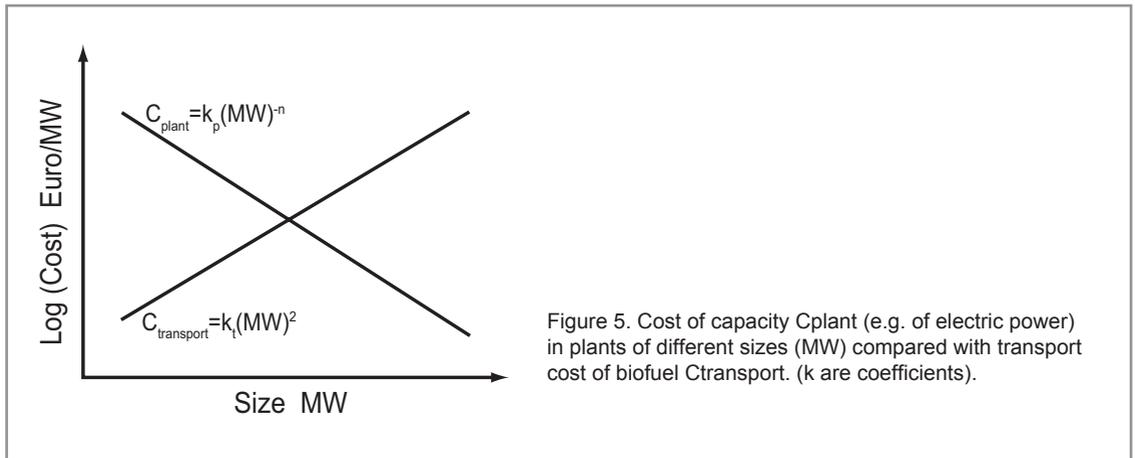
Plant size

There are no formal size limitations. However, there are certain economic restrictions on how far voluminous and disperse materials, such as biomass and waste, can be transported, and that limits the size of a plant fired with these fuels. A maximum supply of biofuels is 200 to 500 MW_{fuel} (corresponding to the fuel supply to the largest boilers in the world, operated fully or partially with biomass: Örebro (Skoglund, 1997) and Alholmen (Kokko and Nykvist, 2005)) in countries where biofuels in the form of forest residuals are abundant (Sweden and Finland). Based on these

extreme cases, a probable maximum supply to one boiler can be estimated to be in the order of 100 MW_{fuel}. Compared to utility boilers of sizes 1000-3000 MW_{fuel}, this means that the maximum quantities of biomass concerned in such boilers are less than 10% of the boiler capacity. A likely order of magnitude is perhaps 5% of the maximum boiler capacity. Such a quantity could be handled without substantial changes in a pulverised boiler and, indeed, in a fluidised bed, if the latter type of boilers were to be built with this capacity.



Example of repowered power plant - FB Boilers in Turow (Bogatynia). At present, co-firing is not used at this specific plant. However, this plant represents a typical power plant where co-firing may become a viable option.



In general terms the size-cost relationships are like in Figure 5. The cost of a plant depends on size according to some power function. The effect of size on cost makes utility plants large, and in such cases there is economic space for efficiency improvements. The same relationship illustrates why it is economically difficult to build similar (smaller) boilers for biomass. If they are built at all, there is no economic space for high-efficiency arrangements. However, in co-combustion this relationship is offset: the biomass fuel is utilised in the high-efficiency large-scale plant. Figure 5 also illustrates the transport limitation of fuels that are evenly available in a circular surface around a plant. From geometrical reasons the cost-size relationship in this case obtains a power of two. However, such relationships are easily broken by market imperfections that even make it possible to transport biofuels over the oceans by boat. Obviously, generalisation is possible only to a certain

extent. Several local and temporal factors that are difficult to express in a general way may influence the application of co-combustion.

However, cost is decisive, influenced by alternative fuel prices and legislation. Therefore, many short-time tests have been reported in the literature, but accounts for plants in long term operation are scarce until the economic condition of biomass utilisation improves, although such a trend is seen in some countries, and an increasing number of plants do operate in co-combustion mode.

In the other extreme, in the small, local plants for co-combustion with waste combustion, efficiency may be of less importance than operational reliability (Back-up for the largest unit in the energy system becomes relatively more expensive for smaller systems than for large ones).

Fuel properties

The properties and the ratio of the fuels burned together are decisive for the outcome of co-combustion. For the gross combustion behaviour of the boiler (combustion chamber, flue gas and ash handling systems) the proximate analysis (moisture and ash contents) and the content of volatiles are important. The analysis of the combustible part of the fuel gives information on the emission precursors (N, S, Cl). The ash forming elements (K,Na,Ca,Mg,Al,Si,P) are important to judge slagging and fouling, and finally, for waste fuels an analysis of the trace elements

(As,Ba,Cd,Hg,Pb,Se,...) is needed. Coal and biomass/waste differ essentially with respect to several of these properties. Examples of the composition of biofuels, wastes and coal are given in the literature (Jenkins et al., 1998; <http://www.ecn.nl/phyllis/>; <http://www.ieabcc.nl/database/biobank.html>; <http://www.vt.tuwien.ac.at/Biobib/biobib.html>). Despite obvious variations from fuel to fuel in each group, there are some typical differences between the three groups, coal, biofuels and organic wastes, summarised in Table 2.

Table 2. Typical differences between fuels

Parameter	Coals	Biofuels	Wastes
Sulphur	Medium to high	Low	Low to medium
Chlorine	Medium	Low to high	Medium to high
Potassium	Bound	Medium to high	Low
Other alkali	Normal	Low	Low to normal
Alumina, silica	High	Low to high	High

The high content of sulphur in coal compared to the other fuels, the high concentrations of chlorine in some coals, biofuels and wastes, as well as the role of potassium in biofuels for formation of deposits during combustion of biofuels should be observed as fuel properties to be further treated below. In case the fuel is used in a pulverised combustor its size has to be reduced. Conventional pulverisers for coal are usually not suitable for biomass. Instead of installing separate pulverisers, additional fuel could be pre-treated (milling, pulping, steaming, or torrefaction) in dedicated plants if the economic consequences are acceptable. In addition, washing would remove a large amount of the alkali. At present it seems common to prepare biofuels in the form of pellets to facilitate transportation to the boiler plant as well as inside of the plant. These pellets have the advantage of volume reduction, see

Table 3, but the pellets are also easier to pulverise than the original fuel. Another route to preparation of biofuels for grinding may be by torrefaction, Bergman et al. (2005). Torrefaction means heating of a biomass to 200-300 °C for a considerable time (in the order of hours) to break down the structure of the material, in this way increasing the grindability and energy density. The small loss of organic gases has to be taken care of.

The table shows that the common forms of biomass are 7-9 times as voluminous as coal and straw has an even greater volume. By pressing the finely chopped or ground material into pellets or briquettes, the volume is reduced to about twice that of coal for the same quantity of energy, which is reasonable for handling.

Table 3. Volume of typical biofuels compared to coal having the same energy content (Calculated average data from various sources)

Fuel	Ash %	Moisture %	Volume (m ³ /m ³ coal) _{MJ}
Coal	10	10	1
Wood pellets	1	5	2
Wood powder	1	5	4
Wood chips	1	50	7
Saw dust	1	50	9
Bark	1	50	8
Straw briquettes	5	<18	3
Straw bale	5	<18	13
Straw natural	5	<18	20

Impact of co-firing

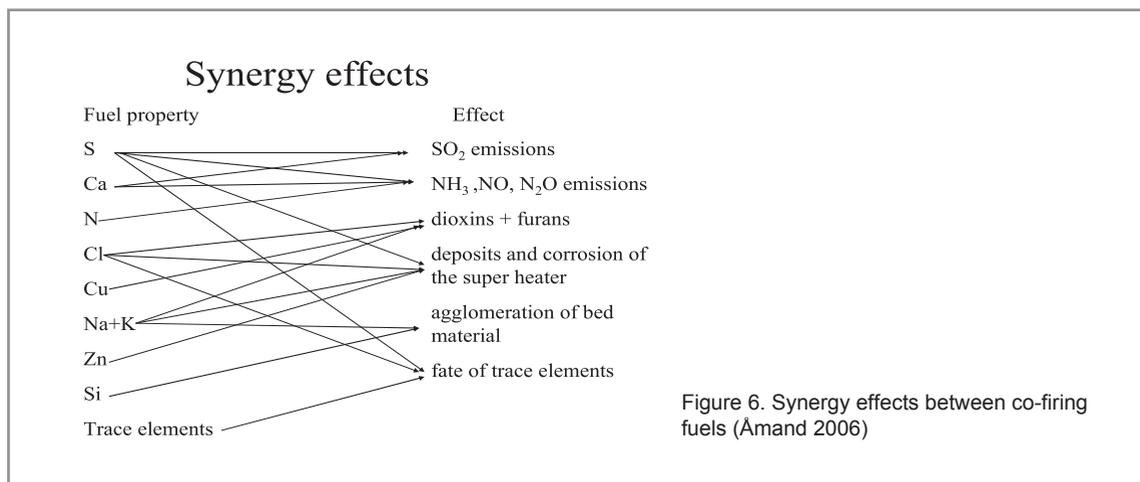
Complications may occur because of the differences in composition of the fuels when an additional fuel is fed to a base-fuel combustor. In extension to what was mentioned above, the potentially influencing factors can be sorted up into four groups:

1. **Energy content and volatiles.** Some added fuels may be moist and the quantity that can be added is restricted by the heat balance of the furnace. An extreme example is wet sewage sludge, whose effective heating value is very low. However, drying of such fuels can be arranged in energy-efficient ways in an external drier, or, in combination with a high-value fuel, direct combustion allows drying in the furnace.
2. **Precursors to gaseous emissions,** mostly nitrogen, sulphur and chlorine. They will be more or less converted into nitric or nitrous
3. **Ash-forming elements,** compounds containing potassium, sodium, calcium, mangan, alumina, silica and phosphorous, just to mention the most important ones. Some of these elements may cause severe problems in the form of deposits on tubes followed by corrosion and "poisoning" of catalyst surfaces. They may lead to bed agglomeration in fluidised bed combustors. They may also affect the composition of the ash in a coal-fired unit, preventing the sale of ashes for secondary utilisation, for instance, in the cement industry.

oxides, sulphur dioxide and hydrogen chloride or dioxins, hence they contribute to undesired emissions, or, expressed in a positive way, the added fuel normally contributes to reduction of emissions if the concentrations are lower in the added fuel than in the base fuel.

4. **Trace elements**, of which the heavy metals are the most important ones: arsenic, beryllium, cadmium, mercury, lead, selenium etc. There are two types of problems related to trace elements: either they are volatilised and emitted to the atmosphere with the flue gases (like mercury and cadmium, depending on the temperature conditions) or they are accumulated in the ashes, causing problems for deposition of ashes.

The impact of these groups varies depending on the type of additional fuel. Sometimes there is a mutual influence between components of various fuels, as illustrated in Fig. 6, that can be called synergy effects. The figure shows that the most influential interacting species (having most connections to other species) are S, Cl and K (+Na). Some of these effects will be treated in more detail below.



Experiences

In the year 2004 co-combustion was employed in 135 plants in the world according to information from various countries: USA, Germany and Finland having most plants in operation (Koppejan, 2004). Important information has been gathered from short and long term tests, in most cases related to the common type of boilers, PC boilers. The situation is simpler in FBC boilers and

extensive testing is not so urgent. Moreover, FBC has been applied early with a great variety of fuels in countries, where an extensive knowledge on handling of the most common biofuels originating from the forest was already available (Sweden and Finland). To summarise the experiences from testing in, principally, PC boiler plants, four co-combustion options are sorted up in Figure 7.

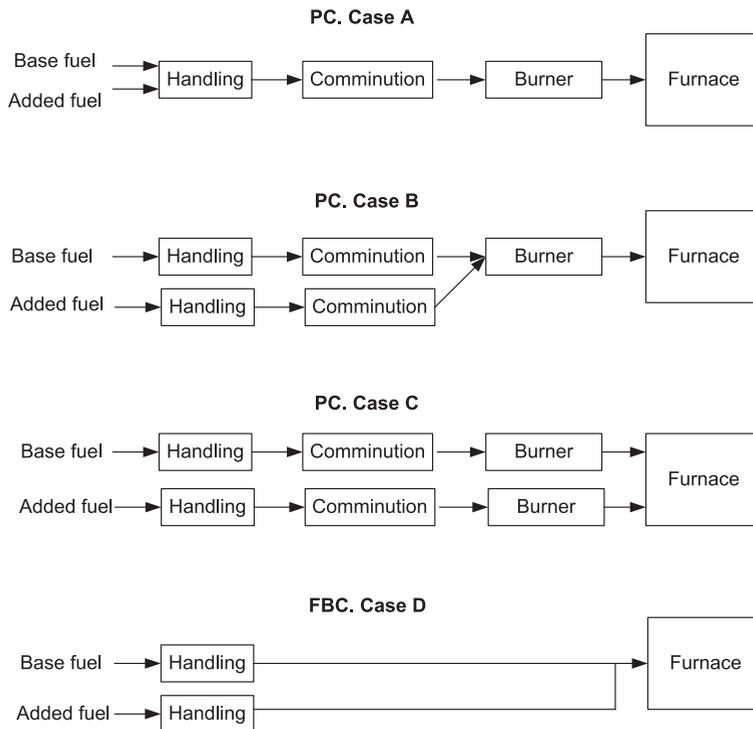


Figure 7. Organisation of the fuel supply during co-firing in PC and FBC boilers

The simplest option is to blend the added biofuel with coal, introducing the mixture through the existing fuel-handling system, and through the existing pulverised coal burners (Case A, Fig. 7). Here, the main constraint on the fuel ratio has been shown to be the behaviour of the blended fuel in the coal mills. Most mills are designed to pulverise bituminous coals depending on brittle fracture of the coal. Biomass does not behave in the same way as coal, and the operation of the mills is not satisfactory for large quantities of added fuel. Furthermore, if the biomass has a considerable content of moisture, the heat balance of the mill is affected in an undesirable way, and the co-fuel part has to be limited

to a few percent of the fuel power (Hughes and Tillman, 1998). However, for such quantities there are no restrictions in the rest of the system.

A similar experience was made by others. For instance, Savolainen (2003) concluded after a three-month test with wet (50-65%) sawdust in fuel-power fractions of 2.5-8% (the volume flows increased with 25 to 50%) that the main obstacle was in the fuel mills. The burners performed well, and this was claimed to be a consequence of their modern design. The only inconvenience found was related to the fuel size: a majority of small particles was accompanied by a certain amount of

larger (several mm) sticks. The latter influenced burnout in a negative way. The conclusions from the test, to be implemented in the future on the company's (Fortum) boilers, were: 1) A separate grinding and feeding system is needed (Case B, Fig. 7). 2) The particle size of the biofuel has to be well controlled, but a rather coarse grinding (compared to coal) is sufficient. 3) The available burners can be used for coal-biomass mixtures.

During a two-year test in the Danish power station of Studstrup, straw was fed through the central tube of pulverised fuel burners (replacing the oil injection lance) (Wieck-Hansen et al., 2000). The burners were fed through a separate feeding system (Case B, Figure 7) with 10 or 20 % of fuel power. Combustion itself does not seem to have been a problem. For instance, the amount of unburned was higher in the bottom ash and less in the fly ash, but there was no extreme loss of carbon. Instead the main concern was deposits and corrosion, not surprising, considering the extreme fuel used. However, also in this respect the conclusion was positive.

The problems mentioned should not be of importance in FBC systems (Case D, Fig. 7). The water content of the added fuel affects the energy balance and thereby the bed temperature, but this can be compensated for by design and operational measures. The size of the added fuel (the size of the ashes) could affect the size of the bed material, but usually the ash content is extremely low in many biofuels, so this should not be a problem and only crushing should be necessary. The remaining concern has to do with the alkali and chlorine content of the ashes. The Alholmen CFB boiler (Kokko and Nylund, 2005) is an ex-

cellent example of the capability of a CFB boiler for co-combustion. The boiler was manufactured by Kvaerner Power. The thermal power is 550 MWth, converted into district heat, industrial heat and electric power. The maximum electric power is 240 MWe (steam data 545/545 °C and 165 bar). The boiler can burn bark, wood, peat and coal, independently, or normally together (in fact, there is an advantage of co-combustion with coal or peat in that these fuels remove ash problems that may occur with mono-combustion of bark or wood waste). The very moist fuels (more than 50% moisture) require wider flue gas paths in the boiler than needed for dryer fuels and dedicated fuel handling systems, but otherwise the design is what could be called a "classical" CFB design (in the best sense of the word). It has now been in operation since the beginning of the year 2002.

However, there are limits of what can be done: in Grenå (Denmark) a 60 MWth coal-fired CFB with up to 60 % straw as an additional fuel had continuous problems of various kinds (Wieck-Hansen and Sander, 2003). The problems could partly have been related to boiler development and were overcome after the introduction of modifications, but partly also to the large fraction of straw, which is an extremely difficult fuel. The conclusion is probably (no systematic tests have been done) that both the quantity of the co-fuel and its properties (potassium and chlorine contents) have to be limited for successful operation. In Sweden and Finland many FBC boilers operate on mixtures of biofuels and waste fuels that are different from coal. Just like in Alholmen, no remarkable disturbances have been reported except such that have already been solved.

Fireside behaviour

The behaviour of fuel mixtures inside combustors needs to be further studied. However, work has already been done, as will be summarised below.

Combustion behaviour-carbon conversion

Biofuels are more volatile than coal. This means that fast devolatilisation will create rapid gas combustion in the vicinity of a burner. This promotes the combustion of coal that contains less volatiles and ignites later when fired alone (Gani et al., 2005). A similar observation has been made also in a comparison between combustion of coal and wood powder under strictly similar conditions (Ballester et al., 2005). The wood flame was luminous already in the vicinity of the burner, and then a second zone of combustion was observed a little farther away from the burner. It was interpreted that the fine fuel particles released their volatiles in the first part of the flame, whereas the second part of the flame was created by some volatiles and char from the larger size fractions of the wood powder. Despite the fact that the fuel particles were carefully produced, the biomass particles were larger than the coal powder, and under the conditions of the tests they required travelling a longer distance in the flame to complete their combustion. The same experience is probably made also in the industrial trials referred to above, where observations were not so detailed: biomass (especially wood) tends

to be produced in a wide particle size distribution, containing not only the small fractions burning fast enough, but also a certain amount of large (long) particles that could give rise to a minor combustion loss. It can be concluded that coal-biomass pulverised mixtures burn without problem, but the size reduction of the biomass to powder requires special attention.

The fast release of volatiles compared to the slow combustion of char also affects the conditions in a fluidised bed, although the size of average fuel particles may be an order of magnitude larger in a bed than in a flame combustor: release and combustion of volatiles anyway tend to take place in the vicinity of the feed point. Dependent on the fuel mix and on the fuel properties (content of volatiles and size distribution), the addition of one fuel to another will mostly be characterised by release and combustion of volatiles. Unless no great change is made in the parameters mentioned, there will be only a small impact of co-combustion on the operation of a fluidised bed boiler.

Deposits on heat transfer surfaces

Some ash constituents evaporate during combustion, undergo chemical transformations, and may settle down on surfaces that have suitable temperature for condensation. Other solid ash constituents can likewise stick to a tube surface, once a film has been formed on the tube. Deposits are formed and corrosion may occur. Investigation of the behaviour of various fuel ashes in fluidised bed (Skrifvars et al., 1998) shows that during combustion of coal and peat, the main components in the ashes are silicates. Sulphur is most likely associated with calcium in solid form, and the remaining sulphur is found in the flue gases, as well as chlorine in the form of HCl. In case of combustion of wood chips, alkali salts appear in the ash samples and in the deposits on tubes. Even though the fuel contains small quantities of chlorine and sulphur, these two elements are enriched in the deposits and in the fly ash. Coal and peat contain more ashes than wood, but the deposits are better behaved and easier to remove than those from wood, although the propensity for deposition of ash constituents from wood is less than that of other biofuels, such as straw. The behaviour of different fuels reflects their

properties with relevance to co-combustion. Judgments on deposit formation are usually based on equilibrium calculations, Andersen et al. (2000); Otsuka (2002); Wei et al. (2002); Yan et al. (1999). The composition of the fuels, the combustion temperature (PC or FBC), the residence time at a certain temperature and the temperature of the deposit are important parameters. It is clear that some of the alkali species (K) are preferentially bound in aluminosilicates in coals, and then not easily released at the combustion temperatures of an FBC, whereas in most biofuels the potassium is free to be released during devolatilisation and char combustion. The alkali compounds of interest are found in gaseous form in the combustion zone and in solid or liquid form at the deposit temperature. It is not known exactly how the active substance, potassium, leaves a biofuel particle, but if there is chlorine present, gaseous KCl is formed both inside and outside of the particle. If there is insufficient chlorine (molar ratio Cl/K < 1), the potassium finds other species and has a stronger tendency to become attached to solid particles, and, hence, deposit formation is reduced. The

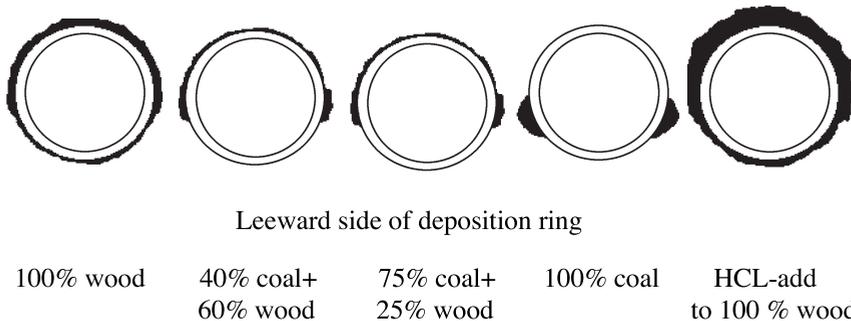
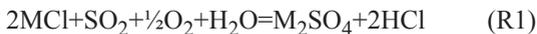


Figure 8. Initial deposits on a 500 °C tube in a CFB at 800 °C in five cases of operation with different mixes of coal and wood and one case with HCl addition. From Miettinen-Westberg et al. (2003).

influence of the availability of chlorine to create KCl, which enhances deposition, was illustrated by Miettinen-Westberg et al. (2003) after addition of HCl to CFB combustion of wood, as seen in Fig. 8.

The figure shows that addition of coal makes the deposits smaller than for pure wood, whereas addition of chlorine produces a catastrophic rate of (initial) deposition (10 times higher than for wood and 20 times higher than for coal). The deposits consisted not only of KCl, and, especially in the coal cases, a number of complex compounds, including oxides, were recorded. According to equilibrium calculations, the presence of sulphur displaces the melting region of the potassium compound (now K_2SO_4) towards higher temperatures (roughly from 800 to 1100 oC, if reduction of the melting temperature in various eutectica is disregarded). This could be one explanation why there are less deposits when more coal is used: K_2SO_4 is formed instead of KCl. If sulphur is present, KCl or alkali metals, MCl, may react with sulphur



There are different opinions on whether this conversion (and others) takes place in the gas phase or in the deposit layer. At least when it takes place in the gas phase, the danger of corrosion from chlorine is reduced and replaced with sulphur-promoted corrosion, which is less severe and more normal in coal fired boilers. It is generally known that the presence of excess sulphur ($S/Cl > 4$) has a beneficial effect for reduction of chlorine-induced corrosion in waste combustors, Krause (1986). This has been illustrated in Fig. 9 (Robinson et al., 2002).

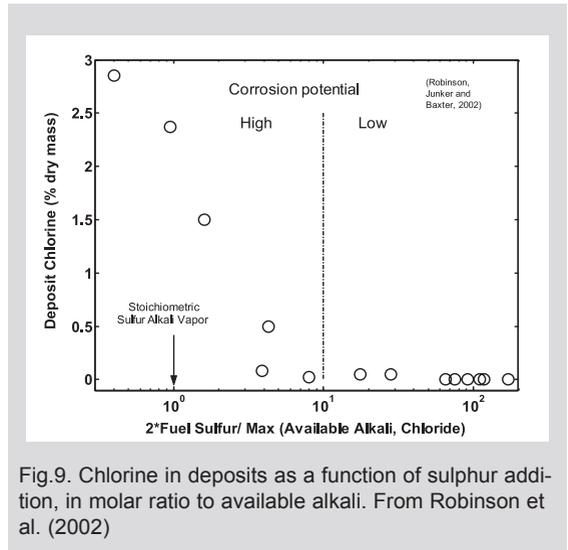


Fig.9. Chlorine in deposits as a function of sulphur addition, in molar ratio to available alkali. From Robinson et al. (2002)

In this figure, available alkali is the alkali that is not bound in minerals but is freely available for reaction and can be washed away from the fuel in water or ammonium acetate. In conclusion, co-combustion with some biofuels or wastes, containing considerable amounts of potassium and chlorine, could lead to enhanced deposits and corrosion. On the other hand, the sulphur in coal has a beneficial impact on this behaviour and considerably reduces the danger of deposits. Moreover, the quantity of additional fuel is normally small and that will further reduce deposits and enhance the effect of sulphur, which is usually present in the base fuel, coal. In fact, test runs with co-firing of biofuels have been reported without any remarks on unusual deposits or corrosion (Hughes and Tillman, 1998) or with the statement that no unusual corrosion was experienced (Savolainen, 2003).

Sewage sludge (2% of total fuel mass) has been co-fired for several years without "any negative influence on the operation of the power block" (Buck and Triebel, 2000), whereas high temperature corrosion was observed in a similar case (Luts et al., 2000). It is not clear from the report whether the latter was caused by the co-combustion or if it would have occurred in any case.

A hypothetical example elucidates the problem from the practical point of view: Assume that a certain combination of coal and biomass could be operated without disturbances, cf. Fig 8. Maintaining the biomass, assume that the coal was substituted with another coal of the same rank; then the growth of deposits in this hypothetical example increased in an unacceptable way. The reason would be that, although the two coals were similar from a general combustion point of view, the sulphur-chlorine relationship was unfavourably changed; the chlorine content was higher in the new coal than in the previous one, and enhanced deposits were caused by KCl.

Many of the tests reported in the literature on co-combustion were carried out during a couple of hours or a couple of days; no problems are reported, but no information is given on the composition of the fuels or on built-up of deposits that could be important in long-term operation. Therefore, some of the published test results on co-combustion, referred to here, become inconclusive with respect

to ash build-up on surfaces and corrosion.

At high temperatures (in flames) formation of K-silicates or K-Al-silicate is possible, (Dayton et al., 1999; Andersen et al., 2000). The formulation is believed to take place also under FBC conditions (Aho and Silvenoinen, 2005; Aho and Ferrer, 2005), and then deleterious potassium would be removed. In addition to the positive effect of sulphur, the experiences indicated that alumino-silicates supplied with many coals could bind the potassium released from biofuels, which could be part of the explanation why deposits were reduced by co-combustion with coal. This could also be part of the explanation why peat seems to have a similar positive effect on reduced deposits during co-firing of peat with biomass and waste, according to a wide-spread Nordic experience (Thorson, 2004; Kokko and Nylund, 2005). An analogous picture is given by sewage sludge, also containing alumino-silicates in the form of used zeolites. Addition of a certain quantity of sludge substantially reduces the initial rate of deposition in co-combustion with wood waste, Åmand et al. (2006). In this case the particle-size distribution of fly ashes in the flue gas duct was measured. This showed that the deposits were promoted by the submicron potassium chloride particles that disappeared when sewage sludge (3-10% of the energy) was added to the combustion in a CFB boiler operated with wood as a base fuel, as illustrated in Fig. 10. At the same time (when sludge was added) almost no deposits were formed.

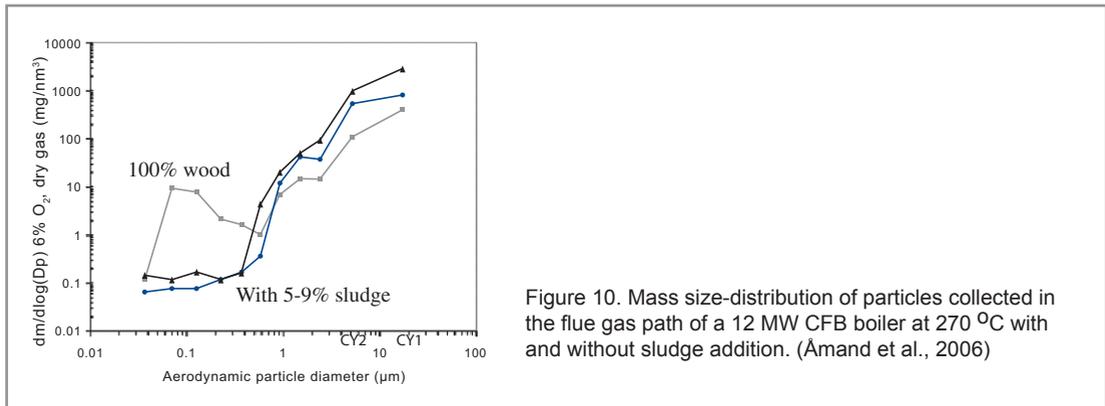


Figure 10. Mass size-distribution of particles collected in the flue gas path of a 12 MW CFB boiler at 270 °C with and without sludge addition. (Amand et al., 2006)

Jiménez and Ballester (2005), measured co-firing of orujillo (agricultural residue) and coal in an entrained flow reactor and found the same type of two-mode particle size distribution with K, S, Cl and P in the submicron particles, while the coarse particles had a composition similar to the overall one of fuel ashes. Chlorine co-existed with potassium during combustion of orujillo only, whereas during co-combustion with coal, chlorine was replaced by sulphur. Si and Al were present in the coal cases but did not play any significant role. In contrast, Seames et al. (2002) measured an increase of submicron particles during co-firing of coal and sewage sludge compared to coal alone. In this case, flame combustion with peak temperatures of almost 1600 K, refractory elements (Fe, Si and Si) vaporise and an interaction between these particles could have been a reason for the observed opposed effect compared to that of Fig. 10, because the impact of alkali vapours should be lower with coal than with biofuels. However, Seames et al. guessed that species derived from sludge (possibly alkali metals) and those from coal (possibly sulphur and/or chlorine) may have been responsible. (Hence, not only the opposite effect was observed but also the opposite explanation was given, compared to the results mentioned above!)

Straw is an extreme biomass fuel with respect to deposits and bed agglomeration because of its high content of potassium and chlorine. Wieck-Hansen et al. (2000) report from the carefully performed two-years test on co-firing with straw (K 1.5 %, Cl 9.55 % dry fuel) in the 380 MWth coal-fired boiler referred to above (Coal S 1%, Cl 0.2%). With 10 energy-% of straw, the corrosion behaviour was more or less similar to that under normal conditions with coal only, but with 20% straw the corrosion rate was increased by a factor 2-3 compared with normal (medium corrosive) rates for coal. The conclusion was that at least 10 energy % straw can be co-fired with coal in a boiler with a standard steam temperature of 540 °C, and even 580 oC could be tolerated without considerable corrosion risk. During these tests the deposits formed contained a large extent of potassium alumino-silicates and potassium sulphate, at the same time as a great deal of potassium was found in the fly ashes in the same forms. Most of the chlorine left the boiler as HCl, and there was little KCl in the deposits, Andersen et al. (2000). Obviously, this is an example of the beneficial effect from the minerals and from the sulphur in the coal on the transformation of the potassium in straw. It should be repeated that straw is an extreme case, as it contains much more potassium and

chlorine than most biomass fuels. Hence, it can be inferred from this carefully performed and analysed test that co-firing of biomass with the main fuel coal can be carried out without immediate danger for deposits and corrosion, provided that the coal is a normally traded one without extreme properties (particularly, with moderate chlorine content).

In addition to deposits on superheater tubes, in fluidised beds there may be a problem with bed agglomeration when employing biofuels, at least if the bed consists of silica sand. Silica sand gradually reacts with potassium to form low-temperature melts, causing the bed to sinter, stopping fluidisation. Addition of a certain quantity of coal or peat would solve this problem. This has been investigated by Lundholm et al. (2005), who conclude that adding a relatively small quantity of peat (5-30%) to combustion of rather difficult bark from spruce

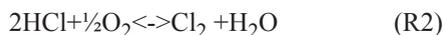
prevented the bed from sintering. Although there were no alkali-retaining minerals in the peat, significant amounts of $KAlSi_3O_8$ and $K_2Ca(CO_3)_2$ were identified in the fly ashes. Furthermore, the lack of sintering was explained by formation of alkali sulphates. Naturally, other bed material than silica sand could also solve the problem of bed sintering: olivine sand or fuel ashes, depending on the ash content of the fuels.

In summary, it seems quite clear that one of the significant drawbacks with burning biomass in boilers, formation of deposits on heat transfer tubes and bed agglomeration in fluidised beds, can be eliminated or at least mitigated by co-combustion with coal and even with peat that may be available as a fuel in some regions. Sewage sludge has the same effect, as will be shown below.

Pollutant formation and destruction

Dioxins, chlorine and sulphur

Some fuels containing chlorine could be suspected to give rise to emissions of dioxins, especially if the ashes of the particular fuel or the coal contain copper or other catalysts for dioxin formation. Many investigations have shown that the emission of dioxin from large coal-fired plant is negligible, despite considerable content of chlorine and potential catalysts in the ash. This led Griffin (1986) to postulate that catalytic removal of the active chlorine Cl_2 , previously formed by



takes place through reaction with sulphur



Reaction (R2) proceeds catalytically at low temperatures, and it has been shown [Raghunathan and Gullet, 1996] that Reaction (R3) contributes to the removal of Cl_2 as soon as there is sulphur available, even at 400 °C. Many researchers refer to Reaction (R3) and prove that sulphur addition reduces the formation of dioxins, e.g. Gullet et al. (1992); Geiger et al. (1992). A further route of dioxin formation was investigated, (Xie et al., 2000), and an influence of sulphur was found on chlorinated phenols, probable precursors to dioxin, as shown in Fig. 11.

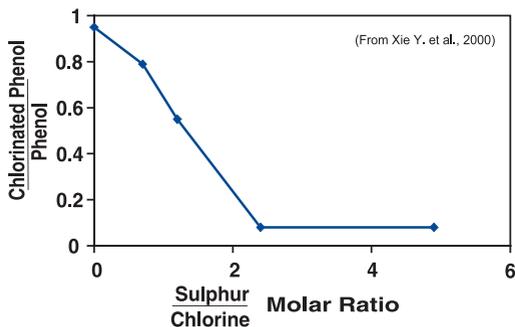


Figure 11. Relative yield of chlorinated phenols as a function of the molar ratio S/Cl. From [Xie et al., 2000]

When the sulphur concentration is sufficiently high compared to the chlorine concentration, chlorinated phenols are not observed. A similar conclusion was drawn by Gullet and Raghunathan (1997) regarding reduction of PCDD/F based on investigations of ashes from a waste combustor exposed to flue gases from natural gas or coal combustion: when

the molar ratio S/Cl was above unity a substantial reduction of the dioxin/furan yield took place.

In summary, it has been stated by many researchers that sulphur has an effect on dioxin emission, although it is not exactly known how this effect takes place, as summarised on Fig 12.

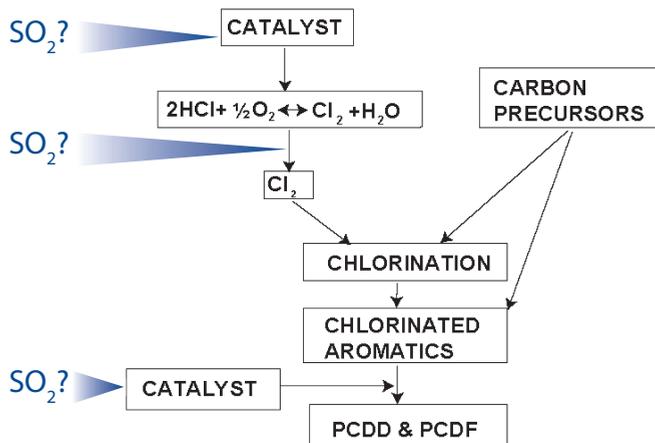


Figure 12. Summary of possible influence of sulphur on formation of dioxin

To some extent the discussion has dealt with the molar ratio S/Cl needed. Tests in large scale plants have indicated that the presence of sulphur, indeed, reduces the dioxin emissions (for instance, Luthe et al., 1998; Lindbauer et al., 1991). However, because of "memory effects" and difficulties related to the operation of long tests under constant conditions in commercial boilers, only a strong indication is provided but no definite proof. Carefully designed tests with contradictory results (Anthony et al., 2001) show in contrast that sulphur has no influence on reduction of dioxins. The tests were carried out with combustion of low-ash wood pellets. The concentrations of dioxins measured were always low in the tests, with or without sulphur addition. The level of concentration could have had some influence: in contrast to the other investigations on the influence of sulphur, showing reductions from in the order of 10 to 1 ng/Nm³TE (Toxic Equivalents) while the emission limit is 0.1 ng/Nm³TE, the tests of Anthony et al. (2001) concern concentrations of a power of ten lower than the emission limit. There are test results from co-combustion with coal in commercial boilers showing seemingly positive results (insignificant concentrations of dioxin/furan), but as no fuel analyses are given, quantitative comparisons cannot be made with the above results.

So far, the conclusion is that dioxin emissions of any importance have not been observed in large coal-fired plants. Then, if sulphur is important for the reduction of dioxin formation, there will be no emissions of dioxin from co-combustion with fuels containing sufficient sulphur, as long as their chlorine content is reasonably low. However, well documented convincing measurements on commercial plants are still needed. In this context one could ask what happens in a fluidised bed combustor, operated with sulphur capture in the bed when the sulphur is removed already in the bed,

while chlorine will be present in the flue gases and may react with lime only at low temperatures, if removed at all. Then the S/Cl ratio will be low in the critical temperature ranges. This is another item of research that awaits being done.

Nitrogen oxides and sulphur oxides

The interest in co-combustion would certainly be stimulated if it can be shown to lead to reduction of harmful emissions of sulphur and especially of nitrogen oxides.

Under oxidising conditions SO₂ is the dominant sulphur-containing product of combustion of fuels containing sulphur. It is proportional to the content of sulphur in the fuel if some minor absorption of sulphur in the ash minerals is disregarded. If the additional fuel contains less sulphur than the coal, the SO₂ pkt emission is reduced proportional to the difference in amount of sulphur in the fuels. Furthermore, there is some absorption of sulphur by potassium in the added fuel, but that is notable only at low quantities of sulphur. For these reasons, replacement of coal with biomass reduces the SO₂ emission.

For PC boilers the emission of N₂O is always negligible, irrespective of co-combustion. The NO emissions, though, are reported to be reduced by co-combustion (Hughes and Tillman, 1998), but the amount of reduction depends on the type of coal (Savolainen, 2003). In a more comprehensive test, including commercial as well as laboratory scale burners (Pedersen et al., 1997), a clear continuous reduction of NO was shown with increasing amount of additional fuel (straw in this case). Similar tests with similar results have been performed by Spliethoff and Hein (1998). From the results presented, two conclusions can be drawn; 1) Some large-scale co-combustion tests concern so small

quantities of additional fuel (<10%) that the impact of co-combustion on NO reduction can hardly be noticed, 2) In flame combustion, the NO reduction achieved is small but clearly seen, at least at large fractions of added fuel to coal, but it also depends to a large extent on the design of the burners and on the preparation of the fuel.

Flame combustion is much more sensitive to the arrangement of the combustion than fluidised bed. Fluidised bed combustion experiments for a wide

range of fuel ratios, using coal and wood, have been performed by Leckner and Karlsson (1993). The results are presented in Fig. 13. The operation of the 12 MW CFB boiler used with various fuel mixes took place at constant bed temperature and air supply. Constant operation conditions could be maintained despite the variations in the heating values of the fuels, because the heat balance of the bed was satisfied by an external heat exchanger and by other arrangements not affecting bed temperature and air supply.

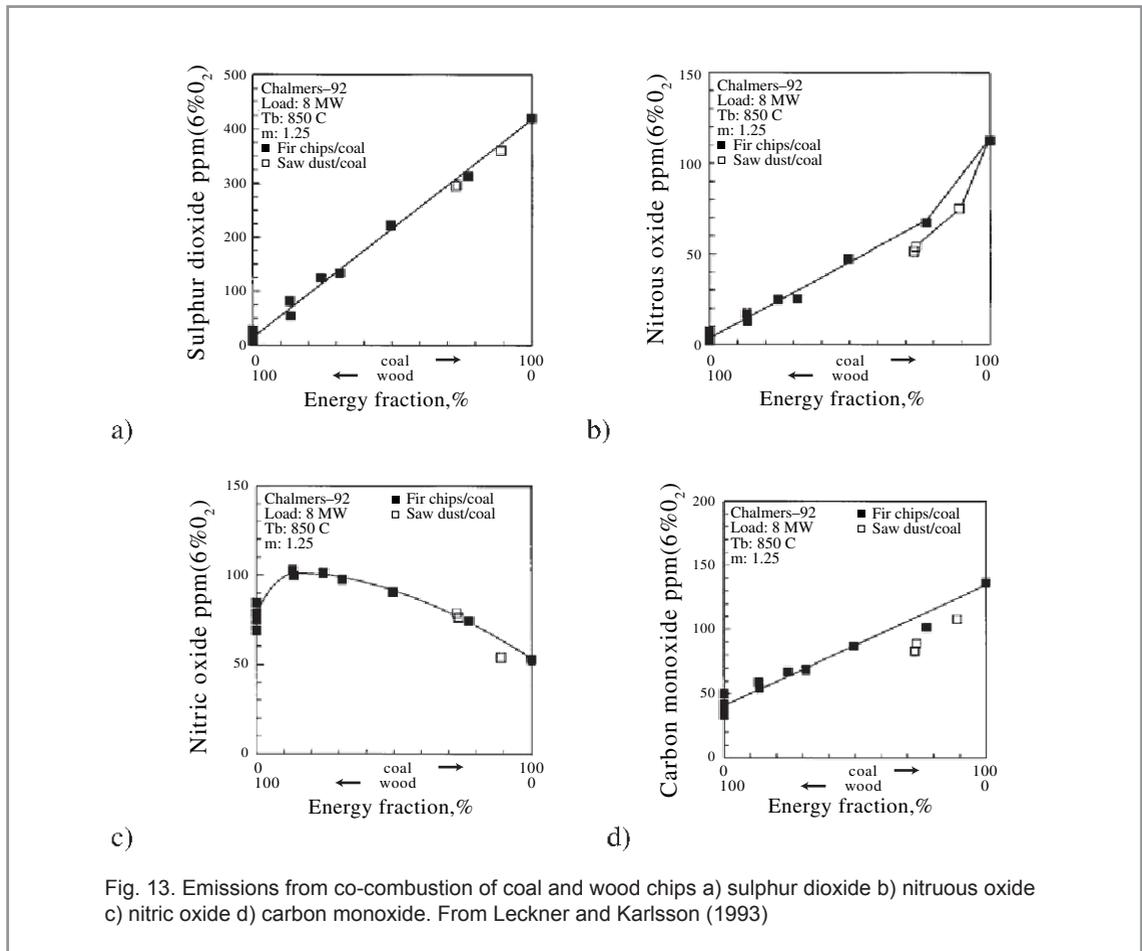


Fig. 13. Emissions from co-combustion of coal and wood chips a) sulphur dioxide b) nitrous oxide c) nitric oxide d) carbon monoxide. From Leckner and Karlsson (1993)

Fig. 13a shows the effect of reduction of SO_2 emissions with increasing fraction of added wood as a consequence of smaller input of sulphur with the added fuel, in principle observed also in pulverised fuel combustors. Here, the amount of sulphur is large in relation to potassium and no absorption by ashes are seen as the fuel ratio changes: the sulphur emission varies linearly with the fuel ratio.

Emission of N_2O , nitrous oxide, is significant in fluidised bed combustion. Fig. 13b shows that the emission increases with the input of nitrogen with coal (the nitrogen content of coal is about ten times higher than that of wood). As repeated in many tests, the emission almost vanishes during combustion of wood, perhaps because the nitrogen is mostly transformed into NH_3 , which is not an important precursor of N_2O at the temperatures concerned, and perhaps also because of the high concentrations of hydrogen observed during fluidised bed combustion of wood. Hydrogen is known to be an active species for reduction of N_2O . This could be the explanation why the replacement of wood chips with saw dust resulted in a slightly enhanced reduction of N_2O , as seen in Fig. 13b (but there is no influence of saw dust in Fig. 13c, and, of course, not in Fig 13a). The saw dust tends to be carried away with the gas to burn in the top of the riser or in the cyclone, increasing the temperature there, an effect that destroys N_2O . In PC combustors the temperature levels are always high enough for the emissions of N_2O to become insignificant, irrespective of the fuel mix.

Nitric oxide, NO, Fig. 13c, shows a strange behaviour. The emission first increases with addition of coal and then decreases. Even more surprising is the fact that the emission from pure wood is somewhat higher than that from pure coal despite the great differences in nitrogen content in the fuels, as pointed out in connection to the N_2O

emission. The explanation is related to the capability of char to reduce NO: the char content in the bed, despite operation with constant power, is very small during combustion of wood and increases gradually when coal is added (it is about ten times higher with 100% coal than with 100% wood). Hence, the ability of the bed to reduce NO by char is smaller with wood than with coal. When coal is first added to a bed burning wood, there is nothing that reduces the larger quantity of NO formed from the coal, and NO increases. As the fraction of coal increases, the char concentration in the bed increases gradually, and the emission of NO falls towards its value for pure coal combustion. This beneficial effect of coal has also been observed in co-combustion of sewage sludge with coal (Leckner et al., 2004). Sludge contains large quantities of nitrogen, and mono-combustion yields high concentrations of NO that have to be abated by flue gas treatment. However, in co-combustion with coal and a suitable arrangement of the air supply, the emissions from co-combustion of sludge and coal are below present emission limits without the need for removal of NO from the flue gas, as will be demonstrated below.

Finally, the CO emission pattern, shown in Fig. 13d, is a characteristic of a well designed CFB boiler; the CO emission is low for wood and higher (but still low) for coal. The reason is found in the tendency for volatiles to burn in the cyclone, increasing the temperature somewhat there and, hence, enhancing burnout. This effect was further stimulated by adding saw dust to coal. There is also a contribution from char combustion: the reason for the inherently higher emissions of CO during combustion of coal in CFB is the dominance of CO production over reduction in char burnout that takes place in the cyclone, which is much more important for coal than for wood (coal contains much more char than wood).

The emission during co-combustion of paper mill sludge and coal has been studied by Tsai et al. (2002) in a 103 MWth CFB boiler. In contrast to the above results, the nitrogen and sulphur contents were almost similar in the two co-fuels. Nevertheless, there was a reduction of both SO₂ and NO concentrations with increasing sludge fraction. The reduction of SO₂ was a result of the lime content in the sludge, and the reduction of NO was explained to be a consequence of the falling bed temperature with increasing sludge fraction (wet sludge with a low heating value). Furthermore, in both cases the concentrations were presented without correction for the increasing amount of water vapour in the gas. It is important to notice that, in general, such tests with FBC have been affected by the unintended variation of several parameters simultaneously, just like the one referred to: in a commercial boiler the temperature cannot normally be maintained constant over wide ranges of parameter variations. A similar problem seems to have affected the co-combustion measurements by Desroches-Ducarne et al. (1998). In this laboratory CFB, 4 m high and with a diameter of 0.1 m, the bed temperature could be maintained, but it is difficult to operate a laboratory-scale CFB combustor: the tests were affected by a high combustion loss during combustion of coal and perhaps some disturbance during the combustion of waste, since the CO concentration was high in that case (the high CO concentration was explained by inhibition of CO oxidation by chlorine, a possible effect). The NO curve (corresponding to Fig. 13c) was straight, but the difference between the nitrogen contents of the fuels was small, so this result seems qualitatively reasonable.

In fact, the peculiar shape of the curves in Fig 13c has given rise to some discussion (Hupa, 2005). Mathematical modelling of the same case has shown straight curves. Although the model used

is quite complex, it is not finally developed, and the results are sensitive to small changes in the assumptions. Comparing the same model results with a simpler semi-empirical qualitative model, the observed shape of the NO vs fuel fraction curve could be qualitatively explained, Leckner and Kilpinen (2003).

Emission legislation

In the European Union there is an explicit legislation regarding co-combustion. If co-combustion is applied in an existing power plant, the emission limits for that plant have to be revised according to the EU Directive on incineration of waste (2000/76/EC), where the emission limits are a weighted value of the limits for 100% base fuel, e.g. coal, and for 100% waste, e.g. sewage sludge. Examples of data are given in Table 4. The weighting factor is the flue gas volume produced during mono-combustion of either fuels. The emission limit (EL) for each pollutant *i* resulting from co-firing is:

$$EL_{i,mix} = \frac{V_w \cdot EL_{i,w} + V_{bf} \cdot EL_{i,bf}}{V_w + V_{bf}} \quad (1)$$

- V_w*: exhaust gas volume from waste only at 11% oxygen content, m³n/h
- V_{bf}*: exhaust gas volume from the base fuel only at 6% oxygen content, m³n/h
- EL_{i,w}*: emission limit for pollutant *i* in a waste combustion plant, mg/m³n.
- EL_{i,bf}*: emission limit for pollutant *i* for e.g. power plants, mg/m³n given in the Directive

The normal conditions are: temperature 273 K, pressure 101.3 kPa and dry gas.

Table 4. Some emission limits for CO, NO, SO₂ and mercury. Daily mean values

	EU Directive combustion plants		EU Directive waste incineration
	solid fuels	biomass	
CO, mg/m ³ _n	local directives		50
Nox, mg NO ₂ /m ³ _n	300	500	200
SOx, mg SO ₂ /m ³ _n	525	200	50
Hg, mg/ m ³ _n	0,05	0,05	0,05
ref. O ₂ , vol-%	6	6	11

An example of the application of the Directive is shown in Figure 14a and 14b, where emission data from co-combustion in a CFB boiler with

coal-wood and wood-sewage sludge (Åmand et al., 2001).



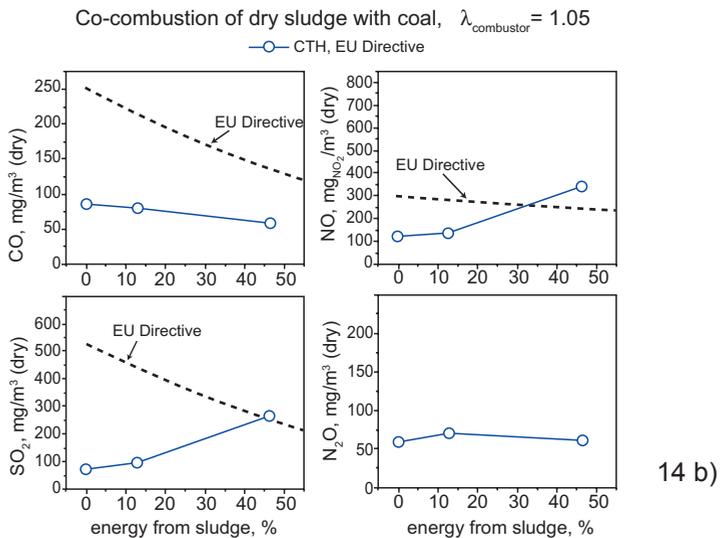
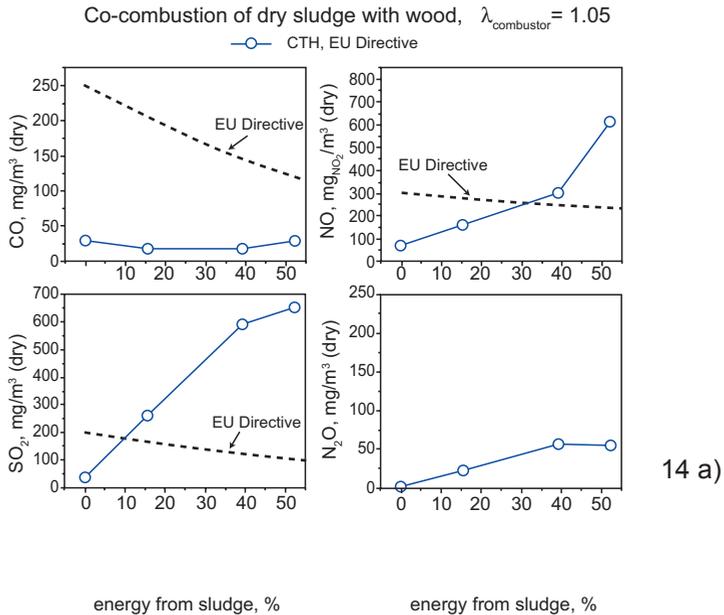


Figure 14 . Comparison between measured values (Symbols) in a CFB boiler firing woods and sewage sludge (a) and coal and sludge (b) and the EU Incineration Directive. From Amand et al. (2001)

Some remarks can be made on basis of the comparison:

- During co-combustion with coal there is no problem in accommodating a rather large fraction of sludge before any emission limit is exceeded, despite the high sulphur and nitrogen contents in sludge.
- During co-combustion with wood, however, the amount of sludge is limited by the peculiar discrimination of sulphur emissions from wood in the EU legislation, see Table 4. In the case of co-combustion with sludge, lime addition to the bed is not an efficient remedy, since the phosphorous in sludge tends to "poison" the lime by forming calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$) before the lime has reacted with sulphur (Elled et al., 2006). It was shown above, though, that even an amount of sludge below 10% has a reducing effect on deposits on tubes, so addition of sewage sludge to a biomass boiler should still be of interest.
- There is not yet any emission limit for the greenhouse gas N_2O .

The emissions mentioned are examples. There are more emissions included in the Incineration Directive. The emission limits are calculated in the same way. The Directive imposes several other conditions to be considered when a boiler is converted from a mono-fuel combustor to a co-fuel combustor:

- Combustion gases should be maintained at a temperature of more than 850 °C for more than 2 seconds (but there is no requirement that this should be from the last injection point of air as in the mono-combustion case).
- No added fuel is allowed as long as the furnace temperature is below 850 °C, for instance during startup.
- The heat generated should be utilised as much as possible.
- The residuals from the process should be minimised.
- The process should be monitored by measuring equipment.

Downstream impacts-deactivation of catalysts

On the one hand, co-firing is desirable for reducing CO_2 emissions from fossil fuels; on the other hand, the NO_x emissions have to be reduced to quite low levels, often requiring a catalytic NO reduction

system (SCR) in the flue gas path. The question is if the co-combustion fuels affect the catalytic surfaces: will there be a catastrophic de-activation of the catalyst, as speculated in Fig. 15?

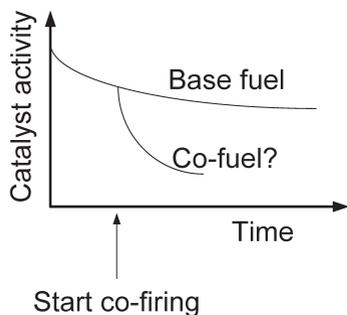


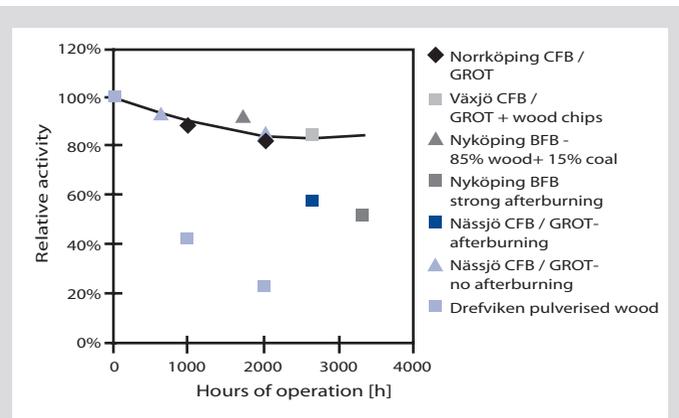
Figure 15. Deactivation of a SCR catalyst. Comparison between a regular case and a hypothetical case where a biofuel poisons the catalyst surface.

Deactivation could take place, caused by deposits of alkali compounds, such as NaCl, KCl, Na₂SO₄, K₂SO₄, on the catalyst's surface or by pore plugging of a surface layer by, for instance, CaSO₄. Other possibilities are deactivation by phosphorous compounds or poisoning by As etc.

The few test results available indicate that conventional catalyst surfaces are gradually deactivated during co-combustion. The straw-firing test referred to above (Wieck-Hansen et al., 2000) reports results from a test-catalyst surface inserted in the flue-gas path at 350 °C (high-dust conditions) and downstream of the electrostatic precipitator at about 200 °C (low-dust conditions). The results were, in brief, that the high-dust catalyst lost about 30 % activity in 2500 hours and the low-dust catalyst 15 %, much higher loss rates than expected for a purely coal-fired unit. However, the test surfaces are shorter than a commercial catalyst surface and could be suspected to be covered faster with dust, in this case dust containing silicon, sulphur and aluminium, but also potassium and phosphate in high quantities. It was believed that deactivation was a result of deposition on the surface and only to a minor extent of potassium blocking the pores.

A Swedish study by Kling et al. (2005) on deactivation of a high-dust test-catalyst surface used co-combustion of wood and waste fuels (mainly related to wood, such as bark) with about the same potassium contents (about 1500 mg/kg dry fuel) but different chlorine contents (low for wood and several times higher for the waste fuels). Also other mineral constituents were higher in the waste fuels. In this case the deactivation was between 40 and 90 % after 2500 hours in a test stand, depending on the amount of waste fuel. The conclusion was that the deactivation depends on alkali interaction with the catalyst surface, but in some cases also lead (from the particular waste fuel used) played a leading role. The potassium content was about the same in all fuels, and obviously, the influence of chlorine was important. It was also observed that the alkali compounds were soluble in water, so it was possible to regenerate the catalyst by washing, thereby prolonging its lifetime.

Figure 16 shows the decay in activity of catalyst test surfaces mounted in boilers burning mostly wood waste from the forest. The scarce information available about the tests seems to indicate that the mode of combustion has an influence.



By comparing the results presented, the conclusion may be (disregarding possible influences of the test conditions) that the beneficial effect of coal in the first test mentioned reduced the rate of deactivation and created a more favourable situation than during co-combustion of fuels related to wood only. There is clearly a need for more general and systematic studies in this field in order to draw safe conclusions.

Figure 16. Performance of catalyst test surfaces in fluidised bed boilers burning forest wastes and pulverised wood. Vattenfall (2006)

Ash disposal

Ash from pulverised coal plants is normally recovered to be utilised in industrial activities, often in the cement industry. This has an economical significance for the utility companies that can sell the ashes, and furthermore, they do not have to deposit the ashes. If co-combustion contributes with an ash that makes this secondary utilisation of ash impossible, the advantages of co-combustion are significantly reduced. This may impose restrictions

(on the quantity of co-fuel and its ash properties) used for co-combustion. In Denmark, where fly ashes are mainly used for cement and concrete, the fly ashes from the Studstrup power station (10% straw) are sold for cement production. Negotiations are conducted to allow a higher fraction of straw and to deliver ashes for concrete production (Sander, 2004).

Sludge co-combustion

Sludge, in general municipal sewage sludge, cannot easily be deposited and combustion is a means to reduce the quantity and at the same time regain energy. Often incineration takes place with some support fuel to maintain a reasonable combustion temperature. Here, it is of interest to evaluate the properties of sludge as a co-combustion fuel for any co-combustion situation, not just incineration. Table 5 gives a survey of the properties of some sewage sludges compared with industrial sludges from the pulp and paper industries and some base fuels, either wood, bark or coal. Depending on precipitation agents, sludges may have different composition; in the present cases Fe and Al are the most notable elements, originating to a large

extent from such precipitation agents. Furthermore, the ash content is high. The moisture content is a parameter of importance (drying) that will not be treated here, but it determines the modes of co-combustion: 1) a minor quantity of sludge added for destruction in a boiler designed for conventional base fuel, 2) a minor quantity of high calorific-value fuel added to an incinerator to maintain an acceptable combustion temperature. In the first case the sludge is probably dried to a moisture content of <30%, whereas in the last case the sludge could have been delivered from a sludge press with a dry substance of about 30%. Here, just a few aspects of sludge combustion that are relevant to co-combustion will be mentioned.

Table 5. Properties of some sludges compared with some base fuels (Åmand and Leckner, 2004).

	Sewage sludge¹	Sewage sludge²	Sewage sludge³	P&P sludge⁴	P&P sludge⁶	Wood pellets	Bark pellets	Coal 7
Precipitation agent	FeSO ₄	Al ₂ (SO ₄) ₃	FeSO ₄	PAC ⁵	not known	NR	NR	NR
Proximate analysis								
Water (wt-%, raw)	72.0	77.8	71.8	71.2	78.6	8.0	10.3	9.0
Ash (wt-%, dry)	46.0	42.6	46.1	11.8	15.0	0.4	3.0	17.5
Combustibles (wt-%, dry)	54.0	57.4	53.9	88.2	85.0	99.6	97.0	82.5
Volatiles (wt-%, daf)	94.4	85.3	88.3	77.4	83.1	81.7	77.6	32.7
Ultimate analysis (wt-%, daf)								
C	52.6	50.2	51.0	49.2	88.9	50.3	53.6	84.9
H	7.2	7.3	7.4	6.5	12.0	6.1	6.2	5.0
O	33.3	36.2	34.1	42.1	77.6	43.5	39.7	7.7
S	1.4	1.2	1.6	1.7	2.7	0.01	0.04	0.73
N	5.4	5.0	5.7	0.46	5.0	0.09	0.46	1.57
Cl	0.1	0.1	0.1	0.03	0.03	0.01	0.02	0.08
Lower heating value (MJ/kg)								
Hu, daf	20.50	19.50	19.49	18.51	17.86	18.80	20.32	33.35
Hu, raw	2.78	2.24	1.17	2.93	1.29	17.20	17.43	24.65
Ash analysis (g/kg dry ash)								
K	13.3	10.7	15.1	2.5	11.6	82	50.2	11
Na	7.3	6.9	8.5	10.9	13.7	6.7	4.8	1.9
Al	73.3	193	82.4	271	108	12.2	13.1	84
Si	127	115	142	84.9	112	79.7	72.4	290
Fe	160	42.1	152	16.1	16.8	20.9	6.8	47
Ca	40	38.0	48.4	1.2	180	164	263	30
Mg	9.9	5.3	11.9	40.0	19.7	26.4	20.1	18
P	58.6	61.3	67.9	1.3	4.5	12.7	11.9	1.0
Ti	4.4	9.6	4.7	36.4	3.6	0.7	1.0	0.69

(1) = used in test series A, C and E; (2) = used in test series B, D and E
(3) = used in test series G; (4) = chemical precipitated sludge from the pulp&paper industry, site A; (5) = precipitation agent is polyaluminium chloride,
(6) = sludge from the pulp&paper industry, site B, mix of fibre sludge and sludge from an biological cleaning step
(7) = bituminous coal also used in "Coal series2" in ref. 4
daf= dry and ash free, raw=as received, NR=not relevant

Sulphur capture with limestone is not efficient in fluidised beds operated with sludge. It has been assumed that this depends on reaction between limestone and phosphorous, removing active lime from sulphur capture, Åmand and Leckner (2004). Phosphorous is an important component in municipal sewage sludge, but it is not present in sludge

from the pulp and paper industry (Table 5). Figure 17 compares sulphur capture in different cases related to the calcium to sulphur molar ratio or to the calcium minus phosphorous to sulphur molar ratio, the latter just to illustrate a possible impact of phosphorous.

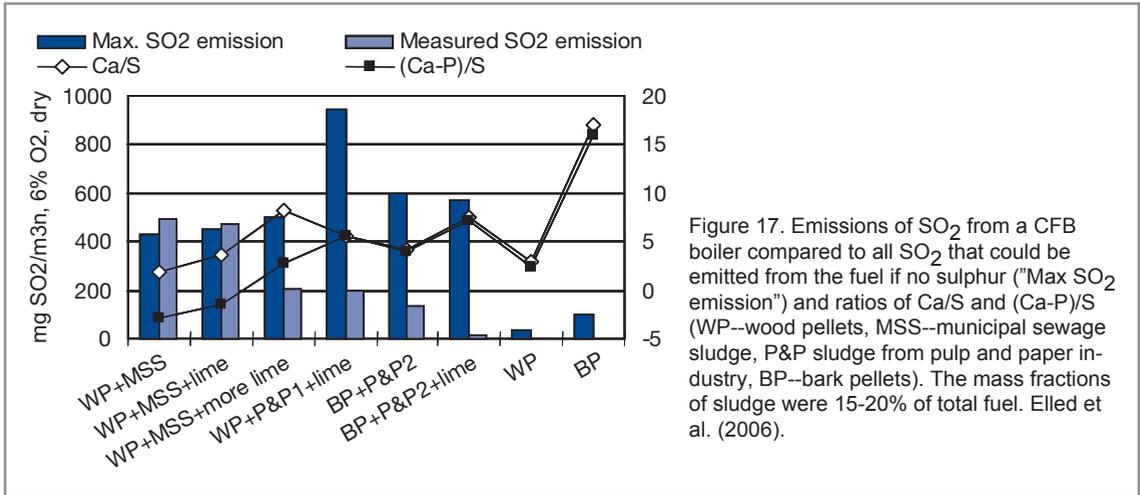


Figure 17. Emissions of SO₂ from a CFB boiler compared to all SO₂ that could be emitted from the fuel if no sulphur ("Max SO₂ emission") and ratios of Ca/S and (Ca-P)/S (WP--wood pellets, MSS--municipal sewage sludge, P&P sludge from pulp and paper industry, BP--bark pellets). The mass fractions of sludge were 15-20% of total fuel. Elled et al. (2006).

The curve with white markers on Figure 17 denotes total lime (added plus fuel) to sulphur molar ratio. The curve with black markers is the same quantity with phosphorous subtracted. The difference between the two curves is the amount of phosphorous. In the first two cases when phosphorous dominated there is no sulphur capture at all. Only in the third case when more lime is added there is some sulphur retention. In the remaining cases with pulp and paper sludge (not containing phosphorous) and wood and bark, retention is satisfactory.

The conclusion is that sulphur capture by lime addition to the fluidised bed is inefficient and requires high excess of lime in co-combustion with municipal sewage sludge containing phosphorous. Instead of absorption of sulphur in the bed, flue gas cleaning could be a solution. A simple method to reduce the sulphur emission is injection of hydrated lime to the flue gas channel to be collected in a bag filter, such as illustrated in Fig. 18. An efficient commercial application of this type is Alstom's NID system.

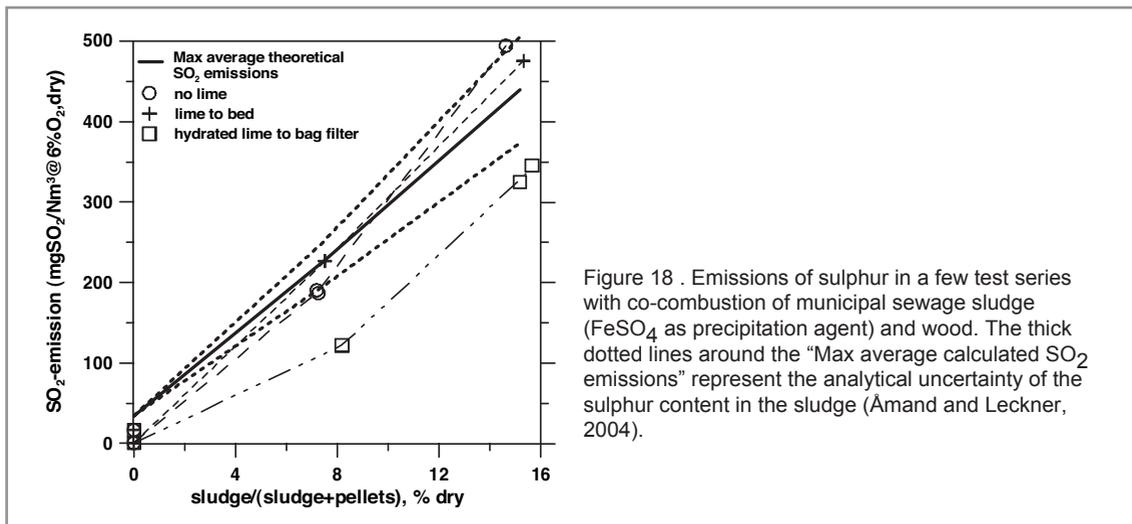
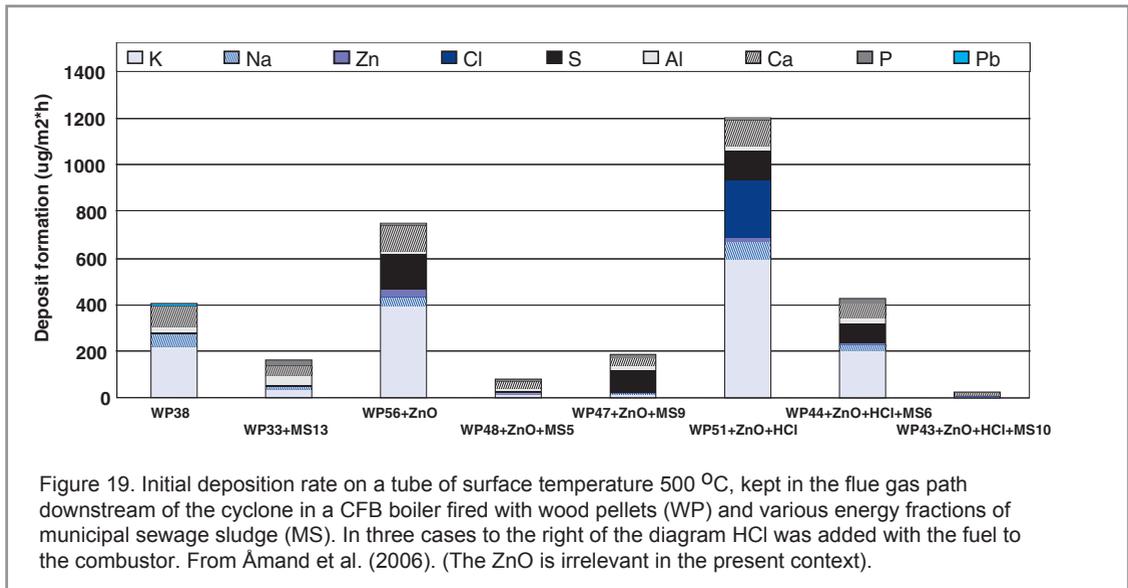


Figure 18 . Emissions of sulphur in a few test series with co-combustion of municipal sewage sludge (FeSO₄ as precipitation agent) and wood. The thick dotted lines around the "Max average calculated SO₂ emissions" represent the analytical uncertainty of the sulphur content in the sludge (Åmand and Leckner, 2004).

The results are supported by equilibrium calculations (Elled et al., 2006; Kim et al., 2005) and also by work studying co-combustion of coal and sewage sludge (Ninomiya et al., 2004), where it was claimed that reaction of calcium with P₂O₅ takes place, rather than between calcium and sulphur. However, there are other suggestions. Belén Folgueras et al. (2004), studying co-combustion in a thermobalance, did not even mention the impact of phosphorous. Instead they identify other possibilities:

- 1) reaction between calcium and iron (2CaO Fe₂O₃),
- 2) volatilisation of alkaline and alkaline earth elements by interaction with chlorine (in this case FeCl₃ was used together with CaO as a precipitation agent), which then would result in less sulphur capture by them,
- 3) reaction between calcium oxide and SiO₂.



Co-combustion with sewage sludge also may have other effects, especially if biofuels are base fuels. It has been mentioned that biofuels may give rise to deposits followed by corrosion, and that coal or peat as co-fuels under certain conditions could have a beneficial effect to reduce deposits. As shown by Åmand et al. (2006) sewage sludge has the same effect, Fig. 19.

In all cases when sewage sludge was added, the deposition rate decreased essentially, even in the

enhanced deposition cases when HCl was injected to promote deposition. Obviously sewage sludge has some beneficial properties despite the fact that it contains impurities in the form of heavy metals that have to be handled properly.

The practical experiences published from large scale applications (Luts et al., 2000; Buck and Treibel, 2000) concern very small fractions of sludge (<4% on dry substance). No important problems are reported.

Conclusions

From the survey presented several conclusions can be made.

On the utilisation

Co-combustion can be applied in existing boilers and with existing technology. Biomass and wastes can be utilised in a simple but efficient way through co-combustion with a base fuel. If the base fuel replaced by the added fuel is coal, the effective emission of CO₂ is reduced. If, on the other hand, the base fuel is wood, it can be assumed that the additional fuel for co-combustion is chosen because the combination of fuels gives some economic advantage and also that the co-firing may serve as a means to reduce waste.

Combustion device

Co-combustion can be carried out in most combustion devices in conventional boilers but there are several additional arrangements possible. Co-combustion in fluidised bed is uncomplicated and in most cases limited only by the heat balance of the bed. In cases where coal, peat or sewage sludge are not used and where biofuels or waste constitute the fuel mix, there are limitations on the maximum steam temperatures in a boiler that have to be respected to avoid deposits and corrosion, as indicated in Table 1.

Co-combustion in pulverised coal utility boilers can be performed with premixed fuels without any particular arrangements up to replacement of a few percent (energy) of the base fuel, limited by the inability of normal pulverisers to handle greater quantities of woody biomasses in a reasonable way. With dedicated handling and comminution systems the contribution of co-firing in pulverised fuel boilers could be up to ten or even twenty energy percent. In this context the enhancement of the grindability of a biofuel by torrefaction could be considered as an option.

Combustion

In a pulverised coal fired flame the addition of a high-volatile fuel promotes ignition. Otherwise, the minor fractions of co-fuel concerned do not play a great role for the progress of combustion. In a fluidised bed there are no particular restrictions for combustion, except that the heat balance of the bed should be such that the bed temperature can be maintained at the desired level.

Deposits on superheater surfaces

The principal concern on the fire side of a boiler is formation of deposits on superheater tubes, accompanied by corrosion related to deposited alkali compounds from the added fuels. Coal, peat or sewage sludge contributes with mitigating the effects of alkali-related deposits that could be caused by the added biofuel. Particularly important are the interactions between K, Cl, S, Al and Si. Molar ratios like K/Cl, S/Cl etc can support judgements on the behaviour of combinations of fuels of interest. The maximum steam temperature has to be chosen in accordance with the combination of fuel used.

In a boiler, predominantly fired with biomass or waste, addition of coal, peat and particularly sewage sludge has been found to alleviate or even completely remove deposition problems.

Catalyst surfaces

Deposition on conventional SCR catalysts from combustion of biofuels does occur. It remains to be seen if, again, the interaction between various fuels just mentioned has a beneficial effect also on the conservation of catalyst surfaces.

Emissions

There is a mixing effect noticed when fuels with significantly different sulphur contents are burned together; otherwise the emissions of NO_x and SO₂ are not significantly affected by the fuel mix. However, it seems that sulphur may have some effect on reducing emissions of dioxins, as well as on the formation of deposits from potassium compounds, characterised by the S/Cl molar ratio that should be greater than unity to have a clear effect.

Synergy effects

Many possible effects of the interaction between fuels, including those mentioned above, called synergy effects, have not been sufficiently treated in the literature, and, indeed, constitute a field for research that will make the selection of fuel combinations safer and that will allow even better utilisation of the positive effects that may arise in co-combustion by combining certain fuels. A few such both positive and negative effects have been exemplified for sewage sludge: reduction of deposits on tubes and a negative impact on sulphur capture in FBC by interaction of phosphorous with lime.

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Pathways to sustainable European energy systems

The European pathways project is a five year project with the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. The focus is on the stationary energy system (power and heat) in the European setting. Evaluations will be based on a detailed description of the present energy system and follow how this can be developed into the future under a range of environmental, economic and infrastructure constraints. The proposed project is a response to the need for a large and long-term research project on European energy pathways, which can produce independent results to support decision makers in industry and in governmental organizations. Stakeholders for this project are: the European utility industry and other energy related industries, the European Commission, EU-Member State governments and their energy related boards and oil and gas companies. The overall question to be answered by the project is:

How can pathways to a sustainable energy system be characterized and visualized and what are the consequences of these pathways with respect to the characteristics of the energy system as such (types of technologies, technical and economic barriers) and for society in general (security of supply, competitiveness and required policies)?

This question is addressed on three levels; by means of energy systems analysis (technology assessment and technical-economic analysis), a multi-disciplinary analysis and an extended multi-disciplinary policy analysis. From a dialogue with stakeholders, the above question has been divided into sub-questions such as:

- What is the critical timing for decisions to ensure that a pathway to a sustainable energy system can be followed?
- What are "key" technologies and systems for the identified "pathways" - including identification of uncertainties and risks for technology lock-in effects?

- What requirements and consequences are imposed on the energy system in case of a high penetration of renewables?
- What are the consequences of a strong increase in the use of natural gas?
- What if efforts to develop CO₂ capture and storage fail?
- Where should the biomass be used – in the transportation sector or in the stationary energy system?
- Are the deregulated energy markets suitable to facilitate a development towards a sustainable energy system?
- Will energy efficiency be achieved through free market forces or regulatory action?
- What are the requirements of financing the energy infrastructure for the different pathways identified?

In order to address the sub-questions in an efficient and focussed way the project is structured into 10 work packages addressing topics such as description of the energy infrastructure, energy systems modelling, technology assessment of best available and future technologies and international fuel markets. In planning of the project significant efforts have been put into ensuring that the project should not only be strong in research but also in management, communication and fundraising.

The global dimension will be ensured through integration with the other three regional AGS pathway projects in the Americas, East Asia, and India and Africa.

More information at Pathways website:
www.energy-pathways.org

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The Alliance for Global Sustainability (AGS) brings together four of the world's leading technical universities – the Massachusetts Institute of Technology, The University of Tokyo, Chalmers University of Technology and the Swiss Federal Institute of Technology – to conduct research in collaboration with government and industry on some of society's greatest challenges.

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