



EUBIA

Analysis of the technical obstacles related to the production and utilisation of fuel pellets made from agricultural residues

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Introduction

Aim of the document

This document aims at giving an overview of the technical problems related to the production and utilisation of fuel pellets made from agricultural residues. On the basis of the guidelines expressed in the technical annex, the EUBIA has gathered and analysed information with regard to (1) the obstacles related to the transformation of agricultural residues (mainly straw) into fuel pellets, and (2) the problems related to the "agri-pellets" utilisation. In addition to these two parts, other critical factors (availability of raw materials, production costs, etc) are emphasized for their importance regarding a successful development of the agri-pellets market.

Methodology

We have first reviewed a wide range of written documents and scientific papers so as to present a comprehensive state of the art on the subject. The second part of the work consisted in direct conversations with actors of the sector. On the basis of existing database and Internet pages, we have established inventories of the main European pelleting equipment manufacturers, pellet producers and pellet appliances manufacturers. Mostly, the main actors have been approached by direct phone calls or by questionnaire.

Summary of conclusions

With the possible shortage of woody raw materials for pellet production in countries such as Sweden and Denmark, and considering the low forestry residues potential in southern European countries, agricultural residues could be largely used in the future for fuel pellets manufacturing. It is therefore of great importance to study the characteristics of this new (and diverse) category of raw material, paying special attention to the problems that they may trigger both at production and utilisation level. The information gathered in this report points out several problems affecting agri-pellets (with a special focus on straw pellets) in comparison with wood pellets.

As far as production is concerned, straw can be pelletised without major difficulty. The global energy requirement for pelleting straw can generally be considered lower to the one related to wood, because straw is delivered at a moisture content (<20%) that allows by-passing the drying stage. However, straw would present a higher abrasive power (in relation with its silica content), possibly inducing an increased wear of the die and rolls if the latter are made of the same steel as for wood residues. In any case, homogeneity of pellets regarding size, water content and particle density (all parameters of great relevance to achieve fully automatic operation and complete combustion) seems quite a well controlled factor in the pelleting process. At a technical level, the main difference between wood and agri-pellets is the somehow higher friability and the slightly lower energy content of the latter.

Technical problems related to agri-pellets reach another order of magnitude as far as combustion processes are concerned. Indeed, agri-pellets combustion triggers several major obstacles regarding emissions (dust, gas and aerosols), deposit formation (slagging, fouling) and corrosion. Another problem is related to the produced ash, in terms of volume generated and quality. All those problems not only depend on the fuel characteristics, but also on the design of the combustion equipment and the way it is operated. Actually, a typical feature agricultural residues in comparison



with wood residues is their higher content in nitrogen (N), sulphur (S), chlorine (Cl) and potassium (K), increased by the use of fertilisers and pesticides/herbicides in agriculture. The presence of those elements leads to relatively important emissions of NO_x, SO_x, and HCl compared to wood pellets. In addition, potassium (K) influence both particulates emission and slagging (by lowering the softening temperature of the fuel) of an increased ash volume (5% for straw – 0.5% for sawdust). Finally, a high chlorine (Cl) content result both in corrosion problem on boiler's surfaces and in formation of dioxins. Those problems can be partly overcome by a range of techniques, ranging from agricultural practices (leaching of the straw in the field) to combustion processes (air-staging) and flue gas cleaning. Finally, improvements could come from the fuel preparation stage, with the addition of some specific anti-slagging agents (e.g. kaolin) or the mixing with sawdust to present final characteristic more convenient with regard to combustion and ash issues. Finally, for a large scale use, in relation with the high ash content and the low melting point, it has been stated that straw pellets could present better results with grate combustion or fluidised bed systems. Co-firing of agricultural residues with fossil fuels is also a very interesting alternative, both technically and economically. The small scale market of devices for straw pellets is still very limited, but some manufacturers already propose multi-fuel grate boilers in the range of 10-60 kW. In all cases, attention must be paid to the flue gas cleaning systems.

Other critical factors have been pointed out, such as the economic advantage for the building of a new straw-fired plant (rather than a straw pellet-fired plant), the importance of the reliability of supply and quality of straw as raw material, and the logistics related issues concerning the development of the small scale market.

As a conclusion, environmental impact as well as current state-of-the-art of combustion technologies indicate that pellets made from agricultural residues (and in general other ash-, N-, K- and Cl-rich fuels) should be used primarily in large scale combustion plants equipped with sophisticated combustion control systems and flue gas cleaning systems, whereas wood pellets should be preferred for residential heating. At a higher degree than for wood pellets, the main technical challenges regarding agri-pellets are the production of a high quality fuel, and technological improvement for small-scale combustion devices. Assuming that economic aspects concerning the agri-pellets energy option are favourable, the agri-pellet market for small-scale use will develop only if equipment manufacturers are encouraged to develop novel, safe and affordable combustion solutions.



Preamble: Why thinking about agri-pellets?

"Pellets for Europe" in the European context

The development of renewable energy is a central aim of the European Commission's energy policy. Several reasons stand for this: firstly, renewable energy has an important role to play in reducing carbon dioxide (CO₂) emissions - a major Community objective. Secondly, increasing the share of renewable energy in the energy balance enhances sustainability. It also helps to improve the security of energy supply by reducing the Community's growing dependence on imported energy sources. Finally, renewable energy sources are expected to be economically competitive with conventional energy sources in the medium to long term [u]. Among the renewable energies, biomass fuels already play an important role in several European countries (near 20 % in Sweden and Finland). In 2000, at the European level, the share of renewable energy was far more modest and contributed to 6% of the total gross inland consumption, from which biomass represented more than 60% [v]. The European Commission's White Paper for a Community Strategy sets out a strategy to double the share of renewable energies in gross domestic energy consumption in the European Union by 2010 (from the present 6% to 12%) including a timetable of actions to achieve this objective in the form of an Action Plan.

Densification and pelleting related advantages

Some practical problems are associated with the use of biomass material as fuel, and in particular with the use of agricultural residues. Those problems are mainly related to the high bulk volume, which results in high transportation costs and demands for large storage capacities, and to the high moisture content which results in freezing and blocking the in-plant transportation systems, as well as in biological degradation. In addition, variations in moisture content makes difficult an optimal plant operation and process control. All these problems may be overcome by densification, which is compressing the material to give it more uniform properties. The main advantages of densified fuels, compared to non-densified ones are the following [t]:

- An increased bulk density (from 80-150 to 600-700 kg/m³), resulting in lower transportation costs, reduced storage volume and easier handling.
- A lower moisture content (lower than 10%), favouring a long conservation and less loss of product during storage.
- An increased energy density and more homogeneous composition, resulting in better control possibilities and thereby higher energy efficiency lower emissions during combustion

The major disadvantage is the somewhat high energy cost for the pelleting process, increasing the price of the end product.

Densified products can be found as briquettes or as pellets. The heating value, moisture content and chemical characteristics are about the same for both but the density and strength are somewhat higher for pellets. The major difference is the size (generally Ø 6 to 12 mm, with a length 4 to 5 times the Ø for pellets), making them easy to use in fully automatic operation, from household appliances to large scale combined heat and power (CHP) plants [t].



Why thinking of refined agricultural residues for energy purposes?

The most important argument for using biomass for energy purposes is that it is CO₂ neutral and therefore does not contribute to increasing the CO₂ content in the atmosphere, thereby resulting in an aggravation of the greenhouse effect.

At the moment, fuel pellets are mainly made from sawdust, wood chips and wood shavings. The market has essentially expanded in Sweden, Denmark and Austria, in relation with natural resources and political reasons. Nowadays, the competition with the particleboard industry and the current increased demand for wood pellets, both on the residential market and for large-scale use, may lead to a future lack of sawdust and shavings. For instance, in Sweden - the main European producer -, wood pellets production capacity (1 Mio t) has reached the national sawdust potential [s], and in Denmark the shortage of national appropriate raw materials obliges to import wood waste from North America and the Baltic States [j, m]. If demand - and prices - continues to rise, other biomass wastes than sawdust, wood chips and shavings will be considered for pellet production. Agricultural residues stand among those future new raw materials. On the other hand, in southern European countries, forest areas are far less important and forest industry is consequently far less developed; in those conditions, the question of the agricultural residues potential may be tackled even more directly.

Agricultural residues refer to the portion of plant material that remains after a crop has been harvested and separated. Primary residues are those that are the result of farm-level activities; they include items such as straw, stalks and leaves that are left over after harvest. Secondary residues are those that result from processing, such as sugar beet pulps, cotton mill wastes, peanut shells, etc. For most crops, and said roughly, primary residues are produced in quantities approximately equal in weight to the crop production, and are already used for different purposes (soil conservation, animal feeding and litter, heating). The amount of secondary residues varies widely depending on the crop and processing methods used.

In this report, among all agricultural residues, a special focus is put on straw, mainly for two reasons: firstly, it is the most important agricultural residue in the EU; indeed, according to a personal estimation, near 23 million tons (Mio t) of dry biomass from straw could be available yearly. The second reason is that straw corresponds to the more tested and pelletised agricultural residue. At the moment, the most advanced European country in that field is undoubtedly Denmark, where more than 750,000 tons of straw (and 1.3 Mio t of wood) are used in power plants, industries, district heating plants, farms and private households. According to the Danish energy policy the part of biomass in the energy supply pattern will continue to expand in the future. Utilisation of wood and straw in Denmark should be doubled to 4 Mio t (53 PJ) by 2005. If we just focus on biomass fired power plants in that country, they should be supplied, by the year 2005, by 570,000 tons of wood (from which 300,000 under the form of wood pellets) and 890,000 tons of straw, from which 130,000 tons as straw pellets [ae].



Technical obstacles related to the densification of agricultural residues

Characteristics of biomass raw materials

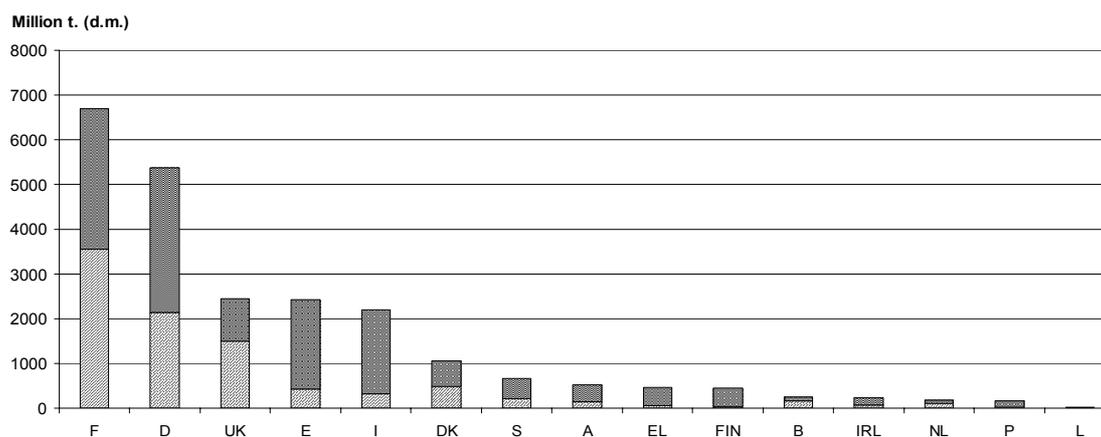
Diversity of agri-residues

Many materials originated by agriculture could be used for production of densified biomass fuels: straw, grain hull waste, sugar beet waste, tree pruning, fruit stones, cacao waste, etc. A project at the Danish Technological Institute testing some of these raw material is presently going on. The aim is to find out what combinations of materials are best suited for pellet production and combustion, with regards to sintering, ash contents etc [j (b)]. On the other hand, regulation BEK nr 638 af 03/07/1997 (Denmark) defines different biomass raw materials suitable for pellet production. Some of them are straw, fruit stone, dry fruit waste, cork, grain, cotton, malt and tobacco waste, with obviously, woody residues (sawdust, shavings, wood chips and wood waste with 1% max. glue), [j (b), p.10]. The first problems which raise for each of those residues are the quantity available, the quality and the collection mode. Those aspects are studied more thoroughly in other contributions. In any case, it is necessary to have in mind that both physical and chemical properties vary significantly within and between the different biomass raw materials. Depending on the application, these variations may be critical for the final performance of the system. Physical properties, such as moisture content, bulk density, particle size and distribution, and mechanical strength are important for the choice of processes and equipment [t]. Furthermore, chemical properties are of great importance for the energy efficiency, environmental pollution and ash related operating problems, as it will be underlined later.

A special focus on straw

In quantitative terms, straw is the most important agricultural residue in Europe. According to a personal estimation, near 23 million tonnes (Miot) of dry biomass could be available yearly in the 15 current member states.

Figure 1. A conservative estimation of straw potential resources in Europe (Miot of dry matter)



| | F | D | UK | E | I | DK | S | A | EL | FIN | B | IRL | NL | P | L | Total |
|---------------|------|------|------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Total straw | 6688 | 5379 | 2439 | 2437 | 2193 | 1060 | 658 | 512 | 465 | 438 | 255 | 240 | 175 | 167 | 18 | 23124 |
| Wheat straw | 3560 | 2145 | 1494 | 436 | 321 | 484 | 221 | 136 | 51 | 43 | 164 | 70 | 103 | 16 | 6 | 9250 |
| % Wheat straw | 53% | 40% | 61% | 18% | 15% | 46% | 34% | 27% | 11% | 10% | 64% | 29% | 59% | 10% | 31% | 40% |

Source: personal estimation, on the basis of Eurostat figures for the primary data, to which have been applied several coefficient : ratio production/residue, moisture content coefficient and availability coefficient (15%). "Total straw" refers to common wheat, durum wheat, rye, meslin, barley, oats, maize, rice and others cereals straw.



Therefore, if any agricultural residue had to enter the large-scale pellet market, straw would surely be the first one and the one processed to the largest extent. Yet, straw pellets are already used in the large scale Amager power plant (run by Energy E2 in Denmark) which is expected to burn 130,000 tons of straw pellets per year when it runs in a normalised operational way (by the beginning of 2004).

Obviously, in addition to straw, there still can be, locally, other specific agricultural residues (such as cotton residues in Greece, olive or vine pruning mainly in southern regions, etc.) and their energetic valorisation as densified fuels can always be tackled with success, but one can imagine that their market development would still remain quite limited. As a consequence, most of the time, the general mechanisms presented in this report will be further illustrated by references to straw. In that perspective, the first point to emphasize might be straw's physical and chemical properties.

Main characteristics of straw

Just as any botanical tissue, straw consists of cells, composed of cell walls and an inside void called lumen. By dry weight, the cell wall substance makes up 80 to 90%, while the balance of 10-20% is deposited within the lumen and consists of silica (5-10%) and extractives (5-15%), most of which are soluble in water. At molecular level, straw cell walls, like any woody cell walls, consist of three molecule types, all classified as carbohydrates: cellulose, hemi-celluloses, and lignin. Cellulose is a rather long and linear chain that is aggregated in fibrils with partial crystallinity. Fibrils are surrounded by molecules that are less oriented and slightly cross-linked. Several molecule types belong into that group, and they are classified as hemi-celluloses. Lignin is the "glue" between individual cells forming plant tissue and between the fibrils forming the cell wall. It is an highly cross-linked, molecular complex. The most significant differences between straw and wood are straw's higher portion of hemi-celluloses and lower portion of cellulose and lignin. A tiny piece of straw tissue or an individual straw cell has therefore lower tensile strength and lower compressive strength. Yet, this is a rather broad statement, and large variations exist among individual species.

Table 13. Comparison of tissue composition for straw, softwoods and hardwoods

| | Straw | | | Softwoods | Hardwoods |
|--------------------------|-------|------|------|-----------|-----------|
| | Stalk | Node | Leaf | | |
| Plant Composition, % | 100 | 100 | 100 | 100 | 100 |
| - Cell Wall | 90 | 79 | 76 | 95 | 93 |
| - Silica | 3 | 8 | 11 | <0.5 | <0.5 |
| - Extractives | 7 | 13 | 13 | 4.5 | 6.5 |
| Cell Wall Composition, % | 100 | 100 | 100 | 100 | 100 |
| - Cellulose | 40 | 40 | 35 | 45 | 42 |
| - Hemi-celluloses | 45 | 40 | 55 | 25 | 38 |
| - Lignin | 15 | 20 | 10 | 30 | 20 |

Source : goldboard

Short description of the pelleting process

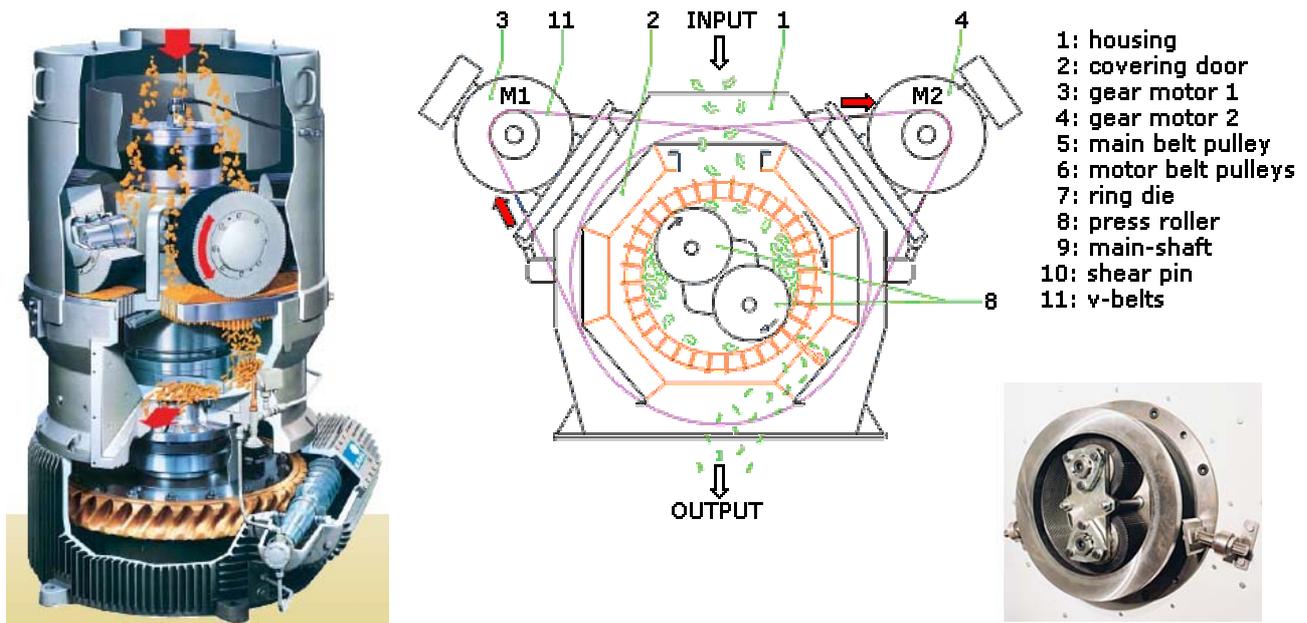
The process of pellet manufacturing was first developed for the livestock feed industry. It can be said to consist of a few basic sub-processes: comminuting of the raw material, drying, pelletising and cooling.

The raw material is first freed from heavy contaminant (rocks, metals and other foreign material), and then grinded in a hammermill or a chipping machine. The particle size is adjusted to a uniform



maximum dimension, which is approximately 85 % or less of the minimum thickness of the pellet to be produced. The often high moisture content of the raw material makes drying necessary. The product from the hammermill is therefore transported to a dryer (generally a rotary drum type one) where the moisture content of the uniformly dimensioned particles is reduced to about 10 % (w.b.). Then, raw material can be conditioned, i.e. steam or organic binding agents can be added (according to legal specifications). After conditioning, the particles are then moved by conveyor to a pellet mill, where the pellets are extruded through the action of rollers acting on a perforated matrix. On the outer side of the latter, a knife cut off the pellets at the desired length. There are two main types of pellet presses: flat die and ring die types (figure 1). The flat die type have a circular perforated disk on which two or more rollers rotate and force the material through the holes. The ring die press features a rotating perforated ring on which rollers (normally two or three) press on the material to the inner perimeter. Residual moisture in the feedstock turns to steam during compression and helps lubricate the compression die. After extrusion, pellets are very hot (90-100°C) and are immediately air quenched down to 25°C. This sets up the lignin and hardens the product, and contributes to maintain its quality during storage and handling. Finally it is screened, so as to separate the residual fines which are generally re-used in the process. Dust free pellets are then ready for storage (in a silo) or for automatic packing (in 25 kg bags or big bags - 1 to 1,5 m³).

Figure 2. Flat die (on the left) and ring die type (on the right) pellet mill.



Sources : Kahl, Salmatec, Larus Impianti

Recently, the Italian company EcoTre has developed a pelletising technology whose process is new: the pellet mill has two dies, and raw material is pressed between them from outside towards the inside cavity of each dye. According to technical specification, specific electric consumption ranges from 0.025 to 0.045 kWh/kg depending on the type of wood. The system operates without the need of any additives and maximum operating temperature of the dies is 55 to 60°C which avoid vapours emissions and permit direct bagging without cooling stage, which lower the investment costs. Another advantage is that material with up to 30 to 35% humidity can be handled, thereby doing away with the need for a dryer. However the company bankrupted a few months ago; therefore the question remains on the use of the patent and on a further development of that apparently promising technology.



Pelleting related problems: a step-by-step analysis

From a botanical perspective, straw is different from wood. This triggers differences in the pelleting process and also in the product performance. Yet, it is not so much a question of inferior or superior to wood; rather, it is a challenge of optimally processing it.

Reception of raw material

Straw is generally received as big bales, weighing up to 500 kg. Results from a study carried out in combustion plants in Denmark can suggest some problems related to raw materials handling (straw, wood chips) [q (q) p.192]. As far as wood chips are concerned, high concentrations of fungi and actinomycetes were seen in areas near the storage areas, cranes and conveyors. If the moisture content was low also high concentrations of dust and endotoxin were seen. The storage of wet wood chips also results in high growth of microorganisms. Regarding straw, high concentrations of bacteria and inhalable endotoxins were also seen in the storage area and near shredders. To minimise the exposure to microorganisms, employees must wear respiratory protection. Finally, straw has a higher dust potential than wood chips, but usually the content of microorganisms is higher per mg of wood dust than per mg of straw dust. It seems that impacts on workers' health have not been studied extensively.

Screening from contaminants

Straw may contain far more contaminants than sawdust. This parameter is affected by the harvesting methods of straw, which are thus of technological significance for pellet manufacturing. Those methods differ in their inclusions of leaves, nodes, and mineral contamination (mud, sand). The shorter the stubble – the stem portion left standing –, the more likely the inclusion of contaminants. On the other hand, just taking the uppermost portion drops the straw yield per unit field area. The Køge straw pellet plant in Denmark experience some problems with respect to the somewhat high contaminant proportion of straw. Although a stone trap is installed to separate the valuable raw material from the foreign objects, it does not always work at 100% and this results in damages on the knives of the straw bales cutter.

Grinding

The main parameters for achieving a high quality pellets are said to be a homogeneous and a well conditioned raw material. Hence preparatory stages (from grinding to conditioning) are of a great importance. Starting material for straw pellet is a tube or pipe of straw with a diameter of 4 to 8 mm. The pipe wall has a thickness of 0.3 to 0.6 mm. In comparison, a woody raw materials are orders of magnitude thicker from 3 mm for sawdust to 15 mm for wood chips. This gives a significant advantage to straw in the quest to achieve a relatively thin and uniform particle thickness. As a consequence, powerful and therefore costly equipment is required to cut wood tissue into flakes with uniform thickness, whereas straw has a better ability to form uniform thick flakes. It should also be noted that bale type affects feedstock throughput. More time is required to process large round bales than square bales. Round bales have full length, wrapped fibres whereas fibres in square bales are shorter and the bales tend to fall apart in flakes [ad]. In any case, the grinding of straw generally include two steps: first straw is cut (or scarified) and then chopped into smaller particles. On the other hand, sawdust and wood chips usually only pass through one grinding machine, essentially to be sure to work with a homogeneous material (comminuting of the largest particles). In those conditions, to grind straw requires a bit more energy than sawdust (even if it is not always significant), and implies an investment in one more machine (for first scarifying).



By-pass of the drying step

Straw delivered to a pellet production plant is in form of an air-dried bale, with a moisture of typically 15% (expressed on a wet basis). In contrast, sawdust has moisture contents far more superior, up to 50% (w.b.). Upon exiting the press, both straw pellets and wood pellets have a moisture of 7 to 9%. Thus, straw requires far less drying than sawdust, if any.

It has been reported that the drying of wet woody materials results in emissions of volatile organic compounds (VOC) [i (f)]. Those emissions contribute to lower the energy content of the raw material. Moreover, in the presence of nitrogen oxides and sunlight, the VOC lead to the formation of harmful photo-oxidants, increasing air pollution and deteriorating the work environment in the surroundings of the dryers. Those photo-oxidants are also harmful to humans as they cause irritation in the respiratory tract and in sensitive parts of lungs; at elevated levels, they are also an important cause of widespread forest and crops damages in Europe. From that point of view, the fact that straw does not require to be dried would avoid the VOC emissions problem during production stages.

Conditioning

Generally, lignin content in wood is high enough to bind the pellets. However, crop residues may require a special conditioning to achieve the necessary strength to prevent the pellets from disintegrating to a powder. Conditioning can correspond to steam (and/or water) application to the raw material in order to soften the material fibres prior to densification. But conditioning also covers the addition of determined binding agents or additives. Apparently, the most common technique used until now is steam conditioning.

Adding of steam and/or water

The material is conditioned with steam (or sometimes water) to the required temperature and moisture content to obtain the necessary malleability of the product, to "activate" the lignin as binding agent, to increase output and decrease the amount of fines. Typical processing conditions would be a conditioning in a cascade mixer with steam at 90-100°C and in a proportion of 5% of the raw material weight. In some cases, steam and water can be added at either the fine grinding step or sprayed directly into the hammer mill. An experiment carried out with switchgrass [ad] and water-adding in the pellet mill, pellets became harder with an exterior sheen evident and fine production was lower. However, water added at the conditioning stage prior to pelleting would have more time to be imbibed in plant fibres. Adding water usually increases pellet moisture at the exit point from the pellet press, but during the cooling process, moisture is lost and final pellet moisture after cooling is unaffected by the addition of water during the process. It has been suggested once that straw does not accept the steam as well as wood residues, but this information could not be confirmed. If it was so, it might come from the existence of a thin wax layer on straw, which normally protect it against rain and insects attacks. Yet, it should be noted that after a certain period of time, the wax layer disappear naturally, and straw loses its shiny aspect.

Binding agents

The use of binding agents has been investigated as a means to increase fuel pellets hardness and thus reducing the dust and fines generated during their transport and handling. Possible binding agents for wood include starch, molasses, natural paraffin, plant oil, lignin sulphate and synthetic agents. Under the German emission control legislation molasses as a residue from sugar production, natural paraffin or starch are allowed [s]. Apart from increasing the product's hardness, additives are also conceivable as a means of improving some chemical characteristics, for example slag formation (during combustion) can be hindered by using kaolin or calcium and magnesium oxides. Binding agents (such as maize or rice) can also be used in order to decrease abrasion. This sort of addition is quite common in Austria for instance. However, a recent publication found that even the



use of binding agents does not always result in low abrasion values, and that abrasion must therefore depend on several other parameters [i (k)].

Considerable discussion on binding agents has taken place in Sweden. Several products were tested before it was found that lignin produced the best results [s]. Lignin is a natural wood constituent, but the one added comes from lignin sulphate which is a by-product of pulp and paper production. The binding quality of lignin sulphate is good but it also increases the sulphur and ash content, which can increase sulphur emissions and cause problems with the combustion equipment. Finally, it can be underlined that modification of operating conditions – changing the thickness of dies, pressing time, pressing temperatures and pressure – can help to improve pellet quality without binding agents.

Milling

A number of properties are commonly known to affect the quality of pelleting, including the moisture content of the material, the density of the material, particle size of the material, fibre strength of the material, lubricating characteristics of the material and natural binders.

Technically and generally speaking, main problems occurring during the pelleting process correspond to die blocking, die breakage, roll cracking, overheating, high energy costs and at times poor end-product quality and high maintenance needs [k]. To prevent blockages of the die and to avoid an overload on the main drive, a by-pass chute seems to be nowadays a standard equipment. Fitted with a manual or an electrically controlled air cylinder, virtually all overloads and blockages can be eliminated [WP Bliss]. No data could be found concerning a possibly increased risk of break down or blockage with straw in comparison with sawdust.

Generally, the same milling machines are used for pelleting straw and wood, but from one product to another, steel dies and rollers are changed. Most of the machines allow an easy removal and re-set up. For straw (in comparison with sawdust), the thickness of the dies has to be more important : this increases the compression length (the friction forces), contributes to liberate more lignin and to obtain a more convenient product quality. In relation with the higher abrasion power of straw (due to the higher silica content), some manufacturers say that wear parts (dies and rollers) have to be made of a more resistant steel when milling straw instead of wood. Yet, other manufacturers say that the same steel wear parts can be used for both raw materials, but doing so, the wear parts life span is likely to be reduced by up to 20%. In that case, assuming an approximate 10,000 tonnes life-span for wear parts when milling sawdust (according to constructor specification), it could decrease down to 8000 tonnes for straw with the same quality wear parts. On the other hand, other persons affirm that they are not aware of that increased wear with straw.

The typical power for pellet presses on the market can be considered to stand between 200 and 500 kW. Small experimental devices can be found from 3 kW power, the biggest mills scoring over 550 kW. The output range for pellet presses ranges from about a few hundreds of kg up to 10 ton/h, the most common ones being 4-6 t/h. In relation with the quality of the raw material, milling production yields are usually higher for straw than for wood. As an example, with the same pellet press of 250 kW, a 4t/h output can be expected for wood pellets, and a 5t/h output for straw pellets while it would amount 20 t/h for feeding granulates (which do not meet the same quality standards).

Another specific problem can be mentioned regarding the dimension of the pellet production unit. Assuming a 200 bars pressure during densification, friction forces remain acceptable with an milling output of 4 t/h. However, if yield decreases, friction forces increase and there is a risk of break down. For that reason, yields should not be under 3 t/h for wood (on a 500 kW press) and 5 t/h for straw (250 kW press).



Cooling

This step, as the storing / bagging step, does not present significant differences from sawdust to straw.

Fines screening

Straw generates more fines than wood during the pelleting process. This is mainly linked to the lower lignin content of straw. However, operation conditions have also an influence. For example, an experimental test in Canada on switchgrass reports that, at the optimum pelleting rate, fine production at the exit point of the pelleter was about 3%, but ranged as high as 25% depending on the amount of water added [ad]. In the same experiment, a total of 7.47 tonnes (7.1 tonnes dry matter DM) of unscreened switchgrass pellets were produced from 9.17 tonnes (7.8 tonnes DM) of raw feedstock. Loss of fines during the pelleting, cooling and temporary storage stages produced a percent yield of 91% on a dry matter basis.

More generally, it is reported that, at the exit point of the press sawdust pellets present a 3-4% of fines, whereas for straw, fines proportion could amount 10%. It is also usually expected a 5% loss of DM in most alfalfa pelleting systems. In all cases, fines are re-directed into the process line (as a fuel in a combustion device or as a raw material in the pellet mill). It can be noted here that some process lines are operated with underpressure in order to minimise dust escape and improve the working environment.

End-products comparison

The two main effects of pelleting are a decreased moisture content and an increased bulk - and thus energy - density. Pelletising straw makes it pass from a 15-20% to a <10% moisture content, and from a 130 to 600 kg/m³ bulk density. It can be noticed that straw pellets have a lower bulk density and a lower energy density than wood pellets. Their friability is also higher, which creates further difficulties in relation with small automatic combustion system.

Table 14. General characteristics of straw and wood pellets, and their respective raw materials.

| | Density (kg/m ³) | Moisture % w.b. | LHV (MJ/kg) | Ash (% d.m.) | Energy density GJ/m ³ |
|----------------------|---------------------------------|--------------------|----------------|-----------------|-------------------------------------|
| Straw (choopped) | 50 | 10-20% | 14.5 | 5 | 0.7 |
| Straw (big bales) | 130 | 10-18 % | 14.5 | 5 | 1.9 |
| Straw pellets | 600 | <10 % | 15.0 | 5 | 9 |
| Wood chips | 250 | 10-50 % | 11-17 | 0.5 | 4.3 |
| Sawdust | 200 | 20-50 % | 12-17 | 0.5 | 3.4 |
| Wood pellets | 650 | <10 % | 17.5 | 0.5 | 11.4 |
| Coal | 850 | 10-15 % | 24 | 12 | 20.4 |

LHV (Lower heating value) varies according to moisture content; Energy density are calculated for dried material.

Presented results are average gleaned from literature (Sources : E2 Energy + [ae]+ woodgas + Danish CBT)

Concerning the quality of straw pellets and wood pellets, European standards are currently under development by CEN (European Committee for standardisation), within the TC 335 workshop.

Productivity and energy requirements

Productivity

Pelleting productivity is measured by manufacturers in terms of production yield, in units of kg per kWh. In the case of sawdust residues, this value varies from about 20-60 kg/kWh, depending on the source of the wood residue; hardwoods are in the low range and softwoods are in the high range [ab]. Other sources suggest an even wider variability of the productivity, comprised between 10 and



100 kWh/t. In theory, the more pliable the fibre, the easier it is to exude through the die. Other factors influencing productive yields include steam and residency time (cooking or conditioning) in order to create a more pliable fibre. Considering straw chemical properties, productivity values can be expected to stand in the high range, just as softwoods. As a comparison, productivity in the alfalfa industry ranges 85-100 kg/kWh, but it must be considered that quality objectives are not the same.

Energy requirements

According to data from manufacturers, a complete pelleting line would typically range a 600-800 kW power for straw processing, from which 250 kW for the pellet mill with an output of 5t/h. There are strong differences concerning the processing of different kinds of biomass raw material, depending to a large extent on the resin content. Hardwood (such as beech or oak) sawdust requires higher pressure forces than softwood and conifers. The pressure forces lead to the specific energy consumption which is between 30 and 50 kWh/t in case of wood milling stage. Considering the quite low lignin content of straw, we can assume that its specific energy is likely to amount 50 rather than 30 kWh/t. In addition, a publication reports that both theoretical and real energy requirement are higher for straw than for sawdust during the milling step. This would come from the structure of the materials: sawdust particles approach spherical strain condition, whereas straw is a far more fibrous material [q (a)].

For wet raw material processing, the highest energy requirement corresponds to the drying stage (approximately 950 kWh are required to vaporise 1 ton of water), and chopping comes in second place. In contrast, straw is already at a convenient moisture content and does not need to be dried. At the milling stage, straw requires more energy than wood to be pressed, but the energy saved by by-passing the drying overcomes this phenomenon. Thus, considering the entire process line, pelleting straw requires less energy than sawdust pelleting. For straw, the more important phase in terms of energy consumption corresponds to the grinding, and the second one to the milling.

Table 15. Comparison of energy consumption between straw and woody raw material pelleting

| Energy consumption (kWh/t) | Sawdust | Woodchips | Straw |
|----------------------------|---------------|---------------|---------------|
| Grinding + screening | 10-20 | 10-40 | 10-30 |
| Drying | 0-400 | 0-400 | 0 |
| Conditioning | 0-10 | 0-10 | 0-10 |
| Milling | 30-60 | 30-60 | 30-60 |
| Cooling | 5 | 5 | 5 |
| Additional equipment | 10-20 | 10-20 | 10-20 |
| TOTAL | 55-515 | 55-535 | 55-125 |

Considering that 950 kWh are required to vaporise 1 ton of water, the drying of a wet woody raw material from 50% moisture content to 10% would represent an energy consumption of $(0.5-0.1)*950=380$ kWh.

Sawdust and wood chips experience a wider variability in relation with the drying step

Energy demand for wood pelletising (including all stages, from grinding to cooling) is comprised in the large range from 80 to 130 kWh/t. The exact value depends on different production factors (lubricants, screening, crushing, mill yield, etc.) [s]. Another source suggest a total energy input of approximately 115 kWh/t for pelleting switchgrass [ad]. In this experiment, electricity use ranged from 119 kWh/tonne for dried feedstock to 74 kWh/tonne for undried switchgrass. Authors also report estimations of 45 kWh/t for pelleting switchgrass (King, 1999) to 30 kWh/t for alfalfa (Tabil and Sokhansanj, 1996). The high energy requirement in the experiment was affected by the low throughput of pellets. Authors suppose that a doubling of pellet output to a range similar to alfalfa would improve energy use efficiency to values similar to those of alfalfa (i.e. 30 kWh/t).



In general pellet manufacturers say that around 1.5% - 2% of the energy content of the wood pellet is necessary for the pelletising process (not including drying of raw material) [s]. Including the drying process with wet raw material (in the case of wet sawdust for example) 7 to 10% of the energy content of pellet is needed for pelletising. If wood chips are pelletised about 20% of the energy content would be required for the manufacturing process (including drying and crushing). These data refer to investigations done by *Raggam & Bergmair* in 1996 who state an energy content of wood of 5200 kWh/ton [s]. The problem with this analyses is that kWh-power (for the pelletising machinery) is mixed up with kWh-heat (energy content of wood), which is not allowable from a physical point of view. Assuming, in a more realistic way, that 1 ton of dry wood (5300 kWh) contains the energy equivalent of 1600 kWh-power or 4750 kWh heat, the above mentioned percentage of energy demand for pelletising would correspond as follows:

- 5 to 6% of the energy content of the pellet is necessary for pelletising dry raw material.
- 12 to 15% of the energy content of pellet is needed for pelletising including the drying process with wet raw material (sawdust)
- 48% of the energy content would be required for the manufacturing process for pelletising of wood chips (including drying and crushing).

Considering values even more typical as far as crushing, drying and milling are concerned, the following values appear:

Table 16. Typical energy consumption (kWh/t) for crushing, drying and milling wood residues, and comparison with pellets energy content

| Energy source | Dry sawdust | | Wet sawdust | | Wet wood chips | | Straw | |
|-------------------------------------|-------------|-------------|-------------|-------------|----------------|-------------|-----------|-------------|
| | En. cons. | % En. cont. | En. cons. | % En. cont. | En. cons. | % En. cont. | En. cons. | % En. cont. |
| Grinding Electricity | 10 | 1% | 10 | 1% | 20 | 1% | 10 | 1% |
| Drying Electricity (10%) Heat (90%) | - | - | 400 | 9% | 400 | 9% | - | - |
| Milling Electricity | 40 | 3% | 40 | 3% | 40 | 3% | 40 | 3% |
| Others Electricity | 30 | 2% | 30 | 2% | 30 | 2% | 30 | 2% |
| TOTAL | 80 | 6% | 480 | 15% | 490 | 15% | 80 | 6% |

En. Cons.: energy consumption (kWh/t) - % En. Cont.: part of the energy content of wood pellets

Energetic assumptions : 1 ton of wood pellets : 4750 kWh-heat or 1600 kWh-power – 1 ton of straw pellets : 4250 kWh-heat or 1400 kWh-power.

In the Køge plant, energy consumption for the pelletising process is said to be equivalent to 4% of the energy content for straw pellets, and only 2% for wood pellets made from wood chips. But this is because 85% of the steam used in the dryer for wood chips is recovered and re-used as a heat source. Without this particularity, wood pellets energy consumption would be expected to be higher to the straw pellets one.

Production costs

The following table gives an idea of the order of magnitude of pelletising costs. From those data, but also from personal communication, it seems that straw pellets production costs are quite similar or even slightly to the wood pellets one. This comes from the raw material differences in price and also of the above mentioned to re-use part of the process energy. Indeed, it should be noted that the straw price also experience some important variations (see part on prices later) which may lead to a greater variability of straw pellets prices than wood pellets ones. In particular, straw prices are quite high in Denmark in relation with wood chips prices. According to data provided by Buhler, the wood pelletising cost in Austria would range 52.2 – 81.3 €/t, and 73.5 – 94.6 €/t with drying of the raw material, but might reach 100 €/t.



Thek and Obernberger analysed the pellet production costs in Austria and Sweden in 2002. Nine plants were investigated, for which production ranged from 430 to 79,000 ton /year, and the variation of the annual full load operating hours ranged from 615 to 8,000 hours per annum. Results showed that production costs are mainly influenced by the raw material costs and, in case of using wet raw materials, by the drying costs. Depending on the operative conditions, those two parameters can cause up to one third of the total pellet production costs. According to moisture content, pellet production costs were found to vary between 79 and 101 euros/t if raw material was wet, and between 52 and 81 euros/t if raw material was dry.

Table 17. Production costs of wood pelletising

| Data in euro/tonne | Wood pellets (1) | Wood pelleting with drying (2) | Wood pelleting without drying (2) |
|--------------------|------------------|--------------------------------|-----------------------------------|
| Raw material | 31.3 | 34 | 53 |
| Drying | 13.0 | 30 | 2 |
| Grinding | 2.1 | 4 | 2 |
| Pelleting | 3.6 | 9 | 14 |
| Cooling | 0.5 | 0 | 1 |
| Storage | 3.0 | 3 | 4 |
| Other | 0.9 | 4 | 4 |
| Personnel costs | 5.5 | 13 | 20 |
| General investment | 1.4 | 3 | 0 |
| TOTAL | 61.0 | 100 | 100 |

Source: (1) : [j (c)], swedish plant, (2) Buhler

Table 18. Wood pellet production costs in Austria and Sweden (in euros, 2002)

| | Average | % of total | Minimum | % of total | Maximum | % of total |
|----------------------|-------------|-------------|-------------|-------------|--------------|-------------|
| Raw material | 33.5 | 36% | 14 | 26% | 51.4 | 38% |
| Drying | 26.6 | 28% | 25.1 | 47% | 29.5 | 22% |
| Grinding | 2.9 | 3% | 0.3 | 1% | 6 | 4% |
| Pelleting | 9.9 | 11% | 7.1 | 13% | 14.8 | 11% |
| Cooling | 0.3 | 0% | 0.1 | 0% | 0.5 | 0% |
| Storage | 2.9 | 3% | 1.4 | 3% | 4.9 | 4% |
| Peripheral equipment | 3.4 | 4% | 0.5 | 1% | 5.2 | 4% |
| Personnel costs | 11.7 | 13% | 4.7 | 9% | 17.4 | 13% |
| General investment | 2.4 | 3% | 0.6 | 1% | 4.1 | 3% |
| TOTAL | 93.6 | 100% | 53.8 | 100% | 133.8 | 100% |

Source: Thek, Obernberger, 2002.

(http://bios-bioenergy.at/bios/downloads/Pellet-Prod-Costs-Paper_PelletConf2002.pdf)



Technical obstacles related to the agri-pellets utilisation

As seen above, the pelleting process affects essentially the physical properties: straw bulk density increases from 130 to 600 kg/m³ when pelletised. The only chemical parameter strongly impacted by the pelleting process is the mean water content and its distribution, which is more homogeneous. Element content does not change significantly during the process, hence chemical composition of raw materials impacts directly on the quality of the combustion process.

Characteristics of agri-pellets compared to wood pellets

The following data (table below) show that commonly used biomass fuels are a relatively homogeneous group with respect to heating value and major elemental composition (C, H, O). However, the content of moisture, nitrogen (N), sulphur (S), chlorine (Cl) and ash vary greatly as does the ash composition. Wood chips and sawdust are by-products of the forestry and wood industry, and are therefore regarded as wastes. But an important characteristic of this sort of waste, compared to other ones, is its relatively high "purity". Wood pellets are clean and homogeneous, with a low content of mineral nutrients. In contrast, chopped logging residues and agricultural residues (wheat straw in the table) present a high content in mineral nutrient.

Table 19. Typical chemical composition for a range of fuels

| | Coal | Peat | Wood chips | Wood pellets | Wheat straw | Wheat straw pellets | Bagasse |
|---|-------|------|------------|--------------|-------------|---------------------|---------|
| Water content (%-ww) | | 53.2 | | 7.7 | 15 | 8 | |
| Higher heating value MJ/kg | 28 | 22.3 | 20.2 | 20.3 | 17.8 | 18.5 | 19.2 |
| Lower heating value MJ/kg | | | 19.1 | 19.0 | 16.5 | 17.2 | |
| Elementary analysis (% d.m.) | | | | | | | |
| Ash | 12.1 | 5.4 | 1.4 | 0.51 | 6.2 | 7.1 | 3.3 |
| Volatiles (% d.b.) | | | 81 | 80 | 78 | 75 | 83.0 |
| Carbon (C) | 74 | 53.6 | 51 | 50.3 | 44.3 | 45.8 | 46.3 |
| Hydrogen (H) | 4.8 | 6.2 | 6.0 | 5.7 | 5.3 | 5.9 | 5.7 |
| Oxygen (O) | 11.4 | 31.2 | 41.8 | | 40.2 | 40.1 | 42.7 |
| Nitrogen (N) | 1.3 | 3.20 | 0.35 | 0.22 | 0.57 | 0.45 | 0.4 |
| Sulphur (S) | 0.35 | 0.19 | 0.03 | 0.03 | 0.15 | 0.16 | 0.2 |
| Chlorine (Cl) | 0.012 | 0.01 | 0.02 | 0.02 | 0.50 | 0.40 | 0.5 |
| Ash analysis (% d.m.) | | | | | | | |
| Silicium (SiO ₂) | 59.9 | 28.2 | 15.9 | - | 51.5 | 39.0 | 72.2 |
| Potassium (K ₂ O) | 1.2 | 1.1 | 11.9 | - | 17.1 | 29.0 | 6.4 |
| Sodium (Na ₂ O) | 1.9 | 0.2 | 0.77 | - | 0.56 | 0.44 | 1.2 |
| Phosphorus (P ₂ O ₅) | 0.6 | 2.3 | 5.84 | - | 2.13 | 4.70 | - |
| Calcium (CaO) | 3.1 | 19.2 | 26.1 | - | 6.57 | 9.90 | 0.9 |
| Magnium (MgO) | 0.7 | 0.7 | 5.68 | - | 1.73 | 2.20 | - |
| Aluminium (Al ₂ O ₃) | 27.4 | 4.3 | 5.10 | - | 0.79 | 0.95 | 1.5 |
| Iron (Fe ₂ O ₃) | 5.2 | 24.0 | 6.07 | - | 0.40 | 0.95 | 1.0 |
| Fusion temperature (°C) | | | 1200 | | 850 | | |
| Melting temperature (°C) | | | 1300 | | 1240 | | 1360 |

Sources: data gleaned and crossed from various sources and database

Dry matter left after straw combustion consists of less than 50% carbon, 6% hydrogen, 42% oxygen, but also of small amounts of N, S, Cl, and other minerals such as silica (Si), and alkali: sodium (Na) and potassium (K). Wheat show higher concentrations of N, S and Cl than wood. K content is also generally higher for straw than for wood. Increased concentrations of the elements



N, S and Cl in straw can be the result of insecticides and fertilisers application. A higher Si content is inherent to straw (cf. botanical characteristics). On the other hand, Ca and Na contents are inferior to wood. In general, those results can be extended to the other types of straw : barley, rape, maize, sunflower, etc.

Beside the data presented in the annex, detailed information on chemical characteristics for a wide range of biomass fuels can be found on different database:

University of technology of Vienna biomass database: www.vt.tuwien.ac.at/biobib

IEA Task 32 biomass database: www.ieabcc.nl/database/biomass.php

Phyllis biomass database: www.ecn.nl/phyllis/dataTable.asp

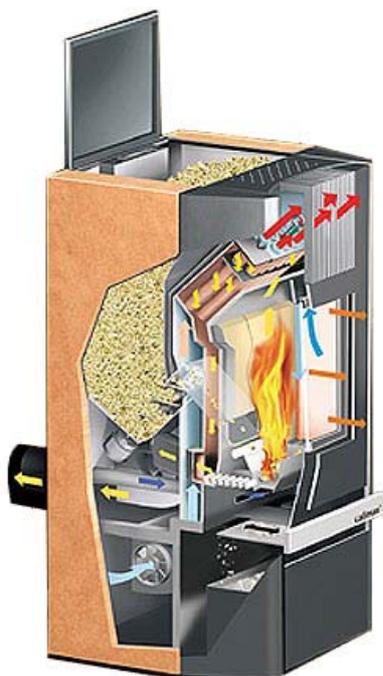
The following part presents the behaviour of all the chemical elements of biofuels during combustion and summarise the problems they trigger regarding emissions, deposit formation and corrosion.

Short overview of the main combustion technologies

The devices used for direct combustion of solid biomass fuels range from small domestic stoves (1 to 10 kW) to the largest boilers used in power and CHP plants (>5 MW). Intermediate devices cover small boilers (10 to 50 kW) used in single family houses heating, medium-sized boilers (50 to 150 kW) used for multi-family house or building heating and large boilers (150 to over 1 MW) used for district heating. Co-firing in fossil fired power stations enables the advantages of large size plants (>100 MWe), which are not applicable for dedicated biomass combustion due to limited local biomass availability. The following part gives an overview of the devices which could *potentially* use straw pellets. The effective use or trials realised with those equipments will be tackled later.

Stoves

Modern pellet stoves are nowadays efficient home heating appliances. While a conventional fireplace is less than 10% efficient at delivering heat to a home, an average modern pellet stove achieve an efficiency between 80 and 90%. Typically small combustion units (stoves and small boilers) have higher emissions of unburned components than larger units where possibilities for combustion control are better. But even small combustion units can greatly enhance their combustion efficiency and reduce the emissions levels of unburned components by introducing new techniques as catalytic combustors and staged air combustion, or simply by better insulation of the combustion chamber and preheating of the inlet air [z]. Pellets, by their small size and low moisture content contribute to a reduction of emissions, whenever air supply is sufficient [t]. Concerning the combustion phase, residential burning of wood pellets show flame temperature up to 800°C during the flaming burning, and below 400°C at the surface of the glowing pellets [i (i)].



Picture 4. Profile of a modern pellet stove
Source: Calimax



Small scale boilers

Most of the small scale boilers for household use were filled batch-wise and had water cooled furnace walls, resulting in low flame temperatures causing low efficiencies and high emissions. In addition, they had traditionally been fired according to demand (direct firing), where the amount of combustion air had been used to control the heat output. This type of combustion control leads to very high emissions of many harmful products of incomplete combustion, such as carbon monoxide (CO), volatile organic compounds (VOC) and tars. Today, many of the small boilers available on the market use two stage combustion systems equipped with ceramic refractory lining and are combined with a suitable hot water tank for heat recovery. In this configuration, the boiler can then be operated at optimal load with sufficient air and high process temperatures independently from the heating demand. This leads to relatively low emissions of all products of incomplete combustion. With this, over the last ten years, boilers thermal efficiencies have improved from an average of 60 to 80-90% [ao (a)], while the emissions of VOC and tars have been reduced 100 fold [t].



Picture 5. Profile of a pellet boiler

Source : Biostar

Burners

One common low-cost solution when changing from heating oil to pellets in small houses is retrofitting the old oil-fired furnace with a new burner designed for pellets [j (c)]. Several pellet burners convenient for substitution for oil burners are already available on the market. These are relatively simple but functional devices that in general give lower emissions than the best firewood boilers [t]. Oil furnaces, however, are not designed for fuels that leave some amounts of bottom ash like wood pellets. Therefore a frequent emptying of ash is necessary to prevent the efficiency from decreasing or even the combustion chamber from filling with ash. This can be taken care of with simple equipment with intervals depending on the season and what kind of pellets that are used.

Picture 6. Profiles of a pellet burner (left) and in replacement of an oil burner on a boiler (right)



Source: ecotec.net / pellx.nu

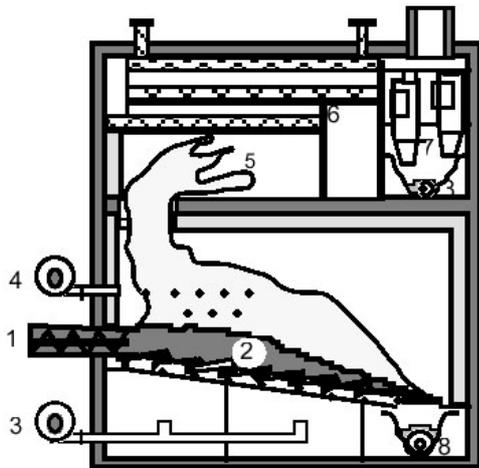


Medium and large scale technologies

The major types of large scale biomass boilers use one of the following technologies: grate combustion systems (stationary or travelling), pulverised fuel (PF) systems or fluidised bed combustion (FBC) systems.

Grate combustors

With the techniques based on grates (such as inclined grate, travelling grate, chain grate and vibrating grate), the fuel is usually fed automatically onto the grate by gravity. As the fuel bed moves, moisture is driven off initially, followed by ignition, burning and finally cooling when the ash is removed. The air supply below the grate is often sectioned so that the flow rates and pressures of the primary combustion air to each section can be independently controlled. Those systems also require a fairly high proportion of the air supplied above the grate as secondary air. Measurements of the temperature within the bed and furnace have shown relatively homogeneous profiles with maximum temperatures of 900-1100°C in the burning area of the bed, but as low as 200-500°C in the drying and ashing zone. Temperatures above the bed and in the freeboard normally ranges between 800 and 1000°C. In the stationary grate design, ashes fall into a pit for collection. In contrast, a travelling grate system drops the ash into a hopper.



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Picture 7. Moving grate with primary air in two stages in the grate and secondary air

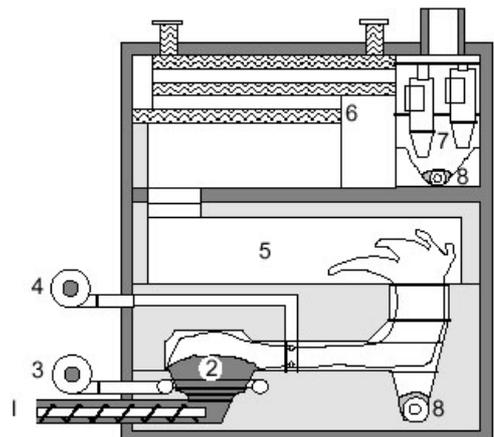
Source: [q (j)]

Stokers

Spreader stokers, which feed the fuel by distributing it on the top of the bed throughout the furnace, and retort (underfeed) stokers are less common for biomass fuels in Sweden, but successfully used in some boilers that have been converted from coal firing.

Picture 8. Understoker furnace with primary and secondary air, mixing zone and post combustion chamber.

Source: [q (j)]



Pulverised fuel systems

Wood and agricultural residues powder is attractive for larger plants, since it allows conversion to biomass fuels with minimal investment for boiler conversion. Burners for wood powder are available in the range of 1 to 30 MW. In pulverised fuel combustion, the fuel is introduced with air in burners similar to those used for oil or coal burners. The particle size must be small (generally below 1 mm) to complete a rapid combustion. Boilers equipped with oil burners or coal powder burners can be converted to use biomass powder fuel, or blends of biomass and fossil fuels. The PF process is somewhat difficult to control and may suffer from too high combustion temperatures (>1200°C) which may result in high emissions of nitrogen oxides (NOx). The high process



temperature may also lead to severe slagging and fouling problems [t]. In the pulverised combustion system, the fibrous structure of straw makes it very hard to grind into reasonably isometric particles. Thus, feeding of pulverised biofuels poses problems unheard of in coal-powder feeding [ag]. Therefore, the use of straw pellets, with a controlled moisture content and a particle size already reduced could offer an interesting opportunity.

Fluidised bed systems

Fluidized bed boilers are well known for their inherent fuel flexibility which is unmatched by any other combustion technology. Fluidized bed boilers can burn fuels with a wide range of calorific values, ash and moisture content. The fluidized bed combustion process has been in use for more than 25 years and is now established as an efficient and environmentally friendly technique.

Fluidised-bed combustors (FBC) burn biomass fuel in a hot bed of granular material, such as sand. The primary air keeps fluidised the bed of sand (making it resembling a boiling liquid), while secondary air, and in some cases tertiary air, may be introduced higher up in the furnace to achieve a staged and more complete combustion. The bed is normally operated at 750-950°C, which are considerably lower temperatures than for grate and pulverised systems. The lower temperatures inhibits the formation of nitrogen oxides (NO_x) from the combustion air and allows fuels with lower ash melting temperatures to be fired. These systems also permit the removal of sulphur dioxide (SO₂) from combustion of high-sulphur fuels simply by addition of sulphur absorbents such as limestone or dolomite in the bed. Besides many different coals, wood, other biomasses and also waste derived fuels have been successfully demonstrated in a number of FBC installations around the world. As this technology allows handling high-ash fuels, it is therefore a very suitable conversion technology for a large variety of agricultural biomass residue.



Two types of FBC are commercially available: the stationary fluidised bed (SFB) and the circulating fluidised bed (CFB). The CFB system process provides excellent conditions for the burning of several different fuels in the same boiler – this has been almost impossible in earlier technologies. Bed material circulation and high turbulence in the combustor ensures good mixing of fuel and combustion air, and also efficient heat transfer to the heat surfaces inside the furnace. An efficient particle separator, cyclone, is the heart of the process and differentiate it from SFB units. The cyclone separates out all particles larger than a certain size from entering flue gas - the particles are characterized by each cyclone type - and returns back to the bottom part of the furnace via the loop-seal located in the bottom part of the cyclone. The CFB process is shown in figure below. The duty of the cyclone is to separate unburned fuel particles and return them to the furnace, as well as to give the limestone particles used for sulphur removal more time react.

Picture 9. Profile of a circulating fluidised bed (CFB)



The following table summarises the main differences between the two FB technologies. A good overview is also given in reference [ak].

Table 20. Comparison between BFB and CFB

| | Stationary fluidised bed | Circulating fluidised bed |
|-------------|--|--|
| Fuels | Good for biofuels (w<63%) Limited with coal proportion (max. 30%) Full capacity on oil and gas | Limited with biofuel moisture (w<58%) Full coal capability Limited capacity on oil and gas (max. 40 %) |
| Process | Coarse bed material Low fluidizing velocity | Fine bed material High fluidizing velocity |
| Operation | Low power consumption Low erosion Low maintenance | Higher power consumption Possibility for erosion More refractory => more maintenance |
| Performance | Good efficiency Low NOx Low N ₂ O Limited SO ₂ removal with limestone | Good efficiency Very low NOx Higher N ₂ O Efficient SO ₂ removal with limestone |

Source: [ak]

To recap, thanks to the well-defined fuel at low water content, pellet furnaces can easily achieve high combustion quality and efficiency (>90%). They are applied both as stoves and as boilers. Until now, they have been exclusively designed for wood pellets, which present a low ash content and a high ash melting point, unlike straw.

Understoker furnaces are mostly used for wood chips and similar fuel with relatively low ash content, while grate furnaces can also be applied for high ash and water content. Stationary or bubbling fluidised bed (SFB) as well as circulating fluidised bed (CFB) boilers are applied for large-scale applications and often used for waste wood or mixtures of wood and industrial wastes e.g. from the pulp and paper industry. In fluidised bed boilers, nearly homogeneous conditions of temperature and concentrations can be ascertained thus enabling high burnout quality at low excess air. The choice of different bed materials in CFB offers additional opportunities of catalytic effects. Further, the option of heat removal from the bed allows controlling the combustion temperature and hence enables an operation at low excess air without excessive ash sintering. Since similar conditions for nitrogen conversion as by air and fuel staging are attained, relatively low NOx emissions are achieved [q (j)]. Regarding pulverised fuel technology, biomass can be co-fired with coal, in particular to reduce SO₂ emissions. The table below recaps the main furnace types which are or could be used for straw pellet combustion.

Table 21. Types of furnaces with typical applications / fuels and possibly suitable for straw pellets

| Application | Type | Typical size range | Current used fuels | Water content |
|-----------------------|-------------------------------------|--------------------|------------------------------------|---------------|
| Small scale | Pellet stoves | 1 kW – 10 kW | Wood pellets | 8 – 10% |
| | Pellets boilers | 10 kW – 50 kW | Wood pellets | 8 – 10% |
| Medium to large scale | Boiler | 50 kW – 150 kW | Wood pellets, other biomass | 5 – 50% |
| | Stoker furnaces | 20 kW – 2.5 MW | Wood chips, wood residues | 5 – 50% |
| | Grate furnaces | 150 kW – 15 MW | All wood fuels and most biomass | 5 – 60% |
| | Stationary fluidised bed | 5 MW – 15 MW | Various biomass, diameter < 10 mm | 5 – 60% |
| | Circulating fluidised bed | 15 MW – 100 MW | Various biomass, diameter < 10 mm | 5 – 60% |
| | Pulverised combustor | 1 MW – 30 MW | Various biomass, diameter < 5 mm | < 20% |
| Co-firing* | Stationary fluidised bed | 50 MW – 150 MW | Various biomass, diameter < 10 mm | 5 – 50% |
| | Circulating fluidised bed | 100 MW – 300 MW | Various biomass, diameter < 10 mm | 5 – 60% |
| | Pulverised combustor (coal boiler) | 100 MW – 1 GW | Various biomass, diameter < 2-5 mm | < 20% |

*: biomass covers typically less than 10%of the fuel input

Source: [q (j)]



Flue gas cleaning technologies

The flue gas from the combustion should be cleaned in order to comply with statutory requirements. Flue gas cleaning equipment may consist of the technologies presented in the table below.

Table 22. Main flue gas cleaning equipment.

| Technology | Process description |
|------------------------|---|
| Cyclone/ Multi-cyclone | Cleaning, thereby extracting dust particles from the flue gas by centrifugal action taking place in vertical tubes. |
| Baghouse filter | The flue gas passes through fine-meshed/pored bags that trap the suspended solid particles. Bags are periodically cleaned from the surface by pressurised air. Operation temperature: up to 850°C, but normally between 160 and 220°C. Operation pressure : up to 50 bars, but normally atmospheric pressure. |
| ESP | Electrostatic precipitator: The flue gas passes through an electric field, and the particles precipitate on electrodes. Dry and Wet ESP can be distinguished. Dry ESP: Operation temperature: up to 480°C, but normally <250°C. Operation pressure : up to 20 bars, but normally atmospheric pressure. Wet ESP : in combination with flue gas condensation unit. Higher precipitation efficiency than dry ESP, but sludge/water separation necessary. Usually operates between 45 and 55°C at atmospheric pressure. |
| Flue gas scrubber | The flue gas passes through a shower so that the particles are trapped/caught in the water. |
| Flue gas condensation | The flue gas is cooled to below the dew point, and the particles are absorbed/trapped by the dew. |

Table 23. Dust precipitation efficiency.

| | | Cyclone – multi-cyclone | Flue gas condensation | Dry ESP | Wet ESP | Baghouse filter |
|----------------------------|-----|-------------------------|-----------------------|-----------|--------------|-----------------|
| Cut size | µm | ~ 5 | | ~ 0.1 | ~ 0.1 | ~ 0.1 |
| Separation efficiency | % | 85 - 95 | 50 - 90 | 95 – 99.9 | 95 – 99.9 | 99 – 99.9 |
| Max. operation temperature | °C | 1300 | < dew point | 480 | At dew point | 850 |
| Max. operation pressure | Bar | 100 | atmospheric | 20 | 20 | 50 |
| Investment | | Low | High | High | High | High |
| Operation costs | | Moderate | Low | Low | Low | Moderate |

Table 24. Conclusion regarding fly ash precipitation technology with respect to the emission limit.

| Emission limit | Best applicable techniques |
|--------------------------|--------------------------------------|
| < 150 mg/Nm ³ | Multi cyclone |
| < 50 mg/Nm ³ | Flue gas condensation units, dry ESP |
| < 20 mg/Nm ³ | Dry or wet ESP |
| < 10 mg/Nm ³ | Baghouse filter, wet ESP |

Source: [a/]

The normal equipment in CHP plants in Denmark (which burn wood residues and straw) is a multi-cyclone to serve as spark arrester and for coarse particles followed by a bag filter. The multi-cyclone cleans the flue gas from 1,000-2,000 mg dust/Nm³ to 500-600 mg/Nm³. Much of the fly ash from straw firing is so fine-grained (below 0.01 mm) that the filter bags are the best and cheapest solution for complying with the requirement of 40 mg dust/ Nm³. The particle content of the dust after filter is under normal operation 20-30 mg dust/ Nm³ with bags without cracks. See also the section on environmental conditions. Electrostatic filters may give problems in connection with straw-fired plants. Two plants that originally had electrostatic filters have replaced them with bag filters. The dust particles are difficult to ionise in the electrostatic filter, and it is difficult to make them leave the electrodes and fall off to the ash system due to the very small mass. Some of the particles therefore condense and deposit like coating in the chimney, and, in particular, when the plant is started up, lumps of soot are carried along and fall down in the neighbourhood of the plant. A few heating plants have installed a flue gas scrubber. The principle is that the flue gas passes through a “waterfall” of atomised water, thereby absorbing the dust particles, thereby transporting



them with the water. This method creates a waste-water problem for the plant instead of an ash deposition problem.

NO_x emissions level may be efficiently reduced by selective catalytic (or non-catalytic) reduction. However, these methods can be both expensive and difficult to use, and are therefore not always applicable to small and medium sized combustion plants.

Table 25. Technologies for NO_x emissions reduction

| Technology | Process description |
|-------------------------|---|
| SNCR (NO _x) | Selective non catalytic reduction: injection of a reducing agent (ammonia or urea) into the hot furnace. Temperature window between 850 and 950°C. SNCR reaches an average NO _x -reduction efficiency of 60 to 70%, but increases CO emission by 10-20 ppm. |
| SCR (NO _x) | Selective catalytic reduction: Injection of a reducing agent in the flue gas downstream the boiler). Reducing agents can be ammonia (between 220 and 270°C) and urea (between 400 and 450°C). It usually reaches a NO _x -reduction efficiency of 80-95%, but implies considerably higher investment costs than SNCR. |

Source: Obernberger

Problems occurring during the combustion stage

Combustion process and combustion products

Biomass combustion is a complex process that consists of consecutive steps : drying, devolatilisation, gasification, char combustion, and gas phase oxidation .The time used for each reaction depends on the fuel size and properties, on temperature, and combustion conditions. During the first phase, free water vaporises. During gasification combustible gases are produced depending on the temperature. There will always be a certain content of carbon monoxide (CO), hydrogen (H₂), methane (CH₄), and other hydrocarbons. Then combustion of gases takes place. If sufficient oxygen is supplied, a complete combustion occurs where the residual products are carbon dioxide (CO₂) and water. Where the oxygen supply is insufficient, carbon monoxide (CO), soot (finely divided carbon), tar, and unburned hydrocarbons (UHC) are produced. Finally, the charcoal burns. At the end of the process, there only remains ash which consists of incombustible inorganic matter. If combustion is incomplete, the ash may contain unburned organic matter. In all cases, as a result of the combustion process, different types of pollutants can be distinguished [q (j)]:

- Unburnt pollutants such as carbon monoxide (CO), unburned hydrocarbon (UHC; C_xH_y in gaseous phase), polycyclic aromatic hydrocarbon (PAH), tar, soot, hydrogen (H₂), HCN, NH₃, and nitrous oxide (N₂O),
- Pollutants from complete combustion such as nitrogen oxides (NO_x : NO and NO₂), carbon dioxide (CO₂)
- Ash and contaminants such as ash particles (KCl, etc.), SO₂, HCl, PCDD/F, Cu, Pb, Zn, Cd etc.

Table 26. Some pollutants and their effects

| Emission | | Effects |
|-----------------|--------------------|---|
| CO ₂ | Carbon dioxide | Greenhouse gas. Combustion of wood pellets and agri-pellets is considered CO ₂ neutral since the CO ₂ is re-absorbed during the plants growth. |
| NO _x | Nitrogen oxides | Three gases : nitric oxide (NO), nitrous oxide (N ₂ O) and nitrogen dioxide (NO ₂). Contribute to smog formation and can cause problems for people with respiratory illness. N ₂ O, like CH ₄ , is a greenhouse gas. |
| SO _x | Sulphur oxides | Mainly SO ₂ (sulphur dioxide). Contributes to acidification of the atmosphere. |
| HC | Hydrocarbons | Contribute to ozone formation and some HC's are classified as carcinogens. |
| PM | Particulate matter | Presumed to affect cardiovascular, respiratory and asthma sufferers |



| | | |
|--------|---------------------------------|--|
| PCDD/F | Dioxin and furan | Polychlorinated dibenzo -p dioxin (PCDD) and polychlorinated dibenzo furan (PCDF) relate to two groups of chemicals belonging to persistent organic pollutant (POP). They are very toxic substances, with embryotoxic effects and attacking human immune system. |
| CO | Carbon monoxide | Poisonous (absorbed by blood and reduces its capacity to carry oxygen). Odour nuisances. |
| PAH | Polycyclic aromatic hydrocarbon | Ex: phenanthrene, naphthalene... Carcinogenic effects. They are intermediate in the conversion of fuel carbon to CO ₂ and fuel hydrogen to H ₂ . |

A high combustion quality, in terms of maximal combustion of the burning gases, is therefore very important for a low emission level. It mainly depends on the combustion chamber temperature, the turbulence of the burning gases, residence time and the oxygen excess. These parameters are governed by a series of technical details such as:

- combustion technology (e.g. combustion chamber design, process control technology),
- settings of the combustion (e.g. primary and secondary air ratio, distribution of the air nozzles),
- load condition (full- or part-load),
- fuel characteristics (shape, size distribution, moisture content, ash content, ash melting behaviour).

Emissions

Gaseous emissions

During combustion, nitrogen (N), sulphur (S) and chlorine (Cl) in the fuel – and present in higher proportion in straw than in wood - may lead to atmospheric pollutants: nitrogen oxides (NO_x: NO, NO₂ and N₂O), sulphur dioxide (SO₂), hydrogen chloride (HCl) and chlorinated hydrocarbons [t]. In addition, Cl influences the formation of dioxins and furans. Emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) such as methane (CH₄), particles, tar and PAH are caused by an incomplete combustion. The incomplete combustion is mainly the result of either low combustion temperatures, short residence times, bad mixing conditions with oxygen (or oxygen shortage) or combinations of these effects [z]. This part will emphasize a few issues related to the pollutants linked to the fuel composition (NO_x, SO₂, HCl and dioxins in the case of straw), and less the problems with regard to the other pollutants which are greatly influenced by the furnace design or the operation mode, and not to the content

NO_x emissions

NO_x emissions from biomass combustion applications originate mainly from the nitrogen content in the fuel, in contrast to fossil fuel combustion applications where nitrogen in the air also contributes to some extent to the NO_x emission level. NO_x emissions from biomass increase with increasing N content in the fuel and with increasing combustion oxygen concentration. Together with the fuel nitrogen content, furnace design and operating conditions are significant parameters which influence the NO_x emissions from boilers [r (a)].

There is a trade-off between emissions of nitrogen oxides (NO_x) on one hand, and emissions of unburnt hydrocarbons (UHC) and carbon monoxide (CO) on the other hand. Decreasing the excess air (oxygen concentration) results in lower NO_x emissions but in increased emissions of unburnt (UHC and CO). In addition, efficiency increases as the excess air is decreased until the losses due to incomplete combustion become too high. So far the development of burners and stoves has been focused on achieving low emissions of UHC [i (l)]. For an annual heating demand of 25,000 kWh, NO_x emissions with an oil burner correspond to about 4 kg NO₂ (44 mg/MJ). Replacing the oil burner with a wood pellet burner results in higher NO_x emissions in the range of 7-21 kg NO₂ per year (77-233 mg/MJ) despite the usually low nitrogen content (<0.2%) in today's commercial pellets. NO_x emissions are expected to be higher with straw, as suggested in the tables below.



Today, both primary and secondary methods are used in NO_x emission reduction. As a primary method, an air-staged combustion can be operated, which correspond a staging of combustion air to two (or three) levels. At the first level (primary air), reducing conditions (oxygen deficiency) are created: the primarily formed nitrogen compounds can be reduced to molecular nitrogen (N₂) if the residence time is sufficient. Then, secondary air (and in some cases tertiary air) is supplied higher in the furnace after the reducing zone to enable complete burnout of hydrocarbons and CO [i (l)]. In order to control the air supply, gas concentrations need to be measured. Lambda sensors are used to control the oxygen level in today's boilers. Different chemical sensors for unburnt products have been introduced on the market. Use of these sensors may provide efficient control for optimal performance with respect to emissions and efficiency independent of variations in heat demand and variations in fuel quality [i (l)].

Staged air combustion is a primary method with the highest NO_x reduction potential. A three-stage air feeding gives about a 40% reduction in NO_x emission compared to the conventional two-stage air feeding [ak]. Typical NO_x level to be reached by three-stage air feeding is around 220-250 mg/NO₂/Nm³ (6% O₂, dry). It can be applied to small combustion unit or stoves and be cost efficient. In addition to the primary methods, secondary measures can be applied but are usually restricted to larger combustion units [z]. They consist in flue gas cleaning techniques, such as non catalytic reduction, or selective non catalytic reduction (seen before); a maximum 60-95% reduction can be achieved.

Sulphur oxide emissions

The burning of sulphur-containing fuels, such as straw, emits the sulphur mainly as gaseous sulphur dioxide (SO₂). SO₂ is a colorless, stinging smelling gas and its smell can be noticed in the air at a concentration of approximately 0.6 to 1 mg/Nm³. A part of the SO₂ can be oxidized to SO₃, but usually, after burning 99 % of the sulphur is in the SO₂ form, and 1 % is present as SO₃.

A few emission data

The results from the table below underline the relation existing between the fuel content and the emissions it originates. For NO_x, SO_x as well as for HCl, straw show higher emission levels. It appears clearly that the higher concentrations of N, S and Cl in straw result in higher emissions of NO_x, SO_x and HCl.

Table 27. NO_x, SO_x and HCl emissions from wood chips, straw and whole crops

| | Wood chips | Straw | Whole crops | EU standard | | |
|-------------------------------------|------------|-------|-------------|-----------------|------------|----------|
| | | | | 50-100 MW | 100-300 MW | > 300 MW |
| Fuel content of (in mg/kg): | | | | | | |
| Nitrogen (N) | 670 | 1750 | 13500 | | | |
| Sulphur (S) | 40 | 470 | 970 | | | |
| Chlorine (Cl) | 44 | 1400 | 3000 | | | |
| Emissions of (mg/Nm ³): | | | | Emission limits | | |
| NO _x | 140 | 260 | 250 | 400 | 300 | 200 |
| SO _x | 10 | 100 | 145 | 200 | 200 | 200 |
| HCl | 0.6 | 36 | 78 | | | |

Source: bayerisches landesamt für umweltschutz; <http://www.bayern.de/lfu/luft/emicontrol/emicontrol1.htm>; directive EC 2001/80/EC

Facing the relative scarcity of data on emissions from straw pellets, it has been decided to refer to straw burning. However, straw behaviour when it is not densified is different from the one expected from straw pellets, specially because the moisture content of the former is generally higher and affected by a higher variability, which impacts considerably on the combustion efficiency and thus, on the emissions.



The following table reminds the main advantages generally put forward to justify a straw utilisation rather than oil combustion : the SO₂ emissions are highly reduced, and considering that the CO₂ is re-introduced in the vegetal cycle, there is no net contribution to the greenhouse effect.

Table 28. Emission comparison between light oil and straw combustion

| | | Light oil | Straw | Light oil | Straw |
|--------------------|--------|-----------|--------|-----------|------------|
| Annual heat output | GJ | 16.200 | 16,200 | 1 MJ | 1 MJ |
| CO ₂ | t/year | 1215 | 1604* | 75,000 mg | 99,000* mg |
| SO ₂ | t/year | 8.1 | 2.1 | 500 mg | 130 mg |
| Dust | t/year | 0.97 | 0.32 | 60 mg | 20 mg |
| NO _x | t/year | 2.4 | 2.4 | 148 mg | 148 mg |

* CO₂- from biomass is considered neutral.

Source: <http://www.lei.lt/Opet/Projekts/narteikiai.htm>

Table below allow a general comparison between different fuels. Results about straw are quite striking. They are taken from measures performed in 13 CHP plants in Denmark, and apply for loose straw and not straw pellets. CO and particle emission are surprisingly high, specially if we compare the proportion for particle emissions between straw and fuel oil, with the proportion which can be deduced from the previous table. However, the same result for SO_x emissions is found. Compared to wood pellets, straw combustion leads to higher emissions for all substances measured: NO_x, SO_x, CO.

Table 29. Typical environmental impact per MJ of produced heat from different fuels

| | Coal | Fuel oil | Natural gas | Wood pellets | Straw | Forestry residues |
|---|---------|----------|-------------|--------------|-------|-------------------|
| Heating plant - Emissions to air [mg/MJ] | | | | | | |
| CO ₂ | 106,000 | 87,000 | 58,000 | 420 | - | 2,800 |
| NO _x | 78 | 130 | 64 | 62 | 90 | 93 |
| SO _x | 79 | 210 | 0.22 | 40 | 130 | 40 |
| CO | 46 | 19 | 12 | 290 | 600 | 300 |
| N ₂ O | 13 | 0.58 | 0.53 | 4.7 | - | 4.7 |
| CH ₄ | 1200 | 2.9 | 2.8 | 5.2 | - | 4.7 |
| Particles | 29 | 0.4 | 0.02 | 0.94 | 40 | 3.7 |
| NH ₃ | 1.9 | 0.66 | 0 | 2.4 | - | 2.4 |
| VOC | 2.3 | 47 | 2.8 | 19 | - | 23 |
| Residues [mg] | - | 12 | 20 | - | - | 1600 |
| Small-scale residential heating facilities - Emissions to air [mg/MJ] | | | | | | |
| CO ₂ | - | 92,000 | 62,000 | 590 | - | - |
| NO _x | - | 106 | 29 | 150 | - | - |
| SO _x | - | 45 | 0.23 | 57 | - | - |
| CO | - | 38 | 13 | 2700* | - | - |
| N ₂ O | - | 0.62 | 0.57 | 1.3 | - | - |
| CH ₄ | - | 3.7 | 3.0 | 200* | - | - |
| Particles | - | 0.42 | 0.02 | 1.3 | - | - |
| NH ₃ | - | 0.12 | 0 | 2.7 | - | - |
| VOC | - | 54 | 3.0 | 1300* | - | - |
| Residues [mg] | - | - | - | - | - | - |

*: Data are taken from wood burning. Combustion of DBF leads to significantly lower emissions of CO, VOC and CH₄, possibly less than half of the amount accounted here. This is due to a more complete combustion in comparison with wood. Figures for straw apply to straw-fired CHP plants in Denmark with bag filter

Source : [j (c)] + [aa] for straw



It should also be noted that with the same fuel, differences in emissions can occur according to the combustion technology. The table below gives a comparison for emissions from wood pellet combustion. Those results should be seen as examples for different burning appliances and not as generally representative. Emissions of carbon monoxide, methane and benzene from the burner are very low on full burner effect, but considerably higher with low effect combustion. This shows that emissions from pellet burning will be almost negligible on use of best technology and favourable combinations of burners and boilers. It can also be concluded that the time for the burner on low effect should be minimised to decrease the total emissions. The idea illustrated for wood also apply to straw.

Table 30. A comparison of the emissions from different pellet burning equipments for residential use (tests on wood pellets)

| | Stove | | Burner | | Boiler | |
|--------------------------------------|-------|------|--------|-------|--------|------|
| | 7 kW | 4 kW | 20 kW | 10 kW | 25 kW | 8 kW |
| Carbon dioxide (CO ₂ - %) | 3.1 | 2.1 | 6.9 | 2.7 | 6.0 | 1.9 |
| Carbon monoxide (CO - ppm) | 500 | 500 | 10 | 400 | 40 | 400 |
| Methane (ppm) | 8 | 7.8 | 0.5 | 5 | 1.5 | - |
| Benzene (ppm) | 0.2 | 0.2 | 0.003 | 0.2 | 0.02 | 0.1 |

Source: [i], p.113.

Aerosols and particulate emissions

During combustion of solid fuels, two fly ash fractions are formed: the coarse fly ashes and the aerosols. These fractions differ significantly concerning their particle size and chemical composition as well as their formation mechanisms.

Coarse fly ashes are particles entrained from the fuel bed with the flue gas. They mainly consist of refractory species (such as Ca, Mg, Si as well as small amounts of K, Na and Al) and their particle sizes can vary between some μm and 100 μm . In contrast with coarse fly ashes, the formation mechanism of aerosol particles is more sophisticated. During the combustion process a part of the volatile compounds (such as alkali metals, S, Cl and heavy metals) is released from the fuel to the gas phase: aerosols are then formed by condensation or nucleation of these volatiles compounds. Aerosols are much smaller than coarse fly ash, as its particles size ranges from 1 nm to 1 μm [q (o)]. Aerosol emissions present high concentrations of heavy metals and sometimes of organic compounds. By their dimension, they can remain suspended in the air for long periods of time and enter the inner parts of lungs.

An experiment carried out in large scale moving grate plant (40 MW) showed that coarse fly ash emissions of a biomass furnace mainly depend on the ash content of the fuel and the load of the combustion unit [q (o)]. With an increase of these parameters the probability of particle entrainment from the fuel bed with the flue gas also increases. With an average content of ash almost ten times superior to wood pellets, straw pellets are thus likely to produce much more coarse fly ash.

As far as aerosols are concerned, their formation mainly depends on the chemical composition of the fuel used. The higher the concentrations of K, Na, Zn and Pb are, the higher the aerosol emissions will be. Straw pellets present higher K content than wood pellets, but lower mean Na, Zn and Pb content. However, considering that the order of magnitude remain quite comparable for the latter elements, K would have a preponderant impact and trigger higher particulate emissions from straw pellets. In addition, experiments show that when converting a plant from a low ash fuel to agricultural fuels, the capacity of dust separators must be increased to handle larger amounts of ash [t].



Table 31. Content in critical elements influencing particles emissions

| Content (mg/kg d.b.) | Wood chips with bark | Wheat straw | Grass | Wood chips | Sawdust |
|----------------------|----------------------|-------------|--------|------------|---------|
| K | 1,376 | 12,958 | 22,770 | - | - |
| Na | 122 | 431 | 617 | - | - |
| Pb | 1.9 | 0.9 | 1.7 | 2.25 | 0.35 |
| Cd | 0.26 | 0.12 | 0.18 | 0.34 | 0.170 |
| Zn | 39.4 | 23.4 | 48.0 | 42.0 | 13.5 |

Source: Odernberger + Phyllis biomass database

In small-scale combustion unit, results tend to show that a well-designed secondary air supply results in a significant combustion of particles between the combustion bed and the flue gas [i (m)]. In addition, several gas dust-cleaning system exist. For instance, in CFB combustion units, fly ash is removed in conventional downstream pollution control devices such as an electrostatic precipitator (ESP) or a bag house. Pebbles and other coarse material which are not fluidised remain in the bottom of the furnace and are removed separately through a discharge system [ak].

Other systems consist of a special designed combustion chamber (which precipitate particles), or a cyclone (which separate the bigger or glowing particles form the flue gas) and filter units (which can be tissue bag filters or electrostatic filters). It worth underlining that many pollutants and detrimental substances are dust bound. Thus a good dust precipitation favours the elimination of most heavy metal compounds and even of dioxins and furans (PCDD/F).

Dioxins and furans (PCDD/Fs)

PCDD/Fs are a group of highly toxic components. Carbon, chlorine, catalysts (Cu) and oxygen are necessary to their formation which occurs in a window temperature between 180 and 500°C. PCDD/Fs can be formed from all biomass fuels containing chlorine, and emissions are highly dependent on the conditions under which combustion and flue gas cooling takes place. Indeed, results of an experiment [q (n)] show that the emission of PCDD/F does not depend so much on the type of fuel. In that case, agricultural residues present a PCDD/F risk emission, but a good control of the combustion process and convenient flue gas cleaning should normally decrease emissions to acceptable values, and, in any case, under the limit value in the EU for waste incinerators is 0.1 ng/m³.

Data in the table below show that burning straw leads to three times higher dust emissions compared to wood chips firing in the same combustion plant. In a way, those results can be extrapolated to a comparison between straw pellets and wood pellets. The gas cleaning systems of plant 1 and plant 2 were working very well; the efficiency of their gas cleaning systems was determined to 98 %. The result for plant 3 is quite different, especially with straw: dust emissions surpassed the emission limit value of 150 mg/m³. In that particular case, the setting of the electrostatic precipitator and/or the cyclone should be improved. Plant 3 revealed a gas cleaning efficiency of only 78 %.

Many pollutants and detrimental substances are dust bound. Thus a good dust precipitation favours the elimination of most heavy metal compounds and even of dioxins and furans (PCDD/F). Data concerning dioxins underline this effect. The PCDD/F concentration in the raw flue gas is reduced after dust precipitation. The precipitation efficiency reaches 54%, which is lower than the dust precipitation efficiency. Consequently, only a part of PCCD/F appears to be bound to dust; the other part is airborne and cannot be eliminated by dust filters. PCDD/F emissions are higher for straw than for wood chips because of the higher chlorine concentration.



Table 32. Dust and dioxins emissions

| | CHP plant | Heating plant | Heating plant | | Guiding value (EU standard) | |
|------------------------|----------------------|----------------------|----------------|------------------------|-----------------------------|-----------------------|
| Power | 11 MW | 1 MW | 0.6 MW | | 50-100 MW | >100 MW |
| Gas cleaning system | electrostatic filter | Cyclone + bag filter | cyclone filter | + electrostatic filter | | |
| Fuel tested | Wood chips | Wood chips | Wood chips | Straw | | |
| Dust | 145 | 230 | 270 | 810 | 100 mg/Nm ³ | 50 mg/Nm ³ |
| Dust | 2.9 | 4.6 | 61 | 180 | | |
| PCDD/F in raw flue gas | 0.007 | 0.050 | 0.039 | 0.105 | 0.1 ng TE/m ³ | |
| PCDD/F clean gas | - | - | - | 0.048 | | |

Source: bayerisches landesamt für umweltschutz; <http://www.bayern.de/lfu/luft/emicontrol/emicontrol1.htm>

As a conclusion, high dust concentrations in the raw flue gas are another technological challenge of biomass combustion. As in recent years the effect of fine dust (e.g. PM 10) on human health is frequently discussed, the reduction of dust emissions will be a main objective in the future. Within the EU, emission limits for particulate emissions are permanently decreasing, specially for small and medium-scale biomass combustion units. However, highly advanced state-of-the-art dust separation systems (baghouse filters, ESP) are, due to their high costs, not applicable, specially for small-scale combustion units. Therefore, there is a need for major R&D efforts the development of highly efficient and economically affordable aerosol precipitation devices [q (o)]. This is particularly the case for biomass fuels rich in N and ash such as agricultural residues, in this framework, small-scale combustion units are of special concern, as they need simple and affordable solutions.

Deposit formation

The inorganic constituents (ash) in the fuels may result in deposits on the heat transfer surfaces of the convection equipment. This is referred to as slagging when the deposits are in a molten or highly viscous state, or fouling when the deposits are built up largely by species that have vaporised and then condensed [t]. Slagging is often found in the radiant (from the flames) section of the furnace, while fouling occurs in the cooler furnace regions where the heat exchanger equipment is located. The detrimental effects of slagging and fouling are high furnace material wear, heat transfer efficiency reduction with pressure drop and increased corrosion of the boiler.

Straw contain potassium and sodium compounds. These alkali compounds are present in all annual crops and crop residues in particular. During combustion, alkali combines with silica and causes slagging and fouling problems in conventional combustion equipment designed for burning wood at higher temperatures. Volatile alkali also lowers the fusion temperature of ash: in conventional combustion equipment having furnace gas exit temperatures above 800°C, combustion of agricultural residue causes slagging and deposits on heat transfer surfaces. Specially designed boilers with lower furnace exit temperatures or low operation temperature (such as FBC systems) can reduce slagging and fouling from combustion of these fuels.

As just said, an increased K content contributes to lower the ash melting point, which favours slagging. Yet, other significant parameters have been identified as contributing to hard deposit formation wood pellets [i (g)]. Higher Si, but also Al and Fe were found in slagging pellets. The critical level of Si (given as SiO₂) was found to be 20 to 25 weight % of the fuel ash, i.e. slagging problems were reported fore higher concentrations than this. Therefore, the far higher K- and Si-content in straw than in wood explain the critical slagging and fouling problems. Furthermore, in the study mentioned above, Si content exceeded once this critical value because of contamination by sand of the raw material. Hence this underlines the necessity of a careful treatment of raw materials so as to avoid mineral contamination. Authors suggest to use an additional cyclone



separator in the pelleting process, for both primary and secondary particulate contaminants, and thereby improve the pellet quality. On the other hand, the impact of such technical solution should be carefully studied as it will rise the production cost. In all cases, slagging related problems affecting straw deserve a special attention, because they lead to reduced accessibility of the appliances, and also to bad publicity for the agri-pellet market.

Table 33. Ash melting temperature for a range of fuels

| Temperatures (°C) | Coal | Wood chips | Wood chips 2 | Pine sawdust | Spruce chips | Wheat straw | Wheat straw 2 | Grey straw |
|-----------------------|------|------------|--------------|--------------|--------------|-------------|---------------|------------|
| Fusion temperature | 1100 | 1210 | 1144 | 1150 | 1340 | 848 | 1056 | 950 |
| Softening temperature | | 1225 | 1172 | 1180 | 1410 | 956 | 1122 | 1100 |
| Hemispherical stage | | 1250 | 1222 | 1200 | 1700 | 1107 | 1161 | |
| Melting point | 1400 | 1275 | 1300 | 1225 | 1700 | 1241 | 1232 | |

Source : TU database, IEA database

Today, several options are used to overcome the slagging problems. They include the modification of fuel properties (by agricultural practices, fuel mixing during pelleting process, addition of products during combustion, co-combustion with another product) and technological solutions (lowering of combustion temperature or other innovations).

Agricultural practices: straw washing in the field

The content of K^+ and Cl^- is a major obstacle for an efficient utilization of straw as a fuel for power production, regarding the slagging problems as well as corrosion aspects (see next part). The most efficient and economically feasible option for the removal of those undesirable components is the leaching of straw using natural precipitation in the field. Regarding the correlation between fallen precipitation in the field and K^+ leached, researchers observed [q (1)] that the effectiveness of washed K^+ reached a maximum with about a 25 mm of rainfall. Beyond that volume, leaching efficiency decreases, supposedly because of a phenomenon of water saturation and in relation with the frequency of the wetting and drying periods. A laboratory experiment confirmed that a much higher washing effectiveness is observed when intercalating drying periods between water applications. To recap, agricultural practice can influence ash characteristics: by delaying straw gathering, a significant change in ash forming elemental characteristics, and thereby also the melting behaviour of the ash can be obtained (mainly K and Cl concentrations decrease). When leached (i.e. potassium and chlorine are removed away), "yellow" straw turns into "grey" straw and has a slightly increased calorific value.

Table 34. Comparison for a few elements between yellow and grey straw

| (% d.m.) | Yellow straw | Grey straw |
|---------------|--------------|------------|
| Nitrogen (N) | 0.35 | 0.41 |
| Potassium (K) | 1.18 | 0.22 |
| Chlorine (Cl) | 0.75 | 0.20 |
| Sulphur (S) | 0.16 | 0.13 |

Source: [aa]

Artificial leaching

A publication affirm that a 75% reduction of inorganic elements in rice straw was achieved by applying 17,5 m³ water per tonne of straw [ao p.184]. After the washing stage, the straw was pressed and the moisture content decreased from 77% to 48%. The total cost of the operation, including comminution, watering, dewatering, water treatment and control of the operation was evaluated to 26 \$/tonne of straw. It seems that straw washing is quite promising and even commercially available. In 1998, it was planned to erect a pilot leaching and dewatering plant with a processing capacity of 500 kg/h of straw [ao p.224].



In order to reduce the corrosive effect of straw upon the boiler plant, the ELSAM - Electricity Utility Group of Jutland-Funen implemented in the spring of 1996 experiments on the removal of the unwanted components by boiling the straw at 160°C. Later it was demonstrated that chlorine and potassium can also be washed out at lower temperatures. At present, it is considered most economical to wash the straw at 50-60°C.

So far, straw washing has only been tested at small plants. According to ELSAM, a plant that can treat 125-150,000 tonnes of straw per annum will most probably cost about DKK 200 million. The energy losses caused by washing, drying and the leaching of organic matter make out approximately 8% of the calorific value of the straw. This cost would be offset though by the prolonged life of the boilers, because corrosion problems are avoided. Washing of straw is also expected to give advantages in respect of the subsequent application of the fly ash, since straw ash that does not contain alkaline salts and other impurities can be used as a filler in building materials [aa].

Adding of anti-slagging agents during pelleting

Experiments showed that straw pellets can be used as a fuel in large boilers, whereas ash and particularly slagging problems make them less suitable for use in small boiler plants. Straw pellets can be pressed with an anti-slagging agent (e.g., kaolin) so as to counteract the tendency of the ash to become viscid and form clinker [aa]. The calorific value of those pellets seems to be somehow lower than the average. The publication does not mention anything about the impact of those additives on emissions.

Fuel mixing during the pelletising process

Straw can be pelletised with sawdust or with another product so as to reduce the Si content (condition absolutely necessary) and eventually. It seems that several tests have been carried out but they did not pass the experimental stage. According to a personal communication, several mix proportions were tested and the 60-70% straw – 30-40% straw lead to convenient results. In this case, compression forces (i.e. die's thickness) has to be decreased.

Adding of calcium (Ca) as anti-agglomeration agent

With a fluidised bed technology, a study focused upon alkali metals said to influence ash agglomeration, phosphorous (P) relatively rich in vegetable biomass, and calcium (Ca) as an additive. During the ash agglomeration test using small fluidised-bed furnace, the ash agglomeration took place at 800-900°C when the Ca is scarce, but is prevented by addition of Ca [q (c)]. Recent results have shown that bed agglomeration can be prevented by co-combustion [t].

Technological solutions

The lowering of the combustion temperature is mainly achieved with FBC technologies (see Technologies Available). Another innovation can be mentioned: in China, an application trying to overcome the sintering problem has recently been developed [i (e)]. It consists in a sort of stirring technique applied to the burning cups of different pellet appliances: the larger sintered structures are crushed regularly and removed simultaneously from the burning cup. The pellet appliances used were mainly designed for cooking, but stoves and small-scale domestic boilers (up to 50 kW) have been tested with success.

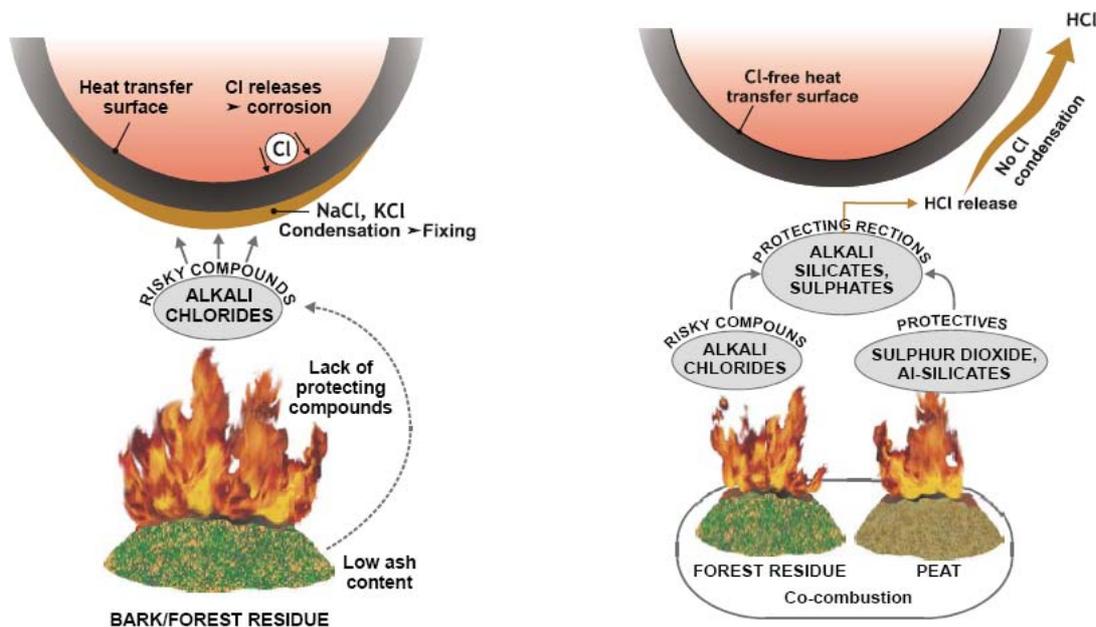
Corrosion

It has been showed that even a small concentration of chlorine (Cl) in fuel will result in the harmful formation of alkaline chloride compounds on boiler heat transfer surfaces. This could first be

prevented by co-firing aluminium silicates containing fuel, such as coal or peat. When those fuels are co-fired with biomass, chloride formation can be avoided.

In addition to aluminium silicates reactions, one parameter that has been often referred to is the sulphur-to-chlorine atomic ratio (S/Cl) in fuel or fuel blend. It has been suggested that if this ratio in fuel is less than 2.0, there is a high risk for superheater corrosion. When the ratio is at least four, the blend could be regarded as non corrosive. At a molecular level, vaporised alkaline metals of biomass ash (Na and K) are bound in sulphur and aluminium silicates compounds; the amount of alkaline chloride in deposits is reduced or these are not formed at all, and chlorine is released as HCl to the flue gas. Those results have naturally led to tackle the co-combustion possibility (see next part).

Figure 3. Corrosion and anti-corrosive mechanisms



Source: [af]

Several field studies have shown that the main contributor to superheater corrosion, independent of boiler type, is chlorine (Cl), in particular alkali chlorides (NaCl, KCl). The relatively low sulfur content in most solid biofuels may introduce corrosion problems in the superheaters. The inhibiting tendency of sulfur to limit superheater corrosion has already been recognized in the 1970s. It is generally known that when the sulfur to chlorine molar ratio (S/Cl) in the fuel is higher than 2.0, corrosion is diminished significantly. Yet, in those conditions, the melting temperature is lowered: the best way to prevent then molten phase corrosion is to keep superheater metal temperature below the first melting temperature of deposits, in practice below 500°C when firing biofuels [ak].

Co-combustion

Several benefits were detected favouring the extensive use of biomass in energy production together with coal. Combustion of high Si-content biomass residues alone produced Cl-containing deposits, which tend to be corrosive. Sulphur and aluminium silicates, present in coal, peat and lignite, inhibited Cl deposition. Even small addition of coal to the feedstock hindered Cl deposition. As a synergetic effect, wood derived biomass strengthened SO₂ capture from the flue gases of coal combustion [q (e)]. In short, co-combustion of biomass and fossil fuels in large scale power stations has been argued for the following reasons:



- SO₂ and NO_x emissions reduced by use of biomass fuels (in comparison with fossil fuels alone). Co-combustion also reduces the net CO₂ emissions
- low capital expenditure (only limited modifications are required to operate on existing plants)
- compensation of the seasonal fluctuations of the biomass availability by the fuel mixture
- eventual higher cost of biomass fuels compensated by fuel mixture.

Co combustion is also a technique that prevent bed agglomeration and fouling in FBC units. Indeed, the risk of bed agglomeration, linked to increased amounts of alkaline metals (Na, K) is strongly reduced when peat is added. However it is questionable if ashes from co-combustion with fossil fuels really should be re-circulated, as required for a sustainable use of biomass [t].

Ash-related issues

The ash content can be considered amounting approximately 0.5% for wood and 3-7% for straw: the difference reaches a factor 10. This first data show that the ash related issue acquire a higher order of magnitude with straw. Problems are essentially linked to the ash management. In order to produce a ideal sustainable biomass fuel system, nutrient cycles should to be closed, and from that perspective, the recycling or storage of agri-pellets ash deserves a special attention.

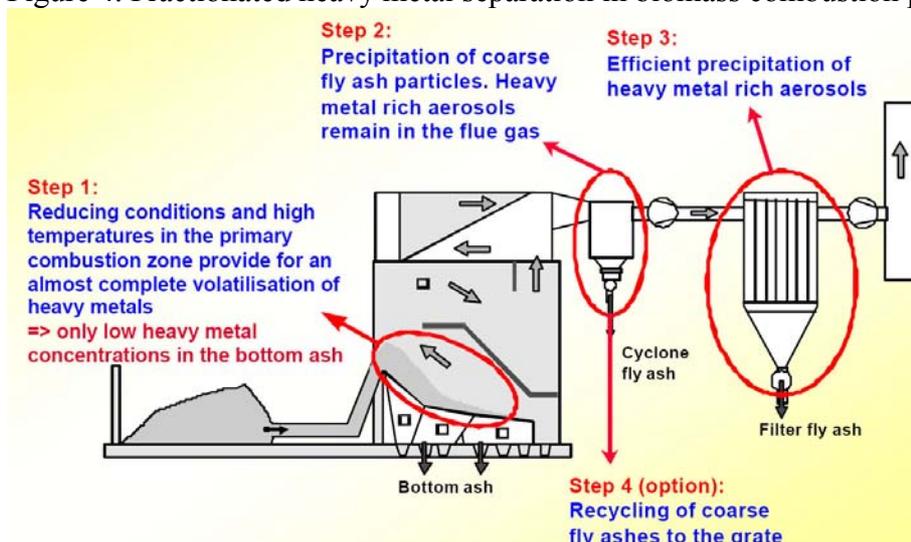
Small scale applications

The first and direct consequence for small scale stoves and boilers of the increased ash residue with straw is that there the ash box under the furnace will have to be emptied more frequently, which is quite negative as far as users' convenience is concerned. Considering that the ash pan should normally be emptied once every 5 to 15 days with wood pellets depending on the consumption, straw pellets would oblige to remove ashes almost everyday when energy consumption reaches a maximum. Obviously, it also depends on the size of the ash pan, and this one seems to increase, precisely to reduce the need for removal and increase the convenience of the appliances.

Large scale applications

Different ash fractions and qualities

Figure 4. Fractionated heavy metal separation in biomass combustion plants



Source: [a1]



Straw typically contains 3-7 % ash. Part of the ash is taken out in the bottom of the boiler and is called bottom ash while the remainder is whirled round in the boiler with the combustion air and further out in a flue gas cleaning system. This part of the ash is called fly ash. In the flue gas cleaning system, the major part of the fly ash is separated, while the remainder is released through the chimney in the form of particle emission.

Straw combustion lead to major fly ash fraction (5-15%) in comparison with woodchips (2-10%). Apparently, sawdust also to a quite high proportion of fly ash. It would be interesting to find data about ash from the combustion of those products but in their densified form.

Table 35. Typical proportions of the different ash fractions

| | Woodchips | Sawdust | Straw, cereals |
|-----------------|-----------|---------|----------------|
| Bottom ash | 60 – 90 | 20 – 30 | 80 – 90 |
| Cyclone fly ash | 10 – 30 | 50 – 70 | 2 – 5 |
| Filter fly ash | 2 – 10 | 10 – 20 | 5 – 15 |

Source: [al]

Each ash fraction has different element contents. Filter fly ash tends to accumulate the largest part of heavy metals. Ash straw is produced is higher quantities, but the content in heavy metals for each fraction seems to lower.

Table 36. Average concentration of potentially fertilising elements and heavy metals in the ash fractions

| | Bark, woodchips, sawdust | | | Straw, cereals | | |
|--|--------------------------|-----------------|----------------|---------------------|-----------------|----------------|
| | Bottom ash | Cyclone fly ash | Filter fly ash | Bottom ash | Cyclone fly ash | Filter fly ash |
| <i>Average concentration of plant nutrient (in wt. % d.b.)</i> | | | | | | |
| CaO | 41.7 | 35.2 | 32.2 | 7.8 | 5.9 | 1.2 |
| MgO | 6.0 | 4.4 | 3.6 | 4.3 | 3.4 | 0.7 |
| K ₂ O | 6.4 | 6.8 | 14.3 | 14.3 | 11.6 | 48.0 |
| P ₂ O ₅ | 2.6 | 2.5 | 2.8 | 2.2 | 1.9 | 1.1 |
| Na ₂ O | 0.7 | 0.6 | 0.8 | 0.4 | 0.3 | 0.5 |
| <i>Average concentrations of heavy metals (mg/kg d.b.)</i> | | | | <i>(Straw only)</i> | | |
| Cu | 164.6 | 143.1 | 389.2 | 17.0 | 26.0 | 44.0 |
| Zn | 432.5 | 1870.4 | 21980.7 | 75.0 | 172 | 520.0 |
| Ni | 66.0 | 59.6 | 63.4 | 4.0 | < 2.5 | < 2.5 |
| Cr | 325.5 | 158.4 | 231.3 | 13.5 | 17.5 | 6.8 |
| Pb | 13.6 | 57.6 | 1053.3 | 5.1 | 21.5 | 80.0 |
| Cd | 1.2 | 21.6 | 80.7 | 0.2 | 1.8 | 5.2 |

Source: [al]

Table 37. Average concentration of potentially fertilising elements and heavy metals in the ash fractions. Results from grate ash combustion

| | Wood | Straw | Hay |
|--|------|-------|------|
| <i>Average concentration of plant nutrient (in wt. % d.b.)</i> | | | |
| P | 9,4 | 12 | 30 |
| Cl | - | 3,7 | 2.4 |
| Ca | 321 | 52 | 69 |
| Mg | 27 | 13 | 18 |
| Na | 66 | 132 | 166 |
| <i>Average concentrations of heavy metals (mg/kg d.b.)</i> | | | |
| Pb | 18 | 2 | 2 |
| Cd | 2.2 | 0,5 | 0.3 |
| Cu | 210 | 57 | 80 |
| Zn | 380 | 25 | 80 |
| Mn | 7850 | 440 | 1750 |

Source: [ao, p.192] -



The recycling alternative

The collected bottom ash and fly ash from the straw-fired boiler are considered residual products and should according to the (Danish) Environmental Act be disposed of in a safe way. Disposal may include recycling or storage. Filter fly ashes have typically a high heavy-metal content, and they are therefore treated separately and generally oriented towards land filling, whereas the rest of the ash (more than 90%) is generally recycled in a sustainable way.

Ash recycling for agricultural applications

Straw ash contains nutrients, primarily potassium and other soil fertilising matter like magnesium, phosphorus, and calcium and can therefore be applied in agriculture as fertiliser. However, filter ashes generally can not be used as fertilisers since heavy metal concentration is too high. In any case, agricultural application of ash must meet national legislations.

In Denmark for instance, where 55000 tons of biomass ash are produced yearly (with approx 200 kg of cadmium) [q (i)], agricultural recycling requires permission from the county. Applications submitted to the County are considered, thereby having regard to the Department of the Environment and Energy Executive Order No. 823 of September 16, 1996 on residual products for agricultural applications. This means, e.g., that the content of heavy metals in the ash should not exceed the limit values stated in the Executive Order. The Danish Environmental Protection Agency may however grant an exemption. In the case ashes do not meet the requirements, they must be stored in a landfill site.

Agricultural recycling of ash is also regulated in Austria. Below, conditions in the two countries for such a an option are compared.

Table 38. Limiting value of heavy metals for agricultural application of biomass ash (mg/kg, d.b.)

| | Limit value in force Denmark (2000) | Limit value in force Austria (1998) |
|----|--|--|
| Cu | 1,000 | 250 |
| Zn | 4,000 | 1,500 |
| Ni | 30 | 100 |
| Cr | 100 | 250 |
| Pb | 120 | 100 |
| Cd | 0.8 | 8 |

Source : [aa], [al]

In Denmark, the possibility for spreading ash is particularly limited by the content of cadmium is a key issue. The ash is divided in different categories to which correspond different spreading conditions.

Table 39. Conditions on ash spreading in Denmark

| Category | Description | Max. Cd content [mg/kg dry matter] | Max. amount of ash returned [tones dry matter/hectare] |
|----------|--------------------------|---------------------------------------|---|
| H1 | Straw ash | 5 | 0.5 each 5 years |
| H2 | Straw ash | 2.5 | 1.5 each 5 years |
| H3 | Straw ash | 0.5 | 5 each 5 years |
| T1 | Wood ash | 15 | 0.5 each 10 years |
| T2 | Wood ash | 8 | 1.0 each 10 years |
| T3 | Wood ash | 0.5 | 7.5 each 10 years |
| H+T | Mixed straw and wood ash | 5 | 0.5 each 5 years |



It seems that ash is strongly alkaline (pH of 11-12) and could cause sharp increase of pH and ion concentration in the soil after spreading [t]. Such phenomenon would be harmful with respect to plant growth. Consequently, ash could be treated (e.g. granulated) in some way to reduce impact on soil and flora and to facilitate a progressive restoration of nutrients. Different techniques have been studied for ash recycling to forest and farm lands. In particular, in order to prevent overexposure to the nutrients, ash pelleting could be foreseen. However, pelleting equipment implies a large investment. A mobile system could be purchased by more plants and be used by the plants in turn. Studies of pelletising and the consequences on soil are currently ongoing.

Depending of the scale of the biomass plant, ash is either recycled to the fields and forests (case of the important plants) or more likely stored in landfills (case of smaller plants) or used in gardens or disposed of in the public waste (individual use).

If straw was used, the amount would be expected to increase substantially, which makes a reflexion on the recycling issue even more necessary. The first aim would be to increase the recycling of ash in order to utilise the contained nutrients, and the secondary aim would be to reduce the costs for ash handling and thereby the improve economy of the plants.

As land filling is quite expensive and even more so because the ash usually needs to be moistened before handling is possible, other possibilities for ash treatment need to be developed. There seems to be no cadmium problem with the bottom ash, so separation of the ash fractions seems inevitable. However, it is not yet possible for plants in all sizes to separate the ash in order to make recycling possible for the bottom ash fraction. As far as district heating plants are concerned, separation of ash fractions seems possible at straw fired plants (while it usually would be too expensive is not feasible at wood chip fired plants). New plants should be equipped with separate ash handling.

In order to utilise the nutrients from the fly ash, a utility owned plant has developed a method for washing the them leaving heavy metals behind in a fraction to be stored. The product is a valuable fertiliser and the process could be carried out centrally using fly ash from both utility owned plants and district heating plants. The fly ash from smaller plants could be transported to a central unit to be processed, but the process is rather costly, as shown in the table below.

Table 40. Overview of economical aspects of ash handling in Denmark

| Prices in Euro/tonne dry matter | Straw ash | Wood ash |
|---|----------------------|----------|
| Land filling incl. transport | 90-120 | 90-120 |
| Costs for separation of fractions | 4-9 | 17-61 |
| Costs for ash analyses | 1-4 | 8-40 |
| Spreading on fields (straw ash)/in forests (wood ash) excl. transport | H2: 14-15 H3: 3-8 | 8-17 |
| Transportation to field/forest | Not assessed | 8 |
| Pelletization of ash | - | 11-13 |
| Washing of fly ash incl. transport | 87 | - |

Recycling for cement applications

In Denmark, applications for a large proportion of the residual products (fly ash from coal) from the energy production have been found in the cement and concrete industry. Straw ash will result in a too high content of alkali metals (potassium and sodium) and chloride in cement. Alkali metals constitute a problem because they can react to flint stone particles in the gravel aggregate with which the cement is mixed during concrete manufacturing. Thereby combinations can be formed that absorb water from the surroundings. This results in volume expansions, formation of cracks,



and problems with the freezing and thawing properties. A high chloride content is problematic because it may result in corrosion of the reinforcement bars.

More specifically, the composition of the fly ash and bottom ash from a coal-fired boiler is of great importance when considering subsequent utilisation of these coal residues. Many are used in the production of cement and ceramic products and so some of their constituents are subject to limitations beyond which they cannot be used. For instance, for utilisation of fly ash in concrete and cement applications, the contents of alkali, SO₃, Chlorine and unburned carbon are critical parameters.

In one trial co-combusting straw, an increase in alkali and unburned carbon was observed in the fly ash. In this application it was concluded that limitations to the use of the fly ash for cement manufacture would be expected with straw proportions above 10%. Co-combusting more than 10% straw would render the fly ash a waste product to be disposed of, rather than a useful constituent of a commercial product. Creating a waste disposal problem by co-combustion of biomass/waste fuels would be unacceptable in many countries and applications.

Summary of the potential technologies and critical points

This part proposes a summary of the points seen above : the relevant parameters to consider when thinking of biomass as a fuel (first table below), the main specific problems related to straw (second table) and finally the technologies currently used, under development or which could be used with straw pellets. In that last point, critical points are emphasized.

Table 41. From physical and chemical characteristics to their effects...

| Parameter | Effects |
|---------------------------------|---|
| <i>Physical characteristics</i> | |
| Bulk density | transport and storage expenditures, logistical planning |
| Unit density | combustion properties (specific heat conductivity, rate of gasification) |
| Particle size distribution | pourability, bridge-building tendency, operational safety during fuel conveying, drying properties, dust formation |
| Share of fines | bulk density, transportation losses, dust formation |
| Durability | quality changes during transshipment, disintegration, fuel losses |
| <i>Chemical characteristics</i> | |
| Water content | storability, calorific value, losses, self-ignition |
| Calorific value | fuel utilisation, plant design |
| Element content | |
| Cl | HCl emission, dioxin/furan emissions, corrosion in superheaters |
| N | NO _x , HCN and N ₂ O emissions |
| S | SO _x emissions, decreased corrosion |
| K | corrosion in superheaters, reduction of ash melting point (favours slagging), aerosol formation, ash utilisation (plant nutrient) |
| Na | corrosion in superheaters, reduction of ash melting point (favours slagging), aerosol formation |
| Mg, Ca | raising of ash melting point, ash utilisation (plant nutrient) |
| P | ash utilisation (plant nutrient) |
| Heavy metals | pollutant emissions, aerosol formation, use / disposal of ashes |
| Ash content | particle emissions, costs for use or disposal of ashes |
| Ash softening behaviour | operational safety, level of pollutant emissions |
| Fungi spores | health risks during fuel handling |

Source : [s]



Table 42. ... and from combustion problems to possible ideas for solutions

| Parameter | Relevant points to be considered |
|--------------------------|---|
| EMISSION | |
| CO ₂ | Straw, as well as other agricultural residues is considered CO ₂ neutral, because released CO ₂ re-integrates the vegetal carbon cycle |
| CO, HC, PAH, tar, soot | Complete combustion: appropriate residence time and oxygen content |
| Dust | Flue gas cleaning systems |
| NO _x | Fuel preparation to lower N content (leaching, fuel mixing) Primary measures: air-staging, fuel staging Secondary measures for N-rich fuels (case of straw): SNCR, SCR |
| SO _x | Possibilities of reduction (ecologically relevant if fuel S-content >0.2 wt% d.b.): Efficient fly ash precipitation; dry sorption with Ca(OH) ₂ ; flue gas scrubber |
| HCl | Possibilities of reduction (ecologically relevant if fuel Cl-content >0.1 wt% d.b.) Efficient fly ash precipitation; dry sorption with Ca(OH) ₂ ; flue gas scrubber |
| PCDD/F | Possibilities of reduction (ecologically relevant if fuel Cl-content >0.3 wt% d.b.) Complete combustion at low excess air ratio, efficient fly ash precipitation at <200°C; dry sorption with activated carbon |
| DEPOSIT FORMATION | |
| Slagging | Lower Si content: fuel preparation (fuel-mixing with sawdust?) Lower K content : fuel preparation (leaching, fuel mixing with sawdust?) Lower operation temperature Anti sintering mechanical systems? |
| Fouling | Lower K content : fuel preparation (leaching, fuel mixing with sawdust?) Lower operation temperature Mechanical cleaning systems? (blowers) |
| CORROSION | |
| K, Cl | Fuel preparation (leaching) Adding of calcium during combustion Lower operation temperature Co-combustion (biomass + peat/lignite/coal) |

Source: Obernberger – Thermochemical biomass conversion chap 4

Stoves and small scale boilers

Until now, no specifically seems to have been designed for straw pellets. The two main reasons are the quasi inexistence of the market, and the consequent lack of funds to develop small scale efficient devices, able to overcome both the higher emissions, slagging and corrosion problems

At the moment, a some manufacturers supply boilers supposedly adapted to the combustion of a wide range of biomass, with moisture content comprised between 0 and 30% or 30 and 50% (REKA for instance). Apparently, emissions standards are met, the small moving grate design contributes to decrease the slagging issue, while a more resistant steel could better to corrosion. However, it seems difficult to avoid the largely reported slagging and corrosion problems with straw.

Direct combustion systems

The ash content and its behaviour (that is to say, mainly its low melting point) would advise a preferred use of grate furnaces and fluidised beds for the combustion of straw pellets. The stokers could experience some serious slagging problems due to the high residence time of the fuel in the combustion zone.

In CFB boilers, the use of straw pellets alone would trigger both corrosion on the heat transfer surfaces, and above all, bed agglomeration. This latter problem has been considered so serious that no attempts have been made to build CFB boilers for straw alone. Therefore, this results in tackling



a co-combustion alternative. The optimum proportion of straw pellets and the other fuel (coal, peat, wood pellets, etc.) would still be to determine.

Co-firing alternatives

Co-firing straw in a pulverised coal boiler is economically attractive compared to the building of a dedicated straw-fired plant. Regarding process techniques, a share of 10 % straw (up to 20% in some cases) for co-combustion seems reasonable. In order to avoid corrosion and fouling, temperature is kept below 545°C. However, high K and Cl content impedes utilisation of fly ash, deactivates the de-NO_x catalyst in flue gas cleaning system and may also lead to increased deposit formation. Generally, ash from biomass firing may be used as fertilisers due to its high potassium content, while coal ash is often used in cement production. Combined firing of coal and straw can give an ash rich in K, Cl, and C which can neither be used in cement industry nor be redistributed within the fields.

The only known large-scale use of straw pellets stands precisely in that category. The Amager power plant was an old coal-fired power plant with an energy output of 136 MW. It has been converted to be fired with straw pellets exclusively, but the system is also supported with an oil firing system. 130,000 tons of straw pellets are expected to be burnt yearly. Among the reasons for this conversion, stands the fact that the coal-fired plant (built in 1971) was not equipped with a flue gas desulphurisation (FGD) system. Such gas cleaning system would have been required by 2004. Biomass combustion, by its natural lower S-content than coal, reduces SO_x emissions and allowed not to install such equipment. The option for using straw pellets (instead of straw bales) is that the grinding equipment, for pulverising the coal before combustion, could be re-used for the densified straw. In contrast, a straw bales feeding system would have meant new investments for handling, feeding and burning the fuel. In relation with the use of straw, corrosion had to be tackled, and the maximum steam temperature has been reduced from 540°C to 480°C. Slagging problems are also expected, but it is difficult to assess this point because, at the moment, the plant is still in the optimisation phase: only a few thousand tons of pellets have been burnt, and oil is providing a large part of the energy. A normalised operation way should be reached by the beginning of the year 2004. Straw pellets are produced in the pellet plant in Køge (south of Copenhagen) which has started its production few months ago. On a yearly basis the plant will produce the necessary 130,000 tonnes of straw pellets which will be transported on ships to the Amager plant. Køge pellet plant will also produce 180,000 tonnes of wood pellets for the new and advanced Avedøre plant.

For its co-utilisation with coal, biomass generally needs to be reduced in size. The degree of size reduction required depends on the nature of the biomass and the nature of the combustion technology. A major problem highlighted in a number of co-firing trials and demonstrations has been the lack of reliability of feed preparation and handling systems currently available when straw was not densified. From that point of view, straw pellets have an advantage as they can use the same grinding and feeding equipment.

To sum up, the nutrient content of pellets determines the optimal final use: if wood pellets are suitable for a combustion in every type of application (from small scale appliances to large scale power plants), straw pellets appear more suitable for a use in large combustion plants (grate, fluidised bed or pulverised combustors) with flue gas purification and increased possibilities for returning the ash to the forest. As pointed out by the IEA, emission reduction measures for biomass combustion are available for all harmful emission components; whether the emission reduction measures are implemented or not is merely a question of emission limits and cost-effectiveness. Though scale-effects ensure that large installations (such as coal power plants) can be equipped



with flue gas cleaning more economically, local availability of the biomass fuel and transportation costs will usually be a limiting factor for size.

Reliability of the raw material

A significant barrier to the development of biomass fuels might be the supply reliability and quality of the raw material, and the consequent quality of densified fuels.

Indeed, one has to be very prudent when opting for straw as a fuel (densified or not) should assess thoroughly the availability of straw, and its variability. It should be noted that straw yields vary greatly with varieties, soil, climatic conditions and fertilising. In addition this last aspect triggers problem on the variability of quality. Straw quantities can vary also considerably by growing season, with markedly lower production in abnormally dry years. The last summer's drought illustrates it perfectly, when very large quantities of straw were required by cattle breeders to feed their livestock. As a conclusion, one cannot hardly rely on regular average straw surplus for energy purpose. Therefore, energy plant should not be over-dimensioned, and, in any case, a support system must be foreseen.

Equipment certification and standards

As there had been no international standards even experts found it difficult to compare the results of the individual European test institutes. Yet, in 1998 the European standard EN 303-5 ("Heating boilers for solid fuels"), which was set up and allows now standardised testing and assessment of biomass furnaces in Europe. If tests are conducted according to EN 303-5, the furnace is operated within the output range stated by the manufacturer. Heat output, boiler efficiency and combustion period are determined. Moreover the composition of the combustion gas is analysed and the exit flue temperature, the draught and the emission properties are determined. At nominal heat output the furnace is to be operated in such a way that continuous running is possible. The minimum heat output can be regulated manually or automatically by a control device.

Several methods and certification systems exist throughout Europe. The Swedish method, called P-marking or P-label, refers to pellet stoves with a maximum capacity of 15kW. It includes careful testing and a verification that demonstrates that the product fulfils the requirements in terms of standards, regulations, technical safety, efficiency and reliability (the list of approved products can be found on www.sp.se/certifiedprodukts)

Table 43. P-label criteria

| | Pellet stove | Pellet burner / boiler |
|--------------------------------------|----------------------------------|----------------------------------|
| Emission limit (mg/Nm ³) | UHC: 75 CO: 2000 Dust: 100 | UHC: 75 CO: 2000 |
| Efficiency | >75% | Boiler with oil burner minus 10% |
| Noise | 45 dB(A) | - |

Stoves approved by the Danish standardisation body all meet a number of minimum requirements concerning efficiency, environmental protection and safety. First of all, the stove efficiency must be at least 70 per cent at nominal output, i.e. the output at which combustion in the stove is at its best. Secondly, the amount of carbon monoxide (CO) in the smoke must not exceed 0.3 per cent. In case of too much CO there is a considerable risk that it also contains tar and PAH, which are



carcinogenic substances. Thirdly, the stove must meet a number of safety requirements, e.g. fire safety requirements. For instance, it must be ensured that embers cannot roll onto the floor when more fuelwood is added; the temperature of the walls surrounding the stove must not exceed 80°C; and the temperature in the chimney must not exceed 350°C. Finally, there are certain general requirements concerning door design, ash grate, ash pan, etc. Before a stove is approved by the Danish standardisation body, it is tested at the Danish Technological Institute in Århus.

In Austria, the quality of pellet furnaces is regulated by ÖNORM EN 303-5 and is valid for heating boilers for solid fuels (biomass and fossil fuels) which can be fed automatically with a nominal boiler capacity up to 300 kWth including furnaces fired by pellets [i (d)].

Table 44. A few guiding values concerning combustion emissions

| | Denmark (1) | France (2) | Austria (3) | TA Luft | UE |
|-------------------|-----------------------|------------------------|-------------|---------------------------|----------------------------|
| Dust | 40 mg/Nm ³ | 150 mg/Nm ³ | 60 mg/M | 50-150 mg/Nm ³ | 50-100 mg/Nm ³ |
| CO | 0.05% vol | No standard | 500 mg/MJ | 250 mg/Nm ³ | |
| NO _x | | 750 mg/Nm ³ | 150 mg/MJ | 500 mg/Nm ³ | 200-400 mg/Nm ³ |
| SO ₂ | | 200 mg/Nm ³ | | 500 mg/Nm ³ | 200 mg/Nm ³ |
| HC (Hydrocarbons) | | | 40 mg/MJ | | |
| HCl | | | | 30 mg/Nm ³ | |
| VOC | | No standard | | | |

(1) In the Danish Environmental Protection Agency Directions No. 6 and 9/1990 on "Industrial Air Pollution Control Guidelines" emission levels that are intended as a guide for straw-fired boiler plants larger than 1 MW input are for dust and CO suggested at 40 mg/Nm³ and 0.05% CO (volume % at 10% O₂ in the flue gas), respectively. However, concerning the CHP plants described here, the environmental approvals in question stipulate individual requirements to be met.

(2) for biomass boilers from 2 to 20 MW

(3) limits for automatically stoked boilers

With the possibility of commercial development and with the risk of a backlash, the standardisation of straw pellets and pellet-fired appliances is gaining relevance. Besides the European standard EN 303-5, the Federal Technical Agriculture Institute (BLT) in Germany has tested and is testing a wide range of boilers, from which more than 200 models have a certification today. However, tests are mainly made with wood pellets, and sometimes with other fuels like grains, but straw has hardly been tested, only many years ago. A new testing project including the assessment of the boilers performances with straw pellets could be launch within a few months. Yet, until now, it is admitted that even if emissions problems can be overcome with specific cleaning gas systems, slagging and corrosion related issues still represent a major challenge.

Confrontation of agri-pellets quality to pellets quality standards

In fully automatic heating systems for residential sector, a high quality of the fuels is required. Several European countries already have implemented standards for such fuels, while other countries are preparing or planning it [i (k)]. High fuel quality, necessary for the combustion of densified biomass fuels in automatic small-scale furnaces is not necessary if these fuels are used in larger industrial furnaces because they are equipped with more sophisticated flue gas cleaning, combustion and process control systems.

Pellets have an advantage in being a standardised fuel, simplifying construction and operation of burners. It is important for the pellet producers to have quality standardisation. It increases the customer's confidence since he knows better the product he buys. However, it is important to have in mind that pellet quality cannot be defined without reference to heating technology, since different heating systems require different fuel qualities. For large heating plants durability of pellets and amount of fines is less important, whereas for use in pellet stoves the pellets must be extremely



durable so that they do not produce too much dust in the storage bunker and do not cause technical problems in the feeding and combustion unit [s]. From that point of view, the different quality of straw pellets would simply suggest a different use, preferentially towards the large scale systems.

Table 45. Synthetic table on national regulations related to pellet quality

| Specification | Austria ÖNORM M 7135 | | Sweden SS 18 71 20 | | | Germany DIN 51731 | | USA Pellet Fuels Institute | |
|---|---|---|--|----------------------------|----------------------------|---|--|----------------------------------|--|
| | compressed wood | compressed bark | group 1 | group 2 | group 3 | 5 length categories otherwise the same [cm] | | standard grade | premium grade |
| dimensions | - pellets: 4 - 20 mm diameter max.100 mm long | - briquettes: 20-120 mm diameter max 400 mm long | max. length 4x diameter**) | max. length 5x diameter | max. length 6x diameter | HP1 >30 length HP2 15-30 HP3 10-16 HP4 <10 HP5 <5 | >10cm Ø 6-10 3-7 1-4 0,4-1 | 6-7,5 mm Ø < 3,6 cm | 6-7,5 mm Ø < 3,6 cm |
| bulk density | | | ≥ 600 kg/m ³ ***) | ≥ 500 kg/m ³ | ≥ 500 kg/m ³ | | | | >40 pounds/cubic ft.+) = 639kg/m ³ |
| durability/fines in % <3mm***) | | | ≤ 0.8 | ≤ 1.5 | ≤ 1.5 | | | <0,5% through a screen of 3mm | <0,5% through a screen of 3mm |
| unit density (US) | ≥ 1.0 kg/dm ³ | ≥ 1.0 kg/dm ³ | | | | 1-1.4 g/cm ³ | | | |
| water content | ≤ 12% | ≤ 18% | ≤ 10% | ≤ 10% | ≤ 12% | <12% | | | |
| ash content | ≤ 0.5%* | ≤ 6.0%* | ≤ 0.7% | ≤ 1.5% | >1.5% | <1.5% | | <3% | <1 % |
| total moisture content (at delivery) | | | ≤ 10% | ≤ 10% | ≤ 12% | | | | |
| (lower) calorific value | ≥ 18.0 MJ/kg*) | ≥ 18.0 MJ/kg*) | ≥ 16.9MJ/kg ≥ 4.7 kWh/kg | ≥ 16.9MJ/kg 4.7 kWh/kg | ≥ 16.9MJ/kg 4.7 kWh/kg | 17.5 - 19.5 MJ/kg ***) | | | |
| sulphur | ≤ 0.04%* | ≤ 0.08%* | ≤ 0.08% | ≤ 0.08% | to be indicated | <0.08 | | | |
| nitrogen | ≤ 0.3%* | ≤ 0.6%* | | | | <0.3 | | | |
| chlorine | ≤ 0.02%* | ≤ 0.04%* | ≤ 0.03% | ≤ 0.03% | to be indicated | <0.03 | | | |
| arsenic | | | | | | <0.8 mg/kg | | | |
| cadmium | | | | | | <0.5 mg/kg | | | |
| chromium | | | | | | <8 mg/kg | | | |
| copper | | | | | | <5 mg/kg | | | |
| mercury | | | | | | <0.05 mg/kg | | | |
| lead | | | | | | <10 mg/kg | | | |
| zinc | | | | | | <100 mg/kg | | | |
| extractable organic halogens | | | | | | <3 mg/kg | | | |
| impurities | made only of un- contaminated wood | made only of un- contaminated bark | | | | | | | |
| binding agents | forbidden | forbidden | amount and sort has to be declared | | | | | | |
| ash melting point | | | initial temperature has to be declared | | | | | | |

Source: [s]

Generally limit values for bulk density, unit density, ash content, water content, calorific value, sulphur, nitrogen and chlorine are fairly similar [s]. The German standard defines a number of chemical parameters. With the exception of Sweden, all standards prohibit the use of binding agents. In Sweden if binding agents are used amount and sort have to be declared. Austrian and German standards do not mention the amount of fines, while in Sweden and the USA fines must not be more than 0.5 to 1.5%. The Austrian standard is currently being reviewed in this respect. The standards do not usually define durability or mechanical stability despite the importance of these attributes: during transport in tankers and the pneumatic filling of storage bunkers mechanical strain on pellets is high and pellets of bad quality produce large amounts of dust. Yet, the amount of fines in fuel pellets is of special importance in the case of small heating systems, which need extremely high pellet quality. If the amount of fines is too high, small heating systems will not work properly. Combustion units in large district heating systems are unaffected by fines. Because of the different requirements of small and large combustion units, a definition of different groups of standards regarding the percentage of fines might be useful [s].

The CEN (European Committee for Standardization) and national standardisation institutes are co-operating to prepare a European standard for biomass fuels. At present the working group is discussing the materials that may be used as biomass and whether only wood and agricultural biomass or also peat and household waste should be included.

Several conclusions can be drawn from the confronting of the above table and the table below (composition of wood and straw pellets). First, even wood pellets sometimes do not meet specific requirement. As far as straw pellets are concerned, most of the quality criteria are respected, with however two considerable exceptions. Indeed, straw pellets would experience difficulties to meet the requirements with regard to the chlorine and sulphur content. On the other hand, nitrogen



content is around the limit values (typically 0.5%). Obviously, the compliance with national regulations should be checked for each pellet batch, because of the large variability already mentioned of the product.

Table 46. Characteristics of wood pellets and straw pellets

| Parameter | Unit | Wood pellets (22 samples) | | | Straw pellets | |
|------------------|--------------------|---------------------------|------|-------|---------------|----------|
| | | Average | min | max | Sample 1 | Sample 2 |
| Diameter | mm | 7.1 | 5.9 | 10.2 | 8.1 | 8.2 |
| Length | mm | 16.1 | 8.6 | 29.6 | 16.6 | 12.3 |
| Bulk density | kg/m ³ | 591 | 520 | 640 | 660 | 540 |
| Particle density | kg/dm ³ | 1.18 | 1.03 | 1.30 | 1.09 | 0.95 |
| Water content | wt.% (wb) | 7.7 | 5.7 | 9.0 | 7.2 | 5.6 |
| Ash content | wt.% (db) | 0.51 | 0.17 | 1.61 | 5.97 | 4.82 |
| GCV | MJ/kg (db) | 20.3 | 19.8 | 20.7 | 18.6 | 19.0 |
| NCV | MJ/kg (db) | 19.0 | 18.6 | 19.4 | 17.4 | 17.7 |
| C | wt.% (db) | 50.3 | 49.5 | 51.9 | 46.1 | 47.2 |
| H | wt.% (db) | 5.7 | 5.5 | 6.1 | 5.4 | 5.7 |
| N | wt.% (db) | 0.22 | 0.20 | 0.64 | 0.55 | 0.53 |
| S | mg/kg (db) | 278 | 52 | 1922 | 745 | 788 |
| Cl | mg/kg (db) | 48 | 10 | 124 | 1158 | 1141 |
| K | mg/kg (db) | 493 | 302 | 1180 | 8680 | 7200 |
| Abrasion | wt.% (wb) | 4.05 | 0.58 | 12.53 | 2.37 | 19.89 |
| Starch content | wt.% (db) | 0.22 | 0.00 | 1.25 | - | - |
| Cd | mg/kg (db) | 0.14 | 0.06 | 0.20 | 0.11 | 0.06 |
| Pb | mg/kg (db) | 0.43 | 0.07 | 2.19 | 0.71 | 0.46 |
| Zn | mg/kg (db) | 13.2 | 9.3 | 25.4 | 10.0 | 6.0 |
| Cr | mg/kg (db) | 0.6 | 0.1 | 3.3 | 2.3 | 1.9 |
| Cu | mg/kg (db) | 1.1 | 0.7 | 2.7 | 2.8 | 2.2 |

Source: [i (k)]

To recap, pellet quality cannot be defined without reference to heating technology, since different heating systems require different fuel qualities. For large heating plants durability of pellets and amount of fines is less important, whereas for use in pellet stoves the pellets must be extremely durable so that they do not produce too much dust in the storage bunker and do not cause technical problems in the feeding and combustion unit. At least two groups of pellet standards should be defined for different combustion purposes (large-scale and small combustion units) [s].

Research priorities

For a small scale biomass use, reliable and cost effective combustion technologies with innovative reduction of atmospheric pollutants should be developed. As far as large-scale plants (>15-20 MW) are concerned, development should concentrate on combustion technologies capable of operating with multi-fuel resources, in particular the co-firing option.

Some national research perspectives

Austria has oriented its research schemes towards the study of aerosol emissions (formation, behaviour and emission reduction), a further development and demonstration of decentralised biomass CHP systems and a deeper study of the deposit formation and corrosion (especially relevant for steam boilers as well as for waste wood and herbaceous biomass fuels) [ah]. Specialists in Switzerland have also set out three research priorities covering, among other themes, the reduction of NO_x, particles, PCDD/F emissions (both with primary and secondary measures), the



improvement of biomass combustion efficiency and the utilisation of ash from biomass combustion [ah].

About co-combustion

Corrosion

Many biomass and waste fuels have constituents which can corrode boiler and combustor materials and which can influence fouling or slagging behaviour. There is as yet no comprehensive database of biomass/waste fuels and their properties in relation to their use with fossil fuels, particularly coal. For this reason each co-combustion project must assess the effects of potential fuels and fuel mixtures on the successful operation of proposed equipment. Each project may also have to back up these assessments with pilot or full scale trials. Overall, more detailed investigations covering different fuel types, fuel mixtures, combustor types and combustion conditions are needed. Where results appear promising long term tests are desirable. The number of tests and investigations, and therefore overall costs, could be limited by a market study to identify the most likely types of boiler/combustor, based on numbers in operation, age of installation and likelihood of successful co-combustion [am].

Emissions

No increase in the concentrations of hazardous gaseous compounds was found in the flue gases from a number of new, retrofitted and trial installations during a range of co-combustion trials. In many cases substantial reductions in emissions were found which were due to biofuel composition, biofuel properties and on the biofuel injection mode. This favourable effect of co-combustion of biofuels was particularly obvious for NO_x emissions and it is possible that further improvements could be secured from further work in this area and further investigations in this area are recommended. Detailed pollutant formation and reduction mechanisms should be intensively investigated for biomass and waste fuels and this could be based on further investigation of their combustion, pollutant formation and slagging behaviour. Moreover, the influence of biofuel co-combustion on the operability of retro-fitted power plant needs further investigation. The effect on burnout and pollutant behaviour of special fuel preparation and combustion techniques, such as air splitting, additives, fuel preparation, and fuel mixture variations should also be investigated [am].

Ash utilisation

The requirements of the whole range of ash uses should be investigated to determine any beneficial or adverse consequences of co-combustion and to provide information for the guidance of project developers. The slagging behaviour of the ash may also affect the physical form in which the ash is retrieved from the combustor which may also affect its final use or any pre-treatment to increase its value. The whole area of slagging behaviour therefore needs further investigation. To determine the leaching behaviour of ashes, where disposal is the favoured option, will also involve a considerable amount of work [am].

Fuel preparation

Preparing, handling and feeding of biomass and waste fuels can be difficult and expensive, both in terms of capital and operating costs. Much of the equipment used in trials and installations to date was originally developed for other purposes and is not ideally suited for the purpose. Substantial engineering development is required directed at preparation of these materials for use as fuels. Furthermore, alternative fuel feeding arrangements for the combustor should be investigated, with the objective of minimising the need for expensive pre-treatment whilst maintaining or maximising environmental benefits [am].



Other critical factors

Agri-pellets prices to the consumer compared with other fuels

Wood pellet market assessment show that there are several conditions for the launching of a new prosperous market: information, co-operation and, last but not least, the cost factor. In many cases, it is the key factor determining the increase or decrease in the use of a determined product. That is the reason why one has to examine very closely all the costs related to a new raw material supply.

Raw material price analysis

It should be noted that the geographic dispersion of the farms increases the collection and transportation costs of residues. Moreover, if other residues than straw were considered for densification, collection costs might be important due to the lack of commercial harvesting machinery for certain residue types. An assessment of the total energetic cost shows that the energetic valorisation of the agricultural (and forestry) residues should concern in priority products easily available, i.e. in a sufficiently quantity and that has no need of being collected, nor transported, and that can be easily dried before the pelleting process. Otherwise, the relative energetic costs related to their utilisation would be too important compared to the total derived energetic benefit [d].

Some studies show that the largest part of the production costs per ton of pellets in both Sweden and Austria are raw material costs (in both countries, the second biggest part of the production costs/t pellets is the raw material drying cost). The investment costs constitute 19 % of the production costs/t pellets in the Swedish factory and 12 % in the Austrian factory [a]. Some indicative figures can be given: the mean biomass procurement costs are close to 40 €/ton in Spain ([q], p.299), 62 €/ton in Denmark and ranging from 45 to 55 €/t in Sweden ([o], p.63)

As far as cereal straw is concerned, we can say that in a general way, the amounts produced per hectare vary with species, variety and local natural conditions (soil and climate). For almost all cereals, genetic selection has deeply changed the grain/straw ratio, without affecting the global biomass production per hectare. In northern Europe, at the beginning of the century, for a total biomass production of 10 t/ha, there would grow 4 tons of grain and 6 of straw. Currently, for a same global production, there are 6 tons of grain and 4 of straw. The situation is comparable as far as rice is concerned: new varieties with high potential yield present a grain/straw ration far more important.

In Denmark, with demands by the large electrical power producers steadily increasing over the recent year due to the Biomass Agreement, the market has been characterised by a certain increase in prices. Thus the cost price is not only an expression of the cost of producing the straw and the profit, but it is also part of the parties' strategy in respect of performing the Biomass Agreement. Consequently, price fluctuations in the range of DKK 360 to DKK 500 (48-68 €) per tonne are seen. In 1997, the "span in price" between the producers of straw and the power plants' purchasers of straw was above DKK 80 per tonne, i.e. DKK 466 and DKK 380 (63 and 51 €) respectively. Tenders for straw were invited by district heating plants east of the Great Belt in 1997 and 1998 with a tender result of DKK 350- 400/tonne (47-54 €/tonne) delivered to the plant. West of the Great Belt, the straw price according to the most recent crop delivery contracts for straw has been in the range of DKK 320-370/ tonne (43-50 €/tonne) also delivered to the plant [aa]. In France, current straw prices can be considered around 25-35 €/tonne. Of course those prices are also very variables, and the episode of the last summer's drought illustrate it perfectly. Cattle breeders needed large



amounts of straw to feed their animals, and a national action oriented the straw stocks to the farmers in need. In those conditions, available amounts of straw for energy purpose sharply decrease.

Towards a reduction of raw material costs?

With the progressive and local shortage of woody raw materials, some large companies affirm that the cost savings gained by increasing the production are often offset by the increased cost of obtaining far further the raw material required to support their production [s]. This statement concerns woody raw material but can absolutely be extended to the case of straw.

A solution could be to carry the production tool to the raw material. A few mobile pelletising mills already exist (Cf. http://www.pelletpress.com/pdf/info-blad_pp300_eng.pdf), but they are not very numerous. For instance, the PP300 Kompakt is a Swedish pellet press, of 30 kW power, produces 8 mm wood pellets with a capacity of 250-350 kg per hour. The whole machine unit is built as a frame construction (2x2 meters) and consists of a matrix and two feeder wheels mounted on a driving fork. The press is accompanied by a 7.5 kW grinder which treats material larger than 3mm. Such a press can meet a specific demand, for instance several farmers wanting to share the investment cost of a pelleting equipment which after can be moved from a place to another. At the moment, some drawbacks exist. First, the productivity is generally low compared to the industrial mills (4-6 t/h). A north-american pelleting mobile unit for agricultural residues of 2-5 t/hour would exist, but we could not check this information. Secondly, the raw material used must be free from contaminants such as stone and metal, which would be a problem with agricultural residues, generally "contaminated" by stones, sand etc. There are generally no cascade mixer for the conditioning.

In the summer of 2001, REAP was expecting to work with a mobile pelleting unit to assess direct, on-farm pelleting technology (<http://www.gks.com/efao/newsletter/EFAOspring2001.html>). In any case, the possibility of a decentralized production of pellet would reduce, from the field, the transportation cost to the combustion plant.

Fuel-prices analysis

As straw pellet market has not developed yet, it is quite difficult to find prices. However, other fuel prices are laid down in the table below to allow a comparison with the straw pellets prices each will be able to gather.

Table 47. A comparison of prices for different fuels in 2003 (prices in €/MW)

| Fuel price including energy taxes and VAT 2003 | Austria | Belgium | Denmark | Finland | France | Germany | Ireland | Italy | Portugal | Spain | Sweden | United Kingdom |
|--|---------|---------|---------|---------|--------|---------|---------|-------|----------|-------|--------|----------------|
| Light fuel oil | 41 | 30 | 78 | 38 | 29 | 40 | 38 | 88 | 26 | 42 | 65 | 27 |
| Heavy fuel oil | | 21 | 52 | 21 | 22 | | 34 | 72 | | 24 | 56 | |
| Natural gas | 54 | 52 | 73 | 20 | 38 | 50 | 40 | 19 | 31 | 49 | 58 | 23 |
| Coal | 32 | | 57 | 13 | 18 | | 30 | | | | 40 | 38 |
| Wood pellets – large scale | - | 30 | 27 | 19 | 29 | 30 | - | 37 | | | 21 | |
| Wood pellets – domestic user | 39 | 50 | 51 | 32 | 53 | 36 | - | 48 | 49 | 44 | 42 | 33 |
| Straw | | | | | 9 | | | | | | | |
| Straw pellets | - | - | - | - | - | - | - | - | - | - | - | - |

Light fuel oil and natural gas prices appear calculated with VAT related to domestic use.

Heavy fuel oil and coal prices appear calculated with VAT related to industrial use.

"-" : no available

Sources: EUBIONET Fuel prices in Europe 2002/2003



The procurement-related advantage of straw on wood chips

A study performed a life cycle assessments on the pre-combustion life of fuels (Straw, wood chips, Danish wood pellets, coal and natural gas). The study was based on actual conditions regarding extraction, farming, cultivation, transportation, and machinery etc. for Danish fuels [q (m)]. The results are that coal and oil are the most energy consuming fuels, when it comes to the procurement. Straw consumes 42% of the energy needed for coal per GJ, wood chips 49% and wood pellets 54% if they are produced in Denmark. Results from the life cycle analysis show that when it comes to greenhouse gas, NOx and SO2 emissions coal is the most emitting energy resource. Both straw and wood chips procurement emits 22% of the quantity of greenhouse gas which are emitted per GJ coal. Wood pellets are emitting 33% and 40% for Danish produced and imported respectively. Similar tendencies have been discovered when it comes to the NOx and the SO2 emissions.

Table 48. Energy consumption and emissions linked to the procurement of several fuels

| | Energy consumption | | CO ₂ emissions | | NOx emissions | | SOx emissions | |
|-------------------------|--------------------|-----------|---------------------------|-----------|---------------|-----------|---------------|-----------|
| | Percent | Rel. coal | kg/GJ | Rel. coal | g/GJ | Rel. coal | g/GJ | Rel. coal |
| Coal | 6.7 | 100 | 11.1 | 100 | 58.4 | 100 | 29.2 | 100 |
| Natural gas | 5.8 | 87 | 3.3 | 30 | 14.0 | 24 | 0.0 | 0 |
| Wood chips | 3.3 | 49 | 2.4 | 22 | 32.1 | 55 | 0.8 | 3 |
| Wood pellets (national) | 3.6 | 54 | 3.7 | 33 | 18.5 | 32 | 0.4 | 2 |
| Straw | 2.8 | 42 | 2.4 | 22 | 24.9 | 43 | 0.7 | 3 |

Percentages are related to the lower heating value

Source: [q(m)]

To fully compare straw pellets to wood pellets procurement costs in terms of environmental impact, it would be necessary to add the pelletising impact related to straw pelleting. If we consider that it is comparable to the one of wood pelleting, straw pellets total procurement energy consumption would reach $2.8 + (3.6 - 3.3) = 3.1$, which is inferior to the energy related to wood pellets. Without even taking into account this adjustment, NOx and SOx emissions for straw procurement are already higher than for wood pellets procurements. Therefore, this study suggest that straw pellets procurement would trigger higher environmental impacts than wood pellets procurement.

The advantageous alternative of direct straw-firing when building a new plant

Today, many direct straw-fired plants are built, preferably to straw pellets one for economical reason. Actually, considering the operation costs, it is much more beneficial to run with straw bales than with pelletised straw. Put in other words, the transportation costs of the straw bales remains far lower than the cost of pelletising. With this in mind, the main possibilities for straw pellet development lay in the conversion of ancient energy plants, as it is illustrated by the Amager example in Denmark.

Depending on the local conditions it could be interesting to evaluate the mean transportation distance above which the pelletising cost could paid for. However, in a country applying a decentralised energy policy, which implies a geographically balanced distribution of the energy plants, it can be assumed that there will always be locally sufficient straw resources and that transportation costs will not pass the pelletising cost. These considerations invite once again to suppose that the real and current market niche for straw pellets corresponds to the conversion of existing energy plants.

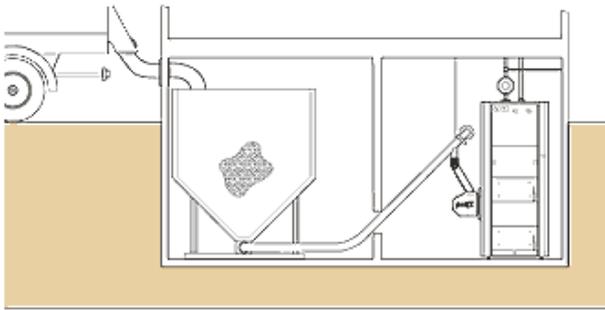


Logistics related problems

The logistics of wood pellets (and therefore agri pellets) – distribution, transport and delivery and to some extent storage of pellets at customers' home – is one of the most sensitive areas in the marketing of wood pellets at the moment. Areas where improvements could be made include costs, quality and customer convenience [s].

Delivery system

By their form, pellets are a pourable fuel which can be transported just like a liquid, such as oil: pellets can be supplied by tank lorry and pumped into the pellet tank by means of a fuel hose. Then, from the fuel tank, they can be automatically fed to a combustion unit by screw or piston charging [s]. Precautions have to be taken against dust production and crushing of pellets during filling procedure.



Source: *pellx.nu*

Straw pellets are more friable and thus produce more fines. An increased amount of fines often causes failure of the feeding systems used in the residential heating sector. An increased amount of dust in the air also rises the risk of dust explosion. To a greater extent than for wood, delivery problems are a challenge to the use of more friable pellets such as the ones made from straw without binding agent.

Storage

Storage in closed rooms and silos is the most common, and pellets are seldom stored outdoors under fly roofs. Pellets should be stored in closed halls or silos so as to protect against moisture and maintain quality. Precautions should be taken against mixing pellets with other stored wood fuel (wood chips). If (even very few) wood chips are mixed with pellets severe problems may be experienced during pneumatic filling, conveying and combustion.

Supplying

Agri-pellets could take advantage of the existing and growing distribution system related to wood pellets. Fuel is normally supplied by specialist suppliers (nowadays mostly dealing with fossil fuels) or feed retailers, most of which are small businesses. For a nationwide distribution system to be established, these businesses need to be motivated, involved and trained to handle pellets.

Weighing of the bulk delivered quantity

Several weighing systems are used to monitor the amount of pellets sold. The most common system is to weigh the tanker on a weighbridge before and after filling of the tank chambers. This is time-consuming and customers do not have direct control over amount of pellets they have bought. A better system is an on-board weighing system installed in the tanker that immediately measures the



amount of loaded or unloaded pellets. The problem is that investment costs for this system are higher.

The emergence of dedicated biomass fuels

Locally, other agricultural residues than straw could be utilised. For example, a study underlines that olive tree pruning can be considered a good material to be used as a fuel in fluidised bed combustion processes, due to the physic-chemical characteristics of this biomass (low alkali and chlorine content and high volatiles content) [q (d)].

Secondary forestry residues

When using secondary forestry residues as raw material for densified biofuel production, the problem of contamination with soil particles arises. These ground particles could lead to a more intensive wear of the densification equipment, and even breakdowns. Hence, processing recycled wood to densified bio-fuels involves costs and problems with contaminations, and this will be the case until a cost efficient technology to clean the recycled wood is found, or to guarantee its cleanliness in some other way.

Energy crops

Recent advances in biomass feedstock development and conversion technologies have created new opportunities for using agricultural land as a means of producing renewable fuels from energy crops, and allowing not to relying on wood and agricultural residues alone.

To qualify as a convenient biofuel, levels of alkali and chlorine have to be low and the general chemical composition has to be stable from batch to batch on delivery. In reality, the biofuels available present a wide diversity in water content, chlorine and alkali levels, ash residue, ash melting point and prices. Straw can be quite aggressive in chemical composition, with high levels of alkali and Cl, which are bound to give corrosion problems in the hot furnace. To ensure a steady flow of the necessary amount of biomass with suitable fuel characteristics, research projects have been engaged to bring forth energy crops with low levels of corrosive components. Salix, Miscanthus and grain have been tested to identify the most suitable crops and processes for biofuel power production [l].

Since the mid-1980's there has been increasing interest in the use of perennial grasses as energy crops. In the US, from 18 perennial grasses, it was evaluated that switchgrass (*Panicum virgatum*) was the native perennial grass which showed the greatest potential. From about 20 perennial grasses tested in Europe, four were chosen for more extensive research programmes, namely switchgrass, miscanthus (*Miscanthus spp.* also known as elephant grass), reed canarygrass (*Phalaris arundinacea*) and giant reed (*Arundo donax*) [q (g)]. Those herbaceous energy crops are perennials that are harvested annually after taking two to three years to reach full productivity

Today, coppiced wood species, eg willow and poplar, are the most widely used energy crops. Other crops such as grasses that may have higher yields, especially in the more southern EU Member States, are being developed. Energy crops are important to the long-term strategy of the EU because they are the only biomass fuel that can be expanded sufficiently to significantly shift the pattern of EU energy supply.

Regarding the set-aside policy of the European Community the production of solid fuels on arable land could be of interest. Energy grain (whole crops) like triticale could be harvested with a well



known production chain. First trials showed that whole crop bales can be used in straw fired district heating systems to produce heat. The combustion properties of energy grain whole crop bales are similar to those of straw. As the whole crop is harvested, the energy yield per hectare is doubled. The higher density of the grain is responsible for the higher density of whole crop bales. This could reduce the specific costs of the combustion unit. However, kernels need more time for a complete combustion than straw and the nitrogen, chlorine and potassium content are different; The high nitrogen content will result in a higher NO_x emission. The reduction of the content of ash, chlorine, potassium and nitrogen could be aimed at by agricultural measures. A research on the environmental compatibility of such a combustion was carried out (*Austria Energetic use of cereal whole crop*, <http://www.eeci.net/>) The most important results is that a NO_x emission reduction required. The heavy-metal concentration in winter-wheat straw and triticale was found to be significantly lower than that in bark and wood chips. The nitrogen content of cereal was 1.6 times higher than the values obtained for straw, which indicates that the use of cereal as a fuel requires primary measures for NO_x-reduction. Special emphasis has to be put on combustion technology and plant control. As could be shown, the chlorine content favours corrosion in the boiler, which indicates the necessity of precautionary measures. Emission peaks of CO resulting from full-load operation and rapid changes of load should also be reduced by an improved process control system. Furthermore, it seems that economic conditions are not favourable.

High concentrations of chlorine, potassium and nitrogen in cereals have negative implications for their use as solid fuels. Most relevant recommendations which were elaborated for a quality management system are (i) the renouncement of KCl fertiliser application directly before and during growing year, (ii) the avoidance of strobilurine group fungicide application, (iii) the performance of a late harvest at dead ripeness or later, (iv) the selection of strains with low K and Cl concentrations and (v) an adapted N fertilisation focussing on high grain yields but low protein contents. [q (h)]



Conclusions

The agricultural sector can represent a valuable source of dry biomass, possibly available for fuel valorisation. The importance of this source varies greatly from a region to another, and the amount of residues depends on several factors: crops varieties, cultivation mode, local soil and climate conditions, geographical dispersion, access possibilities, etc. Therefore the first challenge would be to study the quality and real availability of the residues and also to examine the economic feasibility for collecting them (as the raw material cost will influence the pellet price and hence the development of the market).

Concerning straw pellet production, only a limited experience has been acquired until now. Yet, processes seem quite well controlled. The main critical factors regard the supply of quality raw material (without many contaminants) the friability of the final product.

In comparison with wood, agricultural residues present high ash-, N-, K- and Cl-content. Consequent problems are higher related emissions, deposit formation (slagging and fouling) and corrosion. Many techniques are currently used and under improvement stage to overcome the inherent drawbacks of straw composition. Those technique may consist in diverse action level: agricultural practices, fuel preparation, combustion technologies (grate, fluidised bed and pulverised fuel systems), flue gas cleaning systems and the advantageous possibility of co-combustion of straw pellets with coal for instance. For technological and economical reasons, some of these techniques are also available in large scale plants, and that is why the use of straw pellets is currently more developed in that field. Standards for wood pellets are currently under development at the CEN, but a special standard for straw could be foreseen in connection with its particularly high content in N, Cl and S and the specific use it would best suit (i.e. mainly large scale converted energy plants).

In any case, the use of straw pellets in the residential heating sector cannot be fully recommended at present, because small-scale pellet furnaces are not specially designed for this kind of fuel. From that point of view, only an increased R&D effort could contribute to the development of the agri-pellet market. Meanwhile, the most reasonable hypothesis concerning pellets use is that wood pellets (with low mineral content) and would suit best a combustion in small heating devices, whereas agri-pellets (with high mineral content and slagging tendency) would best fit in large combustion plants with flue gas purification and possibilities for returning the ash to the forest.

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INDEBIF: <http://www.pellets2002.com/index.htm>

"An integrated European market for densified biomass fuels". ALTENER project under EU, whose purpose is to expand knowledge about densified biomass fuels and to establish a European network for these. Among others, the project identifies producers of densified biomass fuels and seeks knowledge on production, distribution, use and markets. A database of wood pellet manufacturers in Europe is included.

EUBIONET: <http://eubionet.vtt.fi/>

European bioenergy networks. AFBnet (Solid biofuels), Waste for Energy (Biogas) and NTB (Liquid biofuels) were established in 1995 by the European Commission to promote the utilisation of bioenergy in Europe. These networks have been integrated together under the cluster EUBIONET (European bioenergy networks) at the beginning of the year 2002. The EUBIONET will continue and consolidate the systems of communication, which have been set up since the creation of the networks. The major aim is to share knowledge and experience, spread of information, transfer of knowledge and know-how in the bioenergy sector. Besides that, also to detect barriers and define strategies to overcome them and to promote contacts between operators, planners and public organisations at all levels. Activities include events, publications, meetings, study tours and contacts to key bioenergy organisations in Europe.

OPET Network: <http://www.opet-network.net/default.htm>

The Organisations for the Promotion of Energy Technologies -OPET Network- is an initiative of the European Commission that aims to promote public awareness of current energy research through a new and challenging series of activities. These activities are intended to further the deployment of innovative technologies and increase the pace of market uptake in respect of research that supports European Energy Policy priorities. By disseminating information about new developments in the European Research Area, they provide an integrated and comprehensive view of on-going research in various areas of work.

OPET Finland: <http://www.tekes.fi/opet/eaenglish.htm>

List of the wood market actors in Sweden: http://www.tekes.fi/opet/pdf/Wood_actors_SWE.pdf

Market actors in Sweden: http://www.aster.it/opet/doc/mactors_sweden.pdf

OPET Aster (Italy): <http://www.aster.it/opet/> (with many links)

OPET SEED - Italian pellet success stories and more: <http://www.aster.it/opet/biomasse.htm>

REAP: <http://www.reap-canada.com/servres.htm>

Resource Efficient Agriculture Production (R.E.A.P.) is a Canadian non-profit organisation dealing with food, fuel and fibre. The web site contains a database of reports, some of which mention wood pellets. This web site is in English and French.

PFI: <http://www.pelletheat.org/>

The Pellet Fuels Institute is a trade association located in Arlington, Virginia, USA. The Pellet Fuels Institute's mission is to be a trade association which represents the fuel preparation and clean burning technology of renewable bio-mass energy resources. The Institute is dedicated to the advancement and promotion of the fibre and densified (pellets) fuel technology that will help solve global ecological problems through the utilization of locally renewable energy sources. The organization exists to (1) Create and represent the ultimate expertise in the residential and commercial (fibre and pelletised) fuel industry and technology; (2) Coordinate and integrate the needs of raw material sources, pellet equipment suppliers and consultants, fuel producers, appliance manufacturers, and distribution entities; (3) Educate, disseminate and promote the ecological, economical, and environmental advantages and benefits of fibre fuel technology; (4) Establish and maintain densified fuel standards; and (5) Provide information and technical support to facilitate the safety, efficiency, emission standards and test procedures specifically designed for densified fuel technology.

COMBUSTION.NET: <http://www.combustion-net.com/>

Canada's clean combustion network. In 1996, government and industry joined to establish Canada's Clean Combustion Network. Natural Resources Canada, Industry Canada, the National Research Council, and Environment Canada agreed to participate in and support the Network in its early stages. The network's formal objectives are: (1) To identify national and international technological development and business opportunities. (2) To establish a national network of expertise and information on stationary combustion and environmental controls. (3) To promote partnerships and collaboration among industry, academe and governments to form the best



alliances for development and commercialisation of individual technologies. (4) To create a sound foundation for formulating a national combustion R&D strategy. (5) To promote Canadian and Network members' R&D capabilities. (6) To foster public and private sharing of specialized combustion R&D facilities.

Special web site dedicated to pellet fuels: http://www.combustion-net.com/pellet_fuels/index.htm

WPME: <http://home.worldonline.dk/imuy/woodpellets/index.htm>:

Wood pellets manufacturers in Europe. Personal web site providing a listing of all the wood pellet manufacturers which currently exist in Europe

O.Oe. Energiesparverband: http://www.esv.or.at/index_e.htm

The O.Ö. Energiesparverband is a regional energy (located in Linz, Austria) agency organized as a non-profit association with 31 members including energy suppliers, energy consultancies, environmental groups, professional associations and firms involved in energy technology and the Upper Austrian government. The O.Ö. Energiesparverband works to promote energy efficiency and the use of renewable energy sources and new energy technologies. The agency's main objective is to help energy consumers use energy more efficiently, thereby reducing the environmental load.

EECI: <http://www.eeci.net/>

European Energy Crops InterNetwork. The information on the EECI-Network is provided by 19 well-known institutes, representing 14 EU countries, involved in research, development and implementation activities of energy crops. New contributions on the latest developments on the production, pre-treatment and utilization of energy crops are published on a regular basis.

REPP: http://solstice.crest.org/articles/static/1/1010424940_6.html

REPP's goal is to accelerate the use of renewable energy by providing credible information, insightful policy analysis, and innovative strategies amid changing energy markets and mounting environmental needs by researching, publishing, and disseminating information, creating policy tools, and hosting highly active, on-line, renewable energy discussion groups.

IEA: <http://www.ieabioenergy-task32.com/overview/environment.html>

Within the IEA Bioenergy agreement, Task 32: Biomass Combustion and Co-firing works on further expansion of the use of biomass combustion for heat and power generation, with special emphasis on small and medium scale CHP plants and co-firing biomass with coal in traditional coal-fired boilers. This is done by generating and disseminating information on technical and on non-technical barriers and anticipated solutions. Database at <http://www.ieabcc.nl/>