



## **04-02: Properties influencing the use of herbaceous biomass for energy**

Compared to the utilization of woody biomass resources, the utilization of herbaceous biomass in energy applications has been rather limited so far. Surprisingly, this does not mean that potential biomass sources such as agricultural residues are not combusted – actually, a large quantity of them is burnt after the harvesting period in the field. This practice represents a source of uncontrolled emissions without any sort of energetic utilization and can also be a potential fire hazard. In addition, herbaceous biomass is being used as a fuel for heating, cooking or other applications in several third world countries, where access to other fuel sources is scarce, although the overall conversion efficiency of such process is generally low.

The answer to the question of why the utilization of herbaceous biomass in Europe, as well as the rest of the world, has generally lagged behind that of other biomass sources can be split in the following three reasons:

- Some herbaceous residues, such as straw, are already part of standard agricultural practices, such as animal feeding. This is discussed in the chapter 02-02 on herbaceous biomass resources.
- In general, the supply chain of herbaceous biomass faces several challenges: low energy density, seasonal variations, susceptibility to biodegradation, etc. These issues are discussed mostly on the chapter 03-02 on the herbaceous biomass supply chains.
- Finally, herbaceous biomass resources have been considered as a more problematic fuel compared to woody biomass due to certain compounds which influence their combustion behaviour. The nature of these compounds and their exact influence on the different energy utilization pathways is exactly the subject of the present chapter.

Despite the shortcomings mentioned above, there are several successful examples of the utilization of herbaceous biomass resources for energy production. For example, one of the most well-known cases is the utilization of straw in Denmark for power production or district heating networks. In addition, increasing the share of bioenergy produced from herbaceous biomass resources, such as agricultural residues and certain types of energy crops, is an important RES target for EU, as has been described in Chapter 02-02.



As discussed in Chapter 04-00, the main processes that can be used from the production of useful energy from any type of biomass, including herbaceous biomass, are the following:

Three different thermal process routes

- Combustion for direct generation of heat and electricity in CHP-plants or co-firing in industrial processes,
- Thermal gasification for subsequent combustion of the gas (“product gas”) in CHP-plants, in industrial processes, or for further chemical processing of the product gas
- Pyrolysis for subsequent combustion of the solid, liquid and/or gaseous product fuel in CHP-plants, in industrial processes or further chemical processing of the pyrolysis product  
The pyrolysis can be high-temperature (about 700 °C) or low-temperature (about 300 °C, “torrefaction”), yielding different ratios of solid residue (“char”), liquid residue (“pyrolysis oil”) and gaseous residue (“pyrolysis gas”)

Two different biochemical process routes

- Fermentation for subsequent combustion of the liquid fuel (alcohol, mainly ethanol) in IC-engines or as an additional fuel in CHP-plants, in industrial processes or as raw material for subsequent synthesis to a new product
- Anaerobic digestion for subsequent combustion of the gas (“biogas”) in IC-engines or as an additional fuel in CHP-plants, in industrial processes or as raw material for subsequent synthesis to a new product

In order to choose the appropriate process technology for the resource, it is important for bioenergy system planners to have a good understanding of the characteristics which differentiate herbaceous resources from other biomass types as well as of the key considerations when using herbaceous biomass in different energy conversion technologies.

### **04-02-01: Overview of herbaceous biomass fuel and ash process properties**

Being a product of the photosynthetic process, as discussed in Chapter 01-00, the dry matter content of herbaceous biomass resources is also typically composed of carbohydrate polymers (cellulose and hemicellulose), phenolic polymers (lignin) and, in lesser quantities, other substances, such as resins, fats and fatty acids, commonly known as extractives.

One key difference of herbaceous biomass over woody biomass is the lower weight percentage of lignin and the increased presence of cellulose and hemicelluloses. Typical reported values are presented in Table 04-02 1. As is evident from the table, the lignin content of herbaceous resources typically ranges from 15% to a little over 20%. Since lignin is less oxidized than hemicelluloses, it has a higher heating value and this typically translates to lower heating values of herbaceous biomass resources compared to woody biomass or some agro-industrial residues, such as olive press cakes. The lower lignin content also affects in some part the combustion speed and, in biochemical processes, the amount of organic matter that can be transformed to the final product (lignin is typically not digested/fermented



but remains in the solid residue, while cellulose and especially hemicelluloses are more easily converted to sugars).

Biomass type	Composition (% wt daf)		
	Hemicelluloses	Cellulose	Lignin
Tobacco leaf	41.5	43.5	15.0
Corn stover	31.3	45.8	22.9
Miscanthus	27.9	50.0	22.1
Switchgrass	33.6	43.9	22.5
Wheat straw	45.2	33.8	21.0
Hardwood	32.3	45.9	21.9
Softwood	24.8	42.7	32.5
Hazelnut shell	30.3	26.7	43.0
Olive cake	21.6	23.1	55.3

**Table 04-02 1:** Cellulose, hemicelluloses and lignin content of several biomass types. The composition is given in dry, ash and extractive free basis.

In thermal processes, the *proximate analysis* and the *elemental analysis* are more typical and useful indications of a biomass's impact. See the **Fuel Analysis Appendix** for more information on these analyses and their impact on combustion conditions. Some more specific considerations on herbaceous biomass fuels are presented below.

As discussed in Chapter 03-02, the moisture content of most agricultural residues is quite low – for straw type fuels typical values indicated in the literature are below 15% wt. Other residues though, such as bagasse has a much higher moisture content, up to 40 – 60% wt and can be very problematic in combustion applications. The moisture content is obviously affected by the weather conditions (for those residues collected or stored in the field) or process conditions (for agro-industrial residues).

Based on the above, the most common herbaceous biomass types are suitable for combustion, at least from a moisture point of view. High moisture residues, such as sugar beet residues, would require either extensive drying before combustion or would be better utilized in biochemical conversion processes.

As is common with most biomass types, herbaceous biomass has a higher volatile content than coals. Herbaceous biomass also tends to have slightly higher volatile content compared to woody biomass or certain agro-industrial residues; a general trend would be that the lower the lignin content, the higher the volatiles a biomass has.

The low moisture content of most herbaceous residues ensures that devolatilization starts almost immediately after the fuel is brought in contact with a high temperature medium. The high volatile content of herbaceous biomass also ensures rapid release of the most of combustible matter into the gas phase.



Thus, a proper design of the combustion chamber is required in order to provide sufficient residence time for the complete combustion of volatile gases. It should also be noted that the ready release of volatiles from herbaceous biomass may pose some safety issues during its handling – release ignition of the volatiles can be easy if the biomass is brought into contact with hot surfaces or its temperature increases to high enough levels outside the combustion chamber.

However, despite the favourable conditions of the low moisture and high volatile content, it is the chlorine and ash content which poses the most significant issues in thermal processes involving herbaceous biomass. The problems are not due to ash quantity (although herbaceous biomass tends to have higher ash content than woody biomass) but of quality.

The quality issues relate mostly to the high concentrations of elements such as alkalis and silica in the herbaceous biomass ash, along with the chlorine content of the fuel. These elements tend to form highly volatile and/or easily melted compounds that affect either certain emissions (e.g. aerosols) or produce operational problems, commonly known as slagging/fouling and corrosion. These issues are discussed in detail in the [Ash Appendix](#). Agglomeration is a specific process issue for fluidized beds and is also due to the low melting temperature of certain biomass ashes; it is discussed in section 04-02-02a.

Regarding the *elemental or ultimate analysis* (see the [Fuel Analysis Appendix](#) for more details), the following key points may be stressed for herbaceous biomass:

- The *Carbon (C)* content tends to be lower than woody biomass due to the lower lignin content of the plants. This leads to lower heating values on a dry, ash free basis.
- *Nitrogen (N)* tends to be present in herbaceous biomass in higher concentrations than woody biomass due to the higher growth rate and the application of N-fertilizers in the field. As a result, NO<sub>x</sub> emissions from the combustion of herbaceous biomass can be higher than those of woody biomass under similar combustion conditions.
- Likewise, *Sulphur (S)* is present in higher amounts in herbaceous biomass than woody biomass and may lead to higher SO<sub>x</sub> emissions or certain operational issues, such as corrosion or syngas cleaning issues in gasification applications.
- *Chlorine (Cl)* is the most important differentiation between herbaceous biomass and woody biomass. Herbaceous biomass species have a chlorine content ranging from less than 0.1% to 2% or more. Thus, increased emissions (such as dioxins and aerosols) as well as operational issues may be expected during the combustion of herbaceous biomass.

Overall, in terms of heating values, the lower lignin/carbon content of herbaceous biomass also means lower HHVs compared to woody biomass fuels. In addition, the higher ash content also contributes to lowering the heating value obtained per kg of fuel. On a dry basis, herbaceous biomass fuels have a range of high heating values between 17 – 19 MJ/kg on a dry basis, while the lower heating value on as received basis is usually between 14 – 16 MJ/kg for straw type fuels. The low moisture content means that the difference between the LHV and the HHV is not as high as in the case of woody biomass.



## **04-02-02: Herbaceous biomass in medium to large scale combustion applications**

### **04-02-02a: Dedicated combustion of herbaceous biomass**

Medium to large scale combustion systems can be used for the production of heat (e.g. process heat, heat for district heating networks), electricity and/or both. The thermal capacities of such systems for herbaceous biomass fuels range from a couple of mega-watts to 50 MW or (in rare cases) more.

Generally, the combustion of herbaceous biomass fuels in such applications is subject to the issues discussed in the **Ash Annex** regarding fouling and corrosion as well as certain environmental issues (discussed in the **Fuel behaviour Appendix**). As a result, a common practice is to feed a boiler operating with dry biomass fuels with a mixture of dry woody biomass (the majority) and a smaller percentage of herbaceous biomass. However, there are also several examples of dedicated boilers for herbaceous biomass fuels. Straw is the most common fuel employed in these systems and the leaders in the related boiler technology are Danish companies.

For power plants operating with herbaceous biomass, the harmful effects of corrosive substances are typically limited by operating the plant at lower steam temperatures compared to coal or woody biomass fired plants; thus such plants exhibit lower efficiencies, as explained in Section 04-00-08f.

There are three main types of technologies that can be used in medium-to-large scale combustion applications (arranged from larger to smaller particle size): fixed beds, fluidized beds and pulverized fuel units.

**Fixed bed systems** are the most widespread technology for dedicated herbaceous biomass combustion units. They are well-suited to all kinds of “problematic” fuels, e.g. high moisture, high ash and with large particle size. Combustion in this type of plant usually takes place on a grate located at the bottom of the boiler.

The biomass fuel is shredded before introduction to the boiler; the biomass shall not be completely pulverized in such a system. Upon entering the combustion chamber, the fuel is essentially undergoing gasification on the grate; the hot flue gases are combusted in the upper levels of the combustion chamber, while the remaining char is combusted on the grate and most of the residual ash is collected at the lower end of the grate. Some part of the ash is transported with the flue gases and must be collected by appropriate cleaning systems, such as electrostatic precipitators. Actually, since the majority of the fuel’s mass and energy is released as volatile gases, the proper design of the upper combustion chamber is essential in order to ensure appropriate mixing with air and sufficient residence times.

The movement of the biomass fuels on the grate can be either due to gravity alone (fixed grates) or by applying some sort of movement of the grate, hence the different technology types: vibrating, moving travelling or rotating grates.

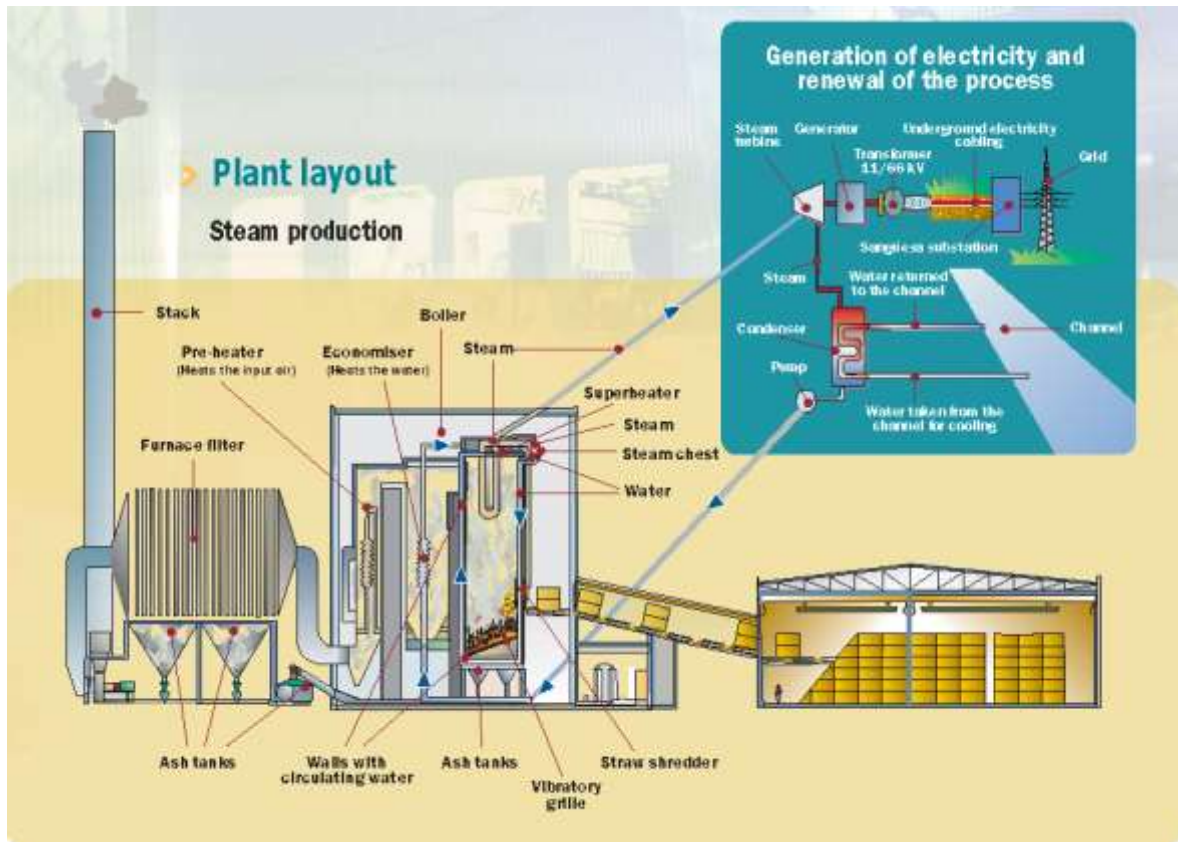


Fixed grates are the simplest and least expensive option but the one with the least control over the combustion conditions; in addition, they are more vulnerable to problems related to molten ash particles.

Vibrating grates are very common with low ash melting temperature fuels, such as straw, since the constant vibration does not allow for the formation of large molten ash agglomerates. However, vibrations also lead to more ash particles in the flue gas, so more extensive measures for flue gas cleaning may be needed. A straw-fired power plant with a vibrating grate can be seen in Figure 04-02 2.

A variation of the grate-fired systems is the use of a “cigar burner”. This burner type is fed directly with a straw bale, without any prior shredding. Part of the bale is combusted above the grate, as it enters the combustion chamber, while another part is combusted on the grate below. The advantage of this system is the fact that constant feeding of the fuel can be achieved even with minimal pretreatment. The disadvantages are that they can handle only baled biomass, the sensitivity to changes in bale size and the relatively high CO emissions and low efficiencies. For these reasons, no new installations use this technology and it has been – for most practical reasons – abandoned.

Due to difficulties in establishing homogeneous combustion conditions, grate-fired systems are usually not the best option for handling mixtures of herbaceous and woody biomass. Some technology options though, such as the rotating grates, claim good results even with fuel mixtures. The control of emissions when the unit is operating at part load is also not so optimal. Finally, although the investment cost is typically quite low, these units need quite high air excess in order to ensure combustion of the volatile gases and thus operate at lower efficiencies.



**Figure 04-02 2:** The straw-fired power plant of ACCIONA at Sanguesa, Spain (Source: ACCIONA)

**Fluidized bed systems** were initially developed in the 1970s in order to handle coals with high concentrations of sulphur, whose combustion would lead to unacceptable levels of  $\text{SO}_x$  emissions in standard combustion systems. The main idea behind this technology is that the fuel is combusted in a bed filled with an “inert” bed material, while air is supplied from the bottom of the combustion chamber. Provided the air velocity is sufficiently high, the bed and fuel particles are lifted from the bed and are effectively “fluidized”.

There are two main varieties of fluidized beds: the bubbling fluidized bed (or BFB), in which the air velocity is relatively low and the particles form a well-defined zone in the combustion chamber resembling a boiling fluid, and the circulating fluidized bed (or CFB), in which the fluidization velocity is higher and the particles are continuously leaving the combustion zone and need to be “circulated” back after passing through a size-separation cyclone.



Fluidized bed systems have several advantages:

- They are able to handle a wide variety of solid fuels, with a wide range of particle sizes, moisture contents and ash contents. This flexibility remains even after the boiler is constructed.
- They have a high thermal capacity and can be returned to operation even if the fuel supply is cut off for some minutes.
- The residence time of the fuel particles in the bed is quite high; thus, a high efficiency can be achieved even at low operating temperatures. This has the added benefit of low thermal NO<sub>x</sub> emissions (see 04-02-02c).
- By using appropriate additives in the fluidized bed, SO<sub>x</sub> emissions can be absorbed and minimized without resorting to expensive secondary cleaning systems.

There are also some disadvantages to this technology, namely the high particle load which requires efficient dust cleaning systems and the increased erosion of the surfaces exposed to the bed. The most important issue however, and the one that is most relevant in the case of herbaceous biomass combustion, is the phenomenon known as *agglomeration*.

As previously mentioned, fluidized beds operate by supplying an air stream of sufficient velocity to the bottom of the combustion chamber. The air velocity depends on the particle properties, e.g. size and density. Too small particles (such as combusted fuel particles) leave the fluidization zone, while too large particles cannot be fluidized and drop to the bottom.

Herbaceous biomass is typically characterized by low ash melting temperatures; thus, ash particles in the fluidization zone are often molten or half-molten and stick to the surface of bed particles which in turn tend to form larger agglomerates. If the size of these agglomerates becomes large enough, then the air velocity does not suffice for their fluidization and they fall to the bottom of the boiler, leading to boiler shut-downs. Alkali metals present in herbaceous biomass may also react with the bed material and form other compounds which melt at low temperatures. Fluidized beds may also be subject to fouling and corrosion issues when firing biomass with high chlorine and alkali content. Finally, fluidized bed will have higher investment costs as compared to grate-fired or pulverized fuel boilers.

To some extent, the agglomeration problem can be controlled by measures that also limit the impact of fouling and corrosion. The use of additives in this technology is easy, but the costs remain quite high. For this reason, the addition of herbaceous biomass in such boiler systems would be limited in thermal shares below 50%; most boiler operators would be happy with even lower values, closer to 20%.

**Pulverized fuel systems** burn a suspension of very fine fuel particles mixed with combustion air. It is currently the most common technology in coal-fired units. Since the fine milling of biomass fuels, and especially of herbaceous biomass (see Section 03-02-04) is quite energy consuming, this technology option for dedicated biomass installations is common only with sawdust and other biomass resources that are easily available as fine particles.





### 04-02-02b: Co-firing of coal and herbaceous biomass

The discussion in the previous paragraphs was targeted to installations that utilize either exclusively herbaceous biomass or a mixture of herbaceous biomass along with woody biomass resources. However, there is another option, that of using herbaceous biomass to substitute a certain thermal share of a fossil fuel, typically a coal variety in an existing installations. This option is known as co-firing (or co-combustion) and offers some very significant advantages, such as the potential for reducing GHG, SO<sub>x</sub> and possible NO<sub>x</sub> emissions from coal-fired power plants. In addition, plants retrofitted to co-firing operation can in most cases switch back to a normal coal-fired mode and are thus better equipped to deal with biomass fuel shortages.

Co-firing is implemented in either pulverized fuel boilers or fluidized bed boilers; fixed bed boilers are practically not used for coal combustion nowadays. There are several different options for implementing co-firing in an existing coal-fired power plant (see Figure 04-02 3):

- **Direct co-firing** means that the biomass fuel and coal are combusted in the same boiler. The simple and least expensive way to do this is to feed the biomass in the existing coal mills and burners (see route 1 in Figure); it is also the least optimized and the one that has the highest potential for impact in coal milling/combustion. A more complex option would be to achieve the required size reduction for biomass in a separate mill, while using the existing coal burners (see route 2). Costs increase due to the installation of new mills and the control of the combustion conditions may not be optimal, but no modifications of the boiler and the combustion chamber are required. Finally, both biomass mills and burners may be installed (route 3). The cost is the highest in this case but the technical risk is much lower. If the biomass undergoes a pyrolysis process called torrefaction (see 04-02-06), then it becomes easily grindable and more like coal in terms of its combustion properties. Then it can be fed directly in the coal mills (see route 5).
- **Indirect co-firing** means that the biomass fuel is fed to a gasifier (see route 4) and the product gas is fed directly to the coal boiler. In this way, any issues related to the biomass ash are kept out of the coal boiler; however, installation and operation costs are much higher and issues related to biomass gasification (see 04-02-05) may occur.
- **Parallel co-firing** means that biomass is combusted in a separate boiler, designed to handle any peculiarities of the feedstock. This boiler may be forced to operate at lower steam temperatures due to issues with biomass corrosion (see **Ash Appendix**), but a coupling of the coal and biomass steam cycles raises the overall efficiency.

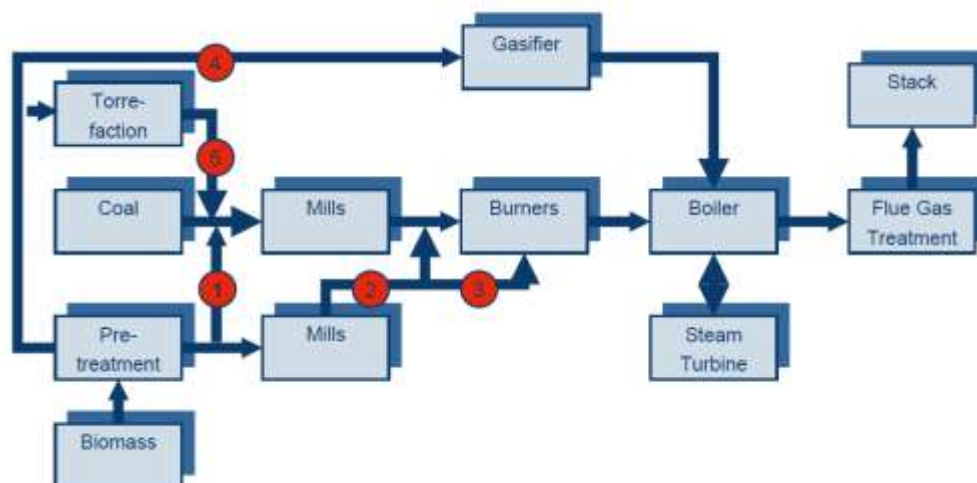
All the above options, apart from torrefaction, have been demonstrated in co-firing applications throughout the world. The maximum share of biomass in the fuel mixture of a co-firing power plant is a function of several parameters, such as fuel and fuel ash properties (both coal and biomass), boiler design and co-firing scheme, ash utilization routes, as well as biomass availability and costs.

A very generic rule of thumb would be that woody biomass can be fed into a coal-fired boiler at thermal shares of up to 20% without major modifications or issues, while for herbaceous biomass the share would be limited to 10% due to its chlorine and alkali content.



Co-firing with high sulphur coals may alleviate some of the corrosion issues for herbaceous biomass, as discussed in 04-02-02b.

Generally though, co-firing is an excellent option for the energy utilization of biomass. For example, one of the most efficient (42% electrical efficiency, 92% total efficiency) and largest CHP plants in the world is Avedøre 2, operated by DONG Energy. Avedøre 2 supplies the Copenhagen district heating network and operates on a multi fuel concept. The main 800 MWth boiler operates with a mixture of natural gas, heavy fuel oil and wood pellets, while a secondary, grate-fired boiler of 105 MWth capacity operates with straw bales. The steam produced from the straw boiler is finally utilized in the same steam turbine as that for the main boiler, thus implementing a parallel co-firing scheme which increases the total efficiency.



**Figure 04-02 3:** Co-firing schemes at coal-fired power plants (Source: KEMA/IEA Task 32)

In recent years, there have been some initiatives in retrofitting old coal-fired units to very high shares of biomass thermal shares for financial and environmental reasons. Belgium is a world leader in these projects: Unit 4 of Les Awirs power plant and Unit 4 of Rodenhuize power plant have already been converted to 100% combustion of wood pellets. The large quantities of pellets required for the operation of such plants are typically shipped from overseas, e.g. Canada. Such initiatives with herbaceous biomass fuels have not yet occurred, partly due to the technical challenges of the feedstock and partly due to the lack of consolidated world markets for agro-biomass pellets.



#### **04-02-04: Herbaceous biomass in small scale combustion applications – residential heating**

As mentioned in the introduction to this chapter, the utilization of herbaceous biomass for the production of heat is very widespread in several third-world countries, as well as in some rural areas of Europe. The efficiency and emissions vary widely depending on the technology and fuel.

Straw is probably the most widely used herbaceous biomass in small-scale heating applications in Europe. A common type of straw heating boiler is the “portion plant” in which the combustion chamber is filled periodically with a straw bale. Smaller systems work with smaller bales and can be fed by hand, while large systems require round or big balers and a loader for the feeding. Automatically fed straw boilers also exist, where the straw is fed through a conveyor system and cut before entry in the combustion chamber. The efficiency of such systems has increased from 30-40% in the mid 1970s to 80% or higher today. Automatically fed systems also tend to be more efficient than manual ones.

Despite these significant technology improvements, herbaceous biomass combustion systems for small scale applications still lag behind their woody biomass counterparts. For biomass boilers, the relevant European standard regarding their performance is EN 303:05. According to this standard, biomass boilers are classified in Classes from 1 to 5, with each class having to meet certain requirements in terms of efficiency and emissions versus feeding system (manual or automatic) and boiler capacity.

In Greece, for example, biomass boilers must be tested and proven to be Class 3 or higher before they can be used in heating applications. This is a requirement more easily met for boilers operating with woody biomass than with herbaceous biomass. Dust emissions for example, and especially the most harmful PM1 emissions, tend to be higher for herbaceous biomass compared to wood biomass due to their higher inorganic volatile content.

The ash content of herbaceous biomass also possesses certain operational and “comfort” issues for herbaceous biomass boilers. Slagging and corrosion are an issue for these boiler types, as well as with their larger counterparts. A pellet boiler operating with straw pellets might find that the ash removal system has been blocked by molten ash. Also, compared to a cleaning interval of one month in the case of wood pellets for example, a straw-fired pellet boiler operator might have to clean the ash box four to six times more often, even if no other issues are observed.

Generally, single-house heating boilers operating with herbaceous biomass is currently not the optimal solution for the utilization of this resource, especially in urban areas. There are however some successful examples of application, which belong to the higher capacities of the “small scale” category. Neighbourhood heating systems in rural areas have been installed in several occasions in Denmark.

Typically, such systems are operated by a farmer with access to significant quantities of cheap straw. The farmer installs and operates the boiler from his facilities, covers his own



heating demand and provides excess heat to up to 70-80 neighbouring houses or other buildings. The distance between the buildings in the network should not be too long to avoid too high pipe losses and to maintain a reasonable project economy. The crucial parameters to take into account are – just as with large district heating systems – the line load and the areal energy density. You will find these parameters discussed in text section 04-00-08j.

#### **04-02-05: Herbaceous biomass in thermal gasification applications**

Thermal gasification is a process which aims to convert a solid fuel completely into a combustible gas mixture, as explained in Section 04-00-04. The process typically requires high temperatures and typically takes place in a reactor which is either a fixed bed or a fluidized bed. The difference with combustion systems is that the oxygen supply during the whole process is less than what is required for complete oxidation of the fuel, so that the product gases retain their heating value.

Generally, the product gas from the gasification process can be used either as a fuel – in which case issues related to ash melting are not of importance – or as a synthesis gas for the production of chemicals – in which case there are more severe requirements in terms of fuel impurities.

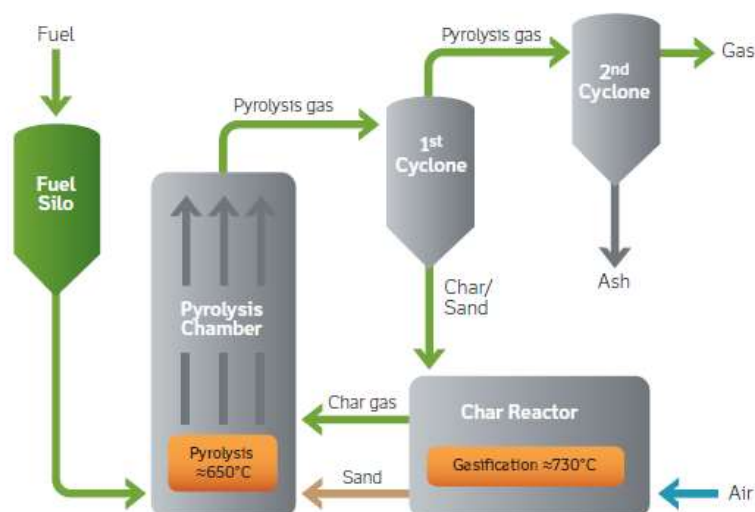
Herbaceous biomass feedstocks in gasification reactors pose two types of problems:

The first one, just as in the case of combustion, is related to the ash content of the fuel. While the product gas can be kept ash-free and therefore be combusted much more easily, ash melting remains an issue in the gasification reactor. Fluidized bed gasification reactors for example may be subject to agglomeration, a phenomenon which was described in section 04-02-03a. In order to alleviate these issues, the Danish company DONG Energy has developed a low temperature fluidized bed gasifier concept (see Figure 04-02 3).

In this process, straw and other problematic biomass types are fed initially into a low temperature (~ 650 °C) fluidized bed, where it is pyrolyzed. The process temperature is low enough to avoid ash melting and significant release of volatile ash species, while the remaining char is gasified in another reactor, at a higher temperature. Two cyclones are used for removal of dust particles; the product gas is then suitable for combustion. A 6 MW demonstration facility is already operating in Denmark; about 95% of the fuel energy is converted into a product gas which is then combusted in a nearby coal-fired power plant.

The second issue of herbaceous biomass gasification relates to the impurities present in the product gas. Since herbaceous biomass has relatively high concentrations of sulphur, chlorine and volatile alkali species, impurities such as H<sub>2</sub>S, HCl, ammonia and aerosol particles tend to be present in higher concentrations compared to the gasification of woody biomass. As previously mentioned, fuel impurities pose significant challenges in some applications of the product gas - for example, its combustion in turbines or fuel cells or its use as a synthesis gas for chemicals production.

A significant portion – as high as one third in some processes - of the energy in the product gas is in the form of sensible heat due to the high process temperatures used in thermal gasification. Cooling the gas makes cleaning easier, but the price paid is a significant loss of energy. Hot flue gas cleaning is on the other hand much more difficult to accomplish and remains a major bottleneck for gasification.



**Figure 04-02 3:** The straw-fed Pyroneer gasifier at Kalundborg (Source: DONG Energy)

#### **04-02-06: Herbaceous biomass in pyrolysis applications**

Pyrolysis is a process occurring at either high or low temperatures. Depending on temperature a varying mixture of combustible gases, liquids and solids is produced.

In order to maximize the liquid product yield, low temperatures ( $\sim 500$  °C), high heating rate and short gas residence time should be employed. The liquid products of biomass pyrolysis are typically a mixture of oxygenated organic compounds, such as furans, acids, ketons, aromatic hydrocarbons, etc; their relative presence in the pyrolysis liquid depends on the feedstock and the process conditions. For example, pyrolysis in the presence of a zeolyte catalyst may result in lower yields of liquid products, with a lower percentage of oxygenated compounds.

For herbaceous biomass, some ash constituents, mostly potassium and calcium, have been found to catalyze the pyrolysis and char forming reactions. Char particles formed from such reactions end up in the liquid fraction as suspended submicron particles and contain part of the fuel ash. Hence, unless an upgrading of the pyrolysis liquid takes place, the release of ash and alkalis during its combustion may present problems.

Up to now, the number of commercial pyrolysis units operating is fairly low, hence the capital costs of such an investment can be quite high compared to other processes.



If the desired product from the pyrolysis process is to be a solid one, then low temperatures and low heating rates are required. This process is commonly known as “torrefaction”. In recent years, many research and technological development activities have been focused on this concept, with the intention to produce upgraded solid biofuels which feature higher energy densities, ease of milling and hydrophobic properties.

Basically, torrefaction is a charring process, and its aim is to produce a fuel that can easily supplement coal in large-scale power plants. So far, most of the activities and demonstrations of the torrefaction technology – of which there are several different concepts available - are focused on woody biomass. For herbaceous biomass, the main issue is the chlorine and alkali fuel content, as discussed in 04-02-02. Reports are conflicting on whether these volatiles species actually leave the solid biofuel during torrefaction or not and hence it is not clear whether this process can be used to solve the issues related to ash melting, fouling, slagging, etc of herbaceous biomass. More information on the torrefaction process as it applies to woody biomass can be found in section 04-01-02d.

#### **04-02-07: Herbaceous biomass in biochemical fermentation**

Bioethanol production from agricultural products – what are commonly referred to as 1<sup>st</sup> generation biofuels – is a technology that has been proven to be fully commercial and is operating in large scale units in countries such as Brazil and the USA. Typical 1<sup>st</sup> generation biofuels feedstocks are rich in sugars and/or starch: sugar cane and corn seeds. However, as these are products that are actually edible by humans, the production of bioethanol from 1<sup>st</sup> generation biofuels is a major argument in the global “food vs fuel” controversy.

The production of bioethanol from 2<sup>nd</sup> generation biofuels, e.g. herbaceous agricultural residues such as straw or corn stover is considered less controversial but much more technically challenging. Such feedstocks contain cellulose and hemicelluloses, which can be broken down into sugars using suitable enzymes. However, the structure of the biomass and the presence of lignin, which is non-digestible, require some form of pre-treatment before the cellulose becomes easily accessible to the enzymes.

The current status of pre-treatment technologies and the lack and/or high costs of effective enzymes that could break down cellulose and hemicellulose were the major bottlenecks in the production of bioethanol from 2<sup>nd</sup> generation herbaceous biomass feedstocks. However, several RTD activities have brought this technology much closer to a commercial scale.

In the USA, the emphasis has been on using corn stover (maize residues) as the feedstock, due to the perceived abundance of the resource and the operation of a number of facilities that already produce ethanol from corn grain. The research focus in Europe has mostly related to bioethanol from straw. As with straw combustion, it is mostly Danish companies that are in the forefront of this technology.

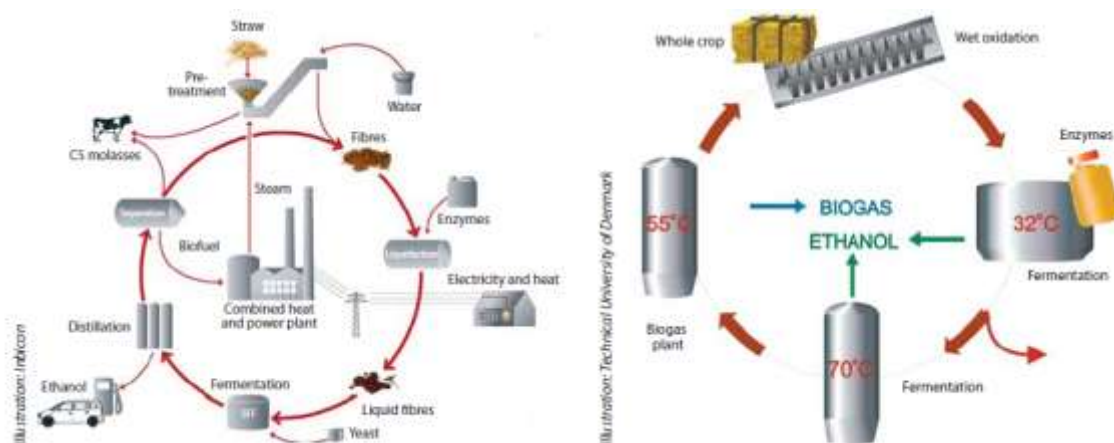
The first concept, developed by DONG Energy's subsidiary Inbicon, is starting by pre-treating the straw at a pressure of 15 bar and a temperature of about 185 °C. This effectively breaks down the structure of the biomass into sugars (with the added benefit of removing chloride salts). After this, the process is similar to the production of bioethanol from 1<sup>st</sup> generation biofuels (e.g. fermentation of sugars into ethanol and distillation of the product).

Any remaining solids, essentially the biomass lignin, can be used as a fuel in an integrated CHP plant to provide the process steam for the straw pre-treatment or it can be used for other purposes. Inbicon is operating a plant at Kalundborg which handles 30,000 tn of straw per year and produces 5.4 million liters of bioethanol, along with quantities of lignin pellets and C5 molasses. More information can be found here:

[http://www.inbicon.com/Biomass%20Refinery/Pages/Inbicon Biomass Refinery at Kalundborg.aspx](http://www.inbicon.com/Biomass%20Refinery/Pages/Inbicon%20Biomass%20Refinery%20at%20Kalundborg.aspx)

A second concept, developed by the BIOGASOL company is also presented on the right of Figure 04-02 3. The straw pre-treatment in this technology is taking the form of "pressure cooking", which is essentially a hydrothermal treatment in a mild acid or base solution. After the biomass "breaks up", enzymes are added in two steps, the first converting glucose from cellulose to ethanol, while the second does the same for xylose from hemicellulose.

The process water, including the biomass residue is then fed to a biogas reaction in order to produce bio-methane. This technology has been applied on a pilot scale, while the work on the "BornBioFuel" project, will bring the technology to a semi-industrial scale.



**Figure 04-02 3:** Bioethanol production from straw using the Inbicon (left) and Biogasol (right) technologies (Source: INBIOM)



### **04-02-08: Herbaceous biomass in biochemical (anaerobic) digestion**

As mentioned in Section 04-00-01, biochemical (anaerobic) digestion is the process which produces a gas consisting mostly of carbon dioxide and methane through the digestion by fungi or bacteria of high moisture biomass feedstocks. Anaerobic digestion works well with feedstocks that are easily digestible, slurries, wet manure, sewage sludge, etc. High moisture contents, instead of being a hindrance, as is the case in combustion applications, are actually favourable to the digestive processes.

For herbaceous biomass fuels, the ease of digestion depends on the links between its structural components: cellulose, hemicelluloses and lignin. Lignin in particular, as in the case of fermentation, is generally not digestible. Therefore, pre-treatment of the herbaceous biomass feedstock and the break-down of its structure in what is known as the hydrolysis step of the anaerobic digestion (see also Chapter 04-03) is often necessary in order to achieve sufficiently high gas yields that render the whole process economic.

There are several pre-treatment methods that can be employed to herbaceous biomass feedstocks before anaerobic digestion: physical, chemical, physicochemical and biological. Typical examples would be steam explosion, hot water extraction, treatment with sulphuric acid, sodium hydroxide or other substances, wet oxidation, etc.

If only herbaceous biomass is used as a biogas production feedstock, then the remaining non-digestible product contains several nutrients as well as unconverted carbon and can be returned to the field as a natural fertilizer. If a mixture of herbaceous biomass and other wastes is used, then this recycling may be subject to limitations, depending on the purity of the residue.

Biogas production from energy crops and some agricultural residues, most commonly maize silage, is very widespread in several European countries and, despite some operational issues that may occur, the technology can be considered as mature. See Chapter 04-03 for more details on this process.

### **04-02-09: Planning aspects for herbaceous biomass applications**

This chapter should have made obvious to the reader that the utilization of herbaceous biomass for energy production poses significant more challenges from a technical point of view compared to woody biomass. This is a major reason which explains why projects which use herbaceous biomass as a feedstock are not so widespread.

Most of the technical issues associated with utilization of herbaceous biomass stem from certain constituents – mostly chlorine and the alkali content in the fuel ash. Since these parameters may vary depending on plant type, soil conditions, storage conditions, etc, it is generally a good practice to perform a number of fuel and ash analysis of the feedstock to be utilized in order to have a good idea of its properties – most, if not all, equipment suppliers will base their designs on such values. Literature data can be used, but they may vary



significantly for actual conditions and for certain feedstocks, such as many energy crops, data can be scarce or conflicting.

Regarding the scale of application, herbaceous biomass is generally ill-suited for small-scale systems, since the emissions and operating issues they present cannot be handled easily by small-systems. Larger scale systems are generally preferable from an operating and environmental point of view, although the actual size may be limited by supply chain considerations and energy demands (heat consumption for example is less concentrated in rural areas compared to urban ones).

Direct combustion is generally the most mature technology, with several examples of operating plants. Biochemical fermentation and anaerobic digestion are next in line in terms of commercial maturity, with other processes lagging behind. In general, the technical risk with such a feedstock is greater and the planner should try to choose utilization options that have a successful history of demonstrations in order to avoid future failures. A lower availability at the first years of operation may also be expected and this will influence the economic performance of the unit.

In order to avoid the issues associated with the herbaceous biomass ash, its use in fuel mixtures is possible – co-firing with coal is a highly efficient process and – due to the large size of most coal-fired power plants – can absorb large quantities of the fuel. The substitution of woody biomass with herbaceous biomass is also possible in most applications – with the possible exception of residential heating. A general rule would be that herbaceous biomass can contribute about 10 - 20% of the energy of the fuel mixture without problems – the final recommendation though remains with the equipment supplier.

Finally, the issue of the handling of the residual products should be considered by the system planner. Ash and/or residues from processes involving only clean herbaceous biomass can usually be returned to the soil as fertilizers. If herbaceous biomass is processed along with other fuels, then nutrient recycling may not be possible if pollutants are present in the residue. Also, in cases where herbaceous biomass is co-fired with coal or woody biomass, the restrictions on the ash handling of the main fuel may pose some limitations on the maximum thermal share of the herbaceous fuel. Check the **Ash Appendix** for more information on the issue of ash utilization.



## References

Regarding herbaceous biomass fuel and ash properties, the first step would be to look into the information available at existing databases. The reader is referred to the following:

- [Phyllis database](#)
- [BIODAT](#)
- [NREAL biomass database](#)

Other published papers or presentations may prove useful, as long as the reader remembers that the ash composition in herbaceous biomass can vary greatly between localities even for the same species. The following references proved to be useful to the authors:

- [\*R.R. Bakker, H.W. Elbersen, Managing Ash Content and Quality in Herbaceous Biomass: An analysis from plant to product\*](#)
- [\*J. Werther, M. Saenger, E.U. Hartge, T. Ogada, Z. Siagi \(2000\) Combustion of agricultural residues, Progress in Energy and Combustion Science, 26\(1\):1-27\*](#)

For a more technical discussion of herbaceous biomass properties and combustion and gasification technologies – but without delving into research papers – the reader is suggested to try the following publications:

- [\*Van Loo S., Koppejan J. \(2008\), “Handbook of biomass combustion & co-firing”, Earthscan, London, United Kingdom.\*](#)
- [\*Grammelis P. \(ed.\) \(2010\), “Solid Biofuels for Energy: A Lower Greenhouse Gas Alternative”, Springer-Verlag, London, United Kingdom.\*](#)

IEA Bioenergy has a number of Task groups dealing with different aspects of biomass utilization. [Task 32: Biomass Combustion and Co-firing](#), [Task 33: Thermal Gasification of Biomass](#), [Task 34: Pyrolysis of Biomass](#) among others found [here](#) are a good source of further information on the subject.

In Europe, the Danish experience in straw utilization is unparalleled. More information on technologies and units operating with straw are available on the following publications:

- [\*Straw to energy – status, technologies and innovation in Denmark 2011\*](#)
- [\*Bioenergy for electricity and heat – experiences from biomass-fired CHP plants in Denmark\*](#)