

CO-FIRING OF BIOMASS WITH COAL: CONSTRAINTS AND ROLE OF BIOMASS PRE-TREATMENT



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PREFACE

This report aims at introducing the aspects of co-firing of biomass with coal. The main focus is given to problems and constraints related to utilizing biomass together with coal for power generation, and the potential of biomass pre-treatment in mitigating these constraints. The work is based on a review of literature sources on the subject.

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Acronyms and abbreviations

BFB	Bubbling Fluidised Bed
BIG/CC	Biomass Integrated Gasification / Combined Cycle
CAP	Common Agricultural Policy
CCP	Coal Combustion Product(s)
CEN	European Committee for Standardization
CFB	Circulating Fluidised Bed
C _x	Number of Carbon atoms in hydrocarbons
d.b.	Dry basis
DME	Dimethyl-Ether
EFG	Entrained Flow Gasifier/Gasification
EN	Euro Norm
EOTA	European Organization for Technical Approvals
ETA	European Technical Approval
EU	European Union
F.C.	Fixed carbon
FBC	Fluidised Bed Combustion
FGD	Flue Gas Desulphurisation
FT	Fischer Trops
GCV	Gross Calorific Value
GWP	Global Warming Potential
IEA	International Energy Agency
mcwb	Moisture content on wet basis
NCV	Net Calorific Value
Nm ³	Normal cubic meter
PC	Pulverised Coal
PF	Pulverised Fuel
RDF	Residue/Refuse Derived Fuel
SCR	Selective Catalytic Reduction
SRC	Short Rotation Coppice
SRF	Short Rotation Forest
SRW	Short Rotation Wood
TDF	Tyre Derived Fuel
V.M.	Volatile Matter
VOC	Volatile Organic Compounds
w.b.	Wet basis
WP	Work Package

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Structure of the report

Chapter one provides an overview of different co-firing configurations, followed by a description of the existing combustion technologies and gasification technologies applicable to coal and/or biomass.

Chapter two presents the background information on biomass properties. Different types of biomass feedstocks used in energy systems are presented, comparison of biomass and coal properties is discussed, and the characteristics of biomass along with their relation to specific challenges related to co-firing of biomass with coal are listed.

Chapter three presents the main environmental aspects of co-firing of biomass with coal. Results from a number of Life Cycle Analysis studies of co-firing systems and biomass systems are presented. The possibilities for utilization of ash produced by different co-firing configurations are presented.

Chapter four describes the main challenges, problems, and difficulties related to co-firing of coal with biomass. The main technical challenges are listed and discussed. Difficulties related to supply of biomass and handling of biomass in power plants are described. Lastly, the non-technical barriers for co-firing development are listed.

Chapter five presents the economic considerations related to co-firing systems.

Chapter six presents different options for biomass pre-treatment, with potential to mitigate some of the constraints related to co-firing. The options discussed include sizing, drying, washing, pelletisation, torrefaction and pyrolysis of biomass, as well as combinations of some of them. For each pre-treatment option, subject to data availability, the economics, related environmental impacts, and energy requirements are presented.

Chapter seven summarizes the main conclusions of the report.

Executive Summary

Currently the most popular option for co-firing applications is direct co-firing, where biomass and coal are utilized together in the same boiler. This is mainly due to relatively low investment cost of turning an existing coal power plant into a co-firing plant. Parallel co-firing units, also called hybrid systems (where biomass and coal are fed into separate boilers jointly producing steam for power generation) are popular too, especially in pulp and paper industrial power plants. The indirect option for co-firing i.e. involving the installation of separate biomass gasifier is expensive and applied only in few European power plants.

In configuration of indirect co-firing as well as parallel combustion, the ashes produced in the process are kept apart. In the case of direct co-firing, coal and biomass ashes are mixed together. Ashes from single coal combustion are mostly utilized in the construction industry. Ashes from biomass combustion face a number of factors constraining their utilization, however potential exists. The case of mixed biomass and coal ashes deserves attention, as mixed ashes are neither completely appropriate for single biomass ash applications, nor are they easy to be utilized in the same applications as single coal ash.

Many different types of biomass can be co-fired with coal. Biomass can be imported or supplied locally and can include wood, residues from forestry and related industries, agricultural residues, and various biomasses in refined form such as pellets. Energy crops could also be perceived as potential candidates for co-firing, except for oil, sugar and starch energy crops, which can be used for production of liquid transport fuels, and their utilization for power production is at current economically unjustified.

There are many successful co-firing systems, however there are various constraints that may be encountered. Most of them originate from fuel properties. Raw biomass fuels usually have high moisture content resulting in a relatively low calorific value of the fuel, low bulk density compared to coal, low ash melting point, chemical composition with potentially high chlorine content, hydrophilic and non-friable character.

The constraints related to co-firing can include fuel preparation, handling and storage, milling and feeding problems, different combustion behavior, possible decreases in overall efficiency, deposit formation (slagging and fouling), agglomeration, corrosion and/or erosion, and ash utilization.

The degree of these difficulties depends on the quality and percentage of biomass in the fuel blend, type of combustion and/or gasification used, the co-firing configuration of the system, and properties of coal. With proper combination of these elements many power plants practice co-firing without major problems. The importance of the problems rises however with increased biomass/coal ratios, and when low quality biomass is used as a feedstock, especially in direct co-firing systems without dedicated biomass infrastructure.

Various measures can be applied to avoid or reduce the problems in co-firing. One of the possibilities is application of biomass pre-treatment, which is an interesting option, because by modifying biomass properties, the source of the problems is addressed, rather than their consequences. The costs of pre-treatment are usually high but can be compensated by better operability of the fuel (handling, storage, transportation) and operability of the boiler and combustion process. For that reason some power plants prefer to utilize more expensive, but less problematic, pre-treated biomass feedstocks for co-firing e.g. pelletized wood in Denmark or the Netherlands. The importance of pre-treatment is likely to increase with tendency to use low quality biomass, which may be a necessity with growing demand for biomass for other (than heat and power) applications such as transport fuels or bio-materials.

An interesting biomass pre-treatment option is its fast pyrolysis into pyrolysis oil. Pyrolysis oil has very high energy density, but cannot be used in direct co-firing systems. Due to the liquid form it requires dedicated infrastructure for transport, storage, feeding, as well as separate conversion unit.

Another interesting option, especially in case of herbaceous biomass (which at current is not often considered for co-firing) might be pre-treatment process combining torrefaction and pelletizing with biomass washing, or combination of biomass pyrolysis with char wash. It might result in biomass properties allowing co-utilization of high ratios of low quality biomass with coal in the existing coal systems without major modifications. These pre-treatment options are not commercialized as it currently stands, and their environmental impacts, technology performance and economics are not known on the large-scale.

Preamble – Note to the reader

In the co-firing area, similarly to other bio-energy systems, it is hard to generalize conclusions, as bio-energy systems are site-specific and require dedicated analysis. Therefore certain conclusions made in this report, might not necessarily find confirmation in every system.

As some issues presented in this report are new and not well developed, certain sections of it are based exclusively on one specific source for which crosscheck was not possible. In this case it should be remembered that along with ongoing research findings, the conclusions presented here might be altered.

Significant number of sources that this report refers to comes from the Netherlands, which is very active in bio-energy research.

The (especially quantitative) data on the problems encountered in co-firing systems is either not available or very general and limited.

The analysis is based exclusively on data and information sources publicly accessible or available through subscription, and has mainly qualitative character.

The focus of this work is mainly relevant to co-firing systems utilizing low quality biomass at high co-firing ratios with coal, in existing coal systems without modifications (direct co-firing).

Introduction

Biomass contributes to around 5% of the European Union's energy supply, and 65% of the total renewable energy production [1], and there is an increasing interest in using biomass for energy. Power generation in coal power plants continues to raise environmental concerns. There is a need to diversify the energy sources and better manage the available fossil fuel resources [2]. Stand-alone biomass plants bring environmental benefits, however involve very high investment costs and may raise concerns regarding the security of feedstock supply. This is because of the seasonal nature of biomass, as well as the fact that in many countries biomass resources are dispersed, and the infrastructure for biomass supply is not well established. Additionally, lower heating values and low bulk densities of biomass (compared with coal), result in much greater volumes of fuel to be transported, handled and stored, and as a consequence, large biomass units (>300MWe) are economically unpractical under present economic criteria [3]. Combining biomass and coal as feedstock for energy production in the existing coal power plants addresses the above-mentioned issues. Coal can mitigate the effects of variations in biomass feedstock quality and buffer the system when there is insufficient feedstock quantity [37, 39]. Co-firing can be done in large units with high thermal efficiency compared to small-scale systems, specific operation costs are likely to be lower [37, 39] and the costs of adapting existing coal power plants should be lower than building new, dedicated systems [3].

Recent reviews of co-firing experience identify over 100 successful field demonstrations in 16 countries, using many types of biomass in combination with various types of coals and boilers [21]. IEA Bioenergy Task 32 is preparing a position paper indicating that co-firing represents among the lowest-risk, least expensive, most efficient and shortest-term option for renewable-based electrical power generation [21].

Co-firing represents the cheapest choice among the renewable power generation options, when biomass resources and coal-based power plant are present in the same region, however in general co-firing is more expensive than dedicated coal systems [21]. As economic advantages for co-firing of biomass with coal so far do not exist, the CO₂ emission reduction and the global climate change mitigation are the main motivations behind the concept development [21].

According to the VIEWLS report [37], biomass demand in stationary applications (heat and power) is the main driving force behind early expansion of bioenergy, and in the absence of policies directing biomass to transport fuel production, biomass use for stationary applications will remain the major demand source for bioenergy up to 2030. Biomass use for co-firing with coal could substantially reduce the CO₂ emissions in the near term, while at the same time stimulate the establishment of a supply infrastructure leading to cost reductions along the biomass supply chain in the longer term, and facilitating the expansion of other biomass applications (e.g. biomass CHP and liquid biofuels) [37].

Combustion is commercially available and proven technology for converting biomass to energy, however improvements are continuously being made in fuel preparation, combustion and flue gas cleaning technologies, as a result of demand to utilize new or uncommon fuels, improve efficiencies, minimize costs and reduce emissions [16]. The co-firing technology has been demonstrated at commercial scales in many system configurations, however there are only few commercialized preparation and handling systems.

The fuel preparation, storage and handling are the major technical challenges associated with biomass co-firing [21, 47, 49]. Other problems are linked with poor or not appropriate fuel quality and include fuel feeding, co-milling, deposit formation, increased corrosion and erosion, and need for new fly ash utilization schemes [21, 44, 47].

The above challenges are not significant in low co-firing ratios, and when high-quality biomass is used, however become important with increasing biomass/coal ratios especially when low-quality biomass is used, and in those cases might have major influence on the economy of the plant. Most of the above drawbacks can, to a certain extent, be avoided by application of appropriate biomass pre-treatments.

Therefore the aim of this work is to give an overview of constraints associated with co-firing systems and identify biomass pre-treatment options with potential to address them. The final goal is to conclude, on qualitative basis, which pre-treatment options for raw, low quality biomass are the most promising with regard to direct co-firing.

It should be underlined that at present co-firing is practiced often without major problems. Co-firing power plants are usually utilizing clean, high quality biomass at up to 5-10 wt% input, often with dedicated biomass infrastructure integrated in existing coal systems. However the tendency is to increase the co-firing ratio, and enlarge the range of biomass fuels by including low-quality feedstock, as with growing demand for biomass for various applications (heat, power, transport fuels, bio-materials) the utilization of low quality feedstocks becomes unavoidable.

The identified in the literature mechanical as well as thermochemical pre-treatment options for biomass are going to be presented, with attention to costs, environmental performance, and energy consumption of these pre-treatments, as well as their role in reducing problems in co-firing systems.

1. Technology options for power production

This chapter provides an overview of different co-firing configurations, followed by a review of the existing combustion and gasification technologies applicable to stand-alone coal, stand-alone biomass, and co-firing systems.

1.1. Configurations of co-firing systems

Energy production in coal-fired power plants by partial substitution of coal, as the main fuel, with biomass feedstock is called co-firing [55]. The definition of co-firing also applies to substitution of coal with other materials e.g. waste. However this report focuses on the systems where part of coal is substituted with biomass (residues or energy crops).

At the present time, experience is being generated with various options for co-firing. Three basic types of technological configurations for biomass co-firing in power plants can be identified [46]: direct co-firing, parallel co-firing, and indirect co-firing.

1.1.1. Direct co-firing

In this option (Fig.1) biomass (a secondary fuel) enters the boiler together with coal (primary fuel). In case of direct co-firing of biomass with coal in large-scale PC boilers, the following options are possible:

- Blending biomass with coal in the fuel yard and transportation of the mix through the coal system with the application of coal processing and combustion equipment (coal mills, crushers, pulverizers, burners) [41]. This is the cheapest and most straightforward option, however problems resulting from differences in the characteristics of the two mixed fuels can occur. Also, some types of biomass cannot be processed this way (for example herbaceous biomass is known to cause many problems during feeding and sizing). It can be applied to biomass like olive/palm kernels or cocoa shells as well as saw dust (in the last case, blending with coal takes place after the coal mills) [67]. There are a number of projects in Europe based on this option, but its application is considered to be limited (i.e. to conventional wall or corner-fired furnaces) [41].
- Separate milling of biomass, mechanical or pneumatic feeding to the boiler followed by firing of the biomass material through existing coal injection system and burners [41]. In this case the fuel mixing takes place in the combustion chamber, thus without impacting the fossil fuel delivery system. This option involves higher investment.
- Installation of new, dedicated biomass milling and sometimes also burning equipment [41]. This option increases the number of biomass materials, which can be fed to the boiler. There are projects in Europe based on this option, although it is relatively complex and expensive to install.

In the direct co-firing configuration, a minimum investment is necessary, but may face various shortcomings resulting from differences between the properties of mixed feedstocks (more in Chapter 4). One of them is that the biomass ashes become mixed with coal ashes. Although coal ashes and, to a lesser extent, biomass ashes might be reused separately, the re-use of mixed ashes may be restricted substantially (more on possibilities for utilization of coal and biomass ashes can be found in Chapter 3).

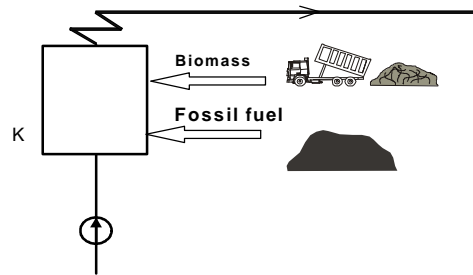


Fig. 1. Simplified process layout of the unit performing direct co-firing (K-boiler), Source: [46] with approval

1.1.2. Parallel co-firing (also called parallel (co-) combustion or co-firing in hybrid system)

In this option (Fig.2) biomass is combusted in a separate (from coal) boiler, supplying steam to a common header. There is no technical possibility of supplying the biomass combusting boilers with fossil fuels, thus the fuel preparation and feeding are physically independent [46].

In this option, the potentially limiting factor in retrofitted power plants can be the capacity of existing downstream infrastructure such as steam turbine. The amount of biomass that could be co-fired could be limited by the steam generator capacity, so it should be made sure that there is sufficient overcapacity of steam turbine to accommodate the extra power from biomass combustion (or that the coal boiler capacity is turned down) [5].

In parallel co-combustion configuration the biomass and coal ashes are kept separately. Since coal and biomass are converted in different units, an optimal system for each fuel can be chosen (e.g. CFB for biomass and PC for coal). The investment in parallel co-firing installations is significantly higher than in direct option, however the possibility to optimize the combustion process, use relatively difficult fuels with high alkali and chlorine contents, and the separation of the ashes are possible advantages [32].

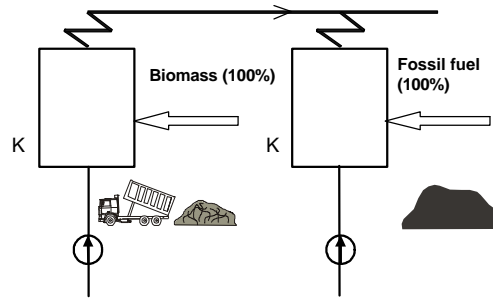


Fig.2. Simplified process layout of the unit performing co-firing in the hybrid/parallel combustion system, (K-boiler), Source: [46] with approval

1.1.3. Indirect co-firing

In this option (Fig.3) biomass is gasified (or combusted)¹ separately and the produced gas is injected and burned in the coal boiler. This technique keeps the biomass ashes separated from the coal ashes, while allowing very high co-firing ratios. The drawback of indirect co-firing option is relatively high unit investment costs [46].

Indirect co-firing by pre-gasification is currently operated in a number of demonstration plants in Austria (Zeltweg), Finland (Lahti) and the Netherlands (Geertruidenberg) [33].

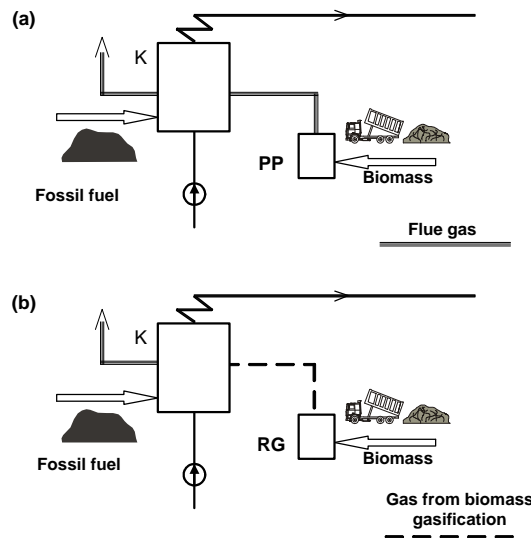


Fig.3. Simplified process layouts of existing boilers repowered with pre-furnace PP (a) or biomass gasifier RG (b), (K-boiler), Source: [46] with approval

The direct co-firing is the most popular option for biomass and coal co-firing currently in Europe [55], mostly due to relatively low investment cost of turning existing coal power plants into co-firing units [46]. Parallel co-firing units are also present, mostly in pulp and paper industrial power

¹ Indirect co-firing is when: A) biomass or biogas is combusted in pre-furnace and the enthalpy of generated flue gas is used in the combustion chamber, in which heating surfaces are mounted, or directly as a heating agent in heat exchangers or B) biomass gasification is carried out in biomass gasifier and the formed gas is supplied to the combustion chamber, where it is burnt in gas burners [46].

plants. The indirect co-firing options are currently considered to be too expensive for European markets, as proved by the co-firing experience in UK [41]. However, when considering the future prospects for co-firing, the tendency is to increase the ratio of biomass/coal, and to be able to utilize a wide range of different biomass fuels including fuels blends. Therefore it may be in the future that the higher investment in more advanced co-firing configurations would pay back by better operability and flexibility of the system.

1.2. Equipment and technology options for coal and biomass combustion

In general, three types of combustion systems can be identified:

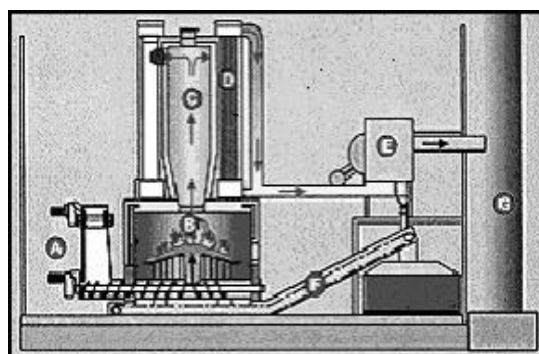
- Fixed Bed Combustion (stoker or grate combustion)
- Fluidized Bed Combustion (bubbling and circulating)
- Pulverized Fuel Combustion (dust combustion)

1.2.1. Fixed Bed Combustion is a combustion concept of solid fuels (coal, biomass) of small and medium size [54]. Fixed Bed systems use grate-fired furnace (Fig. 4) and underfeed stokers. The air passes through a fixed bed, where in the primary combustion chamber drying, gasification, and charcoal combustion takes place, followed by incineration (usually in a separate combustion zone) of the gases produced after addition of extra air [15].

There are different grate furnace types available (up to 20MWth): fixed, moving, travelling, rotating, and vibrating [15]. Underfeed stokers are used in small- and medium-scale systems up to a nominal boiler capacity of 6MWth [15].

The fixed bed boilers are not relevant in case of direct co-firing, they can be a part of more advanced modes i.e. parallel co-firing or in-direct co-firing.

Tab.1 compares the advantages and disadvantages of fixed bed combustion systems.



- A-Fuel feed
- B-Primary Combustion chamber
- C-Secondary Combustion chamber
- D-boiler
- E-Flue gas cleaner
- F-Ash removal
- G-Stack

Fig. 4. Combustion with grate-fired furnace, Source: [54]

Tab.1. Advantages and disadvantages of Fixed Bed Combustion

Advantages of Fixed Bed Combustion	Disadvantages of Fixed Bed Combustion
Grate furnaces	
<ul style="list-style-type: none"> -Low investment costs for plants <20MWth [15] -Low operating costs [15] -Can use almost any type of wood fuels [47] -Appropriate for biomass fuels with high moisture content (10-60% of total weight) [15, 54] -Suitable for fuels with high ash content and varying particle sizes (with a downward limitation regarding the amount of fine particles) [15] 	<ul style="list-style-type: none"> -Mixtures of wood fuels can be used, but mixtures of fuels with different combustion behaviour and ash-melting point e.g. blends of wood fuels with straw or grass etc., are not possible [15] -Increase of temperature (required e.g. due to inhomogeneous combustion characteristics) may cause the melting of ash and cause corrosion problems [54]
Underfeed stokers	
<ul style="list-style-type: none"> -Low investment costs for plants <6MWth [15] -Low emissions at partial load operations due to good fuel dosing [15] 	<ul style="list-style-type: none"> -Suitable only for fuels with low ash content and high ash-melting point [15] -Low flexibility with regard to particle size (up to 50 mm) [15]

1.2.2. Fluidized Bed Combustion

In Fluidised Bed Combustion the bed is a mixture of inert material such as sand and fuel particles. A continuous stream of air is fed through the bed, leading to movement of the particles and causing the bed to fluidise [54]. There are two types of fluidised bed combustion systems (Fig. 5): Bubbling Fluidised Bed (BFB) and Circulating Fluidised Bed (CFB). A fluidised bed consists of cylindrical vessel with a perforated bottom plate filled with a suspension of hot, inert and granular material (usually silica sand and dolomite), which constitutes 90-98% of the total mixture of fuel and bed material [15]. The fuel amounts to only 2-10%. The bed material provides high thermal inertia and stabilizes the combustion process. Thanks to good mixing, fluidised beds can accept various fuel mixtures of e.g. wood and straw, but require good control of fuel particle size (BFB<80mm, CFB<40mm) [15]. The combustion temperature has to be kept low (800-900°C) to prevent ash sintering, which could cause de-fluidisation in the bed [15]. In BFB most of the fluidising bed material remains in the bottom of the furnace, whereas in CFB it is carried upwards with the flue gas and separated in a hot cyclone or U-beam separator, and fed back into the combustion chamber [15] (Fig.5). The potential significant drawback, especially in CFB, is incomplete combustion of fuels in the bed – the unburned carbon, sometimes referred to as soot, is very light and removed from the cyclone together with ash (consequently, ash contains high amounts of unburned carbon, which might restrict its reuse) [5].

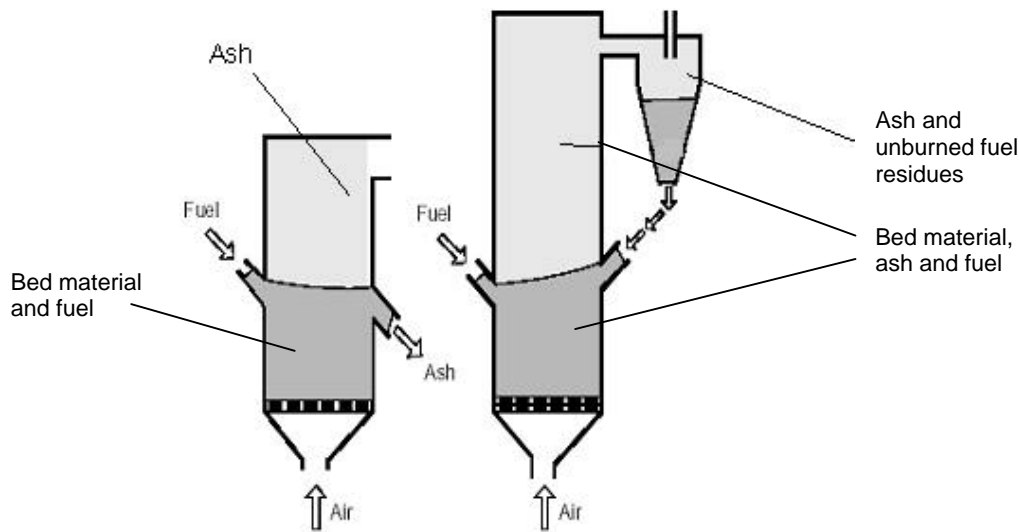


Fig. 5. Bubbling Fluidized Bed furnace (left) and Circulating Fluidized Bed furnace (right), Source: [15]

Tab.2. Advantages and disadvantages of Fluidised Bed Combustion (FBC)

Advantages of Fluidized Bed Combustion	Disadvantages of Fluidized Bed Combustion
<ul style="list-style-type: none"> -Large fuel flexibility in calorific value, moisture content, and ash content, which enables fuel diversification and increases the scope of fuels used in existing power plants [15, 33] -Combustion temperature in the bed is low, which results in low NO_x emissions [15, 33] -Provides an option to directly inject limestone in the bed to remove sulphur cost-effectively (instead of using FGD equipment) [33] -Maximized combustion efficiency even with low-grade fuels [33] -The environmental performance of FBC installations is good, with low emissions of CO (<50 mg/Nm³), NO_x (< 70 mg/MJ after the boiler, eventually reduced to less than 10 mg/MJ when using SCR) and high boiler efficiencies (about 90%) [33] - Fluidized bed technology can be converted from coal into biomass/coal co-combustion with a relatively small investment [47] 	<ul style="list-style-type: none"> -Despite the noted flexibility with regard to fuel specifications, it is not always possible to use the existing feeding installation for feeding biomass by premixing the fuels (which is the cheapest option). In cases where the feeding characteristics of the co-fired fuel vary too much from the primary fuel, a separate feeder needs to be installed [33] -Slagging and fouling on boiler walls and tubes when burning fuels with high alkali content [33] -Bed agglomeration when burning fuels with high alkaline and/or aluminium content [33] -Cl-corrosion on heat transfer surfaces (e.g. superheater tubes) [33] -High investment costs, interesting only for plants >20MWth in case of BFB and >39MWth for CFB [15] -Low flexibility with regard to particle size [15] -High dust load in the flue gas [15] -Loss of bed material with the ash [15] -Incomplete combustion of fuels and high unburned carbon content in the ash, especially in CFB

1.2.3. Pulverized Fuel or Dust Combustion systems (Fig.6) are fed pneumatically with fuels such as sawdust and fine shavings [15]. Fuel quality in dust combustion needs to be rather constant, with a maximum fuel particle size of 10-20 mm and the fuel moisture content of no more than 20 wt% (w.b.) [15].

Tab.3. Advantages and disadvantages of Dust Combustion

Advantages of Dust Combustion	Disadvantages of Dust Combustion
-Increased efficiency due to low excess oxygen [15] -High NO _x reduction possible when appropriate burners used [15]	-Particle size of biomass is limited to <10-20mm [15]

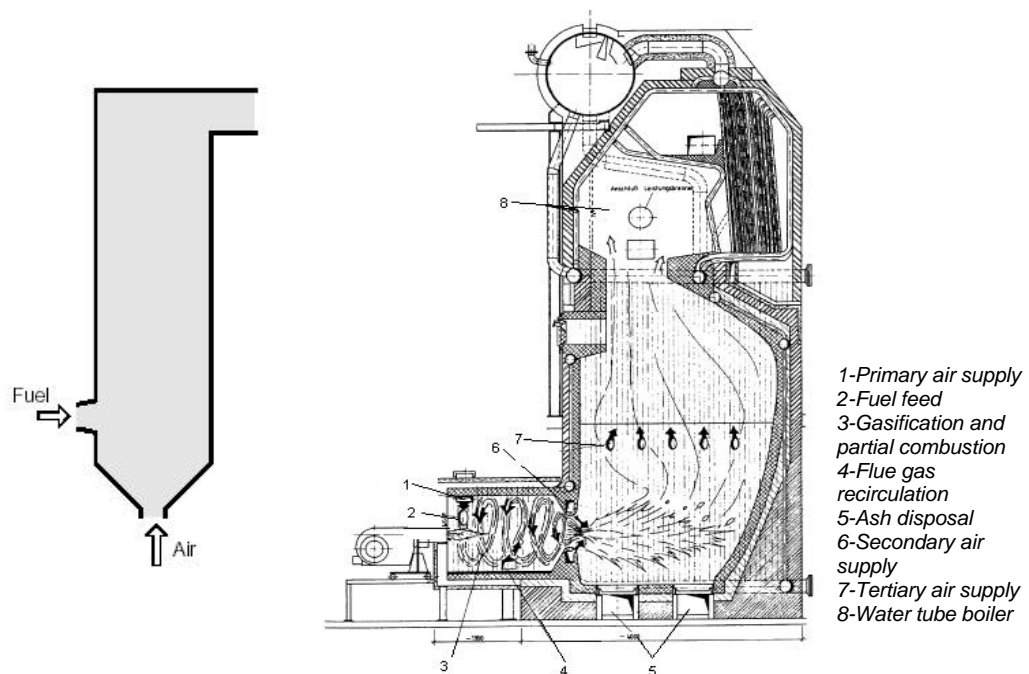


Fig.6. Pulverized fuel technology (left) and muffle dust furnace in combination with a water-steam tube boiler, Source [15]

1.3. Equipment and technology options for biomass gasification

Gasification is an important process to be mentioned with relation to co-firing. As mentioned earlier, gasification can be integrated with a coal-boiler in indirect co-firing systems (in which case gasification of biomass could be considered as fuel pre-treatment). Except for this application, the gasification process can itself constitute the only thermochemical conversion process for power generation, as in the case of IGCC. The IGCC (Integrated Gasification Combined Cycle) is a concept of gasifying the fuel in a gasifier and producing gas to be burned in a gas turbine, followed by

recovery of the heat from exhaust gas from the gas turbine to produce steam to be used in steam turbine for power generation. The IGCC concept can in principle be applied to coal, biomass or combination of the two feedstocks.

Gasification is a thermochemical process converting solid or liquid carbon-based fuels into a gas (syngas, which in case of gasification of biomass can be called bio-syngas). Syngas is rich in a number of components like CO, H₂, CO₂, H₂O, and CH₄, whose proportions depend on the raw material composition and on the gasification conditions such as pressure and temperature. Gasification takes place in the presence of an external oxidizing agent (oxygen, air or steam) and heat. The addition of heat can occur directly (by partial oxidation of the fuel) or indirectly by heat transfer. Unlike combustion, in gasification the amount of the external oxidizing agent is lower, hence only a relatively small portion of fuel is used to generate the required heat. There are two basic types of gasification – direct and indirect (Fig. 7).

1.3.1. Direct gasification

In direct gasification, the thermal energy required for the reaction is produced by initial partial combustion of feedstock with air or oxygen supplied into the reactor. Due to the high content of nitrogen in the air, in the case of air-blown gasification the resulting product gas contains a lot of nitrogen, which reduces the calorific value² of the product gas. On the contrary, if oxygen is used, the resulting product gas contains less nitrogen and thus has a higher calorific value, however the drawback of the oxygen-blown gasification is that it is much more expensive than the air-blown process, due to high cost of oxygen production [51]. Oxygen blown gasification produces gas rich in hydrogen and CO and therefore is of interest for applications with higher added value such as FT Diesel or DME production, whereas it is not directly relevant for power and heat generation at present [5].

1.3.2. Indirect gasification

In indirect gasification the heat required for the gasification process is supplied by additional process, which takes place outside the main gasifier (the heat can be supplied for example by gases or bed material circulated through the heat exchanger or by combustion of char or ash from the main reactor). Steam is the most commonly used indirect gasification agent, because it is easy and cheap to be produced and increases the hydrogen content and consequently the calorific value of the combustible gas [51].

Indirect gasifiers (Fig. 8) are grouped as char- and gas indirect gasifiers, depending on the type of internal energy source [51].

² In general, carbon, hydrogen and sulphur increase calorific value, while oxygen and nitrogen have no negative impact on it, thus – large shares of oxygen and nitrogen in product gas reduce its calorific value.

An indirect gasifier using gas as a heat source (gas indirect gasifier) is a fluidised bed gasifier, equipped with heat exchange tubes. Part of product gas is burned with air as oxidising agent in a pulse combustor. The resulting heat is used for gasifying the fuel that is fed into the reactor.

An indirect gasifier using char as a heat source (char indirect gasifier) consists of two separate reactors: a CFB steam gasifier that converts fuel to product gas and a CFB combustor that burns residual char to provide heat, which is needed to gasify the fuel. Silica sand, which commonly is the bed material, is circulated between the two reactors to enable heat transfer. In such a way, all gaseous and condensable products are reserved for gas production. This process is also known as “fast fluidised process” and generates high product gas yields [51].

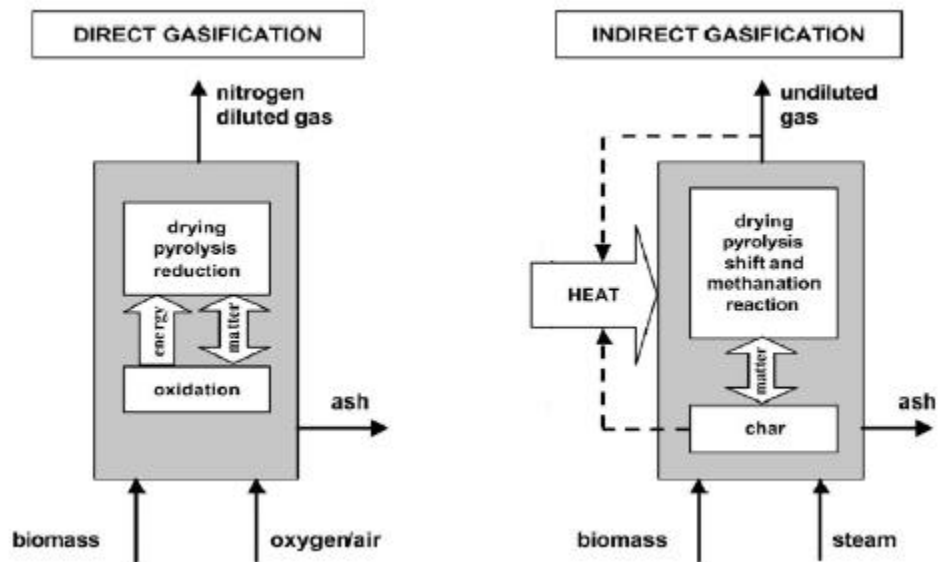


Fig.7. Direct and indirect gasification, Source: [51]

Except for the two described options, there is a possibility to use the bed material itself as a source of heat for gasification process [5]. This is a concept used in a Battelle plant in USA and in a Güssing plant in Austria. The hot bed material is circulated through heat exchangers, and returned back to the main reactor.

Another option would be to make use of carbon-rich ashes recovered from cyclone and burn them to produce heat for gasification process. Further information on possibilities to use fly ash from gasification process as a fuel, can be found in Chapter 3.

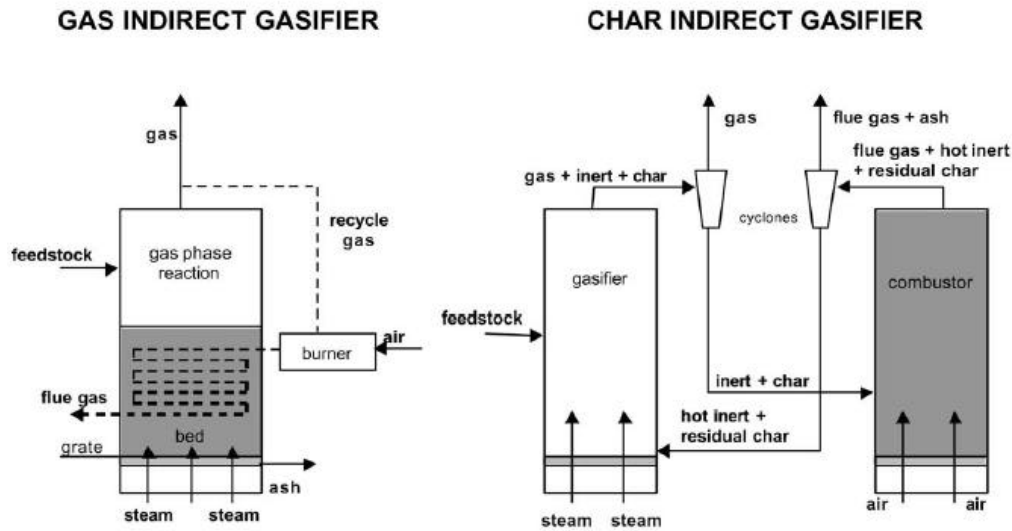


Fig. 8. Indirect gasifiers, Source [51]

Indirect gasifiers are fuel flexible and their main advantage is the higher obtainable quality (purity) of the product gas, compared to conventional fluidised bed gasifiers. This high quality is achieved at the expense of much larger investment and maintenance costs, as well as of higher energy losses [51], and is not of importance for power and heat applications.

1.3.3. Gasification equipment

There are three basic types of gasifiers – fixed bed, fluidised bed, and entrained flow gasifiers.

Fixed bed gasifiers are subdivided into updraft and downdraft gasifiers (Fig. 9). Both require mechanically stable fuel particles of small size (1-3 cm) to ensure an unblocked passage of gas through the bed, therefore the preferred biomass form is pellets or briquettes

Updraft (counter-current) fixed bed gasifier is a counter-current gasifier, where fuel is fed from the top, while air is introduced from the bottom of the reactor. In updraft gasifiers, different combustion stages – drying, pyrolysis, gasification and char combustion – follow each other. The counter flow arrangement is more tolerant to biomass moisture content (up to 40-50%) because drying occurs as biomass moves down the gasifier [23]. The efficiency of the updraft configuration is usually very high. The product gas contains higher hydrocarbons e.g. aromatics, tars, etc, which means that it cannot be used for most applications that require clean gas, such as synthetic fuel, chemical or gas turbine applications, however it is in general good for heat and power production through steam turbine [23]. It should be however noted that indirect gasifiers can produce substantial amount of tars in the product gas, and if the temperature of the gas drops below around 500°C, the tars condensate and can block the whole system [5]. In order to avoid tars condensation, the gas should be kept at higher temperatures. Unfortunately, at higher temperature, there is a drawback of ammonia (from chemically

bound nitrogen in biomass) reacting with oxygen and producing NO_x emissions ($\text{NH}_3 + \text{O}_2 = \text{NO}_x + \text{H}_2\text{O}$) [5]. Since NO_x emissions are subject to emission limits regulations, they can limit the amount of biomass that can be co-fired.

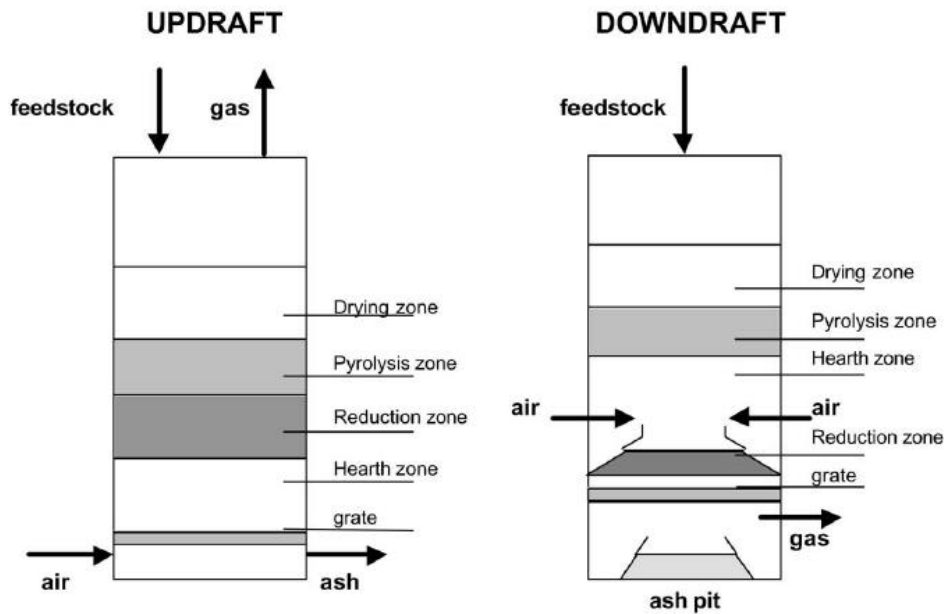


Fig. 9. Fixed-bed updraft and downdraft gasifiers, Source: [51]

In downdraft (co-current) fixed bed gasifiers fuel is fed in from the top, while air is introduced at the sides above the grate, and combustible gas is withdrawn under the grate. This configuration is simple and low-cost [23]. The product gas, consisting mainly of CO, H₂, CH₄, CO₂ and N₂, is relatively clean, with low content of tars and oils, and is hot in the outlet. Such a purity of product gas is typically sufficient for generation of heat and power.

The scaling-up of fixed bed gasifiers is of concern, as the feasible upper limit of updraft gasifiers is usually 10MW, while for downdraft gasifiers it is even lower – up to 1MW (the difference is because in the downdraft gasifiers the air supply cannot be up-scaled easily due to limited access into the reduction zone). The efficiency of downdraft systems is usually high, in comparison with the updraft systems.

Fluidised bed gasifiers are named after the fluidisation process that occurs when a fixed bed of fine solids (typically silica sand) is brought into a fluidised state by contact with an upward flowing gasification agent. The process is based on the same principle as described before for fluidised bed combustion. Two types of fluidised bed reactors are identified (Fig.10.): bubbling fluidised bed (BFB) and circulating fluidised bed (CFB).

Fluidised bed gasifiers do not encounter scaling-up problems. They do not have different reaction zones, but just one isothermal bed. The advantage is that the requirements for particle size of feedstock are not strict. When biomass is used as fuel, the minimum temperature for successful

gasification should be higher than 750°C [52]. But in the same time the bed temperature must be kept below the ash melting point of the fuel, since a sticky ash might glue together with bed particles causing agglomeration and breakdown of fluidisation. Hence, fluidised bed gasifiers are better suited for woody bio-material, which has higher ash melting point (above 1000°C), than herbaceous biomaterial (e.g. straw), whose ash melting point can drop to below 700°C [52].

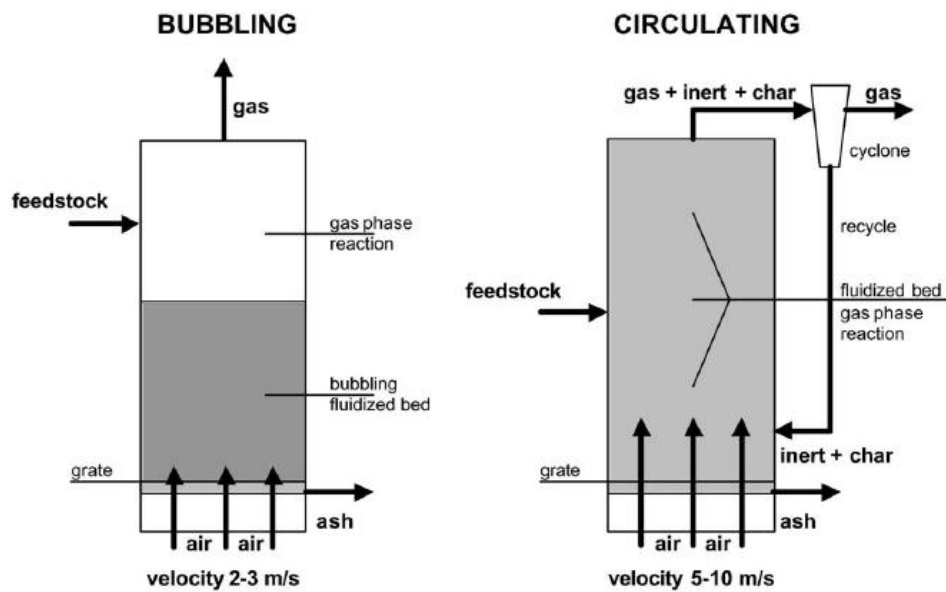


Fig.10. Bubbling and circulating fluidised bed gasifiers [51]

In BFB gasifiers the velocity of the upward flowing gas is lower than in CFB (Fig.10) and the fluidisation of the inert bed, leading to the expansion of the bed, is limited to the lower part of the reactor. In CFB gasifiers the particles are carried upward by the fluidised gas, so that the expanded bed circulates in the reactor itself and occupies the entire reactor chamber. A fraction of sand and char is carried out of the reactor together with the gas stream. This fraction is captured in a cyclone, where the bed material is separated from the gas stream and is returned back to the gasifier [51]. The efficient performance of fluidised bed gasifiers requires a relatively small size of fuel particles to ensure good contact with bed material. Hence, the size of fuel particles should be generally below 80 mm for BFB reactors and below 40 mm for CFB gasifiers. BFB and CFB gasifiers have great fuel flexibility, being able to use fuels of different origin [51], which is, among others, due to high thermal inertia of the bed.

CFB in comparison to the BFB, due to higher gas velocity, gives improved heat transfer and extends char residence time while reducing reactor size and therefore char conversion can be improved and reactor unit costs can be reduced [23].

Entrained flow gasifiers (Fig. 11) convert the mixture of fuel and oxygen into a turbulent dust flame at high temperatures (significantly above 1200°C, even 2000°C) for a very short period of time (a few seconds) and at high pressure (about 50 bar). The typical oxidising agent is oxygen, in order to

reduce the nitrogen content in the gas, and resulting NO_x emissions. In order to achieve high conversion of the feedstock (at a short residence time used) pulverized solid (particle size below 1 mm) or liquid (e.g. pyrolysis oil) feedstock is used.

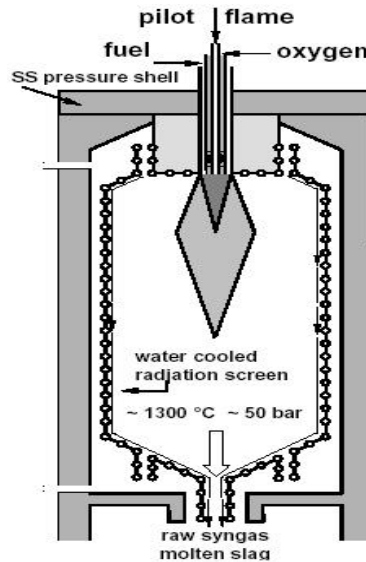


Fig. 11. Example of entrained flow gasifier [52]

Difficulties with ash melting behaviour could occur when solid biomass feedstock is gasified [5]. At such high temperatures the ash will usually be in a liquid phase and part of it will deposit on the walls of the gasifier. The entrained flow gasifiers are designed in a way, that the liquid ashes are moving down and exit the gasifier together with the raw syngas. This behaviour is a result of combination of gasification conditions and fuel properties and therefore, not every biomass type is appropriate to be used in EFG [5]. In addition, producing sufficiently fine powder from biomass for application in entrained flow gasifiers is expensive. Other factors, which contribute to the growth in costs, are the production of pure oxygen and the achievement of the necessary high pressure [52]. Entrained-flow gasification is mature/commercial technology for petroleum residues and beyond the demonstration phase for coal, however for biomass the experience is (very) limited. There are several commercial designs available for coal (GE/ChevTex, Conoco E-gas, Shell), but these will not work with more than 10 to 15% biomass in a coal blend [23]. EFG is used for coal because the gasifier can be slurry fed in direct gasification mode, which makes solid fuel feeding at high-pressures cheap; the slurry feeding however can not be applied to biomass because of its high porosity (lower energy density) and moisture holding capacity in a slurry phase [23]. An entrained flow gasifier could be pneumatically fed, for example for use with sawdust or other finely divided biomass, but the pneumatically fed EFG does not compare to the high pressure feeding benefits achieved by slurry feeding [23]. A company named Emery Energy has hinted at using an entrained flow concept for biomass, but details are not publicly available [23].

Low temperature gasification is a novel gasification concept and is performed in supercritical water (200-400 bar) [54]. Supercritical water gasification is operated at temperatures of 500-700 °C and the process is suitable for processing of a wet feedstock. So far the practical experience with supercritical water gasification is restricted to laboratory/pilot scale experiments [54].

Summary and Conclusions

Currently, the direct co-firing is the most popular option for biomass and coal co-firing, mostly due to relatively low investment cost of turning existing coal power plants into co-firing plants. Parallel co-firing units are mostly used in pulp and paper industrial power plants. The indirect options for co-firing are considered to be expensive, and take long time to be implemented in the European market, as it currently stands. However, when considering the future prospects for co-firing, it might be, that the higher investment in more advanced co-firing configurations would pay back due to the better operability of the system, fuel flexibility and ash utilization possibilities.

Out of three basic types of combustion systems, the application of fluidized bed combustion in co-firing seems to have the highest fuel flexibility regarding moisture content, heating value and ash content, which enables use of fuel mixes and increases the range of fuels to be used in existing power plants.

The state of the art technology for coal gasification is the entrained flow technique (which requires high investments but produces highly immobilized ashes, which makes their reuse readily possible). The well-proven and less costly technology is circulating fluidized bed gasification.

2. Biomass as a feedstock for co-firing

This chapter presents the background information on biomass properties. Different types of biomass feedstocks used in energy systems are presented, biomass and coal properties are compared, and the characteristics of biomass with their relation to specific challenges related to co-firing of biomass with coal are listed.

Biomass is made through photosynthesis process, which uses carbon dioxide from the atmosphere, while releasing oxygen. During photosynthesis the solar energy (light) is captured by pigments in plants and is used to reduce atmospheric carbon dioxide gas into carbohydrates through biological reaction with water [24]. The solar energy is stored in the form of carbohydrate chemicals such as cellulose, hemicellulose and lignin.

Cellulose and hemicellulose are polysaccharides of glucose (i.e. they are polymers of glucose). Hemicellulose has a less ordered structure than cellulose, and can be more easily hydrolyzed to simple sugars and other products. Lignin is an amorphous polymer, and plays an important role in developing structure of the plants [24].

2.1. Biomass feedstocks utilized in energy systems

Biomass feedstocks used for energy purposes can be generally divided into dedicated energy crops and residues (wastes or by-products of various process and activities), and range from woody to grassy materials, as shown in Tab.4.

Examples of common biomass include crop residues (wheat straw, corn stalks, nut shells, orchard prunings, vineyard stakes, sugar cane bagasse, etc.), forest residues (slash, forest thinning), urban wood waste (construction residues, grass clippings and backyard prunings), and several energy crops (Miscanthus, SRC, etc.) [24].

Many different types of biomass can be utilized in co-firing systems. Co-firing experience includes wood, residues from forestry and related industries, agricultural residues, as well as various biomasses in refined form such as pellets, which are especially popular in Denmark and the Netherlands.

Energy crops (plants grown specifically for use as fuels) such as Short Rotation Coppice (SRC) and perennial crops (Miscanthus, switchgrass, reed canary grass), could be perceived as potential candidates for co-firing, however example in Britain shows that none of the energy crop materials are currently available in quantities relevant to co-firing in large power plants (over 50MW_{th}) [41].

It is possible (and practiced) to co-fire imported biomass (usually in form of dried and pelletized wood fuels, which are produced in large quantities in North America, Scandinavia, Russia and in some other Northern European countries) [41]. Also olive processing wastes are available in large quantities, as dry granular or pelletized materials, from countries with large olive oil production (Spain, Italy, Greece, Turkey, Tunisia and Portugal) [41]. The solid residues of the palm oil production

industry in far eastern countries (mainly Malaysia and Thailand) are also available for import into Europe in large quantities [41].

Oil, sugar and starch energy crops can be used for production of liquid fuels with high-energy value (bio-diesel and bio-ethanol respectively) for use in the transport sector and their utilization for power production is not economically justified at current.

Tab.4. Types of biomass feedstocks used for energy purposes, Source [15], [37]

SUPPLY SECTOR	TYPE	EXAMPLE
Agricultural residues	Dry lignocellulosic agricultural residues	Straw (maize, cereal, rice) Sugar beet leaves Residue flows from bulb sector
	Livestock waste	Solid manure (chicken manure) Liquid manure (cattle, pigs, sheep manure)
Dedicated energy crops	Dry lignocellulosic woody energy crops	SRW – willow SRC - poplar Eucalyptus
	Dry lignocellulosic herbaceous energy crops	Miscanthus Switch grass Common reed Reed canary grass Giant reed Cynara cardunculus Indian shrub
	Oil energy crops	Rapeseed Sunflower seeds Soybean Olive-kernel Calotropis procera
	Sugar energy crops	Sugar beet Cane beet Sweet sorghum Jerusalem Artichoke Sugar millet
	Starch energy crops	Wheat Potatoes Maize Barley Triticale Corn (cob) Amaranth
	Others	Flax (Linum) Hemp (Cannabis) Tobacco stems Aquatic plants (lipids from algae) Cotton stalks Kenaf
Forestry	Forestry by-products	Bark Wood blocks Wood chips from tops and branches Wood chips from thinning Logs from thinning
Industry	Wood industry residues	Industrial waste wood from sawmills and Industrial waste wood from timber mills (bark, sawdust, wood chips, slabs, off-cuts)
		Fibrous vegetable waste from virgin pulp production and from production of paper from pulp, including black liquor

	Food industry residues	Wet cellulosic material (beet root tails) Fats (used cooking oils) Tallow, yellow grease Proteins (slaughter house waste)
	Industrial products	Pellets from sawdust and shavings Briquettes from sawdust and shavings Bio-oil (pyrolysis oil) Ethanol Bio-diesel
Parks and Gardens	Herbaceous	Grass
	Woody	Pruning
Waste	Contaminated waste	Demolition wood
		Biodegradable municipal waste
		Sewage sludge
		Landfill gas
		Sewage gas
Others	Roadside hay	Grass/hay
	Husks/Shells	Almond Olive Walnut Palm pit (imported) Cacao (imported)

Explanation of feedstock categorization in the table: dry lignocellulosic feedstock is the category of feedstock, which can be used for thermo chemical conversion (gasification, combustion and liquefaction). Wet lignocellulosic feedstock is a feedstock that can be used for biological conversion (digestion)

Source [15], [37]

2.2. Properties of biomass in relation to co-firing

Generally biomass has proximate analysis of 80% volatile matter and 20% fixed carbon (moisture free and ash free basis), whereas e.g. group-1 bituminous coal has 70-80% fixed carbon and just 20-30% volatile matter [24, 47]. Fig.12. schematically explains the concept of proximate analysis and other types of fuel analysis.

As shown in Tab. 5, the composition of coal differs greatly from that of biomass feedstocks [47], and different types of biomasses show differences within the group, especially with regard to moisture and ash content.

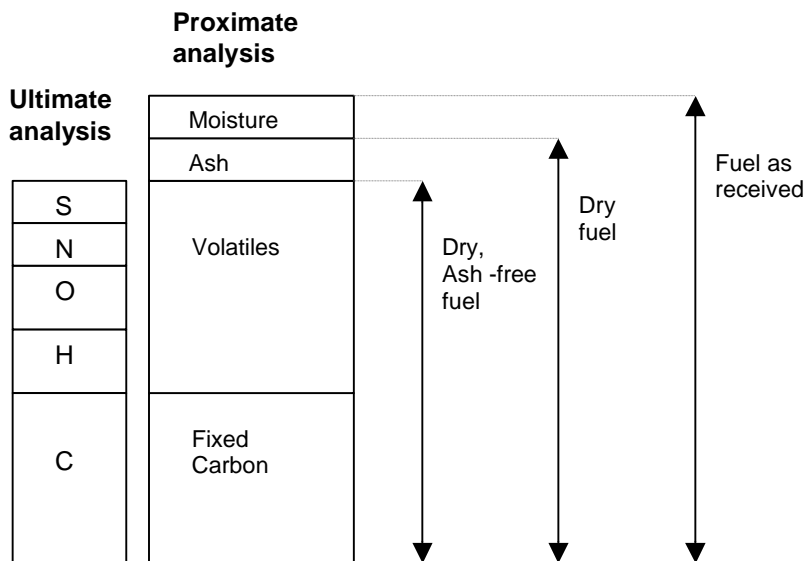


Fig. 12. Types of fuel analysis indicating various ways of characterization of fuels, Source [47]

Tab.5. Typical properties of different solid fuels - CEN-335- Solid biofuels, Fuel specifications and classes, March 2003, Source [47]

Property	Coal	Peat	Wood without bark	Bark	Forest residues (coniferous tree with needles)	Willow	Straw	Reed canary grass (spring harvest)	Olive residues
Ash content (db)	8,5-10,9	4-7	0,4-0,5	2-3	1-3	1,1-4,0	5	6,2-7,5	2-7
Moisture content (w%)	6-10	40-55	5-60	45-65	50-60	50-60	17-25	15-20	60-70
NCV (MJ/kg)	26-28,3	20,9-21,3	18,5-20	18,5-23	18,5-20	18,4-19,2	17,4	17,1-17,5	17,5-19
C, %db	76-87	52-56	48-52	48-52	48-52	47-51	45-47	45,5-46,1	48-50
H, %db	3,5-5	5-6,5	6,2-6,4	5,7-6,8	6-6,2	5,8-6,7	5,8-6,0	5,7-5,8	5,5-6,5
N, %db	0,8-1,5	1-3	0,1-0,5	0,3-0,8	0,3-0,5	0,2-0,8	0,4-0,6	0,65-1,04	0,5-1,5
O, %db	2,8-11,3	30-40	38-42	24,3-40,2	40-44	40-46	40-46	44	34
S, %db	0,5-3,1	<0,05-0,3	<0,05	<0,05	<0,05	0,02-0,10	0,05-0,2	0,08-0,13	0,07-0,17
Cl, %db	<0,1	0,02-0,06	0,01-0,03	0,01-0,03	0,01-0,04	0,01-0,05	0,14-0,97	0,09	0,1 (in ash)
K, %db	0,003	0,8-5,8	0,02-0,05	0,1-0,4	0,1-0,4	0,2-0,5	0,69-1,3	0,3-0,5	30 (in ash)
Ca, %db	4-12	0,05-0,1	0,1-1,5	0,02-0,08	0,2-0,9	0,2-0,7	0,1-0,6	9	no data

db – dry basis

Biomass usually has high moisture content resulting in a relatively low calorific value of the fuel [16, 47]. Fresh wood typically contains 50% of water by weight, whereas the moisture content for bituminous coals is approximately 5% [47]. Moisture content of biomass affects its combustion properties. Higher moisture content will reduce the maximum combustion temperature and increase the necessary residence time of feedstock in a combustion chamber, and consequently could result in an incomplete combustion and increased emissions related to it (volume of flue gas produced per energy unit) [15].

Typically biomass contains fewer ashes than coal and their composition is based on the chemical components required for plant growth, whereas coal ashes reflect the mineralogical composition [34]. In both coal and biomass, ash-forming matter can be present in four general forms: easily leachable salts, inorganic elements associated with the organic matter of the biomass, minerals included in the fuel structure and inorganic material - typically sand, salt or clay [47].

Alkaline metals that are usually responsible for fouling of heat transfer surfaces are high in biomass ashes and are released in the gas phase during combustion [47]. In biomass these inorganic compounds are in the form of salts or bound in the organic matter, but in peat, for example, inorganic matter is bound mostly in silicates, which are more stable at high temperature [47]. The elemental composition of ash (alkali metals, phosphorus, chlorine, silicon and calcium) affects ash-melting behavior [47]. Even a small concentration of chlorine in the fuel can result in deposition of harmful alkaline and chlorine compounds on boiler heat transfer surfaces [47].

With regard to chemical properties of biomass, it generally has less sulphur, fixed carbon, and fuel bound nitrogen, but more oxygen than coal [34].

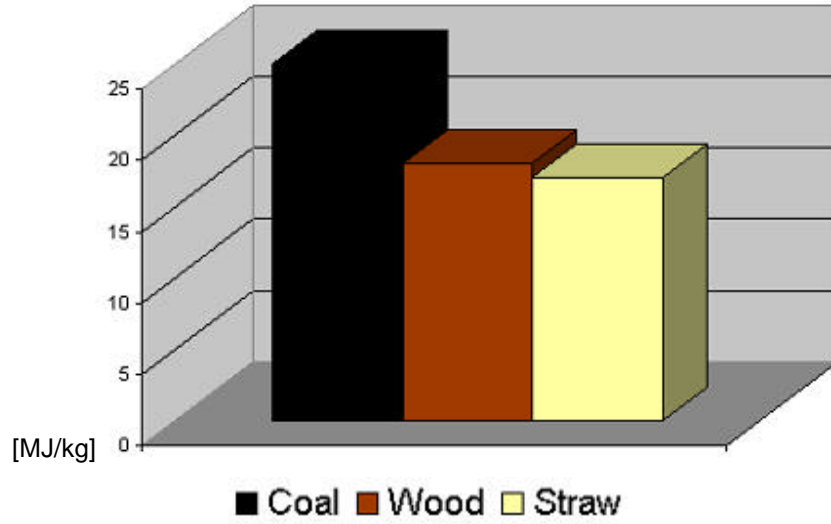
Another characteristics of biomass is that it usually has low bulk energy density (Fig. 13), hydrophilic and non-friable character [21].

Physical and chemical characteristics of biomass and their influence on co-firing are presented in Tab.6.

According to [47] most of the challenges that co-firing poses to boiler operation originate from fuel properties (the differences in characteristics of coal and biomass) and can be summarized as follows [106]:

- Pyrolysis starts earlier for biomass than for coal
- The volatile matter content of biomass is higher than in coal
- The fractional heat contribution by volatile substances in biomass is approximately 70% compared with 30-40% in coal
- The specific heating value [kJ/kg] of volatiles is lower for biomass compared with coal
- Biomass char has more oxygen compared with coal and it is more porous and reactive
- Biomass ash is more alkaline in nature, which may aggravate the fouling problems
- Biomass can have high chlorine content.

Heating values of straw, wood, and coal



Energy density of straw, wood, and coal

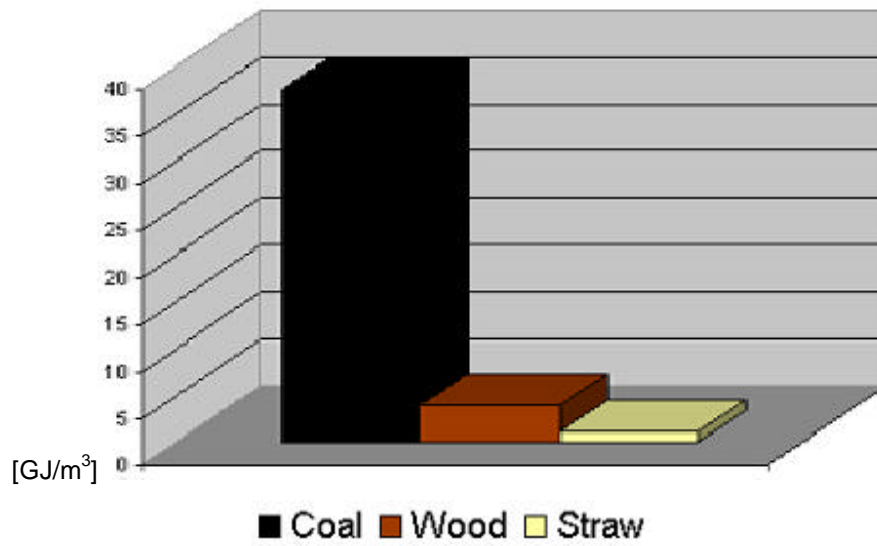


Fig.13. Heating values [MJ/kg] and energy density [GJ/m³] of coal and biomass

Tab.6. Physical and chemical characteristics of biomass feedstocks and their effects on co-firing, Source: [15, 42]

	Properties	Effects
P H Y S I C A L	Moisture content	Storage durability Dry-matter losses Low NCV Self ignition
	Bulk density	Fuel logistics (storage, transport, handling) costs
	Ash content	Dust, particle emissions Ash utilization/disposal costs
	Particle dimension and size distribution	Determines fuel feeding system Determines combustion technology Drying properties Dust formation Operational safety during fuel conveying
C H E M I C A L	Carbon C	GCV (positive)
	Hydrogen H	GCV (positive)
	Oxygen O	GCV (negative)
	Chlorine Cl	Corrosion
	Nitrogen N	NO _x , N ₂ O, HCN emissions
	Sulphur S	SO _x emissions, corrosion
	Fluor F	HF emissions Corrosion
	Potassium, K	Corrosion (heat exchangers, superheaters) Lowering of ash melting temperatures Aerosol formation Ash utilization (plant nutrient)
	Sodium, Na	Corrosion (heat exchangers, superheaters) Lowering ash melting temperatures Aerosol formation
	Magnesium, Mg	Increase of ash melting temperature Ash utilization (plant nutrient)
	Calcium, Ca	Increase of ash melting temperature Ash utilization (plant nutrient)
Phosphorus, P	Increase in ash melting point Ash utilization (plant nutrient)	
Heavy metals	Emissions of pollutants Ash utilization and disposal issues Aerosol formation	

Summary and conclusions

Biomass has usually high moisture content resulting in a relatively low calorific value of the fuel, which might negatively affect its combustion properties. Additionally biomass feedstocks have low bulk density and potentially high chlorine content as well as hydrophilic character. Biomass properties which set demanding requirements for power plant include total ash content, its melting behavior and chemical composition - typically biomass contains fewer ashes than coal but alkaline metals that are usually responsible for fouling of heat transfer surfaces are high in biomass ashes.

Raw biomass has much lower bulk density than coal resulting in expensive storage, transport and handling, and has non-friable character resulting in problems with biomass grindability. Most of the challenges that co-firing poses to boiler operation originate from biomass properties and therefore improving the properties e.g. by pre-treatment can be applied as one of the measures to avoid or reduce these challenges.

3. Environmental performance of co-firing of biomass with coal

This chapter presents the main environmental considerations related to co-firing of biomass with coal. Results from a number of Life Cycle Analysis of co-firing systems utilizing biomass with coal are summarized. The impacts on emissions to air are described. Finally, the possibilities for utilization of ash produced by different co-firing configurations are presented.

3.1. Environmental performance of co-firing systems

In general, biomass is considered to be CO₂-neutral fuel [15, 76, 90], meaning that combustion of biomass should not increase the CO₂ level in the atmosphere, because the amount of CO₂ emitted during conversion process equals the CO₂ which was assimilated into the plants during the process of their growth (where both processes took place within relatively small period of time³). However, the concept of biomass being a neutral fuel is only true, if we do not include the emissions related to biomass harvesting, transportation, pre-treatment etc., and when the total carbon sequestered in the atmosphere remains constant (the cycle of growth and harvest is maintained).

In order to properly estimate the environmental consequences of co-firing, life cycle analyses should be applied, to make sure that not only the energy conversion-related impacts are included, but also other potential environmental burdens along the whole life cycle of biomass are considered. The Life Cycle Assessment studies (see Annex) show in general, that the use of biomass for electricity generation results in environmental benefits in comparison with coal-based systems [56, 57, 58, 59, 60, 61, 63, 64]. These environmental profits include reduction in CO₂ emissions [56, 57, 58, 62]. Co-firing of biomass with coal reduces the emissions of greenhouse gasses (GHG) and traditional pollutants (SO₂, NO_x) [90]. SO_x emissions almost always decrease due to co-firing of biomass with coal, often proportionally to biomass thermal load, as most biomasses contain less sulfur than coal [3, 16, 21, 41]. NO_x emissions can increase, decrease or remain the same when co-firing biomass with coal [3, 16, 21, 41] and the effect is varying with biomass type, firing and operating conditions [21]. For example wood contains relatively little nitrogen and therefore co-firing of coal with wood tends to decrease the total NO_x emissions⁴ [3, 21].

According to the study of Christiansen and Fock the procurement of biomass is generally a less energy consuming process than that of fossil fuels (and coal in particular) [56]. Assuming the above are correct for all bio-systems, utilization of biomass instead of coal, whether in stand-alone or co-firing option, should always bring environmental benefits.

³ By contrast, fossil fuels locked up their carbon over millions of years, a process now being reversed over a period of centuries [76]

⁴ It is sometimes suggested that co-firing of coal with biomass has 10% higher reduction of NO_x emissions (than suggested by the displacement effect of the fuels only), as a consequence of ammonia release, however the industrial experience does not seem to confirm this [21].

It is likely though, that each of the above studies have applied rather different boundary conditions to the analyzed system or have assumed different impacts associated with certain elements in the analyzed chains. For example, if the environmental impact of storage is omitted in one study, and the other study assumes emissions of N₂O from stored biomass as estimated in [35], the impact on the final result with regard to GHG emissions could vary significantly. In this case even small amounts of N₂O emitted during storage of biomass could lead to 310 times higher impact expressed in CO_{2eq} (GWP of N₂O is equal to 310).

Additionally, as mentioned before, and as will be discussed in detail in Chapter 4, there may be various constraints associated with biomass co-firing such as fuel preparation, handling, feeding, unstable combustion, deposit formation, corrosion, erosion, ash deposition and fly ash utilization [21, 44, 47, 49]. Addressing these challenges could result in certain environmental impacts (e.g. if due to corrosion, certain elements of the system need to be replaced, the impact related to disposal of the worn-out element as well as the impact of production of new element should be accounted for in the impact assessment).

Since many of the mentioned problems can be, to a certain extent, mitigated by application of biomass pre-treatment (which is already practiced in some countries e.g. use of pelletized biomass for co-firing in the Netherlands and Denmark), the investigation of environmental impacts of biomass pre-treatment should be given more attention. Further information on environmental impacts related to specific biomass pre-treatments and other elements of the biomass supply chain can be found in Chapter 6.

The above considerations do not imply that the results of the quoted studies are not correct, but underlines that each system utilizing biomass for energy purposes need careful analysis, and its results cannot be simply extended to all other bio-energy systems.

3.2. Ash production and their utilization issues

Current experiences indicate that direct co-firing is possible up to 5-10% of the calorific value of the coal input [2, 15, 67]. Along with increasing biomass utilization in energy production systems such as co-firing, the issue of ash from the combustion process gains significance.

Ash contents of different biomass fuels can vary significantly (Tab.7). Straw and other herbaceous fuels like Miscanthus or grass have usually higher ash contents than wood because they uptake relatively more nutrients during growth. In case of wood fuels, the bark content in the fuel has an influence on the ash content of the fuel, as bark has higher ash content and higher level of mineral impurities such as sand and soil [15].

Tab.7. Ash content of different biomass fuels

Biomass fuel	Ash content (%wt, d.b.)
Bark	5-8
Wood chips with bark (forest)	1-2.5
Wood chips without bark (industrial)	0.8-1.4
Sawdust	0.5-1.1
Waste wood	3-12
Straw and cereals	4-12
Miscanthus	2-8, 8-22
Coal	5-45 (8.5-10.5 on average)

Source [15, 47, 93, 18]

As discussed in Chapter 1, the direct co-firing configuration produces mixed biomass and coal ash, whereas parallel co-firing and indirect co-firing options produce separate biomass and coal ashes. Therefore utilization options for each types of ash (single coal, single biomass, and mixed biomass with coal) are important issues from the viewpoint of environmental performance of co-firing systems, and are discussed below.

3.2.1. Possibilities for utilization of coal ash

The Coal Combustion Products (CCP) include fly ash, bottom ash, boiler slag and fluidized bed combustion ashes. Almost 68% of the total CCPs in EU 15 is produced as fly ash (Fig. 14).

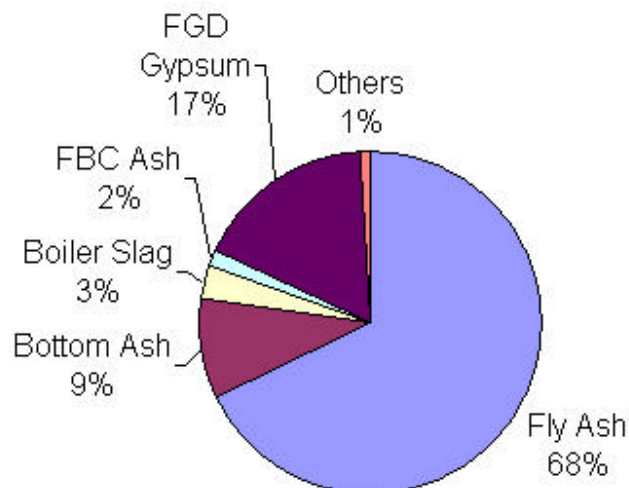


Fig. 14. Production of Coal Combustion Products in EU 15 in 2003 (Total production 65 million tonnes), Source [25]

Practically all of the produced boiler slag and around half of produced fly ash, bottom ash and FBC ash is utilized in the construction industry and underground mining, the other half mostly in restoration

of open cast mines, pits and quarries (Tab. 8). In case of FBC ash, almost 29% has to be disposed, the same applies to around 3% of fly ash and 10% of bottom ash [25]. The above data were based on situation in EU15 in 2003, when the total coal combustion products amounted to 65 million tonnes. In the New Member States the total amount of those products is estimated to be about 30 million tones annually, where most of the fuel burned is sub-bituminous coal or lignite [25].

Tab.8. Utilization and disposal of Coal Combustion Products in EU 15 in 2003 (Total amount 65 million tones), Source [25]

Utilization in construction industry and underground mining	Restoration of open cast mines, pits and quarries	Temporary stockpile	Disposal
52.4%	35.6%	8.0%	3.7%

According to the *European Coal Combustion Products Association* [25] around 30% of fly ashes produced from coal in EU 15 are used as concrete addition and are replacing a part of the cement in concrete. The European Standard EN 450 “*Fly ash for concrete*” is very important because concrete application provides the highest added value for fly ash [25]. EN 450 originally refers only to fly ash of coal origin [25, 92]. In the last few years, the revision of this standard took place [25, 79, 92]. The changes are related to utilization possibilities for ashes originating from co-combustion of biomass and coal, and are described further.

3.2.2. Possibilities for utilization of biomass ash

There are many ongoing research activities focused on characterization of biomass ashes and assessment of the possibilities for their utilization. This section is based mainly on results of the BIOAS and GASASH projects completed at ECN in the Netherlands (the latter project together with VTT, Foster Wheeler, AICIA, PVO and Essent Energy Production), presented in [66].

In case of grate stokers, 95% of the ash produced is the bottom ash consisting of slags, sand and unburned wood, whereas the rest is fly ash contaminated with heavy metals [66].

In case of FBC, the share of bottom ash, in the total amount of ash produced, amounts to 20-30%, the remaining 70-80% is the fly ash [15]. Bottom ash consists mainly of sand, bed material and ash from the fuels, and fly ash contains lots of fuel-bound ash and some fragmented sand [66].

Recycling of biomass ash

Biomass contains only those inorganic elements which have been extracted from the environment where it was grown, thus returning those components in a form of ash, to a place where it originated, closes the mineral cycles, and is the most sustainable form of ash utilization [91].

According to [15] currently the biomass ash produced is either disposed or recycled on agricultural fields or forests, however generally recycling is not a controlled practice. In Finland, Sweden and

Austria it is legally possible, through national legislation, to recycle wood ash in forestry [9, 66, 91]. In Denmark, Austria and Germany wood ash can be utilized in agricultural applications (in Denmark also ash from combustion of straw can be recycled to the field of origin) [91]. Existing Dutch regulations do not allow this form of recycling [91].

Setting up a close ash recycling system for agriculture might be difficult, because ashes have unpredictable composition and possibly large amounts of heavy metals compared to nutrients [92].

If the recycling option (returning biomass ashes to the place where biomass was harvested) is not possible, there are basically three main options for biomass ash utilization [66]: as a fertilizer, as building material and as a fuel.

Utilization of biomass ash as fertilizers or for fertilizers production

Potentially ashes could be used as soil improvers, especially when originating from combustion or gasification where dolomite has been used as bed material, because they are rich in Mg and Ca [66]. However there are a number of factors constraining utilization of biomass ash as fertilizers. Biomass ashes cannot be considered as complete fertilizers due to lack of nitrogen and soluble phosphorus⁵, low nutrient content in comparison with heavy metals, and high inert content [66, 91]. Biomass ashes could be used as a raw material for fertilizers production, however the same disadvantages apply. In both cases, the quality of ashes should be monitored. The concentrations of plant nutrients in ashes from various biomass fuels and the concentration of heavy metals in various biomass ashes are shown in Tab. 9 and Tab. 10.

Except for direct application of ash as fertilizer, there is also an option of indirect utilization by adding biomass ash to agricultural compost [15]. The benefits of this option are not clear, as it is not yet applied at a sizeable scale.

In order to provide a usable product to a farmer, ash pre-treatment can be applied to guarantee the right chemical composition and to make it distributable with conventional manure spreaders [15]. A technology for pre-treatment of biomass ash, used and tested in Sweden, is production of ash granules by hardening the ash with water, which reduces dust formation during ash manipulation and spreading, and also makes the ash more soil-like thanks to reduced leaching of nutrients from the ash (which decreases shock effects on the plants) [15]. More on ash pre-treatment for fertilizer applications can be found in [10].

Often even clean biomass produces fly ash with high heavy metals content and bottom ash with low nutrient content and sometimes a lot of sand, thus in practice the utilization of biomass ash as fertilizer faces many difficulties, but there is potential for development [66].

⁵ Out of the main components of fertilizers (N,P,K), biomass ashes are mainly source of K.

Tab. 9. The average values for concentrations of plant nutrients in various ash fractions of different biomasses Source: Based on [15]

Nutrient	Average concentration % (d.b.) in various ash fraction of bark, wood chips and sawdust combustion plant			Average concentrations % (w/w/ d.b.) in various ash fractions of straw and cereal combustion plants			Average concentrations % (w/w/ d.b.) in various ash fractions of combustion plants using wood residues and waste wood		
	Bottom ash	Cyclone fly ash	Filter fly ash	Bottom ash	Cyclone fly ash	Filter fly ash	Bottom ash	Cyclone fly ash	Filter fly ash
CaO	41.7	35.2	32.2	7.8	5.9	1.2	31.1	28.5	16.7
MgO	6.0	4.4	3.6	4.3	3.4	0.7	2.8	3.0	0.5
K ₂ O	6.4	6.8	14.3	14.3	11.6	48.0	2.3	2.7	7.5
P ₂ O ₅	2.6	2.5	2.8	2.2	1.9	1.1	0.9	1.4	0.4
Na ₂ O	0.7	0.6	0.8	0.4	0.3	0.5	1.1	1.1	3.3

Tab.10. Average concentrations of heavy metals in various ash fraction of various biomass fuels, Source: Based on [15]

Element	Average concentration in mg/kg (d.b.) in various ash fractions of bark, wood chips and sawdust incineration			Average concentration in mg/kg (d.b.) in various ash fractions of straw combustion plants			Average concentration in mg/kg (d.b.) in various ash fractions of waste wood incineration		
	Bottom ash	Cyclone fly ash	Filter fly ash	Bottom ash	Cyclone fly ash	Filter fly ash	Bottom ash	Cyclone fly ash	Filter fly ash
Cu	164.6	143.1	382.9	17.0	26.0	44.0	1234.0	437.0	422.0
Zn	432.5	1870.4	12980.7	75.0	172.0	520.0	6914.0	15667.0	164000.0
Co	21.0	19	17.5	2.0	1.0	<1.0	21.0	30.0	5.0
Mo	2.8	4.2	13.2	<10.0	<10.0	10.0	7.0	11.0	11.0
As	4.1	6.7	37.4	<5.0	<5.0	22.0	17.0	59.0	104.0
Ni	66.0	59.6	63.4	4.0	<2.5	<2.5	179.0	167.0	74.0
Cr	325.5	158.4	231.3	13.5	17.5	6.8	466.0	1415.0	404.0
Pb	13.6	57.6	1053.3	5.1	21.5	80.0	2144.0	8383.0	50000.0
Cd	1.2	21.6	80.7	0.2	1.8	5.2	20.0	70.0	456.0
V	43.0	40.5	23.6	<10.0	<10.0	<10.0	171.0	260.0	153.0
Hg	0.01	0.04	1.47	<0.1	<0.1	0.7	<0.5	0.7	<0.5

Utilization of biomass ash in building applications [66, 91]:

Direct utilization of biomass ash in building applications might be possible only for some types of bottom ash from biomass combustion; other ashes might be used as raw material in the production of building materials [91].

Bottom ashes from fluidized bed combustion or gasification (which contain a lot of sand) could be utilized as building material to replace sand and granulates in road construction and landscaping.

The bottom ash in case of stokers and EFG could be made into granulate and be used in concrete and road construction.

Fly ashes from combustion of biomass are not likely to find a direct application as building material, because they have a powder-like form, so it cannot replace particles like sand or gravel. It could be utilized as component in cement or concrete, but the alkali and chlorine content can be problematic.

One of potential utilization for biomass fly ash is their application as fillers in cement blends and mortars for special applications such as road construction or waterways.

Fly ashes from biomass gasification in fluidized bed are not possible to be utilized in building industry practically at all, however they were successfully tested as fillers in production of concrete-like material (blocks) called C-FIX (for use as pavement), with heavy petroleum residue as a binder.

Utilization of biomass ash as a fuel [66]:

Utilization as a fuel for power and heat generation is possible for ashes with high energy content, thus basically only the fly ashes from fluidized bed gasification of biomass can qualify for this. These ashes have high calorific value due to high amounts of unburned carbon, and are hydrophobic.

According to the estimates in [66], utilization of ashes as a fuel is the best option for carbon-rich ashes, from the economical point of view. Ashes can be reused as fuel directly in a form of a fine powder (in PF boiler), or compacted by pelletisation or granulation. Ashes in forms of pellets, briquettes or granules have the following advantages: their volume is reduced by factor 4-6, they can be stored in ambient air, and the health and safety risks (e.g. dust explosion) are reduced [66]. This application is not commercial as it currently stands, and usually the carbon material is being used to produce heat to vitrify the ash material and to immobilize the leachable components in the ash.

In all above cases, the consistency of ashes quality is a key factor for successful applications, and the ash needs to be provided in quantities high enough, to boost interest and development of ash utilization options [66]. There is no universal solution for biomass ash and the right option needs to be found on case by case basis [66].

The least preferred option (from environmental point of view) is ash landfilling. Ash disposal prices vary between sources and countries. According to [15] the disposal price for wood ash is 200-500 Euro /tonne. According to [66] bottom ash or sintered ash can be disposed at 100 Euro/tonne and fly ash from 50-300 Euro/tonne and is very often the most cost-effective alternative [66]. In some countries ash landfilling is free of charge.

3.2.3. Possibilities for utilization of mixed biomass/coal ash

In the direct co-firing configuration the produced ashes are a blend of biomass and coal ashes, which might restrict their re-use options described previously.

The direct co-firing configuration, being the cheapest option with regard to capital investment costs when adapting coal power plants to co-firing, is the most often practiced solution.

Most of the fly ashes generated through stand-alone coal combustion are used in a cement (and further concrete) production [16]. According to [16] the technical case of prohibiting the use of mixed ashes from co-firing wood with coal for above application appears to be unjustified. While in case of

herbaceous biomass, the data suggest that alkali, chlorine and other properties may compromise a number of important properties of concrete [16].

The results of the impact of herbaceous biomass-derived ashes on concrete properties are presented in study of Larry Baxter [21] where 25% of cement used in concrete is replaced by fly ash containing up to 40% herbaceous biomass-derived material. The general conclusion was that biomass containing fly ashes behave qualitatively similar to coal-derived ashes in terms of structural and performance properties when incorporated into concrete [21].

The concluded impacts of biomass-containing fly ash on concrete properties are manageable and the amount of aerating agent is defined as the only issue requiring monitoring (entrainment of air in concrete plays crucial role in preventing failure during freeze-thaw cycles, and the amount of aerating agent appears to increase with herbaceous biomass content) [21]. If fly ashes from co-firing would be used for concrete production in the same way as ashes from coal combustion, the concrete would fail under freeze-thaw cycles [3].

The European Standard EN 450 "Fly ash for concrete" from 1994 refers to siliceous fly ash only (less than 10% of reactive CaO content by mass) [25]. In 2004 CEN members voted in favor of a revised version of a standard, EN 450-1 [25, 79]. This revised version includes some fundamental amendments, one of them regarding the acceptance of the fly ash obtained from co-combustion [25, 79], defined as "*ash obtained from a mixture of pulverized coal and co-combustion materials, where the minimum percentage, by dry mass, of coal is greater than 80% and where the maximum proportion of ash derived from co-combustion material does not exceed 10%*" [92]. Materials for this co-combustion are certain types of biomass and waste, as listed below [25, 92]:

- Material like wood chips, straw, olive shells and other vegetable fibers
- Animal meal
- Municipal sewage sludge
- Paper sludge
- Petroleum coke
- Virtually ash-free liquid and gaseous fuels

The amount of ash derived from the co-combusted material shall not exceed 10% and this has to be proven by testing the fly ash from co-combustion in the boiler, using the highest intended amount of co-combustion material [25]. In addition, before the ash is used in concrete, its environmental compatibility has to be demonstrated, meeting the requirements in place of fly ash use (the requirements regarding the environmental impact of ash are not harmonized on the European level yet) [25]. If the standards regarding either the kind or amount of co-combustion material are not met, the producer can apply for a European Technical Approval (ETA), which is granted if more detailed, compared to EN 450-1, testing of the fly ash has proven that it is environmentally compatible and that its relevant properties are not affected by the co-combustion [25].

This possibility was used in the Netherlands, a country where fly ashes with higher percentages of co-combustion materials, than those listed in EN 450, were used for years⁶ [92, 94]. A European Technical Approval (ETA) was awarded in October 2004⁷ [92]. ETA sets no limitation to types of co-combustion materials, the maximum percentage of co-combustion material is 40% by mass, and the maximum proportion of ash derived from co-combustion materials is limited to 35% by mass [92]. In the Netherlands, the utilization of ash is the only option anyway, as landfilling of fly ash is not allowed [92]. In one Dutch power plant the mixed ashes coming from direct co-firing of coal with biomass are used for manufacturing of lightweight aggregates such as Lytag aggregates [66] to be used in concrete floors.

Summary and conclusions

Biomass is considered to be a CO₂-neutral fuel, when emissions related to harvesting, transportation, and other elements of biomass supply chain are not included. The review of Life Cycle Assessment studies in general concludes that, in comparison with coal-based systems, the use of biofuels for electricity generation results in environmental benefits. However every system needs individual analysis, as there may be various challenges encountered during co-firing and addressing them can cause certain environmental impacts e.g. in case of co-firing biomass with high Cl content, the impacts related to dealing with increased corrosion in the system (if appeared) would need to be accounted for.

Concerning the emissions related to co-firing of biomass with coal (conversion process itself), SO_x emissions usually decrease, often proportionally to the biomass thermal load, whereas NO_x emissions can increase, decrease or remain the same depending on fuel type, firing and operating conditions.

The issue of utilization of ash from co-firing systems deserves special attention. In indirect co-firing as well as parallel combustion, the ashes produced in the process are kept separately. In case of direct co-firing, coal and biomass ashes are mixed.

Ashes from single coal combustion are mostly utilized in the construction industry. Ashes from biomass combustion can be recycled to the place of origin of biomass, utilized as fertilizer, as building material, and as a fuel for power and heat generation. The last option is possible only for biomass ashes with high energy content, thus basically for the fly ashes from fluidized bed gasification of biomass (however after their use as a fuel, the ashes still remain). There are a number of factors constraining utilization of single biomass ash in these

⁶ When EN 450 allowed only ash from coal combustion to be used for concrete production, the Netherlands, after special investigations, had additional regulations (CUR Recommendations) allowing utilization of fly ash from co-combustion [92]

⁷ ETA was awarded after agreement of all EOTA (European Organization for Technical Approvals) bodies and the European Commission, through the CUAP (Common Understanding of Assessment Procedure) [92]

applications, but the potential exists. Ash landfilling is frequently the most cost-effective alternative.

The case of mixed biomass and coal ashes is often problematic, as mixed ashes are neither completely appropriate for single biomass ash applications, nor are they easy to be utilized in the same applications as single coal ash. Until recently (and in most EU countries until now) the standard (EN 450) for fly ash application in concrete, which is the main destination of ash from coal combustion, did not allow ash from other origins than coal. This standard was revised recently and includes amendment regarding the acceptance of the fly ash obtained from co-combustion. The option to utilize mixed ash in concrete production is fully used in the Netherlands, but in many other European countries, the possibility does not exist at current. Therefore, when analyzing the environmental impacts of co-firing systems, the options for ashes utilization should be included in the assessment.

4. Constraints related to co-firing of coal with biomass

This chapter describes the main difficulties and constraints that may appear in systems co-firing of coal with biomass. Difficulties related to supply of biomass and handling of biomass in the power plant are discussed. The main technical challenges are listed and explained. Finally, the measures applied to mitigate the difficulties related to co-firing are discussed.

Co-combustion of biomass and coal may face many challenges, which, among others, include fuel preparation, handling, storage issues, milling, feeding, different combustion behavior, possible changes in overall efficiency, deposit formation (slagging and fouling), agglomeration and sintering, corrosion and/or erosion and consequently changes in life-time of equipment, ash utilization issues and overall economics [21, 44, 47, 49]. The above listed problems need not to be encountered in every system. In systems with proper combination of technology, biomass, and coal they are likely not to be an issue, as is usually the case in systems co-firing clean biomass at low ratios. However the importance of these challenges increases with trends to raise the biomass/coal ratio, and utilize low quality biomass, especially in direct co-firing systems.

Different types of difficulties (challenges) can be faced depending on:

- Co-firing configuration - e.g. in direct co-firing systems, the milling of biomass can become a problematic issue, for a number of reasons. Existing coal mills have certain capacity while the calorific values of biomass are on average half of that of coal. This can create the limitation to the amount of biomass that can be co-milled with coal in existing mills, and consequently co-fired. Moreover, coal mills or pulverizers cannot process certain types of biomass, due to its fibrous nature. These problems are not likely to be often faced in indirect or parallel co-firing configurations, as the biomass is milled and delivered to the boiler by an independent line (such dedicated line could also be introduced to direct co-firing system), however other issues are challenging there. Some typical technical problems that may be associated with some direct and in-direct co-firing systems are presented in Fig. 15a and Fig.15b.
- Combustion or gasification equipment – e.g. in grate furnaces, mixtures of fuels with different combustion behaviors such as blends of wood fuels with straw cannot be combusted together, whereas fluidized bed combustion systems are more fuel flexible, but may face different problems, such as bed agglomeration.
- The type of biomass used – herbaceous biomass is difficult to size in coal pulverizers or mills, it has high chlorine and alkali content, potentially causing corrosion problems and deposit formation, whereas wood biomass contains less ash and alkali components, which makes this type of biomass a preferred feedstock.

Another way to systematically address the difficulties in co-firing systems is by analyzing where, in the biomass-to-energy chain, the problem is encountered. Challenges can occur during supply of

biomass (e.g. high transportation costs due to low energy density of biomass, self-heating and dry matter losses of biomass during storage), or in the power plant. The latter can be faced at point of the biomass delivery system (storage, handling, milling, feeding), or during conversion process itself (slagging, fouling, etc.) and finally during dealing with the residues from the process (ash utilization issues).

Last but not least there may also be a number of non-technical constraints related to biomass/coal co-firing, such as legislative aspects or negative public perception.

Following, a short characterization of different possible problems associated with coal/biomass co-firing systems is presented. Not all (or any) of the following constraints need to appear in every co-firing system.

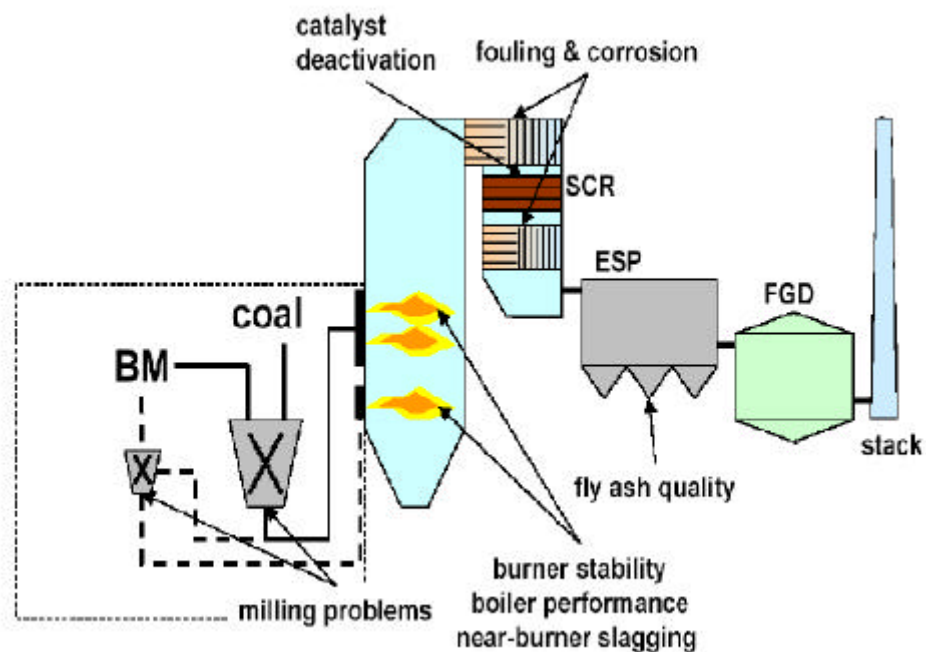


Fig. 15a. Possible bottlenecks in direct co-firing option, Source [67] with approval

Explanations: BM-Biomass, SCR-Selective Catalytic Reduction, ESP-Electrostatic Precipitator, FGD-Flue Gas Desulphurisation

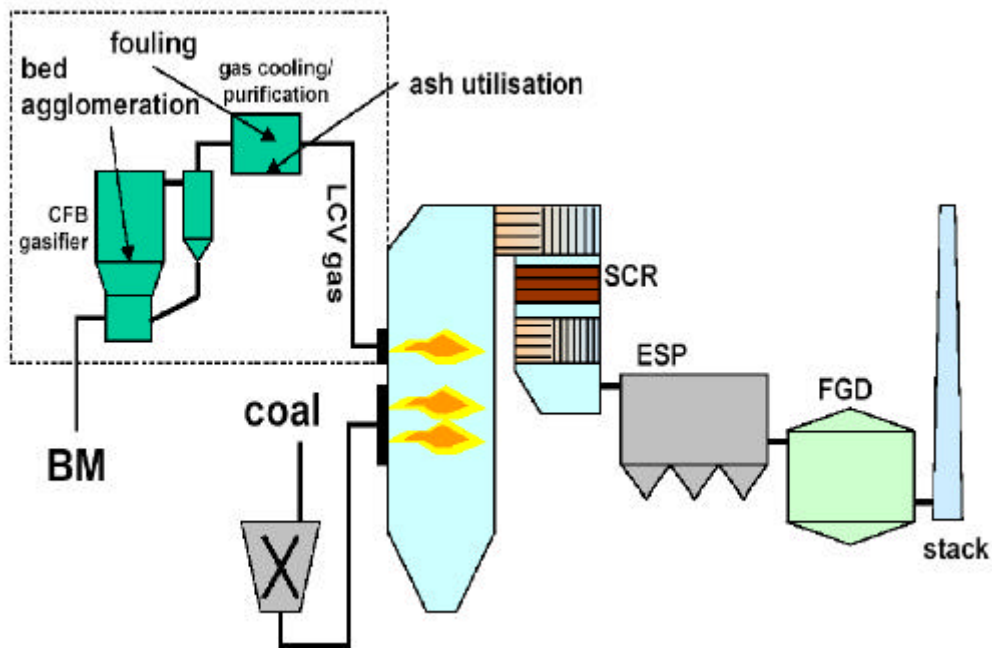


Fig. 15b. Possible bottlenecks in indirect co-firing option, Source [67] with approval
 Explanations: BM-Biomass, SCR-Selective Catalytic reduction, ESP-Electrostatic Precipitator, FGD-Flue Gas Desulphurisation.

4.1. Issues related to supply of biomass

Biomass supply chain consists of (some of) the following elements: transportation, handling, storage, sizing, pre-processing (drying and/or other pre-treatment), and feeding.

Transportation, receiving, handling, storage, pre-processing, and feeding of (especially raw) biomass can cause problems [21, 33, 41]. For example, receiving, handling and storage of fresh wood chips or other wet fuels may cause odour or spore element emissions [33]. Preparation, storage and handling of raw biomass are difficult due to often high moisture content, hydrophilic and non-friable character, particle size variation and high fiber content [21, 47], as well as susceptibility to rotting and heating [67]. More on the properties of biomass is discussed in Chapter 2.

4.1.1. Storage of biomass is usually necessary, in order to guarantee its continuous supply to the co-firing power plant during the year. There are a number of issues associated with storage. During storage, biomass can change its moisture content, energy value and dry matter content due to degradation processes (microbiological activity) [35]. The storage conditions can have considerable influence on biomass properties essential for its energy use [107]. The temperature in a biomass pile rises as the material starts to decay, leading, in extreme cases, to self-ignition and potentially fire [107]. Decomposing of biomass material also leads to material and energy losses. The change in temperature of biomass pile is dependent on the moisture content of biomass - in general, the higher

the initial moisture content of the stored feedstock, the higher the dry matter losses [35]. Temperature changes of biomass pile can be also influenced by the size of stored biomass. The biological activity of microorganisms, which results in heat production, takes place on the surface of the chips, thus the smaller the chip size, the larger the surface area per volume and consequently the higher the biological activity resulting in higher temperatures [35]. Additionally, the smaller the chip size, the less the ventilation of the pile, and the higher dry matter losses (forced ventilation decreases the dry matter losses significantly) [35].

The dry matter losses can, in some cases, be compensated by the lower moisture content due to the drying process occurring as a consequence of heat production during decomposition process [35].

Since moisture content and size of biomass influence its energy content (dry matter losses), the pre-treatments applied (e.g. pelletizing, drying, chipping) could help to stabilize biomass properties in relation to potential changes in its energy content during storage. It should be underlined, that storage of pre-treated biomass has certain demands with regard to storage conditions (e.g. pellets should be stored in closed halls or rooms, silos and bunkers, as they are sensitive to moisture, and after contact with water can lose quality and cause handling problems). The more sophisticated storage conditions provided, the higher the investments in the infrastructure.

4.1.2. Transport of biomass is expensive due to generally low bulk densities of biomass fuels and since the cost of biomass fuel is a critical factor in the economics of co-firing, the costs of transportation (and thus transport distances) are very important issues.

In general biomass heating values [MJ/kg] and particle densities are about half of that of coal, whereas bulk densities [kg/m^3] are about 20% of that of coal, resulting in overall biomass energy density [MJ/m^3] approximately 10% of coal [21]. As a consequence, when co-firing raw biomass at a 10% heat input rate with coal, the volume of coal and biomass can be similar and therefore biomass requirements with regard to transport, storage and handling are very high in comparison to its heat contribution [21].

One way to reduce the transport costs of biomass is to apply densification processes to biomass and bring it in the form of pellets, briquettes or bales. Apart from benefits with regard to transport, it may also bring other benefits with regard to handling, storage, feeding and other elements of the co-firing system.

An issue worth to mention with regard to transport, is that biomass behavior regarding temperature changes, might be similar to the one during storage. Experiments done by Elsam Engineering show that there is considerable short-term temperature increase in lorry-loaded wood chips [89]. The process responsible for temperature rise during transport is probably different, than the one causing longer term heating during storage (which is usually explained by microbiological activity i.e. fungi and bacteria). The reasons behind the temperature development during transport are not clear and further research in this area is needed.

4.1.3. Preparation of biomass feedstocks is often applied, most commonly by its drying and sizing, and there are number of problematic issues associated there.

Sizing of biomass can be difficult due to the non-friable and fibrous character of biomass material [21]. It is usually unnecessary to bring biomass feedstock to the same size as coal particles, however large and aspherical biomass particles can cause problems with fuel conversion efficiency [21]. Sizing can be problematic if coal mills or pulverizers are used. Decisions regarding sizing are often related to transport costs of biomass, as well as drying option (comminution of biomass should always take place before drying, as dryers require sized biomass).

Drying of biomass is applied to improve the combustion or gasification efficiency, reduce the biomass susceptibility to decomposition and consequent dry matter losses, fire and health hazards (fungi production due to biological degradation) [88], and to avoid the need for complex combustion technology and process control, which is required by fuels with varying moisture content [15]. Drying of biomass requires energy, increases the costs, and can cause environmental impacts.

More information on biomass drying and sizing, as well as on more advanced types of biomass pre-treatment can be found in Chapter 6.

4.1.4. Grindability and co-milling – In general, coal mills break up coal by a brittle fracture mechanism, and most biomass materials have poor grinding properties and therefore, some larger biomass particles tend to be retained within the mill, and this can act to limit the co-firing ratio that is achievable in this way [41]. In vertical spindle coal mills, the power consumption might increase with increasing biomass co-firing ratio (the power required to size biomass is higher than for coal due to non-friable character of biomass) and this may represent a limiting factor as well.

In most conventional coal mills, where hot air is applied to dry the coal in the mill, safety might be an issue, as biomass materials tend to release combustible volatile matter into the mill body at temperatures significantly lower than those that apply when milling bituminous coals [41]. As a consequence, it may be necessary to modify the mill operating procedures to minimize the risks of overheating the coal-wood mixture [41].

Despite these potential difficulties and limitations, co-milling of a number of chipped, granular and pelletized biomass materials through most of common designs of conventional coal mills has been carried out successfully on a fully commercial basis in a number of power plants in Europe [41].

4.1.5. Handling - Ideally, the handling and conveying system should be designed according to the fuel properties, therefore many problems are associated with handling of biomass materials in coal plants. The nature of the problems depends on the type of biomass, and some general conclusions regarding handling and storage of biomass can be derived as following [41]:

- Solid residues from the palm oil and olive oil industries (granular agricultural materials) handle well at normal delivered moisture contents.
- Handling of woody biomass, in the form of chips, chunks and sawdust is usually more difficult, mainly due to the wide range of particle sizes and moisture contents.

- Herbaceous (grassy) biomass is commonly handled, transported and stored in baled form, and is more difficult and more expensive to handle than other biomass types. Baled materials are generally not suitable for co-firing by pre-blending, and need further processing.
- Pelletized biomass is generally good for handling, but some of these materials handle very poorly when wet. Pellets absorb moisture from the surrounding air and can swell. They should be stored in dry conditions.

An important issue when handling biomass materials is generation and accumulation of dust. If the accumulated dust gets wet, it can swell and there can be mould growth (therefore application of water misting systems for dust suppression can be problematic). Environmental concerns might be associated with fugitive dust emissions and, in some cases, with odor from the biomass reception and handling activities [41].

4.1.6. Feeding of biomass in co-firing systems can be done by using the existing coal infrastructure or by a separate line. Small amounts of biomass can be used even in PC combustion plants by using the existing coal handling system [49], however in higher co-firing ratios, feeding becomes difficult. There are different types of feeding systems (e.g. wheel loaders, belt conveyors, chain conveyors, screw conveyors, hydraulic piston feeders, bucket elevators) [15]. Depending on the fuel type, different feeding systems are appropriate. Therefore the cause of problems with feeding in co-firing systems is that the properties of biomass/coal blends are not homogenous and certain biomass types can be restricted. In order to increase fuel flexibility of the plant there is a possibility to install a separate feeding line for biomass, however this involves extra costs. The fuel handling system comprises around 5-10% of the total investment costs of the plant and specific investment costs are 230-1047 Euro/MW in case of grate boilers, 218-694 Euro/MW for fluidised bed combustion and 486-901 Euro/MW for gasification [49].

4.2. Technical issues

4.2.1. Boiler capacity and performance - Biomass may contain around 70% of volatiles, while coal is almost pure carbon [33]. The amount of flue gases per unit of energy resulting from biomass is much larger than that of coal, which implies that flow patterns of combustion gases through the boiler can be changed and limit the percentage of biomass that can be co-fired in existing installations [33]. Co-firing of biomass materials, and particularly of wet biomass, can have an impact on the maximum achievable boiler load, depending on the mill constraints, and on the boiler efficiency. At low biomass co-firing ratios and with dry (<10% moisture content) biomass materials these constraints are modest [41].

In general, if there are no large biomass particles, (> 2-5 mm), passing to the burners, the combustion behavior of the blended fuel is acceptable. Biomass materials are more reactive in combustion

systems than most coals and in general the unburned carbon levels in bottom and fly ashes are similar, or less than when firing coal alone.

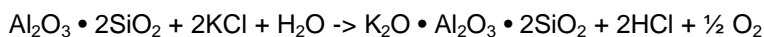
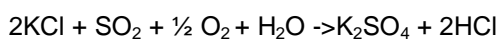
Addition of biomass to a coal-fired boiler does not significantly impact [21, 41, 47], or at worst slightly decreases the overall boiler efficiency of coal-fired power plant [21].

Ash deposition in the near-burner zone can negatively impact the co-firing efficiency or combustion conditions, eventually leading to unburned carbon levels in the ash.

4.2.2. Deposit formation/Ash deposition (slagging and fouling) - Problems may occur due to the alkali contents of some biomass fuels, which together with significantly lower ash melting point of biomass ash, may cause slagging and fouling [29, 32, 33, 47, 67].

Slagging of combustion systems is the deposition of ash on the heat transfer surface and refractory linings in the furnace primarily subjected to radiant heat transfer, whereas fouling is deposition in the heat recovery section of the steam generator subject mainly to convective heat exchange by fly ash quenched to a temperature below its melting point [47]. A process that might appear along with slagging and fouling is sintering, which is paring together of the deposit particles to more compact form. Deposit formation may be subject to light sintering, up to complete fusion, and the degree of fouling and slagging varies throughout the boiler depending on local gas temperatures, tube temperatures, temperature differences, gas velocities, tube orientation, and fuel composition [47]. The possibilities to tailor fuel composition in order to reduce problems with slagging and fouling will be described further (in Chapter 6 on biomass pre-treatment).

According to present knowledge [47], the rate of deposit formation is associated with the reactions between compounds that contain chlorine, sulphur, aluminium and alkaline substances. High-risk chlorine compounds are NaCl and KCl, but they can react with sulphur and aluminium silicate compounds releasing HCl, which is less harmful [47]:



“The S/Cl ratio in the feedstock has been shown to affect Cl deposition and corrosion. It has been suggested that if the S/Cl ratio of fuel is less than two, there is a high risk of superheater corrosion. For a ratio of at least four, the blend could be regarded as non-corrosive. According to recent studies AlSi/ Cl ratio can even dominate over the S/Cl ratio” [47].

4.2.3. Agglomeration – Biomass ash contains significant amounts of potassium, phosphate, and calcium, thus elements generating ashes with lower melting point, which can form sticky layers. In a fluidised bed this can result in bed agglomeration and de-fluidisation [87]. This causes local increase in temperature, which often accelerates the process and can lead to completely sintered bed, with a glassy phase gluing the bed particles together [87].

It is the best for the biomass to be processed in dry ash gasification systems (non-slugging) because its operating temperature is generally up to 950-1000°C and exceeding these temperatures may cause ash fusion and chemical agglomeration problems [24].

4.2.4. Erosion - The common definition of erosion is a progressive loss of material from a solid surface due to mechanical interaction between that surface and a fluid or solid particles carried with the gas or fluid at significant velocities [81,82]. There are different types of erosion. Solid particle erosion and the combination of erosion with corrosion seem to be the most important types with relation to co-firing of biomass with coal. As various types of erosion are often related to each other, determination of the exact erosion type is often difficult.

Solid particle erosion is loss of material resulting from repeated impact of small solid particles in a gaseous medium, whereas the erosion/corrosion (Fig.16) is a metal damage due to simultaneous impact of mechanical erosion and electrochemical corrosion, which interact and usually accelerate each other, leading to synergetic effects in damage [83, 86]. The fluidised bed combustion is likely to suffer from solid particle erosion, due to movement of bed material particles. Erosion is occurring in single coal combustion plants and the relation between erosion and biomass utilization along with coal is not clearly defined. However, considering, the phenomena of synergy between erosion and corrosion, and the potentially higher corrosive characteristics of certain biomass types with high chlorine content, it might be an important issue in some co-firing systems.



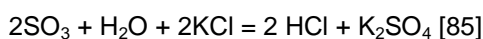
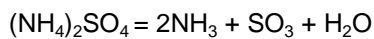
Fig. 16. Erosion and corrosion effects, Source [86]

4.2.5. Corrosion - Chlorine contents in biomass may cause corrosion problems during co-firing [3, 21, 29, 32, 33, 47, 67]. According to [16] sometimes a mitigation of the chlorine-based corrosion takes place, as a consequence of reaction between sulphur from coal and alkali compounds from biomass. The latter can result as alkali chlorides, which can condense from biomass based flue gases, react with SO₂, mainly from coal, and form alkali sulfates, which are less corrosive [21]. However this mitigating effect of coal-derived sulfur on corrosion during co-firing does not take place in reducing conditions, whereas in oxidizing conditions can be slowed down by lower temperatures (by decreasing the kinetic rates of conversion to sulfates) [21]. Additionally, since biomass for co-firing is commonly injected in only few burners, and many boilers do not mix flue gasses effectively in furnace sections, the resulting gas compositions near the boiler exit often reflect the burner-to-burner

variations, which can affect the ameliorating effects of sulfur from coal on biomass-derived flue gases [21].

Corrosion problems during co-firing influence lifetime of affected equipment (causing financial and operational costs).

Results from [84] show that the use of suitable materials and additives can reduce corrosion in boilers that burn biomass even at temperatures as high as 550°C. The additive injected into the flue gas after combustion could be ammonium sulphate, which converts gaseous potassium chloride into potassium sulphate (a much less corrosive compound), resulting in reduced corrosion rates and deposit growth rates by 50% [84].



Another way of addressing the corrosion issues in co-firing or biomass systems is through pre-treatment of biomass by its leaching with water, which can reduce the content of alkalis, sulphur and chlorine in the feedstock [27, 29, 32]. More information on the biomass pre-treatment through washing and its benefits for co-firing systems can be found in Chapter 6.

It is important to underline that the phenomena of biomass-related deposit formation and corrosion are linked [47] and that erosion and corrosion are interacting as well [83, 86]. Deposit formation deteriorates heat transfer of the heat delivery surfaces, resulting in lower combustion efficiency [47]. Chlorine-rich deposits induce hot corrosion of heat transfer surfaces. Although slagging and fouling may be detected quite quickly, corrosion could progress slowly over a longer period and may also occur without any associated slagging or fouling [47]. The damage due to simultaneous impact of mechanical erosion and electrochemical corrosion can lead to synergetic effects [83, 86]. Therefore it is hard to approach each of those issues separately and they should rather be considered in a holistic way.

4.2.6. Ash utilization issues – Biomass materials generally have lower ash contents than most coals, but the nature of biomass ashes is very different from that of most coal ashes. For that reason, the utilization options for the ashes from co-firing (mixed with coal, or separate biomass ash from advanced co-firing modes) may need to be different from that of ashes from stand-alone coal combustion. Therefore utilization options for the ash residues from co-firing can be sometimes constrain for co-firing.

Information on different utilization options for coal ash, biomass ash as well as for mixed ash are discussed in Chapter 3.

4.3. Non-technical barriers

Examples of non-technical co-firing barriers can be listed as follows [33, 67]:

- Uncertainty regarding the economical and political support e.g. tax exemptions or fuel subsidies.
- Legislative aspects: complex or time consuming permission procedures, restrictive fly ash utilization guidelines, stringent emission regulations
- The financial feasibility of co-firing is influenced by unstable biomass prices and insecure supply.
- Power plants are confronted with liberalization of the energy market, thus cost cutting is essential for their survival, whereas co-firing is more expensive than coal based energy systems (unless support such as subsidies is provided).
- Negative public perception: utilization of biomass is sometimes confused with wastes, while the negative perception of coal-energy is associated with co-firing.

4.4. Measures applied to mitigate the problems in co-firing systems

The problems associated with co-firing systems can be addressed by various approaches. This section identifies the applied measures by investigating the literature.

Challenges encountered in co-firing systems can be addressed by application of **downstream measures**, such as change of corroded or worn out equipment, cleaning of deposits by soot blowing, or exchange of agglomerated bed material. The limitation is that application of these solutions cause breaks in plant operation, disturbs continuity in energy supply, and requires plant restarts.

Another option that can address certain problems is **addition of chemicals to the process**. Results from [84] show that an additive of ammonium sulphate, which converts gaseous potassium chloride into potassium sulphate (a much less corrosive compound), could result in reduced corrosion rates and deposit growth rates by 50%. Another option is adding to the process dolomite or kaolin, which increases ash melting point, and can reduce negative effects of alkali compounds. This option addresses only the problems appearing during the conversion-to-energy, and may need monitoring of the chemical composition of the fuel blend and the process conditions, in order to define the appropriate amount of chemical additive to ensure the desired reaction takes place.

Commonly applied option to address certain problems in co-firing systems is **introduction of dedicated biomass infrastructure** to the existing coal system. In direct co-firing systems, coal and biomass are introduced to a common boiler, in principle through existing coal infrastructure. However experience shows that there is usually a need for some improvement in coal infrastructure, or need for dedicated biomass equipment. The British experience with direct co-firing systems proves, that co-firing projects always require significant upgrading of the facilities for storage and handling of biomass, dedicated systems for milling of biomass, and the pneumatic conveying of the milled biomass from the handling/milling facilities to the boilers [41].

An alternative to introducing biomass-dedicated infrastructure into direct co-firing system can be **application of more advanced co-firing mode** such as parallel co-firing (hybrid system) or indirect co-firing. In these options the fuel preparation and feeding lines are physically independent [46]. The advanced co-firing configurations can provide fuel flexibility and better operability of the system (problems with sizing and feeding of biomass are reduced). Since coal and biomass are converted in different units, optimal conditions for each conversion process can be defined. Another potential advantage is that ashes produced are kept separately, which could, in some cases, improve their utilization patterns. But the more advanced co-firing system, the higher the investment required. Also, in case of parallel combustion, the potentially limiting factor could be the capacity of existing downstream infrastructure such as steam turbine. The amount of biomass that could be co-fired could be limited by the steam generator capacity, so it should be made sure that retrofitted power plants have sufficient overcapacity of steam turbine to accommodate the extra power from biomass combustion [5].

Other option for reduction of some problems associated with co-firing can be an appropriate **fuel blend control**, where the optimum percentage of biomass fuel in the fuel blend can be defined with appropriate combustion tests, accompanied with bed material and deposit quality assessments [47]. This approach has limitations: it constraints fuel flexibility, and the defined optimal biomass share in the total fuel may limit the co-firing ratio.

Additionally, as in all previous cases, the issues related to the supply chain transport, storage) are not addressed.

Finally, there is a possibility to address some of the problems in co-firing systems by the upstream solutions, such as **biomass pre-treatment**. This is an interesting option, because by modifying biomass properties, pre-treatment addresses the source of problems, rather than their consequences. Biomass pre-treatment options and their role with regard to co-firing applications are discussed in details in Chapter 6.

Summary and conclusions

Co-combustion of biomass and coal may face various challenges, which include fuel preparation, handling, storage issues, milling, feeding, different combustion behavior, possible changes in overall efficiency, deposit formation (slagging and fouling), agglomeration and sintering, corrosion and/or erosion, ash utilization issues and overall economics.

The degree of the difficulties associated with co-firing systems depends on the quality and percentage of biomass in the fuel blend, type of combustion and/or gasification used, the co-firing configuration of the system, properties of coal and others. In low co-firing ratios, those issues might be of low significance, due to high buffering capacity of coal in the system. In

general the operating and maintenance costs of co-firing systems (vs. coal based systems) increase with higher biomass/coal ratio, and lower quality of biomass used.

Most of the problems encountered in co-firing systems originate from biomass properties. Certain problems could be reduced or even avoided with appropriate fuel blend control. Other way of dealing with these are the downstream solutions (change of corroded equipment, cleaning of deposits, addition of chemicals to the process etc.) as well as the upstream solutions (tailoring biomass properties by pre-treatment, installation of separate equipment dedicated to biomass, investing in more advanced configuration of co-firing system). Biomass pre-treatment is an interesting option, because by modifying biomass properties, it addresses the source of problems, rather than their consequences

5. Economics of co-firing systems

Economics of co-firing are important, and will likely have a significant impact on market penetration of those systems. This section shortly presents the economic considerations regarding co-firing of biomass with coal.

In general, the energy systems which co-fire biomass with coal are more expensive than dedicated coal systems. Therefore, reasons for co-firing are primarily connected with environmental benefits rather than cost-savings [21]. Thus a more appropriate approach is a comparison of the costs of co-firing systems with other renewable energy options, among which co-firing is usually the cheapest, in most situations where biomass resources and coal-based power plant are available in the same region [21].

The capital costs of co-firing projects are usually much lower than those of establishing new, dedicated biomass-to-energy plants, due to the fact, that co-firing systems can be based on already existing infrastructure of coal power plants [41, 76].

Costs related to co-firing (adapting coal-based power plant to co-firing) can be divided into few groups:

1. Capital costs (capital, depreciation, interest costs) - Co-firing installations costs range from \$50-\$300/kW of biomass capacity and are so low, because they mostly make use of existing infrastructure of a power plant [21]. These costs are usually lower than for any other renewable energy option, except for hydropower [21].
2. Fuel costs (fuel procurement, pre-treatment costs and the electricity demand for it) - One of the most sensitive factors in economics of co-firing is the cost of biomass fuel [21]. Even in the case of residues, where the fuel is usually nominally free at the point of its generation, the costs of transportation, pre-treatment and handling increase its effective costs per unit of energy to the extent, that it sometimes exceeds that of coal [21]. That is why the supply chain of biomass fuels deserves to be given attention, as by its optimization, the costs could be reduced.
3. Operation-based costs (O&M) (personnel costs, maintenance) - Operating costs are typically higher for biomass than for coal [21]. This is mainly due to different biomass properties in comparison with coal, such as lower energy density, resulting in high volumes to be handled etc.. The O&M costs usually remain constant irrespective of the actual amount of electricity generated, but some are dependent on it e.g. lubricants and chemicals used in the generation process.
4. Other costs (administration, insurance) – this part of costs is sometimes included in the O&M costs.

Various configurations of co-firing systems involve different investment costs.

Direct co-firing, where biomass is used for power production as a blend with coal, using the existing coal infrastructure, is the cheapest and easiest option to implement. However the problems resulting as a consequence of different characteristics of the two mixed fuels can occur. Also, some types of biomass cannot be processed this way (for example herbaceous biomass is known to cause many problems during feeding and sizing).

The investment in parallel co-firing installations is significantly higher than in direct co-combustion installations, as parallel co-combustion systems involve not only separate biomass supply line (pre-processing, conveying, feeding) but also additional biomass boiler. Thus the fuel preparation and feeding lines of coal and biomass are independent, and the possibility to use relatively difficult fuels with high alkali and chlorine contents and the separation of the ashes are (potentially economic) advantages [32, 46].

The most expensive option is the indirect co-firing configuration, which requires investments in biomass gasifier as well as separate biomass supply line. In this case the potential advantage of keeping separately biomass and coal ashes exists.

As there are a number of considerations faced, related to the cheaper and less advanced co-firing systems, e.g. biomass feeding, behavior of the blended fuel in the coal mill, problems with ash utilization, therefore it may be that the higher investment in more advanced co-firing configurations pay back by better operability of the system.

An important issue with relation to economics of co-firing is that the costs of co-firing are to a large extent related to policy decisions regarding e.g. environmental taxes, subsidies or trade with emission quotas (GHG emission abatement is an increasingly important economic factor behind the concept of co-firing). Therefore a fast change in bio-energy consumption trends can be achieved when political strategic decisions are implemented in related regulations.

Development of co-firing systems could help to build up the biomass supply infrastructure, and facilitate secure markets for energy crop materials in the short to medium term, which is fundamental for securing the fuel supply, and is one of the key issues considered before the start of any bio-energy project [41]. The development of biomass supply infrastructure in relation to co-firing could have positive impact on development of other bio-energy systems, such as utilizing biomass for production of bio-fuels for transportation. It could also reduce risks related to further investments in infrastructure for biomass supply.

On the other hand, with development of biomass markets and expansion of various biomass applications, a competition to obtain the cheap biomass fuels can develop amongst different players in the bio-energy field. As suggested by Kavalov and Petevs, competition to access the cheap biofuels is already observed in the bio-energy field and it sometimes does not favor the optimum utilization of biomass resources [18]. As a result, in the future it may be more difficult to sustain or

increase the recent expansion trends in biomass applications in EU, due to gradual depletion of cheap biomass resources and the push for switching to more expensive ones [18].

This is true, if the nominal costs of biomass fuels are considered. It should be reminded however, that the price of biomass as a fuel, similar to costs of co-firing, could be a subject to political decisions regarding e.g. preferential taxes or government subsidies. For example, Sweden introduced in the early nineties a tax on fossil carbon dioxide, which resulted in rapid increase of wood pellets as a fuel [45].

In general, if subsidies are not considered, the costs of biomass in energy systems consist of two main parts:

- Biomass feedstock costs (the purchase price)

- Biomass logistics costs (transport, storage, handling and pre-treatment)

Examples of biomass prices (and for comparison the fossil fuels prices) are presented in Tab.11 and in Fig. 17-18.

In general, till now, the forestry and agricultural residues are often considered as “no cost” resources. It should be however noted, that the market value of the residual biomass resources, available at zero or very low costs, may increase with growing demand for this residue, which can be explained by economic fundamentals of the price formulation, resulting from the interaction between demand and supply and presented in more details in the work of Kavalov and Peteves [18, 40].

Due to significant transport costs involved with the majority of biomass fuels, it is difficult to estimate precisely the cost of different feedstocks. In general, in comparison with fossil fuels, raw biomass has lower energy density, translating into higher transportation and storage costs per energy unit, and resulting in lower economically effective availability of biomass around power plants (the further away from the power plant the feedstock is available, the less cost-effective it is to increase biomass supply) [18]. On top of this, contrary to the infrastructure for supply of fossil fuels, the biomass supply infrastructure in many EU countries needs to be developed, which requires investment.

Tab.11. Fuel prices in EU-15 (except Luxemburg) in 2002 including all taxes except VAT, Euro/MWh_{th}, Source [80]

Fuel price including energy taxes and excluding VAT	A U S T R I A	B E L G I U M	D E N M A R K	F I N L A N D	F R A N C E	G E R M A N Y	G R E E C E	I R E L A N D	I T A L Y	N E T H E R L A N D S	P O R T U G A L	S P A I N	S W E D E N	U K
Light fuel oil	34	24	62	39	24	35	60	32			23	36	52	26
Heavy fuel oil	-	17	52	26	19 ⁴	-	23	30			-	21	45	
Biodiesel for heating	-	-	50	-	-	-	-	-	72	43	-	-	-	
Natural gas	45	43	58	16	18 ⁵	43	20 ⁸	22			29 ¹¹	42	38 ¹³	22
Coal	27	-	57	12	15	-	-	7			-	4	32	36 ¹⁴
Sod peat	-	-	-	10	-	-	-	14			-	-	14	
Milled peat	-	-	-	9	-	-	-	9			-	-	14	
Wood chips – large scale	17	12	17	9	15	9	-	4	14	23 ¹⁰	4	6	12	6
Wood pellets – large scale	-	28	27	19	24	28	-	-	34	23 ¹⁰	-	-	17	
Wood pellets – domestic user	35	47	41	26	44	34	-	-	44		41	38	34	33
Wood logs – domestic user	24	14	38	28	21	28	7	58	34		13	22	-	18
VAT % - large user	10-20 ¹	6-21 ²	0	0 ³	19,6	7-16 ⁷	-	13,5	10-20 ⁹		6-9 ¹²	16	25	5 ¹⁵
Vat % - domestic user	10-20 ¹	6-21 ²	25	22	19,6 ⁶	7-16 ⁷	-	13,5	10-20 ⁹		6-9 ¹²	16	25	5 ¹⁵

1 - 10% for wood based fuels, 20% for fossil fuels

2 - At the present in Belgium there are discussions about VAT level for wood fuel: 6 or 12%

3 - Also larger users have to pay VAT, but it can be deductible later

4 - 19Euro/MWh for large scale user, 34 Euro/MWh for domestic user

5 - 18Euro/MWh for large scale user, 32Euro/MWh for domestic user

6 - 5,5% for wood logs for domestic user

7 - 7% for wood pellets and wood logs, 16% for wood chips and fossil fuels

8 - 20Euro/MWh for industrial user, 35Euro/MWh for domestic user

9 - 10% for wood, 20% for bio-diesel

10 - Average of different wood fuels including pellets

11 - 29Euro/MWh for industrial user, 35Euro/MWh for domestic user

12 - 6% for natural gas, 12% for fuel oil, 19% for wood fuels

13 - 38Euro/MWh for industrial user, 47Euro/MWh for domestic user

14 - for domestic user

15 - for fossil fuels, for light fuel oil over 2500 liters 17,5%

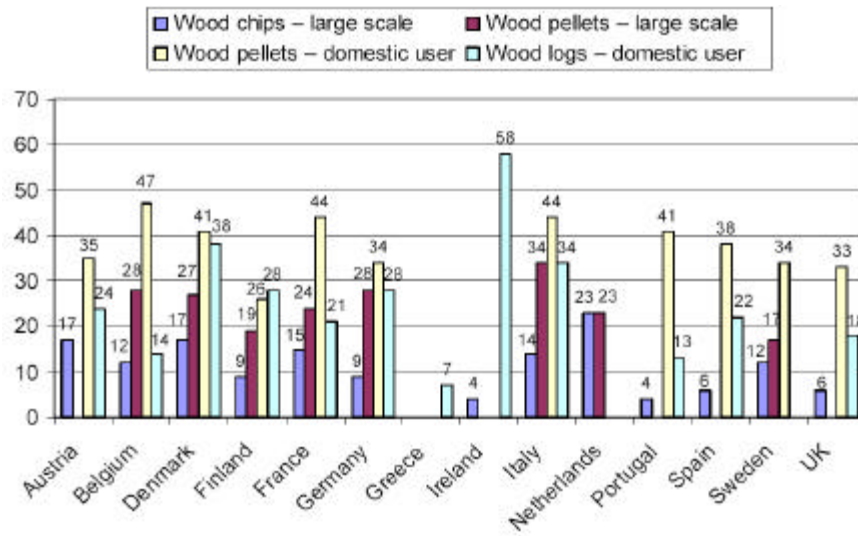


Fig. 17. Wood fuel prices in Europe 2002/2003, Eur/MWh_{th}, Source [78]

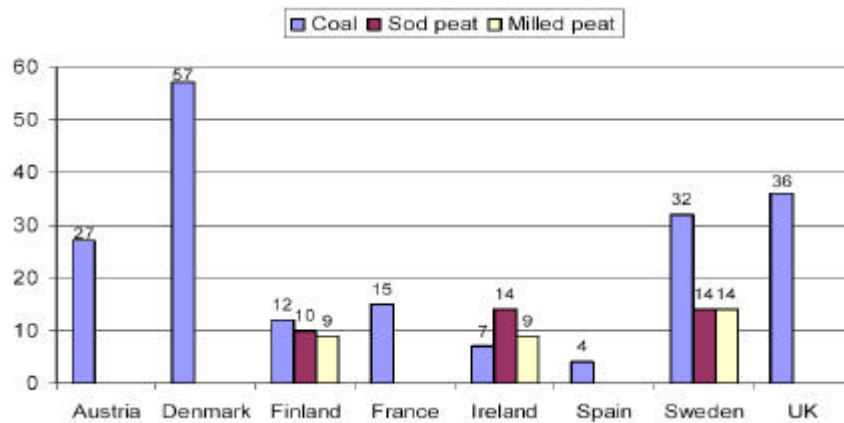


Fig. 18. Solid fuel prices in Europe 2002/2003, Eur/MWh_{th}, Source [78]

Another issue, which may have influence on the economy of the plant, is related to operational challenges associated to co-firing of biomass with coal. These challenges need to be addressed either by modifications in the power plant or by downstream activities e.g. exchange of corroded equipment. Many of the above challenges can also be, to a certain extent, avoided by application of upstream measures such as biomass pre-treatment. The more advanced the pre-treatment of biomass applied, the higher the final cost of the feedstock will be. But the costs of biomass fuel for co-firing depend not only on its procurement costs but also on the costs of operability of this fuel (handling, storage, transportation) and operability of the boiler and combustion process, as well as the end use of the waste. Therefore it may not necessarily be economical to use the cheapest fuel available, if the negative effects on the boiler operation or fuel operability are significant [44]. The analysis of all problems (costs) and benefits along the co-firing chain (from fuel procurement to the conversion process) should be considered, when deciding on the quality, and consequently the price, of the biomass fuels to be used in co-firing.

Examples of supply costs (collection and transport) of different biomass fuels are presented in Fig. 19-22.

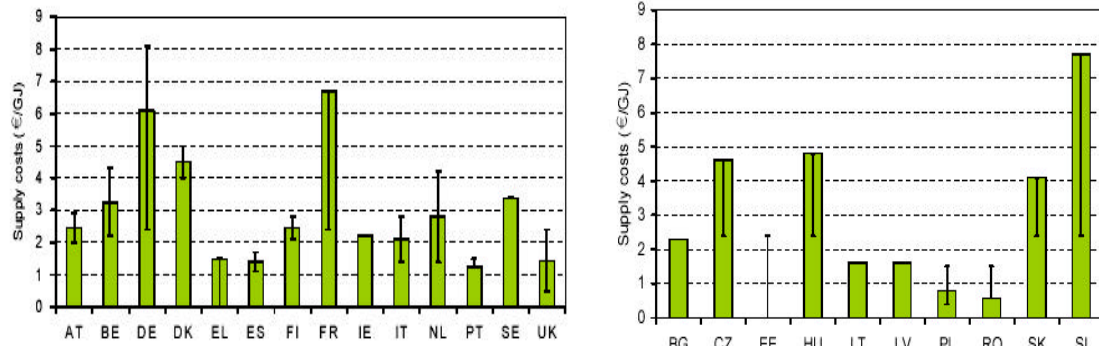


Fig. 19. Supply costs of forests by-products (Euro/GJ), Source [4]

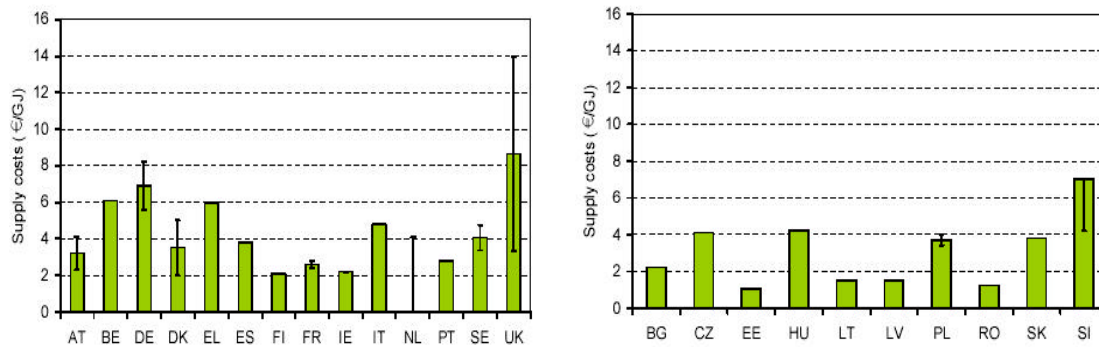


Fig. 20. Supply costs of refined wood fuels like briquettes and pellets (Euro/GJ), Source [4]

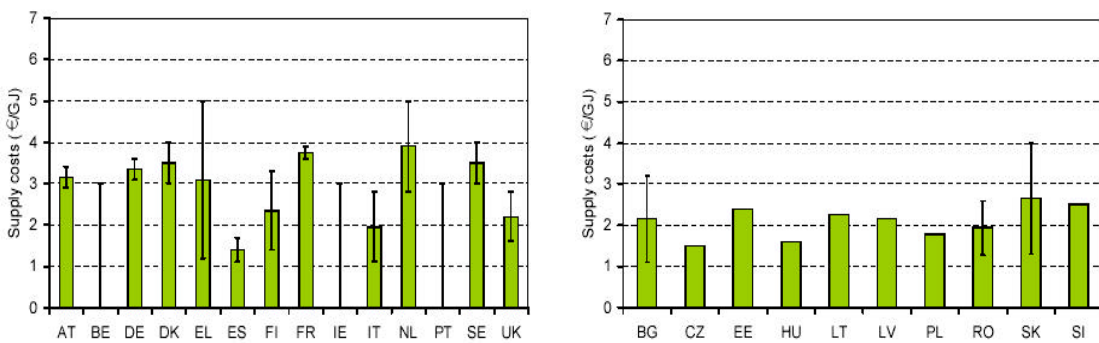


Fig. 21. Supply costs of agricultural residues (Euro/GJ), Source [4]

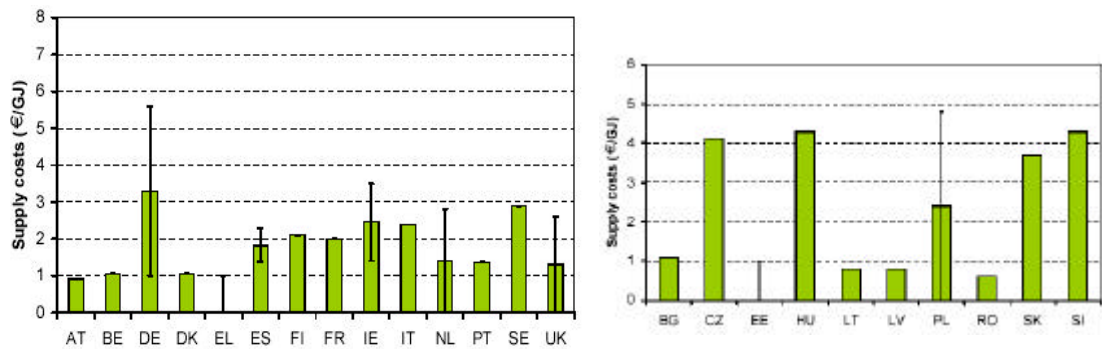


Fig. 22. Supply costs of industrial residues (clean wood fractions from the secondary wood processing industry) (Euro/GJ), Source [4]

Summary and conclusions

Generally, the energy systems co-firing biomass with coal are more expensive than dedicated coal systems. On the other hand, the capital costs of co-firing projects are usually lower than those of establishing new, dedicated biomass-to-energy plants.

One of the most sensitive factors in economics of co-firing is the cost of biomass fuel. The cost of biomass fuel, as well as costs of co-firing, could be a subject to political decisions regarding e.g. environmental or preferential taxes, subsidies, or trade with emission quotas.

In general, costs of biomass as a fuel for energy consist of two main parts: the purchase price and the costs of logistics (transport, storage, handling and pre-treatment). In general, the operation costs of biomass are higher compared to the fossil fuels due to a number of reasons e.g. lower energy density of biomass in comparison with fossil fuels, translating into higher transportation and storage costs per energy unit.

An issue, which could influence the economy of the plant, is related to challenges associated to co-firing of biomass with coal. It is not necessarily economical to use the cheapest fuel available, if the negative effects on the boiler operation or fuel operability are significant.

6. Biomass pre-treatment options and their potential to mitigate the constraints related to co-firing

This chapter presents different options for biomass pre-treatment, with potential to mitigate some of the constraints (if encountered) related to co-firing. For each pre-treatment option, subject to data availability, the economics, related environmental impacts, energy requirements, and potential benefits with relation to co-firing systems are presented.

Pre-treatment of biomass feedstocks can be applied for the following reasons:

1. The wide variety of biomass streams often does not match with the narrow fuel specifications of feeding systems and the conversion processes considered [17].
2. To lower the costs of handling, storage and transportation [16] and to improve transport and storage characteristics.
3. To reduce the need to invest in complex and expensive combustion or gasification installations [16].
4. To reduce the plant's investment, maintenance and personnel costs by using homogenous fuel that is suitable for an automatic fuel feeding combustion system [15].

Biomass properties achieved due to pre-treatment can alleviate certain problems related to co-firing of biomass with coal, such as:

- problems associated with biomass supply chain (e.g. the costs of transportation of pelletized or briquetted biomass are lower than those of untreated biomass)
- operational constraints (certain forms of pre-treatment allow for utilization of coal infrastructure for feeding, milling etc. of biomass, without their costly modifications or installation of separate processing lines for biomass)
- technical constraints (e.g. reduction of corrosion due to biomass washing).

The properties of the same crop can vary depending on production conditions. For example, by applying chlorine-free fertilizers the chlorine content in straw can be reduced, weather conditions (rainfall) can leach out the easily water-soluble elements like K and Cl, moisture content and yield of annual crops depend on the time of the year when harvesting takes place (yields of cereals get lower with time between wax-ripe stage and full ripeness, whereas dry matter content rises) [15]. Therefore the homogenous quality of biomass cannot always be assured.

After pre-treatment the properties of biomass are usually quite uniform. During pre-treatment, mainly the physical characteristics of the feedstock can be influenced, but the chemical properties (for example chlorine content) can also be tailored. Common pre-treatment options are sizing, compacting, and drying [16]. In addition, pelletizing gains popularity in co-firing applications. There are also other possibilities such as washing, torrefaction or pyrolysis, which are not in a commercial stage with relation to co-firing. Furthermore, a combination of different pre-treatments can be applied (e.g. torrefaction with pelletizing, or pyrolysis with char wash). All of these options will be described

below. Genetic engineering can be an option for improving (in a controlled way) fuel properties [16], but it does not fall into the scope of this report.

6.1. Biomass storage

An important element related to co-firing of biomass with coal is biomass storage, which is usually necessary, in order to guarantee continuous fuel supply to the co-firing power plant. The aim of biomass storage is not to influence or upgrade the properties of the feedstock with regard to thermal conversion process requirements, and it is not a pre-treatment option. However storage and its type can affect biomass moisture content, energy value and dry matter content and can be related with biomass pre-treatment (pre-treatments like sizing or drying can influence the changes of biomass properties during storage).

During storage, biomass can change its moisture content, energy value and dry matter content due to degradation processes (microbiological activity) [107]. The results of fuel chip storage research studies from Finland and Sweden show that the temperature in a biomass pile rises very rapidly after an initial period of approximately one week (or longer in winter conditions) as the material starts to decay, leading, in extreme cases, to self-ignition and potentially fire [35, 107]. Decomposing of biomass material also leads to material and energy losses.

According to Wihersaari [35], the expected dry matter losses over a six-month period are twice as high in case of fresh forest residue in comparison with dry forest residue (15.5% and 6.6.% respectively). This is because the change in temperature can be influenced by moisture content of biomass - if the initial moisture content is under 40wt%, the temperature rises fast and decreases after 1-2 months, whereas at moisture content of 50-55wt%, the temperature in the middle of the pile usually remains high during the whole period of storage [35]. In general, the higher the initial moisture content of the stored feedstock, the higher the dry matter losses (Tab.12) and in order to keep the material losses low during long-term storage, the moisture content needs to be low (usually under 20wt%) [35].

Tab.12. Results of tests from Sweden on the dry matter losses with relation to moisture content of the feedstock, Source [35]

Initial moisture content of wood chips	Monthly dry matter losses [wt%]	Total dry matter losses during six months storage [wt%]
58%	2.6	15.6
51%	2.2	13.2
42%	1.1	6.6
32wt%	1.03	no data
20wt% and lower	0.23-0.35	no data

Temperature changes in stored biomass piles can be also influenced by the size of stored biomass. The biological activity of microorganisms, which results in heat production, takes place on the surface of the chips, thus the smaller the chip size, the larger the surface area per volume, and consequently,

the higher the biological activity resulting in higher temperatures (Tab. 13) [15, 35]. Additionally, the smaller the chip size, the less the ventilation of the pile and higher dry matter losses (forced ventilation decreases the dry matter losses significantly) [35]. Material losses are highest in the beginning of the storage period (right after the temperature has quickly risen) and are estimated to be 3.6 wt%/ week (during peak week) and 0.4-0.7 wt%/ week (during following weeks) [35].

To avoid dry matter losses the storage of uncomminuted material or airtight storage of chips is recommended – this also prevents self-ignition [15]. However, in practice it is not easy. Storage of uncomminuted biomass could be an option for intermediate storage close to the field, before supplying the feedstock to the power plant. However, since the transportation of uncomminuted (thus low energy density) materials is costly, in order to reduce those costs, sizing and/or compacting of biomass should be applied before transporting biomass to be stored at the power plant.

Tab.13. Relation between size of chips and temperature change of the stored pile, Source [35]

Average size of chips [mm]	Temperature of the stored pile [°C]
8	Rapid rise to over 60
30	40-50
70	Up to 30

In the light of the above, and assuming the price of biomass fuel as 10 Euro/MWh, the losses of 6.6 and 15.6wt% (for dried and fresh biomass material respectively) would cost 0.7-1.6 Euro/MWh fuel, [35].

The dry matter losses can be, in some cases, compensated by lower moisture content due to the drying process occurring as a consequence of heat production during decomposition process [35].

Since moisture content and size of biomass influence energy content (dry matter losses) of biomass, the pre-treatments applied to biomass (e.g. pelletizing, drying, chipping) could help stabilize biomass properties influencing dry matter and energy content changes during storage. But storage of pre-treated biomass might have certain demands with regard to conditions (e.g. pellets should be stored in closed halls or rooms, silos and bunkers (Fig. 23), as they are sensitive to moisture, and after contact with water can loose quality and cause handling problems). There are different types of storage options: outdoor, indoor, outdoor covered with a sheet, without or with ventilation of the pile (active ventilation with ambient air, active ventilation with pre-heated air).



Fig.23. The round-bottom intermediate storage (1500 m^3) of a biofuel power plant, Source [47]

Environmental impacts related to storage

When the temperature in the biomass fuel stack is high due to biological degradation process, the main GHG emitted is methane (CH_4 is produced only during anaerobic conditions, which typically occur when biological activity is high, thus when temperature is high), whereas when the temperature is dropping, nitrous oxide is emitted (nitrifying bacteria are sensitive to temperatures above 40°C) [35].

This is why it is recommended that comminuted forest residue be used directly after harvesting, ideally within one week [35]. This is however not very easy to be applied in practice, due to seasonal availability of biomass and the intention to use it continuously through the year.

The evaluation of GHG emissions from storage of wood residue by Wihersaari, VTT Processes, in 2005 [35, 108] indicates that in some cases, it can significantly exceed emissions from the rest of the biofuel supply chain (production and transportation).

Wihersaari indicates, by combining emissions data related to composting biodegradable materials and forest residue storage research, that the monthly emissions of naturally dried forest residue would be $840\text{g CH}_4/\text{MWh}/\text{month}$ and of fresh material $1044\text{g CH}_4/\text{MWh}/\text{month}$, which equals 19 and 24 $\text{kg CO}_{2\text{eq}}/\text{MWh}/\text{month}$, respectively. In case of nitrous oxide, the emissions of dried residues were estimated to be $17\text{g N}_2\text{O}/\text{MWh}/\text{month}$ and in case of fresh material $21\text{g N}_2\text{O}/\text{MWh}/\text{month}$, which corresponds to 5 and 6 $\text{kg CO}_{2\text{eq}}/\text{MWh}/\text{month}$, respectively. The total calculated GHG from 6-month wood chip storage are 58 (dried material, 40 wt% moisture content) and 144 (fresh material, 60 wt% moisture content) $\text{kg CO}_{2\text{eq}}/\text{MWh}$ fuel [35].

Since the GHG emissions are almost three times higher in case of the fresh material, and also because the expected dry matter losses over a six-month period are twice as high in case of fresh forest residue than in case of dried forest residue (15.5% and 6.6% respectively) [35], one could conclude that it would be advisable to avoid storing biomass feedstock with high moisture content and thus a drying treatment should be applied before storage.

The quoted above numbers of storage-related GHG emissions are very high, if compared with the estimations of Palosuo et al. in 2000 of 4-7 $\text{kg CO}_{2\text{eq}}/\text{MWh}$ emissions due to collection, chipping and

transportation of wood chips and emissions in the range of 7kg CO_{2eq}/MWh fuel related to nutrient loss compensation with fertilization and recirculation of ash [38]. According to Palosuo et al. *“Utilizing logging residues for energy purposes also decreases forests soil carbon stocks, as there is lack of the decaying residues on the forest site and consequently diminished carbon flow to soil and carbon storage in soil. Altogether the emissions from using harvest residues as biofuel are about 50 kg CO_{2eq}/MWh, out of which around 80% is due to decrease in soil carbon [38]. The effect of comparing these emissions with emissions from utilizing fossil fuels is still very positive, with the potential for 80% of GHG emissions being avoided due to utilization of harvest residues for energy”* [38].

6.2. Biomass pre-treatment options

6.2.1. Drying

Drying is a process of vaporisation of the moisture and is an endothermic reaction, thus when conducted in a combustion chamber, it uses energy released from the combustion process, lowers the temperature in the chamber and slows down the combustion process [15]. For fresh, raw biomass like wood and bark, the moisture contents often exceed 50wt% [20]. In wood-fired boilers, the combustion process cannot be maintained if the wood moisture exceeds 60wt% because the energy demand for evaporating contained moisture and following for heating the water vapour is so high, that the temperature drops below the minimum temperature required to sustain combustion [15]. For large-scale combustion, the maximum biomass moisture content is 60-65wt%, and support fuel is needed to keep the combustion stable above this value of moisture content [20]. In order not to obstruct gasification, the biomass moisture content has to be brought to 5-25wt% [40]. Drying biomass to moisture contents of levels lower than 10-15% is not advised, as it requires large installations and high-energy use [98].

High moisture content of biomass decreases the potential energy input for steam generation, reduces calorific value of the fuel gas produced in gasification, and consequently decreases the efficiency of power generation (both in combustion and gasification systems) [20].

The reason to apply biomass drying can be summarized as follows [98]:

- to improve the combustion or gasification efficiency
- to reduce the biomass susceptibility to decomposition and consequent dry matter losses and self-ignition risks, and reduce problems with storage such as fungi production (hygiene, health hazards)
- to reduce the weight of the feedstock, which can be advantageous during transportation (however since drying does not affect the volume of the feedstock significantly, the weight loss might be not considered important)
- to increase biomass energy content

- to avoid complex combustion technology and process control, which is required for fuels with varying moisture content [15]
- to prepare biomass for other, more advanced pre-treatment (e.g. drying is necessary for the production of pellets or briquettes) [15].

The following drying options are available:

- Open-air drying – in order to reduce its moisture content, the harvested wood is often left outside for a number of weeks [16], and in this way can be dried from moisture content of around 50 to 30wt% (w.b.) [15]. Drying cut straw for several days before baling will also reduce the moisture content, however natural drying has disadvantages of unforeseeable weather conditions [15].
- Utilization of solar energy for heating the air used for drying
- Integration with combustion system by using flue gas/air or superheated steam [20]
- Dryers (belt dryer, drum dryer, tube bundle dryer, fluidised bed dryer). All dryers demand the feedstock to be chip-size, so sizing step will always precede the drying operation [98].

Energy requirements of drying processes

The heat needed to evaporate (remove) 1kg of water from a typical biomass fuel can exceed 2.6 MJ/kg, where typical LHV (net calorific heating value) of dry biomass is 18-21 MJ/kg, and moisture content of fresh, raw biomass like wood or bark usually exceeds 50wt% [20].

Mechanical dewatering (down to 75% moisture content wb) consumes 1,4kWh_{th}/t input [15]. Drying of dung and sludge (75% to 15% moisture content wb) consumes 3GJ_{th}/t water evaporation [15].

Environmental impact caused by drying processes

During drying processes, except for wood particles, also volatile organic compounds (VOCs) can be released and therefore dryers need to be equipped with a flue gas cleaning system [15, 20]. If drying process is integrated with combustion, then except for VOCs, the effluent water containing organics (terpenes, organic acids, alcohols) is produced [20].

Costs related to drying

There are no general rules concerning the economic feasibility of drying of the biomass feedstocks before their combustion and each case needs to be individually assessed by considering the advantages of drying (for example fuel savings, reduction of flue gas volume flow, higher combustion efficiency etc.) [15]. Drying of biomass increases the total cost of fuel significantly and there are no economically attractive biomass drying methods available for large-scale applications, due to which the combustion systems are mostly suitable for a wide range of moisture content [15]. Under Dutch conditions⁸, mechanical dewatering (down to 75% moisture content wb⁹) costs around 5 Euro/ton input, drying of wood from 50 to 15% moisture content wb costs around 12 Euro/ton input, and

⁸ Conversion from original sources assuming 1US\$=1,26 Euro

⁹ moisture content wb = moisture content on wet basis

thermal drying of dung and sludge (75% to 15% moisture content wb) costs around 50 Euro/ton water evaporated [15].

6.2.2. Sizing

Preparation of biomass for co-firing in a boiler requires reducing the material to a smaller size [34]. It is usually not practical and not necessary to bring biomass feedstock to the same size or shape as coal, however large and aspherical biomass particles cause challenges for fuel conversion efficiency (in case of coal such sizes would cause an incomplete combustion, in case of biomass this effect is mitigated due to its highly volatile character) [21].

There are following sizing options for biomass fuels [15]:

- Grinding to 0-80 mm pieces – grinding mills or hammer mills are used to produce particle sizes below 5 mm.
- Chipping to particle size 5-50 mm by drum chippers and disc chippers.
- Chunking to particle size of 5-25 cm – the particle sizes produced by a chunker vary more than those produced by chippers, however the advantage of a chunker is its low power consumption.

Energy demand of sizing

The energy need for chipping is about 1-3% of the energy content of the wood fuel [15]. Chipping (as well as breaking and shredding) typically consumes 15 kWh_e/t input, grinding consumes 25 kWh_e/t input and pulverisation consumes 40 kWh_e/t input [15].

The productivity and power consumption of different sizes of chippers are presented in Tab.14.

Tab.14. Characteristics of different sizes of chippers, Source [15]

Chipper size	Diameter of the biomass feedstock [cm]	Productivity [m ³ bulk/h]	Power consumption [kW]	Fuel-feeding system
Small	8-35	3-25	20-100	Manual, crane
Medium	35-40	25-40	60-200	Crane
Large	40-55	40-100	200-550	Crane

Costs related to sizing

In order to achieve the lowest costs, wood harvesting and chipping in one step is promising in case of early thinning (stems with diameter of less than 15-20 cm and tops), however when utilizing forest residues (branches, tops from clear fellings), it is advisable to use the large-scale chipper at the combustion plant or some other central point [15].

Under Dutch conditions¹⁰ chipping (as well as breaking and shredding) typically costs around 10 Euro/t input, grinding costs around 20 Euro/t input and pulverisation costs around 50 Euro/t input [15].

¹⁰ Conversion from original sources assuming 1US\$=1,26Euro

6.2.3. Baling

Several disadvantages of using raw biomass as energy feedstock may be attributed to the low bulk density of biomass [103]. Baling can be (and commonly is) applied to improve the characteristics of agricultural residues for transportation and storage (Tab.15).

Tab.15. Comparison of transportation of forest residues in Sweden in different forms, fuel moisture content 45 wt% (w.b.), gross vehicle weight 60 t, Source [15]

	Amount	Payloading weight [t]	Energy content [MWh]
Wood chips	105 m ³ bulk	33	85
Unchipped logging residues	135 m ³	18	46
Unchipped logging residues in bales	60 bales	37	95

Pressing to bales (Fig.24) in case of straw is done usually in an extra process step after harvesting the grain and cutting the feedstock, whereas in case of dedicated energy crops (Miscanthus) combined harvesting and baling in one process step is possible [15]. The baled straw has relatively low moisture content, and can be stored for long periods without significant dry matter losses and deterioration in fuel quality [41]. The size of the bales depends on the machine used and the density achieved for a given machine depends on the biomass feedstock (Tab.16) [15].

Baling of forest residues before transport, in combination with centralized chipping is a new approach to reducing production costs of forest wood chips, as transport of baled material can be up to 50% cheaper than transportation of unchipped material, and about 10% cheaper than that of wood chips (due to higher payload) [15].



Fig.24. Different forms of straw bales, Source: [8] (left) and [7] (right)

Tab. 16. Comparison of characteristics of different types of bales, Source [15]

	Small square bales	Round bales	Large square bales	Compact bales
Driving power [kW]	>25	>30	>60	>70
Throughput [t/h]	8-20	15-20	15-20	14
Unit density [kg (d.b.)/m ³]	120	110	150	300
Storage density [kg(d.b.)/m ³]	120 (stacked) 90 (not stacked)	85	150	270 (stacked) 165 (not stacked)
Weight [kg] (moisture content 20 wt% w.b.)	8-20	300-500	500-600	-

6.2.4. Pelletizing

Pelletizing is a compacting process that produces homogenous fuel with a high energy density in cylindrical shapes (Fig. 25) with dimension of 6-8 mm diameter [15]. Currently, pellets are the most appropriate biomass-derived fuel to be utilized in coal-fired plants [96].



Fig. 25. Wood pellets, Source [95]

An important advantage of pelletizing is that it addresses the issue of low bulk density of biomass fuels. Low bulk density of biomass has an impact on transportation costs and can restrict the co-firing ratio due to limited capacity of boiler input systems. Pellets are a refined product, which is dry (Tab.17), permits automatic handling and feeding and has high energy density (8-11 GJ/m³), which reduces costs of transportation as well as the required storage space in comparison with other biomass materials. Pelletizing can be applied to various types of biomass, woody as well as herbaceous. Additionally, the properties of pellets make it easier to grind the feedstock, handle it, and feed into the boiler.

Tab. 17. Properties of pellets, Source [15]

	Wood (pressings)	Bark (pressings)
Moisture content [wt.% (w.b.)]	<12	<18
Ash content [wt.% (d.b.)]	<0.5	<6
NCV [MJ/kg (d.b.)]	>18	>18
S content [wt.% (d.b.)]	<0.04	<0.08
N content [wt.% (d.b.)]	<0.3	<0.6
Cl content [wt.% (d.b.)]	<0.02	<0.04

The pelletizing process consists of drying, milling, conditioning, actual pelletizing and cooling [15, 42], optionally followed by fines separation and packing.

The moisture content of the raw material before entering the pellet press must be 12-17 wt% (w.b.) (for wood dust 8-10% [42]), and it is essential not to exceed these values [15, 42]. If the material is too dry, the surface of the material may carbonize and the binders will burn before the process is finished, whereas if the material is too wet, then the moisture contained in the pressings cannot escape, and enlarges the product volume, making it mechanically weak [15]. Therefore controlled drying of biomass is practically unavoidable, when aiming for pellets production. All types of dryers are in use (drum dryer, direct steam dryer, indirect steam dryer and hot air dryer) [42].

After drying, the particle size of the material must be reduced and homogenized usually by hammer mills, as the material needs to be uniform before feeding to the pellet mill [42].

Sizing is often followed by conditioning by dry steam addition, due to which the particles are covered with a thin liquid layer improving adhesion [15, 42]. In order to improve the durability of the pellets and avoid dust emissions during transportation and storage of the pellets, the conditioning of raw material and/or addition of binding agents can be applied. Most of pelletizing experts do not consider this necessary (lignin in wood acts as a binding agent while it softens during palletizing), however in practice several pellets manufacturers add 0.5-2% starch as a binding agent [42]. Other binding agents include molasses, natural paraffin, plant oil, lignin sulphate and synthetic agents [42]. Certain additives can also improve the chemical composition characteristics of biomass pellets e.g. slagging can be hindered by adding kaolin or calcium and magnesium oxides [42].

Following, the dried, milled and conditioned material is pelletized by a pellet mill, where loose material is compressed into pellets and further cut to the desired pellet lengths [42].

Finally, the cooling takes place, in order to guarantee high durability, stabilize and harden the pellets [15, 42].

Despite numerous benefits of utilizing pellets in co-firing systems, there are also challenges related to it. Problems can appear during uploading and unloading of pellets, as they can be sensitive to mechanical damaging (easily disintegrate and cause dust and handling problems). Some of the pelletized biomass handle very poorly when wet, as pellets absorb moisture from the surrounding air and can swell, loose shape, consistency and cause handling problems [41, 96]. Therefore pellets

should best be stored in a dry condition or storage times should be minimized, to prevent absorbing atmospheric moisture [41].

Pellets are distributed in bags for small-scale applications. In case of co-firing however, the bulk material supply is necessary. The main pellet distribution form in Europe is becoming delivery by a tanker and pneumatic feeding of storage bunker or silos [96]. Pellets should be stored (and most commonly are) in closed halls or rooms, silos and bunkers.

Energy demand of pelletizing

The energy requirements of the pelletizing process vary depending on the raw material type, its moisture content and particle size.

A throughput of pelletizing equipment can vary from 0.75 to 15 t/h (recently even smaller scale pellet presses are produced), depending on the size of equipment, as well as the species of wood (in general softwood¹¹ is processed at a 20-25% higher rate of production than hardwood on identical equipment, and production also rises when bark is included in the raw material).

Energy demand for wood pelletizing (including conditioning such as drying and crushing) is 80 to 130 kWh/t (the exact energy demand depending on various production factors like lubricants use, screening, etc) [42].

In general the energy consumption of the pelletizing process is about 1,5-2% of the energy content of the pelletized fuel in case of sawdust (without accounting for the energy used for drying of the raw material) [15, 42]. If drying process is taken into account, 7-10% of the energy content of pellet is needed for pelletizing in case of straw [42]. In case of wood chips, about 20% of the pellets energy content would be required for the manufacturing process (including drying and crushing) [42].

These data quoted after [42] refer to study of Raggam & Bergmair (1996) assuming energy content of wood of 5200 kWh/t. According to [42] above numbers are not correct, because the kWh-power (used by the pelletizing machinery) is mixed up with kWh-heat (energy content of wood), and additionally the study assumes the raw material for pelletizing being completely dry, which is never true in reality [42]. Considering that 1t of dry wood contains the energy equivalent of 1000 kWh-power or 4500 kWh-heat, the percentage of energy demand for pelletizing should be as follows according to [42]:

- 8 - 13% of the energy content of the pellet is necessary for pelletizing dry raw material
- 10 - 25% of the energy content of pellet is needed for pelletizing including the drying process with wet raw material (sawdust)
- 18 - 35% of the energy content would be required for pelletizing of wood chips (including drying and crushing)

As the pelletizing process requires the raw material to be dry and large part of pellets production costs and energy use is related to the drying process [43, 45], integrating pellet production with district heating can improve the energy balance significantly [45].

¹¹ Coniferous wood

Costs of pellets production

The key costs of pellets production are costs of raw material [45] and costs of drying of wet material [43, 45]. The plant capacity can be an important cost factor as well - the pellet production costs in Sweden were found to be about 30% lower than in Austria, mainly due to larger plant capacities and recovery of heat from the dryers and further selling it to local district heating networks [45]. The prices of pellets for large-scale users in EU 15 varied between 19-34 Euro/MWh in 2002 [80].

Under Dutch conditions the cost of pelletizing varies between around 12 – 40 Euro/ton input¹² [15].

Despite high price of pelletized feedstock, many power plants, especially in the Netherlands and Denmark, commonly use pellets for co-firing with coal. This is mostly to take advantage of their higher energy density, which allows reducing transportation costs and problematic handling and feeding issues in the power plant.

6.2.5. Briquetting

Co-firing of coal with biomass briquettes is an interesting option (although not commonly used), because its properties allow for using coal infrastructure (transport, storage, feeding) without modification of the system [101]. The advantages of briquetting of agricultural residues for boiler applications are [103]:

- the rate of combustion can be comparable to that of coal
- uniform combustion can be achieved
- particulate emissions can be reduced
- the storage properties are improved, and
- transportation, storage and feeding is more efficient.

Briquettes (Fig.26) can be made from biomass, or blends of biomass and coal-dust [104]. The typical diameter of briquettes is 30-100 mm [15]. Briquettes have density of 800-1200 kg/m³ compared to 60-180 kg/m³ of loose biomass [6].



Fig. 26. Biomass briquettes, Source [6]

¹² Conversion from original sources assuming 1US\$=1,26 Euro

The process of briquetting consists in general of the following steps [101]:

- Delivery and blend of biomass together with binding agent
- Mixing and heating of the blend
- Pressing of the blend to the form of briquettes
- Transport of raw briquettes to be stored, during a period of few days, outside (under roof) in order to get mechanical hardness
- Impregnation of the briquettes

Despite numerous advantages of using briquettes for co-firing applications, there are a number of challenges associated with briquetting. Biomass fuels in form of briquettes are characterized by easy moisture uptake potentially leading to biological degradation and subsequent losses of structure (behavior similar to pellets) [101]. Therefore they require appropriate storage conditions or special water resistant covering layers [101]. Hydrophobic substances can be also added during the briquettes production process. However the problem related to application of substances increasing the briquettes' resistance to moisture uptake is their high cost.

Costs related to briquetting

In general, the briquetting process is expensive due to the costs of briquetting process itself, costs of binding agents, costs of energy required for the briquetting process, and costs of impregnation of briquettes [101]. In effect, the price of this refined fuel is high in comparison with other biomass fuels. Under Dutch conditions the cost of briquetting (alike pelletizing) varies between around 12-40 Euro/ton input¹³ [15].

There is a potential for decreasing the costs of briquetting, by substitution of the binding agents with binding substances of residual origin [101]. Well-known binding agents are molasses, fibrous and oily organic wastes, sawdust, starch, limestone, dolomite, etc [104].

An element, which could improve the economics of briquetting, is their production from blends of biomass with low-quality coal-dusts (with high ash content and low calorific value), as coal-dust on its own has very limited utilization potential [101, 104].

Energy requirements of briquetting

The suitability of using biomass briquettes to substitute coal might be debatable, as except for its high costs, a substantial amount of energy might be required for briquetting. Under Dutch conditions the briquetting process consumes 15-80 kWh_e/t input [15].

According to the study of Purohit et al.¹⁴, briquetting of agricultural residues could not be an energetically preferred option over coal for boiler applications, even for places at moderate distances from the coal pithead [103]. However it should be noted that the study has been based on Indian

¹³ Conversion from original sources assuming 1US\$=1,26Euro

¹⁴ The study compared the primary energy embodied in coal mining and transportation of unit amount of coal - from the coal pithead to the end use point - per unit of useful energy delivered by coal, with the primary energy embodied in the briquetting of agricultural residues, at the end use location, per unit of useful energy delivered by briquettes

conditions, and the briquetting technology in India has not reached maturity yet, so there is considerable scope for design improvements to increase reliability and reduce energy consumption for the briquetting [103].

6.2.6. Washing/Leaching

A number of potential problems in biomass thermal conversion systems, such as ash deposit formation (slagging, fouling), corrosion, sintering, and agglomeration, are related to biomass chemical composition (mainly Cl, Na and K contents) [27, 28, 29, 30, 31].

There are several methods to reduce the negative effects related to alkali compounds in biomass. Additives such as dolomite and kaolin are capable of reducing sintering problems by raising the melting point of ash [29]. Vaporization of alkali compounds can be reduced by a decrease in process temperature [29]. Finally, removal of those troublesome elements can be performed by washing (leaching) biomass with water and is especially important in the case of straws, grasses and other herbaceous feedstocks due to their typically high ash contents [27, 29, 32]. Potassium, sodium and chlorine are easily removable in both tap and distilled water [27, 29]. The removal of alkali metals, chlorine and sulphur can be beneficial in increasing the fusion temperatures of straw ash [27].

Herbaceous feedstocks like straw are often left exposed to weather conditions, in order to reduce the chlorine and alkali contents and consequently reduce deposition and corrosion problems [16]. Leaching of the cut straw after harvesting on the field by rainfall has a disadvantage of being dependent on weather conditions, and possibility of straw degradation [15, 29]. Leaving the straw standing in the field (after having harvested only the corn) to leach it out has a disadvantage of need for a second straw harvest [15].

Controlled pre-treatment of biomass by leaching is independent of climatic and weather conditions, the amount of quality improvement can be determined, but high investment and operating costs are involved [15]. In general two types of washing might be applied [29]: simple leaching with water, acid, and ammonia. Around 90% of alkali in biomass is present in water-soluble or ion-exchangeable form, and is susceptible to vaporization during heating [29]. Typical ash-forming components that are leached out by water include alkali sulphates, carbonates and chlorides [47]. Elements leached out by ammonia are believed to be organically associated, such as Mg, Ca as well as K and Na, whereas HCl leaches the carbonates and sulphates of alkaline earth and other metals. Silicates and other minerals remain in the insoluble residue [47].

If biomass washing can effectively reduce problems caused by alkali components in biomass, large-scale washing of problematic fuels prior to combustion may be economically feasible in industrial conversion systems [29]. Reduction of alkali compounds in biomass feedstock might mean savings in maintenance costs (e.g. superheaters would become more durable for longer periods) [84].

6.2.7. Torrefaction

Torrefaction is a thermo-chemical process conducted in the absence of oxygen, at a temperature 200-300°C, at typically 1-hour residence time, during which biomass partially decomposes giving off volatiles and giving the remaining solid as a final product (sometimes referred to as char) [96]. Torrefaction seems to be a promising pre-treatment option, improving the properties of biomass feedstocks in favor of combustion and gasification [17]. Depending on the applied operation conditions, the following property changes can be achieved by torrefaction [17, 96]:

- increase of the heating value per weight unit
- improved hydrophobic nature
- improved grinding properties
- increased uniformity and durability

Torrefaction can help to mitigate certain constraints related to co-firing of biomass with coal, such as size reduction of biomass (which is problematic due to its fibrous structure which is loosened during the decomposition reactions), storage (dry matter losses, fungi growth), or feeding.

An advantage of torrefaction is that different types of feedstocks have quite similar physical and chemical properties after torrefaction, which is a very attractive feature in the light of process optimization and control [100]. Another benefit of torrefied biomass is that its storage is easier and less demanding, as the nature of pre-treated feedstock is hydrophobic (in contradiction to hygroscopic nature and rotting tendency of untreated biomass). With relation to co-firing an important advantage of torrefied biomass is its improved grindability (which appears to be otherwise problematic) - the reduction in power consumption during sizing of torrefied biomass can amount up to 70-90% (in comparison with untreated biomass) and the grindability (power consumption) is similar to that of bituminous coal [99].

In 2003, co-firing of torrefied wood was tested in PC-plant in the Netherlands, where torrefied wood was mixed with coal up to 9% (energy basis), resulting in conclusion that there is room for increasing the co-firing ratio (pulverizer's limits were not reached), and co-firing of torrefied wood can be a viable feedstock option for direct co-firing of biomass with coal [97].

Although the principles of torrefaction are known since 1930, currently no commercial process is available on the market [96]. For successful market introduction, production costs of torrefied biofuels need to be competitive with alternate bio-conversion products and this will have to be tested during scaling-up of the technology [97].

Costs of torrefaction

The economic evaluation of the torrefaction process is based on estimates of ECN [96]:

The production cost of the process is estimated to be 77 €/ton product (2004) for 60 kton/year of product in case of an indirectly heated process (screw reactor). In case of directly heated process concept (based on moving-bed reactor) the investment costs can be reduced by half, and the total production costs could be 56 €/ton product. Additional reduction of costs could be achieved by minimizing the use of natural gas (through optimization of torrefaction conditions and by using

biomass feedstock as utility fuel), minimization of the reaction time, etc. Under optimized conditions it is expected that a torrefaction production plant of 230 kton/year consisting of four parallel production lines, requires an investment of 21 M€ and results in total production costs of about 40 €/ton product (or 18 €/ton feedstock). The required investment of each line (60 kton/year) is then 5.2 M€

Environmental performance of torrefaction

The torrefaction process can be designed as a thermally closed system, where heat required for the process comes from the combustion of torrefaction gas possibly together with utility fuel (directly heated torrefaction, Fig.27) and the gas itself is used as a heat carrier (vs. the indirectly heated concept where the flue gas coming out of the combustion process transfers heat to oil) [96]. The hot gas gives off the heat in the torrefaction reactor, where it is cooled and mixed up with torrefaction gases and following, part of these gases are directed to combustion and the reminder is re-pressurized, heated and returned to the torrefaction [96].

A waste stream may occur from the treatment of torrefaction gas, in case it cannot be combusted, or through the way the hot product discharged from the torrefaction reactor is cooled (e.g. by direct contact with cooling water, producing wastewater) [96]. Emissions to air, in a form of NOx and VOCs, can be encountered as a consequence of drying of biomass as well as a consequence of combustion of the torrefaction gas [96].

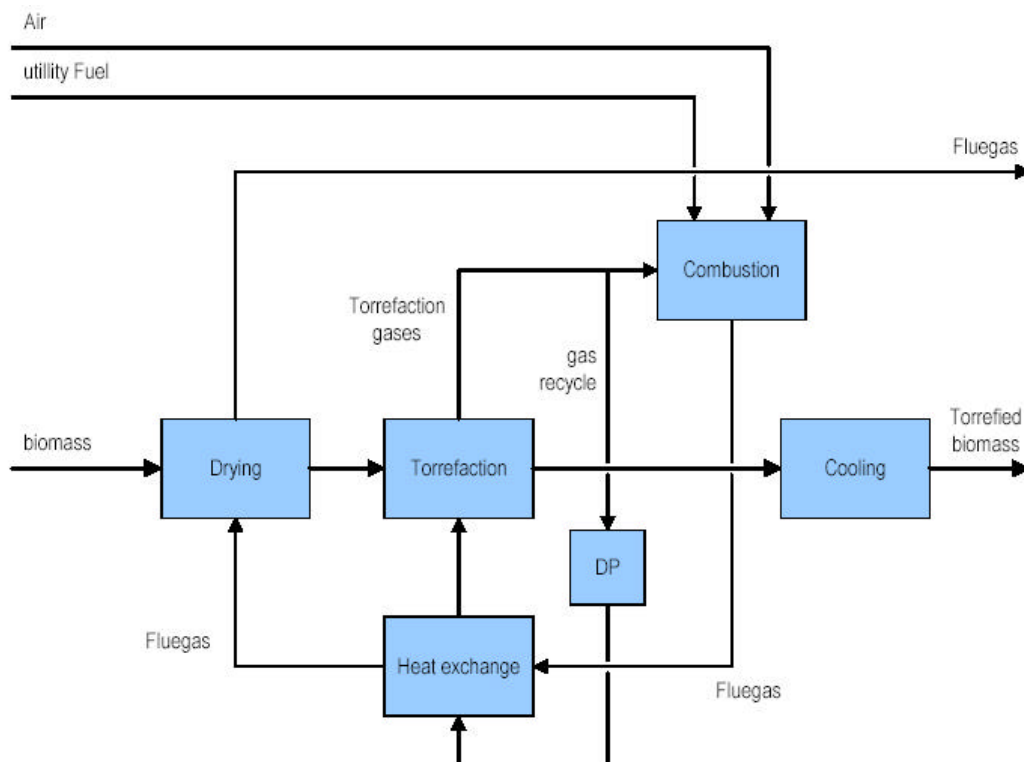


Fig.27. Simplified basic concept for directly heated torrefaction, DP-pressurization of the gas, Source [100]

Energy and mass balance

Typically 70% of the biomass mass is retained in a solid torrefied product, containing 90% of the initial energy content, whereas 30% is converted to torrefaction gases containing 10% of the energy content of biomass [96]. Therefore, the torrefaction provides high transition of the chemical energy from the feedstock to the torrefied product, which is a significant advantage of the process [99]. A typical mass and energy balance of torrefaction process is presented in Fig. 28.

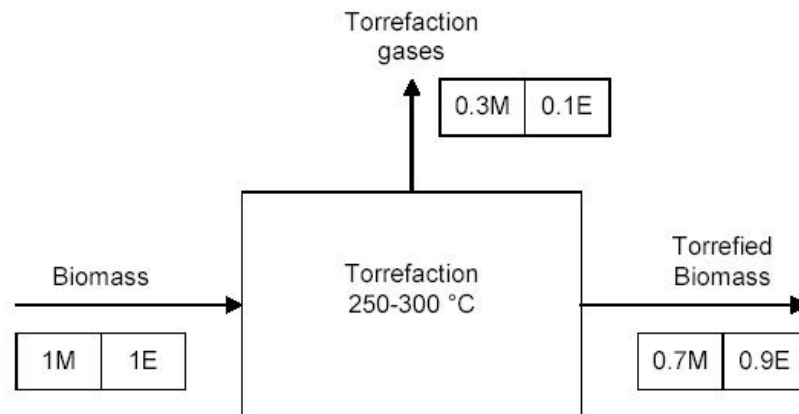


Fig.28 Typical mass and energy balance of torrefaction process, E-energy unit, M-mass unit, Source [99]

8.2.8 Torrefaction combined with pelletizing (TOP Process)

This section describes the so called TOP pellets, which are (torrefied) pellets produced in a process combining torrefaction with pelletizing, and is completely based on the ECN report [99]:

As described previously, in comparison with untreated biomass, pellets have more attractive properties with regard to heating value, grindability, storage, transport and handling. But there are still issues to be solved regarding pellets resistance against moisture uptake, as well as mechanical resistance against crushing and dust formation. Pellets swell when exposed to moisture conditions, and subsequently disintegrate to original feed particles and mass density. Therefore they are demanding with regard to storage conditions, and need to be transported and handled carefully. The biological degradation is decreased after pelletisation, but still can occur. The uniformity of pellets is hard to establish, and there can be variations between pellets made out of softwood, hardwood, and different tree species. Additionally, at current pelletisation is limited to sawdust and cutter shavings as economical feedstock, making the pellet market closely related to the wood-processing industry.

Torrefaction, as described previously, has certain advantages when compared with untreated biomass. Biomass is completely dry after torrefaction, and its moisture uptake is very limited (1-6% depending on torrefaction conditions). The biological degradation of torrefied biomass is practically completely preserved.

However the drawback related to torrefaction is low volumetric energy density (the volume of torrefied biomass is reduced only slightly, ranging from 180-300kg/m³, and despite higher calorific values, the energy density is not improved, being typically 5 GJ/m³).

Torrefaction and pelletisation can be complementary and they can address each other's limitations. Torrefaction can solve the drawbacks encountered with the durability and biological degradation of biopellets. The storage of TOP pellets can be therefore simplified. Additionally, since torrefaction can be applied to wide variety of biomass, the feedstock range for pellets production can be enlarged. In return, pelletisation of torrefied biomass offers solution to low volumetric energy density of torrefied biomass (Tab.18).

The TOP process combines torrefaction and pelletisation, as shown in Fig.29.

Next to synergetic effects with regard to fuel quality (when torrefaction and pelletizing are applied), the benefits can be also found on the level of unit operation. After torrefaction, the size reduction and densification of biomass are significantly enhanced with respect to power consumption (high energy-consumption is avoided), and capacity (the desired production capacity can be established with much smaller equipment). An advantage of combining the processes is that instead of using fossil fuel as utility fuel, the torrefaction gas can be used for drying.

The power consumption of the TOP process is lower than the conventional pelletisation, due to lower energy consumption of sizing and pelletisation (and despite increased power consumption for torrefaction).

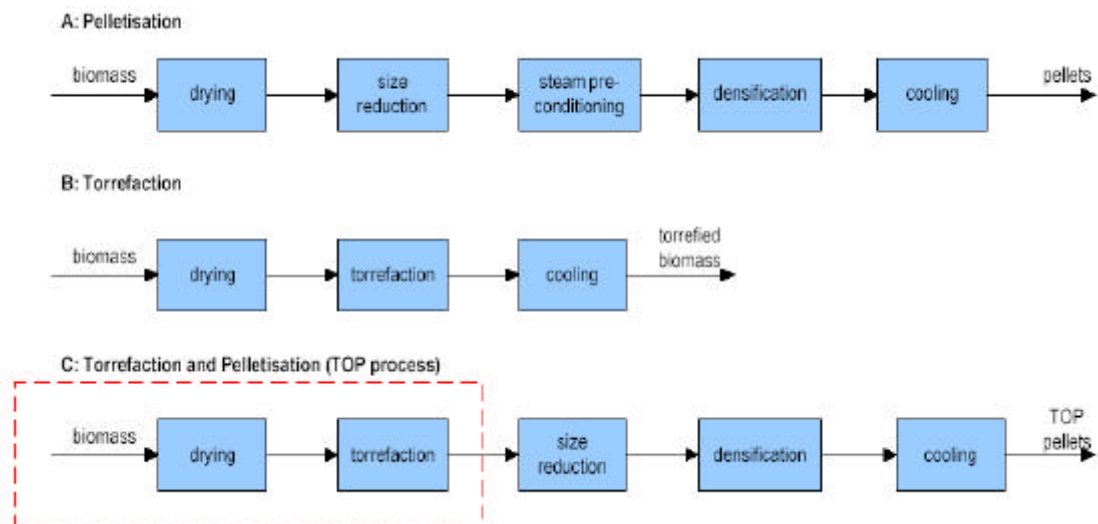


Fig. 29. Basic process structure of pelletisation, torrefaction and TOP process, Source [99]

Tab. 18. Properties of wood, torrefied biomass, pellets and TOP Pellets, Source [67]

Properties	Unit	Wood	Torrefied biomass	Wood pellets	TOP pellets
Moisture content	%wt	35	3	7-10	1-5%
LHV dry	MJ/kg	17,7	20,4	17,7	20,4-22,7
LHV as received	MJ/kg	10,5	19,9	15,6-16,2	19,9-21,6
Mass density (bulk)	Kg/m3	550	230	500-650	750-850
Energy density (bulk)	GJ/m3	5,8	4,6	7,8-10,5	14,9-18,4
Pellets strength		-	-	Good	Very good
Dust formation		Moderate	High	Limited	Limited
Hygroscopic nature		Water uptake	Hydrophobic	Swelling/water uptake	Poor swelling (hydrophobic)
Biological degradation		Possible	Impossible	Possible	Impossible
Handling properties		Normal	Normal	Good	Good

Economics of TOP

According to economic analysis of ECN [99], the total capital investments are higher in case of TOP process (in comparison with conventional pelletisation) due to introduction of torrefaction. The total production costs of the TOP process per ton of product is also higher, however, one tonne of TOP product contains more energy than one tonne of conventional pellets, therefore the correct comparison is between the cost per unit of energy of both products (Euro/GJ), where TOP pellets are cheaper than conventional pellets (Tab.19).

Tab.19. Economic performance characteristics of the pelletisation of sawdust and green wood (hardwood) for the conventional pelletisation process and the TOP process, Source [99]

NOTE: the comparison is between real figures (pellets) and estimates based on results of pilot process (TOP)

	Unit	Sawdust- Conventional pelletisation	Sawdust- TOP process	Green wood – Conventional pelletisation	Green wood – TOP process
Production rate	kt/a	80	56	80	56
Total Capital Investment*	MEuro	3,9	5,6	5,9	7,4
Total production cost**	Euro/t	41	45	54	50
	Euro/GJ	2,6	2,2	3,4	2,5
Financing	Euro/t	2,0	4,4	3,2	5,9
Depreciation	Euro/t	4,0	8,8	6,5	11,7

*Including working capital of about 0,5-0,7 MEuro

**Including cost items financing and depreciation

Capacities and costs are related to tonnages of product

The profitability of TOP product was also evaluated on a basis of logistics and transport costs, considering that the refined product will need to be imported to North-West-Europe from South Africa. The elements considered were delivery of feedstock, transportation and handling on production site in South Africa, intermediate storage, sea transport, transfer operations, storage in European harbor,

and transportation to co-firing power plant. As shown in Fig. 30 the absolute costs involved in the production chain are 30% less for the TOP process (compared with pelletisation), due to lower production volumes (higher energy density) and higher bulk density. The biggest savings are found in production and sea transportation.

Additionally (not included in the analysis) co-firing of conventional pellets requires dedicated storage systems, whereas in ideal case, the TOP pellets can be stored together with coal and be processed using the existing infrastructure for coal, which allows savings to the power plant owners.

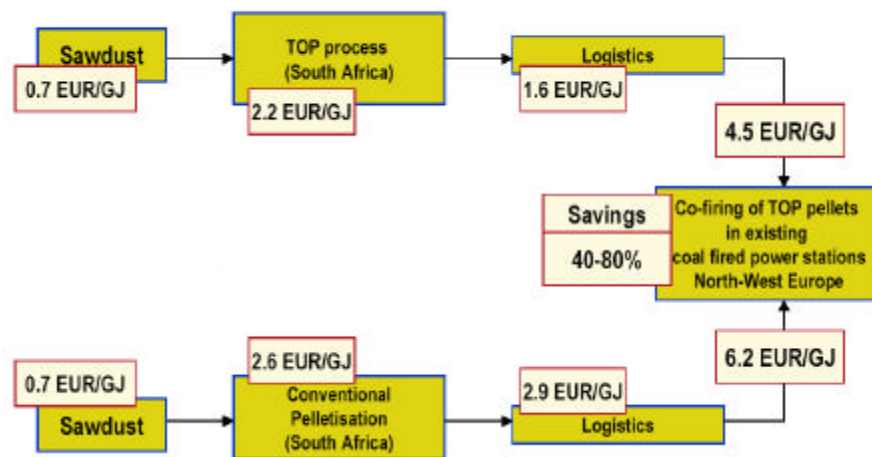


Fig.30. The costs of logistics of TOP pellets vs. conventional pellets, Source [67]

6.2.9. Pyrolysis

Fast (flash) pyrolysis is an option to get directly a liquid product (pyrolysis oil) from biomass by its thermal decomposition at temperatures of 450-550°C. Pyrolysis oil consists of about 70% oxygenated organics and 30% water (weight basis). By a proper design of the pyrolysis process, the content of ash in pyrolysis oil can be minimized. The yield efficiency of the pyrolysis oil production is on average about 70%, depending on the feedstock, process configuration, and conditions. The volumetric energy content of pyrolysis oil is about 19 GJ/m³, which is much higher than that of biomass logs (6 GJ/m³). Thus the transportation costs – a major factor that influences the overall cost efficiency of biomass utilization in energy systems – are reduced significantly.

With regards to energy demand of pyrolysis process, 9,2% of the net heating value of straw is needed to dry and pyrolyse the straw [32].

For application of biomass pyrolysis as a pretreatment process, equipment is needed which can pyrolyse large amounts of straw in relatively low temperatures, however such equipment is not commercially available today [32]. Nevertheless the use of biomass pyrolysis oil in co-firing with fossil fuel has been demonstrated in large-scale coal power station [102].

The application of pyrolysed biomass for co-firing can be sometimes challenging, as the liquid products obtained by means of pyrolysis are rich in water that is detrimental for ignition [105].

6.2.10. Combination of pyrolysis and char wash

The pre-treatment process based on biomass slow pyrolysis, followed by char wash (during which potassium and residual chlorine are extracted from the char by water), where afterwards washed char and pyrolysis gases may be co-fired with coal, was investigated in [32]. This section is completely based on information included in [32] and can be summarized as follows:

- Fluidised bed reactors seem to be the most promising for pyrolysis of straw on a large scale
- During pyrolysis most of the chlorine is transferred to the gas phase as HCl (which is not expected to seriously increase corrosion) or deposits as KCl. No significant amount of potassium is released to pyrolysis gas if the pyrolysis temperature is kept around 500-600 °C
- There was no reduction of the heating value of the washed char
- The extraction of K from char during washing is a two-step process (40-60% is released during the first few minutes, followed by much slower secondary release), whereas most chlorine was released within few initial minutes during char wash
- Analysis of the char extraction leachate indicates that the wastewater from the process can be probably utilized as a raw material in fertilizer production, but the content of K is too low for direct utilization. The main components of the water are chlorine, potassium (1,1 wt%), sulphate and carbonate, whereas the undesirable species (Cd, Hg, phenols) are only present in minor amounts, as they stay in the solid.

Economics of combination of pyrolysis with char washing

The cost of electricity produced through co-firing of straw pre-treated by pyrolysis and char wash seems to be economically favourable in comparison with untreated straw-fired grate boilers, however the pyrolysis technology on power plant scale is not commercially available today (2001) [32]. Co-firing of straw pre-treated by pyrolysis and char wash is also advantageous in comparison with co-firing of straw pre-treated by washing (because of much smaller amounts of solid materials to be washed). But through straw washing, a larger potassium removal can be probably obtained on a smaller pre-treatment plant (which might influence the possibilities for wastewater utilization in fertilizer applications). Tab.20. presents an economical comparison of different straw combustion concepts.

Tab. 20. Economics of different straw combustion concepts, Source [32]

Straw combustion concept	Electricity cost [EUR/MWh] *
Co-firing of raw straw and coal	69
Pre-treatment by pyrolysis and char wash combined with co-firing in existing coal-fired Danish plant, using 130.000 t straw/year	71
Pre-treatment by straw leaching combined with co-firing	73
Separate straw-fired grate boiler	89

*The fuel costs of Danish straw constitutes 43 EUR/MWh

Energy balance

The pre-treatment plant assessed in [32] includes equipment for straw pyrolysis, char wash, straw chopping, wastewater handling, and pyrolysis gas and char injection into the coal-fired boiler. Therefore the whole process includes straw cutting, pyrolysis, char washing and water treatment.

Energy balance calculations showed that the electrical efficiency of firing of pre-treated straw was only 4%-points lower than for coal fuel¹⁵. The energy loss was due to heat loss from the pyrolysis reactor, cooling of char, evaporation of water, and process electricity consumption.

The energy needed to dry and pyrolyse the straw and heat the products are shown in Tab.21¹⁶.

Tab. 21. Calculation of pyrolysis enthalpy of 1kg of straw, Source [32]

Heating of straw 20-100°C [kJ/kg]	Evaporation of water (drying) at 100°C [kJ/kg]	Heating of straw and water 100-300°C [kJ/kg]	Pyrolysis at 300°C [kJ/kg]	Heating of pyrolysis products 300-550 °C [kJ/kg]	Total energy for the pyrolysis and heating [kJ/kg]
137	316	368	0	539	1359

The net heating value of straw was assumed 14,8 MJ/kg, and 1,36 MJ/kg is needed to pyrolyse the straw, resulting in 9,2% of the net heating value of straw needed to pyrolyse the straw [32].

Summary and conclusions

Pre-treatment of biomass with relation to co-firing with coal is applied for various reasons. The wide variety of biomass streams often does not match with the narrow fuel specifications of feeding systems and the conversion processes considered. Other reasons are to reduce the plant's investment, maintenance, and personnel costs by using homogenous fuel that is suitable for an automatic fuel feeding, and to reduce the need to invest in complex and expensive combustion and gasification installations. Further advantages of application of pre-processing to biomass are that the costs of handling, storage and transportation can be lowered, and storage characteristics can be improved. Fig. 31 presents the energy density of coal and various biomasses in a raw form, and after pre-treatment. Tab.22 summarizes the main advantages of various biomass pre-treatment options for co-firing systems.

¹⁵ The electrical efficiency in typical Danish base load coal power plant is 45%, the pre-treated straw can be co-fired with an electrical efficiency of 41% [32].

¹⁶ The calculations was done assuming that the straw is heated to 300°C, immediately pyrolysis takes place and the pyrolysis products are heated to 550°C.

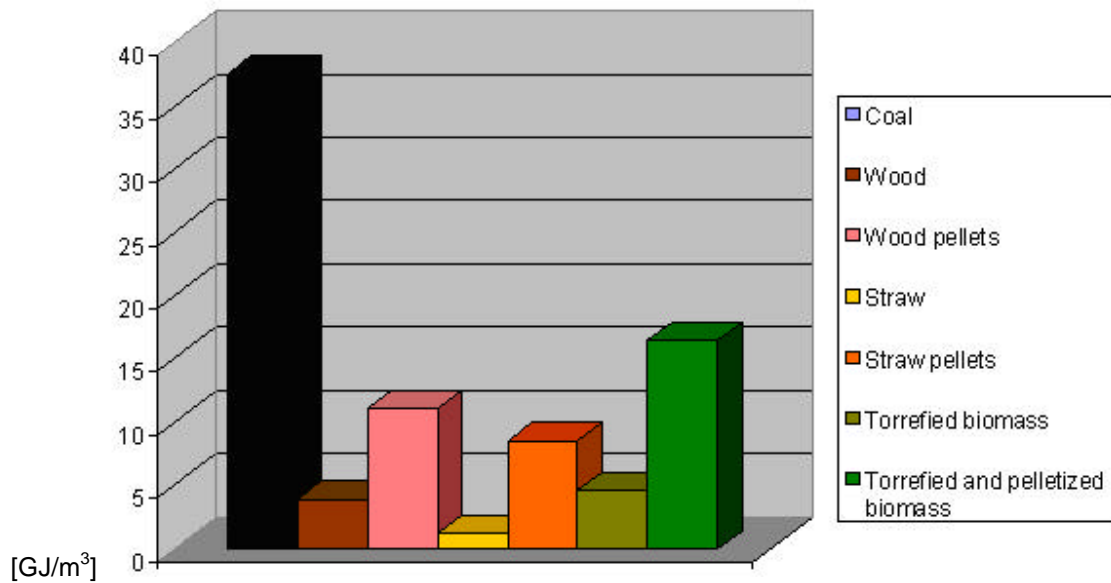


Fig. 31. Volumetric energy content (energy density) of coal and biomass in various forms

Tab.22. Summary of advantages and challenges associated to application of biomass pre-treatment in co-firing systems

Biomass pre-treatment	Positive role in co-firing system	Challenges/comments
Sizing (grinding, chipping, chunking, milling)	-Basic pre-treatment bringing the feedstock to the size required by boiler specifications	-Sizing from the viewpoint of biomass supply costs, should be applied before transportation. But storage of sized biomass can increase microbiological activity and dry matter losses, so the two work against each other. Also due to microbiological activity, biomass storage can be a source of significant GHG emissions (CH ₄ , N ₂ O). -Sizing can be problematic due to non-friable character of biomass -In case of co-milling, the mill capacity can limit the co-firing ratio
Drying	-Reduces dry matter (energy) losses of biomass during storage -Reduces the risk of biomass decomposition, self-ignition risk, and problems with fungi development during storage -Increases potential energy input for steam generation	- Natural drying is commonly applied, however has a disadvantage of unforeseeable weather conditions -Drying in dryers require sized biomass (look at challenges with sizing)
Baling	-Higher energy density, resulting in decreased transportation costs -Lowered moisture content -Better storage properties -Less storage space required	-Biomass in form of bales can be utilized in stoker systems, but its direct co-firing in that form is practically impossible, and it needs to be further reduced in size.

Briquetting	<ul style="list-style-type: none"> -Higher energy density, possibility for more efficient transport -Possibility for utilization of coal infrastructure for storage, milling, and feeding -Less storage space required -Possibility of spontaneous combustion during storage is reduced -Rate of combustion comparable with coal 	<ul style="list-style-type: none"> -Easy moisture uptake potentially leading to biological degradation and losses of structure (similarly to pellets), therefore briquettes require special storage conditions. Hydrophobic agents can be added to briquetting process, but increase their costs significantly.
Washing /leaching	<ul style="list-style-type: none"> -Reduction of corrosion -Reduction of slagging, fouling (ash deposition), sintering and agglomeration of the bed -Consequently reduced wearing-out of equipment, and decreased risk of shut-down of the system for related maintenance -Washing is especially important in case of herbaceous feedstocks. 	<ul style="list-style-type: none"> -Moisture content of biomass is increased after washing -Adding to the process dolomite or kaolin, which increase ash melting point, can also reduce negative effects of alkali compounds – it is not considered as pre-treatment however.
Pelletizing	<ul style="list-style-type: none"> -Higher energy density, with benefits for transportation costs -Possibility for utilization of coal infrastructure for feeding and milling (permits automatic handling and feeding) -Easier grinding -Increased possible co-firing ratio (if constrained by boiler capacity and low bulk density of untreated biomass) -Less storage space required -Dry feedstock (better storage properties, reduced health risks, reduced energy losses, higher calorific value) 	<ul style="list-style-type: none"> Pellets, despite their benefits, can be sensitive to mechanical damaging and can absorb moisture and swell, loose shape and consistency. They are therefore demanding with regard to storage conditions.
Torrefaction	<ul style="list-style-type: none"> -Possibility for utilization of coal infrastructure for feeding and milling -Improved hydrophobic nature – easy and safe storage, biological degradation almost impossible -Improved grinding properties resulting in reduction of power consumption during sizing -Increased uniformity and durability 	<ul style="list-style-type: none"> -No commercial process is available on the market today -Torrefied biomass has low volumetric energy density (biomass volume after torrefaction is reduced only slightly, ranging from 180-300kg/m³, and despite achieved higher calorific values, the energy density is not improved, being typically 5 GJ/m³)
TOP process	<ul style="list-style-type: none"> -Combines the advantages of torrefaction and pelletizing, while addressing the challenges related to both. Torrefaction could solve the drawbacks encountered with the durability and biological degradation of pellets. Additionally, since torrefaction can be applied to wide variety of biomass, the feedstock range for pellets production can be enlarged. In return, pelletisation of torrefied biomass offers solution to its low volumetric energy density. - After torrefaction, the high energy-consumption of size reduction and densification is avoided, and the desired production capacity can be established with smaller equipment. -Higher energy density, resulting in decreased transportation costs -Easy utilization of coal infrastructure for feeding and milling -Less storage space required 	<ul style="list-style-type: none"> -No commercial process is available on the market today -Does not address the problems related to biomass chemical properties i.e. corrosion, slagging, fouling, sintering, or agglomeration of the co-firing systems.

7. Summary, conclusions and discussion

The aim of this work was to provide an overview of possible constraints that can be encountered in systems co-firing coal with biomass, and identify biomass pre-treatment options with potential to address (some of) them. The final goal is to conclude, on qualitative basis, which pre-treatment options for biomass are the most promising with regard to co-firing.

The main conclusions from the literature review performed in this report can be listed as follows:

1. There are many successful commercial co-firing installations, however various constraints can be encountered, especially in the direct co-firing mode (which is the most common among co-firing systems), and with tendency to increase biomass/coal ratio, and use low quality biomass. These constraints include handling, storage, milling and feeding problems, deposit formation (slagging and fouling), agglomeration, corrosion and/or erosion, and ash utilization issues.

2. The problems associated with co-firing systems can be addressed by various measures. Application of downstream measures (e.g. cleaning of deposits by soot blowing or exchange of agglomerated bed material) is one possibility. Another option is addition of chemicals reducing corrosion and increasing the ash melting point in order to avoid agglomeration and deposit formation. A commonly applied option is an introduction of dedicated biomass infrastructure (e.g. for feeding, milling, storage, conveying) to the existing coal system. A more expensive alternative (in terms of investment costs) is an introduction of more advanced co-firing mode such as parallel co-firing or indirect co-firing, where not only fuel preparation and feeding lines, but also conversion units for biomass and coal are independent. Each of these options addresses certain issues (Tab.23), none of them however addresses issues related to costly transport and large volumes of biomass to be stored and handled.

3. Most of the co-firing challenges originate from biomass properties and could be reduced (as one of the possible options) by upstream measures such as biomass pre-treatment. Pre-treatment is an interesting option, as by modifying biomass properties, it addresses problems at their source. Constraints that can be addressed by various pre-treatment options are summarized in Tab. 23.

4. The costs of biomass utilization in co-firing systems depend not only on its purchase price and pre-treatment costs, but also on the costs of operability of the fuel (handling, storage, transport) and operability of the boiler and combustion process. It might not necessarily be optimal to use the cheapest fuel available, if negative effects on boiler operation and fuel operability are significant.

5. The most advanced form of bio-feedstock currently used in co-firing on commercial scale is biomass pre-treated into pellets, and it is commonly used in the Netherlands and Denmark.

6. An interesting option is pyrolysis of biomass into pyrolysis oil, however this option cannot be applied in direct co-firing systems – due to liquid form of the feedstock it requires separate conversion unit as well as dedicated infrastructure for transport, storage, feeding etc.

Tab. 23. The role of various measures in mitigating problems associated with co-firing systems

	Transport cost	Energy losses during storage	Health and safety hazards during storage	Co-milling problems	Feeding (& handling) problems	Corrosion	Deposit formation (slagging, fouling), sintering, agglomeration	Limited co-firing ratio (due to volume)	Ash utilization (if mixed ashes are problematic)
Drying	0	++	++	X	X	0	0	0	0
Sizing	+	—	—	+	+	0	0	+	0
Baling	++	+	+	X	X	0	0	0	0
Briquetting	+++	++ ¹	++ ¹	++	+	0 ²	0 ²	++	0
Pelletizing	+++	++ ¹	++ ¹	++	++	0 ²	0 ²	++	0
Torrefaction	0	+++	+++	+++	+	+	0	0	0
TOP	+++	+++	+++	+++	+++	+	0 ²	+++	0
Leaching	0	0	0	0	0	+++	+++	0	+ ³
Fast pyrolysis	+++	+++ ⁴	+++ ⁴	+++ ⁴	+++ ⁴	—	+	+++ ⁴	+++ ⁴
Pyrolysis with char wash	+++	X	X	+++	+++	+++	+++	+++	+ ³
Dedicated infrastructure	0	+++	++	++	+++	0	0	+	0
Advanced co-firing	0	0	0	+++	+++	+	++	+++	+++
Chemical additives	0	0	0	0	0	+++	+++	0	0
Downstream measures	0	0	0	0	0	+	+	0	0

(+) some potential in addressing the problem
 (++) high potential to address the problem
 (+++) very high potential to address the problem
 (--) negative influence on the problem
 (o) not relevant to the problem
 (x) lack of data

¹ proper storage conditions need to be provided
² unless produced with additives lowering the ash melting point
³ reduction of the amount of bio-ash, not separation of biomass and coal ashes
⁴ feedstock in liquid form, thus dedicated infrastructure is necessary (for storage, feeding, conversion unit), therefore this pre-treatment alone, without dedicated infrastructure, cannot address the problem

7. It seems that biomass pre-treatment by combination of pelletisation with torrefaction might be an interesting option, as it appears that it can to even larger extent (than in case of conventional pellets) mitigate the problems related to high transportation and storage costs, handling, and milling of raw biomass.

8. The only single pre-treatment option with potential to mitigate problems (if encountered) with bed agglomeration, deposit formation (slagging and fouling) and corrosion was identified to be biomass leaching (washing).

9. It might be that combination of biomass washing with pelletizing and torrefaction, as well as combination of slow pyrolysis with char wash, might allow co-utilization of high ratios of low quality biomass (e.g. wheat straw) with coal in the existing coal systems without modifications, while avoiding most of the problems otherwise encountered in co-firing systems fueled with untreated biomass. It should be however noted that these pre-treatments are not at the commercial stage at present. The potential disadvantages of the proposed pre-treatment options are therefore unknown, and the economic and environmental assessments of these options would be needed.

10. It is not possible to define one universal pre-treatment option for biomass for co-firing purposes. It needs to be decided on an individual basis, depending on the quality of raw biomass, the type of co-firing system, desired co-firing ratio, etc. In cases where minimal investment costs are to be made in order to retrofit the existing coal power plant into co-firing plant, and long distance transport of biomass is required, it seems that more advanced pre-treatment can be beneficial. In cases where dedicated biomass infrastructure exists in the system, and the co-firing ratio is low, more basic options (if any) for biomass pre-treatment could be sufficient.

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ANNEX I

Results of LCA studies on co-firing and biomass utilization for electricity generation, Source: Based on [56, 57, 58, 59, 60, 61, 62, 63, 64, 65]

Reference	Issue addressed	Main conclusions
<p><i>Evaluation of the environmental impact of waste wood co-utilization for energy production</i>, G. Skodras, P. Grammelis, E. Kakaras, G.P. Sakellatropoulos, 2004</p> <p><i>Electricity generation from solid biomass via co-combustion with coal. Energy and emission balances from a German case study</i>, D. Hartmann, M. Kaltschmitt, 1999</p>	<p>- The environmental impact (LCA) of co-utilizing lignite with waste wood in an industrial steam boiler</p> <p>- The electricity production by co-combustion of straw and residual wood at 10% blend with hard coal in an existing power plant (DE) is analyzed based on LCA</p>	<p>- Co-utilization of lignite with waste wood is technically feasible and can meet strict environmental standards</p> <p>- Net decrease of CO₂ emissions can be achieved as well as conservation of fossil fuel resources, minimization of waste disposal and reduction of impacts on health</p> <p>- All environmental effects are significantly lower if biomass is used instead of coal</p> <p>- Wood shows lower environmental impact than straw</p> <p>- The consumption of non-renewable energy resources for the supply of straw and residual wood for electricity production is in a range of 5% compared to electricity provision from hard coal</p> <p>- The use of biomass for energy can contribute towards the CO₂ reduction aims of Kyoto protocol (the emissions of CO₂-eq for the provision of electricity from biomass are much lower compared to that from hard coal)</p>
<p><i>Selected emissions and efficiencies of energy systems based on logging and sawmills residues</i>, H. Malkki, Y. Virtanen, 2003</p>	<p>- The environmental impact assessment of the logging (chips) and sawmill residues throughout the whole fuel chain (forest-energy production) using the LCA methodology</p> <p>- Environmental aspects of two sawmill residue chains (big and small scale) and four chipping chains – the terrain and the roadside chipping of logging residues, including both fresh and the dry chipping options were analyzed</p>	<p>- The energy efficiencies of the forest chip systems are quite high</p> <p>- Net CO₂ emissions of the system are quite low</p> <p>- Although wood is a renewable energy source, it has got similarities with fossil fuels, e.g. the emissions of the conversion phase are significant</p>
<p><i>Life cycle assessment of coal by-products based electric power production scenarios</i>, E. Benetto, P. Rousseaux, J. Blondin, 2004</p>	<p>- LCA of six scenarios of coal based electricity production in France. One of them includes co-combustion of S.African coal with wet sawdust, where ashes from the process are landfilled.</p>	<p>- The results showed that the more environmentally scenarios include biomass co-combustion</p>

<p><i>Life cycle assessment of fossil CO₂ emissions reduction scenarios in coal-based electricity production</i>, E. Benetto, E-C. Popovici, P. Rousseaux, J. Blondin, 2004</p>	<p>- LCA of four scenarios of coal-based electricity production, including coal and biomass (waste or cultivated) (pulp only, S. African coal with SRC, S. African coal with wet sawdust, SRC only)</p>	<p>- The biomass co-combustion is always environmentally better than the sole CO₂ capture and/or biomass combustion.</p>
<p><i>Incremental life cycle analysis: using uncertainty analysis to frame greenhouse gas balances from bioenergy systems for emission trading</i>, R.A. Ney, J.L. Schnoor, 2002</p>	<p>- Proposed methodology for verifying greenhouse gas reductions arising from substitution of bioenergy fuel for fossil fuel in electricity generation – to support project-based trading of greenhouse gas emissions. The method utilizes an incremental progression through the fuel life cycle, pausing at each level to evaluate the potential benefits and uncertainties of next-level expansion</p> <p>- A case study is analyzed for greenhouse gas benefits of switchgrass substitution for coal combustion in an existing electric generation facility</p>	<p>- One of the largest contributors to the net greenhouse gas benefit from bio-energy systems, soil carbon sequestration, provides 30g CO₂/MJ benefit, but comes at the expense of an estimated uncertainty, +- 42.5 g/MJ, which represents 62% of total uncertainty for the incremental method. Further research should be focused on improving estimates of soil carbon sequestration rates for the switchgrass production.</p> <p>- The case study reveals that the proposed substitution of switchgrass for coal can provide 102 g/MJ of CO₂-eq reduction, +- 62 g/MJ, for every MJ of switchgrass combusted.</p> <p>- The net greenhouse gas benefit of the project where burning 5% of switchgrass in place of coal, would result in net greenhouse gas benefits of 305000 metric tons of CO₂-eq annually, which at \$6,27/metric tone CO₂, would provide annual financial benefit of over \$1,9 million</p>
<p><i>Life cycle assessment of a willow bioenergy cropping system</i>, M.C. Heller, G.A. Keoleian, T. A. Volk, 2003</p>	<p>- Environmental performance of willow biomass crop production system in New York is analyzed through LCA</p>	<p>-Willow biomass crops are sustainable from an energy balance perspective and contribute additional environmental benefits</p>
<p><i>Book: Sustainability of biomass electricity systems. An assessment of costs, environmental and macro-economic impacts in Nicaragua, Ireland and The Netherlands</i>, R. van der Broek, 2000.</p>	<p>Chapter 6 of the book: - LCA of three life use options in the Netherlands (conventional wheat and SRC/willow for generating electricity, conventional wheat and set aside land for generating electricity with coal and organic wheat for generating electricity with coal</p>	<p>- Forest and sawmills residues could compete with peat, which is the most expensive fossil fuel</p> <p>- Energy crops cannot compete with fossil fuels without extra subsidies, but forestry grants are not available for short rotation willow coppice</p> <p>- The cost-effective route to electricity production are identified: CHP generation for places with constant heat and electricity demand (like hospitals), co-firing of sawdust in a pulverized coal plant would require minimal modifications to the existing plant</p>

	<p>Chapter 7: - Provides and overview of potential biomass resources and conversion technologies available in Ireland</p>	<p>and the same goes for co-firing biomass in a planned peat-fired power station (BFB)</p>
<p>Book: <i>A development perspective for biomass-fuelled electricity generation technologies. Economic technology assessment in view of sustainability</i>, R.V. Siemons, 2002</p>	<p>Chapter 4: <i>Biomass fuel markets</i> - Survey of the demand and supply of side of biomass energy in the EU, providing data about costs at each stage of the fuel supply chain Chapter 5: <i>A Concise Exploration into Technologies for Centralized Biomass-fueled Electricity generation Techniques</i> -Basic technical and economical data of the three main types of biomass fired generation technologies: Combustion Steam Cycles, Combined Cycle and the Liquefaction Combined Cycle. Chapter 6: <i>An economic assessment of concepts for centralized biomass-fueled electricity generation</i> - Main parameters in the assessment are plant size, energy efficiency, investment, electricity price, and CO₂ price</p>	<p>- There is not sufficient supply potential inside the EU for providing biomass in the quantities and qualities required to fulfill the politically formulated penetration targets for biomass based power production – biomass has to be imported from overseas - The author recommends the 'multiple-site bio-oil LCC' as the most promising option, due to the possibility of employing the low cost low-cost biomass resources from outside EU and the use of low-cost means of distribution</p>
<p>Poster: LCA of Procurement and Conversion of Biomass and Fossil Fuels – used for Energy Production in Denmark 1997, Christiansen H.F., Fock M.W., poster presented at the First World Conference and Exhibition on Biomass for Energy and Industry, Sevilla, 2000</p>	<p>Determine the energy consumption and emissions due to procurement of fuels (biomass vs. fossil fuels). Procurement in case of biomass includes activities like cultivating field and forests, pre-treatment of straw and pelletizing.</p>	<p>The study shows that the procurement of biomass is generally less energy consuming process. The general conclusion is that the use of biofuels result in significant environmental benefits (CO₂, NOx and SO₄), which are enhanced if procurement is included in the balance.</p>
<p><i>Life cycle energy and environmental benefits of generating electricity from</i></p>	<p>A life cycle inventory is presented that characterizes the full cradle-to-</p>	<p>"Life cycle analysis demonstrates that electricity generation with willow energy crops, either by co.-firing with coal or in dedicated</p>

<p><i>willow biomass</i>, Martin C. Heller , Gregory A. Keoleiana, Margaret K. Mannb, Timothy A. Volk, 2004</p>	<p>grave energy and environmental performance of willow biomass to-electricity. A willow biomass production model is developed using demonstration-scale experience from New York. Scenarios are presented that mimic anticipated co-firing operations, including supplemental use of wood residues, at an existing coal-fired generating facility.</p>	<p>biomass power plants, leads to reductions in many of the environmental impacts of coal-based electricity production. Consumption of non-renewable resources (coal) is reduced, as are net greenhouse gas emissions. Co-firing biomass at 10% increases the net energy ratio of producing electricity by 8.9%. Similarly, the net energy ratio for dedicated biomass gasification is estimated to be 13, indicating that 13 units of electricity are produced for every unit of fossil energy consumed across the entire system life cycle. For comparison, the net energy ratio of the current US electricity grid is 0.26. This study suggests that the environmental impacts from producing electricity with willow biomass energy crops are similar to using woody residues and that the pollution prevented is comparable to other renewable energy sources (solar and wind)” [64].</p>
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Co-firing of Biomass with Coal: Constraints and Role of Biomass Pre-Treatment**

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Abstract

There are many successful commercial co-firing installations, however various constraints can be encountered, especially in direct co-firing mode (which is the most common among co-firing systems), and with tendency to increase biomass/coal ratio, and use low quality biomass. These constraints can include handling, storage, milling and feeding problems, deposit formation (slagging and fouling), agglomeration, corrosion, erosion, and ash utilization issues. Most of the co-firing challenges originate from biomass properties

The problems associated with co-firing systems can be addressed by various measures. One of them is application of biomass pre-treatment, which is an interesting option, as by modifying biomass properties, it addresses problems at their source.

The aim of this work is to provide an overview of possible constraints that can be encountered in systems co-firing coal with biomass, and identify biomass pre-treatment options with potential to address them. This was done by investigation of the literature.

The pre-treatment options discussed include sizing, drying, washing, pelletisation, torrefaction and pyrolysis of biomass, as well as combinations of some of them.

The most advanced form of bio-feedstock currently used in co-firing on commercial scale is biomass pre-treated into pellets.

An interesting option is pyrolysis of biomass into pyrolysis oil, however this option cannot be applied in direct co-firing systems. It seems that biomass pre-treatment by combination of pelletisation with torrefaction might be an interesting option, as it could to even larger extent (than in case of conventional pellets) mitigate the problems related to high transportation and storage costs, handling, and milling of raw biomass.

The only single pre-treatment option with potential to mitigate problems (if encountered) with bed agglomeration, deposit formation (slagging and fouling) and corrosion was identified to be biomass leaching (washing).

It is not possible to define one universal pre-treatment option for biomass for co-firing purposes. It needs to be decided on an individual basis, depending on various elements such as quality of raw biomass, type of co-firing system, desired co-firing ratio, and others.

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