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Preface

Concerns about climate change and security of supply, both politically and in terms of depletion of fossil sources of fuel, are changing the energy sector at a rapid pace. Energy scenarios now involve wind and solar power at much higher degrees of penetration than previously, but also rely heavily on efficient use of local biomass resources either for direct combustion for controllable combined heat and power production, or further processing of the biomass resource into a syngas or liquid biofuel.

This is already evident: according to Eurostat, the share of biomass in the gross energy consumption of the EU27 in 2010 amounted to 7%, with Lithuania, Sweden and Finland all above 20%. With the EU 2020 targets of 20% renewables across the board in mind, a significant short-term potential for biomass is still to be realized, growing towards the 2050 targets of an 80% CO_2 reduction (compared to 1990 levels). For the power sector alone, reductions in the range 93–99% will have to be implemented in order for the general target of 80% to be achieved. Acknowledging the large contributions expected from other renewables as well as major infrastructure modifications (smart grids), efficient use of biomass will be a major contributor to achieving these goals.

This calls for continued development across the entire value chain, and opens up for some extremely exciting challenges and opportunities.

Several factors determine the best use of the biomass resource available – the biomass itself, the supply chain and logistics, technology and desired outcome. This book sets out to explore all these through three parts. Part I considers issues related to biomass resources and logistics, Part II discusses state-of-the-art thermochemical biomass conversion processes and Part III closes with engineering aspects of biomass conversion on a large scale, as well as providing an insight into biorefineries, where heat and power are part of a larger product scope including materials, chemicals and fuels.

The book opens with Wolf's chapter on fuel flexible combustion, stressing the importance of being able to handle a range of different types of fuel or biomass in order to alleviate the risks of depending only on a single feedstock. Rentizelas develops this aspect with a detailed look at the supply chain, highlighting aspects such as, for example, seasonal variations in supply and how to address these in order to minimize risks when establishing a biomass plant. In the final chapter of Part I, Nikolaisen and Jensen provide a detailed insight into a wide range of biomass feedstocks and relevant pretreatment processes for preparing these as fuels for subsequent biomass conversion technologies.

Part II takes a direct look at state-of-the-art biomass conversion: combustion, gasification and pyrolysis. Mandø discusses aspects of the direct combustion of biomass, highlighting generic effects deriving from the elemental composition of biomass as well as technology-specific effects and requirements. Yin takes a similar approach to co-firing of biomass, both direct and indirect. Then follows a chapter by Neubauer and Liu, focussing on gasification principles, technologies and optimization, and putting gasification into a polygeneration context. Bridgwater and Hornung cover the pyrolysis of biomass; the former focuses on fast pyrolysis, appropriate feedstocks and the derived bio-oils, the latter on intermediate pyrolysis, and he provides examples of intermediate pyrolysis as a component in integrated biomass systems.

Part III takes a more engineering-oriented approach. In their chapter on large-scale biomass combustion plants, Caillat and Vakkilainen cover a range of combustion technologies, and discuss operational as well as design issues for different biomass-technology matches. Widell focuses on intermediate (industrial) scale plants, and considers the details of the design, operation and trouble-shooting issues. In the closing chapter, Lange takes a more holistic approach to the use of biomass, and provides a biorefinery setting, where life-cycle analysis is used as a basis for selecting appropriate feedstocks and products.

This book presents a selection of thermo-chemical technologies for conversion of biomass, not only to produce heat and power, but also intermediate products such as syngas and bio-oils. The technologies are presented on equal terms, and the book does not set out to rank one technology against another, but rather to provide the reader – who may be a researcher, industry professional or simply someone with a genuine interest in biomass and conversion technologies – with relevant, up-to-date and detailed information on the important aspects involved in planning, designing and operating biomass conversion plants. I hope that you find it informative and helpful, and that it inspires further innovation.

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Biomass combustion for power generation: an introduction

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Abstract: The chapter gives an introduction to the main combustion techniques used for turning biomass into power and briefly discusses their relative strengths and weaknesses. The chapter also provides definitions of the main biomass types and discusses recent developments in the application of biomass for power production.

Key words: biomass, power, fuel, combustion.

1.1 Introduction

The use of biomass for heating and light almost defines the birth of civilisation. Ever since the first torch was lit biomass has been an important part of the energy provision in human societies. In the developed world, biomass has been on the retreat since the beginning of the Industrial Revolution as high energy density fuels such as peat, coal, gas and oil became available – but due to the rise of global warming and energy security concerns, biomass is becoming an increasingly important part of the energy mix.

Using biomass for power generation has only rarely been done on a large scale and only as a means of exploiting the availability of residues from sawmills or other industrial processes. In the last decade, biomass has become more popular as it is seen as the only sizeable renewable fuel source for power generation that is available when needed.

The first move into large-scale deployment was co-firing in coal-fired power stations. However, as the climate change issue has become more important, policies have moved away from co-firing towards full plant conversions or new builds since co-firing still burns coal.

1.2 Biomass combustion techniques

We can exploit the energy in biomass by burning it and thereby turning the chemically bound energy into heat and then power. The efficiency of combustion and the ability to exploit the energy within depends on the type of biomass, combustion method, scale and application (see Box 1.1). The three main combustion techniques for biomass in heat and power applications are the same as for coal, namely, grate firing (GF), fluidised bed (FB) and pulverised fuel (PF).

Box 1.1 Combustion techniques

Grate-firing (GF): biomass is placed on a grate and material is moved slowly through the boiler as it combusts with air being supplied through holes in the grate. Particularly suited for coarse and uneven particle sizes but maximum size is limited to approximately 150MWth/50MWe.

Fluidised bed (FB): biomass is mixed with a medium (typically sand) and kept suspended in a mix with incoming air. The temperature in the 'bed' allows a part gasification of the biomass and the method can therefore be used with relatively coarse and wet material (compared to PF). The lower temperature also reduces the NOx and SOx emission associated with the combustion. Sizes generally vary from 30–300MWe.

Pulverised fuel (PF): biomass is grinded to powder and combusted. PF achieves high efficiency in combustion and can be applied in large scale (up to 600MWe), but during and grinding, the feedstock requires energy.

Grate firing is the most widespread technique for burning biomass. The biomass is placed on a grate and moves slowly through the boiler as it combusts with air being supplied through holes in the grate. The technique is particularly suited for coarse material and for uneven particle sizes, but the maximum size of a plant is limited to approximately 150 MWth/50 MWe. The plant type is flexible and relatively simple and the high cost of transporting biomass over large distances means that the size restriction for this method is not an issue.

Fluidised beds are a newer method of combustion. Plants have higher efficiency and produce fewer emissions. The biomass is mixed with a medium (typically sand) and kept suspended in a mix with incoming air. The temperature in the bed causes partial gasification of the biomass and the method can therefore be used with relatively coarse and wet material (compared to PF). The lower temperature also reduces the NOx and SOx emissions associated with combustion. Plant sizes generally vary from 30 MWe to 300 MWe. The relatively complex set-up and the difficulty of running a plant with a part load means that this system is less widespread. All new large biomass plants are expected to be of the fluidised bed variety since it is possible to achieve a fuel flexibility that is higher than with pulverised fuel.

The pulverised fuel method is used for large-scale combustion of biomass in units that were previously coal fired. The biomass is finely ground to a powder and combusted. The biomass must be dry. Using biomass in PF boilers is, however, not problem-free as the higher combustion temperature creates problems with corrosion and slagging. Biomass is therefore often used for co-firing with coal as the chemical properties of the coal mitigate the issues created by the high chloride content of the biomass. PF boilers have high efficiency and can be used on a large scale (up to 600 MWe), but drying and grinding, the feedstock requires energy.

1.2.1 Co-firing biomass

Biomass has been co-fired with coal in traditional plants of all types and this generally creates fewer problems as long as the proportion of biomass is kept low. If more than ~10% is used the chemical components of the coal (sulphur, silicates, aluminium, etc.) can no longer neutralise the corrosive compounds to prevent slagging. Co-firing is covered extensively in Chapter 5.

1.3 Biomass as fuel

Biomass includes a wide range of material but only a few types are suitable for use in the production of heat and power. We will concentrate on biomass that comes from forests and agricultural and food production. The production of biomass specifically for energy conversion will also be discussed. There are more exotic forms of biomass such as algae, seaweed and animal products but these have so far been of very limited significance in the direct production of heat and power.

1.3.1 Forestry biomass

More than 30% of the world is covered with forests and there is an estimated 527 billon m^3 of wood resources (see Box 1.2).[1] The annual wood harvest from the 1.2 billion hectares that is commercially exploited was 3.5 billion m^3 in 2010 – enough to fuel 10% of the world's power demand (assuming 35%

Box 1.2 Forestry biomass

Primary: trunks from fully grown trees.

Secondary: branches and crown from fully grown trees and trunks of smaller trees removed in thinning process.

Tertiary: residues from processing primary forestry-derived biomass.

efficiency, 5.7 GJ/m^3 and a global power demand of 20 100 TWh). If left alone forests do not produce additional biomass as old trees rot thus leaving space for new trees – but when biomass is harvested from a forest, either by thinning or by removal of whole large trees, room is made for additional biomass to be created.

There are three types of forestry biomass:

- Primary: Trunks from fully grown trees.
- Secondary: Branches and crowns from fully grown trees and trunks of smaller trees removed during thinning.
- Tertiary: Residues from processing primary forestry-derived biomass.

Most biomass used for heat and power comes from secondary and tertiary biomass.

Secondary biomass often has no other use than being burnt for energy but because of the low energy content it is often used locally – for instance for producing heat and power for industrial processes such as in the production of paper and in the production of wood for buildings and furniture.

The residues from processing primary wood (tertiary biomass) can potentially be used both for energy and as a raw material for particle board production. Forestry-derived biomass generally has a high energy content and if left to dry the moisture content will be relatively low, both of which make it suitable for heat and power production.

The biggest issue with forestry-derived biomass stems from chloride and silicates, which are concentrated in the bark and which create problems in conventional PF boilers. In consequence, primary and tertiary biomass are the most suitable for energy applications but also are generally more expensive than secondary biomass.

Woodchips versus wood pellets

Woodchips are created by chopping wood into small pieces of typically 1–5 cm. Both primary and secondary wood can be used. Woodchips generally have a high moisture content and can only be stored for a limited time.

Wood pellets are produced from woodchips, which are dried, finely ground (particle size is normally <2 mm) and pressed into pellets. The process of producing pellets requires energy but most of the energy comes from the bark which, either way, has to be removed before pelleting.

Since woodchips require less energy to produce they would be preferred to wood pellets if the conversion efficiency was the same – which is the case if you compare a modern FB boiler with a PF boiler.

Currently, in most cases where biomass is being planned for heat and power, it is either in smaller grate-fired units or by converting existing coal-fired power plants. For the latter, the technology used in the existing plant is often the driver for the choice of fuel or fuel mix, since the potential saving in investment costs outweighs the benefits of choosing the lowest cost fuel. Wood pellets have a higher energy density and do not degrade (rot) so easily and are therefore preferred if the biomass has to be transported over large distances.

1.3.2 Agricultural biomass

Biomass is the natural product of all agriculture but the vast majority of the biomass suitable for heat and power production is straw residues from grain production, essentially because it is dry. Another expanding and potentially larger source of biomass is from energy crops, which are cultivated solely for energy. Other plant residues include husks, shells and kernels from various nuts and fruit-bearing plants, but although their energy content can be high the limited amounts produced means they are of less importance.

Keeping livestock generates biomass in the form of manure. Chicken litter is being burned in a number of places but generally manure is only used for energy purposes through anaerobic digestion and will not be discussed further here.

Straw and other agricultural residues generally have a high ash content and contain chloride and potassium compounds (salts), which cause high levels of corrosion in boilers. The problems with slagging and corrosion can be mitigated by burning at lower temperatures or by co-firing with coal, which has chemical properties that cancel out the effects.

1.3.3 Energy crops and energy plantations

An energy crop is a species that gives the maximum energy yield; primarily they are yearly crops or short rotation crops (with a 2–3 year cycle). An energy plantation is an area of land used exclusively for producing biomass for energy use. Plantations can be based on either energy crops or longer rotation (woody) biomasses.

The growing of energy crops is a relatively new phenomenon. It involves selecting plant species that have a high calorific yield relative to the area cultivated and with chemical properties that makes them suitable for conversion to energy. The most commonly used plants are woody species such as willow and eucalyptus, which can be cultivated in short rotation (2–7 years depending on climate and species). More traditional wood species such as pine can be productively grown in 10–15 year cycles in warmer climates whereas they generally require 40–50 years in temperate climates.

An alternative to woody biomass are switchgrasses (e.g. *Jatropha* and elephant grass), which can be harvested more frequently. As the growing and harvesting cycle is akin to that of grain, they fit better into the production methods used by most farmers, who rotate crops annually and depend on yearly revenue to fund operations. Yearly plants, such as most non-woody energy crops, have the drawback that their chemical properties generally make them less suitable for combustion due to the high ash and salt content.

Energy crops and short rotation energy plantations are a growing market. They enable production of larger quantities and yield a more homogeneous biomass suitable for combustion in large plants. Furthermore, they have the advantage that it is easier to establish that production takes place in a sustainable manner.

1.4 Market development for biomass combustion and conversion technologies

As mentioned at the beginning of this chapter, biomass was the fuel of choice before the Industrial Revolution. In recent times there has been much talk of a green energy revolution where renewables replace fossil energy sources. Biomass is set to play a significant role in this green revolution, as it is the only large-scale renewable energy source that can follow the demand.

The most cost-effective way of establishing new biomass-fired capacity is through co-firing with coal. Large-scale deployments have been carried out in Belgium, Denmark, the Netherlands and the UK amongst other countries. Co-firing is, however, problematic from a climate change perspective because it will only reduce the use of fossil fuels and will not enable a shift away from them altogether.

The second most cost-effective way of establishing biomass-fired capacity is through the wholesale conversion of existing coal-fired power plants. In 2011, the most prominent example of this was the conversion of Tilbury in the UK, which is now set to produce 750 MW of biomass-based electricity. There are plans to convert a number of plants across north-western Europe in the coming years.

The least cost-effective way of establishing biomass-fired capacity is through building new dedicated plants, but there are some advantages which make it attractive. Some biomass is better suited to small, local, typically grate-fired, biomass plants and even large dedicated plants can be economic if they are located somewhere that gives them an advantage in the supply chain.

What these three biomass energy options have in common is that they all will continue to rely on regulatory support to be economically viable. Small-scale plants are favoured in the legislation of most European countries since the benefits to the local community are seen to compensate for the higher cost. Recent developments in the UK and other countries indicate that there will be regulatory support for the cheaper options of co-firing and large-scale conversion, since EU governments are struggling to balance budgets and meet climate change goals simultaneously.

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2

Biomass supply chains

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Abstract: The chapter discusses the biomass supply chain, which is responsible for supplying an energy conversion plant with the correct quantity and quality of biomass at the correct time. The chapter first categorizes the biomass and waste streams and presents analytically the biomass supply chain, discussing its structure and characteristics. It then reviews the latest advances in biomass supply chains. The issue of integrating biomass energy conversion into waste management systems is tackled and the advantages and limitations of using biomass, in supply chain terms, are presented. The chapter concludes with future trends in biomass supply chains and logistics, and proposes sources of further information.

Key words: biomass supply chain, biomass logistics, process chain, waste management.

2.1 Introduction

This chapter discusses the biomass supply chain, which is responsible for supplying energy conversion plants with the required quantities of biomass, at the correct time and the appropriate quality specifications. This is of critical importance, as it may define not only the successful operation of the biomass plant in technical terms, but also its financial viability.

A classification of available biomass types is given in Section 2.2, mainly focused on the biomass characteristics affecting the supply chain. Section 2.3 presents a typical biomass supply chain structure, discusses the specific characteristics that differentiate it from a typical supply chain, analyzing in detail the processes performed and commenting on the stakeholders involved and the cost implications of the biomass supply chain. Furthermore, in this section, the issue of where to locate a biomass energy conversion facility is discussed. Section 2.4 focuses on how to design and optimize a biomass supply chain, based on an analytic review of existing biomass supply chain simulation and optimization models. In Section 2.5, the issue of how a biomass energy conversion facility may be integrated into a waste management system is analyzed. Section 2.6 presents the advantages and limitations of using biomass in energy exploitation facilities, mainly from the supply chain perspective. Future trends in biomass supply chain development are unveiled in Section 2.7 and some directions for sources of further information for the interested reader are given in Section 2.8. Finally, there are references at the end of the chapter.

2.2 Types of biomass and waste streams

Biomass is biological material derived from living, or recently living organisms. Biomass has been used by mankind for energy generation for thousands of years, mainly in the form of wood for heating. However, new technologies have emerged recently that allow more efficient energy conversion of biomass. Together with the fact that biomass is considered a renewable fuel, in the sense that it does not emit additional greenhouse gases into the atmosphere, the interest in using it has increased lately.

Biomass comes from many different sources, and each type of biomass may be found in different forms. Therefore, it is very difficult to give a single, all-inclusive classification of biomass. For this reason, several classifications of biomass will be presented, depending on the aspect examined.

2.2.1 Biomass origin

Biomass may be classified, depending on its origin, into the following broad categories:

Virgin wood

This biomass type mainly includes woody biomass harvested from forests. In this category one may include all forms of wood from forest harvesting, such as logs, branches, bark and sawdust.

Energy crops

Energy crops are plants that are grown specifically for use as a fuel. There are many different types of energy crops, some of which have the advantage of being able to grow on marginal land. In many cases the energy crops that may be used in a specific region depend on the soil characteristics as well as the climatic conditions. Generally, they offer high output per unit of area with low inputs. Energy crops may be further classified into short rotation energy crops (such as short rotation forestry and coppice), agricultural energy crops (already existing crops that may alternatively be used as a fuel source), grasses and non-woody energy crops (such as miscanthus, switchgrass, reed canarygrass, rye, giant reed, etc.) and aquatic biomass (such as algae).

Agricultural residues

Existing agricultural crops and processes yield residues, which can potentially be used for energy applications. Sources of agricultural residues for energy applications can include arable crop residues (such as stalks, straw or husks), organic material from excess production (such as lower quality agricultural products or when there is insufficient demand), animal manure and animal bedding. However, one should keep in mind that many of the above mentioned residues may have alternative uses or markets, and therefore, any decision to use them for energy production must be made in the context of these alternatives and their market prices.

Municipal solid waste (MSW)

MSW is a by-product of the modern way of life, and its management is a burden for every society. MSW may be used for energy production by direct combustion of mixed or sorted MSW, pyrolysis, gasification or even by using biogas from landfill. It should be noted though that only the biogenic fraction of MSW is considered to be renewable, mainly referring to paper, cardboard, wood, food, leather, textiles and yard trimmings.

Industrial waste

Some types of industrial waste may have a significant heating value and at the same time be considered as renewable. Examples are waste from the wood, paper and pulp industries, the textile industry, the food industry, sewage sludge and waste oils.

2.2.2 Availability

Most biomass types are characterized by seasonal availability. This seasonality leads to significant complications and increased requirements from the biomass supply chain. Almost all agricultural-residue biomass, many energy crops and virgin-wood biomass have seasonal availability. The narrower the time window for biomass availability, the more demanding are the issues for the supply chain.

On the other hand, other biomass types are characterized by low seasonal availability. Most types of industrial waste and municipal solid waste belong to this category, though for the latter significant quality variations (moisture, heating value, etc.) may be encountered depending on the season.

2.2.3 Main product or by-product

Some biomass types constitute the main product of a production process, as is the case for energy crops, either woody or herbaceous, from which farmers expect an income similar to the one they currently obtain from other types of agricultural products.

On the other hand, several biomass types are the by-products of other production processes, such as agricultural residues, industrial waste and some types of wood that have no commercial value (e.g. tree trimmings or branches). In most of these cases, the process owners do not receive an income from these by-products, and it is therefore natural that it would be easier to supply these biomass types at a lower price than the ones that constitute the main products of a process, or even at a zero price if the biomass is undesirable or currently its management incurs costs. It is even possible that someone would be willing to pay for disposing of by-product biomass, as is the case with municipal solid waste or some industrial waste, which require expensive treatment or management.

2.2.4 Alternative uses

An important aspect of biomass as a potential fuel for energy generation is whether it currently has alternative uses and whether it is a commodity with an existing market that determines its price. For example, virgin wood has been widely used for furniture and in the construction industry, as well as for heating, for many years. Some agricultural residues are used as forage or animal bedding. Even some industrial waste may have an existing value, such as sawdust, which is used in the wood industry as a raw material or for heat/steam generation. There is also a debate in the literature as to whether biomass sources that are food sources, such as corn, should be used for energy or biofuel generation, or whether energy crops would displace food crops, in the light of the increasing global population and the lack of food supplies (Berndes and Wirsenius, 1996; Berndes *et al.*, 2003).

One should also keep in mind that using biomass types, with an existing alternative use, as a fuel for energy generation will lead to a demand increase and probably to higher prices, until a new demand–supply equilibrium is reached. There is significant potential in examining currently unexploited biomass types, which could be offered at a low price per energy unit.

2.3 Biomass supply chain structure and characteristics

2.3.1 Biomass supply chain structure

A typical biomass supply chain comprises several discrete processes. These processes may include ground preparation and planting, cultivation, harvesting, handling, storage, in-field/forest transportation, road transportation and processing of the biomass to bring it into a form suitable for use at the energy conversion facility. It should be noted though that the exact structure of the biomass supply chain depends on the biomass type and characteristics, on the technology used for energy conversion and on the system design.

Each biomass type is initially acquired in a form that, usually, is unsuitable for use at the energy conversion facility or for transporting. For example, several types of agricultural biomass come in a very loose form (e.g. hay or straw stalks) and baling is required to handle and transport them efficiently. Furthermore, the technology used for energy conversion usually specifies the form and homogeneity that the input fuel should have, which may include limits on dimensions, moisture content, etc. If the system has several small-scale units, one may choose to use centralized storage, adding an extra link to the supply chain.

The main activities required to supply biomass from its production point to a power station (Allen *et al.*, 1998), are the following:

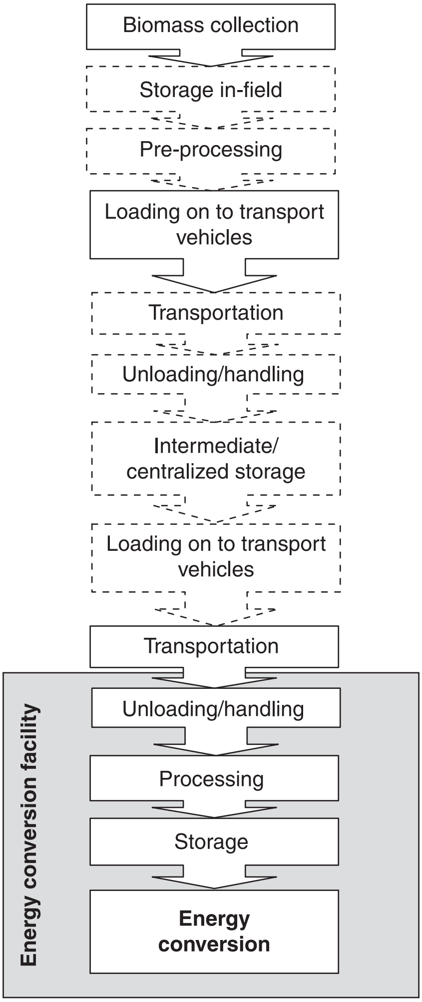
- harvesting or collection of the biomass from a field or forest;
- in-field or in-forest handling and transport;
- loading of and unloading from transportation;
- transportation;
- storage;
- processing.

The typical structure of a biomass supply chain is presented in Fig. 2.1. The dashed nodes are processes that do not appear in every biomass supply chain, but rather depend on its specific characteristics.

The waste supply chain has common characteristics with the biomass one. Collection is performed from a large number of dispersed locations, some form of processing is required (compaction or size reduction, etc.), road transportation to the energy conversion facility is needed and storage is usually performed, though for shorter time periods than for biomass.

2.3.2 Biomass supply chain characteristics

The biomass supply chain has several distinctive characteristics that distinguish it from a typical supply chain. First of all, many biomass types are usually characterized by seasonal availability (Skoulou and Zabaniotou, 2007). The period when these biomass types are available is limited and is determined by the crop harvesting period, weather conditions that may restrict access and a need to replant the fields. Since most of the biomass energy exploitation applications to date use single biomass sourcing, there is a need to store very large amounts of biomass for a significant time, if year-round operation of the power plant is desired. Therefore, the storage requirements are high, which affects the cost of the system and can lead to biomass material loss and quality degradation. For example, the temperature in a pile of chipped (fresh or naturally dried) forest residue usually rises very rapidly after an initial period of approximately one week, which is a sign that the material has begun to decompose, leading to material and energy losses. In tests carried out on wood chips, monthly dry weight matter losses of 1.1% to 2.6% and total losses during a 6-month storage period of 6.6% to 15.6% were found, depending on the initial moisture level (Wihersaari, 2005). Similar research for corn stover (Shinners *et al.*, 2007) found dry weight stover losses of 3.3% and 18.1% for bales stored indoors and outdoors, whereas for switchgrass, dry matter losses ranged between 1% and 13%, depending on the

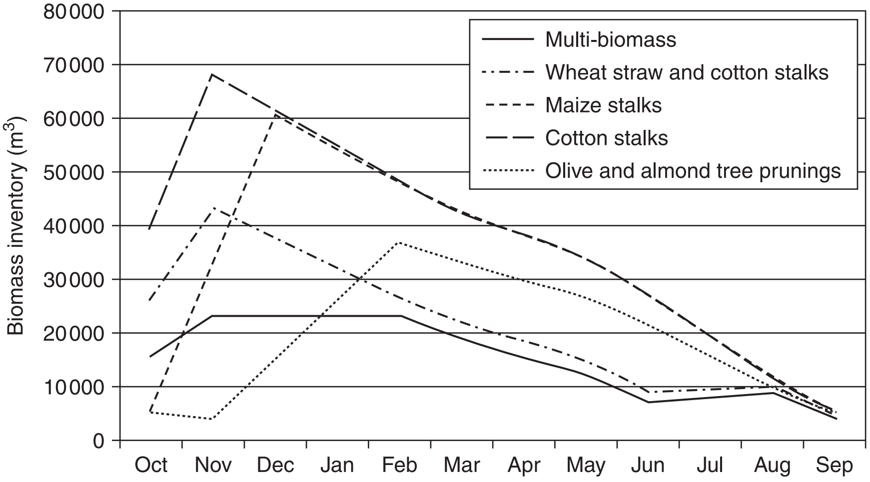


2.1 Typical structure of a biomass supply chain. The dashed nodes are processes that do not appear in every biomass supply chain, but rather depend on its specific characteristics.

storage solution (Sanderson *et al.*, 1997). The limited time frame for collecting large amounts of biomass also leads to a significant seasonal need for resources, both equipment and workforce. This seasonal demand may increase the cost of obtaining these resources, while leading to suboptimal utilization of resources, particularly of the storage space and specialized equipment.

The problems introduced by the seasonality of biomass availability may be avoided, if a biomass source that is available year-round is used, though very rare in practice. The multi-biomass approach has been proposed by some researchers (Nilsson and Hansson, 2001; Rentizelas *et al.*, 2009b), as it may significantly reduce these problems. For example, the simultaneous use of straw and reed canarygrass has been investigated by Nilsson and Hansson (2001). The conclusion the researchers reached was that the specific combination led to a total system cost reduction of about 15–20% compared to a single-biomass case, despite the increased production cost of reed canarygrass compared to straw. Several waste streams, on the other hand, usually have low or even negligible seasonality, and therefore storage requirements are reduced. Storage is primarily for holding safety stock to ensure the uninterrupted operation of the energy conversion facility. An example of the effect of seasonality on the required biomass inventory level for year-round operation of a biomass energy plant with given energy output, which directly determines the storage space required, may be seen in Fig. 2.2. In this figure, two specific single-biomass sourcing strategies (cotton stalks and maize stalks) are compared with two twin-biomass sourcing strategies (wheat straw and cotton stalks, olive and almond tree prunings) and with a multi-biomass strategy (an optimized mix of all the aforementioned biomass types), in terms of the storage space required. The potential for reducing the need for storage space by using a multi-biomass strategy is evident.

Another characteristic of the biomass supply chain is that it has to deal with low-density materials. As a result, there is increased need for transportation and handling equipment capacity, as well as storage space. This problem is exacerbated by the low heating value, which is partly due to the increased moisture of most



2.2 Biomass inventory profile. Effect of seasonality on the required biomass inventory level for year-round operation of a biomass energy plant with given energy output, which directly determines the storage space required.

agricultural and forest biomass types, as well as many other waste streams. The low density of biomass further increases the cost of collection, handling, transportation and storage (Allen *et al.*, 1998). For this reason, processing of biomass and waste is usually required, to increase the material density or reduce its moisture content.

Finally, several biomass types require customized collection and handling equipment, leading to a complicated supply chain. For example, there are different requirements for handling and transportation equipment and storage space configuration if biomass is procured in the form of bales, sticks, logs or chips (Allen *et al.*, 1998). Therefore, the form in which the biomass will be procured often determines the investment and operational costs of the respective bioenergy exploitation system, as it affects the requirements and design of the biomass supply chain. In many cases the processing of biomass and waste streams aims at bringing the material into a form that may be handled using standardized equipment. For example, baling of wheat straw or hay or other types of loose biomass, as well as chipping or pelleting woody biomass, may be used to standardize and homogenize the material and facilitate handling, transportation and storage.

All of the abovementioned factors lead to increased supply chain costs. A biomass energy conversion facility and its supply chain must be designed to reduce the negative effect on the financial yield of the entire system.

2.3.3 Biomass supply chain analysis

In this section the biomass supply chain processes will be further analyzed. Due to the very large number of biomass types available and the different technologies for energy conversion, it is not possible to give a single supply chain design that fits all cases. However, the processes usually performed are listed below.

Harvesting and collection of biomass from the field, forest or collection point

This is the initial process in the biomass supply chain, if one ignores the agricultural operations of ground preparation, planting and cultivation. In-field or in-forest handling and transportation aim to collect biomass from where it is grown, usually with specialized mechanical equipment, and to move it to a point where it can be reached by road transportation vehicles. This process sometimes includes some form of pre-treatment, such as chipping or even pelleting, in order to homogenize or reduce the size of the material collected. More often the processing is performed to facilitate handling and to prevent significant loss of material during transportation and handling, for example, baling (for loose materials). Pelleting is an expensive and energy-consuming process, which produces a fuel (pellets) of high density, high homogeneity, high heating value and low moisture content. Therefore, it is more appropriate for long-distance transportation, when pellets are the final product required or when the biomass is used in plants located in urban areas.

Loading and unloading road transportation vehicles

Once the biomass has been moved to the roadside, it needs to be loaded onto road transportation vehicles for conveyance to the energy conversion facility. The biomass will need to be unloaded from the vehicles at the power station. The loading and unloading equipment greatly depends on the form and the type of the biomass, and whether it has received some kind of processing. It is generally more efficient to bring biomass into a form that standardized loading and unloading equipment (or agricultural equipment) may handle, so that this equipment may be used in other operations when not needed for biomass, in order to spread the fixed ownership cost over longer harvesting or operational periods (Sims, 2002). If specialized equipment is required, then it will result in higher costs and there is a possibility that the biomass operations will bear the full amortization cost, if no alternative use for this equipment can be found. An attractive option is using standardized equipment with a small number of interchangeable parts to fit the biomass specifications better.

For waste streams, there are two options. The first option applies when the transportation distances are short: the collection vehicles transport the waste directly to the energy conversion facility, without the need for loading equipment. The second option entails intermediate trans-shipment, in order to transport larger quantities over larger distances more efficiently. In the latter case, unloading of the collection vehicles and loading of the transportation vehicles is required.

Transportation

Considering the typical locations of biomass availability (i.e. in farms or forests, or in dispersed locations for municipal solid waste), the transportation infrastructure is usually such that road transportation will be the only potential mode for collection and transportation of the fuel. Other factors that favor the use of road transportation are the relatively short distances over which the fuel is transported and the greater flexibility that it can offer in comparison with other modes. Other transportation modes, such as ships or trains may be considered when long distance biomass transportation is examined. Hamelinck *et al.* (2004) came to the conclusion that long-distance biomass transportation is not prohibitive from a financial perspective, as biomass may be procured and purchased at lower prices. On the other hand, the same authors acknowledge the fact that longer transportation distances lead to higher emissions from the biomass supply chain, therefore reducing to a certain extent the environmental advantages of renewable energy generation.

Up to now, it has not been common to transport biomass over long distances, due to its low density and the relatively increased transportation cost. Therefore, the most commonly used transportation method is by road, due to the local nature of these operations. There are varying opinions in the literature on whether it is more economical to use heavy goods vehicles (Allen *et al.*, 1998; Huisman *et al.*, 1997) or agricultural and forestry equipment (Tatsiopoulos and Tolis, 2003) for transportation operations. Ultimately, it appears to be a matter of the average transport distance, biomass density, the carrying capacity and travelling speed of the respective vehicles, as well as the availability of the respective resources. It should be noted though that these two options lead to a significantly different supply chain structure: for heavy goods vehicles, the common approach is to form a contract with a third-party logistics (3PL) provider, and therefore the supply chain operator would have a single point of reference and alternative contractor choices. When using agricultural equipment, the operator would normally have to coordinate a significant number of farmers and equipment owners, and therefore the supply chain management workload would be increased.

Storage

Many types of biomass are characterized by seasonal availability, as they are harvested at a specific time of the year, but since a steady fuel supply is required at the power station on a year-round basis, it is therefore necessary to store them. The storage point could be at a farm, forest or other collection point, at the energy conversion facility or at an intermediate site.

Biomass storage is a very critical link in the supply chain. Most examples considered in the relevant research show that low-cost storage solutions are chosen, without examining the positive effect that more sophisticated – and more costly – solutions may have. Many researchers assume on-field biomass storage (Allen *et al.*, 1998; Huisman *et al.*, 1997; Sokhansanj *et al.*, 2006). Both ambient and covered on-field storage has also been examined (Cundiff *et al.*, 1997). For example, Collins *et al.* (2011) investigate changes to the material after baling hay, as far as heating, moisture and material loss are concerned, examining the storage options of ground storage, plastic wrapping, net wrapping, temporary structures (plastic-covered post-frame structures), reusable tarps or bale coverings, bale sleeves and permanent structures. Similar research on material loss depending on the storage method and the initial moisture level has been performed for many biomass types, such as woodchips (Wihersaari, 2005), corn stover (Shinners *et al.*, 2007) and switchgrass (Sanderson *et al.*, 1997). On-field storage has the advantage of low cost but on the other hand, biomass material loss is significant and biomass moisture cannot be controlled and reduced to the desired level, thus leading to potential problems during energy conversion. Furthermore, health and safety issues exist, such as the danger with the formation of spores and fungi (Allen *et al.*, 1998; Nilsson, 1999) and self-ignition due to increased moisture.

Finally, farmers may not allow on-farm storage of the biomass for a long time, as they may want to prepare the land for the next crop (Sokhansanj *et al.*, 2006). In some cases, however, on-site storage is usual, such as in forest biomass, where logs are left for a period to reduce their moisture content.

Several authors consider the use of intermediate storage locations between the fields and the energy conversion facility (Allen *et al.*, 1998; Nilsson and Hansson, 2001; Tatsiopoulos and Tolis, 2003). For all biomass fuels in which the use of intermediate storage has been modeled, the fuel has to be transported twice by road transportation vehicles: first from the farm, forest or collection point to the intermediate storage facility and then from the storage facility to the energy conversion facility. This will result in a higher delivered cost than a system in which there is only one road transportation operation, i.e. directly from farm, forest or collection point to the energy conversion facility. Using an intermediate storage stage may increase biomass delivered costs in the region of 10% to 20%, as a result of the additional transportation and handling costs incurred (Allen *et al.*, 1998).

Finally, there is the option of siting the storage facility next to the biomass energy conversion facility (Papadopoulos and Katsigiannis, 2002; Tatsiopoulos and Tolis, 2003). The latter work described an innovative storage layout with a biomass drying capability using dumped heat from the power plant. This aims at reducing the biomass moisture content faster to prevent material decomposition as well as the formation of fungi and spores. Using storage facilities attached to the power plant is the only viable way of accelerating the biomass drying process, as dumped heat may be used without extra energy consumption. Furthermore, storage at the energy conversion facility is always required for at least safety stock, to decouple energy generation from unexpected interruptions in biomass supply.

Rentizelas *et al.* (2009a) analyzed three different storage solutions for single- and multi-biomass supply chains, concluding that the lowest-cost storage method was the system-wide most efficient solution among the cases examined. Furthermore, the authors acknowledged that the multi-biomass approach appears to lead to greater cost reductions when combined with relatively expensive storage methods.

Processing biomass

Biomass may be processed to improve its handling efficiency and the quantity that can be transported. This may involve increasing the bulk density of the biomass (e.g. turning forest wood or coppice stems into woodchips or pellets) or unitizing the biomass (e.g. forming straw or miscanthus in the swath into bales). Processing can occur at any stage of the supply chain but will often precede road transportation and is generally more efficient when integrated with harvesting.

Processing may also be required before biomass enters the energy conversion facility. Biomass must be brought to the exact specifications of the fuel feeding equipment of the energy conversion facility, as far as quality, moisture and size are concerned. This type of processing may be performed either before or after storage.

2.3.4 Locating the energy conversion facility

Choosing the location of a biomass energy conversion facility is an irreversible decision with a major impact on the structure and the cost of biomass logistics, for the entire period of the power plants' operational lifetime. This facility location problem is affected by a number of competing forces.

As far as the upstream supply chain is concerned, biomass availability and geographical dispersion are major factors in locating the facility, due to their immediate effect on the mean travel distance, which determines the biomass transportation cost.

A number of factors related to the downstream supply chain affect the total system cost. For a co-generation or tri-generation facility with a district energy supply, the geographical position of the consumers of the district heating and cooling determines the length of the district energy transfer and distribution network. The length of the network not only affects the investment cost, but the heat losses as well. Another factor affecting the facility's location is the geographical position of the locally available grid connection points. The electricity transfer line length is thus determined, which has a direct effect on the investment cost as well as on the related electricity losses (Rentizelas and Tatsiopoulos, 2010).

It should be mentioned that there are even more challenges in siting a biomass facility. A crucial factor is the local communities' acceptance of the project, as local opposition could prevent the construction of such a semi-desirable facility (Upreti and Van Der Horst, 2004). The proximity of a facility to inhabited areas or areas of particular environmental or cultural sensitivity is a factor in a project's acceptance.

The single biomass sourcing strategy, which is the usual case in practice, faces another issue of critical importance: availability of the required biomass over the lifetime of the biomass energy conversion facility. The potential investors in such a facility should either identify a biomass type that can be procured from an existing market, or secure the biomass supply with long-term contracts, in order to avoid the risk of not being able to find the appropriate amounts of fuel in years to come. Therefore, locating a facility should also take into account the local availability of biomass, changes to the dominant crops in the region (e.g. after changes in agricultural subsidies or incentives) and alternative biomass sources that could be used by the energy conversion facility to reduce the risk of a future lack of suitable biomass types.

The bulk of the research into simulation models for biomass energy exploitation assumes that the location of the facility is predetermined. For example, Cundiff *et al.* (1997) considered the bioenergy facility location fixed and their linear programming (LP) model chooses which farms should supply the biomass. Tatsiopoulos and Tolis (2003) located the bioenergy facility in the center of the region examined in a centralized electricity scenario. In a decentralized scenario, the location of bioenergy facilities was determined indirectly by calculating the optimum number of facilities and locating them uniformly on a grid.

However, a significant amount of research has used optimization models to focus on the location problem. Voivontas *et al.* (2001) proposed a GIS-based model to locate a bioenergy conversion facility based on the optimum exploitation of available biomass potential. Papadopoulos and Katsigiannis (2002) focused primarily on siting the bioenergy facility to reduce the biomass logistics costs, and more specifically, on eliminating biomass warehousing needs. In Nilsson's model (1999) the bioenergy facility location was defined by the model user; however, the intermediate storage locations are defined by the simulation model. Nagel (2000) and Freppaz *et al.* (2004) sited heating plants at predefined potential locations. Finally, Rentizelas and Tatsiopoulos (2010) presented a model that defines the optimum biomass energy facility location, taking into account the downstream supply chain for district heating and cooling (tri-generation) as well as limitations concerning the proximity to inhabited areas.

2.3.5 Biomass supply chain stakeholders

It is interesting to comment on the issue of who is the process owner – who organizes and implements the biomass supply chain. This issue is not straightforward, as there are many options available, and there are usually many stakeholders involved in a biomass supply chain. The main options are presented below.

Self-supply

In the self-supply situation, the owner/operator of the energy conversion plant supplies the required biomass to the facility and is responsible for organizing the supply chain. The biomass may be collected from privately owned land and facilities or partly purchased from third-party suppliers. In this supply chain model, the owner/operator is responsible for ensuring adequate supply of biomass at the appropriate quality standards. If the necessary equipment is owned by the operator, attention should be given to ensuring a high utilization factor for it, so as not to overly increase the biomass procurement cost.

Collaborative and co-operative

Collaborative and co-operative supply chains involve a number of biomass producers collaborating to supply fuel to the energy conversion facility. This procurement model has the advantage of higher efficiency, as it allows specialized equipment costs to be shared between members of the co-operative, as well as collaboration on organization, marketing and administration, thus reducing the cost. This model may also offer increased security of supply, as there will always be adequate biomass available to meet demand, even if a particular member is unable to supply at a particular time.

Biomass suppliers, merchants and brokers

Biomass suppliers, merchants and brokers either produce or purchase biomass from producers for the sole purpose of selling it to end customers. These intermediates handle large quantities of biomass, which means that they may offer different grades or specifications of biomass to different customers or applications at different prices. Currently this model is used for many biomass types that have alternative uses.

Of course, these models are not the only ones possible, and combinations of them can also be found. For example, a hybrid collaborative and self-supply model could exist if the biomass energy conversion facility is owned by a municipal organization and the local biomass suppliers are also shareholders of this organization.

2.3.6 Cost implications of the biomass supply chain

The cost of the biomass supply chain is a significant proportion of the total energy generation cost. It is not possible to give exact numbers, as this figure depends on many parameters such as the technology of the energy conversion facility (and therefore its investment and operational and maintenance cost), on the biomass type, the supply chain design adopted, legislation, etc. Many researchers acknowledge that the cost of supplying biomass is critical to the financial viability of the investment, and therefore much work has been done in attempting to reduce this cost.

The cost of producing short rotation forestry wood was investigated using spreadsheet models by Mitchell *et al.* (1999), who focused mainly on biomass production, collection and storage. Allen *et al.* (1998) modeled an analytic supply chain for five biomass types, concluding that 20–50% of the biomass delivered cost is due to transportation and handling activities, whereas an analysis of woodchips produced from energy crops showed that the transportation cost was 18–29% of the delivered cost (Graham *et al.*, 1997). Caputo *et al.* (2005) also found that in the cases they examined, logistics costs (including biomass purchasing cost) ranged between 56% and 76% of the total operating costs of the energy conversion facility.

Rogers and Brammer (2009) found that the key parameter for estimating transportation costs for willow woodchips and baled miscanthus biomass was the number of round trips per day a truck could make rather than the distance covered.

Caputo *et al.* (2005) demonstrated that the effects of all logistic variables are much stronger for combustion-based solutions than gasification-based solutions, owing to the higher biomass consumption characterizing the former. They also mentioned that purchasing and transportation biomass costs represent the main cost items in the total operating costs, which may introduce limitations on the feasibility for both the C/ST (fluid bed combustor and steam turbine cycle) and the G/CC (fluid bed gasifier and combined gas–steam cycle) solutions.

2.4 Development of advanced biomass supply and process chains

One of the most important hurdles in increasing biomass utilization for energy supply is the complexity and the cost of the supply chain. For this reason, many attempts have been made to date to simulate and optimize biomass supply chains on the understanding that significant cost reductions could originate from more efficient logistics.

A large number of simulation models for biomass supply chains exist, usually focusing on one or a few specific biomass types, examining one or more supply chain designs. Examples are the analytical supply chain model for five distinct types of biomass by Allen *et al.* (1998), as well as the analytical supply chain simulation models for forest biomass (Gallis, 1996), cotton (Gemtos and Tsiricoglou, 1999; Ravula *et al.*, 2008; Tatsiopoulos and Tolis; 2003), corn (Benock *et al.*, 1981), *Miscanthus giganteus* (Huisman *et al.*, 1997) and sugar cane (Hansen *et al.*, 2002). Mantovani and Gibson (1992) modeled a collection system for maize residues, hay and wood residues for ethanol production. Mitchell *et al.* (1999) developed a spreadsheet model, where the cost of producing energy crops (short rotation forestry) was investigated, focusing mainly on biomass production, collection and storage. More generic simulation models for biomass supply chains have also been developed, such as in Sokhansanj *et al.* (2006) and De Mol *et al.* (1997), simulating biomass flow from the field to a biorefinery. These generic models can examine different types of biomass, and the user must identify the specific parameters to be entered into the models.

Apart from pure simulation models, optimization has also been used for several aspects of the biomass supply chain, such as the number and location of facilities, the resource requirements, the costs, etc. An LP optimization model was used by Cundiff *et al.* (1997) to optimize a cost function including the biomass logistics between the on-farm storage locations and the centrally located power plant, the construction and expansion costs of storage facilities, as well as the cost of violating storage capacity or lost revenue in the case of a biomass deficit. The authors considered the use of ambient and covered storage and took into account the uncertainty in biomass production levels. Zhu and Yao (2011) developed a mixed-integer linear programming (MILP) model as a multi-echelon, multi-period and multi-commodity supporting logistics system. The aim of this model is to select the optimal locations from candidate locations for biomass production, intermediate storage and bioenergy facilities, and was applied to the switchgrass biomass supply chain.

Several attempts have been made to include uncertainty in biomass supply in simulation or optimization models of the biomass supply chain and to assess its effects on supply chain design. The first stochastic model in biomass supply chain has been the work of Cundiff *et al.* (1997), which focused only on storage facilities for herbaceous biomass. A mixed integer stochastic programing model was also presented (Chen and Fan, 2012) to support strategic planning of bioenergy supply chain systems and optimal feedstock resource allocation in an uncertain decision environment. This two-stage stochastic programing model focuses on finding the least expected system cost by simultaneously solving within the integrated system the optimal strategies for bioethanol production, feedstock procurement and fuel delivery.

Several authors have extended their biomass supply chain modeling or optimization efforts by also including the bioenergy conversion facility, generating electricity or heat. For example, a comparative economic evaluation of various bioenergy conversion technologies was performed by Mitchell *et al.* (1995), using a comprehensive biomass-to-electricity and ethanol model named Bioenergy Assessment Model (BEAM). Tatsiopoulos and Tolis (2003) presented a detailed cotton-stalk supply chain model, which employs LP optimization for biomass delivery scheduling. This model was used for centralized (electricity) and decentralized combined heat and power (CHP) power plant scenarios. In a similar vein, Papadopoulos and Katsigiannis (2002) performed a technoeconomic assessment of a biomass power plant, using a mixture of many biomass types. The authors focused primarily on reducing biomass logistics costs, and more specifically on eliminating biomass warehousing needs by performing a two-stage optimization: firstly, the CHP power-plant location is determined to minimize the transportation distance and secondly, dynamic programing optimization is employed to identify the optimum biomass fuel mix.

Furthermore, a GIS has also been used in several models and studies to provide spatial information. A GIS was used to calculate the exact transportation distances for supplying specific amounts of energy crop feedstock across a region, taking into account the geographic variability in yield (Graham *et al.*, 1997, 2000). Another GIS-based model was developed by Voivontas *et al.* (2001) to estimate the potential for electricity production from multiple agricultural residues. However, the authors do not focus explicitly on the implications of using multiple biomass sources on logistics and warehousing costs. A combination of a GIS and linear mathematical programing was used by Freppaz *et al.* (2004) to calculate the location and capacity of production plants. In this case, the objective function comprises the benefits from selling energy, transportation costs and plant installation costs, but their model is not able to model economies of scale. Panichelli and Gnansounou (2008) used a GIS to estimate transportation costs between forest locations and production plants and to identify two minimal cost locations chosen from a set of predefined possible locations.

Some biomass supply chain models are energy-demand-driven, which means that these models aim at satisfying a currently existing energy demand (electricity and/or heat). Nilsson and Hansson (2001) presented such a discrete-event simulation model, where a biomass supply chain of two fuels (straw and reed canarygrass) is simulated for use in district heating applications. A similar approach, but for only one biomass type, was adopted by Nagel (2000) to determine an economic energy supply structure satisfying an existing heating demand with a district heating network. The problem was formulated as a mixed-integer linear programing (MILP) optimization using a dynamic evaluation of economic efficiency, and binary operators to determine whether to construct a district heating network, a heating plant or a co-generation plant. Freppaz *et al.* (2004) used a combination of a GIS, mathematical modeling and optimization to study the energy supply at a regional level from forest biomass. The system in question attempts to partially satisfy local existing heat and electricity needs. The model employs a GIS to calculate the transportation cost from all potential biomass collection points to all potential CHP plant locations. Then, optimization is performed to find the optimal size of the power plant (and defining which kind of energy to produce for the specific area), and to find the optimal biomass collection and harvesting schedules. A biomass supply chain optimization model for tri-generation applications using multiple biomass sources was presented by Rentizelas *et al.* (2009b). This model optimizes the biomass facility location, its capacity and the amount of each biomass source to be procured, aiming at maximizing the profitability of the investment.

As a concluding remark, many models have been proposed for simulating and optimizing the biomass supply chain. There is such a large number of them because of the different requirements of the numerous applications that these models try to address. Therefore, when modeling a new supply chain it may be possible to use an existing model described in the literature. However, it should be mentioned that every model has its advantages and limitations and care should be taken when adopting one, especially considering the availability of data that will be required to run the model. Due to the large number of possible biomass supply chain structures, there is also the likelihood that a new customized model will be required.

2.5 Integration of biomass combustion into waste management

Biomass combustion is included in the waste management systems of many countries. This biomass could be in the form of municipal solid waste (MSW), where only the biogenic fraction is considered as renewable waste, or in the form of industrial waste. For example, the United States had about 872 operational

MSW-fired power generation plants in the year 2007 (EPA, 2011), generating approximately 2500 MW, or about 0.3% of total national power generation. In Europe, about 20% of the waste generated in the year 2009 was incinerated in about 440 waste-to-energy plants (CEWEP, 2011). There are several ways to integrate biomass combustion into waste management, depending on the structure of the waste management system, the desired results and the level of interference to the existing system.

One way is to pre-treat mixed MSW to remove only materials that do not have energy content, e.g. glass and metals. This type of material separation may also be performed at the source, which means separate collection of mixed MSW, glass and metals. The remaining MSW fraction contains all the other waste streams and may be used for energy conversion.

However, the European Union (EU) Landfill Directive (Council Directive 1999/31/EC) suggests that recycling is preferable to converting waste to energy, and even worse is sending waste to landfill sites. This means that waste should be recycled to the maximum potential extent, before being available for energy conversion. Recycling can be maximized by using a larger number of separate waste streams collected at source. For example, separate collection bins can be used for glass, metals, paper and packaging or recyclable plastics. It should be noted that extensive recycling will remove waste streams of high calorific value and low moisture content, such as wood, paper and plastics, from the MSW before it is exploited for energy generation. This can produce a residual mix of low calorific value and very high moisture content, which means that an auxiliary external fuel source may be required for the combustion or gasification of the waste under the appropriate conditions. It should also be taken into account that the moisture content of the organic waste streams may fluctuate significantly depending on the season, which may pose an extra point of concern for the energy conversion facility.

Another option is to create refuse-derived fuel (RDF) and solid-recovered fuel (SRF) from waste and use it for energy conversion. RDF and SRF are derived by mechanical treatment and potentially biological treatment and drying of the mixed MSW stream, after removing all non-combustible materials, such as metals and glass. These types of fuel may have more standardized specifications, due to the treatment and drying processes. SRF can be distinguished from RDF because it is produced to meet a specific quality specification. RDF and SRF have a significant heating value and relatively stable characteristics; therefore, they are often a commodity with a market value. RDF and SRF may be used for energy generation, as a primary fuel or for co-combustion in coal plants, or as a fuel in cement kilns. For more information on RDF and SRF and their mechanical and biological treatment, refer to Velis *et al.* (2010).

Integrating waste-to-energy in a waste management system has the great advantage of significantly reducing the amount of waste to be landfilled or disposed of. The output after waste energy conversion is usually less than 10% of the incoming volume, depending strongly on the composition of the MSW streams supplied to the waste-to-energy plant. Nonetheless, care should be given to the management of the ashes produced, as they may contain toxic substances such as heavy metals or dioxins. Some researchers claim that these ashes may have several alternative uses, such as in cement or road infrastructure, instead of being landfilled. During the early stages of waste incineration technology, another point of criticism in introducing energy conversion into waste management systems was the concern over the health effects from emissions of dioxin and furan in the flue gases. It should be noted though that the new technologies adopted and the new stricter emissions regulations in many countries have reduced these emissions to such an extent that waste-to-energy facilities are no longer considered a significant source of dioxin and furan emissions (McKay, 2002; Porteous, 2001), compared to the remaining emission sources in modern societies.

Gasification is another promising technology for energy conversion of waste streams. Gasification is a more elaborate method for energy conversion of waste, compared to incineration and combustion. Its advantages are mainly the higher efficiency of energy conversion, since the gas produced can be used in gas turbines, internal combustion engines, fuel cells or even combined cycles, and the fact that the syngas and the other primary products from gasification may be used as feedstock for the petrochemical industry, or have other uses. On the other hand, gasification is more sensitive to variations in the waste input specifications and it is a technology that is still under development.

2.6 Advantages and limitations of using biomass for energy conversion

2.6.1 Advantages

Local availability of biomass

Most biomass types are characterized by local availability. Since the material involved is usually of low density and of low value, it is not suitable for transportation over large distances. Therefore, biomass utilization for energy conversion is an excellent opportunity for developing a rural economy. The biomass logistical operations may be additional income for rural areas, both for farmers, who may be occupied when other agricultural operations are over, as well as for the specialized workforce, which may be required. The value created by biomass is returned to a large extent to the local communities, and the energy conversion facilities will probably be situated close to the biomass production area, therefore creating more local job opportunities. Finally, the potential of co-generation or tri-generation of energy from biomass means that local communities may benefit from receiving heat or cooling from the biomass energy conversion facility at a competitive price and with higher reliability.

Renewable energy generation

Energy generated from biomass is considered as renewable. At a local level, biomass energy may substitute energy generated by conventional fuel sources, such as oil or natural gas for heating, and electricity for cooling. At a national level, dependence on fossil fuel sources may be reduced.

Local generation of energy

The fact that energy is generated locally on a small- to medium-scale reduces the need for a grid infrastructure for long-distance energy transportation. Therefore, the related energy losses are minimized and the investment capital for creating this infrastructure may be spared. This is an advantage for the national grid operator, but it ultimately benefits all electricity consumers, as they are the ones finally paying the grid investment costs through their electricity bills.

Exploitation of marginal lands for energy crops

Some types of energy crops may be cultivated on marginal lands that are currently not used. This may provide an extra income source for rural communities and create jobs.

2.6.2 Limitations

High complexity of the biomass supply chain

The biomass supply chain is characterized by a large number of potential sources as well as a significant number of stakeholders. This, on the one hand, leads to a supply chain structure that must be designed specifically for each case, as the conditions in every case will probably be different, and on the other hand, it renders the management of the supply chain a complex task, due to the number of stakeholders involved.

Limited know-how of logistical operations

Each biomass type has its own characteristics and requirements for handling and storage, and not all these parameters are known with certainty. In some cases, local conditions may even change these requirements. Therefore, each biomass supply chain that deviates from well-known cases should be carefully examined and designed according to the requirements and peculiarities for that specific biomass type. For example, some biomass types may require open-air drying, others forced drying and others may be prone to self-ignition under certain conditions.

Lack of standards and regulation for biomass and equipment

A significant barrier in biomass energy conversion is the lack of established standards for biomass fuel characterization. Several attempts are in progress, with the aim of standardizing the fuel specifications and properties for many types of biomass, as well as the related equipment. The widespread use of standards will allow biomass procurement with predictable quality and reduced fluctuation of properties, which will ultimately facilitate trading and the procurement of biomass, as well as the design and operation of biomass energy conversion plants.

Limited development of markets for biomass

Several types of biomass that have alternative uses have mature markets that define their price and allow the required amounts to be supplied in a straightforward way. For many biomass types, however, there are no such markets and therefore the need arises for the operator of the biomass energy conversion facility to negotiate contracts with a large number of biomass producers. Securing the biomass supply for a long time at predictable and reasonable prices is of paramount importance for the economic feasibility of the investment.

Lack of existing equipment

The biomass types that have alternative uses also have the related equipment for treatment, handling and transportation. For biomass types that are not currently utilized, it could be possible that new specialized equipment must be developed, usually at a premium price. Therefore, it is natural that the most logical choice would be to try to use already existing equipment without or with only minor modification. Alternatively, a compromise could be made by introducing a step into the supply chain, as upstream as possible, to turn biomass into a form that can be handled and treated by standardized equipment. It should be mentioned that developing specialized equipment to perform only seasonal operations for a specific biomass type could overly increase biomass cost, as the equipment amortization cost would have to be allocated to only this biomass type for a short time.

Transportation distance limitation

Biomass energy conversion facilities are subject to economies of scale, as all technological devices. However, the maximum size of such a facility is primarily limited by the biomass supply chain cost, which increases with the size of the facility, due to the larger transportation distances required. Furthermore, the larger the facility the higher are the related greenhouse gas emissions from biomass transportation and the greater the disturbance to local communities due to traffic. For this reason, it is usually more efficient to create small-to-medium-sized facilities, which focus on exploiting local biomass types. It is evident, though, that more efficient logistics may allow the size of biomass energy conversion facilities to be increased.

2.7 Future trends

Biomass supply chain management is in many cases connected to agricultural operations. From a technical and organizational point of view, agricultural operations have seen major progress over the years and have now reached a level of maturity with a slower rate of progress. Therefore, for biomass types that are already agricultural crops, most of the supply chain issues have been dealt with and there is significant know-how. For biomass types that are new or are currently not exploited, there is a challenging need for efficiently organizing the supply chain and introducing technological innovation, based on existing agricultural processes, in order to keep the cost low. Some of the issues that are expected to drive the future evolution of biomass supply chain management, according to researchers, are the following:

Multi-biomass supply chains

Using multiple biomass sources in the same biomass energy conversion plant may provide significant benefits when there is seasonal availability of biomass. Several researchers have documented the potential advantages of such an approach (Nilsson and Hansson, 2001; Rentizelas *et al.*, 2009b) in the logistical operations of biomass. However, the compatibility of the technology used for energy conversion should be examined, as significant variations in fuel quality and characteristics may be expected. The multi-biomass approach may require more flexible energy conversion technologies, allowing a higher degree of variation in biomass properties, in order to be able to exploit many biomass types as well as taking advantage of availability and price changes.

Energy crops

Crops specifically targeted for energy conversion are expected to attract interest in the future. More specifically, crops that have a low operational cost with relatively high yield and the potential to be cultivated on marginal land, are the most likely to dominate. There has been a significant amount of research in recent decades to identify such energy crops, particularly those suited to specific climatic and soil conditions. The development of new energy crops may require new supply chain designs and more innovation, especially if marginal land is utilized, as sparser collection areas may be involved, therefore leading to longer transportation distances.

Biomass markets and trade centers

Biomass types that have existing alternative uses are commodities with market prices defined by demand and supply, which can be traded and purchased in specific markets. This development may be expected also for biomass types that currently have no alternative use, and therefore for which there has been no interest in establishing such markets. However, if the production and supply of these biomass types remains at a local level, it is probable that prices will be determined by contracts between the local energy conversion plant operators and the biomass suppliers. It is expected that in any case, the establishment of markets for more biomass types will provide a better insight into future biomass prices and will reduce supply uncertainty. Furthermore, the development of regional biomass logistics and trade centers should be expected with the aim of optimizing logistics and trading operations, and where different biomass fuels (firewood, chips, pellets, energy crops, etc.) will be marketed at a specified quality.

Long-distance and large-scale biomass transportation

Biomass is a material that is not indicated for long-distance transportation, mainly due to its low volume, high moisture content and low value. However, there are situations where biomass is transported efficiently over long distances, for example, after processing to increase the density, or in situations where biomass is exported from areas with a large biomass potential and low biomass collection and processing costs to areas with high energy demand and prices (Hamelinck *et al.*, 2004). In the future, more efficient processes and standardization in biomass processing and logistical operations may render long-distance transportation more efficient, especially for high energy-content biomass types.

Poly-generation

An interesting option for biomass energy conversion is energy poly-generation. This means generating many types of energy product at the same facility, such as tri-generation (electricity, heat and cooling) or the generation of electricity, heat and biofuels. Generating more energy products at the same facility may significantly increase the efficiency of energy conversion and provide products of high market value. However, customers for the energy products generated have to be identified. For co-generation and tri-generation, a network for district heating or district cooling has to be built, and the potential customers have to be located close to the facility. It is also important to be able to secure long-term contracts with these customers.

2.8 Sources of further information and advice

- There are currently no books specifically on biomass logistics and supply chains. However, chapters discussing biomass supply chain issues may be found in many books dealing with biomass energy conversion, such as the ones by Van Loo and Koppejan (2008), Sims (2002) and Veal (2009).
- An interesting source of further information for many aspects of biomass energy exploitation systems, ranging from biomass characteristics and classification to supply chain issues and energy conversion technologies, is the Biomass Energy Centre. It has set useful standards for biomass equipment and fuels (www.biomassenergycentre.org.uk).
- The US Department of Energy's Office of Energy Efficiency and Renewable Energy has a website dedicated to its biomass program. This site has information and data for various audiences, mainly focused on the US (www1.eere.energy.gov/biomass/).
- IEA Bioenergy was set up in 1978 by the International Energy Agency (IEA) with the aim of improving cooperation and information exchange between countries that have national programs in bioenergy research, development and deployment (www.ieabioenergy.com/IEABioenergy.aspx).
- The Garbrook Advanced Biofuels Resource (ABR) is a knowledge base with information on the logistics of biomass, within the section on the biomass-to-energy supply chain (www.garbrook.com).
- The Confederation of European Waste-to-Energy Plants provides information on energy conversion plants using municipal solid waste or other types of waste in Europe (www.cewep.eu).
- Several conferences on biomass are held around the world each year, most of them dealing partly with the logistics of biomass exploitation. However, there are also dedicated conferences on the biomass supply chain, such as the annual biomass supply chain conference (www.biomasssupplychain.com).
- Finally, the journal *Biomass and Bioenergy* is one of the most important journals on the topic of biomass, with its scope extending to the environmental, management and economic aspects of biomass and bioenergy. However, related articles may be found also in logistics journals, such as the *International Journal of Physical Distribution and Logistics Management* and *Transportation Research Part E: Logistics and Transportation Review,* as well as more generic journals on renewable energy, such as *Renewable and Sustainable Energy Reviews, Renewable Energy, Bioresource Technology* and *Ecological Engineering*.

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3

Biomass feedstocks: categorisation and preparation for combustion and gasification

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Abstract: This chapter addresses the categorisation of biomass followed by the preparation and conditioning of biomass before combustion and gasification, which are the main technologies for heat and electricity generation. The physical and chemical characteristics are described for a range of types of biomass, together with selected examples of the common European standards for measuring biomass. The chapter addresses the problems and limitations of selected fuels and considers future trends for fuels such as mixed biopellets and the potential use of marine biomass.

Key words: feedstock, chemical and physical characterisation, conditioning, classification, standardisation.

3.1 Introduction

Energy is vital for people and industry. Although the consistent global increase in energy consumption during the coming decades will be supplied mainly by fossil fuels, an increasing part will originate from biomass. The International Energy Agency (IEA) estimates that the peak in oil production will occur around 2030 depending on the rate of consumption, the discovery of new oilfields, improved technology for exploiting oil reserves and changes in prices, where increasing prices mean that reserves, which today are unprofitable, will become profitable.

Furthermore, the use of fossil fuels as the prime energy source is facing growing concerns from decision makers and green organisations since the burning of fossil fuels adds climate-changing greenhouse gasses to the atmosphere. Both the increasing dependence on imported fossil fuel and the increase in the emissions of greenhouse gasses are in direct opposition to the long-term European strategy for energy supply.

During the oil crisis in the early 1970s the search for alternatives to petroleum-based fuels initiated the modern use of bioenergy production based on combustion of solid biofuels in heat and power plants. Sweden, Finland and Denmark have been pioneers in the development and use of bioenergy and today these countries are among the leaders, both in terms of production capacity and technology (Faaij, 2006). In addition, Scandinavia has the most mature biofuel market and large amounts of biofuel are imported from the Baltic countries and Canada (Alakangas *et al.*, 2002).

The increased use of solid biomass for energy production can only be achieved by broadening the scope of biomass used in the energy sector. Presently forest and plantation wood, short rotation coppice such as willow and poplar, together with a narrow selection of agricultural products such as wheat and corn stalks constitute the basis for the energy sector. In the future this scope must necessarily expand to include industrial bio-waste, mixtures of different agricultural and wood waste and even aquatic biomass such as microalgae and seaweed.

The utilisation of new types of biomass necessitates the development of new or improved pre-treatment methods so that it can be used with existing fuel conversion technology. Mixtures of feedstocks in pellets and briquettes are another possibility for increasing the use of challenging biomasses that have an undesirable chemical composition.

The characterisation of physical and mechanical parameters demands common standards. The development of standards will help to expand the market for solid biofuels, which is necessary to meet the increasing demand. There are vast amounts of biofuels available worldwide (Parikka, 2004). For example, wood pellets and firewood are intensively exported from the Baltic countries and Canada to Sweden and Denmark (Ericsson and Nilsson, 2004; Heinimö and Ranta, 2005); however, a fully developed market where price and quality are adjusted would dramatically increase the access to biomass and here standards provide the transparency needed.

Beside the immediate need for energy, when the reserves of fossil fuel reach a peak a number of factors will drive a renewed interest in utilising biomass as the primary energy resource. They include climate concerns related to CO_2 emissions, interest in reducing the present dependency on importing energy from politically unstable regions, sustainable use of local or regional biomass resources and because solid biomass is the only resource that can buffer the other renewable energy resources.

3.2 Types of feedstock

3.2.1 Biomass

With the increase in biomass used for energy production and the competition for biomass for a variety of products and uses, all available resources, including mixtures, will become important for energy conversion. Although the global potential biomass feedstock is far from being fully exploited and even heavily exploited areas such as, for example, Scandinavia, where biomass has been utilised on an industrial scale since the early 1970s, the potential of local biomass is large. Global and local resources are described for various scenarios in a vast number of studies: globally by Hoogwijk *et al.* (2003), on a European level by de

Wit and Faaij (2010) and in several national studies, including Scandinavia by Parikka (2004), the Czech Republic by Lewandowski *et al.* (2006) and Japan by Kamimura *et al.* (2012).

Biomass can be categorised in several ways, e.g.:

- woody biomass
- herbaceous biomass
- industrial biomass waste
- aquatic biomass
- manure.

Woody biomass is characterised by trees and woody plants, which typically live for several years. The typical woody biomass utilised for energy is forest trees and short rotation coppice (SRC), such as willows. In plantations, whole tree utilisation is common, e.g. poplar and Norway spruce from the temperate climate zones or gum tree and eucalyptus from tropical and sub-tropical zones and from forest clearings. Additionally, the utilisation of parts of trees – roots, stems and branches – is common; these logging residues are the remains of timber production and constitute an increasingly important part of the biomass used for energy. Feedstock for energy production from woody biomass is most common as chips or the slightly larger hog fuel, sawdust or logs; the latter comminuted at the energy plant before conversion or converted to upgraded fuels such as wood pellets or briquettes.

Herbaceous biomass is from annual, biennial or perennial plants. These die back after the growing season and grow again from seeds or from lower parts of the plant that survive below the soil. Typical herbaceous biomass used for energy production is wheat straw, corn stalks and switchgrass, but also rapeseed, sorghum, miscanthus and triticale are considered as sources of energy. Herbaceous biomass is typically produced in bales, which are combusted directly, or as pellets, which are milled before combustion.

Industrial biomass waste is a more or less unknown biomass resource derived from the fodder and feed industry. The annual amount of industrial waste is enormous and stable from year to year. It would be useful to evaluate the possibilities for mixing this great supply of biomass with or as a substitute for straw or wood. Biomass includes: grain screenings and waste from shea, sunflower, olive, rape, pectin, carrageenan, coffee, tobacco and other industrial waste products. Because of the great amount of raw material that power plants will need to use in the future, it is important that there are alternatives (i.e. increased fuel bands), for example, for when the traditional raw material (wood) will become very expensive or impossible to procure. Research has shown that a mixture of different biomass waste can have a favourable effect on reducing corrosion and slagging.

Aquatic biomass includes freshwater plants, microalgae, and marine microalgae and macroalgae commonly called seaweed. Microalgae are single-celled photosynthetic plants whereas macroalgae are multicellular photosynthetic marine plants. The possibility of utilising aquatic biomass for energy purposes was studied in the ambitious Aquatic Species Program, funded by the Department of Energy, National Renewable Energy Laboratory (DOE-NREL) from 1978–1996 (Sheehan *et al.*, 1998). The interest in utilising marine biomass, such as the lipids in microalgae and the carbohydrates in seaweed, for energy and transport fuel is booming in the 2010s.

Manure is the faeces from farm animals, commonly cattle and pigs, but also from chickens and other animals bred on an industrial scale. It can be utilised for energy production. Manure is typically used for biogas production in an anaerobic digester but the pelletising of pig and cattle manure for combustion is also a possibility.

3.2.2 Physical and chemical characteristics of the feedstock

The fundamental physical and chemical characteristics that influence the utilisation of the feedstock are ash content and composition (which depend on the type of biomass), moisture content, particle size and distribution, bulk density and mechanical durability (for pellets and briquettes, which depends on the pre-treatment). The characteristics of biomass feedstock vary widely and depend both on the kind and species of the biomass and on the applied pre-treatment of the raw material (Table 3.1). The physical and chemical parameters may vary considerably within a feedstock lot (which is a defined quantity of fuel for which the quality is to be determined). For example, the moisture content can vary within a single truckload of woodchips from approximately 20% to approximately 40% (Møller and Esbensen, 2005). In contrast, the physical and chemical parameters for upgraded fuels as pellets and briquettes have comparatively less variation, that is the moisture and ash content in a shipload varies less compared to raw biomass. The requirements for fuel quality and characteristics vary among energy applications and combustion technologies. So relatively cheap, inhomogeneous fuels of low quality should be used as feedstocks in large combustion systems with high-quality management and control systems, which can compensate for

Table 3.1 Physical characteristics of typical biomass feedstock for energy applications

Fuel	Typical particle size (mm)	Common preparation method
Briquettes	Ø > 25	Mechanical compression
Pellets	Ø < 25	Mechanical compression
Fuel powder	< 1	Milling
Sawdust	1–5	Cutting with sharp tools
Woodchips	5–100	Cutting with sharp tools
Hog fuel		Crushing with blunt tools

the variations in the feedstock. High-quality fuels such as briquettes and pellets should be utilised in small-scale applications or as a high-density energy carrier for co-combustion in coal-fired reactors.

The size and size distribution of the particles in a feedstock significantly influence the combustion behaviour and counter pressure (Jenkins *et al.*, 1998; Kristensen *et al.*, 2003; Thunman and Leckner 2005). Several external and internal characteristics such as bridging and the angle of repose are closely related to particle size and shape (Mattson, 1988, 1990). The particle size is thus important for securing the optimal conditions for in-feeding and the combustion of solid biofuels and must be adapted to the selected combustion technology. Moisture content is a key characteristic of biomass feedstock and is essential for the optimisation of boiler settings. Feedstock with high moisture content has a higher flue-gas content, longer burn-out time and thereby longer residence time in the boiler, which all influence the design and control of the boiler. The value of a solid biofuel is based on the calorific value of the feedstock and is calculated as:

$$H_{nv} = H_n\left(\frac{100-F}{100}\right) - \frac{2.442\times F}{100} \qquad [3.1]$$

where H_{nv} is the net calorific value of wet wood, H_n is the net calorific value of dry wood, F is the moisture content as a percentage of the total weight and 2.442 is the latent heat of evaporation of water at 25°C.

Mechanical durability describes the hardness of the fuel pellets and briquettes. Uniform particle distribution is a basic requirement for reliable conveying and combustion in heating systems based on pellets and high mechanical stability means that the numbers of fine particles and broken pellets will be low. Besides influencing the combustion systems, increased amounts of fines can impose a variety of problems from the simple inconvenience of dust in the pellet storage to eye irritation and potentially respiratory diseases from long-term exposure to dust (Dias *et al.*, 2004; Fiedler 2004; Madsen *et al.*, 2004).

The ash content and composition varies considerably between feedstocks, ranging from below 0.5 weight% (dry basis – d.b.) in wood pellets produced from debarked stem wood to 5–10 weight% (d.b.) in agricultural residues, straw and miscanthus. The concentrations of the major ash-forming elements in biomass – silicon, calcium, magnesium, potassium, sodium and potassium – are of great importance for the combustion characteristics. Generally magnesium and calcium increase the melting temperature of the ash whereas potassium and sodium tend to decrease the melting point. The ash melting point is defined as the point where the ash starts to flow and eventually melt leading to slag on the grate and in the bed. The ash-forming elements and the ash melting point vary considerably between biomasses, which should be considered when allocating biomass to different applications.

Co-firing of dried macroalgae in power plants

Co-firing of biomass in coal-fired power plants is a proven technology for CO_2 reduction. The co-firing potential depends on the physical and chemical properties of the biomass product, i.e. moisture content, particle size and content of ash, alkalis, chlorides and other components. As macroalgae is a new type of biomass it will discussed in more detail. From a combustion point of view, dried macroalgae powder is suitable for pulverised-fuel co-firing, but the content of ash, alkalis, chlorides and sulphur is very high. Typical fuel properties of dried *Ulva lactuca* powder, straw and coal are shown in Table 3.2.

On a heating value basis the content of calcium, magnesium, potassium, sodium, sulphur and chlorine in *Ulva lactuca* is very high in comparison with coal and also much higher than in straw. By co-firing *Ulva lactuca* in coal-fired power plants the content of magnesium, potassium and sodium in the fly ash and the content of SO_2 and HCl in the raw flue gas will be significantly increased. The proportion of *Ulva lactuca* used in co-firing is limited by the impact on slagging, catalyst deactivation, corrosion, emissions and residue quality (fly ash, bottom ash and gypsum). It is expected that the influence on fly ash quality will be the most critical factor and a calculation for 0–20% co-firing on a mass basis has been performed. Table 3.3 compares the results with the critical quality requirements for the fly ash used in concrete.

The influence on alkali and MgO content is substantial and the ash quality standards are exceeded even by 10% *Ulva lactuca* on a mass basis, corresponding to 5% on an energy basis. In comparison, when co-firing with 20% straw on a mass basis the content of alkali is increased to only 3.6% and there is no significant change in the content of MgO. It is concluded that the potential for *Ulva lactuca*

Table 3.2 Typical fuel properties of *Ulva lactuca*, straw and coal

Parameter	Unit	*Ulva lactuca*	Straw	Coal
Moisture	%	14	14	14
Lower heating value, as received	kJ/kg	11.4	15	24
Ash	% dry basis	16.5	4.5	12
Si	% dry basis	0.02	0.8	3
Al	% dry basis	0.0	0.005	1.5
Fe	% dry basis	0.13	0.01	0.6
Ca	% dry basis	0.7	0.4	0.3
Mg	% dry basis	1.8	0.07	0.15
K	% dry basis	2.6	1.0	0.2
Na	% dry basis	1.6	0.05	0.05
S	% dry basis	2.0	0.12	0.7
Cl	% dry basis	1.6	0.4	0.05
P	% dry basis	0.16	0.06	0.02
Br	% dry basis	0.03		

Table 3.3 Critical fly ash quality parameters for *Ulva lactuca* co-firing. *Ulva lactuca* percentages on a mass basis

	0% *Ulva lactuca*	5% *Ulva lactuca*	10% *Ulva lactuca*	15% *Ulva lactuca*	20% *Ulva lactuca*	EN 450–1
Alkali (Na_2O + $0.658 \times K_2O$)	2.0	3.8	5.7	7.5	9.3	<5
MgO	2.2	3.4	4.6	5.9	7.2	<4

Note: Even at 10% *Ulva lactuca* inclusion, the levels obtained exceeded the recommended levels for fly ash utilized for concrete as described in EN 450.

powder as a direct co-firing fuel in coal-fired power plants is very limited (Nikolaisen *et al.*, 2011; Bruhn *et al.*, 2011).

3.3 Characterisation, analysis and categorisation techniques

Common product standards are an important driver for expanding the market for solid biofuels, which is necessary to meet the increasing demand for renewable energy from communities in Europe and also many places outside the EU. Product standards allow specific qualities to be defined in a contract and if there is a discrepancy, a set of commonly accepted standards could possibly solve any dispute (Jensen, 2011).

The European Committee for Standardisation (CEN) initiated the development of standards for solid biofuels. The work has resulted in standards for classification, sampling, and physical and chemical testing and currently the International Organisation for Standardisation (ISO) has started the process of including the CEN standards for solid biofuels into the globally recognised set of standards issued by ISO, thus contributing to the further development of an international market for solid biofuels.

3.3.1 Standardisation of solid biofuel

The lack of commonly accepted and internationally recognised standards is generally seen as a barrier to the development of a mature market for solid biofuels and consequently a further increase in the use of renewable energy (Painuly, 2001; Janssen and Feuerholm, 2003).

A number of countries have standards for solid biofuels, which are used on a national or regional level and are maintained by the respective national standardisation bodies. These standards frequently differ with respect to limit values and test equipment, as an example the Swedish (SS187180, 1999), Austrian (ÖNORM M7135, 2000) and American (ASAE, 1996) standards all describe methods to determine the durability of fuel pellets. However, the three standards are based on three different types of test equipment, employing two different test principles (tumbling and pneumatic stress), with different sample pre-treatment and different aperture sizes for determining the particle sizes, which are used for separation among quality classes. These differences are a fundamental discrepancy, which makes it impossible to obtain comparable quality classification results for identical samples tested using the different standardised methods. Consequently, a common standard for testing this specific quality parameter will increase the transparency of the pellet market, making it easier for the consumer to decide whether the price corresponds to the quality of the fuel and to compare across several fuel qualities.

Currently more than 30 items have been identified for standardisation by the European Committee for Standardisation and new items are continuously added to the list (see www.cen.eu). The standards cover five general topics, which together will create a detailed tool that will support and develop the growing market. The topic titled *Terminology*, *definitions and descriptions* covers a single standard describing the basic terminology and descriptions, which form a common vocabulary for the standards. The topic *Fuel specifications*, *classes and quality assurance* includes two standards for describing biomass fuel based on type, origin, and traded forms and properties and gives recommendations to ensure traceability of all processes along the supply chain up to the point of delivery to the end user. The heterogeneous nature of biomass feedstock is challenging for accurate sampling, subsequent determination of a fuel's characteristics and in the utilisation of the feedstock in energy applications. Currently four standards under the topic *Sampling and sample reduction*, address sampling in general, sampling of lorries in particular, sample reduction and finally preparation of sample plans and sampling certificates. Finally two topics *Physical and mechanical test methods* and *Chemical test methods*, describe methods for various physical and chemical tests. These two topics include most of the standards issued and are continuously expanding with new methods and improvements to existing methods.

3.3.2 Description of key methods

It is beyond the scope of this introduction to feedstock characterisation to describe all the issued CEN standards in detail and, additionally, not all methods are equally important. Given the large number of solid biofuels and the number of standards, five methods from the CEN catalogue of standards for testing physical or chemical characteristics of solid biofuel are presented in more detail. The methods are selected based on a combination of relevance across fuels and market size of the fuel where woodchips and wood fuel pellets are dominant.

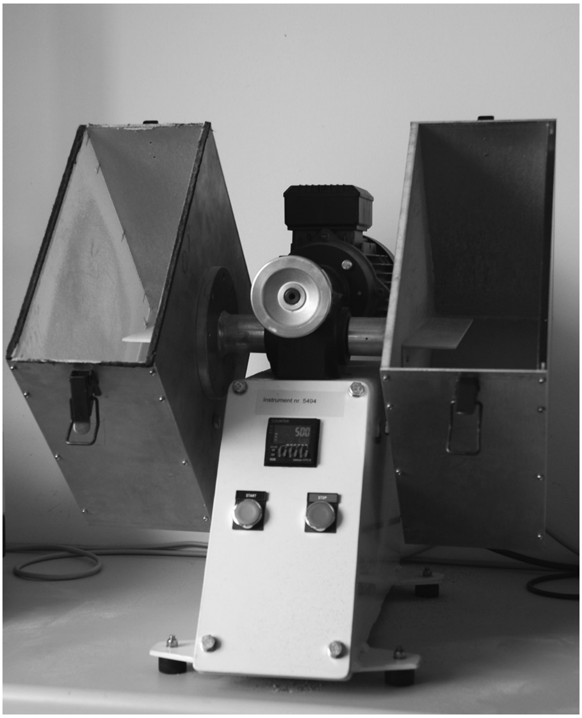
Moisture content can be measured with a range of on-line devices for particulate fuel, such as woodchips, or as the mass loss after drying under defined conditions, the latter being the reference method used in standardisation. Measurements can be made using near infrared, dielectrical and microwave methods. Moisture measurements obtained with on-line devices are less accurate than those from the mass loss method (Jensen *et al.*, 2006). The mass loss determination of moisture content by drying under standard conditions is the reference method, used widely in standards for solid biofuel. The CEN standard for determining moisture content, CEN/TS 14774-1, prescribes drying a minimum of 300 g, but preferably more than 500 g, at 105 ± 2°C until the mass is constant, where the steady state is defined as less than 0.2% mass loss between two succeeding measurements after one additional hour of drying.

The moisture content measured as mass loss is calculated as:

$$MC = \frac{m(wet) - m(dry)}{m(wet)} \times 100 \qquad [3.2]$$

where MC is the moisture content, $m(wet)$ is the mass in grams of the wet sample and $m(dry)$ is the mass in grams of the sample dried to constant weight.

The durability of biofuel pellets is determined by tumbling 500 ± 10 of pellets for 10 minutes in a durability tester (Fig. 3.1). Before the tumbling, all



3.1 Testing equipment for determination of mechanical strength and durability of biomass pellets.

particles with a nominal top size below 3.15 mm are sorted out by sieving so the analysis is performed on pellets or parts of pellets. After the tumbling, particles with a nominal top size below 3.15 mm produced during the test are removed by sieving and the durability is measured as the mass loss, which is calculated as:

$$DU = \frac{mA}{mE} \times 100 \qquad [3.3]$$

where DU is the mechanical durability, mA is the mass in grams of pre-sieved pellets before testing and mE is the mass in grams of the pellets after tumbling and sieving.

Particle size determination can be performed either using image analysis for on-line determination or gravimetric methods using sieving trays stacked in a tower or a rotating drum. The gravimetric methods are widely used for standardisation. The gravimetric methods deliver highly reproducible results with relatively cheap equipment. The drawback is that the classification gives no information about the absolute or maximum length or the shape of single particles, although measurement of length can be performed by hand. If the prime concern for particle size is related to combustion of the fuel, knowledge of the width or thickness may be adequate. The stacked tray method sorts the particles in decreasing particle size and the rotating drum in increasing particle size. The technical specification for determination of the particle size distribution for a solid biofuel is divided into two parts, one for coarse fuels with a nominal top size above 3.15 mm, CEN/TS 15149-1 (Fig. 3.2), and CEN/TS 15149-2 for fine particles with a nominal top size below 3.15 mm. For the coarse fuels a sample size of 10 litres is required whereas fine fuels, such as sawdust and milled straw, only require a sample of 100 gram. A complete classification is found by sieving a sample until the mass flow between any two consecutive sieves is below 0.3% mass change per minute. The particle size distribution is calculated as the mass% (d.b.) of particles retained by each sieve and aperture size, and is reported as the cumulative size distribution.

The ash content is determined as the mass of inorganic matter remaining after combustion of a fuel under specified conditions (CEN/TS 14775). In the standard for ash determination, a minimum 1 gram fuel sample with a nominal maximum size below 1 mm is burnt at 550±10°C until complete incineration, defined as constancy in weight, which in practice means less than 0.2 mg change in mass after an additional 30 minutes of incineration.

The ash content is expressed as a percentage of the mass (d.b.) of the ash relative to the fuel:

$$A_d = \frac{(m3 - m1)}{(m2 - m1)} \times 100 \times \frac{100}{100 - M_{ad}} \qquad [3.4]$$

3.2 Equipment for determination of the particle size distribution of woodchips with a nominal top size above 3.15 mm.

where A_d is the ash content for dry matter, $m1$ is the mass of the empty sample container, $m2$ is the mass of the sample container and the fuel sample, $m3$ is the mass of the sample container and the ash and M_{ad} is the moisture content of the sample.

Ash melting is a complex process that in the CEN standard is described as specific physical changes of a test piece made of biomass ash at characteristic temperatures, i.e. *shrinkage-starting temperature*, *deformation temperature*, *hemisphere temperature* and *flow temperature*. The characteristic temperatures where physical changes occur are better defined as temperature ranges than exact temperatures and considerable variation is found both within and between feedstock types; some typical examples are given in Table 3.3. Moreover, results obtained under a controlled atmosphere in a test oven are not comparable to the highly complex conditions existing in real-scale combustion with inconstant heating rate and gas compositions. The method used in the CEN standard is based on methods described in ISO 540:1995 and DIN 51730:1998 for coal ash, which has a significantly different melting behaviour compared to ash from biomass (Arvelakis *et al.*, 2006). The difficulties using this ash melting method to describe complex processes in full-scale combustion conditions have driven the development of methods to describe ash melting and slagging phenomena.

3.4 Fuel preparation and upgrading for combustion or conversion

3.4.1 The main preparation methods

Chopping

Straw can be chopped by chaff cutting or shredding. A chaff cutter cuts the straw apart and has a high electrical consumption compared to a shredder, and also has higher maintenance costs. Therefore, a shredder is normally used. The shredder makes the straw suitable for baling. In a combustion plant, shredded straw falls through a hopper onto a screw stoker, which passes the straw into the boiler. If the straw is to be pelletised, shredded straw goes into a hammer mill before the pelletising process.

Chipping of forest wood

A chipper for whole-tree chipping or chipping of wood residues in a forest is self-propelled. The chipping elements and a crane are mounted at the front and a high-tipping container is mounted at the rear end for collecting the chipped material. The chipper has an in-feed opening mounted with hydraulic rollers that push the biomass into the chipper. There are three different types of chipper, differentiated by the type of blades they are equipped with and the position of the blades along a rotating axis: disc chippers, drum chippers and screw chippers. A disc chipper has a heavy, rotating disc with rectangular holes in which chipper knives are mounted radially. When rotating, the disc with the chipper knives moves past a fixed steel block, the anvil. The size of the woodchips can be varied by changing the position of the knife. A drum chipper has a parallel-sided rotating drum with attached knives running down the length of its axis. The knives in a drum chipper also pass a fixed anvil. The size of the woodchips can be controlled as in a disc chipper. In a screw chipper, the cutting blade is a rotating, tapered, conical screw thread with a hardened cutting edge, which comminutes the biomass against the inside of the casing. The axis of rotation is in line with the direction of feed, which pulls the material into the chipper and is the only feed mechanism required. Particle size is determined by the pitch of the screw, and can be varied by changing the blade to one of a different pitch (Serup *et al.*, 2002).

Drying

Drying is necessary depending on the final thermal conversion. Fresh woodchips with a moisture content of 40–45% are used directly in a boiler designed for this type of fuel. Straw with 15–20% of moisture is also fired directly without drying. When upgrading wood (or other biofuels) for pellets, the raw material must have about 10% moisture content before the pelletising process begins. Shavings from furniture production do not need to be dried. If the raw material is woodchips or wet sawdust from sawmills, it has to be dried. A moisture content higher than 15% makes the raw material difficult to pelletise. The extent to which a material is dried before pelletising makes a big difference to the energy required in the manufacturing process.

Milling

After drying the raw material is milled in a hammer mill. Milling is necessary because the delivered raw material can be very heterogeneous in size. The size distribution after milling is determined by the sieve in the mill. The sieve can be changed depending on which raw material is being processed.

Torrefaction

Torrefaction is a thermal pre-treatment process at 200–300°C, which produces a biomass with excellent properties for handling, milling and co-firing (with coal in power stations). Although the good quality of torrefied biomass has been demonstrated at laboratory and pilot scales, there are still many technical and economic challenges to be solved before torrefaction is a commercial production technology.

In the period 2010–2012, torrefaction entered into a demonstration phase where several plants have started operation in Europe each with a capacity of 10 000–60 000 tons per year. In the US there are also initiatives underway and the first demonstration plant has started operation. The market potential for torrefied biomass is considered to be enormous, since the product can be used in all types of thermal plants from power plants to domestic boilers. Torrefied biomass has been requested for burning in power stations in Europe since the massive demands for CO_2 reduction by 2020 in Europe's energy plans (National Renewable Energy Action Plan) will require an enormous amount of biomass (wood) to be imported into Europe. Fulfilling these energy plans would require an increase in consumption of at least 400 million m^3 of wood per year in Europe in 2020, mainly imported. There is thus a great pressure on companies developing torrefaction technology, since much of the growth in biomass consumption could be met by torrefied biomass. The expected advantages, which for many still are to be proven, of torrefied biomass compared to raw biomass (wood) are:

- Co-firing with coal can be over 50% compared to raw biomass, which is only up to 15–20% on an energy basis.
- Torrefied pills can be stored outdoors for a reasonable amount of time, unlike wood pellets.
- The energy used in transportation is lower than for wood pellets since the calorific value per kilogram is higher.

- Torrefied biomass has better milling characteristics (size and energy use) than raw biomass.
- Torrefied biomass undergoes very slow biological decomposition compared with raw biomass.

Densification by pelletising

Before pelletisation, 1–2% of water in the form of steam is supplied to the raw material, which is thereby heated to approximately 70°C. Heating ensures that the lignin in the wood is released and this contributes to increased binding of the particles in the final product. In the pellet press, the raw material lies in front of a rolling press, which presses the material down into a die. When the roller rolls again over the hole in the die, new material is pressed into the hole, thereby compressing the raw material into pellets.

Six conditions are important for successful pressing, and thus the quality of the pellets:

- Compatibility between raw material quality, the capacity of the compressing machine and the compressing process.
- The friction capacity of the die.
- The surfaces and the materials of the die and the roller.
- The ratio between the diameter and the length of the holes (the press channel) in the die.
- The thickness of the layer of the raw material above the die and thereby the thickness of the material that is pressed into the die.
- The speed of rotation of the roller.

The distance between the die and the roller affects the quality of the pellets, wearing of the machine and the consumption of energy in the process. Tests have shown that an increase in the distance from 0 to 1 mm causes a 20% higher consumption of energy, but at the same time reduces the volume of dust by 30% in the final product.

Pelletising is carried out using a machine with a ring die or a flat die. The raw material is led into a chamber where one to three rollers press it into pellets through cylindrical holes in the die. When the pellets have passed through the die they are cut or broken into suitable lengths. The die can be changed depending on the raw material. The ratio between the diameter and length of the press channel is very important for the final quality of the pellets.

Pressing increases the temperature of the raw material. The necessary pressure level in the die depends, amongst other things, on the type of raw material. In general, increasing the content of hardwood in the raw material will increase the need for pressure in the pelletising process. Material that requires a higher pressure than the one actually used, may block the holes in the die and thereby interrupt the pelletising process.

The still warm and elastic pellets are transported to a cooling device to be cooled to just above room temperature. Cooling increases the durability of the pellets, which reduces the amount of dust formed during the following transportation and handling. In counter-current cooling, the pellets and cooling air move in opposite directions towards each other so that warm air is used to cool the warmest pellets and vice versa. Counter-current cooling cools the pellets gradually, which reduces the amount of heat stress that the pellets are exposed to because this may decrease the quality of the product. After cooling, the pellets are screened to remove dust and fine particles formed during production. The pellets are then stored loose or packed in bags and the residues from the screening process are recycled back into the production process.

Densification by briquetting

Briquetting is – like pelletising – a process in which the raw material is compressed under high pressure, which causes the lignin in the wood or biomass to be liberated so that it binds the material into a firm briquette.

The most appropriate water content in the raw material for briquetting varies and depends on the raw material. However, the normal water content is between 6% and 16%. If the water content is over 16% the quality of the briquettes will be reduced, or the process will not be possible.

There are hydraulic presses for small capacities from 50 to 400 kg/hour. The raw material is fed into the press by a time-controlled dosing screw, which means that it is the volume of the raw material and not the weight, which is controlled. Briquettes have a fairly good uniform length (square briquettes) and they are mainly used by domestic consumers.

Mechanical presses are available with capacities from 200 kg/hour up to 1800 kg/hour. Briquettes from these presses are normally round and short and they are used in heating plants for larger industries and for district heating plants. A mechanical press is built like an eccentric press. A constantly rotating eccentric connected to a press piston presses the raw material through a conic nozzle. The required counter pressure can be adjusted only by using a nozzle with a different conicity. A mechanical press receives raw material from a speed-controlled dosing screw. The speed of the dosing screw determines the production rate of the press. A change in the specific gravity of the raw material will change the hardness of the briquettes. A mechanical briquetting press will produce a long length of material – a briquette string – which, however, breaks into random lengths depending on the binding capacity of the raw material. A saw or cutter is used to cut the briquette string into briquettes of uniform length.

The briquette string pushed out of the press is very hot because of the friction in the nozzle. The quality of the briquettes depends mainly on the cooling and transport line mounted on the press. A cooling/transport line of at least 15 m is recommended for wood briquettes. The longer the time a briquette remains in the cooling line the harder it will become. Cooling lines up to 50 m long are common.

3.4.2 Use

Combustion units range from a few kilowatts for domestic heating, to district heating plants and large power plants. Most burn pure biofuel but in some plants biomass is co-fired with a fossil fuel, typically coal. Not all biofuels are equally well suited for all technologies, consequently knowing the physical characteristics of the different fuel types is necessary for achieving optimal handling and combustion.

The physical properties of solid biofuels vary both between fuel types and among fuels of the same type. Particle size, ash content, ash melting point and moisture content influence the handling and combustion of biofuels, and consequently they should be taken into account to obtain optimal combustion. Table 3.4 lists the physical properties of typical solid biofuels based on CEN/TS 14961.

Small-scale use

A typical automatic wood pellet boiler could consist of an external pellet store equipped with a screw conveyor for forwarding the pellets to the burner. The external store ensures the convenient, long-term uninterrupted running of the pellet burner. The pellets enter the burner from the top, the bottom or horizontally. In bottom-fed and horizontally-fed burners a screw conveyer feeds the fuel directly onto the grate and in top-fed burners the pellets fall from the top of the burner onto the grate.

Small pellet burners are typically developed and tested on pellets with a uniform size. Too much variation, for example due to excessive amounts of fine particles, may cause failure of the storage and conveying system and may also lead to increased emissions of dust and unsteady combustion (Obernberger and Thek, 2002, 2004). Durability is therefore one of the most important physical parameters of the pellets. High-quality pellets with a high durability and low ash content are normally designated for the domestic market where comfort and convenience matters whereas pellets with a lower quality should go to district heating plants.

Table 3.4 Physical properties of common solid biofuels according to CEN/TS 14961 (2005).

Fuel property	Woodchips	Sawdust	Wood pellets
Moisture content (%)	20–65	20–65	< 20
Particle size (mm)	5–100	1–5	Ø< 25
Ash content (%)	< 10	< 6	< 6
Durability (%)	–	–	> 97.5

Large-scale use with or without co-firing

The large-scale production of electricity, heat and process steam requires a boiler plant and a distribution system for the heated water (a district heating system). District heating plants in general have a silo or pit for fuel storage, a fuel conveying and feeding system, a combustion chamber and various systems for flue gas and ash handling. The combustion system may have a grate or a fluidised bed, or be a powder (suspension) firing system. Each type has specific requirements for the optimal fuel.

With the grate system, the fuel is burnt on a grate and drying, gasification and charcoal burnout take place in the primary air supplied from below. The gasses from pyrolysis are supplied with secondary air and burn above the grate. In grate combustion, the fuel travels or vibrates through the combustion chamber as it burns, producing ash by the end of the grate. This gives a limited amount of time for complete combustion of a single particle, which depends on the moisture content, temperature and retention time on the grate. Thus fuel particle size is important. Fuel that leaves the grate unburnt, either with the bottom ash or through the flue-gas cleaning system, reduces boiler efficiency and increases emissions if the fuel is in the form of unburned gasses. Fuel particles should ideally be small enough to ensure complete burning out of the charcoal but at the same time the particles should not be so small that they float with the flue gas and cause fouling or ash deposits in the boiler. A large proportion of small particles or slagging may cause increased packing of the bed, which leads to increased counter pressure and so block the passage of the primary air through the fuel.

In a fluidised bed, the fuel is burnt in a suspension of a bed material of silica sand, dolomite and fuel, which ensures a high degree of mixing between the oxygen and the fuel. Primary air is added from below the bed and secondary air from above the bed for combustion of gas. Fuel remains in the bed until combustion is complete. However, particles smaller than 2–3 mm can be transported out of the bed with the flue gas before they are combusted (Järvinen and Alakangas, 2000).

Small particles are, on the other hand, essential for combustion plants with dust burners where small particles are mixed with oxygen in the combustion chamber and burnt with a very high efficiency and low emissions of CO and polycyclic aromatic hydrocarbons (PAHs). Important fuel sources for powder-fired plants are wood or, in a single known case, straw pellets that are milled to a fine powder before being combusted. Two examples are the Danish power plant, Avedøre, which consumes 120 000 tons/year of wood pellets and the Amager power plant, which is designed for 130 000 tons/year of straw pellets. The straw pellets are transported by barge to the plant and milled before combustion and exact knowledge of the particle size distribution is decisive for optimising combustion.

3.5 Advantages and limitations of particular fuels

Biomass with high alkali and chlorine contents has often caused problems with the formation of deposits and corrosion. Using additives rich in silicon and aluminium, calcium and potassium, sulphur or calcium can reduce these problems. To test the possibilities for improvement, some of the new biomass fuels were mixed together and new fuels were mixed with different additives. The fuel mixtures were then tested in a thermogravimetric analyser and in an entrained flow reactor. An additive to remedy problems with deposit formation and corrosion in biomass-fired suspension boilers, will ideally fix all potassium in species with relatively high melting temperatures (to minimise the formation of strongly sintered deposits, which are difficult to remove) and release chlorine to the gas phase (to minimise corrosion). However, mixing of a troublesome fuel with an inert additive or a less troublesome fuel may also reduce ash-related problems by simple dilution of the troublesome elements.

Slagging in combustion units is caused by molten ash and is one of the main drawbacks with using biomass fuels, especially when waste biomass fuels originating from industry or agricultural production are used. The problems are caused by the typically higher ash content of these fuels but also due to the typically lower ash melting temperatures compared to fossil fuels or pure wood.

Currently there are solutions for combusting fuels with lower ash melting temperatures, such as e.g. wheat straw, but they have to be adapted specifically to a specific quality of the fuel. Fuel quality however, varies widely between different types of biomass and biomass waste and can also vary with the season and especially during the handling of the fuel, which can cause contamination with soil, dirt or other waste materials.

Compositional and other relevant data for a wide range of biomass, biomass ash and other relevant materials are available from a number of excellent databases of biomass properties:

- Phyllis, named for the Greek goddess of trees and wisdom, compiled by ECN in the Netherlands (www.ecn.nl/phyllis).
- Biobank, compiled by Bios Bioenergiesysteme GmbH in Austria, is available from the IEA Bioenergy Task 32: Biomass Combustion and Co-firing website (www.ieabcc.nl).
- BIOBIB, which is a database of biomass properties compiled and maintained by the Technical University of Vienna, Austria (www.vt.tuwien.ac.at).
- US DOE has also compiled a biomass feedstock composition and property database (www1.eere.energy.gov/biomass/databases.html).

The key technical ash-related problems encountered by operators of biomass combustors and boilers have been associated with:

– The formation of fused or partly fused agglomerates and slag deposits at high temperatures within furnaces and stoves.

- The formation of bonded ash deposits and accumulations of ash materials at lower temperatures on surfaces in the convective sections of boilers.
- The accelerated metal wastage of furnace and boiler components due to gas-side corrosion under ash deposits, and due to ash-particle impact erosion or ash abrasion of boiler components and other equipment.
- The formation and emission of sub-micron aerosols and fumes.
- The effect of biomass ash on the performance of flue-gas cleaning equipment.
- The handling, utilisation and disposal of ash residues from biomass combustion plants and mixed ash residues from the co-firing of biomass in coal-fired boilers.

For biomass gasification and pyrolysis systems, the ash-related issues are largely similar to those for combustion, i.e. the accumulation of ash material within the reactor and associated equipment, the effect of ash on the integrity of the process plant and heat exchangers and the ash-related environmental effects of the process.

Designed fuels

The many biomass products on the market with different combustion qualities and raw material prices make it important to know the cost structure of the different products. In recent years a considerable amount of data has been gathered on different biofuel properties, including the combustion properties of biomass burnt as a pure raw material without anti-slagging additives. Understanding biofuel properties makes it possible to produce recipes for biofuel pellets with a variable content of different biomasses as well as binding agents and anti-slagging additives. In the next few years we will experience growing demand for biofuel pellets, both domestic products and imported products. Therefore, it seems relevant to examine the fuel quality of pellets produced for use in power plants, especially suspension-fired boilers. To ensure a sufficient supply of biomass raw material, it is important to consider using CO_2 neutral fuels for mixture with or as a substitute for straw and wood. CO_2 neutral fuels include grain screenings, waste from shea, sunflower, olive, rape, pectin and coffee production and other industrial waste products. In the future, energy production from biomass will require a significant amount of raw material, so it is important to have alternative sources of supply (i.e. wider fuel bands), in case the normal raw material becomes very expensive or impossible to procure. Previous research has shown that the admixture of additives can have a favourable effect on limiting corrosion and slagging.

3.6 Future trends

Taking the political trends into account, biomass will be considerably exploited in the coming decades. The current situation in Europe (2011) is that the EU member states all have National Renewable Energy Action Plans (NREAPs) for meeting the 20–20–20 goal by 2020 (a 20% reduction in greenhouse gas emissions from 1990 levels, increasing the share of energy consumption produced from renewable resources to 20% and a 20% improvement in energy efficiency). The summation of these plans predicts the use of an enormous amount of biomass, which will not be available in Europe at that time. All of the EU countries plan to import biomass, mostly wood pellets, but the question is, will the exporting countries (Canada, USA, Brazil, Argentina, Russia and south-east Asia) have an adequate supply system in place within the relatively short time frame?

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4

Direct combustion of biomass

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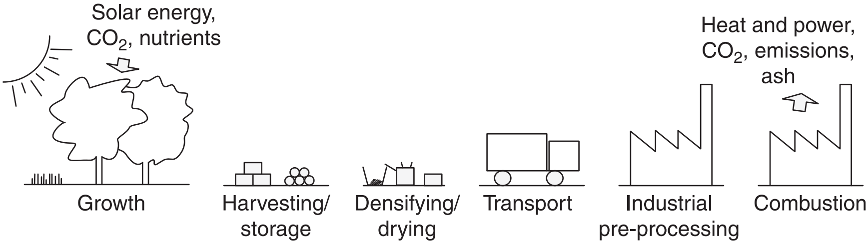
Abstract: This chapter addresses the large-scale combustion of solid biomass to produce heat and power without co-firing of fossil fuels. It introduces the combustion process with a specific focus on issues important in the combustion of solid biomass such as the condition and chemical properties of the biomass fuel, the increased fouling and corrosion of heating surfaces associated with biomass compared to fossil fuels, as well as ash properties and sintering problems. Finally, specific issues regarding the different firing technologies – grate, fluidized bed and suspension firing – are reviewed.

Key words: combustion, fouling, corrosion, fuel characterization.

4.1 Introduction

Figure 4.1 is an overview of the processes ending with the production of heat and power from the combustion of solid biomass fuel. Each of these processes has an effect on the condition and combustion properties of the biomass fuel or on the availability of the biomass and its effect on plant economics.

As biomass grows it transforms the energy of the sun into chemically-stored energy by means of photosynthesis. This energy, which originates from the sun, can later be converted into heat and power via combustion. Plants absorb atmospheric CO_2 as well as nutrients from the ground. During the combustion process, the CO_2 is released into the atmosphere and due to the relatively short cycle this process can be considered CO_2 neutral. The nutrients, as well as trace elements of heavy metals, which are absorbed during growth, together with the



4.1 Overview of processes involved in the utilization of biomass for heat and power production.

structure of the hydrocarbon bonds, influence the different aspects of the thermochemical conversion process such as the heating value of the fuel, the corrosiveness of the flue gas, the stickiness of the ash, etc. Thus it is important to consider all links of the supply chain in order to predict and compensate for potential issues in the combustion process.

The chemical composition and the combustion properties of biomass vary greatly depending on the agricultural species from which the biomass originates but also seasonal and regional variance of the feedstock can result in great differences in the chemical composition of the feedstock. Even when feedstock is from the same agricultural species, differences can arise depending on which part of the plant is used. As such, the chemical composition of heartwood, bark, branches and leaves will differ greatly. As wood grows, mobile elements such as potassium move from the interior heartwood towards the still active growth zones of the tree, leaving the mature stem low in elements that have a deteriorating effect through fouling of the boiler, whereas the growth layers of the tree will tend to promote fouling. The heartwood is also much more resistant to organic deposition and it is much denser than the leaves and branches of a tree, making it ideal for storage and transport. Thus from a pure thermo chemical point of view, the most attractive feedstock is derived from seasoned forests whereas quick turnaround energy crops or straw are generally less desirable. Woody fuels are dried and pelletized to create a high-density product, which can easily be transported by ship and can directly replace coal in the supply chain for larger centralized power plants. Pelletizing does not change the chemical properties of the feedstock but drying increases the energy density with the penalty of having to use energy to reduce the moisture content. The process of pelletizing prepares the feedstock for further processing, for example milling, but the feedstock still has to be protected from the weather and the moisture content has to be monitored to avoid fermentation.

Next to wood, straw is considered as having the most potential as an alternative feedstock for fossil-fuel power plants. Straw is essentially a waste product from the production of agricultural crops. This means that the production of this feedstock does not compete with agricultural products for the limited land resources. Dedicated energy crops or even forests can use up land that could otherwise be used for the production of food. If the hunt for energy results in a shortage of food, energy producers will have a serious ethical dilemma on their hands. However, energy crops are often grown on marginal land that is unsuited for the production of food.

Straw, being derived from a perennial species, has a chemical composition that is detrimental to the combustion process. In the supply chain of straw, it is important to consider handling in the fields and transportation to power plants. Generally straw has a low energy density so before transport the moisture content has to be reduced and the straw compacted. Currently, straw is left to dry in the fields for a period. Thereafter the straw is collected in bales to be transported by lorry to a power plant where the bales can be burned directly or processed further prior to combustion. Since bales have a low energy density, the distance they can be transported and still have a positive energy output, are limited. This also limits the type of plant used in the thermochemical conversion process since larger plants require a larger surrounding area. To give a greater range, straw needs to be densified locally, typically by pelletizing or more recently by torrefaction, before it is transported. However, global supply chains for straw are yet to be implemented. Torrefaction is a mild form of pyrolysis, which involves the controlled heating of the biomass feedstock in an inert atmosphere to release the lighter volatiles and thereby produce a product with a greater energy density. Torrefied biomass is hydrophobic and easier to fracture and thus more suitable for suspension firing, which requires milling of the feedstock (Arias *et al.*, 2008). Leaving straw lying in the fields affects its chemical composition. First of all, depending on the weather conditions during the harvesting and drying period, the feedstock may have a greatly varying moisture content. However, it has also been shown that the amount of chlorine in the straw can be drastically reduced if it is doused in water after it is harvested (Jenkins *et al.*, 1998). The chlorine in the feedstock is a strong promoter of fouling and it can thus be advantageous to let the rain wash away harmful substances from the straw. It also follows that the combustion properties from one batch of straw may vary greatly from another, depending on the ever unpredictable weather.

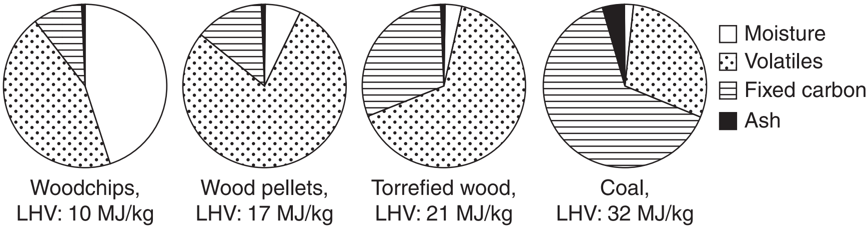
Besides wood and straw, a wide variety of biomass fuel is derived as the agricultural waste products of industrial processes: rice husks, wheat bran, peanut shells, leftovers in the pressing of olive oil, coffee grounds, bagasse, etc. These waste products can be used as an inexpensive fuel to produce the heat or electricity needed for industrial process. Using biological waste products to power production thereby simplifies the disposal process and they can be integrated into the processing facilities (Capehart *et al.*, 2005). These biomass fuels have a wide range of chemical composition, which means that it is difficult to give strategies to cope with problems common to all fuels. Generally, the combustion process and plant has to be designed specifically for the feedstock in question.

The direct combustion of solid fuel has been the focus of considerable research since the start of the Industrial Revolution and general texts concerning different aspects of combustion and systems are widely available. Two recent books deal with the same topic as this text. *The Handbook of Biomass Combustion* by van Loo and Koppejan (2006) is an exhaustive text dealing with practical engineering aspects of biomass combustion. The present text, which is a supplement to this book, considers the development of direct combustion of biomass since the publication of that book and gives a brief overview of current problems and solutions in biomass combustion. *Thermochemical Processing of Biomass* by Brown (2011) deals with the different processing methods for biomass and contains a brief summary of engineering calculations relevant for biomass combustion. This text focuses on the aspects of combustion technology that are especially relevant for the large-scale combustion of solid biomass fuels rather than dealing with basic engineering methodology. Depending on the power plant technology used for the thermochemical conversion, different problems have been identified when using biomass instead of coal. Biomass tends to foul the heating surfaces more than coal, it is more corrosive, the ash from biomass tends to agglomerate and heat release can be vastly different, meaning that boilers have to be redesigned to properly burn biomass instead of coal.

4.2 Basis of biomass combustion

Combustion is defined as the exothermal reaction between fuel and oxygen to form mainly carbon dioxide and water vapour. The heat released can be used to produce electricity via a Rankine cycle. Depending on the condition and combustion properties of the fuel that is to be burned, different furnace designs and firing parameters can be selected to ensure optimal efficiency or uptime. Direct combustion is based on well-established technology, which currently is the principal method of generating electricity around the world. Modern combined heat and power (CHP) plants, which additionally produce heat for district heating, can achieve an overall plant efficiency around 90% for heat and power combined (DONG Energy, 2012). The generation of electricity from power plants deliver a predictable load in contrast to other green technologies such as wind or solar power and can additionally be used actively in the regulation of grid frequency. Biomass is regarded as the most important and potent renewable fuel due to its ability to be used directly as a substitute for coal.

Although coal, as all fossil fuels, has the same origin as biomass fuel, its structure and chemical properties are distinctly different. Figure 4.2 shows the typical composition of wood and coal based on proximate analysis. Three typical wood fuels prepared by different pre-treatment techniques are shown. Woodchips have not undergone any drying and contain a large fraction of moisture. The moisture evaporates when the fuel is burned and the energy required cannot typically be recovered. The heating value of a fuel directly decreases with moisture



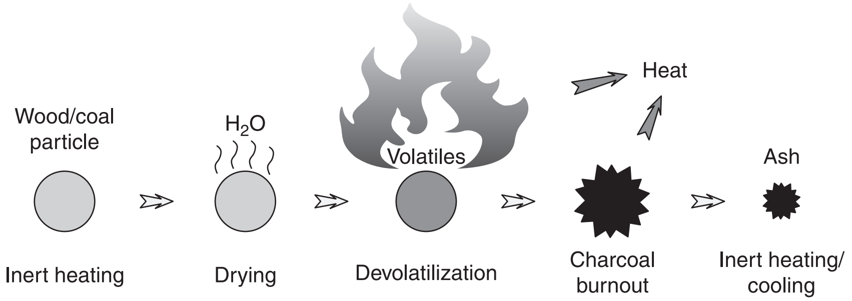
4.2 Composition of typical woody fuel and coal (Pentananunt *et al.*, 1990; Energistyrelsen, 2002; Ye *et al.*, 2004; Holm *et al.*, 2006). LHV: lower heating value.

content and it is very difficult to maintain combustion with a moisture content in excess of 55 wt% (Faaij, 2004). The water content also influences the time required to combust a particle and thereby extends the required residence time in a furnace.

Wood pellets are basically wood that has been dried and where the moisture content has been reduced to below 10% (Hahn, 2004). The heating value of pelletized wood is significantly higher than raw chipped wood. Generally it is not possible to reduce the moisture content in wood pellets much below 10% since the pellet will absorb moisture from the atmosphere. Wood pellets have to be stored in large halls whereas coal, which contains very little moisture to start with, can be stored outside without absorbing water. During storage, it is important to monitor the moisture content and the temperature of the wood pellets as these can be an indication of the onset of bio-decomposition.

The torrefaction of wood is a relatively new process in which the lighter volatiles and moisture are evaporated from the fuel. This upgrades the wood fuel compared to pelletization and typical lower heating values are reported to be between 18–23% (van der Stelt *et al.*, 2011). Additionally, torrefaction removes hydroxyl (–OH) groups, which are responsible for the absorption of moisture, so that torrefied wood, like coal, will not absorb moisture and can be stored under the open sky (Phanphanich and Mani, 2011).

Biomass has a significantly higher content of volatile matter compared to coal and the fixed carbon-to-volatile matter ratio is significantly below unity. Additionally, biomass also begins to release volatiles at a lower temperature and more rapidly than coal, thus reducing the ignition temperature compared to coal. Special attention should be given to the design of the air supply to provide sufficient oxygen because of the faster release of volatile matter in order not to delay combustion (Yin *et al.*, 2004). The basic combustion route of a solid fuel is shown in Fig. 4.3. Volatiles are released from the fuel as a gas when heated and they combust when mixed with oxygen. Combustion of the gaseous volatiles is



4.3 Particle combustion route. For a small particle this is a sequential process while large particles can support several stages simultaneously.

fast compared to the combustion of the solid charcoal and a high ratio of volatiles decreases the residence time of the fuel in the furnace. The remaining charcoal will predominantly retain its original shape and will, during burnout, be reduced to ash.

The global combustion reaction is:

$$\begin{aligned} &C_{X_1}H_{X_2}O_{X_3}N_{X_4}S_{X_5} + n \cdot (3.76N_2 + O_2) \rightarrow aCO_2 + bH_2O + cO_2 \\ &\quad + dN_2 + eCO + fNO_x + gSO_x \end{aligned} \qquad [4.1]$$

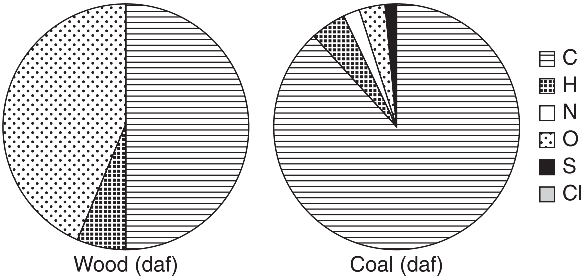
Essentially this states that the fuel is converted into heat, CO_2 and water. However, it does not reflect the true nature of combustion. Even the combustion of the simplest hydrocarbon CH_4 has 277 elementary steps with 49 species according to the most recent models (Turns, 2006). A complete description of the complex mechanisms involved in biomass combustion still remains to be fully explored. Due to limitations in computation resources, simulation of combustion processes often only considers a limited number of reactions and only the most basic of species. One simple but popular reaction framework considers six species: N_2, O_2, H_2O, CO_2, CO and CH_XO_Y and two gas phase reactions:

$$\begin{aligned} &CH_XO_Y + aO_2 \rightarrow CO + bH_2O \\ &CO + 0.5O_2 \rightarrow CO_2 \end{aligned} \qquad [4.2]$$

The volatiles are thus modelled using a single ‘species’, CH_XO_Y, which combusts with oxygen to form carbon monoxide and water according to the elemental composition of the volatiles. One additional reaction is used to model the reaction of carbon monoxide with oxygen to form carbon dioxide. Here two reactions are used as these have been identified as being limiting reactions with respect to the reaction rate. Depending on the level of detail required it is possible to include more reactions and species in an analysis of combustion. The inclusion of further limiting reactions would make the prediction of combustion more precise. Precise modelling of the reaction framework is also necessary for an understanding of the formation of undesirable products of combustion such as NO_x or PAHs. The formation of these gaseous species has the same complexity as in the combustion of coal (Baxter, 2005).

The elemental composition of the volatiles can be obtained from an ultimate analysis of a fuel where the amount of fixed carbon is subtracted. Figure 4.4 shows the typical composition of wood and coal.

It can be seen that wood, as all types of biomass feedstock, contains a large fraction of oxygen compared to coal, which consists mostly of carbon. Wood also has very little fuel-bound nitrogen and sulphur. However, the nitrogen and sulphur content varies considerably depending on the origin of the biomass feedstock. Ultimate analysis is basically a breakdown of the fuel into its elemental components through an analysis of the products that remain after the complete combustion of a small fuel sample. A typical set-up evaluates only the carbon, hydrogen and nitrogen components and the oxygen is found from a mass balance. To properly analyse



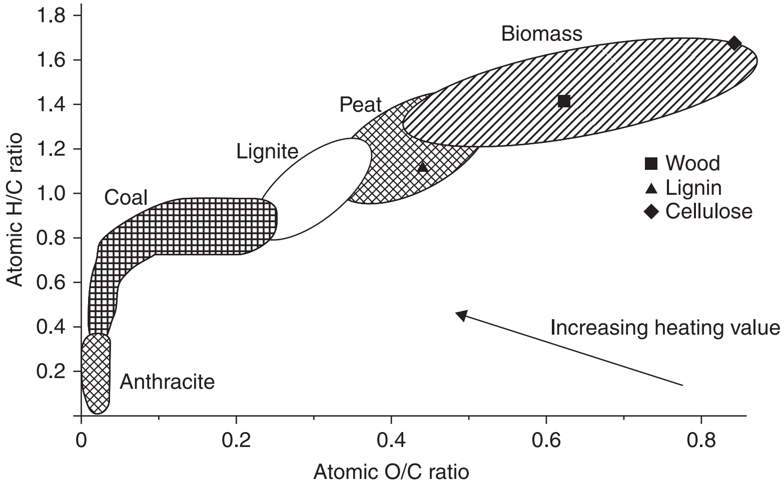
4.4 Elemental composition of wood and coal (Ye *et al.*, 2004; Holm *et al.*, 2006). daf: dry and ash free.

biomass it is necessary to have additional modules to detect sulphur and chlorine, which are important in combustion and which typically are found in significant quantities in biomass. The content of inorganic components is not measured by ultimate analyses and is found through analysis of the ash (Saidur *et al.*, 2011).

Proximate and ultimate analyses are the normal tools used to evaluate traditional solid fuels in addition to measuring the heating value and heavy metal content. Whereas coal can be considered as a relatively homogeneous substance, biomass contains varying amounts of organic constituents with different combustion characteristics, which is not reflected by proximate or ultimate analysis. The main constituents of biomass are cellulose, hemicelluloses and lignin. In addition to the main constituents, biomass also contains small amounts of lipids, proteins, simple sugars and starch as well as inorganic constituents and moisture. The composition of solid fuels is often illustrated using a van Krevelen diagram, which plots fuels according to the atomic ratios H/C and O/C. Figure 4.5 shows a van Krevelen diagram for various solid fuels. It can be seen that biomass fuels have significantly larger H/C and O/C ratios compared to coal.

The release of volatiles from the solid biomass is considered using devolatilization rates typically defined using the Arrhenius equation, which simply models the temperature dependence of the reaction rates. The simplest method for modelling the release of volatiles from a biomass fuel is to use a single rate for the volatiles as a whole. Several researchers have suggested a model framework that uses two or more rates to reflect the release of the different constituents of the biomass fuel (di Blasi, 2008). As for the gas phase reaction network, the consideration of several competing devolatilization rates is required for a more precise analysis. However, in practice the lack of precise data for individual fits, as well as a limited understanding of the basic fluid flows on which the reaction and devolatilization rates are based, will necessarily prevent an accurate prediction of the combustion pattern. Several devolatilization rates are given in the review by Williams *et al.* (2012).

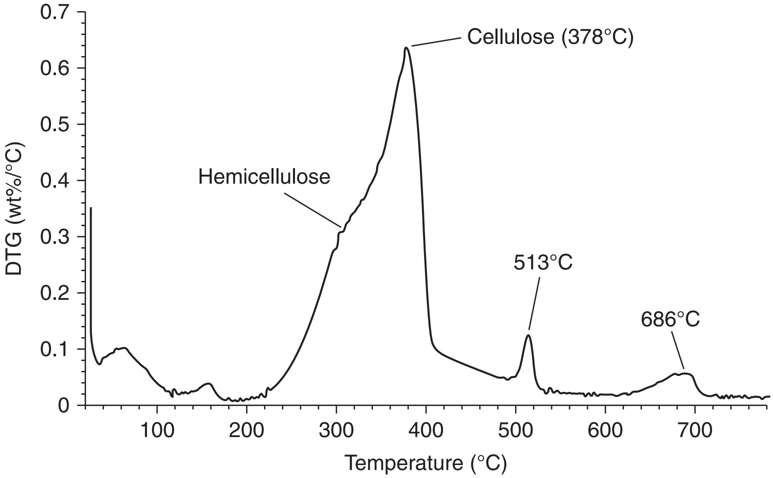
Fits for reaction rates can be found using data from thermogravimetric analysis (TGA). TGA involves heating a sample of the fuel placed on a precise weighing



4.5 Van Krevelen diagram for various solid fuels (Prins *et al.*, 2007).

scale. By analysing the data from TGA, it is possible also to determine the weight loss intensity or more precisely the weight loss per increment of the temperature scale. This is known as derivative thermogravimetric analysis (DTG). Figure 4.6 shows a DTG analysis of wood.

It can be seen that it is possible to determine distinctive peaks relating to the thermal decomposition of the different constituents of the biomass. The first peak



4.6 DTG analysis of wood in an inert environment (Chen and Kuo, 2010).

occurs around 50°C and is for the liberation of moisture from the sample. Located at approximately 300°C and 378°C are the peaks for hemicellulose and cellulose, which are almost merged for the sample shown. For a different sample of biomass, hemicellulose decomposed at 150–350°C and cellulose decomposed at 275–350°C (Chen and Kuo, 2010). The decomposition of lignin is characterized as a gradual decomposition, which occurs at 250–500°C (Chen and Kuo, 2011). Some sources report the decomposition of lignin to linger on up to 673°C (van Loo and Koppejan, 2006). Thus a distinctive peak for lignin cannot be identified in the figure. In addition, there are two unidentified peaks at 513°C and 686°C. These peaks were not observed for other samples tested in that investigation. Since the constituents of biomass, which has various compositions, decompose at different temperatures they should ideally be modelled using different rate expressions. However, in the majority of studies, a single rate or two competing rates for devolatilization are used. Charcoal burnout (not shown in the figure) occurs at 1000–1400°C, after which no further reactivity can be detected.

4.2.1 Emissions

Pollutant emissions and other waste products from combustion are of primary concern for power generation by means of biomass firing. There are often strict limits on the allowed discharge of emissions and extensive flue-gas cleaning has to be employed to meet government legislation. The ash often has value as a component of fertilizer or in the fabrication of cement. It is important for overall plant economy to consider either the sale of the ash or, if necessary, to pay for the ash to be put into a landfill. It is also important to consider the way the public views the plant in order to gain local support. Traditionally, large smoking stacks are viewed very negatively and are associated with poor air quality, smog, respiratory problems, etc. This, undeservedly, has given the direct combustion of biomass in large plants a bad reputation with the broad public compared to wind and solar power.

The primary pollutants from the burning of biomass are similar to those produced by burning fossil fuels. These include particulate matter (PM), the products of incomplete combustion (CO and hydrocarbons), oxides of nitrogen (NO_x) and oxides of sulphur (SO_x). Efficient technology, such as electrostatic precipitators and bag filters, can be used to reduce the number of fine particles in the flue gas to a minimum. Similarly, wet and dry scrubbers can be used to clean SO_x from flue gases. For fluidized-bed systems the addition of limestone or dolomite can be used to reduce the emission of SO_x gasses. The emission of gasses due to incomplete combustion can be reduced by proper management of the air-to-fuel ratio as well as the design of the furnace itself to ensure the temperature and residence time of the fuel particles necessary for complete combustion. Boiler design for the combustion of coal relies on decades of experience. The designs for new biomass boilers are naturally based on existing boilers, but there may be a different combustion pattern for biomass potentially leading to poor operating conditions and incomplete combustion. In particular, for suspension firing of biomass, changes in combustion patterns can be expected due to larger particle size, more extreme particle morphology and the different composition of the biomass fuel compared to coal or other fossil fuels. For example, due to the higher oxygen content in biomass compared to fossil fuels, the stoichiometric air-to-fuel ratio is typically 4–7 whereas it is 14–17 for coal. In general, the technology to reduce emissions of PM, SO_x and products of incomplete combustion effectively is readily available and not different for biomass fuels compared to the burning of fossil fuels.

Emissions of NO_x gasses are one of the greatest concerns for combustion systems no matter the source of the feedstock. NO_x is formed via different formation routes: fuel NO_x originates from fuel-bound nitrogen, thermal NO_x results from the high-temperature reaction between gaseous nitrogen and oxygen and prompt NO_x forms from a reaction between gaseous nitrogen and HC radicals. While SO_x emissions generally decrease in proportion to the sulphur present in the fuel, NO_x depends on both fuel and firing conditions. The investigation by Wu *et al.* (2007) into the formation of NO_x precursors in straw and coal co-firing suggested that biomass predominately forms NH_3 whereas coal predominately forms HCN as gas-phase compounds. In addition, biofuels often have less fuel-bound nitrogen, which acts to reduce NO_x emissions, as demonstrated in co-firing tests at Seward Generating Station (Battista *et al.*, 2000). However, it should be emphasized that the nitrogen content of fuel varies greatly from one type of biomass to another. Also many direct combustion systems for biomass have low flame temperatures, which imply that the fuel-bound nitrogen is the primary concern. Commercial low-NO_x systems employ a technique where the fuel-to-oxygen ratio is controlled to produce fuel-rich zones and low-temperature fuel-lean zones to reduce the formation of NO_x. Again, current knowledge is mostly based on experience with fossil fuels, but there is no reason not to utilize the same principle for biomass combustion.

For straws and grasses, which contain a large fraction of chlorine, it is important to consider acidic gasses such as HCl. In addition to being corrosive to the combustion system, they are also highly corrosive air pollutants. Generally, large fractions of chlorine and other halogens are also promoters of dioxins and furans. This is especially a concern at municipal waste disposal facilities (Brown, 2011).

It is important to consider the trace elements in the biomass feedstock in order to evaluate potential uses of the ash. The amount of trace elements in the fuel will depend on the plant species, the age of the plants and where the plants were grown. Unwanted and potentially harmful trace elements are heavy metals such as lead (Pb), cadmium (Cd), selenium (Se), zinc (Zn) and mercury (Hg), which can have a detrimental effect on plant growth (Kalac *et al.*, 2004). After combustion, heavy metals present in the fuel may have accumulated in the ash in such high concentrations that the ash has to be disposed of as hazardous waste (Thy and

Jenkins, 2010). Heavy metals are often present in urban and reuse-derived fuels (RDF). The best technique is to be selective in the fuel used and to exclude tainted feedstock (Brown, 2011). Methods to remove heavy metals from the ash have been used. These include absorption methods using activated carbon or other sorbents, post-precipitation and ion exchange (Kefala *et al.*, 1999). Generally bottom ash will have a greater content of heavy metals compared to fly ash. Similarly the ash from wood will have a greater amount of heavy metals compared to the ash from herbaceous feedstock. It has been suggested that ash residues from biomass combustion, including bottom ash and fly ash as well as the ash from different origins, may be mixed together and used as a fertilizer for agricultural use (Demirbas, 2005). Much of the ash may be used in this way providing that the concentration of toxic metals, especially cadmium, meet the limitations imposed by legislation.

The emission of the greenhouse gas CO_2 is of less concern for biomass since the short circulation time of CO_2 from the fuel being burned to it being reabsorbed by plants, means that biofuels are commonly considered to be CO_2 neutral. Advances in carbon capture and storage may in the future give rise to plants that actively reduce the CO_2 level in the atmosphere. Currently, the idea of biomass being CO_2 neutral is challenged by the fact that most wood fuel is derived from mature forests, which will take a long time to fully regrow thus making the power generation of biomass a net contributor of CO_2 until there is a balance between harvesting and regrowth. It should be noted that biomass, if left to rot, will release the CO_2 bound within it anyway. Often straw is burned in the fields to improve the crop yield. This means that weed and grass is burned away so light and air can reach new sprouts. The combustion of straw in large biomass plants can eliminate the pollution generated from field burning, due to the controlled combustion environment and extensive cleaning of flue gases, while generating heat and power for consumers.

4.3 Fouling prevention and control

Fouling is the depositing of ash particles and condensing gasses on the heating surfaces of a boiler. Slag is the deposition on the heating surfaces inside the boiler, exposed to predominantly radiant heat. The fouling of heating surfaces will diminish heat transfer rates and depending on the composition of the deposit, it can be the cause of significant corrosion of the heating surfaces. In extreme cases, if not removed severe slagging can build up to such proportions that it can damage the boiler if pieces break off and fall to the bottom of the boiler. Fouling is unwanted and is typically dealt with in traditional coal-fired power plants using soot blowers, which regularly cleanse the heating surfaces using water. For fluidized beds fouling is not a problem for the furnace wall heating surfaces due to the active abrasions from the bed material; however, fouling of convection passes still occurs. Due to the different chemical composition of biomass fuels compared to coal, the composition of the deposits and the rate of deposition for biomass combustion can be much more detrimental to the performance of the boiler compared to a coal-fired plant. Depending on the fuel, the tenacity and strength of the deposit may be higher and the porosity lower for biomass compared to coal. The surface will appear hard and may acquire additional effort to remove (Sami *et al.*, 2001). Possibly the rate of deposition is an even more serious problem. Baxter *et al.* (1998) reported that as little as 10% addition of straw to the fuel supply of a commercial power-plant boiler caused an unscheduled shutdown within hours of operation due to the accelerated build-up of deposits.

Wood and wood-derived fuels do not cause significant fouling problems, which accounts for their widespread popularity as a substitute fuel for coal. On the other hand, herbaceous fuels have high amounts of silica, alkali metals and chlorine, which cause deposition problems at moderate to high combustion temperatures. The main source of problems identified by Baxter *et al.* (1998) are:

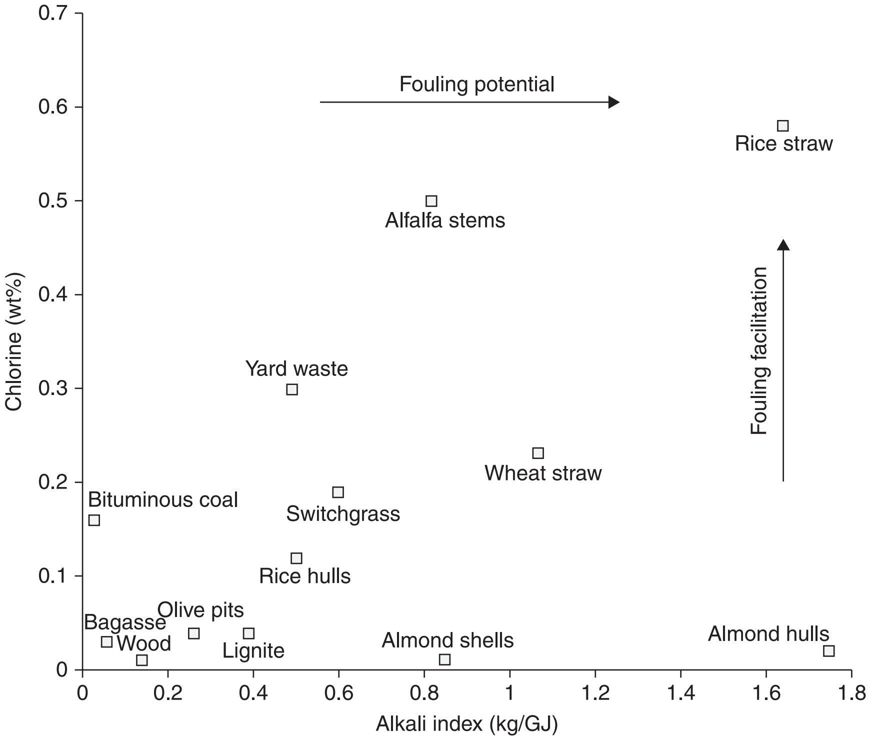
- The reaction of alkalis with silica to form alkali silicates, which melt at temperatures as low as 700°C.
- The reaction of alkalis with sulphur to form alkali sulphates on combustor surfaces.
- Chorine facilitates the transport of alkalis in the fuel to the heater surfaces, which considerably increases the deposition rate.

Chlorine salts are among the most stable alkali-containing gaseous species at high temperatures. Similarly the chorine concentration is a stronger indicator for the amount of alkalis released into the vapour phase compared to the alkali concentration itself (Jenkins *et al.*, 1998). Originally developed for coal, the alkali index is used as an indicator to predict the tendency of fouling and slagging. The alkali index is computed as:

$$Y_{\mathrm{ash}}(Y_{\mathrm{K_2O}} + Y_{\mathrm{Na_2O}})/\mathrm{HHV} \tag{4.3}$$

where Y_{ash}, $Y_{\mathrm{K_2O}}$ and $Y_{\mathrm{Na_2O}}$ are the mass fraction of, respectively, the ash, K_2O and Na_2O in the fuel, evaluated on a dry basis, and HHV is the higher heating value of the fuel. In Fig. 4.7 the chlorine content of different biomass feedstocks is plotted against their alkali index. It can be seen that straws and grasses both have a high content of chlorine as well as a high alkali index, which indicates significant fouling can be expected. Shells and husks have varying alkali index but all have a low chlorine content. Wood, along with sugar-cane bagasse and coal, has both a low alkali index as well as low amounts of chlorine.

The temperature of the heating surface and the gas phase species play an important role in the facilitation of fouling. The temperature of the gas phase determines the availability of the alkali-transporting species and the temperature of the heating surfaces influence the rate of condensation of these same species. Baxter *et al.* (1998) reported that at temperatures below 1000°C the only alkali-bearing



4.7 Fouling characteristics of different biomass feedstocks.

species present in significant quantities is chlorine whereas at temperatures above 1400°C the dominant alkali-bearing species are hydroxides. Typically, high temperatures only occur in the flame zones whereas temperatures below 1000°C are typical for convection passes. When the alkali-bearing species encounter colder heating surfaces they will condense on the surfaces causing fouling.

Soot blowers are used in power plants to control the fouling caused by the condensation of flue gasses on the superheater and convection zone tubes. For coal power, it is possible to use an empirical correlation such as the alkali index to predict the build-up of deposits on the tubes and so determine an appropriate cleaning cycle for the soot blowers. For biomass combustion, it is more difficult to predict the fouling tendency of a specific batch of fuel since it depends both on the type and source of the feedstock. For this reason, empirical correlations are more useful for biomass selection than for fouling control. Romeo and Gareta (2009) suggested using a control strategy with a fuzzy logic control strategy where the steam output is continuously monitored to evaluate the appropriate time for soot blowers to remove accumulated deposits.

4.3.1 Agglomeration and sintering

Agglomeration occurs when the fuel ash melts and sticks together, causing defluidization in fluidized-bed boilers and transport problems in grate-fired boilers. Agglomeration is caused by melting of potassium and phosphorous salts. Also, the presence of silica and calcium in the biomass will act as a promoter of agglomeration (Saidur *et al.*, 2011). In fluidized-bed boilers especially, agglomeration is a serious problem, which has to be dealt with to avoid downtime. In fluidized beds agglomerates appear as large aggregated composites of bed media and ash often bound by fused, glassy material arising from reactions between the bed material and elements of the fuel (Baxter *et al.*, 1998). Different strategies to eliminate the agglomeration problem are used, such as:

- using additives to prevent the formation of salts
- coating the sand particles to prevent reactions with silica
- using alternative bed material
- pre-treatment of the fuel.

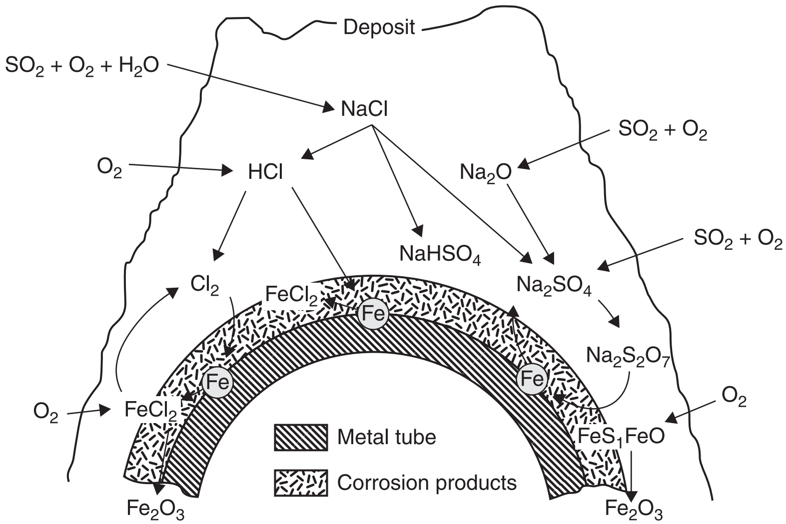
Typical additives to prevent agglomeration in fluidized beds include kaolin, dolomite, limestone and alumina (Llorente *et al.*, 2008). Alternative bed materials include dolomite, magnesite, ferric oxide, alumina, feldspar and various aluminium-rich minerals. However, new problems with these materials have emerged such as higher attrition and entrainment rates, chemical stability, windbox and air nozzle plugging, which make them less attractive compared to sand.

The removal of alkalis, chlorine and other elements are known to increase the fusion temperature of the ash. It has been shown for straw washed in water that it is possible to remove 80% of the alkalis and 90% of the chlorine present in the feedstock (Jenkins *et al.*, 1998).

4.4 Corrosion and additives

Problems with corrosion in large power plants are mainly caused by the build-up of corrosive species, such as metal chlorides, on the heating surfaces inside the boiler. Thus, in addition to acting as a barrier for heat transfer the fouling of the heating surfaces ultimately may lead to destruction of the boiler itself. The severity of corrosion will depend on the composition of the deposit, the material of the heating surface as well as the temperature of both. High-temperature corrosion of superheater tubes has not been experienced in biomass-fired plants due to the fact that the superheater temperature has been kept low (Nielsen, 2000). However, the trend is for higher superheater temperatures in order to improve overall plant efficiency. This may, in turn, lead to severe problems with corrosion as the severity of corrosion greatly intensifies as the temperature of the deposit increases to the melting point of the deposits. Biomass combustion, as has been shown previously, causes extensive fouling of heating surfaces. In particular, straws, grasses and other herbaceous plants contain high levels of alkalis, primarily potassium and chlorine, which when deposited on heating surfaces are potentially corrosive elements. Similarly, compared with deposits from coal combustion, deposits from biomass fuels are denser and more difficult to remove (Demirbas, 2005). The temperature of the deposit is also of great importance for the corrosion properties. If the temperature rises above the melting temperature of the chlorides the corrosion process may be greatly accelerated due to the mobility of the liquid phase. Corrosion of heating surfaces can also be caused by gaseous species. The presence of HCl or Cl_2 will accelerate the corrosion of alloys that are otherwise considered as corrosion resistant due to the breakdown of the surface oxide layer (Nielsen *et al.*, 2000). This is also referred to as active oxidation. Figure 4.8 gives a very illustrative image of the corrosion process for the alkali sodium. The process for other alkalis such as potassium should proceed in a similar manner.

Nielsen *et al.* (2000) thoroughly reviewed the current knowledge of the corrosion processes associated with alkaline chlorates. A more detailed discussion of this topic is beyond the scope of this text. In order to reduce the tendency for fouling and the corrosiveness of the deposits it is desirable to find appropriate additives or fuel mixtures to use with straw especially, and other herbaceous feedstock. Finding appropriate additives has been a hot topic in the past decade or so. An investigation by Jensen *et al.* (2005) tested the ability of phosphorus and calcium to reduce the chlorine content of the ash deposit resulting from the combustion of wood and straw. It was determined that a molar ratio of P/Ca of 0.8–0.9 was optimal and could lead to a large reduction of chlorine in the deposit.



4.8 Sequence of reactions in a deposit on a superheater tube. Reprinted from Nielsen *et al.* (2000).

Higher or lower P/Ca ratios were not as efficient and could even lead to increased deposits. The investigation by Aho and Silvennoinen (2004) suggested that an appropriate mixture of several difficult fuels, which individually would cause fouling when burned, could reduce the deposition of metal chlorides on heating surfaces. Different mixtures of pine bark, chicken litter and paper pulp sludge were investigated. It was found that the high content of aluminium in paper pulp sludge could decrease the concentration of chlorine in deposits due to the formation of aluminium silicate when burned in a mixture with pine bark or chicken litter. Tobiasen *et al.* (2007) tested different Al-Si- and P-Ca-type substances as additives. Testing was carried out in a full-scale 250 MWth straw-pellet-fired suspension-drum-type boiler in Denmark where in turn sand, dicalcium phosphate (DCP), chalk and bentonite were added to the straw. The results showed that chalk and DCP were unsuitable as additives. Sand and bentonite showed more promise but bentonite was deemed to be too expensive for commercial use. Davidsson *et al.* (2008) tested a number of additives in fluidized-bed boilers to prevent both fouling and agglomeration. The additives were elemental sulphur, ammonium sulphate and kaolin, which were added to a bed of silica sand, as well as using olivine sand and blast-furnace sand as alternative bed material. It was found that the addition of kaolin and using slag as a bed material were useful in preventing bed agglomeration. The addition of kaolin, ammonium sulphate and elemental sulphur was effective in reducing fouling. Although kaolin is effective for both purposes, the cost makes the use of ammonium sulphate the best candidate of the tested additives. Mroczek *et al.* (2011) investigated the use of halloysite, which is a clay mineral belonging to the kaolin group. This again proved the effectiveness of kaolin in reducing fouling of heating surfaces.

Nordgren *et al.* (in press) investigated the effects of different wood/straw fuel blends. It was determined that the observed reduction of fouling, compared to burning pure straw, was due to the dilution of the fouling elements in the straw. Tests using mixtures of bark and straw showed some additional reduction in fouling, which was interpreted to be due to the interaction of the fuel elements. Kassman *et al.* (2011) performed tests using straw/peat blends and reported that the chlorine content in the deposits was greatly reduced although the concentration of the gaseous species KCl was not reduced. Tests using fuel blends are thus somewhat inconclusive and a conservative approach would be to only assume that they have a diluting effect on the fouling properties of herbaceous feedstock.

4.5 Technology-specific issues

Three technologies are utilized for the large-scale combustion of biomass: suspension firing of pulverized biomass, combustion using different types of fluidized beds and the burning of biomass on vibrating or moving grates. All three technologies have advantages and drawbacks concerning their use with biomass, and can be seen as supplementary technologies rather than competitive technologies. Grate-fired boilers are characterized by being able to burn almost any type of solid fuel regardless of its condition, but have lower efficiency compared to suspension firing. On the other hand, suspension firing requires high-quality dried and pulverized solid fuels to work but performs best of all the technologies used for the burning of biomass (Evald and Witt, 2006). Biomass fuel used for suspension firing basically uses the same technology as for firing with coal, which is a well-proven concept. This technology includes pulverization in grinding mills, pneumatic transport in pipe systems and the use of intricate swirling patterns inside the burner for optimal combustion. The flow pattern in the burner and inside the boiler has to be engineered in such a way that no unburnt particles escape through the top of the boiler or are deposited in the ash hopper. Fluidized beds appear to be somewhere in-between grate-firing and suspension firing. They have relatively high efficiencies but are also flexible with regards to fuel. One advantage of fluidized-bed systems is that they form less thermal NO_x compared to other firing techniques (van den Broek *et al.*, 1996). A disadvantage of this technology is the high energy cost for the air supply as well as the high wear and tear of the boiler surfaces due to bed attrition. The choice of which firing technique to employ ultimately depends on the feedstock intended to be combusted. If a high-quality fuel such as pelletized or torrefied wood is available, suspension firing is the best choice. For a poor-quality fuel, for example garbage or high-moisture fuels, fluidized beds are the best choice, whereas for difficult fuels whose chemical composition makes them unsuited for fluidized beds, grate firing provides an alternative.

4.5.1 Suspension firing

Suspension firing or pulverized-fuel combustion uses pulverized fuel, which is transported pneumatically and blown into the boiler together with the primary air. For the combustion of coal, the suspension-fired technology is the preferred method due to the high overall plant efficiency and the ability to make quick load changes. The fuel has to be in the form of a fine powder, which burns similarly to gas. The combustion zone can be distributed over a greater volume of the boiler instead of being restricted to a small zone close to the bottom. Burners can be placed in a box formation or in a tangential formation to create an intricate swirling combustion pattern. In the combustion of biomass it is important additionally to factor in the different chemical composition and particle size and shape compared to that of coal when designing new suspension-fired boilers. The crystalline structure of coal makes it very easy to fracture and thereby to grind into a fine powder. The typical average size of coal powder is around 65 μm. Wood and other types of biomass feedstock have a fibrous structure, which means that they do not fracture when pressure is applied and they have to be pulled apart using a not insignificant amount of energy in the milling process. The average size of biomass particles will depend on the milling effort as well as the feedstock. It is not uncommon to see average sizes around 200–300 μm (Mandø *et al.*, 2010). Similarly due to the fibrous structure, biomass particles tend to have very different particle morphology compared to coal particles. Coal particles are nearly spherical, wood particles are typically rectangular and splinter-like whereas straw particles are flattened and flake-like. It is interesting to note that torrefied biomass has been reported to have similar grinding properties as coal, and the milling of torrefied wood results in a much finer powder compared to pelletized wood. In suspension firing, prediction of the flame zones is greatly dependent upon the size and shape of the fuel particles that are to be combusted. When predicting the combustion zones inside boilers, it is typically assumed that a particle is a perfect sphere and isothermal. The much larger size and the distinctive non-spherical shape will generally make such assumptions invalid. Internal temperature gradients inside the particle will cause a longer burnout time for the particle as well as allowing it to sustain several combustion stages (drying, devolatilization and charcoal burnout at the same time); thus, spreading the release of the combustion gasses over the entire residence time of the particle. Particle morphology can cause aerodynamic lift forces to act on particles leading to different particle flow patterns (Yin *et al.*, 2003). The difference in chemical composition, especially the much larger fraction of volatiles in biomass compared to coal, leads to a change in the burning rates and the combustion patterns in general. Some biomass feedstock contains a high fraction of chlorine, which is known to retard flame propagation by terminating free-radical chemical reactions. This greatly complicates predictions of the combustion process and flame zones inside the boiler, which are needed to design a furnace. The difference between pulverized coal and biomass flames has been shown previously from firing in laboratory-scale test furnaces. Ballester *et al.* (2005) compared the flames produced by bituminous coal, lignite and wood, under similar operating conditions and found that wood flames display two distinct combustion zones: an intense combustion zone of volatiles released from small particles close to the burner and a second, further downstream, attributed to devolatilization of larger particles and char burnout. Furthermore, the wood flame is significantly longer and has more unburnt hydrocarbons due to the lower temperatures downstream in the furnace. The study by Damstedt *et al.* (2007) considered 50 wt% straw and coal co-firing and showed that large particles penetrate the internal recirculation zones and elongate the flame structure by forming a secondary combustion zone downstream of the burner. Lokare *et al.* (2005) measured the ash deposition rates from different solid biomass fuels and showed that it varied significantly depending on the type of biomass. Bharadwaj *et al.* (2004) and Lu *et al.* (2008) looked at the devolatilization of large non-spherical biomass particles and demonstrated the insufficiency of modelling such particles as spheres. Similarly, a number of numerical investigations have also been undertaken. Elfasakhany and Bai (2006) looked at several sub-models for wood combustion. They found that the flame temperature and major species are less sensitive to the devolatilization mechanisms while predictions of unburnt hydrocarbons and CO are very dependent on the devolatilization sub-model. Many additional biomass combustion and co-firing issues are thoroughly covered in the reviews by Williams *et al.* (2001), Nussbaumer (2003), Demirbas (2004) and Cui and Grace (2006).

4.5.2 Grate firing

In a grate-fired plant the fuel is transported along a moving or vibrating grate and is combusted before it reaches the end. Primary air is supplied from below the grate creating an intense combustion zone directly above the bed. The ash left over from combustion is transported to an ash pit at the end of the grate and removed. The advantage of the grate-firing technique is its versatility with regard to the fuel. Thus grate-fired plants are often used to incinerate municipal waste, which is a very difficult and inhomogeneous fuel. Depending on the heating value and the moisture content of the fuel, grates can be either water cooled or cooled by the primary air flowing through them. The grate-firing technique is highly attractive for biomass combustion due to its simplicity. The grate-firing technique has only a few problems with ash sintering, since lumps are either simply transported to the ash pit or broken up by the movement and vibration of the grate. Disadvantages of the grate-firing technique are mainly poorer plant economy and the increased amount of fly ash due to the vibration of the grate. Additional information about the current state of the art for the grate-firing technique for biomass combustion can be found in the review by Yin *et al.* (2008).

4.5.3 Fluidized-bed firing

In fluidized-bed boilers a bed, usually consisting of sand particles, is brought into a fluidized state by primary air supplied from below the bed. Solid fuel added to the bed will burn in the oxygen-rich conditions inside the bed created by the primary air. There are two types of fluidized beds: in bubbling fluidized beds the bed particles are kept in suspension at relatively low fluidization velocities whereas in circulating fluidized beds, particles are carried out of the bed at higher fluidization velocities and are separated in a cyclone and reintroduced back into the bed. Due to the bed material inside the boiler, fluidized-bed boilers have high heat transfer coefficients, utilize the entire boiler volume, have a uniform temperature distribution and have a low stable combustion temperature. Fluidized beds are capable of burning very wet fuels and fuel particles of sizes up to 80 mm (van Loo and Koppejan, 2006). Thus very little pre-treatment of the fuel is necessary. The disadvantages of fluidized beds are the high erosion rate of surfaces in contact with the bed material, higher dustload due to the entrainment of particles and agglomeration problems for certain fuels. In particular, the agglomeration problem is of concern since it can lead to unscheduled shutdowns of the plant. Chunjiang *et al.* (2011) investigated the effect of different firing parameters in a laboratory-scale bubbling-fluidized-bed facility using straw as fuel. The results indicated that the size and shape of the bed material can affect agglomeration and smaller bed particles seem to be more prone to defluidization. Similarly the critical parameters affecting agglomeration are the bed temperature and particle residence time. By optimizing the parameters, it was found that it was possible to combust straw in a fluidized-bed boiler at a low bed temperature of 650°C. A similar conclusion was also found by Bolhar-Nordenkampf *et al.* (2006). Additional information about the current state of the art of fluidized-bed firing for biomass combustion is covered in the review article by Khan *et al.* (2009).

4.6 Conclusion

The motivation for using biomass in the energy supply is that biomass is considered CO_2 neutral, it saves foreign currency, it creates domestic jobs and it utilizes waste products from agriculture, forestry, households, trade and industry. If biomass is left on the ground it will break down over a long period of time, releasing its CO_2 and energy slowly. If burned, its store of energy can be used to produce electricity and heat. When considering the shift from fossil fuels to biomass for a large plant, it is important to consider the whole supply chain of the biomass feedstock as well as additional demands for storage, fuel preparation, etc. Wood stands out as a very attractive fuel due to the very low amounts of chlorine and alkaline elements. Wood can be used as a substitute for coal in large power plants. For a herbaceous biomass feedstock, it is important to consider the fouling and sintering properties of the fuel. The plant economy is poorer because of the higher maintenance costs, the larger fuel flow necessary due to the lower heating value and the price of additives needed for reducing fouling and sintering associated with the burning of the biofuel. There are several well-developed systems for biomass combustion. These technologies should be seen as complementary rather than competitive as each is suited to a specific type of biomass.

4.7 References

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5

Biomass co-firing

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Abstract: Co-firing biomass with fossil fuels in existing power plants is an attractive option for significantly increasing renewable energy resource utilization and reducing CO_2 emissions. This chapter mainly discusses three direct co-firing technologies: pulverized-fuel (PF) boilers, fluidized-bed combustion (FBC) systems, and grate-firing systems, which are employed in about 50%, 40%, and 10% of all the co-firing plants, respectively. Their basic principles, process technologies, advantages, and limitations are presented, followed by a brief comparison of these technologies when applied to biomass co-firing. This chapter also briefly introduces indirect co-firing and parallel co-firing and their application status.

Key words: biomass co-firing, pulverized-fuel combustion, fluidized-bed combustion, grate-firing, carbon dioxide reduction.

5.1 Introduction

The worldwide concerns with global warming, because of the emission of CO_2 and other greenhouse gases, and the limited availability of fossil fuels, has spurred interest in using biomass for energy production. Co-firing biomass with fossil fuels (mainly different types of coal) in existing power plants is an attractive option for achieving the pressing near-term targets for significantly increasing the share of renewable energy sources used in energy systems and to reduce CO_2 emissions. Over the past decade, remarkably rapid progress in co-firing has been made worldwide. According to the co-firing database compiled by IEA Bioenergy Task 32 (IEA, 2011), co-firing demonstrations have been performed in about 200 power plants globally so far. These demonstrations have provided a wealth of information, which spans a range of major coal combustion technologies, important fuel types, and co-firing types and levels, as can be seen in Table 5.1.

The global commercial-scale studies and demonstrations show that co-firing different types of biomass at various co-firing levels using different main combustion technologies is feasible. All of the potential problems appear manageable with judicious consideration of fuels, design of burners and boilers, and operating conditions (Baxter, 2005; Hansson *et al.*, 2009; Robinson *et al.*, 2003). Most of the existing commercial studies of biomass co-firing mainly focus on fuel transportation, preparation, and feeding. However, fundamental combustion studies must be performed to determine combustion behavior characteristics in controlled laboratory settings and to aid in the design and optimization of co-firing processes.

Table 5.1 Summary of co-firing experience/plants worldwide

Key items	Contents
Number of plants	About 200 worldwide
Plant capacity	5–4000 MW_e, with the majority in the range 50–700 MW_e
Fuel	All types of commercially significant fuel, e.g., lignite, bituminous coal, and petroleum coke
Biomass	All major categories of biomass, e.g., herbaceous and woody fuel, agricultural residues, energy crops, peat, and sewage sludge
Combustion technology	About 48% equipped with pulverized-fuel (PF) boilers, 24% with bubbling fluidized-bed (BFB) boilers, 19% with circulating fluidized-bed (CFB) boilers, and 9% with grate-fired boilers
Co-firing concept	Direct co-firing in 95.4% of plants; indirect co-firing with pre-gasification or pre-pyrolysis: 3.6%; parallel co-firing: about 1%
Co-firing level	Up to 100%. The majority co-fire 1–40% biomass on an energy basis

This chapter provides an overview of the research, development, and demonstration (R&D&D) status of different co-firing technologies and concepts: the basic principles, main processes, key operational and environmental issues, challenges, and technical breakthroughs, and further R&D needs. Based on the percentages in Table 5.1, the popular technologies are introduced and compared: direct biomass co-firing, pulverized-fuel (PF), fluidized-bed combustion (FBC), and grate-firing. Indirect biomass co-firing and parallel co-firing are then introduced. In the conclusion, the constraints for the successful replication of the demonstrated technologies for biomass co-firing are mentioned.

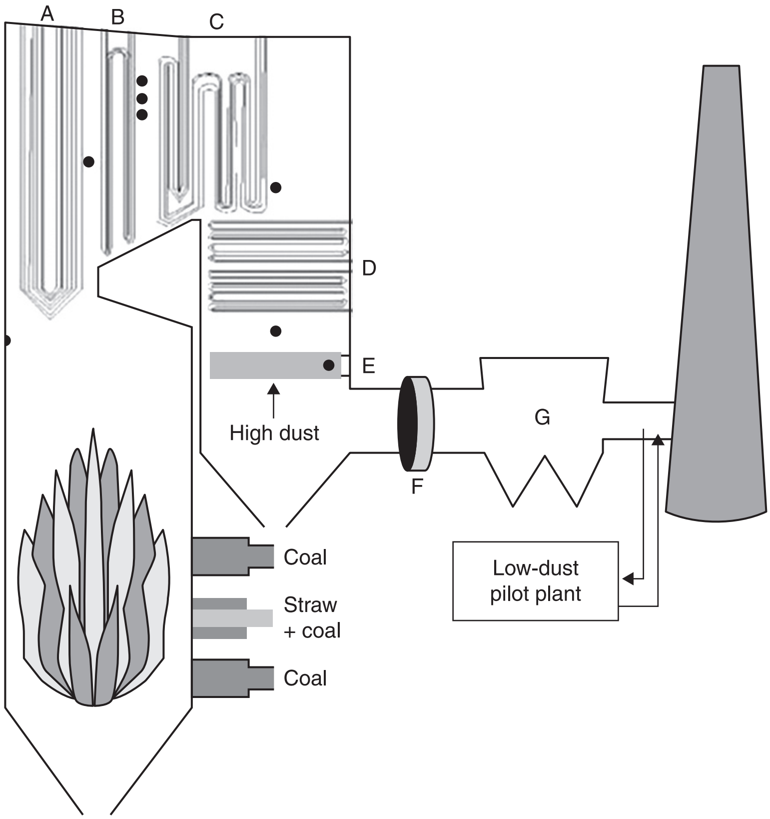
5.2 Direct co-firing technologies

5.2.1 Pulverized-fuel combustion

In a conventional pulverized-coal (PC) boiler, coal is pulverized into fine particles (70 wt% smaller than 75 μm): the majority of coal particles are between 10 μm and 150 μm with an average around 60 μm. The coal particles are nearly spherical, having an aspect ratio of 1 to 2. Primary air, typically at 55°C to 95°C, pneumatically conveys PC via a fuel distribution pipework (large pipes split into smaller ones through bifurcators or trifurcators) to the burners, which are located in the lower portion of the furnace. The concentration of particles in the fuel pipes is diluted, with a typical volumetric concentration of 0.01% to 0.1% (Yan and Stewart, 2001). The rate of coal feeding is set by the combustion controls based on the requirements for steam generation. Most of the secondary air, typically pre-heated to about 315°C, is supplied to the wind-boxes enclosing the burners. In order to control NO_x emissions and complete combustion, another portion of the secondary air may be diverted from the burners and introduced to the upper portion of the furnace as over-fire air. The secondary air supplied to the burners is mixed with coal particles in the throat of the burner. During mixing and interacting with the gas in suspension, the coal particles heat up, devolatilize and undergo char oxidation, creating sources for reactions in the gas phase. This process is termed ignition and burning. As the gases and unburned fuel move away from the burner and into the upper portion of the furnace, the combustion process continues. Final burnout of the gases and char depends on the coal properties, coal particle fineness, overall excess air and air distribution, fuel–air mixing, and the furnace thermal environment. The heat released during combustion is transferred to water tubes in the combustion chamber walls. The generated high-pressure and high-temperature steam is fed into the turbine/generator to produce electricity. The products of combustion, i.e., hot flue gas laden with ash particles, eventually leave the furnace and enter the convection pass. After being sufficiently cooled down and treated by gas-cleaning systems, the combustion products are finally emitted into the atmosphere.

Because of their high efficiency, PC-fired boilers are the most widely used utility boilers today. For instance, across the European Union there are more than 450 large power plants equipped with PC-fired boilers. As a result, co-firing biomass in existing PC-fired power plants will lead to a significant increase in the share of renewable energy sources in energy systems and a reduction in CO_2 emissions.

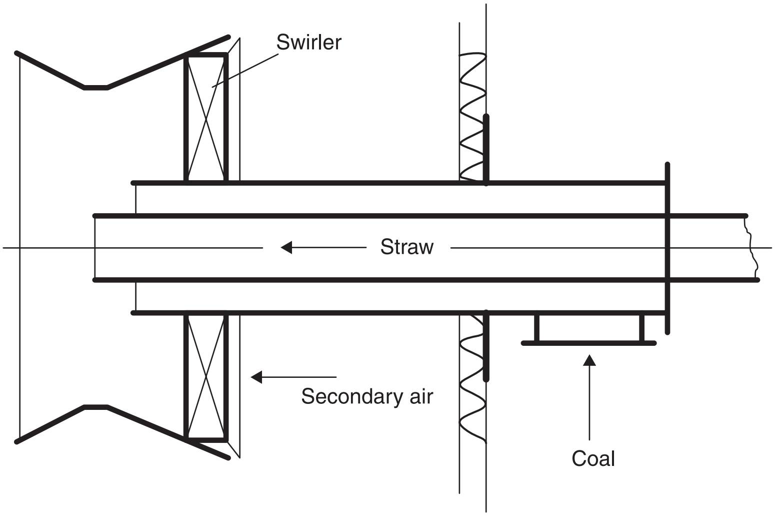
One of the first full-scale tests of co-firing biomass in a utility PF boiler in the world is introduced, as an example of co-firing. The Danish utility company Elsam converted a 150 MW_e PC-fired utility boiler (Studstrup Unit 1) for straw/coal co-firing, and conducted a unique two-year (from January 1996 to February 1998) demonstration program co-firing up to 20% straw on an energy basis (Andersen *et al.*, 2000; Hansen *et al.*, 1998; Wieck-Hansen *et al.*, 2000). As shown in Fig. 5.1, the boiler, which has been operating since 1968, is a two-pass wall-fired boiler. The boiler is equipped with 12 conventional axial swirl burners, located at three heights. There are four burners at each of the three levels. The four burners at the medium-level were converted into co-firing burners. Modification of the burners involved a few changes, as depicted in Fig. 5.2; the oil lance and flame watch were relocated in order to clear the center pipe of the burner for pneumatic straw feeding. A new straw handling system was built, as sketched in Fig. 5.3. The demonstration showed that huge amounts of straw can be handled properly. After the two-year test, it was concluded that the full-scale co-firing demonstration had been a success. Co-firing biomass in utility PF boilers was viable, at least for up to 20% straw on an energy basis. Such co-firing did not cause any serious problems and boiler performance was only marginally affected. Corrosion increased slightly, but not more than if low-to-medium corrosive coals



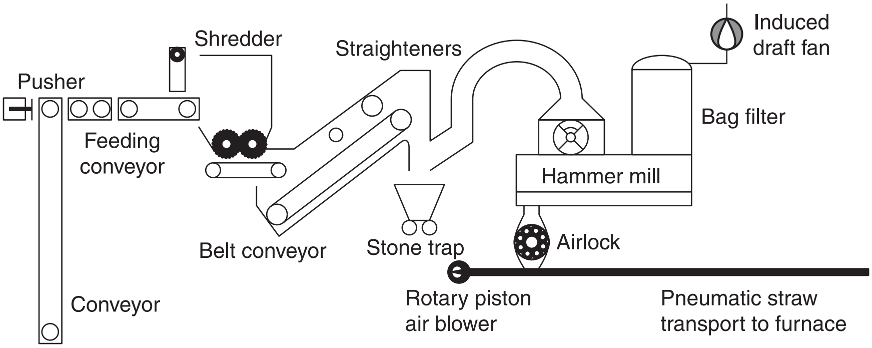
5.1 Schematic view of the straw/coal co-fired boiler at Studstrup power station (adapted from Wieck-Hansen *et al.*, 2000). A: platen superheaters (SHs) – first and second passes; B: secondary SH; C: re-heater; D: primary SH – upper and lower banks; E: economizer; F: air pre-heater; G: electrostatic precipitator (ESP).

had been used. Fouling was not critical but slagging increased with increasing straw share. Emissions were not much affected, other than there was an increase in HCl and a decrease in SO_2. The applicability of the ash residues was reduced and new methods must be developed. For instance, the fly ash from co-firing could be used for cement, but its use for concrete is restricted mainly because of the higher fraction of unburned carbon in the ash. Selective catalytic reduction (SCR) installations for NO_x control must be carefully placed depending on the type of fuel and the total economy.

Compared with FBC and grate firing, PF combustion systems have a higher requirement for consistent fuel quality, which could be one of the main practical problems when biomass is co-fired. Biomass fuels come from a large number of different sources in a wide variety of forms. They generally have a higher moisture



5.2 The straw/coal co-fired burner at Studstrup power station (Wieck-Hansen *et al.*, 2000).



5.3 Straw line at Studstrup power station (Wieck-Hansen *et al.*, 2000).

content, higher volatile matter content and higher oxygen content than coal. Moreover, raw biomass particles are often fibrous and non-friable. Therefore, it is not economical to attempt to pulverize biomass to the same size as coal particles. Pulverized biomass particles used in suspension co-firing are often much larger in size and more irregular in shape than pulverized coal particles. Because of these differences, co-firing biomass in PF boilers is significantly different from firing coal alone and has a significant effect on combustion and emission characteristics. Commercial-scale studies of co-firing biomass in PF boilers mainly focus on overall process and performance (e.g., fuel preparation and feeding, emissions and deposition), somewhat as the above co-firing example demonstrates.

Fundamental research into fuel particle motion in feeding lines, ignition and flame characteristics in the near burner zones is still severely limited. The following sections give a state-of-the-art overview of the key issues and R&D activities, as well as further research needs for improving biomass co-firing in PF boilers. These issues will be introduced sequentially, along the pathway of fuel particles.

Effect of fuel particle size and shape and on-line particle sizing

As mentioned above, pulverized biomass particles are very different from coal particles in many aspects including their size and shape distribution. The preparation and resulting size distribution of wheat straw for suspension co-firing in a utility boiler at Studstrup power plant in Denmark (Rosendahl *et al.*, 2007) is used as an example to illustrate this issue. Raw straw is delivered to the power plant in bales, each of which weighs 500 kg. The straw bales are processed in the system as sketched in Fig. 5.3. They are automatically shredded to give a continuous flow of straw into the system. The straw passes through the hammer mill, where it is crushed and fragmented by the rotation of the hammers on the rotor. The spacing between the hammers and the outer casing determines the maximum size of the fuel particles. A sample of 1.2 kg, considered as representative of the straw after preparation for injection into a PF flame, was collected for particle size and shape analysis. For highly irregular biomass particles, neither traditional sieving nor a Malvern Mastersizer (using laser diffraction) can produce the actual, representative size distribution of the particles (Carter and Yan, 2007). Therefore, the 1.2 kg sample was analyzed manually: sorting the individual particles piece by piece, measuring their dimensions (e.g., length and diameter), grouping them, and finally weighing each group. The measured aspect ratio is almost linearly proportional to the particle length and could be up to 30–40 for long particles. From the measured results, as detailed in Yin *et al.* (2004) and Rosendahl *et al.* (2007), the following Rosin–Rammler size distribution was derived:

$$Y_l = e^{-(l/\bar{L})^n} \qquad [5.1]$$

where Y_l represents the mass fraction of straw particles of length greater than l, $\bar{L}$ is the mean length and n is the spread parameter. Size distribution parameters are given in Table 5.2.

In most current retrofits for co-firing biomass in PF boilers, the biomass is first pelletized and then the biomass pellets (instead of raw biomass) are transported to the power plants, as in, e.g., the Amager Unit 1 in Denmark. The biomass pellets are separately ground in traditional coal mills and pneumatically transported to the burners. Even though this process results in somewhat smaller biomass particles than the previous process, it still produces large, non-spherical particles, which need special consideration during retrofitting and in optimizing the original PF burners for co-firing (Mandø *et al.*, 2010). The very different physical

Table 5.2 Size distribution parameters for straw particles prepared for suspension co-firing

Particle type	Description	Measured length and mass fraction			$\bar{L}$ (mm)	*n*
		Min. (mm)	Max. (mm)	%wt		
Nodes	Solid pieces	6	180	10.9	46.0	1.843
Heads	Whisk-like, hollow	6	140	4.2	37.5	1.397
Straw pieces	Hollow, near cylindrical	0.3	60	84.9	16.0	1.272

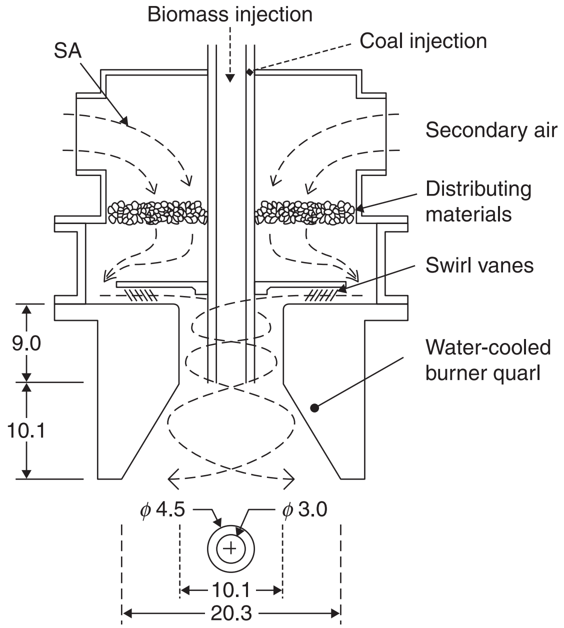
properties (e.g., density, size, and shape) of biomass particles greatly affect particle dynamics, heat and mass transfer to the particles, and their conversion in co-firing furnaces.

Particles travel in the fuel pipework at a speed typically in the range 15–25 m/s though the speed can be as high as 40 m/s (Yan and Stewart, 2001). Recent observations of a single irregularly shaped particle under laboratory conditions indicated that the particle can spin at around 65 000 RPM (revolutions per minute) (Roberts *et al.*, 2007). Despite various advances in flow visualization and characterization, very little is known about the dynamic nature of biomass/coal particles in a suspension. An advanced model has been developed to track large, highly non-spherical, relatively light particles in two-phase flows, which has been partly validated by experiments (Yin *et al.*, 2003). In the model, almost all of the important forces are retained in the equation of motion of the particles. Since some of the forces are dependent on particle orientation, the equations of rotation are also solved simultaneously to give the evolution of particle orientation and spin, and coupled with translation motion. The model was then implemented in a numerical simulation of biomass suspension co-firing (Yin *et al.*, 2004). The results very clearly show the remarkable difference in the fates of large, non-spherical biomass particles and equi-volume spherical particles, and also demonstrate the importance of accounting for particle non-sphericity in biomass suspension co-firing. If a model does not accurately predict particle motion, it is less likely to predict particle combustion reliably. Moreover, if particle conversion has not been predicted correctly and the resulting furnace design is poor, the aerodynamic forces on a particle may not be sufficient to sustain the weight of a large particle and thus the fate of the particle could be totally changed: falling into the bottom ash hopper instead of exiting the boiler as fly ash. Based on the simulation results, suggestions for how to better fire large biomass particles in PF boilers are given. For instance, the level of the co-firing burner could be optimized. If biomass particles are fed into the furnace through the lowest burners, large biomass particles may fall directly into the ash hopper resulting in a high unburned loss. If the biomass feed to the burners is switched to the higher levels, the down-falling, unburned large biomass particles may be combusted by the coal burners at lower levels. The upward gas flow from the coal burners at lower levels may also alter the direction of the down-falling large biomass particles because of the mass loss during biomass particle conversion, which effectively increases the residence time of large biomass particles in the furnace. However, this type of optimization is very dependent on particle size and reactivity.

The above suggestions have been somewhat verified by recent studies. For instance, the burnout of pulverized wood particles in a large PF boiler was studied, with a particular focus on the effect of the level of the co-firing burner ($z = 12$, 17, and 22 m) and wood particle size ($d_p = 0.5$, 1, 1.5, 1.75, 2, 2.5, 2.6, 2.75, 3, and 4 mm) on the burnout (Saastamoinen *et al.*, 2010). It was found that firing wood particles at the lowest burner level ($z = 12$ m) produced no unburned particles in the fly ash whereas the number of particles hitting the bottom before reacting was high. Burning from the second burner level ($z = 17$ m) also resulted in complete combustion at the top and there were fewer particles reaching the bottom. Particles larger than about 2 mm reached the bottom. Firing at the third level ($z = 22$ m) produced partially burned particles at the top of the furnace; large particles can achieve a higher burnout than smaller ones in some cases because of the longer residence time. Large particles fall downward against the gas flow. After drying and partial devolatilization, the particles become lighter and follow the upward gas flow better. For all three firing levels, particles larger than 4 mm will fall to the bottom ash hopper without burning.

The complex aerodynamics of large, non-spherical biomass particles in a suspension will be further complicated if the biomass and coal particles are pre-mixed and then transported in pipelines to the burners, as implemented in Amager Unit 1 in Denmark (Mandø *et al.*, 2010). In this scenario, there are more uncertainties. For instance, is the biomass/coal flow a homogeneous mix or do the biomass and coal separate out as they travel along the curved pipe, particularly after a bifurcator or trifurcator? How does the moisture content in the biomass affect fuel blending and delivery?

Besides these particle dynamics issues, the very different size and shape characteristics of biomass particles also greatly affect the pattern of particle conversion. When biomass particles are large enough for the Biot number to be greater than 0.1, the intra-particle heat and mass transfer will play an important role in fuel particle conversion. Straw/coal co-firing in a 150 kW swirl-stabilized dual-feed burner flow reactor was studied recently, both experimentally (Damstedt, 2007; Damstedt *et al.*, 2007) and numerically (Yin *et al.*, 2010, 2012a). The dual-feed swirl burner is shown schematically in Fig. 5.4. The design resembles the industrial co-firing PF burners used at Studstrup station in Denmark, as sketched in Fig. 5.2. The pulverized straw particles and coal particles are independently fed into the burner through two concentric injection tubes (i.e., the center and annular tubes). To study the effect of intra-particle heat and mass transfer on the conversion



5.4 Dual-feed swirl burner cross section (Yin *et al.*, 2010). SA, secondary air. Dimensions in cm.

of large biomass particles, a one-dimensional particle conversion model was developed and implemented for computational fluid dynamics (CFD) simulations of the 150 kW burner flow reactor. A large biomass particle is discretized into a number of shells (i.e., control volumes). For each control volume, the mass, energy, and species balance equations for the gas and solid phases were solved, and the relevant process rate equations and empirical correlations were used in the closure of the balance equations. It was found that for pulverized biomass particles of a few hundred microns in diameter, the intra-particle heat and mass transfer is a secondary issue at most during conversion, and the global four-step mechanism proposed by Jones and Lindstedt (1988) may be better for modeling the combustion of volatiles. The straw particles were found to be hardly affected by the swirling secondary air jet due to the large fuel/air jet momentum and large particle response time, and they traveled in a nearly straight line and penetrated through the oxygen-lean core zone. The coal particles were significantly affected by the secondary air jet and swirled into the oxygen-rich outer radius with increased residence time. Therefore, a remarkable difference in the fate and overall burnout of the two fuels was found.

In short, the physical properties of biomass particles are very important for the overall performance of a PF co-firing furnace. Biomass particles can be much larger than coal particles and still achieve complete burnout, because of their lower density, higher content of volatiles, and greater reactivity. However, to control and improve biomass co-firing in PF furnaces, it is crucial to know the detailed properties and reactivity of biomass particles and to understand the fundamental particle dynamics and conversion issues. Only in this way, will it be possible to optimize the co-firing configurations and operation conditions. If the fuel being fired can be accurately measured and identified on an on-line continuous basis using advanced imaging technology (e.g., size, shape, moisture, and share of different coal/biomass particles), the co-firing process can be better controlled and further optimized by adjusting the boiler settings to those best suited to the fuel type or blend.

Biomass/coal suspension co-firing characteristics in near-burner zones

Of the different co-firing technologies and configurations, the integration of biomass firing systems into wall-fired boilers could be the most challenging due to the many different burner designs on the market (Laux *et al.*, 2002; Yin *et al.*, 2004). Despite some quite successful demonstrations of co-firing biomass in PC burners and boilers, the literature on the fundamental characteristics of biomass/coal co-firing flames in near-burner zones in controlled laboratory settings is still very limited. Some of the key studies from the literature are discussed here. Experimental and numerical results of bituminous coal and pine sawdust co-combustion in a well-controlled, 0.5 MW down-fired dual-fuel burner reactor have been reported, in which one fuel stream was through the central orifice and the other was in a surrounding annulus. For the pine sawdust/coal flames, the co-firing ratio and fuel injection mode were found to have a significant effect on flame ignition, combustion aerodynamics, and NO_x emissions (Abbas *et al.*, 1994). Experiments on coal co-firing with straw, miscanthus, beechwood, and sewage sludge were performed in a dual-fuel burner, into which two different fuels can be introduced separately through a central orifice and a surrounding annulus, or pre-blended. It was found that burner design and operation mode had a great influence on the NO_x emissions of the co-firing flames (Spliethoff and Hein, 1998). Design considerations for co-firing biomass in wall-fired pulverized-coal boilers were derived using CFD simulations, which concluded that significant differences in volatility, reactivity, and ash characteristics between the biomass and coal must be considered when a biofuel firing system is to be integrated into an existing low NO_x firing system (Laux *et al.*, 2002). A CFD modeling study examined the co-firing of pulverized coal and biomass with particular regard to the burnout of the larger diameter biomass particles. It was concluded that the combustion of small (200 μm) wood particles was rapid whilst the rate of combustion of larger particles was dependent on their composition, size, and shape (Backreedy *et al.*, 2005). Comprehensive experimental studies of coal, biomass, and co-firing flames in a burner flow reactor were carried out to investigate the effect of biomass co-firing on flame structure and emissions

(Damstedt, 2007; Damstedt *et al.*, 2007). The effect of co-firing coal and biomass on flame characteristics and stability was studied experimentally, using vision-based measurement techniques. The biomass additions were found to affect the characteristics of the flame, particularly the flame ignition points and brightness. However, flame stability was little affected providing the addition of biomass was no more than 20% by weight (Lu *et al.*, 2008; Molcan *et al.*, 2009).

Deposition, corrosion and environmental effects in downstream processes

There has been considerable research into the release of potassium, chlorine, and sulfur and the resulting deposition and corrosion during biomass co-firing (e.g., Aho and Ferrer, 2005; Frandsen, 2005; Jöller *et al.*, 2005; Miltner *et al.*, 2006; Müller *et al.*, 2006). Chlorine is a major factor in ash formation. Chlorine facilitates the mobility of many inorganic compounds, in particular potassium. The ash deposition rate for biomass can greatly exceed or be considerably less than that from coal. The deposition rates from co-firing biomass and coal lie between the observed rates for the individual fuels but are generally lower than one would expect if interpolating from the behavior of the individual fuels (Demirbas, 2005). After a decade of working on the deposition and corrosion problems associated with biomass co-firing, Frandsen (2005) concluded that deposition and corrosion will most likely not be major problems during coal/straw co-firing in PF boilers provided that a high quality coal is used. Instead, fly ash quality and the poisoning of SCR catalysts for NO_x reduction may be more important and limiting factors. For the latter, it was found that the deposition of submicrometer-sized particles on the monolithic SCR catalyst is the main reason for the deactivation of the catalyst (Larsson *et al.*, 2006).

Biomass/coal co-firing is expected to reduce air pollution due to emissions substantially (e.g., CO_2, SO_x, and NO_x) compared to not co-firing (Mann and Spath, 2001). However, there are new problems, which require further study. For instance, biomass/coal co-firing may promote higher particulate matter emissions through particle coagulation, favored by the higher inorganic alkaline content of biomass and by lower combustion temperatures. Another environmental issue concerns the emission of trace metals (arsenic, beryllium, cadmium, mercury, and lead), which depends on the source of the biomass. Biomass/coal co-firing may modify the partitioning of trace metals between the particulate and gaseous phases, thus enhancing the fraction of volatile metals, which are harmful and difficult to clean up.

5.2.2 Fluidized-bed combustion

Fluidized-bed combustion (FBC) uses a mixture of particles suspended in an upward flowing airstream, which combine to exhibit fluid-like properties. Combustion takes place in the bed with very intense mixing of gases and solids, high heat transfer to the furnace, and a low combustion temperature. The principal advantages of FBC systems include: (1) high fuel flexibility, including the capability of using fuels with a high content of sulfur or ash; (2) the capability for firing low-grade fuels, e.g., biomass, refuse-derived fuels, and wastes, and for co-firing different types of fuels; (3) *in situ* desulfurization during combustion by adding limestone or dolomite sulfur sorbents to the fluidized bed; (4) low NO_x emissions due to the low-temperature combustion and the char inventory in the recirculating bed materials; (5) intense heat transfer characteristics, allowing for a compact boiler arrangement; (6) use of crushed fuel with relatively large particles, leading to reduced milling costs; and (7) relatively small installation, because there is no need for flue-gas desulfurization and pulverizing facilities. As a result, FBC has been widely used in industry for burning low-grade solid fuels and recovering energy. It is also a proven technology for power generation. The FBC process falls between PF combustion and grate firing with respect to the required size of the fuel feed. When fuel is introduced into the bed, it quickly heats up, ignites, and burns. The flow of air and fuel to the dense bed on the distributor is controlled so that the desired amount of heat is released to the furnace on a continuous basis. Because of the long fuel residence time and high intensity of the mixing process, the fuel can be efficiently burned in a fluidized-bed combustor at temperatures considerably lower than conventional combustion technologies. There are two types of fluidized-bed combustion technology: bubbling fluidized-bed combustion (BFBC) and circulating fluidized-bed combustion (CFBC). Table 5.3 briefly compares their key characteristics.

Table 5.3 BFBC and CFBC comparison

	BFBC	CFBC
Superficial gas velocity in bed	Typically 2–3 m/s: sufficiently high to maintain the bed in fluidization state (with a high degree of mixing) but low enough that most solid particles lifted out of the bed fall back into the bed again	About 4.5 m/s in dense bed and 5–7 m/s in freeboard: particles are carried upwards away from the bed surface (very high solid loading in the gas in the freeboard) and are captured by separators and re-circulated to the furnace
Excess air	1.2–1.3	1.1–1.2
Air flow split	About 50% of the combustion air is fed from the bottom distributor; the rest is fed above the bed	50–70% of the combustion air is fed from the bottom distributor; the rest is fed through over-fire air ports
Fuel particle size	Below 80 mm in diameter recommended	Smaller fuel particle size required (0.1–40 mm in diameter)

(*Continued*)

Table 5.3 Continued

	BFBC	CFBC
Bed material	Usually silica sand of about 0.5–1.0 mm in diameter	Usually smaller silica sand particles of 0.2–0.4 mm in diameter
Bed temperature	650–850°C	Typically 815–870°C
Bed density	About 720 kg/m^3	About 560 kg/m^3
Gas residence time	Bed height: 0.5–1.5 m; gas residence time within the bed: 1–2 s	Gas residence time within the whole furnace is 2–6 s
Combustion process	Combustion mostly occurs in the bed due to lower gas velocity and coarser fuel particles	Combustion is not limited to the bed: many fuel particles are elutriated into the freeboard, collected by separators, and recycled to the furnace
Pollutant emissions	Very low SO_x emissions due to in-bed sulfur capture by limestone addition; NO_x is more difficult to control and often requires complicated air systems and also selective non-catalytic reduction	Very low SO_x emissions due to in-bed sulfur capture by limestone addition; also very low NO_x emission, mainly due to the char inventory in the re-circulating bed materials, which efficiently reduce NO_x
Unit capacity	Lower cost, simpler construction, and suitability for fuels with higher moisture content. Units are offered up to 300 MW_{th} and the smallest economically feasible size is 5–30 MW_{th}. More typically, units have a power output lower than 100 MW_{th}, mainly as industrial non-utility technology	Units have higher combustion efficiency, lower limestone consumption, lower NO_x emissions, and quicker response to load changes. Units typically range from 100–500 MW_{th}. The smallest economically feasible size is 20–30 MW_{th} and can be offered up to 400–600 MW_{th}

There are many small- and medium-capacity BFBC units in operation worldwide. For instance, in China more than 2000 BFBC units were in operation by the early 1990s. In contrast with BFBC, there are more than 1200 CFBC plants worldwide with a total installed capacity of about 65 GW_{th}. The dominant region to date is Asia with some 52% of the installed capacity (34 GW_{th}). North America accounts for some 26% of worldwide capacity (17 GW_{th}), and Europe has around 22% of capacity (14 GW_{th}). Almost all of the Asian CFBC capacity is located in China where about 900 CFBC plants, of average size around 30 MW_{th}, are in operation. Some 200 more, mostly small, plants are either being commissioned or under construction (PowerClean, 2004).

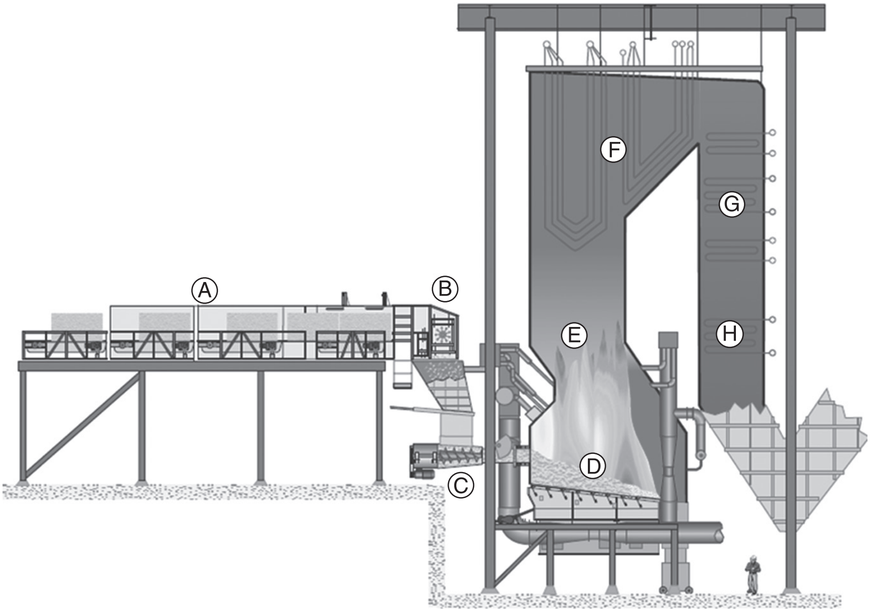
Although the FBC of solid fuels is a well-established and widely used technology, operational problems are encountered in industrial practice. One of the most important problems is the occurrence of agglomeration at high temperatures, where bed particles adhere to each other to form larger agglomerates. This process is often not recognized until there is sudden defluidization, which often leads to a costly shutdown of the whole installation. Firing biomass fuels in fluidized-bed combustors may increase the risk of bed agglomeration and defluidization, because biomass fuels often have lower ash melting temperatures. For instance, using silica sand as the bed material, bed agglomeration and defluidization have been reported when firing coffee husks, sunflower husks, cotton husks and stalks, mustard stalks, soya husks, pepper waste, groundnut shells, coconut shells, wheat straw, and so on (Yin *et al.*, 2008a). The current status of research into agglomeration mechanisms, detection, and prevention in FBC units was critically reviewed recently (Bartels *et al.*, 2008).

The Alholmens Kraft plant in Finland (550 MW_{th} CFB) is an example of a biomass co-firing plant equipped with FBC units. As mentioned before, about 43% of co-firing plants are equipped with FBC systems (24% BFBC and 19% CFBC), only slightly fewer than those equipped with PF boilers, which is about 48%. The Alholmens Kraft plant is one of the largest FBC power plants co-firing biomass in the world (Alholmens Kraft, 2011). It was commissioned in 2001 and burns 45% peat, 10% forest residues, 35% industrial wood and bark residues, and 10% heavy fuel oil or coal. The design of the plant allows great fuel flexibility; the boiler can burn mixtures of wood and coal from 100% wood to 100% coal. The heavy fuel oil and coal are reserve fuels only for exceptional cases, such as problems with fuel handling. The main steam parameters are 194 kg/s, 165 bar, 545°C.

5.2.3 Grate firing

Grate firing was the first combustion system used for solid fuels. Now it is used mainly for burning biomass. Grate-fired boilers burning biomass in combined heat and power plants range from 4 to 300 MW_e in capacity (many are in the range 20–50 MW_e). The heat release rate per grate area may be up to about 4 MW_{th}/m^2 as a result of high volatile and low ash characteristics of typical biomass fuels. Grate firing of biomass for heat and power production has been comprehensively reviewed by Yin *et al.* (2008a), which presents the state of the art for grate-fired boilers burning biomass: the key elements in the firing system, the important combustion mechanisms, recent breakthroughs in the technology, the most pressing issues, current research and development activities, and critical future problems to be resolved. Here only a brief overview of biomass grate-firing is given.

Figure 5.5 shows a modern 108 MW_{Fuel} grate-fired boiler burning wheat straw, which was experimentally and numerically studied by Yin *et al.* (2008b). A modern grate-fired boiler consists of four key elements: a fuel feeding system, a



5.5 A modern 108 MW$_{\text{Fuel}}$ straw-fired vibrating-grate boiler (Yin *et al.*, 2008a). A, straw transport belt; B, straw rotary rake; C, stoker screw; D, fuel bed on a water-cooled vibrating grate; E, freeboard; F, second and third superheaters; G, first superheater; H, economizer.

grate assembly, a secondary air (including over-fire air) system, and an ash discharge system.

Typical fuel-feeding systems used in biomass-fired grate boilers are mechanical stokers. For instance, stoker screws are used to feed the straw onto the water-cooled vibrating grate in the 108 MW$_{\text{Fuel}}$ grate boiler. For biomass fuels that are very heterogeneous in size and contain a relatively large mass fraction (30% or higher) of fine particles (i.e., a few millimeters and smaller), a spreader is needed to reduce the tendency for fuel size segregation, since the grate is typically only suitable for relatively coarse particles. The finer biomass particles combust in suspension when they fall into the upward flowing primary air; while the remaining heavier and larger pieces fall and burn on the grate surface.

The grate, the defining component of a grate-fired boiler, is located at the bottom of the combustion chamber. The grate has two main functions: the lengthwise transport of the fuel, and the distribution of the primary air entering from beneath the grate. The grate may be air-cooled or water-cooled. A water-cooled grate requires a little air for cooling (the primary air is for combustion) and flexibility is achieved by using an advanced secondary air system. Grates are classified as stationary sloping grates, travelling grates, reciprocating grates, and vibrating grates. The key characteristics of different grates are compared in Table 5.4.

Table 5.4 Different types of grate and their main characteristics (Yin *et al.*, 2008a)

Type of grate	Major features
Stationary sloping grate	The grate does not move. The fuel burns as it slides down the slope under gravity. The degree of the slope is an important characteristic of this kind of grate. Disadvantages: (1) it is difficult to control the combustion process; (2) there is a risk of the fuel avalanching.
Traveling grate	The fuel is fed onto one side of the grate and burns while the grate transports it to the ash pit. Compared to a stationary sloping grate, it has improved control and a better carbon burnout efficiency (due to the small layer of fuel on the grate).
Reciprocating grate	The grate tumbles and transports fuel by reciprocating (forward and reverse) movements of the grate rods as combustion proceeds. The solids are finally transported to the ash pit at the end of the grate. Carbon burnout is further improved due to better mixing.
Vibrating grate	The grate has a kind of shaking movement, which spreads the fuel evenly. This type of grate has fewer moving parts than other moveable grates (and thus lower maintenance and higher reliability). Carbon burnout efficiency is also further improved.

The primary air and secondary air supply system plays a very important role in the efficient and complete combustion of the biomass. For grate firing, the overall excess air for most biomass fuels is normally set to 25% or above. The ratio of primary air to secondary air tends to be 40/60 in modern grate-fired boilers burning biomass, instead of 80/20 in older units, which gives much more flexibility to an advanced secondary air supply. The primary air distribution, together with the movement of the grate, significantly affects mixing and biomass conversion in the fuel bed, as well as the combustion mechanism. The majority of biomass-fired grate furnaces are cross-flow reactors, where the biomass is fed in a thick layer perpendicular to the primary air flow. The bottom of the biomass bed is exposed to the pre-heated primary air while the top of the bed is within the furnace. The fuel bed is heated by over-bed radiation from flames and refractory furnace walls until the top surface of the fuel bed ignites. An advanced secondary air supply, representing one of the real breakthroughs in grate-firing technology, is one of the most important elements for combustion optimization in the freeboard. The gases released from biomass conversion on the grate and a small number of entrained fuel particles continue to combust in the freeboard, where the secondary air plays a significant role in mixing, burnout, and emissions. Advanced secondary air supply systems employed in modern grate boilers include, e.g., air-staging to form different local combustion environments, optimization of the secondary air jets (e.g., in terms of the number of jets, jet momentum, diameter, location, spacing, and orientation) to induce local recirculation zones or rotating flows, and the use of static mixing devices with or without air injection.

In grate-fired boilers burning biomass, the emissions of pollutants due to incomplete combustion (which also lowers the combustion efficiency) can be one of the main problems. This problem has been mitigated to some extent in modern grate-fired boilers by using advanced secondary air systems. Another important problem is the formation of deposits and corrosion, especially when co-firing biomass with a high chlorine content (e.g., straw). Deposits reduce both the heat transfer ability of combustor surfaces and the overall process efficiency, while corrosion reduces the lifetime of the equipment. Of the different measures to mitigate or even eliminate the deposition and corrosion problems, the use of additives is of most interest. Additives can raise the melting temperature of the ash formed during biomass combustion, prevent the release of gaseous KCl, react with KCl to form less corrosive components, or have a combination of these effects. The injection of an additive, such as ChlorOut (ammonium sulfate), into the combustion gases in a specific temperature window upstream of the superheaters, is attractive since it is less dependent on the combustion technology. Co-firing problematic biomass fuels with appropriate coals can also greatly mitigate the deposition and corrosion problems in grate boilers. To further develop grate-firing technology for better biomass combustion, some measures have been recently addressed (Yin *et al*., 2012b).

5.2.4 A comparison of the different direct co-firing technologies

To better summarize the different direct co-firing technologies, a comparison of their main characteristics is given in Table 5.5.

Table 5.5 Comparison of different direct co-firing technologies

Advantages	Disadvantages
Grate-firing systems	
• low investment costs for plants <20 MW_{th} • low operating costs • very low dust load in the flue gas • many biomass fuels have low melting points; grate-fired units are insensitive to bed agglomeration • little wearing of bed components	• in new grate furnaces, low NO_x emissions can be achieved by using advanced secondary air systems; in old units, efficient NO_x reduction requires special technology • high excess O_2 (5–8 vol%) decreases efficiency • combustion conditions not as homogeneous as in fluidized-bed furnaces • achieving low emission levels at partial load operation requires sophisticated process control

(*Continued*)

Table 5.5 Continued

Advantages	Disadvantages
BFBC units	
• no moving parts in the hot combustion chamber • air-staging helps to reduce NO_x to some extent • high flexibility concerning moisture content and kind of biomass fuel used • low excess oxygen (3–4 vol%) raises efficiency and decreases flue gas flow	• high investment costs: the smallest economically feasible size is 5–30 MW_{th}, preferably > 20 MW_{th} • high operating costs • reduced flexibility for particle size (<80 mm) • utilization of high alkali biomass fuels is critical due to possible bed agglomeration without special measures • high dust load in the flue gas • NO_x is more difficult to control than CFBC, often requiring selective non-catalytic reduction • loss of bed material with the ash without special measures • extensive wearing of bed components due to high solid velocity and concentration
CFBC units	
• no moving parts in the hot combustion chamber • low NO_x emissions mainly due to the char inventory in the circulating bed materials, as well as low temperature combustion and air-staging • high flexibility concerning moisture content and kind of biomass fuel used • homogeneous combustion conditions in the furnace if several fuel injectors are used • high specific heat transfer capacity due to high turbulence • use of additives easy • very low excess O_2 (1–2 vol%) raises efficiency and decreases flue gas flow	• high investment costs: the smallest economically feasible size is 20–30 MW_{th} • higher operating costs due to higher pressure drop over the dense bed • low flexibility for particle size (< 40 mm) • high sensitivity concerning ash slagging, and utilization of high alkali biomass fuels is critical due to possible bed agglomeration • high dust load in the flue gas • loss of bed material with the ash without special measures • extensive wearing of bed components due to high solid velocity and concentration • partial load operation requires special techniques
PF furnaces	
• low excess O_2 (4–6 vol%) increases efficiency • high NO_x reduction with efficient air-staging and mixing possible if cyclone or vortex burners are used • very good load control and fast load changes possible	• low fuel flexibility • strict requirements on particle size of the biomass fuel • high wear rate of the insulation brickwork if cyclone or vortex burners are used • an extra start-up burner is necessary

Source: van Loo and Koppejan, 2008; Yin *et al.*, 2008a.

5.3 Indirect and parallel co-firing technologies

Indirect co-firing involves the pre-treatment of biomass fuels. For instance, biomass or wastes are first converted to gaseous or liquid fuels via thermochemical conversion. Then the gaseous and liquid fuels are co-fired together with the main fuel. In contrast with direct co-firing, indirect co-firing has several technical and economic benefits, especially for coal-fired PF boilers. Until now, all industrial-scale and commercially operated indirect co-firing applications have been based on biomass gasification and co-firing of product gas in larger PC boilers. One of the key issues with indirect co-firing is the degree of cleaning of the fuel gas needed prior to co-combustion in the PF boiler. Bio-oil production via pyrolysis or liquefaction is under development, and this could be another way to implement indirect co-firing.

Another indirect co-firing method is based on the integration of steam cycles, in which separate biomass and fossil-fuel boilers are integrated based on the steam cycle. For example, steam can be generated in a biomass-fired boiler and superheated in a coal- or natural-gas-fired boiler. Although parallel firing installations involve significantly higher capital investment than direct co-firing systems, they may have advantages such as the possibility of using relatively difficult fuels with high alkali metal and chlorine contents and the production of separate coal and biomass ash streams. Avedøre Unit 2, near Copenhagen in Denmark, is a parallel co-firing project. The main component is a large ultra-supercritical (USC) power plant. The plant has a supercritical boiler, rated at 430 MW_e, a flue-gas cleaning plant, a steam turbine, and an electrical generator. There are also two gas turbines (rated at 51 MW_e each), which generate peak load electricity and pre-heat the feedwater to the USC boiler via exhaust heat recovery units. The USC boiler was designed for coal, gas, and oil firing. Originally, it fired natural gas (nowadays it fires pulverized wood pellets). The 108 MW_{Fuel} grate-fired boiler, as sketched in Fig. 5.5, fires 100% wheat straw and provides steam to the USC plant. This parallel co-firing plant has unique operational capabilities, because all of the key components, i.e. the USC boiler, the biomass boiler, the steam turbine, and the two gas turbines with their heat recovery units, are integrated into one process.

5.4 Conclusion

The increased need for a reduction of CO_2 emissions from energy production has resulted in the development of different co-firing technologies and demonstrations of them on an industrial scale. Biomass co-firing has been demonstrated on different scales using different combustion technologies. The different direct co-firing technologies (e.g., PF, FBC, and grate-firing) are considered to be mature and feasible. Gasification and co-firing of product gas in PF or other boilers is also a mature technology but hot gas cleaning is still in the demonstration phase.

Indirect co-firing based on separate parallel boilers with an integrated steam cycle has been demonstrated successfully. However, there still exist some technical barriers for successful replication of these demonstrated technologies for biomass co-firing, which include technical constraints related to biomass feedstock pre-processing, combustion systems and processes, flue-gas cleaning systems, and the usability of solid by-products and residues, as summarized in the report from the EU Commission (2000). Fundamental research and development are still needed to achieve problem-free biomass co-firing with improved performance, e.g., increasing the share of biomass in co-firing, higher co-firing efficiency, lower emissions, and better system reliability and availability.

5.5 References

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6

Biomass gasification

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Abstract: The gasification of biomass promises plentiful options for efficient feedstock utilization. Often, the main goal is the provision of energy in the form of heat or power (or cooling) by burning the combustible gases. Another goal of biomass gasification is the generation of synthesis gases for further catalytic synthesis into base chemicals or storable energy carriers such as liquid fuels (methanol, mixed alcohols, Fischer–Tropsch liquids and dimethyl ether) or gaseous fuels such as substitute natural gas (SNG) or hydrogen. This chapter describes the fundamentals of gasification, technological developments and future trends for different sizes of plants and gives an overview of the process chains incorporating biomass gasification.

Key words: gasification fundamentals, gasification reactions, gasifier, gasification technology, biomass gasification applications, biomass gasification future trends.

6.1 Introduction

Biomass gasification has attracted renewed interest in the past 20–30 years. Considerable effort has been expended on applying gasification technology, and getting it ready for the market and to develop it into a mature and functional but also competitive technology. The main driver for the interest in biomass gasification is the versatility of the gases produced. Compared with the proven and mature combustion technology, gasification is still struggling with challenges such as tar or other trace impurities, which cause operational problems for downstream gas utilization. Examples of such gas utilization are in gas engines or turbines or when catalysts are used to reform the combustible gas.

6.2 Basic principles and feedstocks

6.2.1 Gasification

In contrast to the pyrolysis processes covered in Chapter 7 (by A. Bridgwater) and in Chapter 8 (by A. Hornung), gasification processes aim to maximize the conversion of a solid feedstock into useable gases. In the reactor the feedstock is exposed to a high-temperature atmosphere and hot particles, which heat the fuel leading to thermal decomposition. In addition and in contrast to pyrolysis, the material is brought into contact with a gasifying agent. At reasonably high temperatures (ca. 800–1400°C), reactions between the gasifying agent and the solid carbon structure originating from the supplied feedstock take place, forming carbon oxides or hydrocarbons (which are the main components of the product or producer gas). Using steam as a gasifying agent, lower temperatures (down to about 600°C) can be applied and this is called steam reforming. See e.g. (ab) sorption enhanced reforming (AER/SER) in Section 6.3.2. The term 'product gas' refers more generally to the product of thermochemical reactions whereas the term 'producer gas' is used for the gases generated in a gas producer (gasification reactor) with air as the main gasifying agent. When oxygen or steam is used as the main gasifying agent, the product gas of a gasification reactor is often called 'syngas'. Depending on the type of reactor, the nature of the solid feedstock, the composition of the gasifying agent, the reaction temperatures and residence times, and the gas flow through the gasifier, some carbon in the feedstock might remain unreacted and leave the reactor with the mineral matter (ash). Table 6.1 lists the main constituents of the product gas resulting from biomass gasification.

Depending on the desired composition of the product gas, air, pure oxygen, steam, or a mixture of air, oxygen and steam can be chosen as the gasifying agent. The use of carbon dioxide is also possible but much less frequently applied. In principle, the conversion of carbon into gases is also possible through the reaction of the solids with hydrogen (hydrogasification) or mixtures of steam and hydrogen (steam hydrogasification). The latter might be of interest if substitute natural gas (SNG) is to be produced and no oxygen is available. Air is a very common gasifying agent because it is almost free ('almost' because the compressor consumes energy) and readily available. However, using air as a gasifying agent causes dilution of the product gas with the nitrogen in the air, resulting in a product gas having a low heating value. Steam can also be used as a gasifying agent as it can be produced easily, albeit with some form of heat input needed to evaporate water, though the reforming reactions with steam are endothermic and therefore additional heat must be supplied to the reactor. This could be achieved by adding pure oxygen to the steam but the oxygen has to be produced by cryogenic air

Table 6.1 Principal constituents in product gases from biomass gasification

Target compounds	CO, H_2, CH_4, C_2H_x, C_3H_x
'Inert' (non-combustible) compounds	CO_2, H_2O, (N_2)
Trace contaminants	NH_3, HCN, other organic nitrogen compounds H_2S, COS, CS_2, other organic sulphur compounds HCl, NaCl, and KCl aerosols
Condensable fraction	Benzene, toluene, and xylene (BTX), tar, hetero-organics, (water)
Particles	Ash, mineral matter/salts, char, aerosols

separation (the Linde process), pressure-swing adsorption (PSA), using membranes or by water splitting via electrolysis. All existing oxygen production processes require expensive installations and consume substantial amounts of energy. Cryogenic air separation is a commercially available technology but it is only suitable for large gasification plants.

Chemical reactions

The transformation of a solid fuel into gaseous substances by gasification takes place in hundreds of reaction steps with dozens of intermediates. It is a very complex reaction network influenced by feedstock properties, reactor design, gasifying agents, temperatures, residence times, and pressure. Here only the main reactions in the gasification process will be presented and discussed. For more detailed information on gasification reactions, refer to other literature sources (e.g. Larendeau, 1978; van Heek, 1987; Marsh, 1989; Hiller, 2012). In general, the gasification reactions can be distinguished as gas–solid (heterogeneous) reactions and gas–gas/gas–vapor (homogeneous) reactions. The 'solid' in many literature sources is just given as pure carbon. In reality, the solid (char) generated in gasifiers consists to a large degree of carbon but also of chemically-bound hydrogen and oxygen and further heteroatoms and other ash elements that the biomass has assimilated during its growth. It is far away from 'pure carbon' and has some very unique properties. The content of mineral matter or ash elements in, e.g. woody biomass char, can be expected to be around 10%, which can be up to 20 times higher than the value in the supplied biomass feedstock. The reactivity of the char depends on many factors such as particle size, the porous structure (internal surface area and pore size distribution), and the minerals incorporated within the surface structure, which result in active sites (Radovic *et al.*, 1983, 1991; LaHaye, 1991b). These active sites play a major role in char conversion. Several ways of inhibiting further reactions are also known. Thus the true heterogeneous reaction rates for chars are very difficult to determine and any published data should be treated with care.

1. Reactions with molecular oxygen (combustion reactions)

$$C + O_2 \rightleftarrows CO_2 \qquad \Delta H = -110.62\,\text{kJ/mol}$$

$$2\,CO + O_2 \rightleftarrows 2\,CO_2 \qquad \Delta H = -283.15\,\text{kJ/mol}$$

$$2\,H_2 + O_2 \rightleftarrows 2\,H_2O \qquad \Delta H = -242.00\,\text{kJ/mol}$$

These combustion reactions are exothermic. The partial combustion of some of the feedstock and some of the formed gases and vapors generates the heat needed for the endothermic conversion reactions. This is also how heat is supplied in autothermal gasifiers, where the required heat of reaction is produced by partial oxidation within the gasifiers.

2. Reactions with carbon dioxide
Boudouard reaction:

$$C + CO_2 \rightleftarrows 2\ CO \qquad \Delta H = +172.54\,\text{kJ/mol}$$

Hydrocarbon/CO_2 reaction:

$$C_nH_m + n\ CO_2 \rightleftarrows 2n\ CO + m/2H_2$$

As stated earlier, carbon dioxide is used as a gasifying agent although much less frequently. Carbon dioxide is formed by the thermal decomposition of oxygen-containing biomass feedstock. The equilibrium condition for the Boudouard reaction is strongly temperature dependent. With higher temperatures, more CO will be formed.

3. Reactions with steam
Heterogeneous water–gas reaction (although the 'water' is actually 'steam' in gasification processes, 'water' is still used as a descriptive term in many gasification reactions):

$$C + H_2O \rightleftarrows CO + H_2 \qquad \Delta H = +131.38\,\text{kJ/mol}$$

Hydrocarbon/steam reaction:

$$C_nH_m + n\ H_2O \rightleftarrows n\ CO + (m/2 + n)\ H_2$$

Water gas-shift reaction (homogeneous water–gas reaction, shift conversion):

$$CO + H_2O \rightleftarrows CO_2 + H_2 \qquad \Delta H = -41.16\,\text{kJ/mol}$$

The heterogeneous water–gas reaction requires a heat supply and so is a reaction between hydrocarbons and steam, which leads to the formation of hydrogen. In allothermal steam reformers, which receive the required heat of reaction from external heat sources, these reactions will be predominant. The water gas-shift reaction is an exothermic reaction and the heat released, although much smaller than the heat needed for the heterogeneous water–gas reaction, is utilized within a gasification process.

4. Reactions with hydrogen
Methanation (methane forming reaction, hydrogenating gasification, hydrogasification):

$$C + 2H_2 \rightleftarrows CH_4 \qquad \Delta H = -75.00\,\text{kJ/mol}$$

The methane formation reaction is a relatively slow reaction, which is favored at higher pressures. It is under examination for the generation of SNG.

Numerous scientific investigations of gasification reactions have been made (Hiller *et al.*, 2012; Walker *et al.*, 1959; Jüntgen and van Heek, 1981; Larendeau, 1978; van Heek *et al.*, 1987; Figureido and Moulijn, 1986; LaHaye *et al.*, 1991; Marsh and Kuo, 1989; Gómez-Barea and Leckner, 2010). The progress of the

Table 6.2 Relative reaction rates of four major heterogeneous reactions in gasification (Larendeau, 1978)

Reaction	ΔH_{298} (kcal/gmol)	Temperature range for which $K_p > 1$	Relative rate at 800 K and 0.1 atm
$C + CO_2 \rightleftarrows 2CO$	41.2	$T > 950\,K$	1
$C + H_2O \rightleftarrows CO + H_2$	31.4	$T > 950\,K$	3
$C + 2\,H_2 \rightleftarrows CH_4$	–17.9	$T > 820\,K$	3×10^{-3}
$C + O_2 \rightleftarrows CO_2$	–94.1	$T < 5000\,K$	10^5

ΔH_{298} is reaction enthalpy at 298 K. K_p is equilibrium constant.

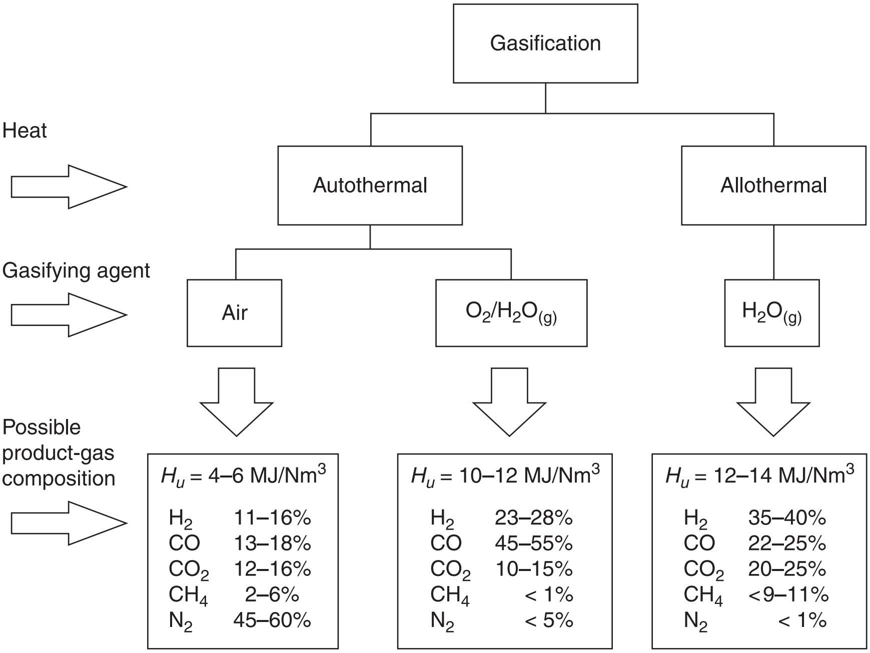
reactions further depends on the temperature, pressure, reaction rates, contact between the individual compounds and the gas flow; the latter strongly influences the residence time of the reaction compounds. There has been a great deal of discussion on whether equilibriums are reached for the individual reactions.

Larendeau (1978) compared relative reaction rates of four major heterogeneous gasification reactions at 800 K (Table 6.2). The reaction rate of the Boudouard reaction was used as the basis for comparison and hence was set to 1. Compared with the Boudouard reaction, the heterogeneous water–gas reaction is three time faster. The oxidation reaction of carbon is about four to five orders of magnitude faster than the Boudouard reaction and the heterogeneous water–gas reaction, and hence equilibrium can be assumed for the carbon oxidation reaction. Further, it can be concluded that the oxygen introduced into autothermal gasifiers is converted rapidly so that oxygen will be available only in limited areas. The reaction between hydrogen and carbon is about three orders of magnitude slower than the steam/carbon and CO_2/carbon reactions. The formation of methane via this route is therefore of lower importance in the overall reaction scheme. Mühlen (1983) though showed that it should not be neglected, especially under high pressure.

Figure 6.1 shows the commonly applied gasification principles. Gasification with air leads to a product gas diluted by nitrogen. The presence of oxygen causes partial oxidation of the supplied fuel, which generates the heat for the process. This is called autothermal gasification since the heat needed for the endothermic reactions that lead to the desired gas compounds is generated in the reactor itself. In order to generate gases with higher heating values, nitrogen has to be kept out of the process. This can be achieved by steam gasification or steam reforming of the biomass. In this case, heat from an external source must be supplied and this is called allothermal processing. If pure oxygen is available (as in larger gasification units, where it is produced by air separation units) oxygen and steam can be mixed in an autothermal process producing product gases with acceptable high heating values.

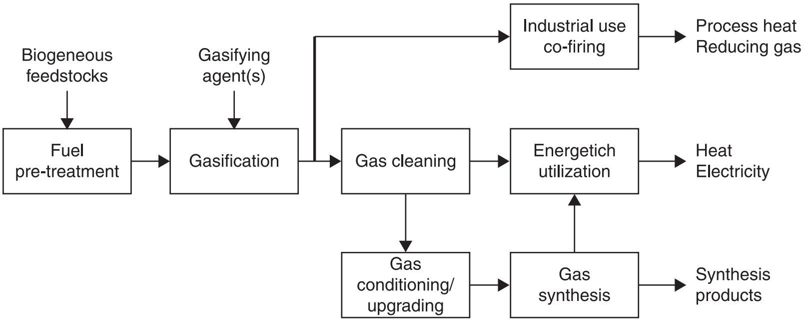
6.2.2 Fuel-gas production and utilization

The product gas from gasifiers is either directly used in industrial applications as fuel for combustion or as a reducing gas e.g. in steel manufacturing (Fig. 6.2).



6.1 Product-gas composition from different gasification concepts. H_u is the lower heating value.

To use the energy in gas engines or gas turbines, the product gas will be combusted. The removal of tar from the product gas is more important when it is used in gas engines than in gas turbines, and even more important when used in fuel cells because trace elements, such as sulfur compounds, are likely to cause irreversible effects to active catalytic sites. A fuel gas should have a high heating

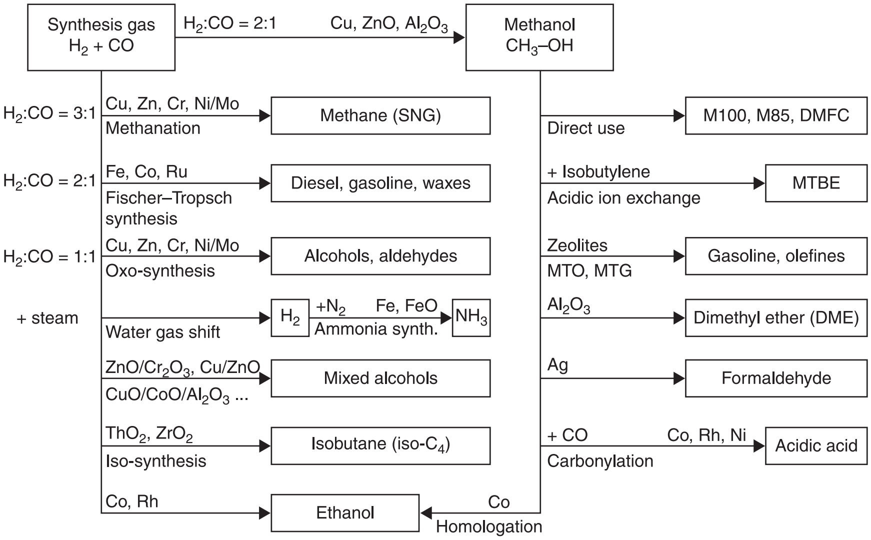


6.2 Utilization paths of product gases from biomass gasification (adapted from Hofbauer, 2009).

value and appropriate combustion properties. A high hydrogen content is beneficial for fuel cells but could be troublesome for engines or turbines. Contaminants in the product gas cause few problems when co-firing in boilers, whereas turbines cannot tolerate particles or alkali metals. Tar in the product gas can be a serious issue in gas engines because the gas has to be cooled down in order to fill the cylinders with energy equivalents, when tar will form deposits.

6.2.3 Synthesis gas production

Synthesis gas, or more commonly syngas, is a mixture of carbon monoxide (CO) and hydrogen (H_2) and it is used in catalyzed gas synthesis reactions. Since the product gas produced by gasification using oxygen and/or steam as the gasifying agent contains large amounts of CO and H_2, the product gas is often called syngas. The ultimate aim of biomass gasification for syngas production is to form desirable gaseous and liquid hydrocarbon products from biomass feedstocks. Figure 6.3 gives an overview of pathways for gas synthesis. On the left-hand side the H_2/CO ratio is given as required for the individual reactions. The commonly used catalytic systems are indicated above the arrows. Gas synthesis in combination with gasification dates back to the 1920s when these hydrogenation processes were studied and brought into operation with coal processing. Readily available oil and gas more or less ended the development around about the 1950s but the catalytic systems were introduced into refineries. One exception is the Sasol Plant in South Africa, where coal was gasified in updraft fixed-bed reactors and liquid fuels were



6.3 Principal synthesis pathways from synthesis gas (adapted from Dayton, 2002).

generated on a large scale via the Fischer–Tropsch process. Synthesis gas is mainly made from methane (natural gas) nowadays.

Many of the processing paths shown in Fig. 6.3 have been tested for biomass gasification over the past three decades. One of the main goals has been to produce liquid fuels from (woody) biomass, the so-called second generation biofuels. Attempts have been made to produce methanol, Fischer–Tropsch fuels, and dimethyl ether. There is also interest in producing mixed alcohols. A great deal of research has been on the conversion of synthesis gas to methane. In several European countries there are established natural gas supply networks into which synthetic methane gas could be fed. Furthermore, these natural gas grids usually have their own underground storage facilities, which are used to balance the different demands in summer and winter. For these countries, synthetic methane could replace fossil fuel natural gas in the future. See also Section 6.6 on future trends.

6.3 Basic reactor types

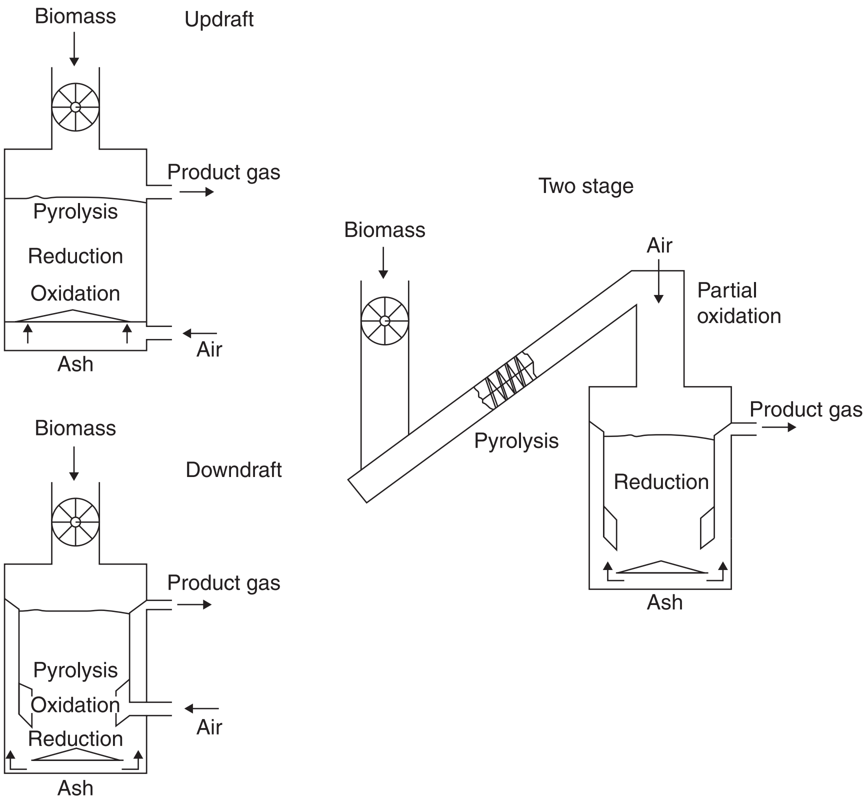
6.3.1 Moving bed (fixed bed)

Moving-bed gasifiers were the first type of gasifier used. They originated in the early 1800s. At that time biomass was the primary source of energy. The first uses of the gas were for lighting (Fouquet and Pearson, 2006). The first gasworks used biomass as fuel feedstock before they switched their fuel supply to coal. Starting in the late 1930s, for about one decade gasifiers were used to produce gas to power cars, especially with the scarcity of petrol during the war. Around this time, many manufacturers of biomass gasifiers produced moving-bed gasifiers for transport applications. The basic types including updraft, downdraft, double fire or cross fire moving-bed gasifiers were developed and used in real applications (Ostwaldt, 1942; Kroll, 1943; Reed and Das, 1988).

In a moving-bed gasifier, a bed of solid fuel moves slowly downwards. A characteristic of this type of gasifier is the formation of four zones (drying, pyrolysis, oxidation, and reduction). The reactors can be operated as updraft or downdraft gasifier depending on the location of the feeding point for the gasifying agent. Figure 6.4 shows the main principles of moving-bed gasifiers. Differences include the limited scale-up possibilities for downdraft gasifiers and the high tar content of the product gas from updraft gasifiers. A double-fire gasifier combines both principles whereas the new staged gasification systems separate the pyrolysis zone (where tar precursors are formed), from the partial combustion zone and the hot reduction zone, leading to strongly reduced tar content in the product gas.

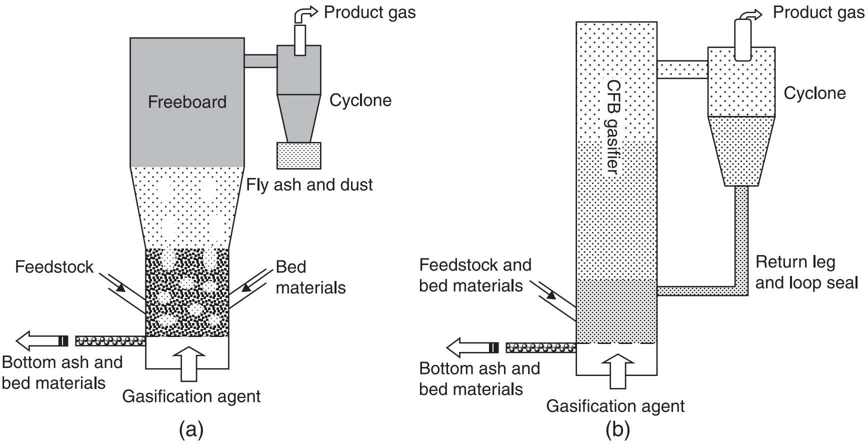
6.3.2 Fluidized bed

The principle of fluidization was first reported by Winkler in the early 1920s (Feiler, 1972; Werther, 2012) and has been used for gasification since then.



6.4 Moving-bed gasifiers.

Fluidized beds have the advantages of good temperature distribution, and high mass and heat transfer rates. Fluidized-bed gasification systems can be scaled quite well and are commonly used from a medium scale to a large scale. Attrition of the bed materials, together with the entrainment of the unreacted char and mineral compounds from the feedstock (ash) often leads to high concentrations of various solid particles in the product gas, which need to be taken care of for downstream gas utilization. Larger fluidized-bed reactors can be operated as circulating fluidized-bed (CFB) reactors thus increasing the conversion of solids. Due to the fluid-like properties of fluidized beds, additional reactive bed materials, heat carriers, or other functional materials can be mixed with the bed materials (Pecho *et al.*, 2008). Furthermore, it is possible to combine two fluidized-bed reactors, e.g. to use and to regenerate active bed materials for oxygen transfer into the gasifier (the oxygen donor process, Dallas *et al.*, 1986) or to remove carbon dioxide from the gasifier (carbon capture, Curran *et al.*, 1967), or in (ad)sorption-enhanced reforming (AER/SER) (Marquard-Möllenstedt, 2008; Hofbauer, 2011). Such combinations are known as dual-fluidized beds (DFB) (Corella *et al.*, 2007).



6.5 Fluidized-bed gasifiers: bubbling fluidized-bed gasifier (a), circulating fluidized-bed gasifier (b).

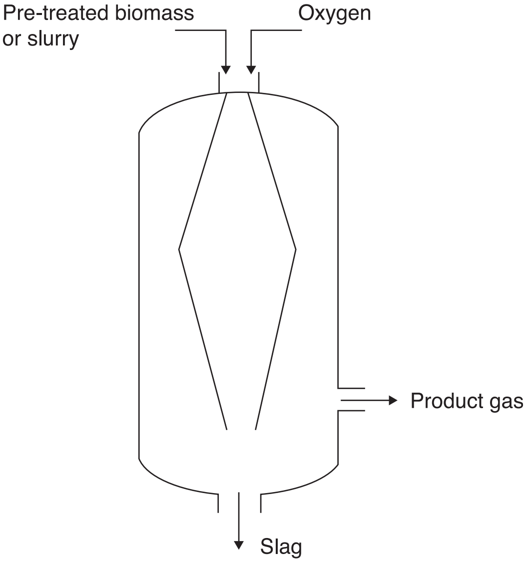
The term 'chemical looping' describes the current efforts being made to make use of these phenomena to actively influence the reactions. Figure 6.5 shows the principles of typical fluidized-bed reactor systems.

6.3.3 Entrained flow

The third basic reactor type that is used for biomass gasification is the entrained-flow reactor. Here very fine biomass particles are gasified in a flow of oxygen or a mixture of oxygen and steam. The fine biomass particles may be produced by milling, which can be very energy intensive. An alternative to direct milling for producing fine biomass particles is pyrolysis/torrefaction followed by subsequent milling, which is currently very popular due to its lower energy consumption. Nearly complete gasification is achieved at very high temperatures of 1100–1400°C and at high gas-flow velocities. The mineral compounds in the fuel will melt and a liquid layer of downwards flowing slag protects the wall material from the high temperature. In addition to the high conversion rates of solids, another advantage of entrained-flow gasifiers is the high degree of conversion of the feedstock. Entrained-flow gasifiers produce more or less tar-free product gases. To avoid excessive heat loss and reduced efficiency, the installations tend to be large. They are most often found combined with synthesis gas utilization as they can be operated at elevated pressures. Figure 6.6 shows an example of an entrained-flow gasifier.

6.3.4 Process technologies and performance issues

Gasification technology has been studied by industry and scientists for several decades. It has seen numerous ups and downs and has to compete with other



6.6 Entrained-flow gasifier.

technologies, which are well established and much more mature. There are many different types of process technologies; they are used to process different fuels and were developed to fulfill different aims. Therefore they are hardly comparable. The performance of a gasification system has often been measured in terms of operating hours reached per year. Just a few years ago, the performance was measured by how far away from about 8000 hours a year a gasification system could continuously operate but now the performance target is to achieve a continuous operational time of around 8000 hours per year for several years. Progress has been much slower than expected but functional systems are now entering the market. Especially for small- and medium-sized applications, systems are no longer just demonstrators and prototypes. Systems are run by clients or, in some business models, by operators, under the control (and with the immediate help) of the manufacturer. Current gasification technology for utilizing biomass can be divided systematically into:

- Small scale: fixed bed and multistage processes for combined heat and power (CHP) production.
- Medium scale: fluidized-bed and dual fluidized-bed processes for CHP and syngas production (e.g. for further methanation and injection into gas grids).
- Large scale: syngas production in large circulating fluidized-bed reactors or entrained-flow gasifiers, co-gasification of biomass feedstocks with fossil fuels.

The future trends for biomass gasification will be further discussed in Section 6.6, which includes a discussion of the current situation and predictions for the near future.

6.4 Monitoring and control, and performance optimization

6.4.1 Tar analysis and monitoring

One of the challenges in bringing gasification technology into successful use and to a degree of maturity is dealing with tar. There are several definitions and descriptions of tar, and different schemes for classifying it. Physically and chemically, tar is a mixture of condensable hydrocarbons formed by thermal decomposition of and chemical reactions between the organic compounds present in the gas phase of thermochemical conversion plants. Gasifier for tar consists mainly of monoaromatic and polycyclic aromatic compounds (PACs), most of them being polycyclic aromatic hydrocarbons (PAHs) if the gasification temperatures are above ~700–800°C. At lower temperatures and with sufficient steam more phenolic substances and organic acids can be found in the tar (similar to the case of pyrolysis).

Generally speaking, tar is a sticky, highly viscous substance with a yellowish, brownish to deep black color and with a pungent smell. It causes many problems in gasifier installations and remains a main technical hurdle for continuous operation over longer periods of time. Furthermore, it is an economic barrier for gasification technologies since gas cleaning and, in particular, dealing with tar requires costly gas treatment equipment (Knoef, 2012; Milne *et al.*, 1998; Dayton, 2002).

An understanding of the situation within a plant is required for dealing with tar. A number of different methods for determining the tar content, the concentration of individual tar-forming species, and the tar concentration have been tested (International Workshop, 2011; Knoef and Neubauer, 2012). Standardization efforts led to the tar protocol or tar guideline, which was finally summarized as technical standard CEN/TS 15439 (CEN, 2006) in Europe. This wet-chemical sampling approach aims to achieve the comparability of results from different measurements. The main drawback of CEN/TS 15439 is the long sampling duration. In addition, this method cannot give information about the dynamic behavior of a plant. A further drawback of wet-chemical analyses is the requirement for a well-equipped laboratory with analysts familiar with the method. The results will not become available until hours or days after the sample was taken. Hence other methods for on-line measurement have been developed for scientific work and also as on-line monitoring tools for industrial applications, which can deliver analytical data about the process conditions in real time or with little delay. For more detailed information refer to Knoef and Neubauer (2012).

6.4.2 Trace contaminants

Depending on the final utilization of the gases produced, other gas contaminants may become problematic. Strict requirements for the conditions and gas purity are usually needed for process steps using catalysts in further reforming reactions. Fuel cells also require high purity gases. Gas turbines are sensitive to particles and corrosive compounds such as alkalines but are quite tolerant of hydrocarbons. Methanation catalysts should not come into contact with sulfur compounds over long periods of time because this will lead to inactivation (poisoning) of the catalysts. To understand these phenomena, the number of sulfur compounds analyzed was increased from the normal H_2S, COS, and CS_2 to include organic species (thiophenes and others), by the National Renewable Energy Laboratory (NREL) (Carpenter, 2011). In total, 16 different sulfur compounds in product gas samples were analyzed. The results showed that there were differences in their interaction with the washing media used in gas-cleaning steps, which means that detailed analysis is required before catalysts can be used for longer periods, which will improve plant reliability. When product gas is combusted, e.g. in an internal combustion engine, any ammonia present is easily converted into nitrogen oxides, which is also important because it makes controlling emissions more difficult. Other compounds of interest in direct combustion applications include the slip of CO (the CO from the fuel gas that 'slips' through combustion in a piston engine), which is generated in the combustion process itself, and the emission of light aromatic compounds that might originate from the highly volatile fraction of the tar-forming species.

6.4.3 Gas cleaning and overall plant efficiency

Gas cleaning is an essential part of any gasification system. Cleaning removes the contaminants mentioned above and other undesired compounds from the product gas. It includes the separation of particles, the removal of tar and further removal of trace contaminants depending on the final use for the gas. For catalytic processes, a shift in the concentration of the main components of the gas might be necessary as well as changing the temperature and pressure of the gas (gas conditioning).

Conventional gas cleaning and conditioning include cooling the gas, filtering out particles and scrubbing contaminants using appropriate cleaning agents (Rezaiyan and Cheremisinoff, 2005). Disadvantages of conventional gas cleaning and conditioning mainly include the costly equipment needed and disposal of waste streams. Since gasification is a high-temperature process and in many downstream processes hot gases are needed, there is a need for high-temperature gas cleaning (Stevens, 2001). For integrated gasification combined cycle (IGCC) applications, the removal of particles is mandatory but tar is not a big problem if the final gas temperatures remain above the tar dew points ($T > \sim 300$–350°C).

Nevertheless the catalytic conversion of the tar has been considered for these processes and especially for pre-conditioning syngas (Dayton, 2002; Devi *et al.*, 2003). For a recent overview of applied downstream gas-cleaning methods refer to Zwart (2009).

Overall plant efficiency for gasification processes is usually expressed as cold gas efficiency – the chemical energy in the cold product gas compared with the energy of the biomass feedstock fed to the plant correlated with the respective mass flows. Another way of expressing efficiency is the energy content of the feedstock correlated with the final product of the syngas process, e.g. methane or a Fischer–Tropsch diesel. For liquid fuels, the calculation will be made on a well-to-wheel basis. For SNG production, an energy-based efficiency for producing methane from the fuel of about 60% is expected by several authors. For CHP plants, the efficiency will be around 80% or over if the heat is utilized. Electrical efficiencies of comparably small CHP plants range between 25% and 35%. For the Värnamo IGCC plant, electrical efficiencies for different loads (70% and 100%) of between 26.2% and 31.8% were reported. The theoretical overall efficiencies when heat is utilized, for example for district heating, have been reported as 77.0% to 80.6% (Sydkraft, 2001).

6.5 Advantages and limitations

6.5.1 Advantages

The product gas produced by gasification processes can be utilized in many ways. In contrast to the flue gas of a combustion process, product gas still contains a substantial amount of storable chemical energy. Subsequent use of the energy via combustion is less prone to emission problems since cleaning of the gas is already an essential part of the process. Product gas can be converted to electricity and heat in internal combustion engines, gas turbines, and fuel cells. Tests with Stirling engines have been reported and an organic Rankine cycle has been coupled with an engine, e.g. Hofbauer (2011). The route via synthesis gas has many possibilities as discussed in Section 6.2.3. In recent years, polygeneration has been developed, which combines syngas use and direct energy utilization according to actual demands (of a region or depending on the season). Combustible gases like methane and hydrogen might have an important role in the transition to a larger share of renewables in energy supply systems. This represents a further application opportunity for biomass gasification processes, which can be tailored to produce syngas or hydrogen-rich product gas.

6.5.2 Limitations

The gasification of biomass has to compete with other more established technologies such as combustion and anaerobic digestion (AD). Both combustion and AD are simpler and have been around for longer so that there is more trust in them. Gasification systems also tend to be rather complex since they need a fuel preparation unit and a reactor matched to the fuel properties. Moreover, they do not work without a gas-cleaning system matched to the requirements of the downstream system that will finally convert the product gas into useful energy or energy carriers. A complete gasification system has to function efficiently. Even when this is the case, the initial investment in a gasification system can be prohibitively high. The overall economics of biomass gasification systems are dependent on many factors such as plant cost, good operability and the location of the system as well as the available infrastructure, e.g. the heat distribution network.

As mentioned above, gasification technology has to deal with tar-forming substances and a number of trace contaminants if syngas is utilized. There will always be technical solutions for these challenges but time, money, and patience are needed and still there is the risk of failure and economic loss if one of these runs out.

A further limitation of biomass gasification technology is plant size. In order to function well, the quality of the biomass fuel must meet the specifications (depending on the type of gasifier) all year round. Further, sustainability criteria for the feedstock have to be met. Biomass fuels are not available for free like the sun or the wind. So fuel costs have to be taken into account as well as transportation costs for moving the fuel to the gasification plant. Economic viability can only be achieved by nearly trouble-free continuous operation and by maximizing the income from selling electricity and heat or syngas products according to seasonal and regional demands. A biomass gasification plant has to fit in with the existing infrastructure or else a new infrastructure will have to be built, which leads to further costs.

For small gasifiers, the cost share of gas cleaning tends to be very high. Gasification systems are needed, which can generate clean gas without significant investment in gas cleaning and especially without large external waste streams. The latter would either need someone to make use of them (which would generate some revenue or make it possible to get rid of them at low cost) or they need careful disposal. See also Section 6.6 on future trends.

Besides the economic risks associated with fuel supplies, which need to be of adequate quality and quantity, and selling heat and electricity (CHP plants), SNG, hydrogen, and liquid products, the main challenge for biomass gasification is still gas cleaning, which can ensure trouble-free continuous operation of the gasification system. The future trends in the next section show in part how developers will deal with gas cleaning. There are different gas-cleaning strategies and adaptions to reactors for dealing with tar or for removing trace contaminants from synthesis gases at various scales and for various uses of the gas (Neubauer, 2011; Knoef, 2012).

6.6 Future trends

6.6.1 Gasification for combined heat and power

This sector has seen many ups and downs in the past years. One trend is towards downdraft small moving-bed gasifiers, e.g. Spanner RE^2 (Bleul, 2012), which produce a gas with a low tar content. The plants are manufactured in small numbers so that the costs are controlled. Another issue is the required high degree of automatization and measurement so that remote control and simple maintenance are possible, e.g. Burkhardt GmbH, Mühlhausen, Germany (Weichselbaum, 2012), which ensures proper operation of the plant. A German study (Schüssler *et al.*, 2009) showed that the performance of a gasifier does not just depend on technology but to a large degree on the experience of the operator and the time and effort expended; there are significantly different results even for the same type of plant. Corella *et al.* (2008) considered the operator as one of 12 operational parameters for good gasifier operation. For larger moving-bed systems, a trend for staged gasification can be seen; plant manufacturers include: Viking, Denmark (Henriksen *et al.*, 2006); TK Energy AS, Denmark (Friehling *et al.*, 2007); Weiss A/S, Denmark (Grøn, 2011); Cleanstgas, Austria (Timmerer *et al.*, 2012); Pyroneer, Denmark (Stoholm *et al.*, 2010; Stoholm, 2012); and Xylowatt Notar, Belgium (Dalimier *et al.*, 2012). This might be the right way to overcome the troublesome tar issue without the high expenses needed for washers or comparable equipment.

Furthermore, there are increased uses of fluidized-bed systems; plant manufacturers include: agnion (Kienberger *et al.*, 2012a; Kienberger, 2012); Repotec/Vienna University of Technology (Güssing) (Hofbauer *et al.*, 2002); Oberwart (Hofbauer, 2011); Villach (Klotz, 2010); and Gothenburg (Gunnarsson, 2011). There is a trend for scaling up fluidized-bed systems. The larger plants though are mainly intended for SNG production. Some will operate as CHP plants, while others in the future will run under different polygeneration modes; plant manufacturers include: agnion (Kienberger *et al.*, 2012a; Kienberger, 2012) and Taylor Biomass (Paisley, 2011). The first plants are already being operated by clients: Oberwart, Villach (Austria), Senden (Germany) – all of which are Güssing-type, fast internally circulating fluidized-bed (FICFB) reactors (Hofbauer, 2011; Klotz, 2010) and Grassau, Germany (agnion) (Kienberger *et al.*, 2012a; Kienberger, 2012).

6.6.2 Synthesis gas production

Biomass gasification with the aim of producing synthesis gas for further catalytic conversion into methane is now being demonstrated. In Sweden, two plants are planned for the production of SNG from syngas (Gunnarsson, 2011; Fredriksson Möller, 2011). In Austria, the process has been demonstrated in the Güssing plant.

Various cities (Gothenburg, Sweden (GoBiGas), Senden, Germany) and big energy companies such as E.ON Gasification Development AB, Sweden (Bio2G) (Fredriksson Möller, 2011); and GDF Suez, France (the GAYA project) (Mambré, 2010) have become involved in biomass gasification by setting up their own gasification plants for SNG production, which appears to be one of the major future trends.

The production of Fischer–Tropsch fuels from biomass gasification suffered a major setback when Choren Industries, which had a demonstration plant, went out of business in mid-2011. This demonstrates the risks associated with gasification technology, which has been accompanied by a diminishing trust in the technology since the collapse of the Arbre IGCC project in the UK (Rensfelt *et al.*, 2003). The Värnamo IGCC demonstration plant (Sydkraft, 2001; Waldheim, 2011) was supposed to be retrofitted to produce dimethyl ether (DME) for the Chrisgas Project. Public funding stopped in 2011, though additional industrial co-funding was expected. The plant was initially planned as a demonstration unit and therefore the location chosen was not optimal for continuous operation (e.g. for heat sales to a neighboring community).

For another demonstration project – the Bioliq plant at the Karlsruhe Institute of Technology Germany – the initial plans to produce Fischer–Tropsch fuels were changed to DME due to the better flexibility in the use and further processing of DME and because the relevant catalysts have higher resistance. There are current plans for large demonstration gasification plants mainly for SNG production, though some are for liquid fuel production. The questions of what are the right scale and right size of the plants have not been answered though. This is a very complex topic with many relevant factors such as: the sustainable biomass supply at steady quality, biomass pre-treatment, gasification processing and complexity, location and infrastructure, investment and operational costs, market prices for fuels or chemicals to be substituted, subsidies including direct payments, feed-in tariffs, carbon credits, and so on.

6.6.3 Adaptable processes, polygeneration and combination with other kinds of renewable energy

The processes mentioned above, except for some demonstration units, have a single goal of producing a gas for co-combustion in industrial processes, e.g. the Lahti plant (Breitholtz, 2012), producing heat and electricity (CHP and IGCC), generating SNG or generating synthesis gas to produce liquid ‘second-generation biofuels’ or chemical feedstock. The main challenge is the profitable and continuous operation over long periods of time. Polygeneration with biomass gasification as a way to adapt to seasonal demands has been addressed before. Recently, Sterner and Specht (Sterner, 2009; Specht *et al.*, 2009) considered the transformation of energy supply systems to provide more renewable energy, including volatile solar and wind power. There are times when electricity generation exceeds the capacity of the electricity networks while sufficient storage capacity for electricity, e.g. pumped-storage hydropower plants or compressed air energy storage (CAES) plants, is not available. The possibility of converting the excess electricity to gas (hydrogen) by electrolysis and the further use of the hydrogen to form methane (SNG) by reacting it with carbon dioxide (the Sabatier reaction) has been discussed as a power-to-gas process (also called wind gas or sun gas). As mentioned above, natural gas grids have large storage capacities. This transformation of electricity to chemical energy should not just be seen as storage for electricity, since the overall efficiency of converting electric power to hydrogen and back to electricity, e.g. by reversible fuel cells, is relatively low (ca. 40%). It also gives the possibility, e.g. by making use of the oxygen produced, for a biomass gasification process delivering synthesis gas, which could be upgraded to SNG. The high-temperature gasification process has options for coupling with more efficient high-temperature electrolyzers. The operational and economic boundary conditions still seem quite unstable for these kinds of solutions but technically they should be possible and might open interesting opportunities for the desired transformation of energy supply systems.

6.7 Sources of further information and advice

There are many sources for further information that can be used to follow the progress in this field, which deal with gasification and with a special focus on biomass utilization. They include scientific journals, books, reference works, conferences and organizations that deal with these kinds of technology or with the scientific progress in certain areas. Nevertheless, the technical implementation, the political framework, and research and developments are cyclic so that conferences disappear, research groups change or the focus of their work changes. Gasification technology might not be mature at all but it has a long history. The reasons for technical development and the focal points shifting from the technology being a gas supply for cities, to synthesis gas production for the nascent chemical industry, as an alternative fuel supply for transportation during the war, as an alternative to foreign oil and gas, and as a climate friendly technology with high overall efficiency. At the end of the nineteenth century and in the 1920s until the early 1950s, the technology was in widespread use. Basic research was conducted throughout the 1960s; the oil crisis in the late 1970s led to the intensive efforts in the 1980s and from the 1990s there have been environmental and climate concerns. Literature was published throughout these times and inventions were made. Biomass gasification technology has seen several generations of re-inventions and repeated collecting of practical experience. For this reason, the list of journals, reference works and conferences, which is given below, cannot be complete but it does give resources for finding the current status of the technology and it is a starting point into this challenging scientific and technological field.

Conferences

- *European Biomass Conference and Exhibition*, annually in May or June in a European city (www.conference-biomass.com).
- *tcbiomass2013 – The International Conference on Thermochemical Conversion Science*, every two years in Chicago (http://www.gastechnology.org/tcbiomass2013/pages/default.aspx)
- DGMK *Konferenz Konversion von Biomassen*, every two years (www.dgmk.de).
- *International Seminar on Gasification 2xxx*, annually by the Swedish Gas Centre in Stockholm, Gothenburg or Malmö (www.sgc.se).
- *International Conference on Polygeneration Strategies*, every two years in Austria.
- *Gasification Technologies Conference 2xxx*, annually in San Francisco or Washington, DC; the main focus is on large-scale industrial gasification including biomass gasification (www.gasification.org).
- *International Conference on Application of Biomass Gasification*, annually Stuttgart, Germany.

Conference proceedings from previous conferences

- *Proceedings of the NATO Advanced Research Workshop on Fundamental Issues in Control of Carbon Gasification Reactivity*, Cadarache, Saint-Paul-les-Durance, France, 30 July to 3 August 1990 (LaHaye and Ehrburger, 1991).
- *Proceedings of the NATO Advanced Study Institute on Carbon and Coal Gasification – Science and Technology*, Alvor, Portugal, 20–31 May 1985 (Figureido and Moulijn, 1986).
- Bridgwater, A. V. and Kuester, J. L. (1988) *Research in Thermochemical Biomass Conversion*. Elsevier Applied Science, London, New York (conference held in April 1988, Phoenix, Arizona).
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Reference works

Ullmann's Encyclopedia of Chemical Technology. Wiley. Sections on gas production, fluidized-bed reactors, tar and pitch, and carbon.

Books

- Basu, P. (2010) *Biomass Gasification and Pyrolysis: Practical Design and Theory*. Academic Press.
- Higman, C. and van der Burgt, M. (2008) *Gasification*, 2nd edition. Elsevier Inc, Massachussets.
- Knoef, H. A. M., (ed.) (2012) *Handbook Biomass Gasification*, 2nd edition. Biomass Technology Group BV, Enschede.

Scientific journals

- *Biomass and Bioenergy* (Elsevier)
- *Biomass Conversion and Biorefinery* (Springer)
- *Energy and Fuels* (ACS Publications)
- *Fuel* (Elsevier)
- *Fuel Processing and Technology* (Elsevier)
- *Industrial & Engineering Chemistry Research* (ACS Publications)

Related to this topic:

- *Carbon* (Elsevier)
- *Analytical and Applied Pyrolysis* (Elsevier)

Organizations and networks

- International Energy Agency (IEA), IEA Bioenergy Task 33: Thermal Gasification of Biomass (www.ieabioenergy.com/Task.aspx?id=33).
    - ‘Observation on the current status of biomass gasification’, S.P. Babu, leader of Task 33: Thermal Gasification of Biomass, 17 March 2005, (www.ieabioenergy.com/media/58_BiomassGasification.doc).
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7

Fast pyrolysis of biomass for the production of liquids

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Abstract: This chapter examines the fast pyrolysis of biomass to produce liquids for use as fuels and chemicals. The technology for fast pyrolysis is described and the characteristics of the main product bio-oil. This primary liquid is characterised by the many properties that affect its use. These properties have caused increasingly extensive research to be undertaken to address properties that need modification and this area is reviewed in terms of physical, catalytic and chemical upgrading. Of particular note is the increasing diversity of upgrading methods.

Key words: biomass, biofuel, bio-oil, fast pyrolysis.

7.1 Introduction

Solid biomass fuels and residues can be directly utilised for energy as in combustion, but there is considerable advantage and interest in converting them to more valuable and flexible energy forms as liquids or gases. This paper focuses on fast pyrolysis to produce liquids as a particularly flexible way of processing biomass, including residues and wastes. This route for liquid production is particularly interesting as the liquids are produced in high yields and can be easily stored and transported; they can be used for energy, chemical production or as an energy carrier. Pyrolysis has been used for thousands of years for charcoal production but it is only in the last 30 years that fast pyrolysis has become of considerable interest because the process directly gives high yields of liquid of up to 75 wt.%. The liquids can be used directly in a variety of applications[1] or as an efficient and effective energy carrier. A number of reviews have recently been published.[2–4]

7.2 Pyrolysis principles and products

Pyrolysis is thermal decomposition occurring in the absence of oxygen. Lower process temperatures and longer vapour residence times favour the production of charcoal. High temperatures and longer residence times increase biomass conversion to gas, and moderate temperatures and short vapour residence times are optimum for producing liquids. Table 7.1 shows the product distribution obtained from different modes of pyrolysis, showing the considerable flexibility achievable by changing process conditions. Three products – gas, liquid and

Table 7.1 Typical product weight yields (dry-wood basis) obtained by different modes of pyrolysis of wood

Mode	Conditions	Liquid	Solid	Gas
Fast	~500°C, short hot vapour residence time ~1 s	75%	12% char	13%
Intermediate	~500°C, hot vapour residence time ~10–30 s	50% in 2 phases	25% char	25%
Carbonisation (slow)	~400°C, long vapour residence	30% in 2 phases	35% char	35%
Gasification	~750–900°C short hot vapour residence time	5%	10% char	85%
Torrefaction (slow)	~290°C, solids residence time ~10–60 min	0% unless condensed, then up to 10%	75% solid	25% including vapour

solid – are always produced, but the proportions can be varied over a wide range by adjustment of the process parameters.

7.2.1 Principles of fast pyrolysis

In fast pyrolysis, biomass decomposes very quickly to generate vapours and aerosols, charcoal and gas. After cooling and condensation, a dark brown homogeneous mobile liquid is formed from the vapours and aerosols with a heating value about half that of conventional fuel oil. Table 7.2 summarises the key properties. The essential features of a fast-pyrolysis process for producing liquids are:

- Very high heating rates and very high heat transfer rates at the biomass particle reaction interface usually requiring a finely ground biomass feed of typically less than 3 mm in the smallest dimension as biomass has a low thermal conductivity.
- Low feed moisture content as water in the feed ends up in the liquid product.
- Carefully controlled pyrolysis reaction temperature of around 500°C to maximise the liquid yield. For wood this reaches up to 75wt.% on a dry-feed basis for most biomass, and drops to 55–65% for grasses and other higher ash materials.
- Short hot vapour residence times of typically less than 2 s to minimise secondary reactions.
- Rapid removal of product char to minimise cracking of vapours.
- Rapid cooling of the pyrolysis vapours and coalescence of the aerosols to give the bio-oil product.

7.2.2 Products of fast pyrolysis

The main product, bio-oil, is obtained in yields of up to 75 wt.% on a dry-feed basis, together with the by-products, char and gas. Both can be used to provide heat for pyrolysis or drying the biomass feed.

Bio-oil

Pyrolysis oil typically is a dark brown, free-flowing liquid, which approximates to biomass in elemental composition. It is composed of a very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water from both the original moisture and as a pyrolysis reaction product. The liquid is formed by rapidly quenching and thus 'freezing' the intermediate products of flash degradation of hemicellulose, cellulose and lignin. The liquid thus contains many reactive species, which contribute to its unusual attributes. Solid char may also be present. Depending on the initial feedstock and the mode of fast pyrolysis, the colour can be almost black through dark red-brown to dark green, being influenced by the presence of micro-carbon in the liquid and chemical composition. Hot vapour filtration gives a more translucent red-brown appearance owing to the absence of char. A high nitrogen content can impart a dark green tinge to the liquid.

The typical maximum yield of bio-oil from woody materials is around 75 wt.% and contains 70% of the energy of the biomass (see Fig. 7.1). Fast-pyrolysis liquids have a higher heating value of about 17 MJ/kg as produced, with about 25 wt.% water that cannot readily be separated. While the liquid is widely referred to as 'bio-oil', it will not mix with any hydrocarbon liquids. It is composed of a complex mixture of oxygenated compounds that provide both the potential and challenge for utilisation. Some important properties of this liquid are summarised in Table 7.2.

Table 7.2 Typical key properties of wood-derived crude bio-oil

Physical property	Typical value
Moisture content	25%
pH	2.5
Specific gravity	1.20
Elemental analysis	
C	56%
H	6%
O	38%
N	0–0.1%
HHV as produced	17–18 MJ/kg
Viscosity (40°C and 25% water)	40–100 MPa.s
Solids (char)	0.1%
Vacuum distillation residue	Up to 50%

Note: HHV: higher heating value.

There are a range of characteristics of bio-oil that require consideration for any application and recently they have been thoroughly reviewed:[4]

- Acidity or low pH from organic acids.
- Ageing leads to an increase in viscosity and possible phase separation.
- Alkali metals can be a problem in stored oil, but as nearly all the natural ash in biomass ends up in the char, effective char separation will minimise ash. Some alkali metals can dissolve in the acidic environment during storage.
- Char is difficult to completely separate from the vapours while maintaining a small hot vapour residence time, so there will always be a small level in the bio-oil.
- Chlorine can be a contaminant with chlorine-contaminated biomass feed.
- Colour may be a problem in some direct applications such as substitution of resins for wood panels such as plywood, where the resin will appear black.
- Contamination of feed, for example by soil during harvesting, will result in altered pyrolysis reactions and potential reduced yield and/or phase separation due to the catalytic effect of the minerals in the soil.
- Distillation is not possible as with conventional hydrocarbon fuels, since the thermal stability above 100°C is poor and cracking results.
- The high viscosity of raw bio-oil creates pumping and atomisation problems for combustion.
- Low H/C ratio leads to high hydrogen consumption in hydro-processing upgrading.
- Incompatibility of materials arises from components in the bio-oil reacting with processing equipment such as seals and gaskets.
- Miscibility with hydrocarbons is very low because of the highly oxygenated nature of most of the chemicals that make up bio-oil. Blending and emulsions have been studied to address this problem.
- Nitrogen can adversely affect odour in high nitrogen feedstocks. High nitrogen also produces higher NO_x in combustion.
- Oxygen content affects mixing and upgrading and results in stability and ageing problems.
- Phase separation (inhomogeneity) can result particularly with high ash feedstocks, contaminants in the feed, high moisture feed, poor char separation and high hot vapour residence times.
- Smell or odour arises from the complex oxygenated organic chemicals especially aldehydes and ketones, which are derivatives of cellulose and hemicellulose.
- Solids arise from incomplete char and inert material separation.
- Structure is a largely unknown phenomenon of bio-oil, but is believed to be a micro-emulsion.
- Sulphur arises from contaminants in the feed.
- Temperature sensitivity is derived from the rapid processing method of fast pyrolysis and the controlled cessation of secondary reactions. Heating leads to

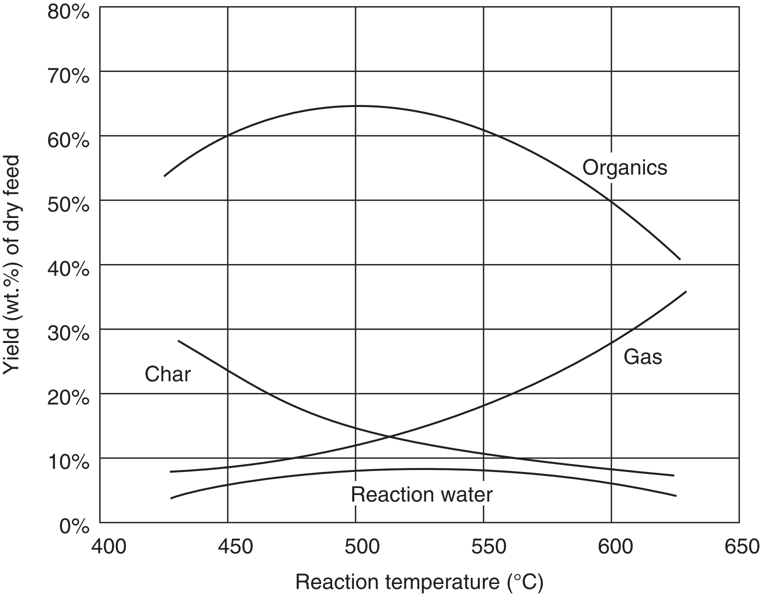
an increase in viscosity (ageing) and eventually to irreversible phase separation into a heavy organic phase and a light low-viscosity watery phase.

- Toxicity is an important consideration in handling bio-oil. A comprehensive assessment found that while bio-oil is not benign, there are low levels of risk to humans and the environment.
- Viscosity is variable according to feedstock, technology, method and temperature of liquid collection and other factors. There is a greater temperature effect than found in hydrocarbon fuels, which helps in some viscosity-sensitive applications.
- Water has a complex effect on bio-oil: increasing the water content reduces viscosity, reduces heating value, improves stability, lowers density and increases (improves) pH.

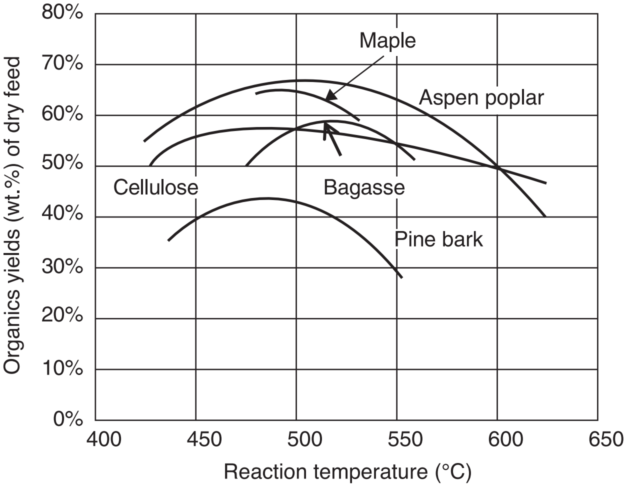
Oasmaa and Peacocke reviewed physical property characterisation and methods,[5] which play a major role in the determination of the many properties that require specification.

Yield

Liquid yield depends on biomass type, reaction temperature, hot vapour residence time, effective char separation and low biomass ash content, the last two having a catalytic effect on vapour cracking. Figure 7.1 shows the temperature dependence



7.1 Variation of products from aspen poplar with temperature.[6] Total liquid yield is the sum of organics, reaction water and feed water.



7.2 Yield of organics from different feedstocks.[6]

of the four main products and Fig. 7.2 shows the yield for a variety of feedstocks.[6] Since it is the organic components that have an energy value, the yield of organics is more important than total liquid yield, since a poorly manufactured bio-oil may have a very high water content and consequently a very low heating value, and will probably be phase separated.

The total liquid yield is the sum of organics, reaction water and feed water. Similar results are obtained for most biomass feedstocks, although the maximum yield can occur between 480 and 520°C depending on feedstock. Grasses, for example, tend to give maximum liquid yields of around 55–60 wt.% on a dry-feed basis at the lower end of this temperature range, depending on the ash content of the grass. It is important to note that maximising liquid yield does not necessarily maximise liquid quality.

A homogeneous liquid is usually formed, which consists of what is considered to be a micro-emulsion of water-soluble oxygenated organic compounds supporting micelles of pyrolytic lignin. This micro-emulsion is stabilised by naturally produced surfactants.

Char

The by-product char is typically about 10–15 wt.% of the products but holds about 25% of the energy of the biomass feed. It can be used to provide the required process heat by combustion or it can be separated and exported, in which case an alternative fuel is required for the pyrolysis reactor. As it retains virtually all the alkali metals, effective char removal is important and acts to upgrade the bio-oil as well as being a valuable product for soil conditioning, fertilisation and carbon sequestration.

In fluid-bed processes, a large part of the char will be of a comparable size and shape as the biomass feed. In transported-bed and circulating-fluid-bed reactors, the char is usually burned within the process in a close coupled combustor and thus there is no char produced as a by-product.

Fresh char is pyrophoric, i.e. it spontaneously combusts when exposed to air so careful handling and storage are required. This property deteriorates with time due to oxidation of active sites on the char surface.

There is some interest in combining the char with the bio-oil to form a slurry, notably at the Karlsruhe Institute of Technology (KIT), Germany, in order to maximise the energy yield of the process. Yields of 85–90% energy in the slurry compared to the biomass input have been reported.

Gas

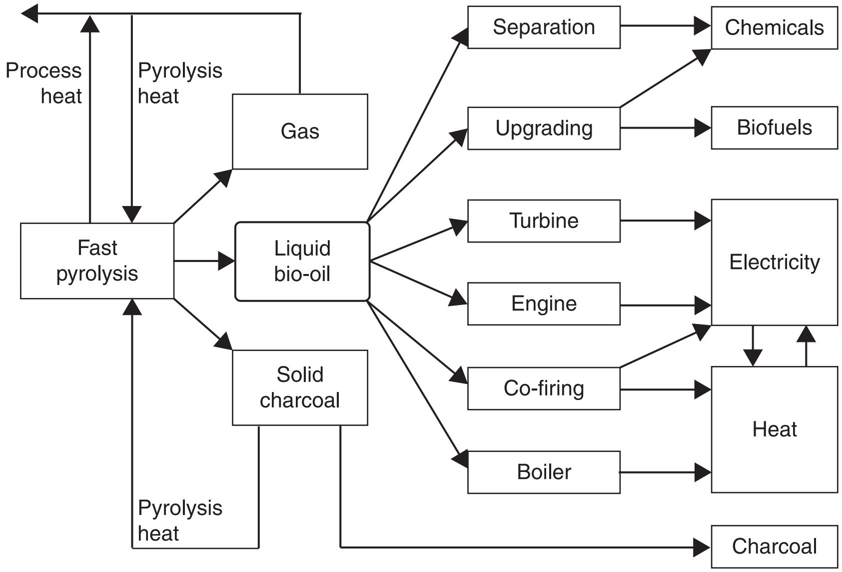
The gas contains CO_2, CO, H_2 and CH_4 and minor components of higher hydrocarbons. It contains about 5% of the energy of the biomass and is thus not a major energy resource. In fluid-bed, circulating-fluid-bed and transported-bed systems, most of the gas is recycled for fluidisation.

7.3 Applications of bio-oil

Bio-oil can substitute for fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation, which was thoroughly reviewed in 2004[1] and many aspects have not changed very much. The most significant changes since then are:

- An appreciation of the potential for fast pyrolysis to be a pretreatment method, i.e. for bio-oil to be an effective energy carrier.
- Greater interest in bio-oil as a precursor for second generation biofuels for transport.
- Greater awareness of the potential for fast pyrolysis and bio-oil to offer more versatile process routes to give a wider range of products and contribute to biorefinery development.
- Considerably greater interest in upgrading bio-oil sufficiently for it to be used for heat, power and other applications with greater confidence by users.

Figure 7.3 summarises the possibilities for applications for bio-oil and the main developments are expanded below.



7.3 Applications for fast-pyrolysis products.

7.3.1 Bio-oil as an energy carrier

Biomass is a widely dispersed resource, which has to be harvested, collected and transported to a conversion facility. The low bulk density of biomass, which can be as low as 100 kg/m^3, means that transport costs are high and the number of vehicle movements for transportation to a large processing facility is also very high, with consequent substantial environmental and economic impacts.

Conversion of biomass to a liquid by fast pyrolysis at or near the biomass source will reduce transport costs and reduce environmental concerns as the liquid has a density of 1200 kg/m^3 – up to twelve times higher than lower density crops and residues. This not only reduces the number of vehicle movements and costs by up to 87%, it also reduces the costs of handling and transportation by virtue of it being a liquid, which can be pumped. It is also possible to mix the by-product char with bio-oil to make a slurry, which improves the energy content of the product, but the pyrolysis process will then require that its process energy needs are met from another source. Small decentralised fast-pyrolysis plants are proposed to produce 100 000 to 300 000 t/y of liquids, which are transported to a central processing plant – such as a gasification plus a Fischer–Tropsch or methanol synthesis plant.

7.3.2 Bio-oil combustion

Bio-oils are combustible but not flammable. Bio-oil requires significant energy for ignition due to the high level of non-volatile and non-flammable constituents, but once ignited it burns with a stable self-sustaining flame. An extensive study of the fundamentals of the combustion of single bio-oil droplets was carried out at Sandia National Laboratory.[7,8] This showed a unique multi-step process involving vaporisation of volatiles leaving a cenosphere of solid carbon which results in particulate and/or higher CO emissions. Under the same conditions, conventional fossil-fuel oil demonstrated only quiescent, sooty burning from ignition through burnout. The burning times of bio-oils were comparable to those of No. 2 fuel oil under the same conditions. The adiabatic flame temperature for bio-oil is relatively high at 1400–1700°C compared to 1900–2000°C for orthodox fuels. This is due to the significantly lower stoichiometric air-to-fuel ratio for bio-oil of about 7 compared to 14 for orthodox fuels.

There is growing interest in bio-oil combustion in boilers, furnaces, engines and turbines as the benefits of a liquid fuel are more widely established and appreciated. There are clear differences in combustion behaviour and emissions for different bio-oils; lower quality oils with higher viscosity, water and solids content showed significantly worse performance. Emissions are generally lower than from burning heavy fuel oil except for particulates. Proper handling of bio-oil is essential: there is generally some preheating to around 50°C or a little higher to reduce viscosity and improve atomisation, and compressed air is used for atomisation. Quality is also important, for example, a higher water content leads to lower NO_x but higher particulates in flue gases. Other test work in North America and Europe,[1] confirmed the similarity in combustion behaviour with conventional fuel oils.

A consistent and better quality bio-oil that is available at an attractive price is necessary for commercial, large-scale applications. Storage, pumping, filtration, atomisation and optimisation of the burner/boiler design to improve performance and reduce emissions only require relatively minor modifications to existing equipment. Bio-oil is a suitable boiler fuel as long as it has consistent characteristics, provides acceptable emission levels and is economically viable.

Co-firing

Co-processing of biomass with conventional fuels is potentially a very attractive option that enables full economies of scale to be realised as well as reducing the problems of product quality and clean up.

In most current co-firing applications, solid biomass is added to the coal feed. Typically, biomass meets up to 10% of the energy demand of a power station although proportions are now being substantially increased. A few applications involve conversion to a fuel gas via gasification followed by close coupled firing in the power station boiler. There are a few examples of co-firing fast-pyrolysis liquids including a coal-fired power station at Manitowoc in the USA, which uses the by-products from the manufacture of liquid smoke produced by Red Arrow.[9,10] The combustion of bio-oil is clean and efficient with no adverse effects on boiler operation or on emission levels. There is also some limited experience of successfully firing bio-oil in a natural gas-fired power station in the Netherlands. Co-firing offers attractive opportunities for market penetration of bio-oil as the overall costs are relatively low because the power cycle in a coal-fired power plant is already in place. In addition, co-firing has the advantage over co-combustion (where biomass fuel is mixed with coal before or during combustion), in that the biomass residual ash is not mixed with the coal ash, which has an existing market as a construction material.

Engines and turbines

Diesel engines have a high efficiency (up to 45%) in power generation and can also be adapted to combined heat and power systems (CHP). Medium- and slow-speed engines are known for fuel flexibility and can operate on low-grade fuels. The main concerns for operating diesel engines on bio-oils are some specific properties of these liquids such as difficult ignition (due to the low heating value and high water content), corrosiveness (acids) and coking (thermally unstable compounds). Turbines are more efficient at higher capacities but modern micro-turbines have improved performance. The potential advantages of using bio-oils for power generation have led to a range of research activities.[1] In 2011 Ensyn announced a substantial diesel-engine-based power plant in Canada with a wood waste input of 400 t/y, with additional plans for Malaysia and Italy.[10]

7.3.3 Chemicals

For many centuries wood-derived pyrolysis liquids have been a major source of chemicals such as methanol, acetic acid, turpentine and tars. At present, most of these compounds can be produced at a lower cost from fossil-fuel feedstocks. Chemicals are always attractive commercial possibilities owing to their much higher added value compared to fuels and energy products. This suggests a biorefinery in which the optimum combination of fuels and chemicals are produced.

The chemicals in bio-oil are derived from random thermal decomposition of hemicellulose, cellulose and lignin. Although over 400 compounds have been identified in wood fast-pyrolysis oil, their concentrations are usually too low for economic separation and recovery. Up to now, therefore, the technology for producing products from the whole bio-oil or from its major, relatively easily separable fractions, is the most developed. Reviews on this subject, including consideration of higher-value products, have been published by Radlein,[11] Czernik and Bridgwater[1] and Dobele.[12] Some of the chemicals that have been produced are shown in Table 7.3. The chemical groups regularly mentioned in the literature are listed in Table 7.4.

Strategies for separation or recovery of any of these chemicals need to consider market value, costs and process. The natural first step is to evaluate components with the highest concentration since the processing will be easier and the costs

Table 7.3 Some chemicals produced by fast pyrolysis

Acetic acid	Hydroxyacetaldehyde	Preservatives
Adhesives	Levoglucosan	Resins
Calcium-enriched bio-oil	Levoglucosenone	Slow-release fertilisers
De-icer	Maltol	Sugars
Food flavourings	Phenol	
Hydrogen	Polyphenols	

Table 7.4 Numbers of chemicals, by group, regularly mentioned in the literature[28]

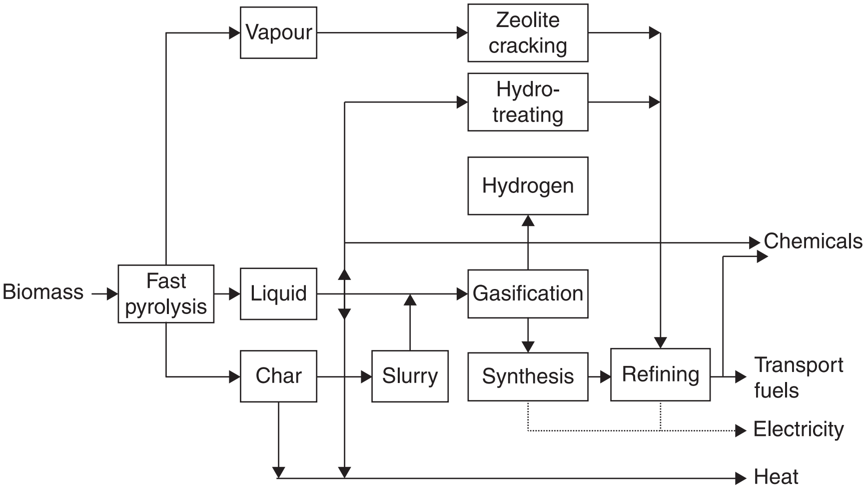
Acids	12
Alcohols	4
Aldehydes	5
Esters	1
Hydrocarbons	6
Ketones	32
Oxygenates	16
Phenolics	56
Steroids	15
Sugars	8
Total	*155*

lower. However, this may not prove the best strategy, and methodologies need to carefully consider capital and operating costs, product values and residue or waste utilisation or disposal. The opportunities for optimisation are considerable and challenging, and are likely to involve a range of process generation, evaluation and optimisation tools including process synthesis and linear programming.[13]

7.3.4 Biorefineries

Many chemicals are manufactured from petroleum feedstocks though only a small proportion of total crude oil production, around 5%, is used for chemical manufacture. However, the value of these chemicals is high and the sector contributes revenues comparable to that from fuel and energy products. There is a clear economic advantage in building a similar flexibility into the biofuel market by using some of the biomass in the manufacture of chemicals. In fact, this makes even more sense in the context of biomass because it is chemically more heterogeneous than crude oil and the conversion to fuel, particularly hydrocarbons, is not so cost effective. Figure 7.4 suggests a role for fast pyrolysis at the heart of a biorefinery.

While biorefineries are not new, the recognition of their strategic and economic potential is relatively recent. A biorefinery can be defined as the optimised use of



7.4 Fast-pyrolysis biorefinery.

biomass for materials, chemicals, fuels and energy applications, where use relates to costs, economics, markets, yield, environment, impact, carbon balance and social aspects. In other words, there needs to be optimised use of resources, maximised profitability, maximised benefits and minimised wastes.

A key feature of the biorefinery concept is the co-production of fuels, chemicals and energy. As explained earlier, there is also the possibility of gasifying biomass to make syngas, a mixture of hydrogen and carbon monoxide, which can be used in the subsequent synthesis of hydrocarbons, alcohols and other chemicals. However, this process is energy intensive so a significant proportion of the energy content of the biomass is lost in processing with energy conversion efficiencies from biomass to biofuels being around 45–50%[14] so electricity generation is viewed by some as the most efficient use of biomass.[15]

Since the empirical chemical composition of biomass, approximately $(CH_2O)_n$, is quite different from that of oil $(CH_2)_n$, the range of primary chemicals that can be easily derived from biomass and oil are quite different. Hence, any biomass chemical industry will have to be based at least in part on a different selection of simple "platform" chemicals than those currently used in the petrochemical industry. Since the available biomass will inevitably show major regional differences, it is quite possible that the choice of platform chemicals derived from biomass will show much more geographical variation than in petrochemical production.

It is currently envisaged that biorefineries should initially focus on a limited number of platform chemicals for earlier implementation.[16] Evolution will mean non-edible feedstocks such as cellulose or lignin can be turned into well-defined, useful carbon sources at high purity but at a lower cost than from starch or sugar feedstocks. For example vegetable oils can be transformed into a variety of high-value chemicals, particularly surface active chemicals; therefore, it is wasteful merely to burn them as biodiesel, which should be derived from less valuable bio-feedstocks.[17]

7.4 Feedstocks

7.4.1 Introduction

Biomass is a diffuse resource, produced over very large areas, and thus requiring large land areas with substantial logistical problems in collection and transport as well as high costs. Typically, a sustainable crop of 10 dry t/ha/y of woody biomass can currently be produced in northern Europe, rising to perhaps 15 or 20 dry t/ha/y for energy crops in southern Europe and more tropical areas. Crop development through breeding and modification will eventually increase these yields. Thus an area of 1 km^2 or 100 ha will currently produce around 1000 dry t/y, enough for a power output of around 150 kW_e at low conversion efficiencies or up to 300 kW_e at high conversion efficiencies. A 50 MW_e biomass-fired power station will thus require a planted area of around 200 km^2. This is one reason for the increased interest in internationally traded biomass, using dock-side conversion facilities.

A further consideration with almost all forms of biomass is their seasonality: coppiced crops can usually only be harvested during the winter months, and energy crops and agricultural residues are even more seasonal, typically being available for only a few months a year. Either extensive provision for storage has to be made, or a multi-fuel system is required. Increasing research efforts are underway to develop processes that can handle a number of different fuels, either mixed or separately. This option also addresses the increased difficulties of processing high ash materials in fast pyrolysis when blending can provide a sufficiently low ash fuel to produce a good quality oil.

An alternative solution to the dispersed nature of biomass is to ‘concentrate’ it locally through conversion to a higher density liquid as discussed above. This is being actively examined as an alternative way of improving the logistics and economics of moving solid biomass from field or forest to a conversion or utilisation facility in order to benefit from economies of scale.

7.4.2 Biomass feedstocks

Any form of biomass can be considered for fast pyrolysis. While most work has been carried out on wood due to its consistency and comparability between tests, nearly 100 different biomass types have been tested by many laboratories ranging from agricultural wastes such as straw, olive pits and nut shells to energy crops such as miscanthus and sorghum and solid wastes such as sewage sludge and leather wastes. All feedstocks give appreciable yields of liquids, with cellulose giving the highest yields at around 85–90 wt.% for dry feed, hard and soft woods giving typically 70–75 wt.%, straw and bagasse giving 50–55 wt.% and bark giving 30–35 wt.%. Those biomass types that contain appreciable quantities of ash, particularly alkali metals, give reduced liquid yields due to the catalytic cracking effect of the ash. This was shown above in Fig. 7.2. Some of the types of biomass that have been successfully processed by fast pyrolysis are shown in Table 7.5.

Table 7.5 Different types of biomass processed by fast pyrolysis

Biomass components
Avicel pH102 cellulose
Avicel cellulose
Cellulose
Iotech cellulose
Microcrystalline cellulose
Lignin
Agricultural waste
Bagasse
Corn stover
Corn starch
Grain screening
Flax shives
Olive waste
Rice husks
Sunflower hulls
Sorghum bagasse
Sugar cane bagasse
Straw
Straw, wheat
Wheat chaff
Energy crops
Miscanthus
Sweet sorghum
Tobacco
Wood energy
Aspen poplar
Beech
Birch
Eastern red maple
Maple
Mixed soft wood
Mixed wood waste
Pine
Poplar whole tree
Poplar
Poplar, hybrid
Poplar, IEA
Spruce
Sugar maple

(*Continued*)

Table 7.5 Continued

Wood wastes
Aspen poplar bark
Bark
Peat
Black peat
Brown peat
Peat moss
Peat
Swedish peat
Waste
Newsprint
Sewage sludge

A concern with the feed materials is their physical characteristics, particularly the size and shape after comminution. After size reduction, some material tends to form long thin fibres, which knit together and become very difficult to handle, store and feed into a reactor. This may be a major limitation on their use.

7.4.3 Reception, storage and handling

After harvesting, the biomass has to be transported to the processing site where it is weighed, stored and reclaimed for preparation and pretreatment. Storage can be a simple concrete pad with a front-end loader for small capacity plants through to complex and substantial automated bulk handling systems, analogous to those found on pulp and paper mills, for large plants.

A key feature of most types of biomass is that they cannot be harvested all year round or they are only available for limited periods. Examples include wheat straw, which is produced from July to October, miscanthus, which is usually harvested from March to April while senescent, and deciduous trees, which are usually only harvested when dormant from November to March. Therefore either substantial storage is required or multi-feed pyrolysers are needed.

7.4.4 Preparation

Biomass requires several preparation steps, summarised in Fig. 7.5, which include:

- Drying to reduce moisture content to the preferred level for subsequent conversion.
- Comminution to produce material of the optimum size and shape for subsequent conversion.

- Screening or sieving to separate the required feed particle size, which may include rejection of oversized pieces for recycling to a re-chipper or rejection of undersized pieces for utilisation elsewhere in the process such as combustion for heating the drier.
- Optional steps dependent on the particular biomass being processed such as magnets for ferrous metal removal.

Preparation can be partly carried out at source, such as chipping in the forest to minimise transport and handling costs, but there will always be a requirement to monitor and control biomass characteristics to ensure optimum operation of the conversion plant. This applies particularly to particle size and shape and moisture content when the economies of scale and the availability of heat and power make operation in the conversion plant more effective and more efficient.

7.4.5 Pretreatment

There has been considerable interest in both torrefaction and fast pyrolysis as methods of pretreatment for biomass to reduce costs and environmental impact and improve efficiency. The advantages of converting solid biomass into a liquid bio-oil have been discussed above. There is the additional cost and loss of efficiency in liquefaction of biomass to be set against the reduced transport and handling costs and reduced secondary processing costs.[17]

The interest in fast pyrolysis as a pretreatment step arises from the following considerations:

- Bio-oil from fast pyrolysis has a density of 1200 kg/m^3 compared to some biomass with a bulk density as low as 100 to 150 kg/m^3. The energy content of bio-oil is about the same as biomass by weight. Transport costs are thus much lower since most solid biomass transportation is constrained by volume rather than weight.
- The alkali metals in biomass, which can cause severe problems in gasification and gas cleaning, are almost entirely retained in the char almost all of which is separated out in the fast-pyrolysis process.
- Handling, storing and transporting liquids are much easier and hence lower in cost in both financial and energy terms than solids. This applies to both at the bio-oil production site and at the reception of the biofuel production site.
- Feeding liquid to a gasifier is easier and thus lower in cost than solids, particularly when pressurised.
- Gasifier products will have lower tar content and much lower alkali metal content, thereby reducing gas cleaning and maintenance requirements

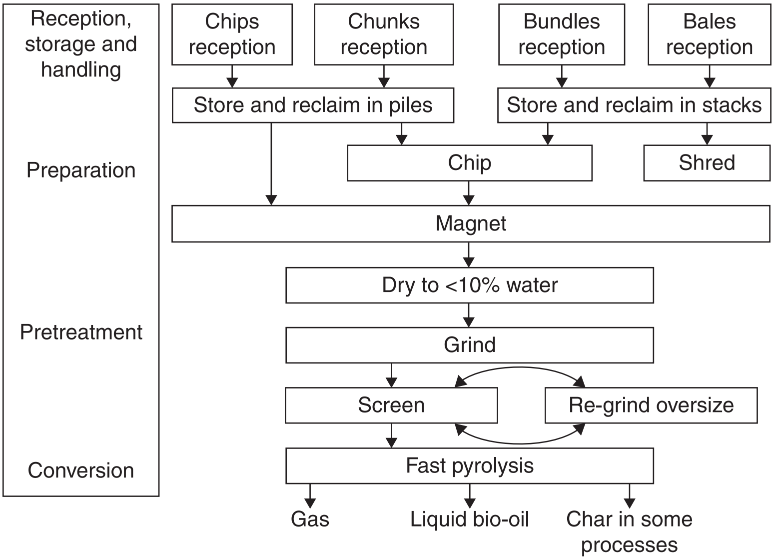
These considerations have led to the concept of multiple decentralised and relatively small fast-pyrolysis units collecting biomass from a smaller area and delivering liquid to a central processing plant for gasification and synthesis of biofuels. The challenges facing this concept include:

- The provision of several smaller fast-pyrolysis plants has a diseconomy of scale, thus increasing the capital cost of the system.
- The inclusion of an additional step of fast pyrolysis reduces overall process efficiency.

7.4.6 System and economics

A complete front-end system is summarised in Fig. 7.5 from reception of a variety of feed materials to the fast-pyrolysis step.

The steps for reception, storage and handling, preparation and pretreatment are significant in economic terms with capital costs ranging from 5% to 21% for capacities from 5 to 20 MWe,[18] and 10–15% for a large gasification-Fischer–Tropsch synthesis plant. There is not a standard formula for this and costs depend on the type of biomass and the sophistication of the step – a high capital cost usually means low labour costs. The handling and transportation of bio-oil is becoming increasingly controlled and a thorough review of requirements and recommendations has been published.[19]



7.5 Biomass reception, storage and handling, preparation and pretreatment.

7.5 Fast-pyrolysis technology

7.5.1 Fast-pyrolysis reactors

In the early development of the technology, research and development focussed on developing and testing different reactor configurations, but more recently attention has focussed on the quality of bio-oil and its upgrading to a more consistent and useful liquid fuel.[4] A brief summary of the main technologies and their characteristics is provided below and a more comprehensive review has recently been published.[3]

Bubbling fluid beds

Bubbling fluid beds have the advantages of being a well-understood technology that is simple in construction and operation, good temperature control and very efficient heat transfer to biomass particles arising from the high density of solids. Heating can be achieved in a variety of ways and scaling is well understood. However, heat transfer to fluid beds at large scales of operation has to be considered carefully because of the scale-up limitations of different methods of heat transfer. Fluid-bed pyrolysers give good and consistent performance with high liquid yields of typically 70–75 wt.% from wood on a dry-feed basis and are thus used extensively in research and development. Small biomass particle sizes of less than 2–3 mm are needed to achieve high biomass heating rates, and the rate of particle heating is usually the rate-limiting step. There is probably an upper limit on throughput of a single reactor of around 10 t/h dry biomass.

Vapour and solid residence times are controlled by the fluidising gas flow rate and is higher for char than for vapours. As char acts as an effective vapour-cracking catalyst at fast-pyrolysis reaction temperatures, rapid and effective char separation is important. This is usually achieved by ejection and entrainment followed by separation in one or more cyclones, so careful design of sand and biomass/char hydrodynamics is important. The by-product char is typically about 10–15 wt.% of the product but about 25% of the energy of the biomass feed. It can be used to provide process heat by combustion or it can be separated and exported, in which case an alternative fuel is required for the pyrolysis reactor. Depending on the reactor configuration and gas velocities, a large part of the char will be of a comparable size and shape as the biomass feed. Fresh char is pyrophoric, i.e. it spontaneously combusts when exposed to air so careful handling and storage is required. This property deteriorates with time due to oxidation of active sites on the char surface.

The high level of inert gases arising from the gas flows required for fluidisation, results in very low partial pressures for the condensable vapours and thus care is needed to design and operate efficient heat exchange and liquid collection systems. In addition, the large inert gas flow rates result in relatively large equipment thus increasing cost.

Circulating fluid beds and transported beds

Circulating fluid bed (CFB) and transported-bed reactor systems have many of the features of bubbling beds described above, except that the residence time of the char is almost the same as for vapours and gas, and the char is more attrited due to the higher gas velocities. This means that larger particles can be used than in fluid beds, but conversely it means that the char has much smaller particles than fluid beds requiring more careful removal. CFBs are suitable for larger throughputs than fluid-bed systems but the endothermic nature of pyrolysis places increasing demands for effective heat transfer as throughput increases. The upper limit for an individual reactor may be 20–30 t/h with higher throughputs from multiple reactors or systems.

Heat is usually supplied from the recirculation of hot sand from the secondary char combustor, which can be either a bubbling or circulating fluid bed. In this respect the process is similar to a twin fluid-bed gasifier except that the reactor (pyrolyser) temperature is much lower and the closely integrated char combustion in a second reactor requires careful control to ensure that the temperature, heat flux and solids flow match the process and feed requirements.

Rotating cone

The rotating cone reactor developed by BTG,[20] is a relatively recent development and effectively operates as a transported-bed reactor, but with transport effected by centrifugal forces in a rotating cone rather than a gas. A 250 kg/h R&D unit is operational, and a scaled-up version of 50 t/d was commissioned in Malaysia in mid-2005. A 120 t/d plant is at an advanced planning stage with construction anticipated to start later in 2013.[21]

The key features of a rotating-cone reactor are that hot sand and biomass are mixed at the base of the rotating cone and centrifugation drives the mixture up the inner wall of the rotating heated cone. The vapours are collected and processed conventionally. Char and sand drop into a fluid bed surrounding the cone, whence they are lifted to a separate fluid-bed char combustor where the char is burned to heat the sand, which is then dropped back into the rotating cone. Carrier gas requirements in the pyrolysis reactor are much less than for fluid-bed and transported-bed systems; however, gas is needed for char and sand cycling to the combustor. As with CFB and transported beds all the char is burned so it is not a by-product.

Ablative pyrolysis

Ablative pyrolysis is substantially different in concept compared with other methods of fast pyrolysis. The mode of reaction in ablative pyrolysis is like melting butter in a frying pan – the rate of melting can be significantly enhanced by pressing the butter down and moving it over the heated pan surface. In ablative pyrolysis, the hot reactor wall melts the wood that is in contact with it under pressure and as the wood moves away, the molten layer then vaporises to a product very similar to that derived from fluid-bed systems. As reaction rates are not limited by heat transfer, larger particles can be used and in principle there is no upper limit to the size that can be processed. The process is limited by the rate of heat supply to the reactor. There is no requirement for inert gas, so the reactor and ancillary equipment are smaller and thus more intensive. In addition the absence of fluidising gas substantially increases the partial pressure of the condensable vapours leading to more efficient collection and smaller equipment. However, the process is surface-area controlled so scaling is less effective and the reactor is mechanically driven, and is thus more complex. There is little interest currently in this approach to fast pyrolysis.

7.5.2 Technical challenges of fast pyrolysis

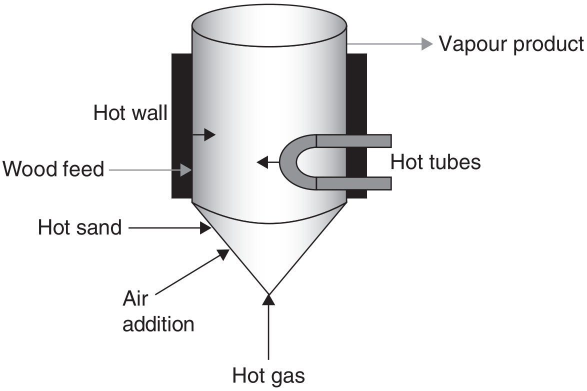
There are a number of technical challenges facing the development of fast pyrolysis, of which the following are believed to be the most important.

Heat transfer in fast pyrolysis

As pyrolysis is an endothermic process, there is a substantial heat input required to raise the biomass to the reaction temperature, although the heat of reaction is relatively insignificant. This is particularly important in demonstration and commercial systems. By-product char and gas can be used in fluid-bed and other indirectly-heated systems, and the char is completely combusted in circulating fluid bed and transported-bed systems. The char typically contains about 25% of the energy of the feedstock, and about 50–75% of this energy is typically required to drive the process. The by-product gas only contains about 5% of the energy in the feed and this is not sufficient for pyrolysis. Concentration of ash in the char can lead to problems in combustion from alkali metals although no reports are known to have been published on this topic. The main methods of heat transfer for a fast-pyrolysis reactor are shown in Fig. 7.6.

Char removal

Char is a vapour-cracking catalyst so rapid and effective separation from the pyrolysis product vapours is essential. Cyclones are the usual method of primary char removal; however, some fines always pass through the cyclones and collect in the liquid product where they can accelerate ageing and exacerbate the instability problem. In addition during storage, the alkali metals in the ash in the char can leach out into the bio-oil. Some success has been achieved with hot vapour filtration, which is analogous to hot gas cleaning in gasification systems.[22–25]



7.6 Some modes of heat transfer for a fast-pyrolysis reactor.

Problems arise with the sticky nature of fine char and disengagement of the filter cake from the filter.

Pressure filtration of the liquid for substantial removal of particulates (down to <5 μm) is very difficult because of the complex interaction of the char and pyrolytic lignin, which appears to form a gel-like phase that rapidly blocks the filter. Modification of the liquid micro-structure by addition of solvents, such as methanol or ethanol, which solubilise the less soluble constituents, can improve this problem and also contribute to improvements in liquid stability.[26] Centrifugation has been found to be successful for char removal, but the residue char and unseparated bio-oil require utilisation or disposal.

Liquid bio-oil collection

The gaseous products from fast pyrolysis consist of aerosols, true vapours and non-condensable gases. These require rapid cooling to minimise secondary reactions and to condense the true vapours, while the aerosols require additional coalescence or agglomeration. Orthodox aerosol capture devices such as demisters and other commonly used impingement devices are not reported to be as effective as electrostatic precipitation, which currently appears to be the preferred method in both laboratory- and commercial-scale units.

The vapour product from fluid-bed and transported-bed reactors has a low partial pressure of condensable products due to the large volumes of fluidising gas, and this is an important design consideration in liquid collection. This disadvantage is reduced in the rotating-cone and ablative-reaction systems, neither of which requires inert gas for fluidisation, which leads to more compact equipment and lower costs.[27] Simple indirect heat exchange can cause preferential deposition of lignin-derived components leading to liquid fractionation and eventually blockage in pipelines and heat exchangers. Quenching in recycled product bio-oil or in an immiscible hydrocarbon solvent is widely practised.

7.5.3 Bio-oil challenges

Some of the properties and characteristics of bio-oil have attracted particular attention and these are discussed further below.

Acidity or low pH

The pH of bio-oil is typically around 2.5 due to the relatively high concentration of organic acids. This requires a careful choice of materials and stainless steel is often specified although polyolefins are suitable where temperature and pressure permit.

Ageing and stability

Ageing of the bio-oil is a well-known phenomenon caused by continued slow secondary reactions in the liquid, which manifests as an increase in viscosity with time. It can be reduced or controlled by the addition of alcohols such as ethanol or methanol. A higher water content also improves stability but needs careful control as discussed below. In more extreme cases phase separation can occur. It is exacerbated or accelerated by the presence of fine char. This has been reviewed by Diebold.[28]

Bio-oil has been successfully stored for several years in normal storage conditions in steel and plastic drums without any deterioration that would prevent its use in any of the applications tested to date. It does, however, change slowly with time, most noticeably there is a gradual increase in viscosity. More recent samples that have been distributed for testing have shown substantial improvements in consistency and stability, demonstrating the improvement in process design and control as the technology has developed.

Ash

The ash content of biomass has an effect on organic liquid yields through primary and secondary catalytic cracking reactions of the organic vapours. This results in increased water and carbon dioxide and reduced organic yields. Although the total liquid remains about the same, the water content is much higher possibly resulting in phase separation and the heating value is lower due to the higher water content. Generally, ash levels below around 2.5 wt.% will lead to a homogeneous single-phase liquid, although high potassium levels will lower this datum.

Ash comes from the nutrients in the biomass, of which potassium is particularly important, and from soil and related contamination introduced in growing and harvesting. Ash management is therefore important. Ash reduction can be managed through feed blending and through water or dilute acid washing, although the financial and energy cost implications of washing can be significant.

Distillation

Pyrolysis liquids cannot be completely vaporised once they have been recovered from the vapour phase. If the liquid is heated to 100°C, it starts to rapidly react and continued heating eventually produces a solid residue of around 50 wt.% of the original liquid, which is mostly char or coke, and some distillate containing volatile organic compounds from the primary liquid and from cracking reactions and water.

Particulates

The particulate levels in bio-oil are derived from char carry-over and inert material carried over from the fluid-bed material, which are not removed in the primary solids removal stage of, typically, cyclones. This aspect and the use of hot vapour filters were discussed above. The char is relatively soft and friable but will still impact on atomisation, such as required for combustion, and any close-tolerance application such as in an engine. Since all the alkali metals in the biomass go into the char, any char carry over to the liquid will give an ash presence in the bio-oil. Over time, this ash is likely to leach and dissolve in the aqueous solution, in the form of, for example, potassium acetate. Char will also tend to contribute to ageing as it will retain some catalytic activity.

Phase separation

After formation of the primary fast-pyrolysis vapours, further secondary reactions begin almost immediately, catalysed by char and ash. The hot vapour residence time is thus an important determinant of both yield and bio-oil quality. Generally, the longer the hot vapour residence time and the higher the ash content, the more cracking reactions occur, leading to the formation of water and carbon dioxide and lower organic yields. The resultant high water content leads to a phase-separated product.

Phase separation is a consequence mainly of high water content in the product, which can arise from a high water content feed, high ash feed, poor char separation and/or long hot vapour residence times and combinations of these factors. Once bio-oil is phase separated, it cannot readily be reconstituted, although the addition of ethanol or methanol can restore homogeneity; mild heating and mixing can also restore some degree of homogeneity.

Water content and its effect

The liquid produced contains varying quantities of water, which normally forms a stable homogeneous mixture, ranging from about 15 wt.% water up to about

30 wt.% water, depending on the feed material, how it was produced and subsequently collected. A typical feed material specification is for a maximum of 10% moisture in the dried feed material, as both this feed moisture and the water of reaction from pyrolysis, typically about 12% based on a dry feed, both go into the liquid product. Pyrolysis liquids can tolerate the addition of some water, but there is a limit to the amount of water which can be added to the liquid before phase separation occurs; in other words the liquid cannot be dissolved in water. Water addition reduces viscosity, which is useful; it reduces the heating value, which means that more liquid is required for a given application; and it can improve stability. The effect of water is therefore complex and important.

Environment, health and safety

As bio-oil becomes more widely available, attention will be increasingly placed on environment, health and safety aspects. A screening study was completed in 2005 to assess the ecotoxicity and toxicity of 21 bio-oils from most of the commercial producers of bio-oil around the world, with a complete assessment of a representative bio-oil.[29] The study included a comprehensive evaluation of transportation requirements as an update of an earlier study[30] and an assessment of biodegradability.[31] The results are complex and require more comprehensive analysis but the overall conclusion is that bio-oil poses no significant health, environmental or safety risks.

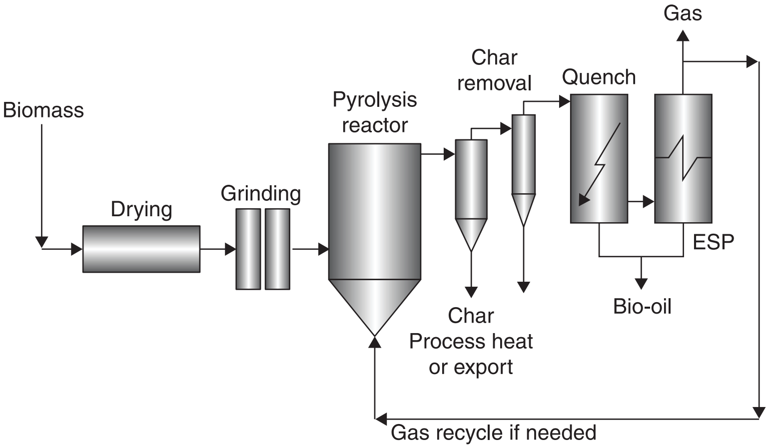
7.5.4 Char and gas

Char and gas are by-products, typically containing about 25% and 5% of the energy in the feed material, respectively. The pyrolysis process itself requires about 15% of the energy in the feed, and of the by-products, only the char has sufficient energy to provide this heat. Nearly all the ash components in biomass go into the char so a 1% ash biomass will result in approximately a 10% ash char for a 10% char yield.

The heat for fast pyrolysis can be derived by burning the char, which makes the process energy self-sufficient. However, char combustion has its own challenges as the high ash content of the char requires careful consideration of the thermal characteristics of the ash. More advanced and/or complex configurations include gasifying the char to a lower-heating-value gas and then burning the resultant gas to provide process heat with the advantage that the alkali metals in the char can be much better controlled. The waste heat from char combustion and any heat from surplus gas or by-product gas can be used for feed drying and in large installations can be exported or used for power generation. An important principle of fast pyrolysis is that a well-designed and well-run process should not produce any emissions other than clean flue gas i.e. CO_2 and water, although these will have to meet local emissions standards and requirements.

7.5.5 Integrated fast pyrolysis

Although the heart of a fast-pyrolysis process is the reactor, it only accounts for around 10–15% of the capital cost of the system. The rest of the process consists of biomass reception, storage and handling, biomass drying and grinding, product collection, storage and, when relevant, upgrading. This is depicted in Fig. 7.7.



7.7 Fast-pyrolysis reaction system. ESP: electrostatic precipitation.

7.6 Fast-pyrolysis bio-oil upgrading

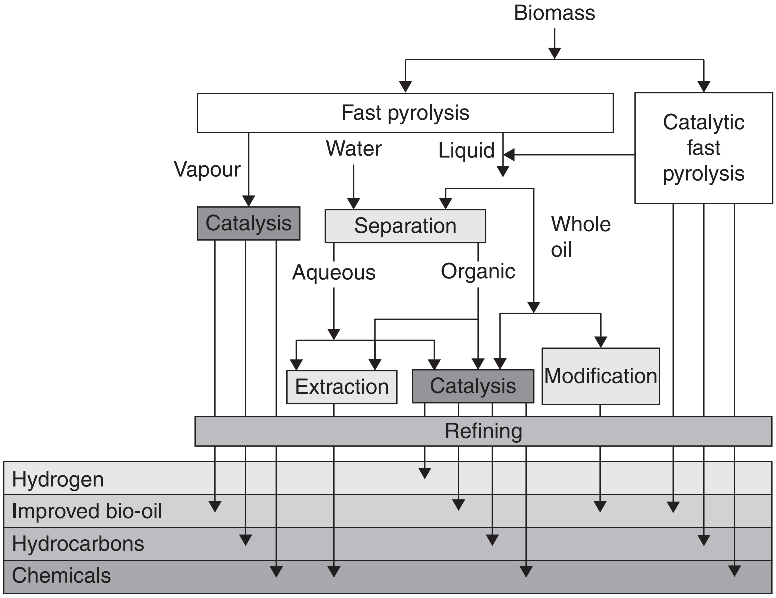
Bio-oil can be upgraded physically, chemically and/or catalytically. These have been extensively reviewed recently[4] and only a summary of key aspects is included here. The characteristics that cause most concern are the non-miscibility with hydrocarbons, ageing effects that can cause instability, low pH and solids. These four aspects are briefly summarised as they seem to cause the greatest concern in the utilisation and application of bio-oil. A summary of the main methods and interactions for upgrading fast-pyrolysis liquids and the resultant products are shown in Fig. 7.8.

7.6.1 Physical upgrading of bio-oil

The most important properties that adversely affect bio-oil fuel quality are incompatibility with conventional fuels from the high oxygen content of the bio-oil, high solids content, high viscosity and chemical instability.

Filtration

Hot-vapour filtration can reduce the ash content of the oil to less than 0.01% and the alkali content to less than 10 ppm, much lower than reported for biomass oils



7.8 Overview of fast-pyrolysis upgrading methods.

produced in systems using only cyclones. This gives a higher quality product with lower char;[31] however, char is catalytically active and can potentially crack the vapours, reduce yield by up to 20%, reduce viscosity and lower the average molecular weight of the liquid product. There is limited information available on the performance or operation of hot-vapour filters, but they can be specified and perform similar to hot-gas filters in gasification processes.

Tests on a diesel engine with crude and hot-filtered oil showed a substantial increase in burning rate and a lower ignition delay for the latter, due to the lower average molecular weight of the filtered oil.[32] Hot-gas filtration has not yet been demonstrated over a long-term process operation. A little work has been done in this area by NREL,[33] VTT and Aston University,[34] and very little has been published.

Liquid filtration to very low particle sizes of below around 5 μm is very difficult due to the physico-chemical nature of the liquid and usually requires very high pressure drops and self-cleaning filters.

Solvent addition

Polar solvents have been used for many years to homogenise and reduce the viscosity of biomass oils. The addition of solvents, especially methanol, has a significant effect on oil stability. Diebold and Czernik[35] found that the rate of viscosity increase ('ageing') for an oil with 10 wt.% of methanol was almost 20 times less than for the oil without additives.

Blends

An extension to the addition of solvents for homogenisation is the production of multi-component blends containing bio-oil. Some work has recently been carried out on homogeneous blends of bio-oil, biodiesel and bioethanol.[36] The advantages lie in the utilisation of mixed biomass-derived liquids, which gives control over fuel properties such as viscosity, boiling range and flashpoint.

Emulsions

Pyrolysis oils are not miscible with hydrocarbon fuels but they can be emulsified with diesel oil with the aid of surfactants. A process for producing stable micro-emulsions with 5–30% of bio-oil in diesel has been developed at CANMET.[37] The University of Florence, Italy, has worked on emulsions of 5% to 95% bio-oil in diesel[38,39] to make either a transport fuel or a fuel for power generation in engines that do not require modification to dual fuel operation. There is limited experience of using such fuels in engines or burners, but significantly higher levels of corrosion and erosion were observed in engine applications compared to bio-oil or diesel alone. A further drawback of this approach is the cost of surfactants and the high energy required for emulsification.

7.6.2 Catalytic upgrading of bio-oil

Natural ash in biomass

Before considering catalytic upgrading of bio-oil, it is important to appreciate firstly that biomass contains very active catalysts within its structure. These are the alkali metals that form ash and which are essential for nutrient transfer and growth of the biomass. The most active is potassium followed by sodium. These act by causing secondary cracking of vapours and reducing liquid yield and liquid quality, and, depending on the concentration, the effect can be more severe than char cracking.

Ash can be managed to some extent by selection of crops and harvesting time but it cannot be eliminated from growing biomass. The ash can be reduced by washing in water or dilute acid and the more extreme the temperature or concentration, respectively, the more complete the ash removal. However, as washing conditions become more extreme, firstly hemicellulose and then cellulose are lost through hydrolysis. This reduces the liquid yield and quality. In addition, washed biomass needs to have any acid removed as completely as possible, which is then recovered or disposed of, and the wet biomass has to be dried.

So washing is not often considered a viable possibility, unless there are some unusual circumstances such as the need to remove contaminants. Another consequence of high ash removal is the increased production of levoglucosan, which can reach levels in bio-oil where recovery becomes an interesting proposition, although commercial markets need to be identified or developed.

Catalysts

Catalysts can be included in a fast-pyrolysis process in several ways:

- Integrated into the biomass prior to fast pyrolysis, for example, by impregnation.
- Mixed with the biomass prior to fast pyrolysis.
- Integrated into the fast-pyrolysis reactor, for example, by replacing fluid-bed material or adding to fluid-bed material.
- Close coupled to the fast-pyrolysis reactor within the fast-pyrolysis reaction system and operating on the hot pyrolysis vapours at similar temperature conditions but with independent control of process parameters such as residence time and space velocity.
- Coupled to the fast-pyrolysis reactor operating on the hot pyrolysis vapours with independent control of process parameters such as temperature, residence time and space velocity.
- Decoupled operation on the condensed liquids locally or remotely.

In all cases, consideration needs to be given to recovery, regeneration and disposal of the catalyst.

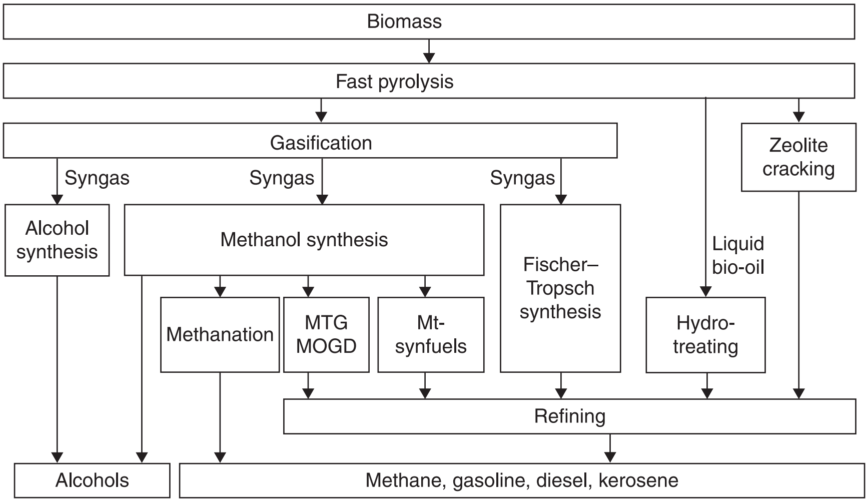
Upgrading to biofuels

Upgrading bio-oil to a conventional transport fuel such as diesel, gasoline, kerosene, methane or LPG requires full deoxygenation and conventional refining, which can be accomplished either by integrated catalytic pyrolysis as discussed below or by decoupled operation as summarised below and depicted in Fig. 7.9. There is also interest in partial upgrading to a product that is compatible with refinery streams in order to take advantage of the economy of scale and experience in a conventional refinery. Integration into refineries by upgrading through cracking or hydrotreating has been reviewed by Huber and Corma.[40] The main routes to a chemically or catalytically-upgraded product are:

- hydrotreating
- catalytic vapour cracking
- mild cracking
- esterification and related processes
- gasification to syngas followed by synthesis to hydrocarbons or alcohols
- steam reforming for hydrogen.

Hydrotreating

Hydro-processing displaces oxygen as water by catalytic reaction with hydrogen. This is usually considered as a separate and distinct process to fast pyrolysis and can therefore be carried out remotely. The process is typically carried out at high pressure (up to 20 MPa) and moderate temperature (up to 400°C) and requires a



7.9 Upgrading of bio-oil to biofuels and chemicals. MTG: methanol to gasoline. MOGD: Mobil olefins to gasoline and distillate.

hydrogen supply or source.[41] Full hydrotreating gives a naphtha-like product, which requires orthodox refining to derive conventional transport fuels. This would be expected to take place in a conventional refinery to take advantage of know-how and existing processes. A projected typical yield of naphtha equivalent from biomass is about 25% by weight or 55% in energy terms excluding the provision of hydrogen. Taking into account hydrogen production by gasification of biomass reduces the yields to around 15 wt.% or 33% in energy terms. The process can be depicted by the following conceptual reaction:

$$C_1H_{1.33}O_{0.43} + 0.77H_2 \rightarrow CH_2 + 0.43H_2O$$

There is a substantial hydrogen requirement in all hydrotreating processes to hydrogenate the organic constituents of bio-oil and remove the oxygen as water. The hydrogen requirement can be met by processing an additional amount of biomass to produce hydrogen, for example, by gasification. This is about 80% of that required to produce the bio-oil. The process is thus less efficient than simple performance figures often present. If only the organic fraction of bio-oil after phase separation is hydrotreated, the hydrogen required can be produced by steam reforming the aqueous phase. There has been extensive research on reforming the aqueous fraction of bio-oil as discussed below. There is also a high cost due to the high-pressure requirement.[42,43] Catalyst deactivation remains a concern from coking due to the poor C/H ratio.

The catalysts that were first tested in the 1980s and 1990s were based on sulphided CoMo or NiMo supported on alumina or aluminosilicate and the process conditions are similar to those used in the desulphurisation of petroleum fractions. However, a number of fundamental problems arose including: (i) the catalyst supports of, typically, alumina or aluminosilicates were found to be unstable in the high water content environment of bio-oil, (ii) the sulphur was stripped from the catalysts thus requiring constant resulphurisation and (iii) coking rapidly inhibited catalytic activity. The research was mainly based at Pacific Northwest National Laboratory (PNNL), USA,[44–46] and at Université Catholique de Louvain (UCL) in Louvain-la-Neuve in Belgium.[42,47] A recent design study of this technology for a biomass input of 2000 dry t/d for production of gasoline and diesel has been carried out by PNNL.[48]

More recently, attention has turned to precious metal catalysts on less susceptible supports, and considerable academic and industrial research has been initiated in the last few years. Of note is the work by UOP in Chicago with PNNL in the USA to address the scientific and technical challenges and develop a cost-effective process.[49] Model compounds were used initially to understand the basic processes[50] and both whole oil and fractions have been evaluated. Tests were carried out on both batch and continuous flow processes and work to date has been based on low-temperature (up to 380°C) catalytic hydrogenation of bio-oil using different metal catalysts and processing conditions to give a range of products including petroleum refinery feedstock. The University of Groningen in the Netherlands is also active in fundamental research on hydrotreating bio-oils and model compounds using ruthenium on carbon.[51,52] Different levels of upgrading are being studied, from stabilisation with low levels of oxygen removal through mild hydrotreating to two-stage hydrotreatment with substantial oxygen removal.[53]

In all cases the upgraded product needs conventional refining to produce marketable products and this would usually be expected to take place in a conventional refinery.

Zeolite cracking

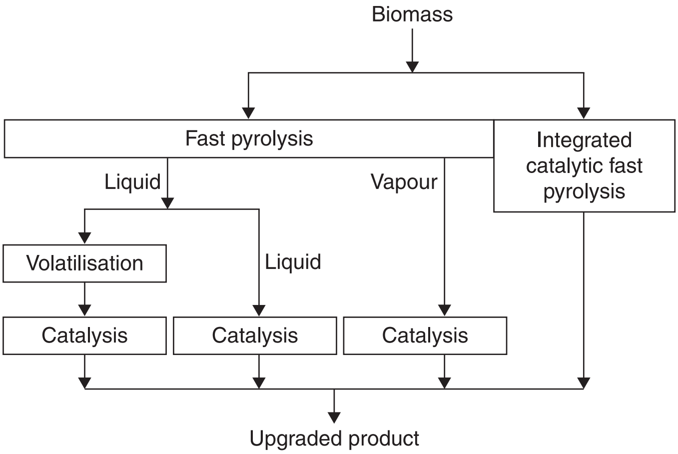
Zeolite cracking displaces oxygen as CO_2, as summarised in the conceptual overall reaction:

$$C_1H_{1.33}O_{0.43} + 0.26\ O_2 \rightarrow 0.65\ CH_{1.2} + 0.34\ CO_2 + 0.27\ H_2O$$

There are several ways in which this can be carried out as summarised in Fig. 7.10. The zeolite upgrading can operate on the liquid or vapours within or close coupled to the pyrolysis process, or they can be decoupled to upgrade either the liquids or revaporised liquids.

There is an increasing amount of research into zeolite-based catalytic cracking of fast-pyrolysis products to form aromatics, which are of considerable value as intermediates in the chemical industry. A comprehensive survey of this work has recently been published.[4]

Catalytic vapour cracking over acidic zeolite catalysts causes deoxygenation by simultaneous dehydration–decarboxylation producing mostly aromatics[54] at around 450°C and atmospheric pressure. Oxygen is ultimately rejected as CO_2 and CO in



7.10 Methods of upgrading fast-pyrolysis products with cracking catalysts.

a secondary oxidising reactor, which burns off the coke deposited on the catalyst. This would operate in much the same way as fluid catalytic cracking in a refinery. The low H/C ratio in bio-oils imposes a relatively low limit on the hydrocarbon. A projected typical yield from biomass of aromatics suitable for gasoline blending is about 20% by weight or 45% in energy terms.[55] The crude aromatic product would be sent for refining in a conventional refinery or petrochemical complex.

7.6.3 Other methods for chemical or catalytic upgrading of bio-oil

Other methods include non-physical methods and those catalytic processes not covered in hydrotreating and zeolite-related processes:[4]

- Mild cracking over base catalysts of only the cellulose- and hemicellulose-derived products, which aims to minimise coke and gas formation. Crofcheck at the University of Kentucky[56] has explored ZnO and freshly calcined Zn/Al and Mg/Al layered double hydroxides to upgrade a synthetic bio-oil based on earlier work in Finland.[57]
- Esterification and other processes are being investigated and developed for improving the quality of bio-oil without substantial deoxygenation. Properties that are mostly addressed are water content, acidity, stability and reactivity.
- Hydrogen can be recovered from syngas from gasification of bio-oil and bio-oil/char slurries.
- The water-soluble (carbohydrate-derived) fraction of bio-oil can be processed to hydrogen by steam reforming.[58,59] This has been accomplished in a fluidised-bed process by several researchers using commercial, nickel-based catalysts

under conditions similar to those for reforming natural gas. The process depends on a viable use for the organic lignin-derived fraction of bio-oil, for example, as a phenol replacement in phenol-formaldehyde resins[60] or for upgrading this organic fraction.

7.7 Economics

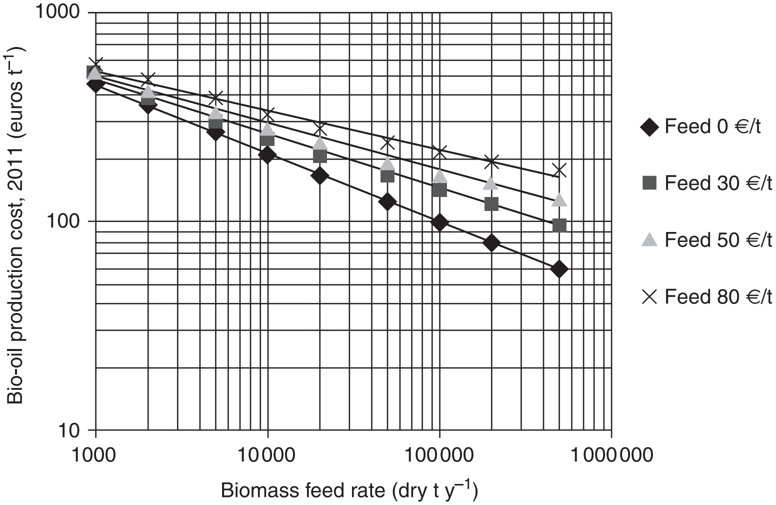
The total installed capital cost of a fast-pyrolysis system, starting from the prepared and dried feed material through to a liquid bio-oil product in storage tanks, is given by the following equation:

$$\text{Capital cost fast-pyrolysis plant}_{2011}\ (\text{euros million}) = 6.98 \times (\text{biomass feed rate dry } (\text{t h}^{-1}))^{0.67}$$

The cost of production of bio-oil is given by the following equation:

$$\text{Production cost bio-oil}_{2011}\ (\text{euros t}^{-1}) = 1.1 \times [B + (H \times 16\,935 \times F^{-0.33})]\ Y^{-1}$$

where B is the biomass cost in euros dry t^{-1}, H is the capital and capital-related charges, default value is 0.18, F is the biomass feed rate in dry t y^{-1}, and Y is the fractional bio-oil yield weight, default value is 0.75 for wood and 0.60 for grasses. The effect of scale for four dry-basis feed costs from 0 to 80 euros t^{-1} is shown in Fig. 7.11.



7.11 Bio-oil production costs.

Fast-pyrolysis technologies to produce liquid fuel have been successfully demonstrated on a small scale, and several demonstration and commercial plants are in operation, but they are still relatively expensive compared with fossil-fuel-based energy, and thus face economic and other non-technical barriers when trying to penetrate the energy markets.[61]

7.8 Conclusion and future trends

Liquid bio-oil produced by fast pyrolysis has the considerable advantage of being storable and transportable, as well as having the potential to supply a number of valuable chemicals. In these respects it has a unique advantage. It is, however, disappointing to see that the lessons of past work are either not considered or forgotten in the rush to get new research underway. Fast pyrolysis has some basic and essential requirements if good yields of good quality bio-oil are to be achieved.

The potential of bio-oil is increasingly being recognised, and there is rapid growth in research into improving bio-oil properties, particularly for dedicated applications and for biofuel production. Much of the research is still at a fundamental stage, even with regard to the use of model compounds and mixtures of model compounds that purport to represent whole bio-oil. It is doubtful if a limited component mixture can adequately represent the complexity of bio-oil. Some of the most interesting and potentially valuable research is on more complex and more sophisticated catalytic systems and these will require larger-scale development to prove their feasibility and viability.

Biorefineries have considerable scope for the optimisation of fast-pyrolysis-based processes and products, and these will require development of component processes in order to optimise an integrated system. They will necessarily include provision of heat and power for at least energy self-sufficiency.

There is an exciting future for both fast pyrolysis and bio-oil upgrading as long as these focus on delivering useful and valuable products.

7.8.1 Summary of challenges

- Economically-viable processes are essential for industry to become seriously involved. Inducements are likely to be necessary for some time.
- Economy of scale is important.
- Markets need to be identified and possibly developed for new products.
- Biomass cost is important for low-value products.
- Fast pyrolysis has the advantage of being a storable and transportable product that permits economies of scale.
- Early developments will be more successful with simple processes and fewer products.
- Processes, products and markets will need to be developed.

- Optimisation of processes, products and systems is essential.
- Process synthesis offers a family of useful design and evaluation heuristics.

7.9 Sources of further information and advice

A list of significant review publications on biomass fast pyrolysis and related aspects has been compiled by Di Blasi and updated by Bridgwater from 1982 up to the beginning of 2011.[62] For each source a set of key words is also provided.

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Antal MJ (1982) 'Biomass pyrolysis: A review of the literature. Part I – Carbohydrate pyrolysis' in *Advances in Solar Energy*, Boer KW, Duffie JA (eds), American Solar Energy, Boulder, CO, vol. 1, pp. 61–111. *(pyrolysis, products, carbohydrates, chemical kinetics)*

Antal MJ (1985) 'A review of the vapor phase pyrolysis of biomass derived volatile matter' in *Fundamentals of Biomass Thermochemical Conversion*, Overend RP, Milne TA, Mudge LK (eds), Elsevier, London, pp. 511–537. *(biomass, cellulose, tars, tar cracking, chemical kinetics)*

Antal MJ (1985) 'Biomass pyrolysis: A review of the literature. Part II – Lignocellulose pyrolysis', in *Advances in Solar Energy*, Boer KW, Duffie JA (eds), American Solar Energy, Boulder, CO, vol. 2, pp. 175–255. *(biomass, cellulose, tars, tar cracking, chemical kinetics)*

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Antal MJ, Mok WSL, Varhegyi G, Szekely T (1990) 'Review of methods for improving the yields of charcoal from biomass', *Energy & Fuels*, 4, 221–225. *(biomass, pyrolysis, charcoal)*

Bridge SA (1990) 'Flash pyrolysis of biomass for liquid fuels', MSc thesis, Aston University, Birmingham. *(biomass, pyrolysis, fast pyrolysis technology, products)*

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Bridgwater AV (1999) 'Principles and practice of biomass fast pyrolysis processes for liquids', *J. of Analytical and Applied Pyrolysis*, 51, 3–22. *(biomass, fast pyrolysis, pyrolysis technology, bio-oil)*

Bridgwater AV (2003) 'Renewable fuels and chemicals by thermal processing of biomass', *Chemical Engineering Journal*, 91, 87–102. *(biomass, fast pyrolysis, bio-oil, chemicals, gasification)*

Bridgwater AV (2004) 'Biomass fast pyrolysis', *Thermal Sciences*, 8(2), 21–49. *(biomass, fast pyrolysis, bio-oil)*

Bridgwater AV (2011) 'Upgrading biomass fast pyrolysis liquids', in *Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power*, Brown RC (ed.), Wiley Series in Renewable Resources, Wiley-Blackwell. ISBN: 978-0-470-72111-7. (*fast pyrolysis liquid, quality, upgrading, catalysts*)

Bridgwater AV (2011) 'Review of fast pyrolysis and product upgrading', *Biomass and Bioenergy*, 1–27. (*pyrolysis technology, liquid bio-oil, upgrading, catalyst*)

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Bridgwater AV, Peacocke GVC (2000) 'Fast pyrolysis processes for biomass', *Renewable and Sustainable Energy Reviews*, 4, 1–73. *(biomass, pyrolysis, pyrolysis technology, products)*

Bridgwater AV, Czernik S, Piskorz J (2002) 'The status of biomass fast pyrolysis' in *Fast Pyrolysis of Biomass: A Handbook*, Bridgwater AV (ed.), CPL Press, Newbury, vol. 2, pp. 1–22. *(biomass, fast pyrolysis, pyrolysis technology, bio-oil)*

Bridgwater AV, Meier D, Radlein D (1999) 'An overview of fast pyrolysis of biomass', *Organic Geochemistry*, 30, 1479–1493. *(biomass, fast pyrolysis, pyrolysis technology, bio-oil)*

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Chiaramonti D, Oasmaa A, Solantausta Y (2007) 'Power generation using fast pyrolysis liquids from biomass', *Renewable and Sustainable Energy Reviews*, 11, 1056–1086. *(biomass, pyrolysis, bio-oil, power, gas turbine, engine, co-firing)*

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Czernik S, Bridgwater AV (2004) 'Overview of application of biomass fast pyrolysis oil', *Energy & Fuels*, 18, 590–598. *(biomass, fast pyrolysis, bio-oil, bio-oil applications)*

Czernik S, Bridgwater AV (2005) 'Applications of biomass fast pyrolysis oil' in *Fast Pyrolysis of Biomass: A Handbook*, Bridgwater AV (ed.), CPL Press, Newbury, vol. 3, pp. 105–120. *(biomass, fast pyrolysis, bio-oil, bio-oil applications)*

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8

Intermediate pyrolysis of biomass

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Abstract: A comparison of fast and intermediate processes is given. New developments in technology are described for intermediate pyrolysis and an advanced integrative combination of biomass based processes is proposed.

Key words: pyrolysis, intermediate, fast, slow, combined heat and power (CHP), gasification, Haloclean, pyroformer.

8.1 Introduction

Pyrolysis in general terms is a thermo chemical conversion in the absence of oxygen. Pyrolysis reactors have various designs and the pyrolysis process can be categorised according to the process conditions as fast, intermediate or slow. Each type of pyrolysis can deal with different types of biomass, but very often the shape and the moisture content of the biomass are critical. For fast pyrolysis, the materials usually have to be finely ground and dry (exceptions from this are ablative systems in which a solid piece of biomass is pressed against a hot surface). Intermediate pyrolysis is able to process larger particles up to pellets and chips and also material with a water content of up to 40%. Slow pyrolysis is the classical approach: it is used for charcoal production and can even handle logs. The pyrolysis of non-woody biomass and the application of its products is more difficult than the pyrolysis of woody biomass. Intermediate pyrolysis is the preferred process for non-woody biomass. The liquids, gases and biochar produced have very different qualities to those produced by the fast and slow processes. Section 8.1.1 introduces the fast and intermediate pyrolysis processes. Intermediate pyrolysis technologies are then reviewed in more depth.

The products of pyrolysis are seen as suitable fuels for engines after upgrading or direct combustion, whilst the gases can be used as direct fuel for combined heat and power (CHP) plants. The liquids may be used in a biorefinery. Usually the processes produce large amounts of water, with some organic matter and have a heating value of around 3 MJ/kg. Very often, especially if non-woody biomass is used, the organic phase produced is very reactive and has high viscosity – such as the bituminous matter from straw and fast pyrolysis. Therefore, one strategy is to prevent the production of liquids and to convert the vapours using a suitable reforming or gasification step. Section 8.4 reviews the use of intermediate pyrolysis within a biorefinery, also termed an integrated project. Within such schemes, biochar can be produced as well as biofuel. Section 8.5 outlines future trends in this field.

8.1.1 Characteristics of fast and intermediate pyrolysis

In fast pyrolysis, thermal energy is transferred within seconds into the organic material and the resulting vapours are removed from the hot reaction zone within seconds. Both parts of the process usually have residence times of 0.5 to 2 s. The character of the products is mainly defined by the high energy flow into the sample and high levels of tar formation are typical. In particular, during fast pyrolysis of non-woody biomasses, the resulting liquids are more viscous and have a higher tar content compared to those from intermediate pyrolysis. Fast pyrolysis is of interest for liquid production from woody biomass, though, as the liquid is produced in very high quantities, up to 75%.[1]

Intermediate pyrolysis differs from fast pyrolysis in terms of the heat transfer to the feed. The heating rates are much lower, in the range of 100 to 500°C/min. This leads to less tar formation as more controlled chemical reactions take place instead of the thermal cracking of the biopolymer. The vapour residence times are very much dependent on the reactor type, but in fast pyrolysis they can be as low as 2 s. In the pyrolysis of woody materials, intermediate pyrolysis produces much lower liquid fractions, about 55% compared to 75%. Nevertheless, this is valid only for the pyrolysis of woody feeds and changes to a more equal scenario with other biogenic materials.[2] The conditions for fast and intermediate pyrolysis are summarised below.

Fast pyrolysis

- High heating rates, up to 1000°C/s
- Feedstock is finely ground material: particles of several millimetres down to tens of microns
- Reaction temperatures from 400 up to 550°C, higher; lower temperatures are given in the literature
- Residence time of the feed < 2 s
- Water content of the feed as low as possible << 10 wt%
- Short vapour residence times of 1 to 2 s
- High cooling rates needed for the vapours to reduce thermal post-decomposition.

Intermediate pyrolysis

- Moderate heating rates, up to 200–300°C/min
- Coarse, shredded, chopped or finely ground materials can be used as single feed or in mixtures, particles of several centimetres down to dust can be used

- Typical reaction temperatures from 400 up to 550°C and even down to 350°C
- Residence times of several minutes, up to 10 min
- Water content of the feed up to 40 wt%
- Short vapour residence times of 2 to 4 s
- High cooling rates needed for the vapours to reduce thermal post-decomposition.

8.1.2 Fast pyrolysis process technology

Several different types of fast pyrolysis reactors have been developed. Some of those in operation or the subject of recent investigation are outlined briefly below. Fast pyrolysis is covered in more detail in Chapter 6. One type of fast pyrolysis reactor currently used is the bubbling fluidised bed, a simple and well-understood technology with good temperature control and efficient heat transfer due to high particle density.[3,4,5] A circulating fluidised-bed reactor is more complex than a bubbling fluidised-bed reactor. In this technology, the residence time for the char is shorter, so inevitably more char is found in the pyrolysis oil. A countermeasure is to use filters to retain the particles; for examples of this technology see the literature.[6,7,8] A very different type of reactor is the ablative reactor. In this design heat transfer is optimised by having a very large heat transfer surface and the small sample surface is pressed against it. The reaction rates are not limited by heat transfer.[9,10] An example of a mechanical fluidised bed is a twin-screw mixer reactor heated by a solid heat carrier. The core of the fast pyrolysis system is a reactor with twin screws rotating in the same direction, cleaning each other because of their intertwining flights, and a heat carrier loop, which can be designed in several different ways.[11] The heat carrier can consist of sand or steel shot. An alternative is the rotating-cone reactor,[12,13] which operates as a transported-bed reactor. Centrifugal forces in the rotating cone cause transport of the feed. Residual char from pyrolysis is oxidised to heat up the sand in a bubbling-bed char combustor and the hot sand transfers heat to the feedstock.[14]

8.2 Intermediate pyrolysis technologies

Prior to 2000, several problems with fast pyrolysis in the conversion of biomass had been identified.

Recent developments in intermediate pyrolysis have overcome the problems in fast pyrolysis. The conditioning of the biomass and the low moisture content are major difficulties in fast pyrolysis, for example, as well as the production of high levels of tars and the frequent contamination of liquids with high amounts of ash and char. Using filters to limit this usually fails, due to the reaction characteristics of the mixture, which tends to block the filters in a short time. Slow pyrolysis is not a suitable alternative, since this has a significantly lower yield of the organic phase. In general, slow pyrolysis is only used for the production of solid materials like charcoal and it is very seldom seen in combination with combustion to produce heat and power. Since 2000, two significant developments in intermediate pyrolysis have occurred, which have helped to overcome these problems. The Haloclean reactor (Section 8.2.1) and the pyroformer (Section 8.2.2) have set new milestones in terms of the quality of the liquids and their yields for non-woody biomass, the quality of the biochar and finally the suitability for filter systems and even direct coupling to gasifiers. These technologies are outlined below.

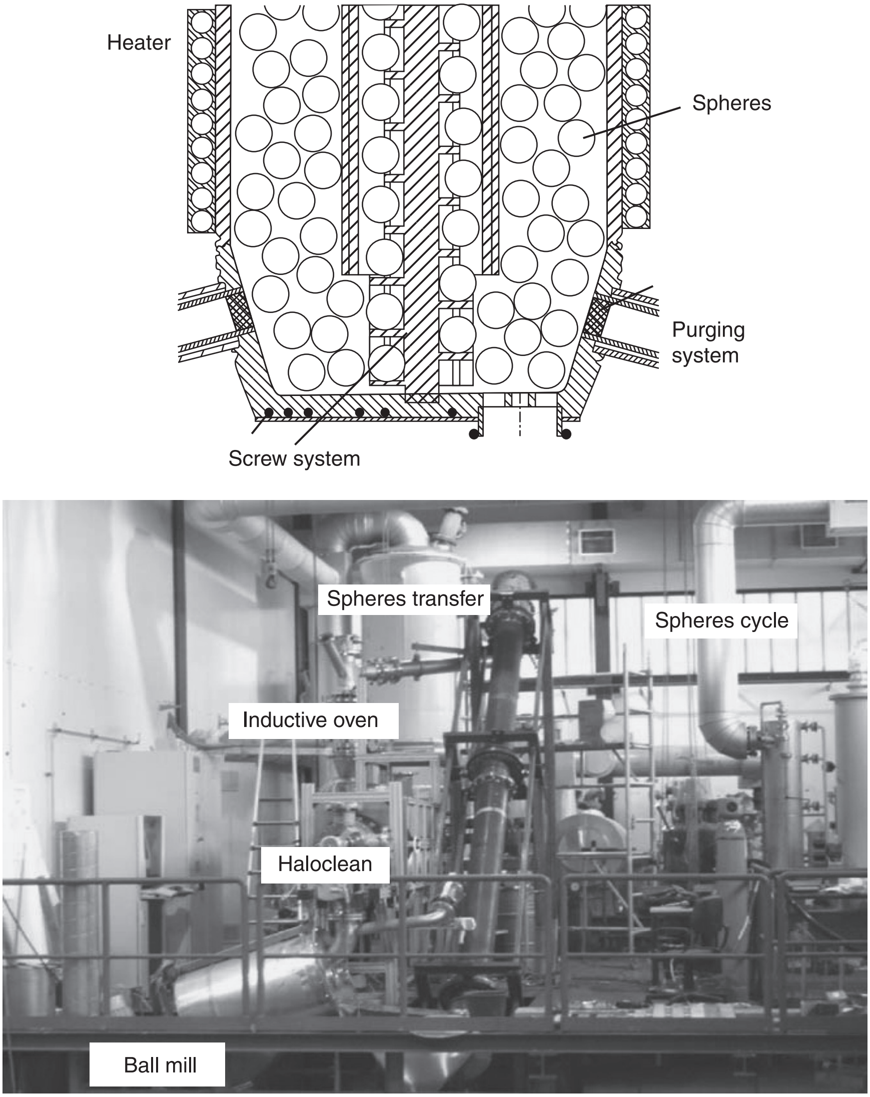
8.2.1 Haloclean rotary kiln

The Haloclean rotary kiln was designed especially for the pyrolysis of high amounts of inert or thermoset-containing materials (Fig. 8.1). The invention is based on experiences with a vertical reactor system for pyrolysis, the so-called cycled-spheres reactor,[15] which was developed[16] to improve heat transfer to poorly heat transferring materials like plastics and biomass. A cycled-spheres reactor was used on a laboratory scale to describe decomposition using micro-kinetic analysis.[18] Using a reaction vessel filled with spheres improves heat conductivity by an order of magnitude of at least one.[9] The system uses a screw to cycle the metal spheres. This basic idea was kept and transferred to an industrial-like reaction system, a rotary kiln.[19]

Because of the screw, residence time control in a rotary kiln is completely different to existing kiln types. The feed and heat-transferring spheres are transported in distinct volumes through the kiln. By using the screw in forward and backward movements, the residence time can be made very long, and the material is permanently in motion and being mixed. The system is indirectly electrically heated by an outer oven and by the screw. The system has been realised in a pilot scale[20–22] and was transferred to a technical scale (20 000 t/a) in 2009. The disadvantage of the system is the use of ambient pressure. Only a slight overpressure of several millibars is possible, due to the rotary kiln reactor and therefore coupling to a gasifier with a pressure drop of several 100 mbar is not possible.

8.2.2 The pyroformer

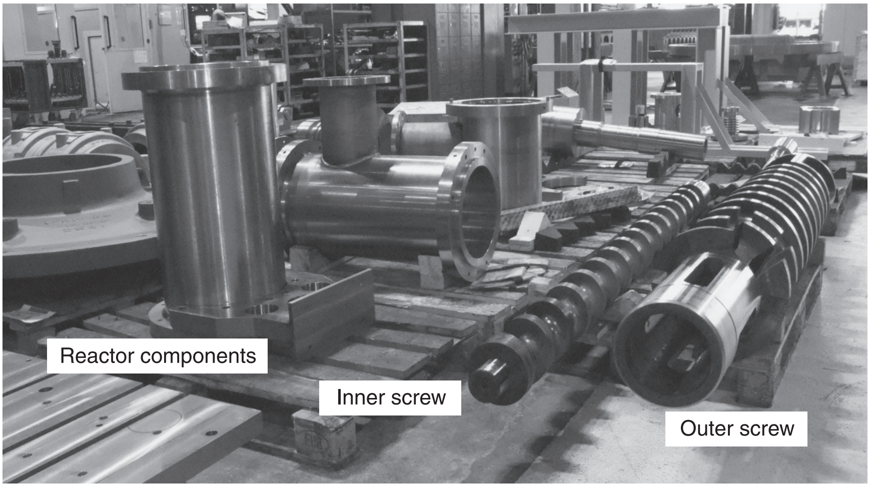
A pyroformer consists of a gas-tight reaction chamber suitable for up to 1 MPa. A pyroformer[23] combines pyrolysis with enhanced char catalysed reforming, thereby increasing gas production. The higher gas production rates are favourable especially if the pyrolysis is coupled to a gasification system. A reactor has two coaxial screw units (Fig. 8.2). The inner auger transports the biomass through the reactor and the outer screw transports the char back to the inlet zone, where the char is mixed together with fresh biomass. The char is therefore both heat carrier and reaction partner. The pyroformer exists in sizes of up to 100 kg/h and can be scaled up to 2.5 t/h. Larger units can be fired by char or oil as well as via heat transfer from hot syngas. In all cases, the lower char layer in the reactor shields the biomass from excessively high temperatures and lowers the heat transfer rate, which is important in preventing fast pyrolysis reaction conditions.



8.1 A schematic of the cycled-spheres reactor[15] and a Haloclean reactor.[17]

8.2.3 Generation of particle-free and dust-free pyrolysis vapours using a hot-gas filtration unit

CHP plants are sensitive to particles, dust and inert materials such as ash. For the long-term stability of CHP plants one must avoid feeding them pyrolysis liquids and gases containing dust, tar or ash.[24] Particle-free pyrolysis vapours



8.2 Pyroformer screw system.

can be produced via hot-gas filtration using ceramic filter candles at 450°C to 500°C. Examinations of the filter candles show that the particles collected are granular and free of tar and therefore fall off the filter or can easily be removed. This is one of the biggest advantages of intermediate pyrolysis: the low content of high molecular tars in the primary vapours and the low particle content.[25, 26]

8.3 Applications of intermediate pyrolysis and comparison with fast pyrolysis

8.3.1 Pyrolysis of straw and combined biochar production

The pyrolysis of straw is still a problem for most of the existing fast and slow pyrolysis units. The Haloclean process was tested in 2005 over five weeks for the conversion of 19 t of straw into liquids, gas and char. The liquids and char produced were successfully converted to synthesis gas in a commercial scale entrained flow gasifier.[27] The Haloclean reactor operated with a temperature range of 320°C to 500°C. A very important result from these tests is that the shape and size of the feed can be variable without changing the performance of the reactor. Generally, the amount of pyrolysis gas increases with increasing temperature: at 400°C the amount of pyrolysis oil decreases because more and more pyrolysis oil is degraded to pyrolysis gas.

Pyrolysis char: $H_o = 26\,\mathrm{MJ/kg}$; where H_o is the upper heating value
C: 63%, H: 3.7%, N: 1.1%, O: 12.9%

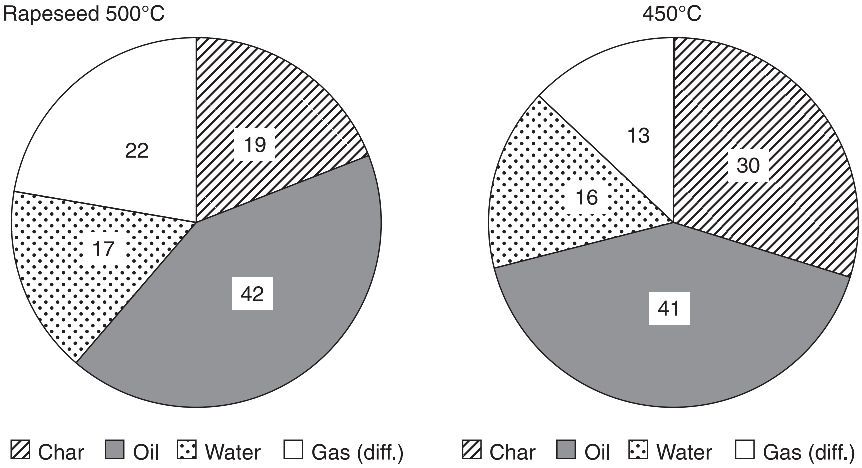
Ash contents of the char: SiO_2: 59%, Al_2O_3: 0.3%, Fe_2O_3: 0.7%, CaO: 7.3%, MgO: 2.1%, P_2O_5: 3.4%, Na_2O: 0.4%, K_2O: 23.8%, SO_3: 3.1%

Pyrolysis liquid: H_o = 7 MJ/kg (approximately 50% water phase) and 18% highly phenolic phase (H_o = 24 MJ/kg)

8.3.2 Power generation from rape

Intermediate pyrolysis is used to convert oil-bearing biomass and production residues like rape cake from rape oil production into fractions suitable for CHP.[17,19] Using hot-gas filtration and an aerosol precipitator, dust- and tar-free pyrolysis vapours and dust- and aerosol-free pyrolysis gases can be realised. Figure 8.3 shows the yield of the related products from rape at temperatures between 450°C and 500°C.

Figure 8.3 shows that at a temperature of 450°C, the yield of pyrolysis char is about 30% while the yield of pyrolysis liquids is about 57% and the yield of pyrolysis gas is 13%. In CHP electric power generation, pyrolysis liquids as well as pyrolysis gases can be fired into the CHP plant. Therefore, the maximum yield of liquids and gases is required. By shifting the pyrolysis temperature, the yield of pyrolysis char is reduced drastically and a higher amount of pyrolysis gas is produced; the yield of pyrolysis liquids is increased, too. The amount of pyrolysis char reaches levels of about 19% so that 81% of the pyrolysis products are suitable for electric power production. Medium-sized pyrolysis plants with throughputs of 12 000–24 000 t/a are used as local heat and energy supply plants at industrial sites.



8.3 Yield of pyrolysis products from rapeseed.

8.3.3 Production of biochar

Slow pyrolysis and intermediate pyrolysis are the most appropriate technologies for producing biochar as well as heat or heat and power. In both cases, usually about 25 to 35 wt% of biochar is produced at temperature levels between 350°C and 500°C. The residence time can be reduced significantly using intermediate pyrolysis. Furthermore, this process can be coupled to provide heat and power beside biochar and is therefore likely to be a commercially applicable system.[2,28]

In the pyrolysis of char, it has been shown that the C:O ratio of the char can be changed significantly by varying the pyrolysis temperature (Table 8.1). An O:C ratio lower than 0.2 appears to provide, at a minimum, resistance against microbial degradation.[29]

The Haloclean technology produced 6 t of biochar from straw during a 5-week test.[24,30] Recently biochar has also been produced using the pyroformer technology with even better O:C ratios and therefore long-term stability of the char. The values are 0.055 for biochar from sewage sludge and 0.064 for biochar from rapeseed, both prepared at 450°C and 10 min residence time.[31]

8.3.4 Comparison of fast and intermediate pyrolysis techniques

The literature is generally indicating that fast pyrolysis is the method of choice for turning biomass into the maximum amount of liquid and the minimum amount of gas.[1] This is true (see Table 8.2 and related arrows) only for wood and usually leads to a liquid phase high in water, acids and tars. In terms of other feedstocks like straws, grasses or industrial residues from agricultural products like husks, the picture is quite different. Intermediate pyrolysis has working conditions that prevent the formation of high molecular tars and it produces dry and brittle chars suitable for different applications like fertilisation or combustion. The ultimate advantage of this type of processing is that the feedstock does not need to be milled and larger-sized feedstock can be used, so the char is easily separated from the vapour. The vapour has a low ash content independent of the ash content of the material before pyrolysis, and it can be passed to a coupled gasifier.[2,28]

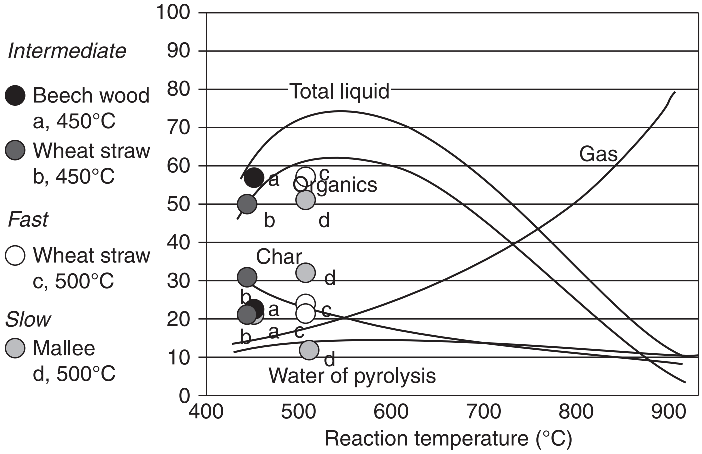
Table 8.1 C:O and O:C ratios as a function of pyrolysis temperature; residence time is 7 min for wheat straw in the Haloclean plant using intermediate pyrolysis

	Temperature (°C)				
	25	325	375	400	450
C:O ratio	0.9	1.3	2.1	2.9	3.4
O:C ratio	1.1	0.77	0.48	0.34	0.29

Table 8.2 Yield and composition of pyrolysis fractions from fast pyrolysis[1]

	Fast pyrolysis 500°C	Slow pyrolysis 420°C	Slow pyrolysis 500°C	Slow pyrolysis 600°C
Total liquid, wt% on dry feed	75.0	51.9	52.8	51.9 ⬅
Char yield, wt% on dry feed	8.5	33.6	31.9	32.0 ⬅
Gas yield, wt% on dry feed	10.9	13.4	11.3	11.4
Closure, wt% on dry feed	94.4	98.9	96.0	95.3
Heating rate, °C/min	–	14.5	13.7	12.6
		(Slow pyrolysis liquid from dry ice and acetone condenser – water and light ends)		
Water content (%)	20.8	45.9	48.2	43.8 ⬅
Char content (%)	0.04	0.02	0.03	0.03
Viscosity, cP	53.8	1.4	1.1	1.8
pH	2.4	2.3	2.5	2.4
Elemental analysis (%)				
C	43.9	28.13	28.00	27.39
H	7.4	9.38	9.38	9.55
N	0.07	0.03	–	–
O by difference	48.6	62.5	62.7	63.1
HHV (wet) (MJ/kg)	14.4	6.8	6.4	7.1
		(Slow pyrolysis liquid from EP – heavy organic fraction)		
Water content (%)	–	8.6	11.3	7.8
pH	–	2.8	2.6	2.6
Elemental analysis (%)				
C	–	54.8	53.75	55.30
H	–	7.14	7.41	7.23
N	–	0.10	0.13	0.16
O by difference	–	38.0	38.72	37.32
HHV (wet) (MJ/kg)	–	21.3	20.4	21.8

Figure 8.4 shows the typical behaviour of wood during fast pyrolysis at different temperatures. Sample (a) shows that even under intermediate pyrolysis conditions almost similar results can be achieved. Even though two liquid phases are obtained the total is quite similar. Only the gas and char yield varies: less char and more gas are produced. With wheat straw, intermediate pyrolysis (b) and fast pyrolysis (c) show very similar behaviour, no longer matching the slopes for wood. The slow pyrolysis of mallee (d) clearly shows that intermediate pyrolysis is a new type of treatment. Compared with fast pyrolysis, slow pyrolysis produces similar or more advantageous products using less sophisticated technological approaches and therefore with lower investment costs.[2,28]



8.4 Production yields for the different phases from fast pyrolysis as a function of temperature; results for mallee, fast pyrolysis at 500 °C, 75% liquid, 9% char, 11% gas.[1] Due to increased fragmentation reactions instead of pyrolysis the amount of high tars increases in liquid phases from fast pyrolysis.

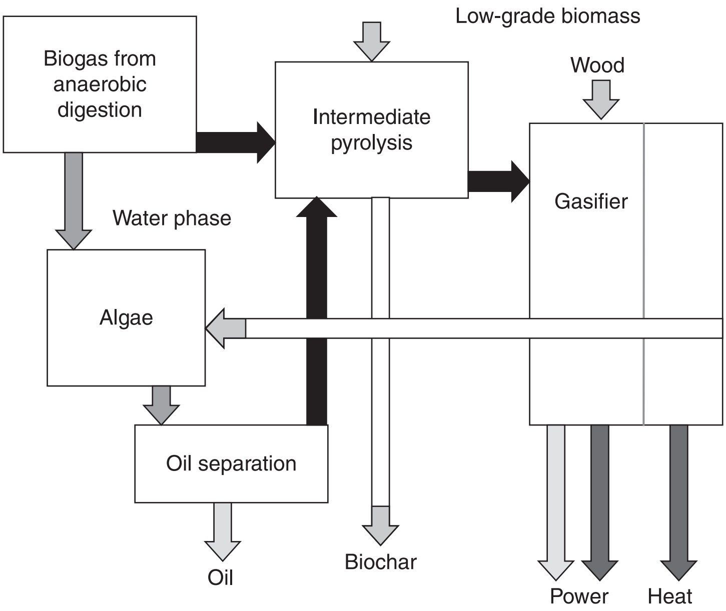
8.4 An integrated project including intermediate pyrolysis

The pyrolysis of biomass is an important process or process element for turning biomass into liquid and gaseous products. Worldwide, companies are looking at ways of liquefying wood and other types of biomass to find an intermediate product higher in energy per volume. Potential applications range from co-firing and firing in biomass boilers, as a fuel for gas engines and dual fuel engines, to a feed for gasifiers. Furthermore, the chemical components in the liquids are of interest for biorefineries as high-value products can be extracted and the char from pyrolysis is of increasing importance as it can be used to produce so-called biochar. Biochar can be used to fertilise agricultural land and in addition it acts to sequester carbon instead of carbon dioxide. Today the most promising chars for biochar applications are produced by intermediate pyrolysis.[2,28]

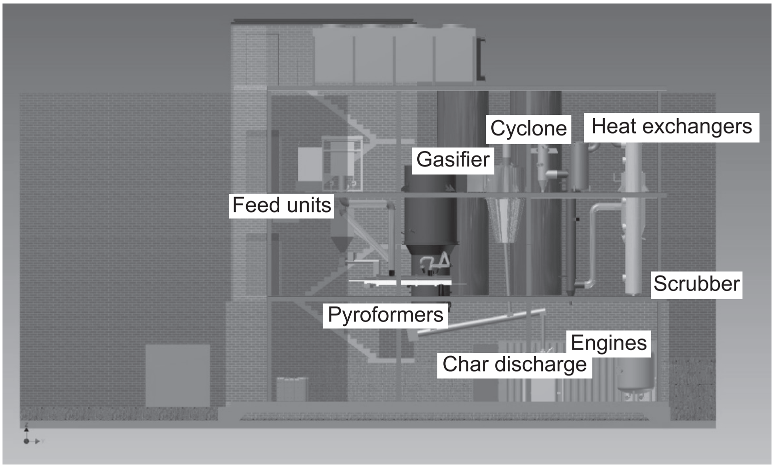
8.4.1 Biothermal valorisation of biomass (BtVB)

Many companies are currently exploring methods to produce fuels via pyrolysis or synthetic diesel via gasification using Fischer–Tropsch synthesis. Usually these processes use dry or very dry feedstock or feeds with a specified condition and size. More flexible systems tend to need to operate on a very large scale to remain economical. However, Aston University recently applied for a new patent for the BtVB process, which involves the biothermal valorisation of (ash-rich) biomass. The process combines a new kind of pyrolysis (intermediate) with gasification in an integrated technology.[2,32–34] All kinds of biomass and biogenic residues can be processed in this way and there is also great flexibility in terms of feed size and moisture content. The BtVB process couples residues and effluents from a biogas unit to a thermal line consisting of a pyrolyser (pyroformer) and a gasifier (fluidised bed) as well as an algae production unit (manufactured by Varicon Aqua) to generate new feedstock. Finally, minerals adhere to the charcoal from pyrolysis, which can be used for carbon sequestration and refertilisation of soils (Fig. 8.5 and Fig. 8.6).[2,28,32–34]

The core of the process is an intermediate pyrolysis step. The pyrolysis vapours (about 60–75% of the energy) pass directly to a gasifier for gasification; no filtration or condensation of the vapours is required. The gases from the gasifier are used to power a gas or dual fuel CHP plant. The ash remains in the char, which can be used for fertilisation or even combustion. The fertiliser produced is commonly known as black earth and has a high added value based on the fertiliser content and the carbon sequestration achieved. This utilisation of char is the only way to convert CO_2 into stable carbon via plants and furthermore, to remove it from the atmosphere. Alternatively the char can be used for combustion in biomass power plants or co-combustion with coal in power plants. In that case, the soluble elements of the pyrolysis char are dissolved in water and used as a fertiliser and the rest of the char is then combusted. The char could be stored in a mine so that it can be used in the future.



8.5 BtVB process.



8.6 The combined pyroformer/gasifier CHP application at Aston University, Birmingham, UK, 0.4 MW_e. The engines are the diesel engines used for power generation.

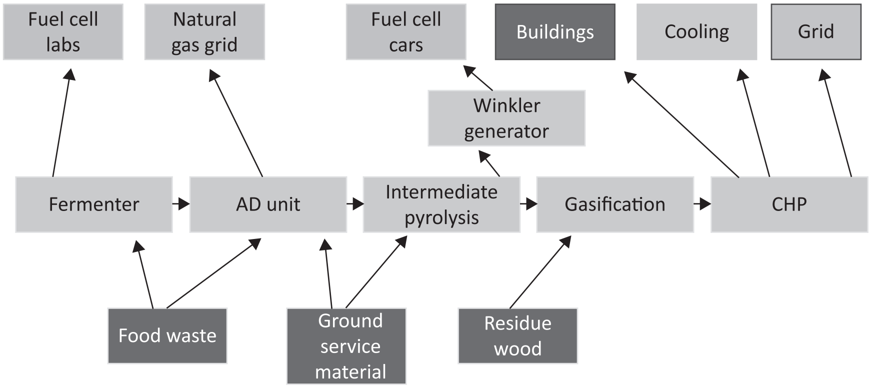
A very efficient fertiliser cycle can be achieved by introducing algae cultivation into the process and using lignin-rich residues from biogas processes, waste water or water from anaerobic digestion for fertilisation.[35] The fertiliser as well as the heat and the carbon dioxide required are produced by the different process stages (biogas production, gasification and engines) and therefore contributing to cutting the costs of algae production.

Birmingham 2026

The UK Government has established aggressive targets for CO_2 levels with reductions of 34% by 2020 and of 80% by 2050. Regions across the UK have established programmes to reduce CO_2 emissions accordingly, and in some cases have been even more aggressive. For example, Birmingham City Council has committed to a target 60% reduction of CO_2 by 2026.[36] Through the Birmingham 2026 initiative,[36] Birmingham plans to be the UK's first sustainable city with a low-carbon energy infrastructure and well prepared for the impact of climate change. Key objectives include reducing CO_2 emissions by 60% and increasingly reducing, reusing and recycling waste. The BtVB process has been selected as part of this scheme.

8.5 Future trends

The introduction of the new BtVB process shows that it is possible to produce clean fuel gases and sequestered carbon products (biochar) simultaneously. At the



8.7 Fully integrated technologies for providing heat, power, hydrogen, methane and biochar. AD, anaerobic digestion.

heart of the process is intermediate pyrolysis, which can use a very broad range of fuels of varying quality including sewage sludge, wood waste, algae residues, general municipal waste, energy grasses and ground service materials, even with high moisture. Materials that might otherwise be landfilled are used to produce fuel via pyrolysis and gasification for combined heat and power (CHP) systems. The overall process is not just carbon neutral, but actually carbon negative (up to 25% of the carbon can be saved as biochar and sequesters) since it returns carbon (and potassium, phosphates and nitrogen[32]) to the soil in the form of fertiliser.

Other products, apart from heat and power, produced in biorefineries of this type are hydrogen gas, synthetic natural gas (SNG) and Fischer–Tropsch diesel. Figure 8.7 shows the full integration of a hydrogen bio-economy based on the integration of existing technologies with minor adaptations. All residues are converted further. Biochar is the only remaining material; however, it could be converted to additional hydrogen via reforming or gasification. Connections to the grids for power, hydrogen and methane deliver the biofuels and power, while heat can be used in decentralised systems for buildings, greenhouses or to cool buildings or food.

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9

Large-scale biomass combustion plants: an overview

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Abstract: For a long time biomass was combusted mostly on a small scale. Now the largest biomass boilers are over 500 MWth. This chapter tries to outline the main methods for large-scale biomass combustion. The main boiler types are the grate and bubbling-fluidised bed boilers although circulating-fluidised bed and pulverised firing do play a role. Particular emphasis has been placed on emissions, the effect of fuel quality and operating issues.

Key words: steam boilers, biomass combustion, fluidised bed combustion, grate firing, fouling, corrosion.

9.1 Introduction

The definition of what constitutes a large-scale installation for energy production is not quite clear. For instance, according to EU directives on combustion, a large-scale power plant has an output of at least 50 MWth (the large combustion plant directive, European Council Directive 2001/80/EC and European Council Directive 2010/75/EU). However, some other authors consider large-scale power plants have an output of over 10 MWth (Obernberger, 2006). While this question remains open, it should be noted that the classification affects the technologies considered. Thus if the lower limit is set at 50 MWth, then one would exclude some types of installations, such as the many currently installed fixed grate and bubbling-fluidised bed (BFB) boilers. If the first type does not seem to be suited for large-scale power output, the second one might, at least from a technical point of view. The main types of large-scale biomass-fired installations will be addressed in the following sections.

9.2 Technologies

The different types of solid fuel combustion technologies depend mainly on the fuel type, the scale and the application (i.e. district heating, power, combined heat and power). In any case, a combustion unit has four main systems:

- fuel-feeding system
- air supply system
- combustion chamber
- ash discharge system, which may also collect ash from the boiler.

Additionally, there is the flue gas recirculation (FGR) system, the heat exchange system (i.e. water tubes or shell-fired boilers) and the regulation (automatic control) system.

The main combustion installations built and used nowadays and the associated biomass fuel types are summarised in Table 9.1. These technologies can be classified as a function of the relative velocity between the gas flow and fuel particles into:

- packed beds
- fluidised beds
- pulverised fuel systems.

The first category includes moving-grate furnaces (travelling, reciprocating or vibrating) and underfeed stokers with rotary grates. The last two classes are represented by bubbling-fluidised beds (BFBs), circulating-fluidised beds (CFBs) and pulverised-fuel (PF) systems. All of these technologies will be briefly described in the following sections.

The characteristics of the biomass will influence the type of technology to be used, i.e. for large particles, spreader stokers will be preferred, moving-grate systems require homogeneous feedstock, small material is best with CFB, very

Table 9.1 Common combustion technologies

Installation type	Output (MWe)	Fuel type	Moisture content (wt%)	Ash content (wt% dry basis)	Particle size (smallest dimension, mm)
Moving grate	0.15–150	All biomass fuels	5–60	< 50	< 150
Bubbling-fluidised bed	5–120	Bark, woodchips, sludge, bagasse	5–60	< 10	< 100
Circulating-fluidised bed	15–250	Bark, woodchips, sludge	5–60	< 10	< 100
Pulverised wood burner	5–80	Wood, pellets	< 20	< 1	< 5
Pulverised coal–wood co-combustion (wood fraction > 10%wt)	100–1000	Wood, sawdust, pellets	< 20	< 1	< 2–4

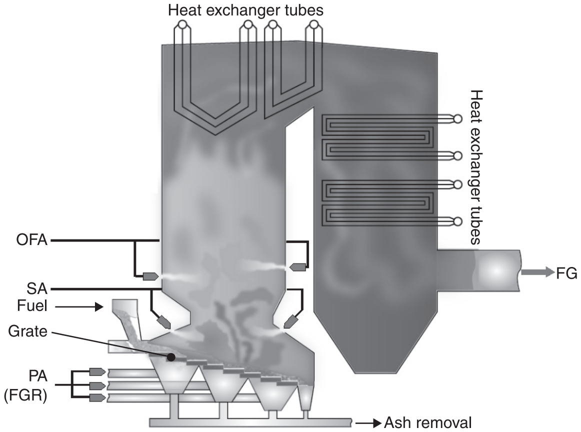
Source: van Loo and Koppejan, 2008.

small (sawdust) or dry (pellets, torrefied biomass) and thus easy to mill biomass will be preferred for PF burners. With a fluidised bed, sorbents (lime, etc.) can be injected for acid gas abatement. Large amounts of biomass cannot be burned in PF burners as the rate of unburnt material increases. Most of the biomass volatilises and burns fast, but the remaining char will need a long time to react. Grate technology is cheaper and will require less auxiliary energy than fluidised bed technology.

9.2.1 Moving-grate furnaces

Moving-grate systems are discussed in detail by Yin *et al.* (2008), and only the main characteristics are summarised here. These furnaces use a grate assembly (horizontal or sloping) as a support for combustion (see Fig. 9.1). The fuel is fed onto the grate typically by a mechanical stoker system (feeding screw, hydraulic pusher, etc.). The movement of the grate ensures the fuel transport and mixing along the grate during combustion. The primary air is supplied under the grate in one or more separated zones. The secondary and tertiary (also called overfire) airflows are injected into the combustion chamber above the fuel bed. From the grate inlet to the end of the grate, the main reaction fronts can be distinguished: drying and heating, devolatilisation and char burnout with ash formation.

In order to achieve good conversion rates of the solid, the fuel bed must be as homogeneous as possible. This depends strongly on the grate movement and the primary airflow distribution. Moreover, the drying and initial heating of the fuel being an energy sink, flue gases may be recycled under the first part of the grate in order to compensate for the vaporisation heat of the fuel moisture. At the end of the grate, the solid residue (ash with some unburnt char) falls into the ash pit before being removed (wet or dry removal).



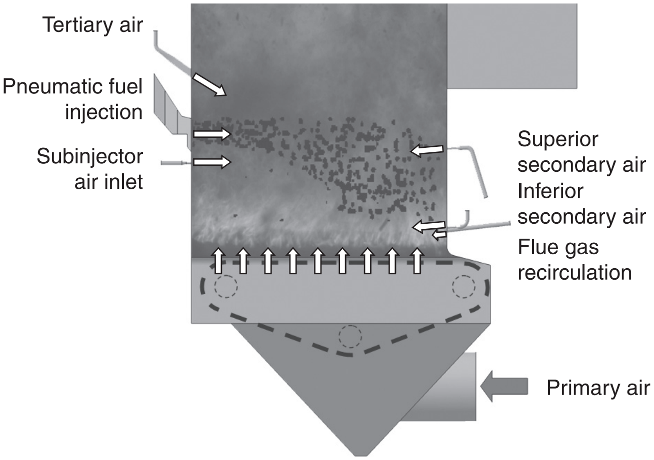
9.1 Moving grate boiler. FG – flue gas; FGR – flue gas recirculation; OFA – overfire air; PA – primary air; SA – secondary air.

The combusting gases formed in the fuel bed during the devolatilisation step (together with some light particles of ash) are entrained by the primary flow above the fuel bed. There, mixing with the secondary and overfire airflows will ensure their complete combustion.

The hot combustion gases flow through several bundles of heat exchanger tubes, where thermal energy is transferred to the fluid flowing within the tubes (water or steam). Finally, the flue gas leaves the boiler for the gas treatment system. Grate boilers can burn a variety of types of biomass but they lack the ability to react fast to changing biomass conditions (moisture variations).

Travelling grate

In travelling-grate systems, the grate has a continuous movement. As a consequence, the heterogeneous reaction fronts (drying, devolatilisation and char burnout) are segregated, leading to high-temperature gradients within the fuel bed and finally to an average carbon burnout efficiency. Thus, in order to achieve good performance, this system requires a relatively small height for the fuel bed. This is achieved by spreader-stoker boilers, where the fuel is fed mechanically (a system of rotary blades) or pneumatically (see Fig. 9.2). Fuel particles fly through the flames to the opposite side of the grate. The distance travelled is a function of mass and the fuel particles fall at different positions on the grate. During their flight, the fuel particles are dried and partially (or completely) devolatilised. Thus, better conversion is achieved with a smaller grate surface area. However, due to the tendency of small biomass particles to be carried away with the flue gas which subsequently increases the amount of unburnt fuel in the fly ash, their use in recent biomass applications is limited.



9.2 Spreader stoker system.

Particularly uniform moist fuels can be burned in an underfed stoker with a rotary grate. This type of grate also has a continuous movement, but circular. Different parts of the grate turn in opposite directions to each other, ensuring a good mixing of the fresh and combusting fuel.

Reciprocating grate

Reciprocating grates have a forward-backward movement, which ensures, besides the translational movement of the bed, the rolling of the fuel particles (see Fig. 9.3). This leads to a better homogeneity of the fuel bed and a more efficient burnout. This type of boiler is commonly under 30 MWth and they are used for electricity generation from biomass.

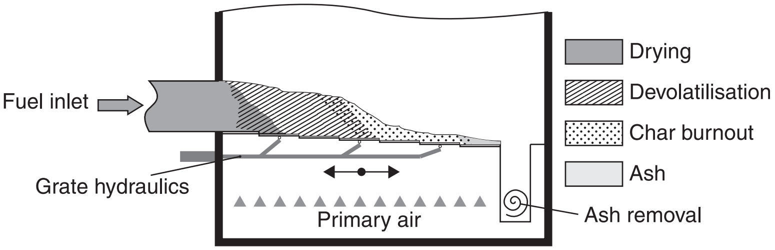
Vibrating grate

A vibrating grate consists of water-cooled panels mounted on leaf springs. The panels are vibrated via connecting rods driven by a motor (see Fig. 9.4). The fuel is spread on top of the grate and starts drying and then devolatilising. The residual char burns and turns to ash. The fuel bed moves towards the lower end of the grate where the ash is removed. The vibrating frequency can often be adjusted to match the fuel characteristics.

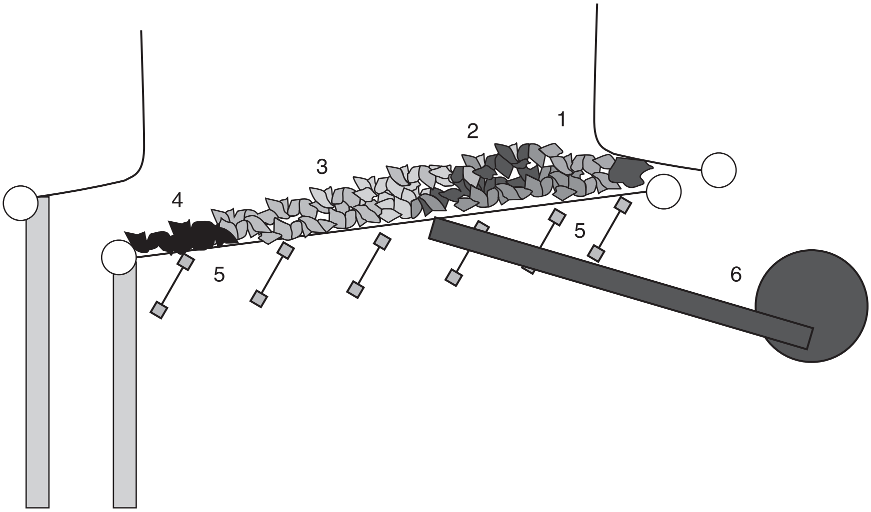
Vibrating grates do not require a complex movement mechanism, thus they are more reliable with lower maintenance costs. The grate vibrations spread the fuel particles evenly over the grate. Consequently, a better mixing within the fuel bed is achieved and the char burnout is further improved.

9.2.2 Fluidised bed

The 1970s saw the quick acceptance of a new combustion method: fluidised bed (FB) firing. In fluidised bed firing the fuel is mixed with hot inert bed material such as sand or ash, which promotes fast combustion. Since the furnace temperature is low, there are low NOx emissions. The bed behaves as a fluid



9.3 Reciprocating grate.



9.4 Vibrating grate. 1: Drying; 2: devolatilisation; 3: char combustion; 4: ash; 5: leaf springs; 6: vibrating mechanism.

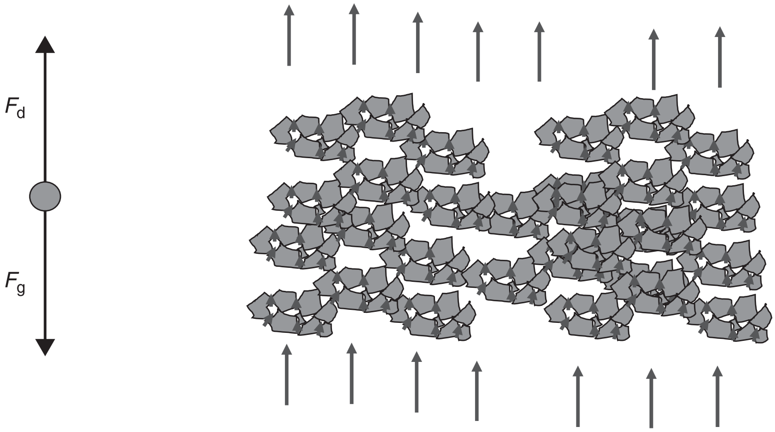
because air and flue gases move through the bed. A more common example of the same phenomena is quicksand.

The main benefits of fluidised bed systems are:

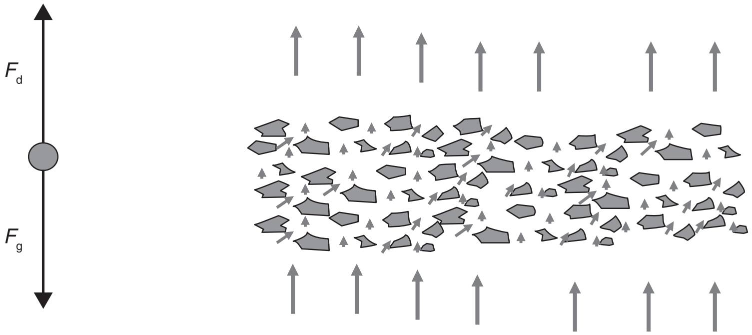
- All the available heat in the fuel can be utilised to maintain the combustion temperature, without radiation losses to the walls.
- The fluidised sand layer on the bottom of the furnace helps to maintain stable combustion conditions.
- The hot sand and ash mixture effectively dries and volatilises the fuel. The volatilised gases and fine fuel particles are then combusted above the bed in the secondary air. The distribution of the air allows the temperature profiles to be controlled, which affects emissions, most importantly NOx emissions.
- The residual char and larger fuel particles are combusted inside the bed.
- The high thermal inertia makes this system ideal for fuels with varying heating values and moisture contents such as bark, woodchips, forest residue, peat, sawdust, rice husks, recovered fuel, de-inking and water treatment sludge and many other recycled products.

There are two main types of fluidised bed boilers: bubbling-fluidised bed boilers (BFBs) and circulating-fluidised bed boilers (CFBs). In bubbling-fluidised bed boilers the bed stays mainly in the bottom of the furnace. In circulating-fluidised bed applications, bed material is drawn from the furnace, separated from the flue gases and reintroduced into the furnace. The development of fluidised bed firing started in 1922 when Winkler patented coal gasification. The first circulating fluidised bed boilers were patented by Lurgi in the 1960s. BFBs are used mainly in units smaller than 100 MWe. CFBs are used in larger units up to 300 MWe.

Starting from a stationary bed, if the velocity of the primary air increases sufficiently, the ash, sand and fuel particles will be entrained by the airflow. Thus, the bed is now 'floating' above the primary air feed level, and the distance between particles has increased (see Fig. 9.5 and Fig. 9.6). This is the basis of the bubbling-fluidised bed. Up to 90–98% of the mass of a fluidised bed is inert material such as ash, sand, silica or dolomite (van Loo and Koppejan, 2008). The presence of the inert material enhances heat transfer, leading to a uniform temperature



9.5 Principle of BFB operation: the flow of gases can form voids, but drag forces (F_d) are lower than gravity forces (F_g).



9.6 Principle of BFB operation: the flow of gases is high thus drag forces can overcome gravity except when particles form clusters and fall back.

distribution within the bed. In addition, a fluidised bed has better mixing, less combustion instabilities and an improved burnout. A direct consequence of the enhanced mixing is that less excess air is needed. Thermal NOx emissions are low since the temperature level in the bed is below 1200°C (mechanisms for forming nitrogen oxides are discussed in Section 9.5.2). SOx emissions can be controlled by adding limestone or dolomite to the inert material. On the other hand, fluidised bed technology requires a higher investment and maintenance costs than grate-fired systems. Moreover, a fluidised bed is sensitive to bed agglomeration, exhibits extensive wear due to high particle velocity and the partial load operation is complex. Typical operating parameters for BFB boilers can be found in Table 9.2.

Circulating-fluidised bed (CFB) furnaces have higher fluidisation velocity than BFB systems. Thus, in a CFB, the bed is completely dispersed and the solid particles follow the gas flow (see Fig. 9.6). Consequently, a filtering device (usually a cyclone filter or a U-beam system) is needed to capture the solid particles and to feed them back into the furnace. CFB technology allows a higher level of turbulence and thus better heat transfer, which leads to a more uniform temperature distribution and higher burnout efficiency than BFB furnaces. On the other hand, with CFB boilers the dust load of the flue gas is higher, there is increased loss of bed material and they require smaller fuel particles. The latter has a direct impact on operating costs since biomass is often fibrous and thus difficult to grind. Typical operating parameters for CFB boilers can be found in Table 9.3.

9.2.3 Pulverised-fuel burners

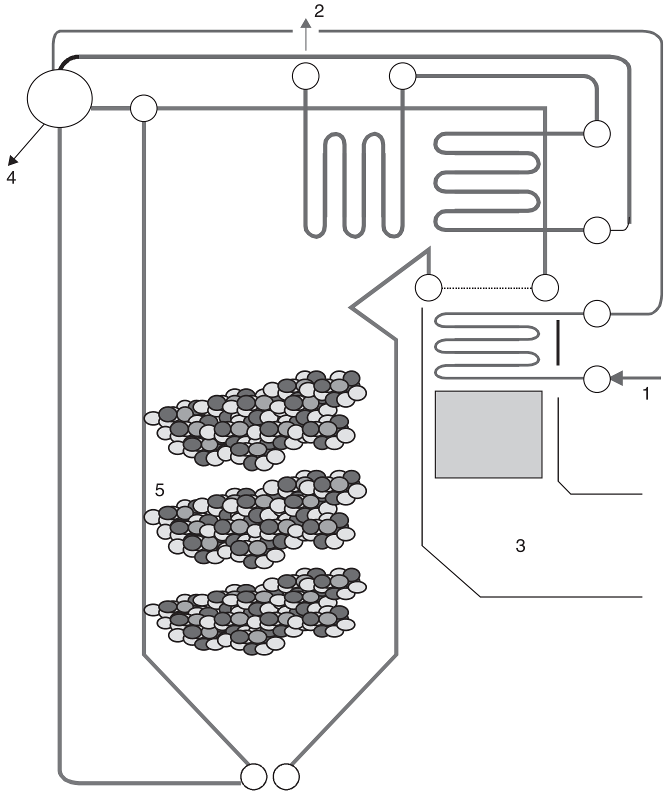
Pulverised-fuel (PF) technology is widely used for large coal-fired power plants. In such systems, the fuel particles are injected pneumatically at high velocity (the primary air is used as a carrier) through a burner nozzle into the furnace (Fig. 9.7).

Table 9.2 Typical operating parameters for BFB boilers

Parameter	Unit	Value
Volume heat load	MW/m^3	0.1–0.5
Cross-section heat load	MW/m^2	0.7–2
Pressure drop over the bed	kPa	2–12
Fluidising velocity	m/s	1–3
Height of the bed	m	0.4–0.8
Temperature of primary air	°C	20–400
Temperature of secondary air	°C	20–400
Bed temperature	°C	700–1000
Freeboard temperature	°C	700–1000
Excess air ratio	–	1.1–1.4
Density of bed during operation	kg/m^3	1000–1500

Table 9.3 Typical operating parameters for CFB boilers

Parameter	Unit	Value
Volume heat load	MW/m^3	0.1–0.3
Cross-section heat load	MW/m^2	0.7–5
Total pressure drop	kPa	10–15
Bed material particle size	mm	0.1–0.5
Fly ash particle size	μm	< 100
Bottom ash particle size	mm	0.5–10
Fluidising velocity	m/s	3–10
Temperature of primary air	°C	20–400
Temperature of secondary air	°C	20–400
Bed temperature	°C	850–950
Temperature after cyclone	°C	850–950
Excess air ratio	–	1.1–1.3
Density of bed	kg/m^3	10–100
Recirculation ratio	–	10–100



9.7 Pulverised fuel boiler. 1: Feedwater to economiser and then to the drum; 2: steam from superheaters; 3: flue gases from the furnace; 4: blowdown to remove impurities; 5: combustion chamber.

High-power output requires a swirl burner. In this configuration, the secondary air is fed around the fuel nozzle through a system of blades, which create rotational movement. The high turbulence and small particles give a faster and more efficient combustion with higher energy density. Thus, an efficient partial load operation can be easily achieved. However, besides the small particle size (milling difficulties for biofuels are discussed above), this technology requires a uniform fuel quality and low fuel moisture content. For these reasons, the use of PF burners with biomass is recommended for milled pellets, for waste from the wood industry (sawdust mainly) and for co-combustion with coal (biomass share 5–20%). In addition, this type of biomass has a high content of volatiles and therefore fuel feeding requires special care. Nevertheless, the development of biomass torrefaction (which enhances grinding) may allow the use of PF burners for biomass applications to a larger extent.

9.3 Fuels

Biomass is formed by photosynthesis. Biomass fuels are renewable if they originate from well-managed areas (i.e. where plants or trees are replanted) since their combustion does not increase the amount of carbon dioxide (CO_2) in the global atmosphere. Carbon dioxide released during burning can be assumed to be recycled with the growing of these fuels. The age of biofuels ranges from a few months to several years. Biofuels are highly volatile because of a relatively high hydrogen (H) content. The proportion of volatiles in most biofuels is around 70–80%. The carbon content and heat values are low compared to fossil fuels.

9.3.1 Biomass sources

Several sources of biomass can be considered for use in large combustion plants:

- Wood or residues from forest exploitation (wood pieces, wood shavings, tree trimmings): Whether from industry or individuals, this kind of wood can have significant variability and can be contaminated by soil, plastics or even chemical products. Emissions of pollutants, fouling and slagging may be important issues.
- By-products from silviculture and wood industries (sawdust, pellets, chips, bark): During wood processing, sawdust and small pieces of wood are generated. Wood of lesser quality (not straight enough or with knots) is discarded. This residual wood can be gathered and processed for transportation.
- Dedicated crops (e.g. miscanthus) can be used for biomass production. However, in some cases the land was previously used for food production, thus dedicated crops may contribute to food price inflation, and it may be better to use secondary biomass resources.

- Farming residues (corn cobs, maize stalks, wheat straw, rice husks, bagasse, etc.) are by-products from agriculture and they can generally be gathered in similar ways as the main crops. Some are used as animal food.
- Many different residues from food industries (olive pits, peanut shells, coffee grounds, sunflower seed husks, etc.) can be gathered and burnt to provide energy. They can be of various natures and have different quantities of energy.

9.3.2 Fuel stock and feeding

Bark

Bark is one of the most typical types of wood fuel. The outer surface is removed from wood logs in sawmills and pulp mills before the wood is processed to make sellable goods. Around 10–15 wt% of the wood ends up as 10–20 mm wide and 5–15 cm long brown strips called bark. Bark can be dried but often is not. It is fired as-is. The biggest handling problems are with long thin string-like pieces, which are hard to move and tend to become wrapped around transportation screws and conveyors. Typically bark is fed by screws to chutes where it drops into the combustion chamber.

Woodchips

Woodchips are becoming more and more widely used as a biofuel for energy production. Wood is typically chipped at the place of origin to about 5–15 mm thick chips. White woodchips contain only the thick, stem part of the wood. Green woodchips contain smaller branches, bark and even leaves and other growing parts of the tree (Selkimäki *et al.*, 2010). If wood is brought to the plant as whole wood logs then they need to be crushed on site. Woodchips are transported by conveyors and fed by screws to the combustion chamber.

Pellets

Pellets are small, dense, cylindrical, pressed wood products. Pellets substantially increase heating value (lower heating value – LHV) per biofuel volume. This reduces the transport cost so pellets are typically sold in international markets. Transportation, storage and handling are the same as for coal, gravel, etc. Pellets have low biological activity and are stable during storage. Pellets deteriorate rapidly when wet so it is recommended that they are stored in silos. They also create dust, which can be a fire hazard. Wood pellets are a well-defined commodity product with standardised quality parameters. Pellets are a homogeneous manageable fuel for power plants. Pellets are typically blown into the combustion chamber.

Torrefied biomass

Torrefaction is the treatment of biomass using pyrolysis. The process occurs at a relatively low temperature of 225–300°C. During torrefaction hemicelluloses and lignin present in wood are decomposed to some extent. Some dehydrogenation (chemical elimination of water) occurs. Torrefaction increases calorific value and if the result is pelletised then the density can be even higher than standard pellets. There is some cracking of the organic structures in the wood resulting in some of the heat energy in the wood being released as gases during torrefaction. The main advantage of torrefied wood (biocoal) is that it can be burned in PF boilers without major modifications to the equipment (van der Stelt *et al.*, 2011). In FBs, the high alkali content may lead to bed sintering and deposits.

9.3.3 Biomass characteristics

Biomass characteristics vary and play an important role in plant operation and performance. Important characteristics of biofuels for different combustion installations are listed in Table 9.4, and properties that affect combustion, operation and equipment are listed in Table 9.5 with comments.

Moisture

A general problem with biomass is its high humidity content; the energy needed to vaporise the water is generally lost. Generally, moisture content can be minimised at a low cost by just air drying, but biomass with a humidity up to 60% in mass can be accepted in some combustion systems. Also, the grinding required for a pulverised-fuel burner can be really problematic with wet ligneous materials (>20 wt%).

Volatile matter

The volatile matter is the gaseous phase formed from the thermal degradation of the material. It can be divided into two parts: light volatiles and tar (which comprises the bigger molecules that condense at ambient temperature). The volatile matter content is naturally high for many types of biomass. This property makes biomass easy to ignite. The volatile matter from biomass has a low LHV due to its high oxygen content. The amount of volatile matter present is strongly dependent on the nature of the pyrolysed material and the pyrolysis conditions, temperature and heating rate. The quantities of tar produced are also dependent on those parameters.

Ash

Ash is the residue after combustion. Biomass ash is naturally alkaline. Ash content is usually small for wood but can reach up to 20% in mass for some biomasses (see Table 9.6). The alkali nature of biomass ashes tends to lower the fusion point

Table 9.4 Important characteristics of biofuels for different combustion installations (Strömberg, 2006)

Characteristics	Pulverised-fuel boilers	Grate boilers	FB/CFB boilers
Calorific value	Medium to high > 15 MJ/kg	Wide range from about 5 MJ/kg for dry fuels, depending on refractory and boiler design	Wide range from about 5 MJ/kg for dry fuels
Moisture content	< 15% moisture content. Dry fuel necessary for quick ignition	Relatively insensitive to moisture content. Range 5–60%, depending on boiler design	High moisture content may be acceptable. Range 5–60%, depending on design
Ash content	< 1% for converted oil-fired boilers. Other pulverised-fuel boilers more insensitive	Travelling grate is insensitive. Stationary grate – low ash content	Insensitive to ash with high melting point. Low ash content is preferred if ash is difficult
Volatile content	Depends on boiler type, but > about 30%	Depends on grate design	If high volatile content – greater demands on fuel spreading
Particle size (not coal)	Depends on fuel reactivity, but requires finely pulverised fuel. Particle size < 1 mm, about 20% < 0.1 mm	Risk of fuel falling through the grate and entrainment with fine-grained fuels. Depends on grate design and primary air proportion. Can be designed for large particle size, up to 300–400 mm	Finely pulverised fuel may be entrained and will burn high up in the boiler. Particle size of 50–100 mm performs best

of ashes leading to fouling and slagging. Light ashes from combustion can be used as replacement of pozzolans in cements (van Eijk *et al.*, 2012). An increase in the ash content can also be coming from contamination; it can be from soil, rocks, plastic, metals, chemical treatments, etc. Those contaminants can lead to severe problems like pollutant formation, fouling and slagging (Hupa, 2012; Romeo and Gareta, 2009).

Heating value

Biomass power content is lower than other usual fuel such as coal, gas or oil. This lower power capacity is linked to a higher content in oxygen. During devolatilisation

Table 9.5 Biofuel properties that affect combustion, operation and equipment

Characteristics	Pulverised fuel boilers	Grate boilers	FB/CFB boilers
Particle form	The particle form may affect the volatiles and feed properties. Irregular, spiky and fibrous particles increase the risk of bridging and irregular feed	Influences the pressure drop across the fuel bed. Long pieces (rags, strips) may cause problems on the grate and also in fuel feed	May be of significance for how the fuel is spread on the bed
Flow and feed properties	May be of importance for the design of the conveyor system	Of some importance to fuel feed	Must be suitable for handling by a rotary vane feeder. Of some importance to fuel feed
Strength	–	The fuel must not disintegrate to give a high proportion of fines	The fuel must not disintegrate to give a high proportion of fines

Source: Strömberg, 2006.

the oxygen goes with the volatile matter mainly under the form of H_2O, CO_2 and CO. Thus the biomass volatile matter has a low LHV and the solid residual consequently has a higher LHV. But still, as most of the dry material devolatises, the energy release in gas phase is higher than that from solid combustion.

Ultimate analysis

The ultimate analysis, or the carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine content, is given in Table 9.7 for different types of fuel. It determines some of the properties of the biomass:

- The carbon content increases the heating value. Some of the carbon will be in the volatile matter and another fraction will form most of the char.
- Hydrogen also contributes to the heating value of the fuel and during pyrolysis most of the hydrogen will be in the volatile matter.
- The oxygen content *e contrario* reduces the heating value.
- The nitrogen content of the fuel is a significant source of NO_x pollutants. A high concentration in the fuel, such as for the agricultural and horticultural waste, will lead to higher NO_x concentrations in the flue gases (see Section 9.5.4).
- Sulphur is the source of SO_x pollutants.

- Water in the combustion gases will hopefully lead to the formation of HCl rather than Cl_2.

Density

Large-scale plants, obviously, need more fuel than smaller ones. Consequently, the handling, storage, and transportation costs are more important. Many types of biomass have a very low energy to volume ratio. Increasing the energy density is a key feature in biomass preparation. The mass and energy densities of different renewable fuels are listed in Table 9.6.

9.3.4 Biomass preparation

After collection and handling, biomass fuel must be prepared in order to burn properly. The main measures are listed here.

Drying

The simplest way to dry biomass is to let air take away the moisture; the biomass stockpile can be protected from rain by a plastic sheet. If the plastic sheet is not permeable, the biomass will retain some moisture. Ideally the biomass stockpile will be stored under a roof.

Mechanical processing

- Baling is the traditional agricultural method for handling straw, it is well known and functional, it works without adaptation for miscanthus, which is a new type of crop.
- Chipping or crushing: Raw trunks cannot go directly into a furnace; the wood must be broken into smaller pieces, by either chipping or crushing. The wood can be dried before or after fragmentation. Drying after fragmentation leads to some decay, raising the temperature with a small probability of auto-ignition. Also 5 to 10% of the wood mass is lost. Drying before chipping leads to much

Table 9.6 Densities of different renewable fuels (Clarke and Preto, 2011)

Fuel	Density (kg/m^3)	Energy density (GJ/m^3)
Baled biomass	160–255	2.8–4.7
Ground biomass	200	3.6
Briquettes	350	6.4
Pellets	550–700	9.8–14.0
Torrefied pellets	800	15.0
Bio-oil	1200	20

Table 9.7 Ultimate and proximate analyses for different types of fuel (Theis, 2006)

Mineral/fuel	Sludge	Wood	Grass	Straw	Husks	Bark	Peat	Coal
Moisture, wt%	64.3	15.9	30.7	10.4	9.0	13.0	41.2	8.1
Ash, wt% dry	19.4	0.6	3.6	8.6	10.8	3.7	5.5	11.8
Volatiles, wt% daf	87.8	84.1	83.5	81.1	79.8	76.5	73.9	38.4
HHV, MJ/kg daf	18.8	20.3	19.7	19.5	20.5	21.3	22.9	33.8
LHV, MJ/kg daf	17.9	19.0	18.5	18.1	19.1	19.7	21.4	31.1
C, wt% daf	51.2	51.2	49.6	48.8	50.4	53.8	57.4	79.4
H, wt% daf	6.24	6.15	5.72	5.99	6.28	5.84	6	5.29
O, wt% daf	41.4	42.4	43.9	43.9	42.6	40	35.5	12.2
N, wt% daf	<1.5	<0.5	<1.5	<1.5	<1.5	<0.5	1.9	1.5
S, wt% daf	<1.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.3	1.4
Cl, wt% daf	0.43	0.027	0.196	0.496	0.143	0.022	0.059	0.25
Si, mg/kg dry	46 000	N/A	6775	17 025	14 000	422	12 615	25 148
Al, mg/kg dry	27 700	N/A	100	1579	2700	188	4181	13 123
Fe, mg/kg dry	1747	N/A	109	1417	2300	90	6387	7255
Ca, mg/kg dry	88 600	N/A	1273	4694	13 000	13 622	6200	5421
Mg, mg/kg dry	2870	N/A	534	1818	5100	728	634	1666
Na, mg/kg dry	1725	30	319	610	1090	40	144	1142
K, mg/kg dry	1652	680	7633	11 634	22 233	1627	548	1287

Notes: LHV: lower heating value, HHV: higher heating value, daf: dry, ash free.

finer particles and a higher energy requirement for chipping. Since there are spaces between the chips, chipping can double the volume i.e. halve the energy density. Transporting raw trunks means transporting a smaller volume.

- Sawdust has a low energy to volume ratio so it is not transported much; it can be efficiently used in a pulverised-material burner as it is already a fine product and does not require energy for pulverisation.
- Pellets are formed under pressure, which significantly densifies the product (see Table 9.6). The lignin is degraded and provides adhesion. Pelletisation can be used for a considerable number of products. If the products do not contain lignin, a cohesion agent can be added.
- Briquettes are produced in a similar way as pellets, but in a bigger size and with a lower density.

Thermal processing

- Heating can be used for drying, but wood is naturally hydrophilic, so it re-absorbs moisture very quickly. Drying through heating is consequently used just before combustion. The biomass ignites easily, necessitating temperature control to avoid self-ignition in pipes.
- Torrefied biomass is made by heating biomass in an inert atmosphere at 280–320°C for a few minutes. The biomass loses water, moreover it becomes hydrophobic, so the material will not re-absorb moisture. There will be a small loss of volatile matter, which can be burnt to furnish heating for the process (see Chapter 3 of this book).
- Pyrolysis can be used to treat biomass; it is performed by heating in an inert atmosphere at a higher temperature than torrefaction:
  - At low temperature (450–500°C) and long residence time (from 5 minutes to some hours) to produce char that is brittle and with a better energy density. The volatile matter produced can be used in a thermal process.
  - At low temperature (450–500°C) and fast residence time (order of seconds). The volatile matter is mainly tar, which is used to produce oil. The amount of char produced is minimal. The energy density of the oil produced is much higher but the liquid obtained is very acidic and can cause problems in handling.

9.4 Operational issues

The key operational challenges in large biomass combustion units are the boiler's availability and maintenance costs. If the biomass contains chlorine then the presence of sticky fly ash with the related problems of fouling and corrosion of the superheater tubes is a common phenomenon. Fuel ash from different fuels burnt together may also interact with each other in a surprising way, thus sometimes leading to excessive fouling or bed sintering problems (Hupa, 2012). Grate boilers can experience slagging, which stops the fuel flowing on the grate. Biomasses in general contain alkali metals, especially potassium and often chlorine, which are corrosive, so biomass firing in PF boilers can cause corrosion of the superheater (Duong and Tillman, 2010). The use of biofuels in fluidised bed boilers may cause several operational problems because of fuel impurities. Sintering of bed material is a problem with high alkali fuels.

9.4.1 Slagging and fouling

The fouling of combustor surfaces is a major issue that has played an important role in the design and operation of combustion equipment. Slagging and fouling reduces heat transfer and causes corrosion and erosion problems, which reduce the lifetime of the equipment. The main contributions to fouling are from the inorganic material in the fuel. The behaviour of these inorganic materials is less well understood than that of organic materials. Because biomass fuels contain a larger variety of inorganic materials compared to coal, issues of fouling, corrosion and pollutant emissions need to be explored. This is particularly true for some agricultural residues and new trees growth where the fly ash can have a relatively high alkali metal content (Theis, 2006; Werkelin *et al*., 2005). As a result, biomass can cause unplanned downtime due to corrosion fouling and slagging in the high-temperature convective elements (the superheater). For example, 1 m of the stainless steel pipe in a heat exchanger costs approximately €200 (in 2012) and the total length of piping in one 340 MW boiler's superheater is close to 5 km (giving the potential to save €1M and more with production losses). It would be interesting to use materials resistant to the steam and metal surface temperatures.

Fouling of the heat transfer surfaces means that the tubes are covered with deposits which:

- hinder heat transfer,
- plug gas passages increasing velocities and causing a drop in pressure, and
- can even cause structural damage because of the uneven heat flow.

Table 9.7 lists typical mineral impurities. The impurities come from the inorganic material in the plants that formed the fuel, inorganic material that was harvested with the fuel and inorganic material that is added during fuel handling. When the fuel burns in the furnace, the impurities react with each other and the surrounding gases to form ash. Because of the high temperatures, the components in the ash frequently undergo several changes of state. Ash can form hard-to-remove and corrosive deposits. Fouling is influenced by ash behaviour. Ash that contains a molten fraction is often more fouling than solid ash.

- Sulphur might be present in plants by assimilation and absorption of SO_2 from the atmosphere or by absorption through the roots. The common forms of sulphur are organic sulphur and sulphates.
- Chlorine in biofuels can exist as chloride ions and its concentration depends on the nutrients in the soil. As a rule, the amount of chlorine in soil is slightly higher than required for plant growth, thus the chlorine content of a fuel is more indicative of the soil than the nature of the plants.
- Phosphorus appears in its most oxidised form in plants and the amount does not decrease during metabolism. The main form is dihydrogen phosphate ions (H_2PO_4), and it usually remains in the organic form or is converted into esters or pyrophosphates, incorporated into the organic structure.
- The silicon in plants is due to the absorption of silicic acids from the soil. Silicon is present in most plants at a macro-nutrient level (0.1–10% dry basis). It is found as a hydrated oxide ($SiO_2 . nH_2O$) in crystalline forms or in amorphous forms.
- Calcium exists in the cytoplasm and forms the structure of cell walls and can be accumulated as an oxide or oxalate, if there is an excess.
- Aluminium is toxic to plants and is found only in small quantities as an impurity in the soil. The concentration of aluminium in plants does not usually exceed 300 ppm on a dry basis.
- Alkali and alkaline earth metals (sodium and potassium) occur in organic structures. They are usually deposited as a water-soluble fraction, so they are easily volatilised and hence more reactive with other components, which lead to problems such as fouling, corrosion and agglomeration. Potassium is the second most widespread component of grasses and straw. Potassium is deposited as univalent ions (K^+) and can be found in the growing regions of a plant or can appear as an impurity from fertiliser. Hence, it is believed that fuels with a higher content of alkali and alkali earth metals are more problematic for combustion.

Bed agglomeration

Agglomeration of a fluidised bed is the most typical problem and a very aggravating one since it can appear suddenly (Brus *et al.*, 2005; Zevenhoven-Onderwater *et al.*, 2001). In bed agglomeration the ash in the fluidised bed reaches a state where individual ash particles start to stick to each other and sand particles. The lumps formed do not fluidise and the bed quickly – in some tens of seconds – loses its ability to operate. Because of the specific ash-forming constituents of biomass fuels, they are especially problematic. The suggested dominating bed agglomeration mechanism for typical wood fuels is coating-induced agglomeration with subsequent attack (reaction) and diffusion by calcium into the quartz as well as the direct formation of low-melting potassium silicate due to potassium compounds in the biomass.

9.4.2 Ash melting

Deposits in boiler heat transfer surfaces are not static but depend on process conditions. Ash deposition is often time dependent, i.e. the ash properties change across a deposit cross section. The most important property of the ash is its strength, which depends on the ash melting behaviour and its sintering rate. Deposit strength depends mainly on its porosity.

First melting temperature

The melting behaviour of deposits in boiler heat transfer surfaces determines many of the properties of the deposits. The first melting temperature (FMT) is the temperature at which melting first appears in a boiler deposit, which is also the start of the regime where fouling problems occur. Understanding and predicting the first melting temperature is particularly important in terms of superheater corrosion.

Liquid content

When biomass boiler dust is heated, it at first behaves like a solid. At the first melting temperature, liquid appears. Above that temperature, a state where the deposit is partially molten and partially solid exists. Depending on the type of system, after a small or larger rise in temperature, all of the ash is molten.

Typically, biomass boiler heat surface deposits are eutectic mixtures. In eutectic mixtures the components do not mix together but remain separate during heating and cooling. In minimum melting mixtures the compounds are reasonably similar so they can form a single solid structure. It is typical that in salt systems the melting temperatures of the mixtures are lower than individual melting temperatures.

The temperature where 15 wt% of the deposit is in a molten state and 85 wt% is in a solid state is called T15 or the sticky temperature. The temperature where 70 wt% of the deposit is in a molten state and 30 wt% is in a solid state is called T70 or the flow temperature. Biomass boiler dusts tend to stick to the heat transfer surfaces and form hard deposits when they are between T15 and T70. An example showing the effect of water content on material behaviour is plaster. If it is dry, it will fall off the wall. If there is too much water the plaster will again fall off the wall. But between these states the plaster will stick to the wall. The liquid content can be predicted with computer programs (Backman *et al.*, 1996).

Sintering

Sintering is the process where dust particles that have stuck to a heat transfer surface gradually densify and harden. Originally loose and porous material becomes solid, almost crystal-like. As deposits densify, their strength increases exponentially, and they become more difficult to remove by soot-blowing. Because of the end product the process is often called deposit hardening.

Fume particles sinter at temperatures above 300°C. The rate of sintering increases rapidly with temperature. The sintering and hardening of biomass boiler deposits is affected also by the deposit packing density, dust and flue gas composition (Frederick and Vakkilainen, 2003).

These fine particles apparently sinter and harden into difficult-to-remove bank deposits by two mechanisms:

- evaporation of sodium chloride from the particles and recondensation, forming a neck at the point of contact between two particles;
- transport of mass from the particles to the neck by solid-state diffusion.

As sintering proceeds, the neck between the fine particles grows until ultimately individual particle shapes cannot be seen. Beyond that point the grain size of the structure grows as mass from smaller, individual particles is transported to the larger ones.

In real biomass boiler deposits the sintering behaviour is much more complex. These deposits contain fine fume particles, large carryover particles and intermediate-sized particles. Each particle type has its own composition and so its own sintering behaviour. The actual deposit sintering behaviour is then the sum of the sintering of all of these different materials.

9.4.3 Corrosion and abrasive wear

Corrosion is typically divided into areas based on its location:

- water-side corrosion;
- combustion-gases-side high-temperature corrosion;
- combustion-gases-side low-temperature corrosion.

Water-side corrosion occurs on the steam/water side of the boiler tubes. Most often the cause is impurities in the feedwater. Combustion-gases-side high-temperature corrosion occurs in the superheaters. High-temperature corrosion is often caused by ash deposition. Low-temperature corrosion occurs in the economisers and air heaters. Low-temperature corrosion is often associated with the formation of acidic deposits. If it is known that the environment is corrosive, then appropriate materials can be selected, though often only experience can give an answer to this.

High-temperature corrosion

By high-temperature corrosion we mean corrosion in the superheaters caused by chemicals (vanadium, chlorine, etc.) and the molten phase of deposits (sodium, potassium, etc.). Fuels contain minor impurities. These impurities often tend to become enriched and form ash deposits. In particular vanadium, sulphur and alkali metals cause corrosion. A known corrosive agent is the vanadium in some oils. The ash in boilers can contain up to 40–70% vanadium pentoxide, V_2O_5, which causes corrosion when the metal surface temperature is 580–650°C.

Often high-temperature corrosion is concentrated on the windward side of the tube (the side facing the incoming flue gas). The ash mainly sticks to the windward side of the tube and a molten layer exists at the tube sides. The actual corrosion rate depends on ash properties and tube temperature.

A typical method of preventing high-temperature corrosion is to use alloyed materials. Often it is enough to add chromium to lower the corrosion rate. Other popular metals to add are nickel and molybdenum. The choice of the right material is, however, often a matter of trial and error.

Acid corrosion

When flue gases cool, their ability to hold species in gaseous form weakens and the species start to condense. The acid dew point is the temperature below which this condensate is acidic. The sulphur dew point refers to conditions where sulphur trioxide starts condensing. Also HCl condensation is possible.

Chloride corrosion

Chloride in fuel forms Cl_2 and HCl in gaseous form. If these gases touch tube surfaces, ferrous chloride forms, which reacts with oxygen to form ferrous oxide releasing chloride and the cycle repeats. Chloride corrosion has been studied mainly in connection with waste burning and recovery boilers.

Alkali corrosion

Sodium and potassium form ash with low melting points, 500–600°C. Adding chloride further decreases ash melting points. With a high enough liquid content, ash flows down the superheater surface. Uniform thinning can be seen. Potassium can become enriched in the superheater tubes even if the potassium content in the biofuels is low (Orjala *et al*., 2001).

Corrosion prevention

Corrosion can be prevented by carrying out regular checks of heat transfer surfaces. Usually these show corrosion phenomena and action can be taken before anything serious happens. Once corrosion is observed or it is known from experience that a surface in a boiler is prone to a certain type of corrosion, it is a matter of choosing the right materials. It is important in corrosion prevention to learn from experience.

Erosion

Erosion is caused by particles hitting the heat transfer surface. The erosion rate increases with the kinetic energy of the particles. Erosion depends strongly on ash characteristics and the local velocity field. In addition to erosion of the heat transfer surface, the solid fuel transport and handling equipment suffer from erosion. In fluidised beds, erosion is controlled by welding a protective hard surface to the tubes and using refractory-coated surfaces. Hard substances in fuels are alumina, quartz and pyrite. In addition some minor impurities such as kyanite, topaz and orthoclase are hard but their content is very low.

9.5 Environmental aspects

Biomass combustion produces solid and gaseous pollutant emissions that need to be treated not only to follow existing or future emissions standards (Table 9.8), but also to minimise possible effects on human health and environment. Primary pollutants from combustion can be classified into two groups: one from incomplete combustion or oxidation and the other from the inorganic species in the biomass fuel (Yin *et al.*, 2008):

- Incomplete combustion leads to CO, C_xH_y, polycyclic aromatic hydrocarbons, tar, unburnt char emissions and soot.
- The combustion setting and fuel nitrogen content play an important role in the formation of nitrogen oxides (NO_x: NO, NO_2, N_2O).
- The presence of inorganic species will lead to particulate matter emissions, SOx, HCl, salts (KCl, etc.), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, and heavy metals.

Table 9.8 Emission limit values, expressed in mg/Nm^3 at 6 vol% of O_2 in the exhaust gases, for large-scale combustion plants

Emission type		50 to 100 MWth	100 to 300 MWth	> 300 MWth
SO2	Biomass	200	200	(200) 150
	General case	(850) 400	200	200
NOx	Biomass	(400) 250	(300) 200	(200) 150
	General case	(400) 300	200	(200) 150
Dust	All solid fuels	(50) 20	(30) 20	(30) 10
	Biomass			20

Note: 2001/80/EC EU directive and 2010/75/EU IED, LCP in parenthesis if different from IED.

Depending on the pollutant, measures can be taken by:

- selection or treatment of the fuel;
- primary reduction techniques (in the combustion zone);
- air pollution control abatement systems.

The main reduction techniques are summarised in Table 9.9 and described below; more detailed descriptions may be found elsewhere (e.g. van Loo and Koppejan, 2008).

9.5.1 Primary reduction techniques

Incomplete combustion is generally due to poor mixing of the air and fuel, insufficient residence time, insufficient temperature and low total excess air. Thus, significant improvement can be obtained in new but also in existing boilers by:

- Improving primary, secondary and tertiary air distribution, this includes verification when a boiler is commissioned, or after major modifications; NOx emissions are also strongly affected by air staging.
- Controlling the global excess air: a typical value of oxygen (dry) concentration is between 7 and 11% as a function of fuel moisture (the oxygen set-point value is proportional to the moisture content).
- Adjusting the residence time of the fuel on the grate or in the combustion zone, i.e. through the grate velocity or by an appropriate choice of fuel size distribution and the size of the combustion zone of the particles burning in suspension (more than 1.5 s is generally used for the time in the combustion zone); the design of the combustion chamber is also important.
- Optimising the solid bed temperature: preheated primary air may be necessary to optimise drying and devolatilisation of the bed; sufficient air must be supplied for the char burnout on the bed.
- Controlling the temperature of combustion of volatiles (> 850°C), bearing in mind that incineration regulations say that they must be at 850°C for a minimum of 2 s; there are similar recommendations for biomass boilers.

In any case, the automatic control loop (regulation system) plays an important role, and should be carefully analysed to achieve optimal performance of a biomass boiler. The control algorithms should take into account the following parameters and the relationship between them:

- O_2 and CO concentrations in the flue gas, fuel moisture: this will allow a better estimation of the O_2 concentration set-point value, but requires on-line CO concentration and fuel moisture content measurements.
- Temperature measurements at several points in the furnace: this will give information about the heat exchange process, and thus implicitly about slagging and fouling.

Table 9.9 Main air pollution control techniques

Technique	Dust	Metal particles	Metallic gases	Acidic gases	NOx	PCDD/F	VOC	CO
Primary reduction techniques	X	X	X	X	X	(X)	X	X
Mechanical: (multi)-cyclone, venturi scrubber, (dry and wet) electrostatic precipitator, bag filter	X	X						
Neutralisation: calcareous or sodic reagents			(X)	X		(X)		
Active carbon injection			X			X	(X)	
Selective non-catalytic reduction (SNCR)					X			
Selective catalytic reduction (SCR)					X	X	(X)	(X)

- Direct measurement of the fuel and mass air flow rates: these values will allow a more accurate calculation of other parameters, such as the primary to secondary air ratio.
- Integrating the fuel moisture into the estimation of the draught set-point value in order to achieve an optimum value for the residence time of the gases inside the boiler.

For grate systems, the primary air distribution and flue gas recirculation (if any) under the grate should be correlated with the evolution of reaction fronts within the bed (drying, devolatilisation and char burnout) in order to enhance heterogeneous combustion and to limit fly ash emissions.

9.5.2 NOx formation and reduction

This section discusses formation mechanisms for nitrogen oxides during combustion, distinguishing between thermal NO, prompt NO and fuel NO. Recently some additional routes have been identified through which NO and other oxides of nitrogen are formed – the NO_2 route and the N_2O routes. The detailed reaction mechanisms can be found in Kuo (2005), Fenimore (1970, 1979) and Turns (2000).

NOx reduction techniques

Apart from the natural reduction mechanisms described in the section above, NOx emissions formed during solid fuel combustion can be reduced by application of so-called primary and secondary measures (Miller and Tillman, 2008; van Loo and Koppejan, 2008; Di Nola, 2007; Roy *et al.*, 2009). Primary measures decrease the amount of NO produced during the combustion process, whilst secondary measures remove nitric oxide from the flue gases. Primary de-NOx measures comprise low-NOx burners (burner air staging), overfire air (furnace air staging), reduction of the excess air level, flue gas recirculation and reburning. Secondary

Table 9.10 Summary of NOx reduction measures and their potential

Control method	De-NOx potential (%)
Low excess air level	0–15
Overfire air	0–30
Low-NOx burner	40–70
Flue gas recirculation	0–20
Reburning	0–70
SCR	80–95
SNCR	15–50

Source: Di Nola, 2007.

measures are represented by selective non-catalytic (SNCR) and catalytic (SCR) reduction, where ammonia or urea are injected into the flue gas. They are usually more complex to implement and require high investment costs. These measures are, however, applicable for large power plants rather than for small-scale combustion applications. NOx emissions from biomass combustion applications are in general low, compared to coal and oil combustion. In small-scale domestic systems, such as pellet stoves and boilers, the most important option for reducing NOx emissions is to control the quantity of fuel nitrogen in the biomass. Table 9.10 summarises NOx reduction measures and their potential.

NO reduction occurs as homogeneous (gas phase–gas phase reactions) and heterogeneous (solid phase–gas phase reactions) reduction. NO can be homogeneously reduced by OH-, CH_i- and NH_i- radicals, which are present in sufficient amounts in fuel-rich conditions, such as those created through air/fuel staging. The typical homogeneous reduction reactions are:

$$NH_2 + NO \rightarrow N_2 + H_2O \tag{9.1}$$

$$NH + NO \rightarrow N_2 + OH \tag{9.2}$$

$$CH_i + NO \rightarrow HCN + OH_{i-1} \tag{9.3}$$

NO is reduced to HCN and is recycled in the fuel nitrogen reaction scheme. HCN can be converted to either N_2 or NO depending on local conditions by the following reactions:

$$HCN + O \leftrightarrow NCO + H \tag{9.4}$$

$$NCO + H \leftrightarrow NH + CO \tag{9.5}$$

$$NH + H \leftrightarrow N + H_2 \tag{9.6}$$

$$O + N_2 \leftrightarrow NO + N \tag{9.7}$$

Heterogeneous reactions of NO comprise reactions with solid carbon, which occur in the pores of char particles. Heterogeneous reactions are not as significant as the homogeneous reactions, and NO reduction is usually achieved by gas phase reactions (Di Nola, 2007).

Research has shown that NOx formation during biomass combustion processes at temperatures between 800 and 1100°C mainly results from fuel-bound nitrogen. Measurements in Austrian and Swiss furnaces (van Loo and Koppejan, 2008) (grate firings and underfed stokers) show a logarithmic dependence between the concentration of nitrogen oxides emitted and the concentration of nitrogen in the biomass fuel used. Swedish research results also indicate a clear dependence of NOx formation on the nitrogen content in the fuel in CFB furnaces, although the overall NOx emissions produced are considerably lower than in fixed-bed combustion systems – between 30 and 100 mg/Nm^3 (milligrams per standard cubic metre, for dry flue gas, 11 vol% O_2) for woodchips with 0.15–0.22 wt% of nitrogen in the fuel (van Loo and Koppejan, 2008). Furthermore, the results achieved in various European countries clearly show that the air supply, the geometry of the furnace and the type of furnace are major influencing variables for NOx formation. In order to reduce NOx formation, primary measures have been comprehensively investigated for grate firings, BFB and CFB furnaces. The results show that primary and secondary air should be injected in geometrically well-separated combustion chambers. Furthermore, the air fans should be frequency controlled to ensure a primary air ratio of 0.6–0.8 in the furnace. Moreover, the excess oxygen amount, determined by the secondary air, should be as low as possible while still guaranteeing complete combustion. Flue gas recirculation can enhance mixing and also contribute to a well-defined temperature in the primary combustion zone.

Fuel nitrogen content

In biomass combustion, the fuel nitrogen content is the main factor influencing total NOx emissions. The nitrogen content in biomass fuels can vary widely, from <<1% in core wood up to ~10% content in meat and bone meal. Animal manure and waste is typically characterised by a high fuel-bound nitrogen content. Woody biomass typically contains little nitrogen, while the nitrogen content of waste wood may reach 2.5% (van Loo and Koppejan, 2008). The fuel nitrogen in waste wood comes from urea formaldehyde and related glues, which are used to manufacture plywood, particleboard and panelling (Miller and Tillman, 2008). Straw, cereals, grass and olive residues are reported to have a higher nitrogen content (more than 0.6 wt% d.b.) compared to woody biomass.

The effect of fertilisation may be to increase the fuel nitrogen content in proportion to the nitrogen dose in the fertiliser. Bonomelli *et al.* (2005) studied the plant *Echinacea purpurea* and the effect of fertilisation on its composition. They reported that 100 kg/ha of nitrogen fertilisation increased the nitrogen concentration in all parts of the plant (roots, shoots, flowers and leaves) from 1.8% to 2.8%. After treatment with the highest nitrogen dose, there was proportionally more nitrogen in the shoot stems compared to the flowers. This was not surprising, since an increase in nitrogen fertilisation tends to decrease the proportion of floral structures, delays blooming and stimulates vegetative growth.

Char concentration effect on NOx reduction

Dong *et al.* (2007) experimentally investigated NO reduction under the influence of biomass char. For rice husks, they found that NO conversion to N_2 is higher with increasing char fraction in the biomass. They also concluded that the presence of CO can improve the NO–char reaction; however, the CO level is related to the combustion process itself rather than fuel preparation. The same trend was confirmed by Wang *et al.* (2011) for wheat straw char. Other research groups (Sorensen *et al.*, 2001; Garijo *et al.*, 2003) also reported that the NO formed may be effectively reduced to N_2 over biomass char as a result of its catalytic effect on NO formation and reduction. Therefore, partitioning of fuel nitrogen between the volatiles and the remaining char during devolatilisation is potentially important for final NOx formation. The split between the volatile nitrogen and char nitrogen is roughly proportional to the volatile matter in the fuel (Miller and Tillman, 2008). Because biomass fuels have higher yields of both light gases and tar, and lower char yields, a comparatively larger fraction of the fuel nitrogen may be released with the volatiles. The latest experiments, for a broad range of woody biomass fuels (sawdust, bark, waste wood and medium-density fibreboard) in a lab-scale packed bed batch reactor, indicate the fraction of the volatile nitrogen increased with increasing fuel nitrogen content (Stubenberger *et al.*, 2008).

Fly ash

In their review Yin *et al.* (2008) suggest the positive effect of fly ash on NOx reduction. When co-firing biomass (bagasse, woodchips, sugarcane trash and coconut) with bituminous coal in a 18.68 MWe travelling-grate boiler (Narayanan and Natarajan, 2006, 2007) both NOx and SO_2 were reduced, and the biomass ash promoted NOx reduction. Chen and Gathitu (2011) demonstrated that biomass fly ash derived from a pine-bark-fired grate boiler is an effective material for reducing NO in the post-combustion zone where the temperature ranges from 300 to 600°C.

On the other side, no clear trend for NOx reduction was found in other biomass/coal co-firing experiments (Molcan *et al.*, 2008). Lissianski *et al.* (2001) also tested various metal-containing additives in the combustion and reburning of natural gas. When using fly ash as an additive they found a minimal effect on NOx reduction.

Potassium, calcium and sodium

Ren *et al.* (2009) studied the effect of minerals on NOx emissions. Using TG-FTIR on-line analysis they looked at the formation of nitrogen-containing species during the pyrolysis of rice straw, wheat straw and corncobs. They found that potassium (in the form of KOH) and calcium (CaO) may help to reduce nitrogen species (NH_3, HCN, NO and HNCO), of which NO was reduced the most during pyrolysis. Sodium has similar effects on NOx reduction as potassium. Up to 28% NOx reduction was achieved with 500 ppm of sodium or potassium in the flue gas (Lissianski *et al.*, 2001).

9.5.3 Particulate emissions and filtration

Particulate matter formed by combustion

The formation of particles during biomass combustion depends on several factors, which include:

- the physicochemical characteristics of the fuel (size, chemical composition, humidity, ash content, ash melting temperature, etc.);
- the techniques employed in the furnace (type of furnace, air staging, heat exchangers, etc.);
- the operating conditions (flow rates, temperature, cooling, etc.).

The size and chemical composition of particles emitted by combustion processes can give information about their origin and formation:

- Smaller particle of less than 100 nm correspond to the nucleation of gas particles to form solid condensed particles.
- Particles from a few hundred nanometres up to around 1 μm correspond to heterogeneous formation, where gases condense at the surface of existing solid particles.
- Particles larger than 1 μm may correspond to non-volatile matter transported by the turbulent gas flow from the combustion zone, the partial melting of the ash or from incomplete combustion.

Size distribution

The size distribution of combustion-generated particles is generally multimodal, testifying to several formation pathways. Before air pollution control systems, concentrations may vary between tens or hundreds of milligrams per cubic metre, and the size distribution is mainly unknown (Jöller *et al.*, 2007). After abatement, the concentration may be reduced to a few mg/Nm^3. The majority of the particles are smaller than 2.5 μm, with in some cases a significant number of nanoparticles. However measurements of the size distribution in industrial conditions are difficult (Buonanno *et al.*, 2009).

Chemical composition

Solid fuel combustion comprises drying, evolution and burning of volatiles, and solid phase combustion. Biochar combustion will produce, by fragmentation and melting, relatively large particles (micrometres to millimetres), which will form bottom ash and fly ash (approximately 1 to 200 μm). Their formation is strongly correlated to the initial ash content of the biomass, and more specifically on the quantity of refractory material, i.e. materials that do not melt at the furnace temperature, for example silicon, calcium or magnesium oxides.

At the same time, the combustion of non-volatile matter will lead to progressive evaporation of elements such as sodium, potassium, sulphur and chlorine; those elements will form, by nucleation and condensation, small particulate sulphates (1 nm to 1 μm) and potassium (or sodium) chloride such as KCl, K_2SO_4 or NaCl. Those elements can also condense or be adsorbed at the surface of other particles. Other minor elements, present in lower concentrations in biomass, can also evaporate and follow similar behaviour, thus participate in the composition of the smallest particles. This is the case for cadmium, lead and zinc, the latter being usually the most abundant (Sippula *et al.*, 2009).

Fine and ultrafine particles are generally richer in the following elements: potassium, sodium, sulphur, chlorine, zinc and lead (Obernberger *et al.*, 2006), which may be used in the formation of the following: K_2SO_4, KCl, $(KCl)_2$, K_2CO_3, Na_2SO_4, NaCl, $(NaCl)_2$, ZnO, $ZnCl_2$, PbO and $PbCl_2$ (Jöller *et al.*, 2007). Ash and fine particles are usually classified using the proportion of major elements (aluminium, calcium, iron, potassium, magnesium, sodium, phosphorus, silicon and titanium), minor elements (arsenic, barium, cadmium, cobalt, chromium, copper, mercury, manganese, molybdenum, nickel, lead, antimony, thallium, vanadium and zinc), and sulphur, chlorine and oxygen content (Baxter *et al.*, 1998).

The chemical composition of the fuel (mainly carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine) will affect the particle formation mechanism. Sulphur and chlorine will produce particulate sulphate and chlorinated salts, following a similar mechanism as for potassium. Particulate matter may also be formed with the interaction of acid gases (SO_x and HCl) with basic gases such as ammonia (NH_3). More complex mechanisms such as the nucleation of chloride (KCl) on sulphates (K_2SO_4) may occur, depending on the temperature (Christensen *et al.*, 1998; Jimenez and Ballester, 2005, 2007). Particle formation mechanisms have been more widely studied for coal; comparatively, biomass is richer in potassium, silicon and calcium, and has less aluminium, iron and titanium, in some cases leading to different types of particle (Demirbas, 2004).

The combustion of volatiles released during the early phase of fuel pyrolysis will also lead to the formation of small particles ($PM_{0.1}$ to $PM_{2.5}$), through the evolution of aromatic organic compounds (VOC) to polycyclic aromatic hydrocarbons and soot. Those phenomena, occurring in the flame, are strongly influenced by the combustion parameters.

Important parameters

Oxygen concentration is one of the most important parameters in particulate matter formation. Good oxidation of combustion products will limit the production of particulate matter; mixing, temperature and whether the setting is transitory or stationary are also of importance.

9.5.4 Acidic gas formation and neutralisation

The sulphur and chlorine content is very low in common biomasses; if this is not the case, SO_x and HCl can be formed. Classical air pollution control, developed for incineration or coal combustion, can be utilised.

In short, dry, semi-dry (or semi-humid) and humid techniques exist. The principle is to inject a reactant (solid or liquid) that will react with a gaseous pollutant (SO_2, SO_3 or HCl) to form a solid or liquid phase, which can be easily collected in a bag filter or in a cleaning tower. For example, sodium carbonate (solid) can be pneumatically injected into the combustion gases, after the combustion zone at 140–300°C, to react with SO_2 to form sodium sulphate (solid):

$$Na_2CO_3(s) + SO_2(g) \rightarrow Na_2SO_3(s) + CO_2(g) \tag{9.8}$$

When the gases cool down, sodium sulphate is also formed in the presence of oxygen:

$$Na_2SO_3(s) + ½O_2(g) \rightarrow Na_2SO_4(s) \tag{9.9}$$

Sodium carbonate can also be used for HCl abatement according to the following reaction:

$$½Na_2CO_3(s) + HCl(g) \rightarrow NaCl(s) + ½CO_2(g) + ½H_2O(g) \tag{9.10}$$

An increase in the humidity of the gases will increase the efficiency of those reactions. Similar reactions occur when using lime at lower temperatures than used with sodium carbonate:

$$Ca(OH)_2+SO_2+H_2O+½O_2 \rightarrow CaSO_4+2H_2O \tag{9.11}$$

$$CaO(s) + 2HCl(g) \rightarrow CaCl_2(s) + H_2O(g) \tag{9.12}$$

9.5.5 Active carbon injection

In some cases, dioxins may be created by biomass combustion, but the formation rate is not directly linked to the chlorine content of the fuel (Lavric *et al.*, 2004). However, with exceptionally high-chlorine-containing biomasses, high values have been observed (Uloth and van Heek, 2002; Leclerc *et al.*, 2006). The formation mechanisms have still not been well explained for biomass combustion. Typically the dioxin levels from biomass combustion are low. If dioxins are formed (limit value is 0.1 ng/Nm^3 @ 11% O_2) then active carbon injection is recommended, before capture in a bag filter.

9.6 Future trends

The EU wants to double the usage of biomass by 2020 and also to increase the share of CHP in power generation. Using ash beneficially, ash valorisation, still poses various practical problems although in principle these have been worked on for more than thirty years.

Large-scale commercial torrefaction is still waiting for higher CO_2 prices within the European Union Emissions Trading System. Large-scale pellet production is already a reality. The first commercial biomass gasifiers and pyrolysers are in operation and their effect on biomass usage is awaited.

There is currently debate about biomass sustainability and how much of it there is (Royal Society, 2008; European Climate Foundation, 2010). The argument is not about the carbon in biomass, which is renewable. The argument is about the magnitude of the economic, societal and climatic changes that increased use of biomass may cause. Biomass burning is still seen as carbon neutral by the Intergovernmental Panel on Climate Change (IPCC, 2011).

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10

Industrial-scale biomass combustion plants: engineering issues and operation

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Abstract: Biomass-fired steam boilers are finding increasing use in industrial-scale applications for both heat and power generation. This chapter compares the main technologies for biomass combustion – spreader stoker, mass burn and biomass bubbling fluidised bed (BFB)/circulating fluidised bed (CFB) – and discusses specific issues to be addressed in the design of biomass-fired steam boiler plants. Examples of recent biomass-to-energy plants are given in order to illustrate how project-specific factors influenced the design. A section is dedicated to non-wood biomass fuels and how their characteristics affect plant design. Conversion of existing coal-fired boilers to biomass firing is also discussed. The final part of the chapter deals with operational issues of biomass-fired plants.

Key words: large-scale biomass combustion plants, travelling grate spreader stoker combustion, design considerations for biomass combustion plants, biomass fuel quality management, conversion of grate-fired boilers from coal to biomass.

10.1 Introduction

Biomass-fired steam boilers are finding increasing use in industrial-scale combined heat and power (CHP) applications. The main drivers of this development are political and economic (e.g. renewable energy obligations and incentive schemes, the continued rise in fossil fuel prices and disposal costs for waste products, increasing taxation on fossil fuels). However, the desire to market ones products as 'green' is also a factor gaining importance. Seen from a government perspective, the potential creation of jobs locally and reduced dependence on imported (fossil) fuel also provide incentives for the promotion of energy from biomass.

However, utilising biomass rather than fossil fuel requires different technology that is adapted and tailored to the characteristics of biomass fuels. This chapter briefly describes the main technologies for biomass combustion and attempts to highlight the specific areas that need to be addressed in the design of biomass-fired steam boiler plants. Some of the challenges arising from external factors in biomass energy projects (e.g. legislation, incentive schemes) are also addressed. Examples of three recent biomass-to-energy plants are given in order to illustrate how project-specific factors influenced the design.

The term biomass covers a wide range of different fuels with widely varying properties and different challenges. An illustration of this is shown in Table 10.1,

Table 10.1 Qualitative comparison of various biomass fuel types and their properties

Fuel	Moisture content	Nitrogen content	Sulphur content	Chlorine content	Ash content	Alkali content	Fouling/ slagging tendency	Main challenges
Virgin wood	High	Low	Low	Low	Low	Low	Low	CO
Clean waste wood (chipboard, pallets, etc.)	Low–medium	Low–medium	Low	Low	Low	Low	Low	NO_x
Sander dust (chipboard, oriented strand board, etc.)	Very low	High–very high	Low	Low	Low	Low	Low	NO_x, erosion (abrasive ash)
Spent brewery/distillery grains	Very high	High	Medium	Low–medium	Low–medium	Low–medium	Low–medium	Low calorific value, fouling, NO_x, SO_2
Olive seeds	Low	Low–medium	Medium	Medium	Medium	Medium	Medium	Fouling
Meat and bone meal	Very low	Very high	High	High	Very high	High	Medium–high	Fouling, corrosion, SO_2, HCl, unburned content in ash
Chicken litter	Medium	High	High	High	Very high	High	High	Fouling
Contaminated recycled wood	Low–medium	Medium–high	Medium	Medium–high	High	Low	High*	Fouling, corrosion, NO_x, SO_2, HCl

* Due to chlorine and heavy metal content (notably zinc and lead).

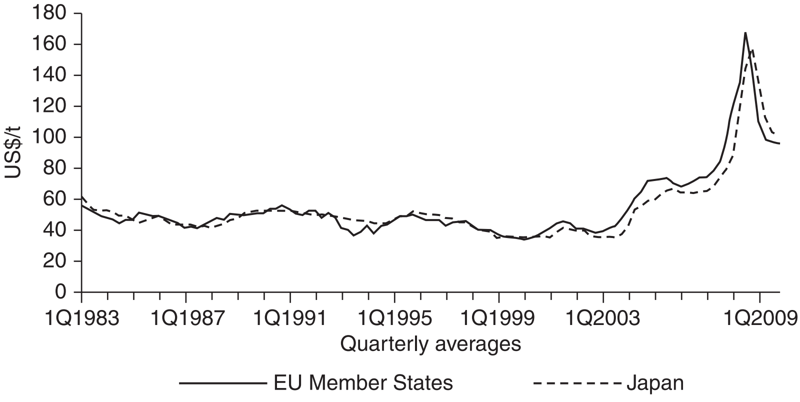
which lists some biomass fuels and their comparative properties and challenges. It is obvious that fuel properties have a key influence on plant design. A section is therefore dedicated to non-wood biomass fuels and describes the characteristics of some selected non-wood fuels and how they affect biomass projects and plant design.

The possibilities for converting existing coal-fired boilers to biomass firing are also discussed, and examples of successful conversion projects are given. Finally, a part of this chapter is dedicated to operational issues relating to biomass-fired plants and possible means for mitigating operational problems related to corrosion and fouling.

10.2 The suitability of industrial-scale plants for biomass combustion

One of the main reasons for the increase in the use of biomass energy is the cost of fossil fuels. Fossil fuel prices have more than doubled in the last decade – coal prices, for instance, have increased from approximately \$35/t in 2000 to \$90/t in 2010, briefly reaching \$160+/t in 2008 (see Fig. 10.1). All indications point to even higher fossil fuel prices in the future. Biomass prices have also increased in the same period – mainly as a result of increased demand for biomass – yet in some cases biomass prices are now lower than fossil fuel prices, meaning there is a large incentive to switch to biomass in regions and industries where biomass is readily available. Some projections for future biomass prices even point to significantly decreasing biomass prices in the coming decades (e.g. E4tech, 2009).

Direct combustion of biomass in a steam boiler is a mature, proven technology for converting biomass to energy – in contrast to biomass gasification and



10.1 Historical steam coal import costs (IEA, 2010: 41), © OECD/IEA 2010.

pyrolysis technologies that have been 'emerging' for many years, but which are still some way off full-scale commercial realisation (Schwager *et al.*, 2003; Cannon and Welch, 2003; Paterson and Weeks, 2003). Combustion is thus the technology most readily available for industries wishing to switch from fossil fuels to biomass.

Indeed, many industries characterised by large energy use coupled with experience in handling biomass and/or with access to large quantities of biomass waste products (notably wood processing and paper industries) have long since turned to biomass as a substitute for fossil fuels. Despite the high investment costs for biomass-fired plants (due to larger boilers, extensive fuel handling systems, etc.) these companies are finding that by replacing fossil fuels with biomass, they are not only reducing CO_2 emissions and dependence on imported fuels, but are also making a net profit from the sale of 'green' electricity and/or a reduction in their fuel costs (though biomass fuels bought on the open market may have a higher cost than coal on an energy basis, they are generally cheaper than oil or gas).

Since the energy density of biomass is seven to ten times lower than that of coal on a volumetric basis and two to four times lower on a mass basis, haulage costs are correspondingly higher and this puts a natural limit on the size of biomass-fired plants, as fuel must be sourced within a limited distance from the plant in order to avoid excessive transport overheads. In practice it is thus rare to see biomass-fired CHP plants with fuel heat input above 100–150 MW, and many are below 50 MW.

There are exceptions, however, and in recent years a number of utility-sized plants have been proposed. These plants are often based on bringing in biomass to Europe by ship (from Canada, South America, etc.) to reduce transport costs. The idea behind these large-scale plants is that as the size of the plants increase, so does the electrical efficiency. Although this is correct, the size of the plants generally also limits the possibility of designing the plants for CHP generation, as there are few heat consumers (whether industrial process plants or public district heating networks) that can utilise the large quantities of heat available from the plant.

Seen from a socio-economic view, using locally sourced biomass (as opposed to imported biomass) is more beneficial to the region where the plant is located, as it can provide jobs and boost the local economy (through haulage companies, fuel production and pre-treatment, etc.). This is reflected in some incentive schemes – as an example, the French CRE4 biomass tender gives higher ratings (and thus a higher probability of getting a licence) for projects using locally sourced fuel or certain types/specific sources of biomass (e.g. algae, wood chips from mountain regions) (CRE, 2010), while the Italian green certificate scheme awards more green certificates to plants that use biomass sourced within a 70 km radius of a plant (Scoditti, 2009).

An alternative to dedicated biomass-fired plants is biomass co-firing at existing coal-fired power plants. Co-firing will normally have lower specific electricity production costs, as both investment costs as well as operating costs are lower.

However, co-firing at non-CHP utility power plants results in lower total utilisation of the biomass than in a dedicated biomass-fired CHP plant and fuel moisture and particle size limits of e.g. pulverised coal-fired boilers mean that additional energy is required for pre-treatment of the fuel. Some biomass fuels may also be ill-suited for co-firing – either because they have a negative influence on combustion (e.g. increased emissions), on the boiler (e.g. increased slagging, fouling and corrosion) or on the combustion residues (ash properties), or because it is difficult or costly to treat the fuel so that it can be co-fired.

Small-scale bioenergy plants (< 15–20 MW fuel heat input) are widespread in many parts of Europe, and in many cases this is the 'natural' size for biomass-to-energy plants as they are often adapted to limitations in the local availability of biomass fuel. However, the high initial cost associated with electricity generation (high-pressure steam boiler, steam turbine-generator set) means that it is often difficult to achieve good feasibility for power generation in plants of this size. Small-scale plants are therefore better suited for pure heating applications, where investment costs are less prohibitive.

In conclusion, it is the belief of the author that industrial-scale biomass-to-energy plants can provide an optimum balance between feasibility and overall energy efficiency for power-producing plants. The focal point of this chapter is therefore industrial-sized steam boiler plants in CHP or purely power generating applications.

10.3 Biomass combustion technologies

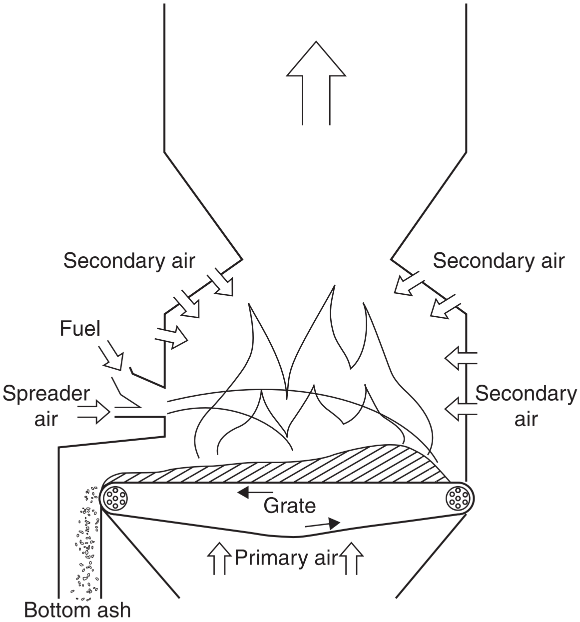
The three main technologies used for biomass combustion in industrial-scale plants are:

- spreader stoker
- mass burn grate
- fluidised bed combustion (FBC).

Each technology is described below and a comparison is made between them.

10.3.1 Spreader stoker

Spreader stoker firing was developed in the 1930s as an improved way to burn coal and was applied for burning biomass a few years later. A spreader stoker combustion system essentially consists of a number of fuel feeder/distributors (spreaders) and a combustion grate (stoker); see Fig. 10.2. The fuel distributors located at the furnace front throw the fuel into the furnace and spread it uniformly across the grate. Biomass-fired plants typically use pneumatic fuel distributors (air-swept spouts), while coal-fired units use mechanical overthrow or underthrow distributors. For units firing both coal and biomass, combination spreaders are used (see also Section 10.4.5 below).



10.2 Travelling grate spreader stoker combustion system.

The grate provides a surface for combustion of the heavier fuel particles and a means of distributing the primary (undergrate) air supply over the fuel bed. The most common grate type is the travelling grate, which is a type of conveyor belt with cast iron bars mounted on heavy-duty chains. The grate travels slowly (typically with a speed of 1–3 m/h) towards the front of the furnace where the ash is discharged. The travelling grate has proven to be robust in operation and flexible in handling fuels with widely varying heating value and ash content. Vibrating grates are sometimes used as an alternative to travelling grates. Here the ash is conveyed towards the front by intermittent vibration of the grate. A vibrating grate is typically water cooled, which permits use of higher primary air temperatures than the travelling grate. Its design also allows for a zoned primary air supply. However, the upsets in the fuel bed caused by vibration of the grate results in load and CO emission peaks. In addition, the plant is sensitive to loss of the water-cooling of the grate.

Combustion in a spreader stoker boiler is a combination of grate and suspension firing: the fine, light particles burn in suspension above the grate, while the larger and heavier particles land and burn on the grate in a relatively thin layer. Due to the even distribution of combustion across the grate, a relatively small grate area is required. This permits operation with excess air ratios less than 1.25, and in a well-designed biomass-fired spreader stoker boiler excess air ratios as low as 1.1–1.15 are possible. Spreader stoker biomass combustion relies heavily on staged combustion, where sub-stoichiometric excess air ratios (typically 0.5–0.6) are used for the primary air supply. This keeps combustion temperatures on the grate at 800–1000°C. Complete combustion of the remaining gasified fuel is achieved by the gradual injection of secondary (overfire) air at several levels above the grate.

Refractory lining of the furnace walls is normally not necessary, as the low excess air ratio results in sufficiently high combustion temperatures. The thin fuel layer on the grate means that the load response is fast. The start-up time for a spreader stoker boiler is also short, typically three to five hours from cold boiler to full load.

The best spreader stoker boilers achieve uncontrolled NO_x emissions on par with bubbling fluidised beds (see Section 10.3.3 below) – or better – though in most cases the emission levels are somewhat higher; CO emissions are generally higher than for FBC boilers.

Of all the firing technologies mentioned in this chapter, spreader stoker firing is the one with the lowest operating and maintenance (O&M) costs, mainly due to the low excess air ratio (meaning low electrical consumption) and the low equipment maintenance costs (e.g. typical lifetime of grate bars is eight to ten years). Capital costs are also among the lowest, as spreader stoker plants are generally compact in size and based on relatively simple, robust systems.

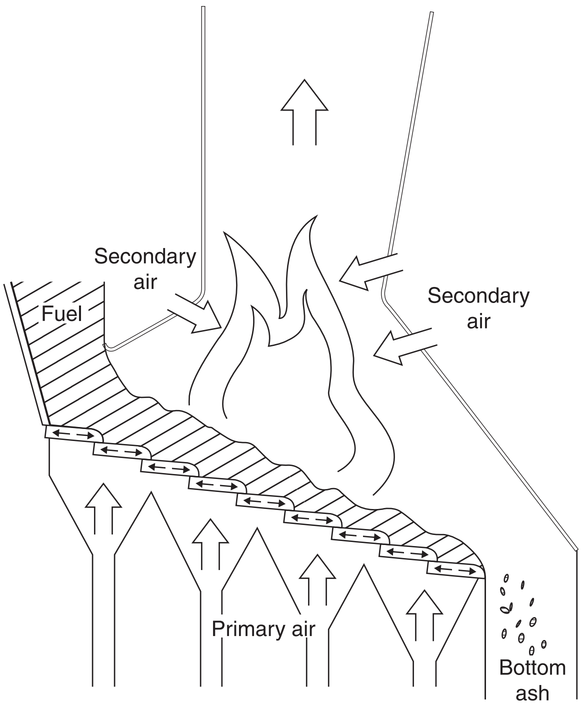
Spreader stoker firing is considered as 'best available technology' (BAT) for biomass combustion according to the EU large combustion plant BAT reference document (EC, 2006).

10.3.2 Mass burn grate

In mass burn combustion systems the fuel is fed continuously onto a grate at one end and then progressively burns as it moves towards the other end of the grate where it is discharged. Fuel feeding is typically by some form of ram or stoker screw. The forward motion on the grate is either by gravity (inclined grates) or mechanically induced (vibrating grates and reciprocating pusher-type grates); see Fig. 10.3.

As the fuel is fed onto the grate in a relatively thick layer, the various stages of the combustion process (drying, devolatilisation and burnout) occur more or less in separate zones along the grate. The primary air supply is therefore divided into zones to account for the different air requirements in the different phases of combustion. Due to the thickness of the fuel bed, fuel residence time on the grate is large and the technology thus requires a larger grate area than other technologies. As a consequence, the excess air ratios are typically high – of the order of 1.3–1.5 – meaning that boiler efficiency is 2–3% lower than for other technologies.

A refractory lining of the lower furnace is often used in order to improve drying and ignition of the fuel. Due to the large mass of fuel on the grate, load response



10.3 Mass burn grate combustion system.

is generally slow and due to the large amount of refractory material, start-up times are significantly longer than for spreader stoker plants.

The sequential nature of combustion along the grate means that locally very high temperatures may occur. This often causes excessive slagging of the grate, the refractory lining and occasionally also the convective heat transfer surfaces (due to non-uniform furnace conditions), thus requiring regular shutdowns for manual cleaning of the plant.

The main advantage of mass burn grates is their ability to burn fuel of larger particle size than both spreader stoker and FBC units. Although fuel preparation costs are lower than for the other technologies, O&M costs are generally high due to the large excess air ratio (high electrical consumption) and high costs for refractory and grate maintenance (regular replacement of grate elements is common and refractory repair is often necessary during annual maintenance shutdown). Capital costs for the pressure part are on par with spreader stoker plants, but the higher excess air ratio means that installations for combustion air and flue gas (fans, ducting, flue gas treatment, etc.) are larger, again leading to capital costs at the higher end of that for spreader stoker boilers.

Mass burn grates have their main application in waste incineration plants where fuel size and quality can vary greatly and where the priority is disposal of the waste rather than operating costs and energy efficiency. For most biomass fuels, mass burn grates are generally inferior to spreader stoker and FBC systems, with the possible exception of straw, where vibrating grates are well proven (EC, 2006).

10.3.3 Fluidised bed combustion

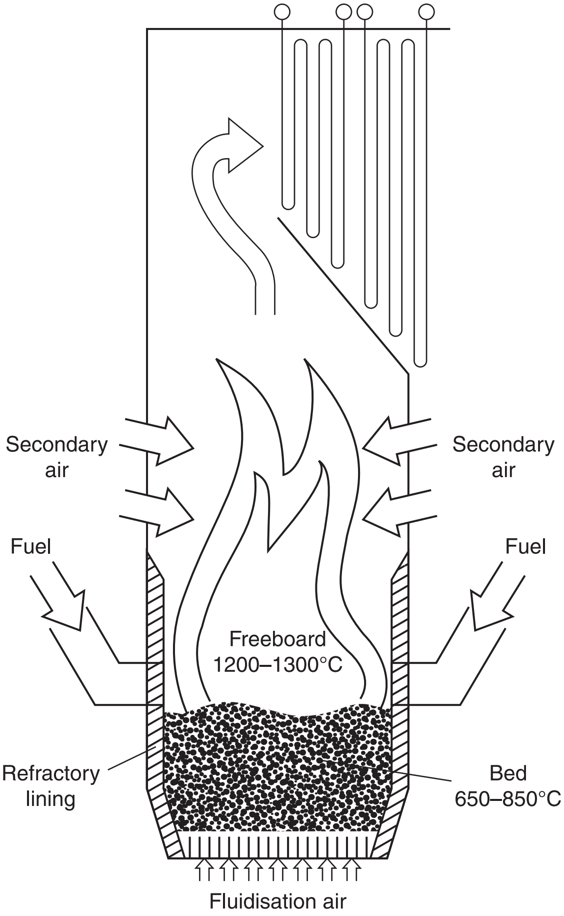
Fluidised bed combustion is the newest of the three technologies described. In FBC the fuel is burned in a bed of hot, inert particles (typically sand and ash), which is kept in suspension by the upward flow of combustion air injected through the bottom of the furnace. Heat and mass transfer rates are greatly enhanced in the bed. This increases the conversion rate of the fuel as well as heat transfer to the heating surfaces, which in turn results in good burnout at lower temperature than required in grate combustion.

At low fluidisation velocities a dense, bubbling bed is formed in the lower part of the furnace. This type of fluidised bed is normally termed a bubbling fluidised bed (BFB); see Fig. 10.4. As the velocity is increased the bed expands upwards until there is no longer a distinct transition between the bed and the freeboard (the region above the bed). Bed material is then carried with the flue gas out of the furnace and must be separated from the gas and returned to the furnace – typically using a large cyclone or impact-type separators. This type of fluidised bed is known as a circulating fluidised bed (CFB); see Fig. 10.5. The two technologies have different pros and cons, which are described in more detail later in this section. First, a description of some of the common traits of FBC is given.

The air for fluidisation is injected at the bottom of the furnace through a large number of nozzles. The bed bottom typically has an open area between the nozzles to allow large ash particles and tramp material to be removed. The design of the bed bottom is a critical part of FBC and for 'difficult' fuels (e.g. waste wood, high alkali fuels), blocking of nozzles and ash removal openings due to slagging or high tramp material content may occur (Forsberg, 2010).

Normally the lower part of the furnace is lined with refractory to protect the furnace water-walls from erosion. In order to heat the bed material at start-up, an auxiliary burner (i.e. an oil or gas burner) is required. The start-up period (where supplementary fuel is needed) is typically of the order 8–15 h (van Loo and Koppejan, 2008), as the furnace must be heated slowly in order to prevent damage to the refractory lining. Due to the large thermal inertia of the bed material, load stability is good even with variations in fuel moisture.

When burning coal, the bed temperature in a fluidised bed is normally below the ash melting point, meaning that fouling is also reduced compared to other coal combustion technologies. However, biomass fuels generally have lower ash melting points, in some cases less than 900°C. This means bed temperature is limited by the ash properties and must be carefully controlled in order to avoid bed sintering (which will require shutdown of the plant for manual cleaning). Regular replacement of bed material to limit the alkali content in the bed may also be necessary.

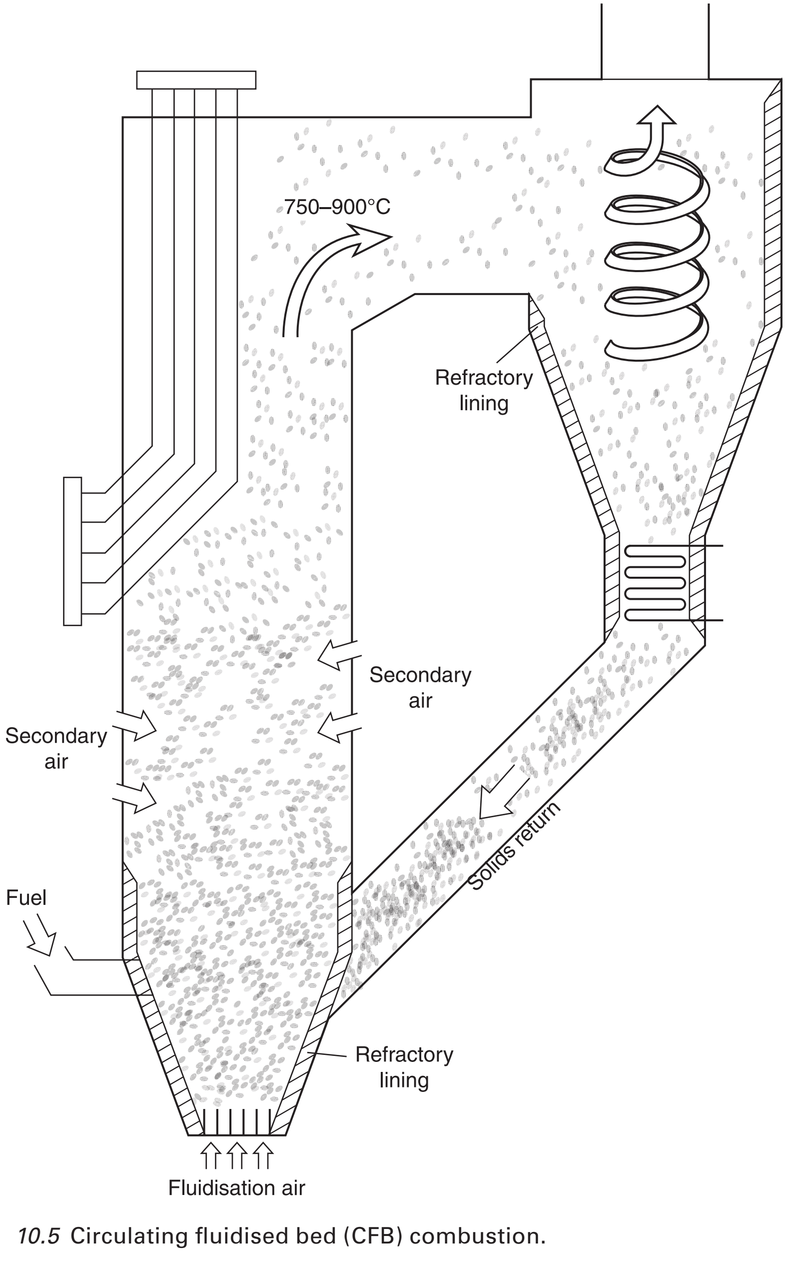


10.4 Bubbling fluidised bed (BFB) combustion.

In general FBC plants have low NO_x and CO emissions due to the low combustion temperatures and the low excess air ratio made possible by the efficient mixing in the bed.

Operating costs for FBC boilers are generally high due to high electrical consumption (30–100% higher than for spreader stoker plants due to the high-pressure combustion air fans), increased wear (erosion of tubes and refractory caused by the bed particles), bed material replacement costs, increased disposal costs (more ash as some of the bed material ends up in the ash and there is a higher proportion of fly ash, which has a higher disposal cost than bottom ash), etc. Capital costs are also significantly higher than for grate-fired boilers (EC, 2006; Evald and Witt, 2006; van Loo and Koppejan, 2008; DeFusco *et al.*, 2010).

FBC is considered as 'best available technology' (BAT) for biomass combustion according to the EU large combustion plant BAT reference document (EC, 2006).



10.5 Circulating fluidised bed (CFB) combustion.

Bubbling fluidised bed (BFB)

BFBs typically operate with fluidisation velocities of 1–2 m/s and a sand particle size of 0.5–1.5 mm. The material density in the bed is high (approximately 1000 kg/m^3) and the height of the bed is normally 0.5–1.5 m. The distinction between the bed and the so-called freeboard above the bed is quite clear. Fuel feeding is through a number of fuel ports in the furnace side wall. Just as in spreader stoker combustion, good distribution of the fuel is essential in order to reach low excess air ratios, as horizontal mixing in the bed is limited. The maximum particle size permissible for BFB combustion is of the order 80–100 mm, but the content of fine particles must be limited to avoid carry-over from the furnace (van Loo and Koppejan, 2008; EC, 2006).

The temperature in the bed is typically maintained in the range 650–900°C through sub-stoichiometric combustion at excess air ratios of 0.35–0.5. Flue gas recirculation (FGR) is sometimes used to maintain the fluidisation velocity at lower loads. The burnout of volatiles as well as combustion of fine particles is achieved in the freeboard through injection of secondary air. Typical overall excess air ratios are 1.2–1.3 (van Loo and Koppejan, 2008; DeFusco *et al.*, 2010; Rainio *et al.*, 2009).

BFB combustion has many similarities with spreader stoker combustion in that it is based on staged combustion with clear separation of the primary and secondary stage. The main difference is the use of a fluidised bed rather than a grate to support the fuel during combustion.

The higher pressure drop required for fluidisation means that electrical consumption in BFB plants is relatively high, although flue gas flow is low due to the low excess air ratio. Wear in the lower part of the furnace and in the superheater is also high, due to the high loading of solids. Bed material replacement is relatively low in a BFB, but depends on the ash properties of the fuel. Capital costs are somewhat higher than for grate-fired plants.

Circulating fluidised bed (CFB)

CFBs typically operate with fluidisation velocities of 5–10 m/s and a smaller sand particle size than BFBs, typically 0.1–0.6 mm. There is no distinct bed, but the solids loading varies from approximately 640 kg/m^3 in the lower furnace to approximately 40 kg/m^3 in the upper part of the furnace with roughly two-thirds of the solids concentrated in the lower 1.5 m of the furnace. The high velocity carries sand particles with the flue gas; these particles are separated in a hot cyclone or by U-beam separators and returned to the furnace. The recirculation of material ensures a long residence time for burnout of the fuel and the high loading of solids in the furnace provides high heat transfer rates. High particle separation efficiency is required to ensure burnout of the fuel and minimise bed material loss.

Fluidisation air represents 50–70% of the combustion air and the remaining air is injected as secondary air at different levels. The bed temperature is generally somewhat higher than in BFB (750–900°C) and is not controlled by bed combustion stoichiometry but rather by cooling through heat exchange surfaces in the bed or in the bed material return leg. More accurate control of bed inventory than in BFB combustion is required to maintain stable operation. The bed bottom area is smaller than in a BFB and fuel distribution is therefore easier. On the other hand, reduced particle size is normally required (40 mm) (EC, 2006; van Loo and Koppejan, 2008; DeFusco *et al.*, 2010; Rainio *et al.*, 2009).

Due to their efficient mixing, CFB combustors can achieve very low excess air ratios (1.1–1.2) and very low CO emissions. The low excess air ratios combined with low combustion temperatures enable CFBs to achieve very low NO_x emissions. CFB boilers also have the advantage that in-bed desulphurisation is possible by adding lime to the bed. This is an advantage when burning coal, as the direct addition of lime to the bed reduces overall lime consumption and allows the use of cheaper qualities of lime than in post-combustion flue gas desulphurisation. However, since most biomass fuels have low sulphur content, the possibility of in-bed desulphurisation is less relevant in biomass combustion. In-bed desulphurisation is also possible in BFBs but with lower reduction rates possible.

CFBs can have high emissions of nitrous oxide (N_2O) – a very potent greenhouse gas – as combustion at low temperatures favours formation of N_2O over NO. Nitrous oxide has received less attention by legislators, however, and is more difficult to measure than NO_x; therefore this aspect of FBC is often overlooked (EC, 2006; van Loo and Koppejan, 2008).

Some of the drawbacks of CFB combustion are high operating costs due to increased wear (due to high particle loading), high electrical consumption and bed material loss. CFB furnaces are also taller than BFB and grate furnaces (which in some cases causes conflict with building height limitations), and capital costs are significantly higher. For smaller units (below 30–50 MW fuel heat input) CFBs are rarely able to compete with other technologies (van Loo and Koppejan, 2008; DeFusco *et al.*, 2010).

10.3.4 Comparison of technologies

A comparison of the main characteristics of each technology is given in Table 10.2. As mentioned above, both spreader stoker and FBC plants are generally superior to mass burn grate plants in most applications – especially as emphasis on plant emissions, performance and availability increases. CFB combustion is only competitive for larger units and for industrial-scale projects. The choice is thus often between spreader stoker and BFB. When costs are evaluated over a reasonable time period, it has been our experience that in most cases a spreader-stoker boiler provides a more cost-efficient solution than BFB and CFB boilers, since the spreader stoker boiler can achieve the same boiler efficiency (or better) and similar emission levels as a BFB boiler, but with lower operating and capital

Table 10.2 Comparison of industrial-scale biomass combustion technologies

	Spreader stoker	Mass burn grate	Bubbling fluidised bed (BFB)	Circulating fluidised bed (CFB)
Fuel requirements				
Max. particle size	100 mm	300 mm	80–100 mm	40 mm
Max. moisture content	~55%	~55%	~60%	~55%
Other requirements	Suitable for pneumatic or air-assisted injection	Limited content of fines	Limited fines/alkali content	Limited alkali content
Boiler efficiency	High	Low	Medium–high	High
Excess air ratio	1.1–1.25	1.3–1.5	1.15–1.3	1.1–1.2
Uncontrolled emissions				
CO, VOC	Medium	Medium–high	Low	Low
NO_x	Low–medium	High	Low–medium	Low
Load stability and control	Good	Poor	Very good	Very good
Cold start-up time	Short, typically 3–4 h (of which 1–2 h with start-up burner)	Long, due to slow heating of refractory. Start-up burner mainly used for ignition	Long (8–15 h or longer), due to heating of bed and refractory. Start-up burner required until bed is close to normal operating temperature.	Long (8–15 h or longer), due to heating of bed and refractory. Start-up burner required until bed is close to normal operating temperature.
Capital cost				
Boiler and combustion system	Low	Low–medium	Medium–high	High
Flue gas cleaning	Low–medium	High	Low–medium	Low
Auxiliary systems	Low	Low	Medium	High
Total	Low–medium	Low–medium	Medium–high	High

Operating costs				
Fuel consumption[1]	Low	High	Low	Low
Fuel preparation costs	Medium	Low	Medium	High
Electrical consumption	Low	High	Medium–high	High
Wear	Low[2]	Medium[3]	Medium[4]	High[4]
Consumables[5]	Low–medium	Low–medium	Medium	Medium–high
Ash disposal costs[6]	Low	Low	Medium–high	High
Total	Low	Medium	Medium–high	High
Specific operating risks, problems	Fuel pile-up on grate (insufficient primary air, poor combustion control)	Excessive slagging, mechanical grate problems	Bed agglomeration Bed bottom slagging preventing ash removal	Bed agglomeration Tube rupture (due to high wear)
Best Available Technology for large biomass plants?[7]	Yes	Only for straw (vibrating grate)	Yes	Yes

Notes:

1. For same steam generation; directly related to boiler efficiency.
2. Mainly carbon re-injection system; grate wear typically low.
3. Replacement of refractory and grate elements.
4. Replacement of refractory, repair of bed bottom and bottom ash system, erosion/corrosion of superheater.
5. For example, fuel additives, flue gas cleaning reactants (urea/ammonium for selective non-catalytic reduction (SNCR); lime for desulphurisation), bed material.
6. Dependent on: ash quantity, split between bottom ash and fly ash as well as unburned content of ash.
7. In the sense of EC (2006).

costs. This conclusion is also supported, for example, by Bowman *et al.* (2009) in their comparison of spreader stoker and BFB.

Choice of combustion technology is not all, however – something which should be kept in mind when comparing different plants and different solutions. Other aspects of plant design (fuel handling, boiler heat-transfer-surface design, flue gas cleaning systems, control systems, plant layout, etc.) are equally important. The approach to these can differ significantly from one company to another, one of the reasons being that different biomass boiler suppliers have different roots: some originate in the paper industry, some in the power plant industry, while others come from waste incineration or district-heating applications. These roots are often the origin of a preference for one combustion technology over another, and also influence other design aspects since different industries have different standards, conventions, conditions, design rules, etc. Overall capital costs as well as plant performance are also influenced by a number of project-specific factors – some of these factors are addressed in the next section.

10.4 Biomass combustion plant engineering issues

Biomass combustion plants are much less 'standard' plants than e.g. oil- or gas-fired boilers. The reasons for this stem from the widely varying fuel properties of different biomass fuels as well as from legislation and project-related factors. This section addresses some of these issues and how they relate to the design of biomass combustion plants, namely:

- how legislation, political incentives and project-specific factors influence plant design;
- the design elements and considerations that need particular attention in biomass combustion plants;
- how the different characteristics of different biomass fuels affect biomass-to-energy plants.

The possibilities for converting coal-fired boilers to biomass firing and the challenges associated with such conversions are also briefly outlined.

10.4.1 Influence of political incentives and project-specific factors on plant design

Environmental legislation and renewable energy incentive schemes differ from country to country and often have a direct or indirect effect on the design of a plant. Some of the aspects that may vary are:

- CHP incentives, e.g. added incentives for CHP plants, minimum efficiency requirements, etc. The value of these incentives may determine to which degree heat utilisation will be a part of a given project. This will affect the plant design parameters and where biomass plants can be located.

- Fuel-specific incentives, e.g. incentives depending on type or source of fuel. This will provide a bias towards certain fuel types, which will have an influence on the selection of fuel handling and combustion technology.
- Emission limits; taxation of emissions, e.g. NO_x or SO_2 taxes. This may favour technologies that achieve low emissions of the pollutant subject to taxation or especially stringent limits.

Some examples of how these mechanisms have been used are given in Table 10.3. An overview of the mechanisms in place in different countries can also be found in REN21 (2011).

The difference in legislation between countries results in differences in the development and design of biomass plants from one country to another. Although

Table 10.3 Examples of specific promotion mechanisms in biomass incentive schemes and related legislation from selected EU countries

Country	CHP	Specific fuel types/ sources	Emissions
France	Minimum total plant efficiency required to qualify for biomass electricity licence under CRE biomass tender; projects with higher efficiency more likely to gain licence or are awarded higher electricity price (www.cre.fr).		Charge on SO_2, HCl, NO_x, N_2O, VOC, particulates (www.ccip.fr).
Italy		Additional green certificates awarded to plants using fuels sourced within 70 km of plant (Scoditti, 2009).	Charge on NO_x and SO_2 for emissions in excess of large combustion plant limits, applies to plants > 50 MW fuel heat input.
UK (DEFRA, 2009)	'Good Quality CHP' schemes provide additional renewable obligations certificates (ROCs) to CHP plants depending on degree of heat utilisation.	Non-wood fuelled plants gain ROCs for 'Good Quality CHP' at lower efficiencies than wood-fired plants.	
Sweden (Lindgren *et al.*, 2004)	NO_x charge refunds based on amount of heat utilised.		Very high charge on NO_x (approximately 200 times French charge).

the objectives of the legislators are often similar, e.g. higher fuel efficiency, lower emissions, etc., the influence of individual incentives or the different effects of a given incentive on different industries may sometimes lead to unforeseen or undesirable results. One example is heavy taxation of NO_x emissions (as in Sweden), which has resulted in a focus on reducing NO_x at the expense of increased emissions of CO, N_2O and NH_3 (Lindgren *et al.*, 2004). Similarly, if basic incentives for biomass are high compared to CHP incentives, there may be little added value from utilising the heat – leading to a higher proportion of plants producing only electricity.

In addition to the legislative conditions, there are also project-specific factors that influence plant design. These include:

- Site-specific factors, e.g. the size of the site; building permit conditions; existing facilities and structures on the site; noise, water and flue gas emission limits; access for fuel deliveries (road, rail, sea). These factors will influence the choice of technology, plant design, equipment selection, etc.
- Fuel properties, e.g. type of biomass; fuel moisture; fuel size; fuel delivery form (chipped/shredded, dust or powder, whole logs/bales, etc.); fuel quality (amount of oversize and tramp material); odour and hygiene factors. No plant is able to handle all types of biomass. Fuel properties thus have a major influence on the choice of technology, design, materials selection, operating concept, etc. – not only for the combustion plant itself but also for the fuel handling and flue gas treatment systems.
- Overall process design, e.g. CHP or power generation only; degree of integration into other processes (fuel pre-treatment, industrial processes); operational cycles (base load, load modulation, seasonal variations, etc.). The overall process design influences selection of steam data, control concept, required turndown of systems, equipment design, etc.
- Operating philosophy, e.g. supervised or unsupervised operation; degree of automation; equipment redundancy; fuel logistics (handling of fuel on site, storage requirements, etc.). The choices regarding operating philosophy will affect plant system design, instrumentation, control system, fuel handling, etc.
- Other end user requirements, e.g. technology preferences (e.g. spreader stoker or FBC); preferred suppliers; specific requirements for technical solutions, design margins, and so on; requirements for waste water recovery; etc.

Some of the factors listed are particularly relevant for biomass combustion plants while others apply also for other types of combustion plants – yet all must be considered at some stage in the design phase. Some of the biomass-specific issues relating to the design of biomass combustion plants are discussed in the next section.

10.4.2 Designing high-efficiency biomass combustion plants

Although they seldom reach the news, there are numerous examples of failed biomass-to-energy plants. Typical problems are:

- The boiler does not reach the rated output and/or steam data.
- The plant cannot burn the fuel it was designed for (typical for wet fuels).
- Stack emission limits are exceeded.
- Fouling and corrosion issues cause frequent shutdown of the boiler for cleaning and/or repair.

Many of the problems stem from plant designers lacking an understanding of how biomass fuel properties influence combustion and plant behaviour. In this section, some of the key areas that need to be addressed when designing biomass combustion plants are outlined. Although the main emphasis in this section is on design considerations for spreader stoker plants, some comments on how some of the parameters relate to BFB and CFB plants are also given.

Furnace design

Just as coal-fired boilers are not designed in the same way as oil- or gas-fired boilers, neither can biomass-fired boilers be designed as coal-fired boilers, if they are to function efficiently. Biomass firing requires a larger furnace (i.e. a larger radiation heat transfer surface) than coal firing. There are several reasons for this: biomass combustion typically has less flame radiation and due to the higher moisture, biomass fuels typically yield higher flue gas mass flows than fossil fuels, resulting in lower combustion temperatures. The result is that a larger heat transfer surface is needed. The high volatile content of biomass means that combustion staging can be used to a higher degree (i.e. there is a larger fraction of secondary air). This extends the combustion zone higher into the furnace and lowers the heat transfer rate. In addition, the lower ash melting point of most biomass ash means that lower superheater inlet temperatures are possible. All in all this leads to the need for a larger furnace (or radiation pass). Ignoring this fact is often the root cause of problems in poorly functioning biomass combustion plants.

A requirement for determining the necessary furnace size is the degree of fouling and slagging of the furnace walls that can be expected. A furnace size which is adequate for firing fresh wood chips may be severely inadequate if the fuel is contaminated recycling wood. During the lifetime of a plant, changes in fuel source and quality may lead to unforeseen changes in the degree of fouling and means to counter this may be needed (see Section 10.5.2).

Fuels with widely varying moisture content also present a challenge. Often the furnace must be designed for the fuel with the highest moisture content, but this will result in low furnace exit temperatures when dry fuels are used. A lower furnace exit temperature also means a lower flue gas temperature at the inlet of the superheater and may thus prevent the plant from reaching the nominal live-steam temperature. This problem can partly be offset by using FGR to increase the flue gas flow and reduce furnace heat transfer (so-called tempering) when firing dry fuels, and this shifts heat transfer towards the convective part (i.e. superheater/economiser).

Steam data and heat-transfer-surface design

The selection of steam data for the boiler and the design of heat transfer surfaces (mainly the superheater but also air preheaters (APHs) and the economiser) and their location in the flue gas path must take into account the fuel and in particular the behaviour of the fuel ash.

Fuels with high chlorine content are likely to yield more corrosive conditions in the boiler, especially in combination with a high alkali or heavy metal content. There are, however, different ways to keep corrosion rates at an acceptable level:

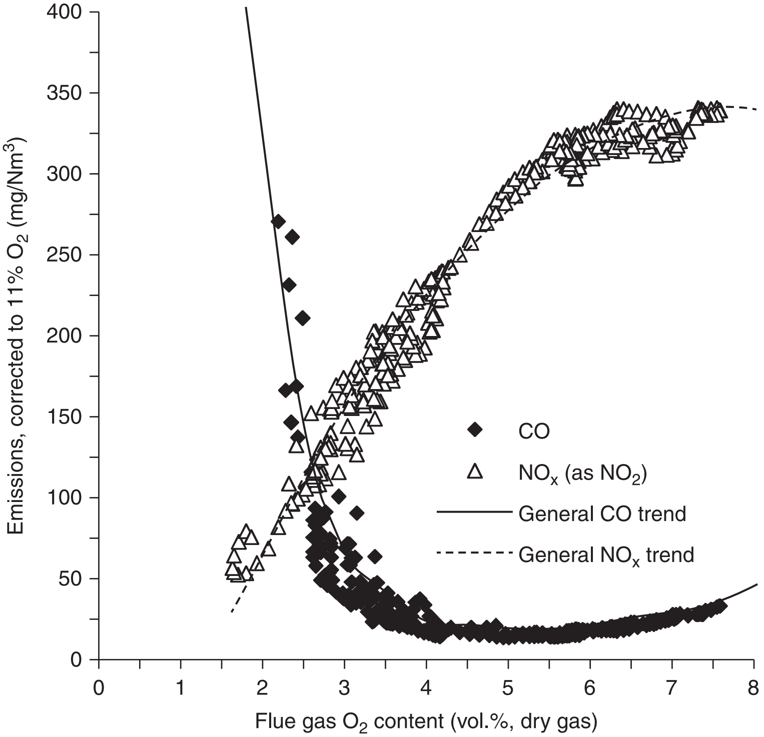
- lower steam data (pressure/temperature)
- higher-grade tube materials and/or high alloy overlaying of tubes
- locating the superheater (especially the final stage) in areas of lower flue gas temperature where the equilibrium gas content of aggressive chlorine compounds is lower
- designing the superheater with larger tube spacing and lower flue gas velocities (to prevent blockage and erosion of tubes)
- using smaller superheater bundles (to enable better penetration of soot blowers).

Some of these rely on keeping tube surfaces at a low temperature to make corrosion unlikely, while others work to prevent slagging and blockage of the tube bundles (a common cause of erosion/corrosion). For heavily slagging fuels the use of water soot blowers in the furnace and/or the radiation pass can be an effective means of maintaining reasonable superheater inlet flue gas temperatures.

Excess air

The key to efficient biomass combustion is operation at low excess air ratios. A good spreader stoker boiler will typically be able to operate continuously at excess air ratios of 1.15–1.2. Not only does a low excess air ratio mean higher boiler efficiency, it is also an important parameter in controlling emissions. This is illustrated by the typical behaviour of CO and NO_x emissions for varying excess oxygen content (Fig. 10.6).

The figure shows CO and NO_x emissions measurements from tests on a spreader stoker biomass boiler for different excess air ratios. It is clear from the measurements that as flue gas O_2 content (and thus the excess air ratio) increases, NO_x emissions increase – a behaviour which is well known (Johnson, 2002). Most likely this is a direct consequence of the increased availability of O_2 for the NO formation reaction. Although NO formation is known to be strongly dependent on temperature – and temperature decreases with increasing excess air ratio – the O_2 dependence apparently dominates. Other factors such as grate heat release rate,



10.6 Measured CO and NO_x emissions as a function of excess oxygen content (source: AET).

air preheating, fuel nitrogen content and particle size also affect NO_x emissions (Johnson, 2002).

CO emissions, however, have a minimum at a certain (low) flue-gas O_2 content. At lower O_2 content, CO emissions rise sharply, while at higher O_2 content CO emissions increase more gradually. For a given plant the O_2 content that corresponds to the minimum CO emissions will depend on factors such as fuel moisture, combustion conditions, air preheating, etc. More efficient injection of secondary air (better mixing) will generally shift this point of minimum CO emissions towards lower O_2 content.

It should be noted that the excess air ratio influences not only CO and NO_x emissions but also fuel burnout, combustion stability, etc. The lower limit of the excess air ratio is therefore not necessarily determined by emissions. In general, successful operation at a low excess air ratio requires:

- uniform fuel feeding and distribution,
- efficient mixing of volatiles and air (secondary air system),
- good combustion control.

Each of these factors is described below.

Fuel feeding

Some of the properties of biomass that cause problems in fuel handling (see below) also influence fuel feeding. Poor material flow properties, combined with varying bulk density due to variations in particle size and moisture content, lead to variations in the degree of filling of, e.g., screw conveyors. Since dosing of biomass is often volumetric, this leads to variations in fuel-feeding rates. Ensuring constant filling of conveyors or using gravimetric rather than volumetric dosing can greatly improve fuel-feeding accuracy, which makes combustion control easier and contributes to better load stability. More accurate fuel feeding also allows operation at lower excess air ratios.

Another aspect of fuel feeding that applies mainly to spreader-stoker and BFB boilers is fuel distribution. Inhomogeneous fuel distribution can be an obstacle in achieving good combustion conditions and low excess air ratios. CFB boilers generally have a smaller furnace cross section at the fuel injection level and efficient mixing of the fuel in the furnace, meaning that fuel distribution is less critical.

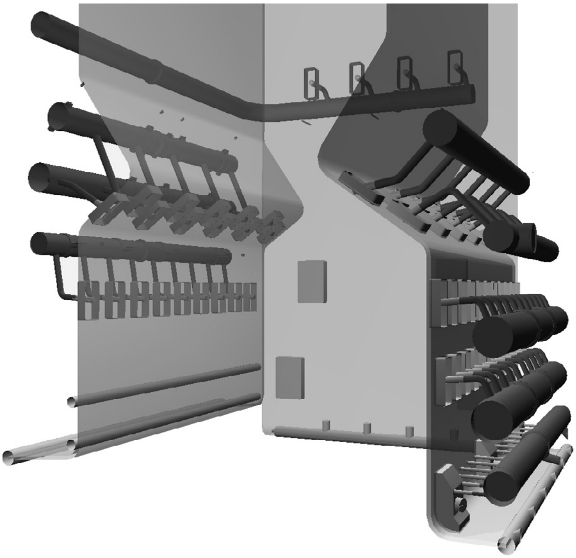
Primary versus secondary air

Due to the high volatile content of biomass, a large fraction of the combustion air (for spreader stoker boilers and BFB typically 50–70%, for CFB somewhat less) is supplied as secondary (overfire) air. This has several advantages:

- More secondary air means less primary air. In grate-fired boilers this reduces the amount of fine fuel particles lifted off the grate and thus the amount of carryover of unburned material from the furnace. In BFB boilers less primary air means a lower bed temperature, meaning lower risk of bed agglomeration.
- Staged combustion means that NO formation in grate (or bed) combustion is limited due to low temperatures and lack of oxygen. This normally leads to reductions in overall NO_x emissions.
- Secondary air injected at high velocities through properly located nozzles provides a way to achieve better mixing of air and volatiles, so that less excess air is required. As mentioned above, this generally results in lower CO and NO_x emissions.

Less primary air also means slower fuel conversion, however, and lower grate/bed combustion temperature, and thus longer fuel residence time – consequently there is a certain minimum primary air ratio, below which stable combustion cannot be maintained. The value of this minimum depends on fuel moisture, combustion air temperature, excess air ratio, etc.

Good mixing of secondary air and fuel volatiles is required to achieve low emission levels. A good secondary air system also offers some flexibility in *where*



10.7 Secondary air system for a biomass-fired travelling grate spreader stoker boiler.

the secondary air is injected as varying load, fuel moisture, etc., may require changes in the distribution of secondary air for optimum combustion. An example of a secondary air system that provides both flexibility and the possibility of good air jet penetration is shown in Fig. 10.7. Dividing the secondary air system into different levels that can be controlled individually, provides a way to adapt secondary air injection in response to varying plant load, fuel moisture, etc. The use of a limited number of adequately sized nozzles enables good penetration into the combustion zone.

Further air staging (such as a tertiary air system located even higher in the furnace – as shown in the figure) is a well-known technique that can provide further NO_x reductions. Plants that fall under the EU Waste Incineration Directive (WID) (European Parliament and Council Directive, 2000/76/EC), have limited possibilities for this, however, due to the requirement to maintain 2 s flue gas residence time above 850°C after the final injection of combustion air.

Combustion control

Combustion control must adapt the fuel and air supply to variations in fuel feeding and fuel quality, as both these will affect the combustion rate of fuel in the furnace. The varying properties of biomass fuels will naturally cause variations and disturbances in combustion. Accurate fuel feeding and good fuel distribution as well as good fuel management to provide uniform fuel quality, all make combustion control easier, but stable operation at very low excess air ratios is dependent on robust and intelligent algorithms to control fuel feeding and combustion air supply. The design and implementation of these algorithms is only possible with a full understanding of the combustion process, fuel feeding and the limits of the control system.

Some combustion systems have inherent behaviour that affects combustion conditions; one such example is vibration grates: the vibration of the grate causes movement in the fuel layer, which rapidly increases the combustion rate, causing a sudden drop in O_2 and increased load and CO. In order to counteract this, algorithms that redistribute primary and secondary air during the vibration periods are sometimes used.

Combustion temperature

The optimum adiabatic combustion temperature for grate combustion is 1300–1400°C in order to achieve a reasonable trade-off between NO_x and CO, although actual combustion temperatures of course are somewhat lower due to radiation heat loss to the furnace walls. The actual combustion temperature depends mainly on fuel heating value, excess air ratio, combustion air temperature and combustion zone heat loss through radiation.

Wet fuels have lower heating values and thus burn at a lower temperature. In order to obtain sufficiently high temperatures for complete burnout of CO, operation at low excess air combined with air preheating is often used. Alternatively, a refractory lining of the furnace walls may be used in order to reduce the heat loss from the combustion zone, but use of refractory entails high maintenance costs, long start-up times and increased slagging.

Dry fuel burns at higher temperatures, where formation of thermal NO may result in high NO_x emissions. One way of lowering the combustion temperature is the use of FGR, where a part of the stream of flue gas is taken from the cold end of the boiler and returned to the furnace. FGR increases the flue-gas mass flow to be heated by combustion and thus cools the flame. The key to effective NO_x reduction through FGR is to inject the recirculation flue gas at the right location, such that reduction of the temperature is achieved before completion of combustion.

Carbon re-injection

Due to the low density of biomass char particles (typically 50–100 kg/m^3) there will be a certain amount of unburned carbon particle carryover from the furnace in a grate-fired biomass boiler. In order to reduce the unburned loss and prevent glowing particles from damaging downstream de-dusting equipment, a mechanical pre-separator is commonly installed upstream of the flue gas cleaning equipment. Since the particles captured in the pre-separator (and in the boiler hoppers, e.g. under the superheater) have a high carbon content they are re-injected into the furnace. The smaller particles that pass through the pre-separator will normally have lower unburned content than the larger particles and therefore the carbon content of the fly ash can be kept low (Bergqvist *et al.*, 2004; Johnson, 2002).

Flue gas cleaning and emissions control

Flue gas cleaning equipment obviously needs to be tailored to the fuel and the emission limits. All biomass combustion plants need some form of particulate removal equipment to limit dust emissions. Effective particulate removal is also the most effective means of controlling emissions of heavy metals and one of the means of limiting dioxin and furan emissions. Pulse-jet cleaning bag filters are normally the preferred technology for particulate removal. Typical particulate emission levels for bag filter systems are 1–2 mg/Nm^3. Selection of the correct filter material for the operating conditions is essential, but with the right material and beneficial operating conditions (in particular constant flue gas temperature; for some materials also low flue gas NO_2 content) bag lifetimes of five years or more can be achieved. Electrostatic precipitators (ESPs) may also be used, but are more sensitive to flue-gas particulate loading and flow inlet conditions and have lower particulate removal efficiencies.

If acid gases (i.e. So_x, HCL and HF) must be removed (either because the fuel contains high amounts of sulphur or chlorine, or because the emission limits on HCl and SO_2 are strict), this can normally be accomplished with dry injection of hydrated lime upstream of a bag filter. Hydrated lime injection has the advantage that it is a simple process, which is efficient at normal boiler exit flue gas temperatures (130–160°C). Where higher reduction efficiencies are required, bicarbonate can be used instead of hydrated lime. However, this requires higher flue gas temperatures (150–200°C) to be effective. Other alternatives are wet or semi-dry desulphurisation processes, but these are not always compatible with bag filter installations and generally have higher installation costs. Note that dry sorbent injection is generally not compatible with ESPs.

For fuels with low nitrogen content (e.g. virgin wood chips), NO_x emission limits can often be met using only primary emission reduction measures such as staged combustion, low excess air ratio and FGR. FGR can also be used to maintain full-steam superheating when burning dryer fuels (see 'Furnace design' above).

For high-nitrogen fuels or under more stringent emission limits, selective non-catalytic reaction (SNCR) systems, where ammonia or urea is injected into the furnace, are typically used. Reduction efficiencies of up to 50–80% are often possible, depending on the permissible ammonia slip (excess unreacted ammonia in the flue gas). If further NO_x reduction is needed, a selective catalytic reaction (SCR) unit can be fitted after the boiler. SCR units work best at temperatures of 250–400°C. This is normally above maximum operating temperatures of bag filters, and typical solutions for installation of SCR units therefore include:

- Use of so-called high-dust catalysts installed upstream of a bag filter.
- Use of ESP for dust removal, and installation of an SCR unit downstream of the ESP. If acid gases must be removed, this SCR configuration will generally require installation of separate acid gas removal equipment downstream of the SCR.
- Installation of an SCR unit downstream of the bag filter, with reheating of the flue gas before entry into the SCR unit and subsequent heat recovery downstream of the unit.

Most catalysts are sensitive to alkali and heavy metals and may suffer from catalyst poisoning if they are subjected to biomass fly ash. Therefore it is often preferable to install the SCR unit downstream of dust removal equipment, i.e. as in the last two configurations described above. SCR units can achieve NO_x reduction efficiencies of 70–95%, but in most cases SNCR provides a more cost-efficient means of NO_x reduction when the cost per kilogram of NO_x reduction is evaluated.

Carbon monoxide emissions are mainly influenced by the combustion conditions and can be reduced using primary control techniques such as low excess air, air preheating, effective secondary air systems, etc. Although catalytic converters for CO reduction are available, these will normally be too costly for most biomass plants and they suffer from the same drawbacks as mentioned for SCR units above.

Fuel storage, handling and management

Many types of biomass have poor material handling properties and other undesirable characteristics such as:

- long particles (e.g. straw, crushed wood – so-called ‘hog fuel’, from short rotation crops), which cause bridging in silos and bins, and particles get stuck, etc., often requiring equipment for removal of the oversize fraction;
- high moisture content (e.g. virgin wood, “green” fuels, poultry litter, etc.) contributing to bridging, material sticking to equipment and poor storability due to the risk of self-ignition or decomposition;
- low bulk density, requiring large conveyors and storage facilities;
- high tramp material content (e.g. forest residues, recycling wood) causing increased wear, equipment failures and/or malfunctions and typically requiring some form of separation equipment (e.g. magnets, eddy current separators, stone traps);
- unpleasant smells (e.g. poultry litter, meat and bone meal), causing the need for fuel storage ventilation systems, closed conveyors, etc.

Understanding how a particular fuel behaves in fuel handling and storage processes and the limitations that apply for the fuel is important in selecting suitable equipment and systems for those tasks. Some specific considerations for non-wood biomass fuels are given in Section 10.4.4. Some advice on fuel quality management is given in Section 10.5.1. In addition, Bigün *et al.* (2005) provides methods for assessing availability and risks in fuel handling systems.

Summary

A summary of the design considerations outlined in the sections above is given in Table 10.4. The list is not exhaustive, but is an overview of some of the most critical issues.

Table 10.4 Design considerations for biomass combustion plants

Design aspect	Design consideration
Furnace	Sufficient radiative heat transfer surface to ensure flue gas temperature < 900°C into superheater (SH); < 750°C for difficult fuel (high alkali, chlorine, heavy metals)? Degree of slagging or fouling? Water soot blowers required? Residence time sufficient for CO burnout? 2 s above 850°C if WID compliance required?
Steam data, heat-transfer-surface design	Clean wood (high steam data) or difficult fuel (conservative data)? Location of SH in flue gas path; order of SH sections Tube spacing; tube bundle size Tube material(s) Flue gas velocity (heat transfer vs. erosion)
Fuel feeding	Bulk material flow properties Fuel variations to be expected (moisture, size, type) Fuel distribution (number of feeding points)
Secondary air system	Location of secondary air injection Sufficient penetration of secondary air jets? Flexibility in secondary air distribution? Tertiary air required?
Combustion control	Control of fuel feeding and air supply Monitoring of combustion (O_2, temperature, etc.)
Combustion temperature	Air preheating required? Variable preheating? FGR required? Location of FGR injection? Furnace refractory?
Flue gas cleaning, emissions control	Primary reduction means (air staging, FGR) Particulate removal (bag filter vs. ESP) De-NO_x required? SNCR vs. SCR Acid gas removal required? Hydrated lime vs. bicarbonate
Fuel storage and handling	Basic storage concept (silos, open storage, stacking, etc.) Consideration of material flow properties (bridging, adhesion, etc.) Safety aspects (dust, odour, fire and explosion, hygiene, etc.) Selection of conveying (mechanical vs. pneumatic, closed vs. open conveyors) Fuel treatment requirements (screening, tramp material removal)

10.4.3 Examples of industrial-scale biomass-to-energy plants

As mentioned earlier in this chapter, each biomass-to-energy project is subject to different conditions – legislation, incentive schemes, project drivers, fuel availability, possibility for heat utilisation, planning condition restraints, etc. – the sum of which is specific to that project and which contributes to the moulding of the plant design. Examples of how these different factors influenced plant design are given below for three biomass-to-energy projects built in recent years. All three plants have natural-circulation drum boilers based on travelling grate spreader stoker technology. The main data for the plants are given in Table 10.5.

Table 10.5 Comparison of main data for Gütersloh, Linz-Mitte and Western Wood plants

	Gütersloh	Linz-Mitte	Western Wood Energy Plant
Year commissioned	2000	2006	2008
Boiler steam data	68 t/h, 70 bar(a), 455°C	42 t/h, 67 bar(a), 462°C	58 t/h, 92 bar(a), 512°C
Fuel(s) (MC: moisture content)	Recycling wood, A1–A4 (MC 25–35%) Sander dust (MC < 15%)	Virgin wood, bark (MC 30–55%)	Virgin wood, uncontaminated recycling wood (MC 35–55%)
Biomass combustion system	Travelling grate spreader stoker Dust injection nozzles	Travelling grate spreader stoker	Travelling grate spreader stoker
Auxiliary burner	20 MW oil burner for start-up and support firing*	10 MW natural gas burner for start-up	15 MW oil burner for start-up
Air preheaters (APHs)	None	Low-pressure steam APH to 100°C Flue gas APHs with bypass control: – primary air 100–315°C – secondary air 100–400°C	Three-stage steam APHs High-pressure APH controllable in range 170–280°C
Flue gas recirculation (FGR)	Yes, for primary NO_x control	No	Yes, for tempering

(*Continued*)

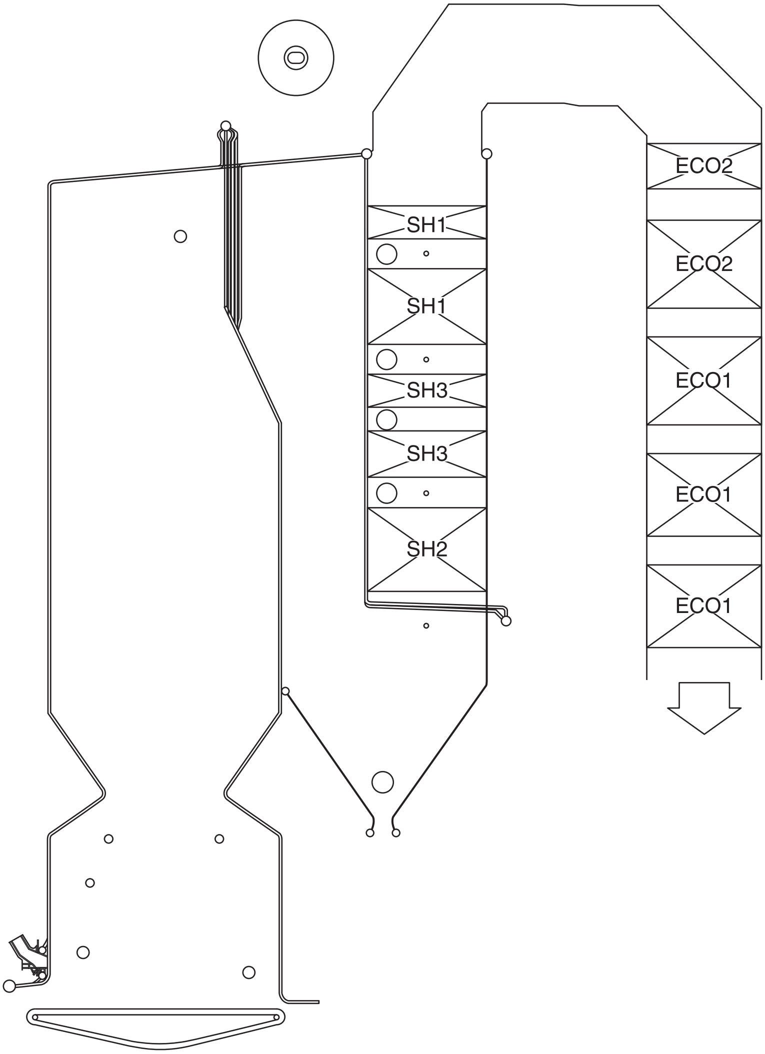
Table 10.5 Continued

	Gütersloh	Linz-Mitte	Western Wood Energy Plant
Flue gas cleaning	SNCR de-NO_x (urea) Hydrated lime injection Bag filter	Bag filter	Bag filter
Emission limits (24 h average)			
O_2 reference	11 vol.%	13 vol.%	6 vol.%
CO	50 mg/Nm^3	100 mg/Nm^3	250 mg/Nm^3
NO_x, as NO_2	200 mg/Nm^3	200 mg/Nm^3	250 mg/Nm^3
Particulates	10 mg/Nm^3	25 mg/Nm^3	10 mg/Nm^3
Total organic carbon (TOC)	10 mg/Nm^3	20 mg/Nm^3	20 mg/Nm^3
SO_x, as SO_2	50 mg/Nm^3	–	–
HCl	10 mg/Nm^3	–	–
Dioxins/furans	0.025 ng/Nm^3	–	–
Other features	Alloy 625 cladding of lower furnace Water soot blowers in furnace and radiation pass		
Boiler efficiency	~89% at 20% MC	~91% at 50% MC	~92% at 49% MC
Energy utilisation	13.3 MW_e condensing extraction turbine Up to 32 MW turbine extraction steam at 9 bar(a) for wood chip dryers Up to 6 MW saturated steam from steam drum for thermal oil heating Flue gas heat (180°C) utilised in chip dryers	8.9 MW_e back-pressure turbine 21 MW district heating condenser	16.5 MW_e condensing turbine

*Since the plant burns contaminated wood, it must maintain 2 s flue gas residence time above 850°C. If the furnace exit temperature is too low, an oil burner can be used to maintain the temperature above the limit.

Gütersloh

The Gütersloh CHP plant was built by a consortium of AET and Siemens for the German particle-board manufacturer Pfleiderer AG and was commissioned in 2000.



10.8 Cross section through the Gütersloh boiler. Alloy 625 cladding of lower part of furnace prevents salt-melt corrosion of walls. Superheater (SH) located in third pass to ensure proper cooling of flue gas before contact with superheater tubes. ECO, economiser.

A cross section of the Gütersloh boiler is shown in Fig. 10.8. The Gütersloh plant burns a combination of recycling wood (German waste wood categories A1 to A4) and sander dust (from particle-board production as well as externally sourced). In addition to supplying up to 13.3 MW electricity to the grid, the plant also supplies steam for two large rotary steam tube dryers that dry the fine wood chips used in the particle-boards. The flue gas from the boiler is led to the dryers to improve plant efficiency and some of the steam generated by the boiler is used to heat thermal oil for the particle-board press. At the time the plant was built, the cost of recycling wood was close to zero (or even negative), as the only alternative disposal route for recycling wood was incineration. Combined with the fossil fuel savings for the drying of wood chips this provided a strong financial incentive for building the plant. The boiler is equipped with a separate firing system for sander dust (which is too fine to be burned on the grate). Recirculated flue gas is injected with the dust to provide primary NO_x reduction as the nitrogen content of the dust is very high (up to 10% on a dry basis).

Since the plant was designed to burn contaminated recycling wood (waste wood categories A3 and A4), it fell under the German waste incineration regulation (17. BImSchV), which represents the German implementation of the EU Waste Incineration Directive (WID); furthermore, since the plant was built in an urban area, the environmental permit specified particularly stringent dioxin emission limits and monitoring requirements.

Due to the nature of the fuel, which contains high levels of chlorine, heavy metals, etc., the steam parameters and boiler flue gas path design are somewhat conservative. The furnace water-walls initially suffered high material loss rates due to salt-melt corrosion. A decision was therefore quickly made to clad the lower furnace walls with alloy 625 using overlay welding. This resulted in elimination of the water-wall corrosion and the plant has since operated for more than ten years without replacement of the furnace wall tubing. Water soot blowers were, however, subsequently installed to clean the furnace and radiation pass walls during operation.

The plant owner, Pfleiderer, publishes daily emissions values from the plant on the German version of its website (http://www.pfleiderer.de/de/verantwortung/).

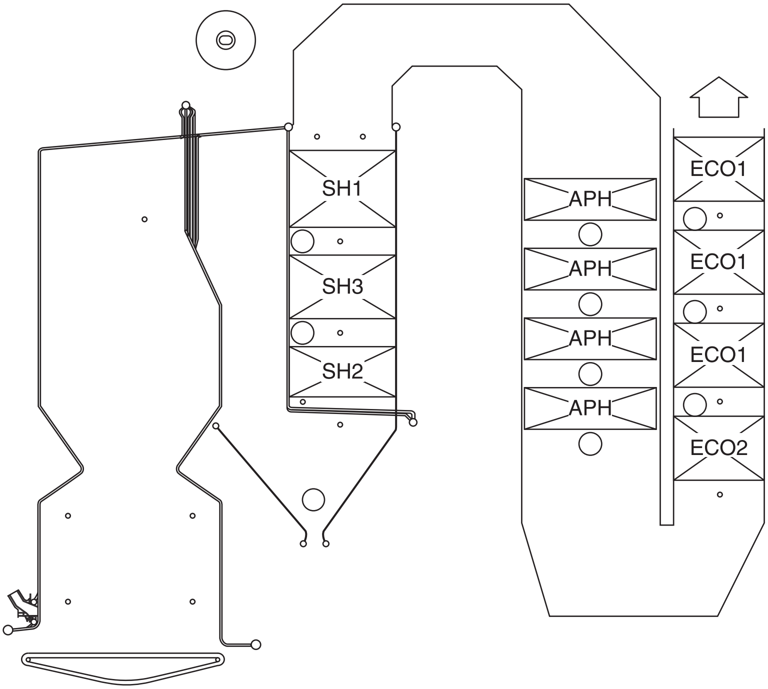
Linz-Mitte

In the city of Linz in Austria, the local utility company, Linz AG, has several CHP plants producing electricity and supplying district heating for the city. In 2003, a decision was made to build a biomass-fired CHP plant to act as a base load unit for the district heating network. The plant uses only virgin wood – bark, sawmill residues and logs (the latter being chipped on site at the CHP plant) – but with a moisture content that can vary from 30% to above 55%. Due to the potentially high moisture content of the fuel, the boiler was equipped with flue gas air preheaters providing primary air temperatures up to 315°C and secondary air temperatures up to 400°C.

The boiler supplies steam for a back-pressure steam turbine and the condensation heat is fully utilised in the district heating network. The plant's overall net efficiency is 83–84%. A cross section through the boiler is shown in Fig. 10.9.

Western Wood Energy Plant

The Western Wood Energy Plant (WWEP) near Port Talbot in Wales was commissioned in 2008. A photo of the WWEP plant and a cross section of the



10.9 Cross section through the Linz-Mitte boiler. Flue gas air preheaters (APH) located before economiser to achieve primary air temperatures > 300°C and secondary air temperatures > 400°C.

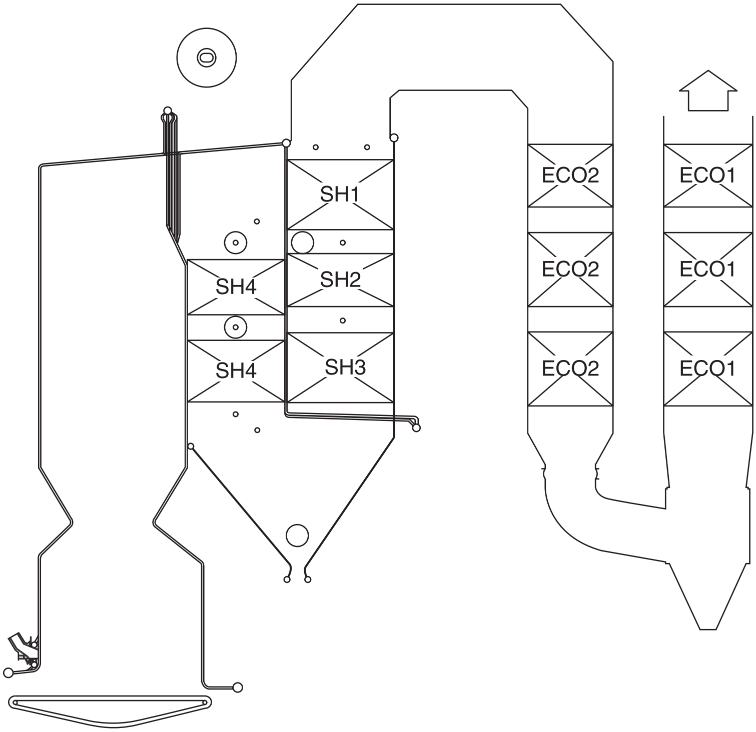
boiler are shown in Fig. 10.10. The plant was erected on a greenfield site and burns virgin and clean non-virgin wood. Because of the limited possibility of utilising the waste heat in the area, it is purely a power generating plant and the emphasis in the design of the plant was thus on high electrical efficiency. The steam parameters are at the higher end (92 bar/512°C) and the plant was designed with multiple-stage feedwater and air preheating to improve cycle efficiency. As the fuel consists of only clean wood, the boiler design allowed for the higher steam data without the use of high-alloy materials. Performance tests on the plant have shown a net electrical efficiency of approximately 30%.

Although the plants described above differ in design and application, there are also several common denominators: availability (> 8200 h/a), low excess air ratios (1.15–1.2) and low maintenance costs (< 2% of investment cost per year).

10.4.4 Designing for different types of biomass

Fresh wood has been the traditional biomass fuel used by man since the dawn of time and woodchips may be considered as the 'standard' biomass fuel. However,

(a)



(b)

10.10 Western Wood Energy Plant. (a) Photograph of plant and (b) cross section of boiler. Last superheater stage located in second pass to achieve live steam temperature of 512°C (photograph: Colin Jones, WBOC).

there are also other forms of wood (e.g. recycling wood, sander dust) and other types of biomass (e.g. straw, bagasse, poultry litter, sludge, short rotation crops such as willow, miscanthus, sorghum, etc.) that can be used as fuel. As Table 10.1 shows, the properties of different types of biomass can vary widely and most of these 'alternative' biomass fuels are more difficult, costly or risky to use in a biomass-to-energy plant than woodchips. This is typically due to one or more of the following factors:

- Lower ash melting point (often combined with higher ash content), causing increased fouling, slagging and corrosion. Applies to most non-wood biomass fuels.
- High content of chlorine, sulphur, alkali metals and/or heavy metals, increasing corrosion and requiring additional flue-gas cleaning. Applies to, e.g., recycling wood, straw, poultry litter, spent grains.
- High nitrogen content, increasing NO formation and thus requiring additional or more efficient NO_x reduction means. Applies to, e.g., sander dust, recycling wood.
- High fuel moisture, requiring fuel dewatering (pressing, drying). Applies to, e.g., spent grains, sludge.
- Environmental issues in handling (odour, dust, hygiene issues), requiring fuel storage ventilation, special safety and/or material handling procedures, etc. Applies to, e.g., poultry litter, meat and bone meal, sludge.
- Poor storage and mechanical handling properties, causing bridging, blockage, fuel decomposition or degradation, etc., and typically requiring more complicated and costly fuel handling and storage systems. Applies to, e.g., straw, wet/sticky fuels.
- Low energy density (due to high moisture or low bulk density), meaning higher transportation and storage costs. Applies to, e.g., sludge, spent grains, straw.
- Uncertain economic and political conditions, for example, short rotation crops (SRC) have yet to make a big impact on biomass energy utilisation. In their review of barriers for large-scale implementation of SRC, Alker *et al.* (2005) report that one of the major show-stoppers is the lack of unified political support for SRC schemes, meaning that few developers are willing to initiate projects based on SRC.

A review of industrial-scale biomass boilers built in Europe in recent years revealed that approximately two-thirds of the boilers were designed to burn more than one type of fuel. Despite the many problematic issues with these alternative biomass fuels, there must thus be compelling factors that make them viable. Some of these factors are outlined below.

Political and environmental factors

Different legislative measures stemming either from political objectives or environmental concerns promote the use of alternative biomass fuels, for example:

- Limitations on waste disposal: e.g. the EU Landfill Directive (Council Directive 1999/31/EC), the EU Nitrates Directive (Council Directive 91/676/EC) and the EU ban on using meat and bone meal (MBM) in animal feed. This type of legislation forces waste producers to search for alternative disposal routes, combustion being one such route.
- Incentive schemes providing additional benefits to plants burning non-wood biomass – see Table 10.3 for examples. This usually stems from a desire to promote the development of technology for 'new' biomass types or the use of locally generated fuels.

One political initiative that has had a direct influence on the use of non-wood biomass is the Danish ban on burning excess straw in fields, which has been in force since 1989. The ban was part of an overall energy plan to promote the use of biomass for energy purposes – a plan which included subsidies for straw-fired plants. In 2010 a total of 26.3 PJ of straw (corresponding to approximately 1.6 Mt) was utilised for energy purposes. Approximately 80% was used in power plants, CHP plants and district heating plants. The remainder was used in industry, in the agricultural sector and in domestic installations (Energistyrelsen, 2011).

Techno-economic factors

Two of the main reasons for looking at alternatives to woodchips are fuel costs and fuel availability – in some areas the cost of woodchips is very high (due to limited availability and/or high demand) and in areas with few forests the amount of woodchips available is often scarce. For industries that produce biomass wastes or by-products, which can be used as fuel, there can be a substantial cost advantage compared to externally sourced woodchips: not only is the fuel available at low or no cost, the total fuel cost may actually be negative, if combustion of the fuel eliminates or reduces the need for more costly disposal alternatives. Typical examples of such biomass wastes are sander dust from wood panel manufacturing, bagasse from sugar cane plants and waste from paper mills.

Biomass-fired plants burning recycling wood are also common in some countries (Germany, Sweden, Austria, etc.). Although recycling wood can also be burned in a traditional municipal solid waste (MSW) incinerator, the use of recycling wood in a dedicated biomass-fired plant has various advantages:

- Less contamination of the MSW incinerator ash: Wood ash has a relatively high chromium content, which 'contaminates' the incinerator ash and makes it unsuitable for later utilisation.
- Many incinerator plants operate close to their maximum capacity. The high calorific value of recycling wood means that 1 t of wood will typically displace 1½–2 t of other waste. Taking recycling wood out of the incinerator fuel stream means that the incinerator can handle a larger tonnage of waste.

- Recycling wood is easier to handle than MSW, both in terms of fuel storage and flue-gas treatment. The cost of utilising it in a biomass-fired plant is thus lower than in an incinerator plant.

Some examples of plants firing non-wood biomass fuels are given in Table 10.6. Design considerations for some of the fuels mentioned above are outlined in the sections below.

Recycling wood

It may seem somewhat peculiar to describe recycling wood as an alternative to wood as a biomass fuel – and uncontaminated recycling wood is indeed similar to other clean wood fuels in most respects. Contaminated recycling wood, however, has ash properties more similar to MSW than to clean wood and thus offers additional challenges in the design of the plant.

Contaminated recycling wood differs from most other biomass fuels in that it can have a significant content of elements not originating in the biomass itself and it is therefore classified as waste. This means that plants burning contaminated wood normally must be compliant with European Parliament and Council Directive 2000/76/EC, commonly known as the Waste Incineration Directive. Since the origin of recycling wood can vary greatly, so do fuel properties and degree of contamination. However, a common factor in contaminated recycling wood is typically high chlorine, nitrogen and heavy metal content (e.g. lead, zinc, chromium, arsenic and copper) originating from various forms of wood treatment (surface treatment, glue, preservation chemicals, etc.). These contaminants are typically enriched in the fine fraction of the fuel compared to the coarse fraction (Jermer *et al.*, 2001). Removal of the fine fraction of the fuel (e.g. by screening) can thus help to improve fuel quality significantly.

Fuel handling properties of recycling wood are similar to those of fresh wood, but recycling wood has notably higher ash and tramp material content. Screening equipment (e.g. oversize screens, stone traps, magnetic and eddy current separators) is thus a compulsory part of the fuel handling system in order to achieve high plant availability. Aluminium and scrap metal in particular are undesirable guests in the combustion zone since nails, molten aluminium, etc., can block grate air holes and larger pieces of metal may cause mechanical problems.

In most 'difficult' biomass fuels a high content of sodium and potassium combined with high chlorine content is the root cause of slagging, fouling and corrosion problems. Although recycling wood often contains significant amounts of chlorine, the sodium and potassium content is typically on par with fresh wood and the alkali metals are thus not the main culprits. Instead it is the heavy metal contaminants (in particular lead and zinc, often originating from paint) that are contributors to slagging and corrosion. Lead and zinc chlorides have low melting

Table 10.6 Examples of biomass combustion plants burning non-wood fuels

Plant, year plant came into operation	Fuel	Combustion technology	Steam data	References, sources of data
Slagelse CHP plant (DK), 1990	Straw	Air-cooled push grate	40 t/h, 67 bar, 450°C	Nikolaisen *et al.* (1998)
Masnedø CHP plant (DK), 1996	Straw, woodchips	Water-cooled vibrating grate	43 t/h, 92 bar, 522°C	Nikolaisen *et al.* (1998)
Elean Power Station (Ely, UK), 2000	Straw	Water-cooled vibrating grate	149 t/h, 92 bar, 522°C	www.eprl.co.uk www.bioener.dk
Fibropower (Eye, UK), 1992	Poultry litter, feathers, horse bedding	Stepped reciprocating grate	50 t/h, 65 bar, 450°C	Raubenheimer (2003) www.eprl.co.uk
Fibrogen (Glanford, UK), 1993	Meat and bone meal (MBM)[1]	Travelling grate spreader stoker	68 t/h, 65 bar, 470°C	Raubenheimer (2003) www.eprl.co.uk
Thetford (UK), 1999	Poultry litter	Travelling grate spreader stoker	150 t/h, 65 bar, 450°C	Raubenheimer (2003) www.eprl.co.uk
Gösser Brewery (Leoben, AT), 2003	Brewery spent grains[2]	Push grate	Not available	Steiner (2004) www.holzfeuerung.ch
Biowanze (Wanze, BE), 2008	Wheat bran (bioethanol production residue), natural gas	Water-cooled vibrating grate (wheat bran)[3] Natural gas burner	100 t/h, 93 bar, 430/520°C[3]	www.volund.dk
Helius CoRDe Ltd (Rothes, Scotland), 2013 (expected)	Distillery spent grains,[4] woodchips	Travelling grate spreader stoker (woodchips) Pneumatic injection nozzles (spent grains)	42 t/h, 84 bar, 452°C	www.aet-biomass.com

Notes: 1. Originally designed for poultry litter, converted to burn MBM in 2000. 2. Mechanically dewatered in band press and dried using flue gas. 3. Bran boiler provides superheating to 430°C; external natural gas-fired superheater provides final superheating to 520°C. Flue gas from the gas-fired superheater passes to the bran boiler. 4. Mechanically dewatered in screw press and dried in rotary steam tube dryer.

points (approximately 500 and 300°C respectively) and can form eutectic mixtures with even lower melting points. This can cause severe salt-melt corrosion of furnace water-walls and superheater tubes.

An effective (though expensive) means of protecting the furnace walls is overlay cladding with e.g. alloy 625. Conservative steam data (typically maximum 80 bar, 460°C) possibly combined with austenitic materials are typically used to avoid or reduce corrosion of superheater tubes. Flue gas temperatures at the superheater inlet are normally kept below 750°C. Increased superheater tube spacing and reduced tube bank size are used to facilitate efficient soot-blowing. Keeping superheaters clean prevents high flue gas velocities caused by blockage and therefore mitigates tube erosion, which otherwise can severely accelerate tube material loss, especially when combined with corrosive conditions.

Although recycling wood normally has a modest moisture content, a large furnace volume is required in order to compensate for the high degree of fouling and also to ensure sufficient residence time (minimum 2 s above 850°C) for WID compliance.

Usually flue gas cleaning must include acid gas removal (e.g. dry sorbent injection) and commonly also secondary NO_x reduction (e.g. SNCR). The use of bag filters rather than ESPs is also the norm. Depending on the fuel and the emission limits, injection of lignite coke may be necessary to capture dioxins, furans, mercury and other volatile heavy metals. WID requirements for emissions monitoring are generally more comprehensive than for non-WID plants.

It should be noted that although recycling wood may contain certain harmful substances (creosote, PCP, arsenic, chromium, lead, etc.), this does not necessarily cause high pollutant emissions. Organic substances contained in the fuel (creosote, PCP, dioxins, etc.) are normally destroyed in the combustion process, while indestructible compounds (arsenic, chromium, lead, etc.) end up in the ash and can thus be captured by traditional dust removal techniques – mercury being the exception due to its high volatility. Dioxins and furans can be formed post-combustion on the surface of fly ash particles and efficient dust removal will thus limit the dioxin emitted to the air. In most cases, good combustion burnout combined with suitable flue gas cleaning measures (see above) will ensure that flue gas emissions of these substances are kept well below limit values. Special measures concerning handling of the ash (in particular the fly ash) may be necessary, however, as the fly ash in particular will have an increased content of, e.g., heavy metals and dioxins.

Straw

Straw is a natural biomass waste arising from farming of cereal crops (wheat, rye, oats, etc.). As a biomass fuel it is characterised by relatively high contents of potassium and chlorine potentially causing severe fouling and/or corrosion.

Despite its undesirable ash properties, straw is used in several biomass-to-energy plants that operate with relatively high steam data (see Table 10.6), most notably in Denmark and the UK. Because of the ash properties, design of the heat transfer surfaces is crucial for successful operation of the plant. The attraction of straw is its widespread availability, but it is a biomass fuel associated with many challenges in both the supply chain and in fuel handling and storage. Some of these challenges are outlined below.

Since straw is commonly delivered in bales, the fuel handling system for a straw-fired plant is very different from most other biomass fuels: provisions for allowing many different types and sizes of bales (e.g. Hesston bales, small bales, round bales) add complications to fuel reception, storage and handling systems. Therefore fuel procurement specifications will normally specify the type of bale to be used. Obviously this forces farmers to adapt their baling systems. In addition, the seasonal cycles in agriculture mean that large quantities of fuel need to be stored for long periods of time. In order to maintain good fuel quality it is essential that the moisture content is kept low, again meaning that sheltered storage is required.

Fuel reception and storage systems are commonly based on a stacking system using overhead cranes, which require sophisticated controls to ensure first-in, first-out in order to prevent 'dead' areas of the fuel storage. The conveying system that feeds the combustion plant also needs to be designed to handle individual bales rather than a continuous flow of bulk material and is more reminiscent of an airport luggage handling system. A key part in the process is the removal of strings from the bales; this process can be severely complicated if bale sizes, number of strings, etc., vary.

The bale form of the fuel has led to the development of specialised straw combustion systems feeding the fuel in more or less compact form onto a reciprocating or vibrating mass burn grate. Some of these systems rely on various types of shredders to loosen up the bales before combustion. The increase in volume after shredding is considerable, since the bulk density of loose straw is very low.

Poultry litter

Poultry litter is a waste resulting from poultry farming. It consists mainly of poultry manure, but also contains feathers, spilled feed and the straw, sawdust, etc., that is used as bedding in poultry operations. Poultry litter has mainly been utilised in industrial-scale plants in the UK, and later also in Holland and the US. The developer of most of these plants has been Fibrowatt, a company that specialises in poultry litter-fired plants. Some of the technical issues related to poultry litter are outlined below. A more detailed review of the particularities of poultry litter combustion is given by Raubenheimer (2003), who provides an excellent summary of the experiences from Fibrowatt's three UK plants (see Table 10.6).

Poultry litter has highly variable moisture content – although the average moisture content lies around 40–45%, the moisture in individual deliveries can vary from 20 to 60%, depending on where in the poultry houses the litter is taken from. Poultry litter also has high ash content. Due to its ash properties (high chlorine, potassium, sodium, phosphorus, etc.) it is a fuel that causes severe fouling and slagging of heat transfer surfaces. This obviously requires careful design of the flue gas side with particular attention to tube spacing and heat transfer surface cleaning measures (e.g. soot blowers).

Fuel handling is also somewhat complicated by the fuel properties: the fuel is odorous and fuel stores must be equipped with ventilation systems to minimise odour and dust release. The exhaust from the ventilation system must be handled to minimise odour release. The fuel is also sticky and exhibits poor material flow properties. Crane handling systems are preferred for handling the fuel in storage (Raubenheimer, 2003); facilities for mixing fuel may be needed, as moisture content can vary significantly depending on the source of the fuel.

Although FBC has been successfully used for poultry litter combustion, the preferred technology for poultry litter firing is travelling or vibrating grate spreader stoker (with pneumatic fuel feeding), since FBC is more costly but offers no significant advantage over grate firing (Raubenheimer, 2003). Pneumatic conveying of the fuel is possible, but requires special measures to prevent blockage of conveying lines.

10.4.5 Conversion from coal to biomass

Although many have been replaced by oil- or gas-fired boilers, there are still a number of coal-fired industrial-scale boilers in operation across Europe. Many of these are travelling grate boilers producing steam for driving a turbine and/or for process purposes. As coal prices continue to rise and companies strive for ways to reduce their CO_2 emissions and dependence on fossil fuels, it is only natural that owners of these coal-fired boilers consider the possibility of converting their boilers to biomass firing. Gillum *et al.* (2009) provide a good overview of conversion strategies and criteria for evaluating the possibility and feasibility of converting coal-fired boilers to biomass.

As with the design of new biomass-fired boilers, successful conversion of such boilers requires an understanding of the differences between the two fuels and how biomass firing can be accommodated within the restraints of existing installations. Some of the technical obstacles that must be overcome are:

- Insufficient furnace volume: As outlined in Section 10.4.2 above, biomass firing requires a larger furnace volume than coal firing. If space limitations do not allow the furnace to be extended (e.g. by extending the furnace walls downwards), de-rating the boiler may be an option.
- Superheater design: Lower ash melting points and higher corrosion potential mean that superheaters designed for coal firing will often suffer problems

when the boiler is converted to biomass. In some cases changing the order of the superheater stages in the flue-gas path by modifying the external connection piping may be possible, or part of the superheater sections can be removed to allow larger spacing. Replacing superheater tubing with higher-grade material tubes, or lowering the live steam temperature are other options that can be used to counteract corrosion.

- Limited secondary air systems: Older coal-fired boilers typically have limited secondary air systems. Conversion to biomass requires redesign of the secondary air system (fan, ducts and nozzles) to give a larger fraction of secondary air. Often the available space or the design of the original boiler may limit the possibilities for locating the secondary air ports.
- Grate design: Grate combustion of coal requires more primary air than grate combustion of biomass and coal combustion grates are designed accordingly. Possible problems encountered when used for biomass include overheating (due to reduced cooling air flow) and poor air distribution (due to the low pressure drop resulting from the reduced flow).
- Incomplete information: Only rarely are the original drawings, design notes, etc., available. Even though the original material may be present, any modifications made since the plant was built are most certainly not fully documented.
- Constraints of existing plant: Working within the restrictions of an existing boiler-house will always present challenges – more often than not space is limited and constraints given by the existing plant will frequently necessitate compromises between possible and optimum solutions.
- Flue gas cleaning: Biomass generates more fly ash than coal. In plants that use ESPs the increased particle loading may result in increased particulate emissions. Planning permits for conversion projects may also stipulate stricter emission limits meaning that additional flue gas cleaning may be necessary.
- Fuel variations: Biomass fuel quality is not as constant as coal quality. Both management and operating staff must understand that one of the keys to successful operation of a biomass-fired plant is proper fuel management, i.e. ensuring that adequate fuel quality is maintained. Varying fuel quality also has implications for combustion control and the control system will most likely have to be adapted to the new fuel.
- Old habits: Operating staff used to the old coal firing may be reluctant to adapt to new procedures, different plant behaviour, etc. For example, many coal-fired plants operate at relatively high excess air ratios as outlined in Section 10.4.2 above, but good biomass combustion is achieved at low excess air ratios. Convincing boiler operators that operating at such levels is possible and necessary is not always easy.

Despite all these obstacles, it is often possible to adapt a coal-fired boiler to biomass firing. Two examples of successful conversion projects are given below.

Boehringer Ingelheim Pharma

Boehringer Ingelheim is a pharmaceutical company, located in Ingelheim, Germany. In 2003 a conversion of their existing 70 t/h travelling grate coal-fired steam boiler was initiated. The purpose was to convert the boiler to burn recycling wood in order to reduce greenhouse gas emissions and fossil fuel use and thus improve the environmental image of the company.

One of the major modifications was to cut down the lower part of the furnace and replace it with new water-wall sections with openings for new fuel feeders and secondary air/FGR nozzles. Air-swept biomass spreaders were installed in the boiler front wall and the old coal silos (which turned out to be heavily corroded) were cut down and replaced by new biomass feed silos. The existing travelling grate was turned 180° to discharge at the boiler front and the original dry bottom ash system was replaced by a wet ash conveyor. The secondary air system was also extended and FGR was installed for primary NO_x reduction. In locating the secondary air nozzles it was necessary to take into account both the physical restrictions of the existing plant as well as the requirement for 2 s flue gas residence time above 850°C after the final air injection. This last requirement was mandated by the fact that the plant would burn contaminated recycling wood and would thus require WID compliance.

The superheater was modified to increase the tube spacing in the sections exposed to the highest flue gas temperatures and the coupling was modified to locate the superheater final stage further towards the cold end.

The boiler originally had a quench reactor upstream of the ESP. By removing this, space became available for installation of an additional economiser section and a coarse separator to remove unburned carbon. A carbon re-injection system was also installed to feed the separated carbon particles back to the furnace.

Due to the stricter emission limits in the environmental permit for the retrofitted plant an SNCR system was installed to reduce NO_x. In addition, the existing ESP was replaced by a bag filter with bicarbonate injection for acid gas removal and a new emissions monitoring system was installed. The boiler control system was also adapted to the new combustion system.

The converted plant was successfully commissioned in 2004 and has operated on 100% recycling wood since. The only major problem encountered was blocking and corrosion of the superheater: the original superheater spacing was less than what would be used for a new recycling wood-fired boiler given the relatively high flue gas temperature at the superheater inlet. As there was a desire to maintain steam data close to the original operating level (76 bar/525°C), major modifications to the superheater were not possible, however. This meant that over time, the final sections experienced considerable fouling and also some corrosion. A working solution was found by lowering the live steam temperature somewhat and installing a system to inject a sulphate solution into the flue gas to minimise the chloride content in the ash.

Verdo Randers

In Randers, Denmark, the local utility company, Verdo (formerly Energi Randers), operates two 113 t/h steam boilers that supply steam for a common back-pressure steam turbine connected to a district heating condenser. The boilers were built in 1980 as coal-fired travelling grate spreader stoker boilers and produce steam at 110 bar/525°C. In 2002 the boilers were rebuilt to enable up to 40% co-firing of biomass. The main incentive for the conversion was the Danish tax on coal for heating use – the extra cost of biomass would be outweighed by the reduction in coal tax.

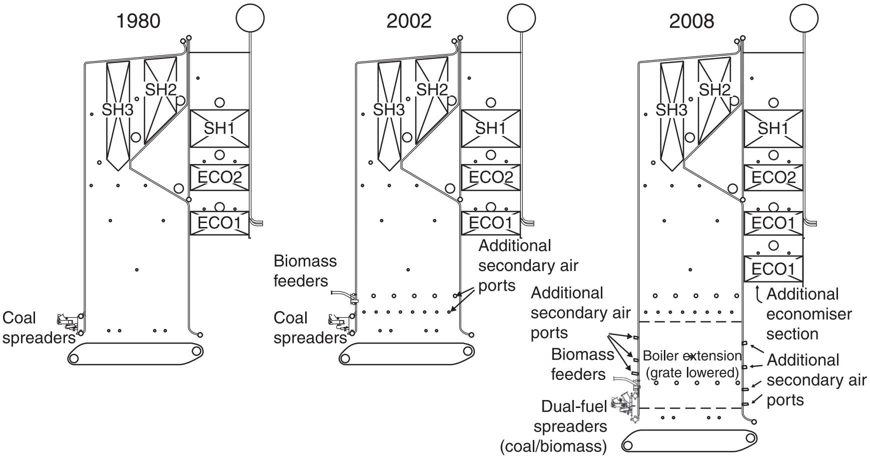
The possibility of co-firing was achieved by equipping the boilers with a system for pneumatic injection of dry biomass such as pellets, olive seeds, shea nut residue, etc. The secondary air system was also extended and the control system was adapted to handle two fuels.

The successful operation of the co-firing system provided the basis for a further increase in the biomass firing capability and in 2008 the boilers were rebuilt again: this time the purpose was to enable the boilers to fire up to 100% biomass (to reduce the dependence on coal and further reduce net fuel costs), while still retaining the coal-firing possibility (to provide security of supply in case of biomass fuel delivery failure). The solution chosen for fuel feeding was to replace the original overthrow coal spreaders with new water-cooled dual-fuel spreaders. The new spreader design features an air-swept biomass spout above a mechanical underthrow coal spreader. The original co-firing system was also retained to provide full fuel flexibility.

While the first co-firing project did not involve major modifications of the furnace (other than installation of additional ports for fuel feeding and secondary air), the conversion to 100% biomass necessitated an extension of the furnace. Fortunately the original boiler house had a deep basement, which allowed the furnace of each boiler to be extended 4.8 m downwards. The existing grates were moved accordingly and reused and the secondary air system was further extended with six additional injection levels. The superheater was modified and part of the superheater was converted to an additional economiser section. Modifications were also made to the carbon re-injection and bottom ash systems. A 'history' of the boiler before and after the conversions is shown in Fig. 10.11.

The boiler control system was also adapted for the modified plant. This included modifications to combustion control as well as facilities for setting the desired split between the coal feeders, biomass spreaders and the co-firing system.

The plant was started up on coal and initially experienced problems with the coal feeders, causing poor distribution on the grate. A number of modifications were made to the feeder geometry, which alleviated most of the problems. Following a further troubleshooting and optimisation period in which the biomass firing was also commissioned, the plant has operated very well. An overview of the evolution of the combustion system through the different 'phases' of conversion is given in Table 10.7.



10.11 Verdo Randers boiler before and after conversion from coal to biomass. Lower part of furnace extended and fitted with additional secondary air ports.

Table 10.7 Evolution of the Verdo Randers plant combustion system

	1980 Original plant	2002 Converted to co-firing of biomass	2008 Converted to fire any combination of biomass and coal
Fuel	100% coal	60–100% coal 0–40% dry biomass < 20 mm	0–100% coal 0–100% biomass (spreaders) 0–40% dry biomass < 20 mm (nozzles)
Fuel feeding system(s)	6 × Overthrow coal spreaders	6 × Overthrow coal spreaders 3 × Biomass injection nozzles	4 × Dual-fuel spreaders: • coal underthrow spreaders • biomass air-swept spouts 3 × Biomass injection nozzles
Furnace height (incl. radiant superheaters)	16 m	16 m	20.8 m
No. of secondary air levels	1 front wall, 1 rear wall	1 front wall, 1 rear wall 2 left wall, 2 right wall (new)	2 left wall, 2 right wall 3 front wall, 4 rear wall (new)

As the above two examples show, it is possible to successfully convert coal-fired grate boilers to biomass combustion. However, there will always be inherent limitations in an existing boiler that cannot be circumvented. A crucial part of such a conversion project is therefore a good understanding of these limitations in order to enable good compromise solutions to be found.

10.5 Operational routes to optimise performance and tackle problems

Achieving high availability in a biomass combustion plant requires a combination of good plant design and proper operational procedures: even the best operator cannot fully compensate for a poorly-designed plant, and even the most well-designed plant will have low availability if not operated properly. Many issues concerning plant design have been outlined in the previous sections. This section will treat some of the operational issues that need attention in order to optimise plant availability and performance.

10.5.1 Fuel quality management

Fuel quality has a key influence on plant availability – the cause of most unplanned outage in a biomass plant is without doubt the fuel. As described in Section 10.4.2, biomass is often a difficult material to handle in bulk solids systems. In addition, many combustion disturbances originate in fuel variations, and slagging and corrosion on the flue gas side can often be traced to the fuel composition. Not all disturbances caused by the fuel can be avoided, but knowledge of how the fuel affects the operation of the plant is important in developing a fuel handling strategy for the plant. Some recommendations for fuel quality management are therefore given below.

Fuel supply

- Ensure that fuel specifications contain the right requirements. Different parameters have different significance – some will affect plant operation and availability, while others will influence emissions, ash quality, etc. Specifying limits for all possible properties may not be the right way – identify the relevant ones and try to find the appropriate limits for those. This will probably require input from the boiler supplier, fuel suppliers and relevant authorities.
- Work with fuel suppliers to ensure that they are aware of the importance of fuel quality. It may be useful to examine the origins of the fuel they supply.
- Be aware of changes in the fuel; changes in fuel quality can indicate changes in the fuel source.
- Develop a plan for fuel delivery logistics – to ensure smooth flow of traffic, a safe working environment and uninterrupted plant operation. This includes taking permissible fuel delivery hours into account and providing sufficient space for vehicle movement/waiting on site.
- Keep records of all fuel delivered to the site, including analysis results of samples taken from the fuel. This helps in determining the source of any fuel that lies outside the fuel specification.

- Establish procedures for regular inspection, sampling and analysis of fuel deliveries.
- Visually inspect all fuel deliveries; this is the easiest and cheapest form of fuel quality control. Although it does not provide specific details of fuel properties, it allows immediate recognition of fuel that is obviously out-of-spec.
- Immediately reject fuel that is clearly outside the specification.

Fuel storage and handling

- Provide adequate on-site fuel storage to last through public holidays, etc., or other periods of no fuel delivery.
- In plants where manual handling of the fuel in storage is used, it is vital to ensure that fuel storage operators understand both aspects of fuel quality: fuel delivered to site should be within specification; fuel fed to the boiler should be as uniform as possible. Fuel storage operators provide the link between fuel deliveries and fuel feeding.
- Establish a strategy for fuel storage and handling: whether to store different fuel types/qualities separately or whether to mix before storage, how to ensure a 'flow' of fuel from the different storage areas, etc. Ideally this strategy should be integrated in plant design from the beginning.
- Establish routines for regular sampling and analysis of fuel from the fuel-handling system.
- Pay attention to the amount of rejects (oversize, metal, plastics and other foreign objects) in the fuel – this is also an indicator of fuel quality.

Fuel-quality monitoring

Due to the sheer volume of fuel that is handled in an industrial-scale biomass combustion plant, it is difficult to monitor the entire fuel stream. Online monitoring of moisture is a technology which is constantly improving, however. Moisture sensors providing qualitative indications of fuel moisture are now available at reasonable cost, but typically require recalibration for major changes in fuel type. Accurate quantitative monitoring is still difficult and requires costly equipment. Online monitoring of other parameters (size, trace elements, chlorine, alkalis) is not yet commercially available. Monitoring of fuel quality must therefore still largely rely on spot checks (analysis of fuel samples) and visual inspection of the fuel.

Visual inspection of fuel

Visual inspection of the fuel can be used to provide a general impression of fuel quality. Parameters that can be gauged by visual inspection include:

- fuel type and mix (e.g. woodchips, bark, sawdust, waste wood)
- fuel size (e.g. overall fuel size, content of fines/sawdust, amount of oversize particles)
- foreign object content (e.g. content of sand, stones, metal, plastics, etc.).

Fuel sampling

Sampling of solid fuels is a science in itself. Some of the main factors to consider are:

- where to sample: at the source, at delivery, in the fuel storage, in the fuel-handling/feeding system
- frequency of sampling: number of samples per fuel delivery, sampling interval in fuel handling/feeding, etc.
- how to sample: size of sample, how to take random samples from e.g. deliveries, how to avoid size fractionation of the fuel due to mechanical handling, etc.
- purpose of sampling: time/volume averages versus instantaneous/individual values, recording (e.g. for accounting purposes) versus targeted analysis (e.g. to find cause of fuel-related problems), parameters for analysis (moisture, size, trace elements, etc.).

Fuel analysis

Samples of fuel will usually be taken with the intent of subsequent analysis in mind. Depending on the purpose of the sampling, different parameters can be determined by analysis. Typical parameters of interest are:

- Moisture: Fuel moisture has a major influence on combustion and is easily determined using a scale and an oven. Provided the fuel fed to the boiler is relatively well mixed, the moisture usually changes relatively slowly. Routine moisture analysis of fuel samples taken from the fuel feeding system, for example once or twice per shift, is thus a useful means of detecting changes in moisture that may require adjustment of the combustion system settings. Regular moisture analysis of fuel delivered to the site will help in rejecting fuel with excessive water content.
- Size: Fuel size distribution can be determined by sieve analysis. There are standardised methods for sieve analysis, but as a rule they are not targeted at the large, irregular particles characteristic of biomass fuels. However, even a simple sieve analysis will give a good indication of the size distribution of the finer fractions (< 20–30 mm) of the fuel.
- Proximate/ultimate analysis: Proximate analysis provides details of moisture, volatile matter, fixed carbon and ash content as well as gross calorific value

(GCV). Ultimate/elementary analysis provides details of the carbon, hydrogen, oxygen, nitrogen and sulphur content. These analyses are usually done by off-site laboratories. Regular proximate and/or ultimate analysis of fuel samples is normally not needed, as the elementary composition of a biomass fuel generally does not vary significantly. It may, however, be useful to perform occasional analyses for ash, nitrogen and sulphur content in particular, if variations in these parameters are suspected to cause variations in plant operation.

- Trace element analysis: Trace element analysis is mainly relevant in trying to detect fuel with increased content of undesirable elements such as chlorine, sulphur, alkalis and heavy metals. The analysis is normally done by an off-site laboratory and is often quite costly. It is thus most relevant when deviations from the normal fuel are suspected, or when documentation of fuel quality compliance is required for e.g. operating permits.

10.5.2 Handling fuel-related corrosion and fouling problems

The wide variety of biomass fuels, each with its own characteristics, means that sometimes even the most well-designed plant operated under the best possible fuel quality management plan can suffer from fouling and/or corrosion. In this section some hints on possible solutions that can be applied after construction of the plant are given.

Switching to higher-quality fuel will usually entail additional fuel costs, but in some cases it can be a cost-effective solution if there are severe fuel-related problems such as corrosion, heavy fouling, etc. Recycling wood in particular can cause problems in boilers not designed for it. When lost revenue due to frequent outages is added to the direct costs of replacing superheater tubing, manually cleaning the boiler, etc., the overall cost may exceed the fuel cost savings. An alternative to a complete change of fuel can be removal of particularly troublesome fractions of the fuel – e.g. removing fine particle fractions from recycling wood will normally reduce chlorine and heavy metal content significantly.

A common problem in plants burning high-chlorine fuels is corrosion and/or slagging. Typically the corrosion and slagging potential of the fuel is more severe than the plant designer expected, or (just as often) the actual fuel burned contains more ‘nasty’ elements than the design specification stated – either because the original specification was inadequate or because fuel quality changed after the plant was designed. If ‘curing the disease’ by switching to a less problematic fuel is not possible, the only option may be to treat the symptoms.

One way to reduce slagging (and thus often corrosion) – and for FBC, bed agglomeration – can be to introduce additives that bind, e.g. alkalis to higher melting-point compounds. Adding kaolin to the fuel is one such method that works to bind potassium, sodium and zinc (see, e.g. Andersson *et al.*, 2003). Injection of sulphur compounds (e.g. ammonium sulphate) into the flue gas to shift the equilibrium towards alkali and heavy metal sulphates rather than chlorides is another method that has proven to be effective (Andersson *et al.*, 2003). The introduction of additional sulphur will, however, increase the flue gas SO_2 content and thus the need for SO_2 removal in downstream flue gas cleaning equipment. Fouling of furnace walls can also be kept under control through the installation of water soot blowers.

Fuels such as recycling wood may contain significant amounts of heavy metals and chlorine. This cocktail can cause severe salt-melt corrosion – reducing the lifetime of furnace walls to two to three months in some cases. Fuel additives such as kaolin and sulphates (as mentioned above) may reduce the corrosion, but an alternative solution is to clad the tubes using overlay welding of a corrosion-resistant alloy. Alloy 625 – although costly – has been the alloy most commonly used, and if coverage is good, corrosion is often completely eliminated. Overlay welding is best suited to furnace walls and is less useful for superheaters, however, as the corrosion resistance of the alloy is limited to temperatures above 400°C. Post-construction application to superheater tubes would also mean complete replacement of superheater tubes, as access to the internals of the tube banks for welding would not be possible.

Other measures for preventing corrosion include lowering steam temperatures, modifying the superheater (e.g. increasing tube spacing by removing tubes, or coupling superheater stages differently) or installing additional soot blowers to improve cleaning of superheater tube banks.

10.6 Future trends

The biomass-to-energy sector consists of many different technologies, plant sizes, fuels, legislative conditions, etc. Simple predictions of the future developments in this sector are thus difficult. However, it is clear that legislation and political initiatives will continue to have a major influence on the external conditions for biomass projects.

In many respects biomass combustion technologies are mature technologies, where quantum leaps are rare. Still, the natural technological progress towards higher efficiencies and lower emissions is constantly ongoing. Plants are designed with higher steam data, and some plants are already using reheat cycles to improve electrical efficiency. The use of more and more difficult fuels will work in the opposite direction as far as efficiency is concerned, however, as these fuels might require more conservative designs.

The financial crisis that has swept the world in recent years leads potential investors to focus more on capital costs. This in turn typically means less emphasis on high performance, reliability and overall quality.

The increased focus on CHP promotes higher total efficiencies and requires more attention to possibilities for integrating biomass-to-energy plants in industrial processes and/or district heating/cooling schemes.

The uncertainties regarding fuel availability and the increasing demand for biomass will mean that fuel flexibility will be an important element of any new plant. If (or, perhaps, when) a take-off in the establishment of energy crop schemes occurs, the adaptation of technologies for these fuels and their supply chains will be required. Since the main barriers seem to be non-technical (Alker *et al.*, 2005), the main change may have to come from the political side.

10.7 Sources of further information and advice

The International Energy Agency (IEA) provides a large number of reports, predictions, recommendations, etc., on energy from biomass, (e.g. IEA, 2007a, b), many of which are available on the IEA website (www.iea.org).

IEA Bioenergy is an organisation under the auspices of the IEA, which aims to improve cooperation and information exchange between countries in the field of bioenergy. The work of IEA Bioenergy is structured around a number of tasks that deal with specific subjects such as biomass combustion, short rotation crops for bioenergy systems, etc. The outputs of these tasks are typically workshops, technical assessments and guidelines, etc. For more information, see their website (www.ieabioenergy.com).

EC (2006) – referenced above – provides a good overview of preferred technologies for biomass combustion plants and also covers aspects such as fuel unloading, storage, handling and pre-treatment.

The Swedish thermal energy research association Värmeforsk has funded and coordinated research in the bioenergy area for several decades. Their website (www.varmeforsk.se) has hundreds of reports on various aspects of biomass utilisation.

The European Committee for Standardisation (CEN) has a technical committee (CEN/TC 335) for developing standards for solid biofuels. The standards are intended to provide harmonisation of e.g. terminology, fuel specifications and classes, quality assurance, sampling and testing of biomass fuels. The technical committee has already issued a large number of publications on these subjects – either as technical specifications or full European standards. It is likely that these standards will find widespread use in the biomass sector in the near future. More information can be found on the CEN website (www.cen.eu).

Although not a substitute for specific fuel analyses, the Phyllis database for biomass and waste (www.ecn.nl/phyllis), run by the Energy Research Centre of the Netherlands, is a good starting point for finding fuel properties for many different types of biomass.

10.8 Acknowledgements

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11

Biorefineries: increased value from biomass conversion

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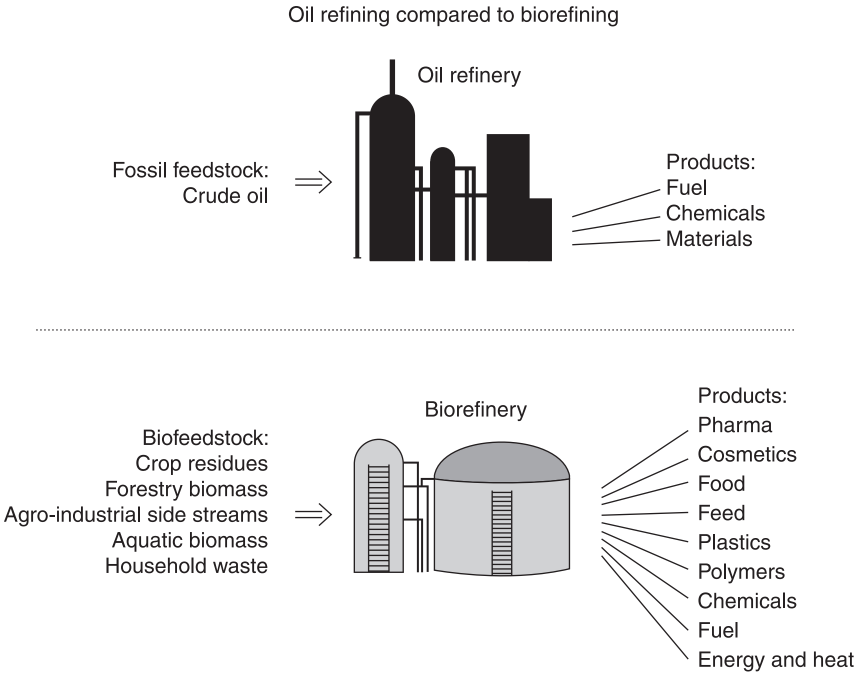
Abstract: *Biomass* is much too precious to be used only for the production of heat and electricity. Biomass and biowaste have the potential to be used much higher up in the value chain, e.g. as food ingredients, animal feed, chemical building blocks, materials, fuels, and phosphorous-rich fertilizer. *Biorefineries* will take over from oil refineries. A biorefinery can use all of the different components in optimized value-adding purposes. They represent the next generation of industrial biotechnology, building on the use of microbes and microbial products to convert biomass. The *bioeconomy* will be a prominent part of smart and sustainable society in the future.

Key words: biomass, biowaste, value chain, biorefinery, knowledge sharing.

11.1 Introduction

Much of the renewable energy produced globally comes from biomass; along with wind and water and the up-and-coming solar and geothermal sources of energy, biomass energy is already of significant importance in the transformation of fossil-based societies to non-fossil-based societies. However, seen from a slightly longer perspective, renewable carbon from plant materials is much too precious to be used only for production of heat and electricity. Energy in the form of heat and electricity remains a low-value, bulk product, at the absolute bottom of the value cascade. Biofuel has a significantly higher value; it is a renewable alternative for the transport sector and provides versatility regarding future products based on a sugar platform. However, in the future, renewable carbon will most likely be used globally for purposes much higher up the value chain. Renewable carbon from plants has huge potential for use as a substitute for crude oil and within non-energy applications such as for construction materials, chemical building blocks, packaging, plastics, fibers, polymers, fertilizer, feed and food. A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, heat, and value-added chemicals from biomass. In the future, the conversion of plant biomass to a range of products will take place in a biorefinery, complementing and substituting for the many products we currently get from crude oil, which are converted in an oil refinery (Fig. 11.1).



11.1 Biorefinery versus oil refinery. The feedstock for a biorefinery is renewable biomaterials (primarily plant residues), from many sources and composed of many types of molecular structures; for an oil refinery the feedstock is the fossil crude oil, composed of mostly carbon structures as most of the other molecular components have degraded over time. Product differentiation is broad for both an oil refinery and a biorefinery. However, a biorefinery can produce products much higher up the value chain than an oil refinery, due to the many intact molecules in the renewable biomaterials (proteins, glucans, secondary metabolites, etc.).

Biorefineries should be seen as the newest extension to the classical field of biological production. Biological production and biological solutions will be increasingly brought into use as we meet the challenge of globally using our natural resources more efficiently and in a more sustainable way. Biological production uses plant materials to grow microbes to produce value-added products. The classical biological production method is brewing beer and baking bread. Biomass biotechnology is a rapidly growing segment of industrial biotechnology all over the world. The largest segment of industrial biotechnology is the use of enzymes in the substitution of chemical production processes by biological production processes (e.g. in the textile, paper and pulp, and detergent sectors). Furthermore, the microbial production of enzymes as process agents is a large industry in itself, dominated globally by only two major players: Novozymes A/S and Genencor, a business division of DuPont A/S.

Overall fermentation yield, conversion efficiency, and production costs are major competitive factors in industrial biotechnology. Therefore, industrial biotechnology and biological production require the optimization and refinement of both technology and processes. The profit margin in industrial biotechnology is low compared to the pharmaceutical sector, where production costs are a much smaller part of the total price structure. This means that to make industrial biotechnology commercially viable we need to attract the best scientists, biologists, and engineers, and the most skilled workers to modern biological production plants and biorefineries. It also means that this is a very attractive investment area for countries that have access to the necessary skills and want to compete internationally, create new jobs based on new knowledge and develop export opportunities for produced goods as well as for new proprietary technologies.

Biorefinery technologies will become an integral part of many different industrial and agricultural segments and value chains. It is a challenge to combine biorefining technology with biomass combustion, since burning the material cuts off all other options for obtaining value-adding components from the renewable materials (e.g. carbon polymers, phosphorus, and proteins). However, combustion can be used constructively in a biorefinery to dispose of the last remnants of the biomass/biowaste; the components that can add more value have been removed, refined, and developed for more optimized use. Hence, combustion and biological conversion of biomass are synergistic.

This chapter will consider biorefineries with a holistic, 360° perspective, from the feedstock to the product. Biorefineries will be evaluated from both a sustainability and a resource optimization point of view, and from a frontier science perspective for further optimization – all with a global outlook.

11.2 Biorefinery feedstocks and concepts

11.2.1 Feedstock for biorefineries

The feedstocks for biofuel and biorefineries are used to produce first-generation and second-generation biofuels. To produce a first-generation biofuel, the cereal or grain (i.e., the primary food-relevant component of the crop) is converted directly into biofuel, e.g. bioethanol; a second-generation biofuel is produced from crop residues (e.g. wheat straw, corn stover, or woodchips). This chapter considers biomass feedstock for second-generation biofuels. However, it is time to challenge the concept of these two generations, since there are many in-betweens, grey zones, and outsiders; several of these are interesting seen from a sustainability perspective. Below are some examples.

Biowaste as feedstock

Second-generation feedstock is not just crop residues. Most importantly, it includes many types of biowaste, e.g. the side streams of agro-industrial production, municipality waste, and garden and park residues. It also includes eco-service grass clippings from marginal land where the biodiversity is threatened by an excess level of nutrients. The eco-service harvesting of biomass removes excess biomass from areas with elevated levels of nutrients, for example, due to the run-off of fertilizer from neighboring cultivated fields or from nitrogen-rich precipitation from adjacent pig farms. This type of biomass can be used as a feedstock in a biorefinery, thus doubling its advantages. This chapter will address all these types of feedstock, which are considered to be a basis for second-generation bioproducts and do not use components directly available for food and feed.

Whole crops as feedstock

Use of the entire crop, e.g. by harvesting the entire maize or *Triticale* plant and using it in a biorefinery, can, in certain soil and weather conditions, result in the production of animal feed in amounts similar to using all the acreage directly for an animal feed crop such as barley for pig feed. Furthermore, higher-value products such as food ingredients, chemical building blocks, polymers plus biofuel can be produced along with the animal feed. This type of biorefinery will require a combination of the simpler first-generation enzyme technology with complex second-generation enzyme technologies, so that all of the harvested biomaterial is used efficiently.

Marine resources for feedstock

When facing the challenge of feeding and fuelling the predicted 9 to 10 billion people on Earth, more and more consideration is given to marine resources (marine macroalgae, seaweed, or seafood waste) in the production of both bioenergy and important value-adding products such as food ingredients, nutraceuticals, and cosmetics made from natural resources. There is a considerable and interesting potential in using such marine and freshwater bioresources. New research is needed to select the best species from nature to grow or harvest, and to design the best processes. New technologies are needed to solve the inherent challenges, e.g. harvesting the microalgae in an energy-efficient way. Furthermore, great caution is needed to ensure that we do not cause environmental damage, lose biodiversity, disperse invasive species, or pollute the marine environment, in the open sea as well as on shore and in inland lakes. This field of research should be expanded to include all groups of plants that grow in the sea, both the macroalgae and the flowering plants that grow submerged in or floating on water (e.g. *Zostera* or eelgrass), and to the value-adding conversion of seafood waste.

To group biowaste, household waste and agro-industrial side streams as second-generation products is easy and well accepted. But what do we call whole crops harvested as a biorefinery feedstock? And what term should we use for biomass harvested from the sea and lakes? New terminology is needed. One suggestion is to introduce a certification system, globally accepted, and use the term ‘certified feedstock for biomass conversion’ for biomass that passes sustainability criteria, which takes into account the environmental impact, the use of the harvested material, land use, and the level of inputs (water, nutrients, and energy) needed for production.

The impact of climate change is placing a special focus on agricultural production. This is also true for the production of biorefinery feedstocks. Climate change has both positive impacts, for example with the possibility that new crops will soon be harvested in northern Europe, and negative impacts, such as the irregularity of the water supply and water scarcity, putting pressure on agricultural production in vast parts of the world and therefore also on the efficient use of water for growing biorefinery feedstocks and in biorefinery processes.[1–5]

11.2.2 Biorefinery concepts

In the near future, we will see a whole spectrum of different types of biorefineries being developed. Some will be highly specialized, tailor-made for a specific type of agro-industrial production, handling and upgrading the value inherent in the side streams and reusing surplus energy streams in a synergistic, symbiotic manner. Others will be more general and will set global trends, for example producing a multiplum of products, animal feed, biofuel, solid fuel, and feedstock for a neighboring power plant out of corn stover or wheat straw.

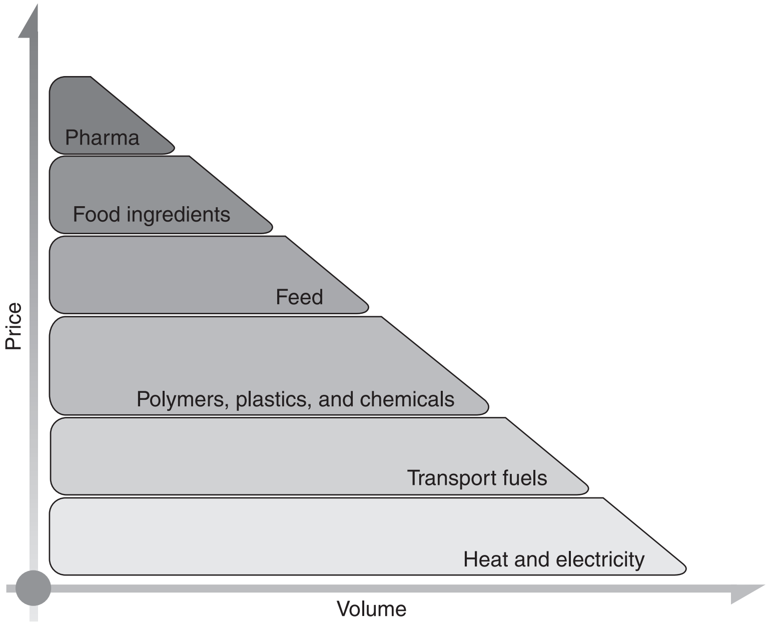
The biorefinery concepts are legion and cannot be fully covered in a single chapter. Further, biorefineries are undergoing such rapid technological and market-adaptive economic changes that they are a target that is moving too rapidly to describe in full. Instead an attempt will be made here to describe some of the basic principles, technologies, challenges, and dilemmas.

First and foremost is the feedstock. This is most often plant material consisting primarily of sugar polymers. The most abundant of the sugar polymers is cellulose. Cellulose has the formula $(C_6H_{10}O_5)n$, and is a polysaccharide consisting of a linear chain of D-glucose, which create the three-dimensional crystalline structures of cellulose fibers. The next in importance is hemicellulose, which contains mostly pentoses, e.g. xylose. Hemicellulose is often found in the form of complex branched polymers composed of several different types of pentoses. Next is lignin, which has a polyphenol structure that acts as a gum between the network of cellulose fibers and hemicellulose polymers. Together C6, C5 and lignin are called lignocellulosic materials. Lignocellulosic materials give plants the strength to resist biotic and abiotic stress (e.g. wind). Lignocellulose is resistant to degradation, especially when the plant material has been matured and dried as in straw and stover.

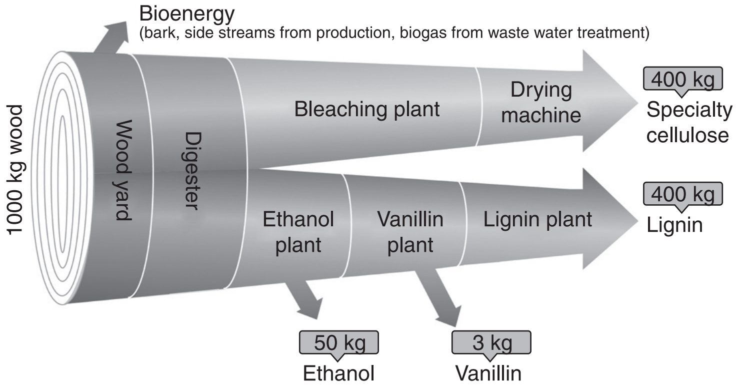
Besides the lignocellulosic materials, plant materials hold varying amounts of proteins, pectins, lipids, and a host of small molecules (salts, acids, vitamins, pigments, flavors, and other secondary metabolites).

A biorefinery is constructed to use all of the different components for optimized value-adding purposes. The value of the different parts of biomass is illustrated schematically in Fig. 11.2. Heat and electricity are at the absolute bottom of the cascade with regard to created value. Biofuel gives higher value; animal feed, chemicals, and other materials even higher. At the top of the cascade are nutraceuticals and pharmaceuticals.

To optimize the use of the feedstock materials, the biorefinery process should be planned first and foremost to preserve and utilize the highest-value components. Second the process should be efficient and use a very high percentage of the entire feedstock, along with the minimum amount of energy and water. Biorefinery processes can be planned to use almost 100% of the feedstock materials. In this way it resembles for example ducks in China or pigs in Denmark. Every single part of the animal is used, especially in a globalized world: Denmark now exports pig ears to China since there are no users nearby. Similar developments in biorefinery product differentiation are possible and harbor an interesting potential for increased efficiency in the use of natural resources.



11.2 The biomass feedstock of a biorefinery contains an entire spectrum of potentially value-adding products. Care must be taken in designing the biorefinery pretreatment and processing regimes so that all the value cascade products remain intact and can be recovered and used. In an optimized biorefinery, only the leftover products from the process are burnt to produce bulk low-value energy and heat.



Cellulose	**Lignin**	**Vanillin**	**Ethanol**
Construction materials	Concrete additives	Food	Car care
Cosmetics	Animal feed	Perfumes	Paint/varnish
Food	Dyestuff	Pharmaceuticals	Pharmaceutical industry
Tablets	Batteries	Biofuel	
Textiles	Briquetting		
Filters	Mining		
Paint/varnish			

11.3 The biorefinery concept is not new. An excellent example of an established biorefinery production and business is the Norwegian company Borregaard, which produces an entire spectrum of value-adding products from woodchip lignin.

The origin of the feedstock determines the height of the biorefinery products in the value cascade (Fig. 11.2): multicomponent biowaste will normally not be used in the production of pharmaceuticals and sludge will not be used to produce food ingredients. The pretreatment procedure will similarly limit the level to which the biorefinery product can be developed. If the pretreatment conditions are harsh (high temperature, strong acids, or high pressure), many molecules disintegrate and cannot be recovered. This also happens to proteins if they are not recovered before harsh treatment. Furthermore, harsh chemical and physical treatments may lead to the production of toxic compounds.

Borregaard in Norway is an example of a well-established biorefinery, which uses all of the lignocellulosic material in wood (Fig. 11.3).[6–11]

11.3 Improving feedstocks

11.3.1 Biomass breeding

From the very beginning of agriculture, farmers have made continual efforts to select the best seeds for the next crop season. Modern plant breeding uses sophisticated tools combined with talent, skill, and molecular insights as well as vast amounts of data and experience to support informed choices about what gives robust and high-yielding crop varieties and phenotypes. This effort has primarily been used to improve the germ plasm to give improved yields under varying field conditions. The number of leaves or the thickness and height of the stem are almost never a specific breeding target, for example, when generating a new cereal variety. In fact almost the opposite is true: an important part of the breeding effort over the last century has aimed at producing cereals with shorter stems, which have a higher ratio of grain to biomass.

What is the future for biomass-focused breeding? The outlook now seems very promising. Since higher amounts of biomass have not been targeted efficiently by earlier breeding efforts, there appears to be a vast potential for increasing biomass yield. Further good news is that this may not necessarily lead to a lower grain yield. Plants have an inherent potential for using the energy from the sun more efficiently to simultaneously produce more biomass and high grain yield. This would be an important step forward for increasing the amount of feedstock for biorefineries without decreasing the amount of food and feed produced per hectare.

Another target for biomass breeding is making the composition of the biomass better suited for industrial biorefinery processing. A higher proportion of parenchyma cells, lower amounts of deposited lignin or lignin with a different composition could be beneficial. Very interesting research results have been published in this area, for example from lignin-targeted research collaborations in the EU Seventh Framework Program. Significant results in this area have, however, not yet been realized in practice under field conditions. The most recently released corn varieties in the US may, however, start a new trend.

A third target is to breed for a self-processing capability within the plant. Significant efforts following this line have been made worldwide. Many technologies have been developed, with interesting inventions made, patent applications filed, and patent claims issued. Around a decade ago, this seemed to be an important part of the modern biorefinery field. However, right now the extra transaction costs required for genetically modified (GM) variants of crop plants seem to be too high overall. Molecular insights have been gained from work on transformants in research laboratories, but these insights will be used to improve crop varieties rather than to develop industrial GM plants for biorefinery feedstock purposes.

We expect, however, that the development of biorefinery technologies and the establishment of many new biorefinery plants will trigger a trend for using new specialized crop plants and new crop plant varieties. Crop plants that have higher amounts of high-value compounds (e.g. tailor-made medicines or healthy food ingredients) would generate higher incomes from biorefinery investments.[12–16]

11.3.2 Pretreatment

The recalcitrant nature of lignocellulosic plant materials is the reason that a pretreatment procedure is needed before exposing the materials to biological (enzymatic) biomass conversion. Milling – even if to fine particles – is normally insufficient for letting large enzyme proteins gain access to the cellulose and hemicellulose structures.

Several regimes for the pretreatment of biomass have been developed, and commercial companies have been formed to offer these procedures for a given feedstock. Among the most commonly used procedures are acid hydrolysis, steam explosion, wet oxidation, and combinations and hybrids of these. It is beyond the scope of this chapter to provide details of such pretreatment procedures (additional information can be found in the literature). However, more general aspects of pretreatment will be highlighted here in brief.

- Pretreatment is costly, in terms of the required investment, the cost of the energy consumed, and the energy lost.
- Pretreatment not only opens the plant structures but also disturbs them in a manner that is not always known. It may lead to the remaining lignin binding even more tightly to the plant carbon structures, giving the enzymes new obstacles in the access required and the aqueous conditions needed to decompose the material into free sugars.
- Pretreatment may lead to more polluted process water. The biologically active, scrambled phenols that result from changing the structure of lignin will put pressure on nature if released untreated.
- Pretreatment procedures lead to a build-up of inhibitors in the fermentation broth. Such inhibitors are known to inhibit the growth of the microbes in the subsequent fermentation step.
- Pretreatment may destroy important components of the biomass, reducing the entire efficiency of the biorefinery.
- Pretreatment may lead to the formation of additional epitopes to which the enzyme proteins might unspecifically adhere. This increases the amount of enzyme needed, adding to the costs of the biorefinery process and adding significantly to the overall cost of production.

Needless to say, it can be seen from this list that there is much room for improvement of pretreatment regimes. Optimally, a much gentler pretreatment procedure should be developed. Much thinking is being invested into developing a biological pretreatment process – e.g. inspired by the well-known silage process. The risk here, however, is that silage microbes will consume the energy content of the biomass.

In the cow rumen, physical massaging and chewing is sufficient for the bacterial and rumen chytrid enzymes to gain access to the substrate. Perhaps, in time, we will learn from the cow rumen biomechanism how to solve the pretreatment dilemma. One thing is certain: we know from nature that it can be done – not only in ruminant animals but also in the gut channels of termite larvae, butterfly larvae, earthworms, and others. Meta-transcriptomic discovery projects are currently underway in the Lange Laboratory, Aalborg University, Copenhagen to improve our understanding of cellulose decomposition in the biome of a larval gut channel. To use this knowledge efficiently, biomass composition, pretreatment, and enzyme as well as chemical catalysis must be considered together.[17–21]

11.4 Conversion by enzymes and microorganisms

11.4.1 Enzymatic biomass conversion

The history of second-generation biofuels

It has been relatively easy to get the first-generation biofuels to function. (Actually biofuels have been known and used since the time of Henry Ford. A Ford Model A could run on biofuel made from corn.) The enzymatic conversion of starch is easy. It requires only two enzymes and a simple pretreatment regime before the C6 sugars are readily available to yeast, which ferments them into ethanol. Fermentation from sugar cane is even easier as the sugar is readily available for fermentation. However, breaking down recalcitrant lignocellulosic materials has long been seen as being very difficult. The development was expected to take so long that leading companies announced that university efforts and significant public financing would have to be invested to make second-generation biofuels technically feasible and commercially viable.

The US Department of Energy (DOE) was the first to offer significant incentives and financial support for R&D efforts for the biomass conversion of lignocellulose. The reason for this pioneering move was, however, not meant to produce renewable energy only. It was equally intended to stimulate the development of technologies that would allow for additional income for corn farmers in the US Midwest. Regardless of the objectives, it was a clever move!

The DOE's support was public and competitive (see the DOE website, listed in Section 11.7). Grants had built-in milestones that had to be met to open the door for next-stage funding. Furthermore, grants were given to competing companies, including Novozymes' US daughter company and Danisco's US business division, Genencor. European funding came much later, with less built-in competition and more limited requirements for integrated collaboration between academia and industrial R&D.

Considerable progress has been achieved, although at a rather slow pace – this was a difficult problem to crack. However, in 2008, both major global enzyme producers, Genencor and Novozymes, announced they would launch an enzymatic blend for the commercial production of second-generation biofuel in 2010, which would be ready to use in the buses driving the participants of COP15 in Copenhagen, at the end of 2010.

And they did! However, the financial crisis that started in 2008 changed and cooled the investment climate. The level of investment for the construction of second-generation biomass conversion plants – the expected forerunners for biorefinery plants – fell to unexpectedly low levels. The implementation of second-generation biomass conversion technologies has moved much more slowly than expected.

However, in two areas of the world the process has continued at high speed: in China (with corn stover as biomass) and in South America (with bagasse, a product left over from the production of sugar from sugar cane).

Investments in the US and in the BRIC countries (Brazil, Russia, India, and China) are now increasing again. In 2012, progress in the EU finally seemed to gain momentum. And now, many of the blueprints are changing from second-generation biofuel plants to biorefineries, producing e.g. biofuel, animal feed, or phosphorus fertilizer, and using the leftover biomass for combustion. However, additional higher-value products must be made from the biomass for biofuel to become cheap enough to compete on price against gasoline (the price of which is going down again after entry of the shale gas to the energy market). Gasoline is still being used without being priced or taxed at a level sufficient to pay for cleaning up the inherent CO_2 emissions – in spite of the effects of climate change, which are now manifest throughout the world.[22–26]

From wild-type fermentation over monocomponents to enzyme blends

In the first few decades of the modern use of enzymes (the 1960s to the 1980s), enzymes were sold as enzyme blends extracted from wild-type filamentous fungi (primarily species of *Trichoderma*, *Aspergillus* and *Humicola*) or from bacteria (primarily Gram-positive genera). The mid–1980s began a new era. The first GM microbial production organisms (transformed to hold and express a single foreign enzyme gene) were introduced, taken successfully through the regulatory process and gave astonishingly positive results. Now it was possible to optimize the production of a single type of enzyme protein in a single fermentation tank!

There was another important element in the development of industrial biotechnology in Europe. The use of microbial genetically-modified organisms (GMOs), grown in fermentation tanks under biologically contained conditions, tested under strict regimes, and guided carefully by the regulatory authorities, was accepted by the public, by international regulatory and trade organizations, and by non-governmental organizations. This did not happen overnight but through a long, inclusive, and very serious dialogue between the industrial biotech companies and the public stakeholders. The process was in all aspects (including the product) different from the attempted introduction of GM plants into Europe. I sincerely hope that future technologies will be introduced with as much transparency, evidence, and care and respect for public opinion.

From that point, the development of monocomponent enzymes specifically tailored to solve a specific problem such as an industrial process, really took off.

This resulted in an impressive portfolio of enzymes for all aspects of modern life (see the links to Novozymes' and Genencor's websites in Section 11.7).

The development was stringent, resulting in a few optimal production organisms, with GRAS (generally recognized as safe) status for worker health, consumer exposure, and the environment. Enzyme proteins were refined through protein engineering to be efficient under realistic end-user conditions. There was a bump in the road: some sensitized people who used detergents to which enzymes had been added suffered allergic reactions. This was taken seriously and primarily solved through new formulations.

This business concept of one optimized gene, expressed in one highly optimized production organism, producing one protein, formulated into a stable product, and sold for one specific job to the consumer, worked extremely well and business was booming. However, this business and technology platform did not provide an organic basis for the development of second-generation biomass conversion enzyme technology.

Biomass conversion posed a problem, which led to a change in the basic business model. The problem was straightforward despite its complexity: the conversion of lignocellulose is so complex and requires the simultaneous action of so many enzymes that it could not be achieved economically using a mixture of independently produced monocomponent enzymes.

The obvious winning concept for second-generation biomass conversion is to select a fungus with an excellent capacity for protein expression and secretion and insert all the key enzyme genes needed into this strain. Additionally, developing production and recovery conditions with lower costs could close the gap and make second-generation biofuel produced from biomass competitive with gasoline. Comparisons are difficult because of different tax regimes, but overall, prices are close enough in countries where politicians have implemented incentive structures and market-stimulating goals, that conditions are conducive to a switch from fossil- to non-fossil-based energy.

Additional developments will take place over the next few years, and will be faster if investments are made, which allow for broader and more scale-up uses. The technologies will only be developed fully when more of such full-scale applications are being brought into use globally.

The most significant step forward may, however, be to move from where we were yesterday, with bioenergy as the only focus, to a true biorefinery concept. Higher-value products produced along with biofuel in the same biorefinery and from the same feedstock, may drive down energy prices to a level where biofuel is truly competitive with gasoline.

11.4.2 Microbial biofuel production

Pretreatment followed by enzyme treatment converts cellulose to monomer C6 sugars, and hemicellulose to soluble C5 sugars. The monomers (and certain amounts of dimer and trimer sugars) are used by the fermenting microorganism, which produces bioethanol or biobutanol. The fermenting organism most often used is baker's yeast, *Saccharomyces cerevisiae*. It readily ferments C6 sugars, but not C5 sugars to any significant extent. Huge efforts have been invested throughout the world to get *S. cerevisiae* to also ferment C5 sugars, which would increase the amount of ethanol produced from most biomass feedstocks by 30% to 50%! Many other types of organism have been extensively tested to try to exploit the full potential of C5 sugars.

To date, so much significant progress has been made in this area that it is now possible to make bioethanol from C5 sugar. However, just as this was achieved, a new development arose: perhaps profitability (and sustainability) would be improved if the C5 sugars were used instead for animal feed, human nutraceuticals, or food ingredients. Separating the C5 sugars (which would be used for upgraded food and feed purposes) and the C6 sugars (which would be used as the basis for chemical building blocks, materials, and biofuel), and using the leftover fraction for combustion feedstock or biogas, may be the most constructive way forward.

Time will show. The most likely scenario is where different biomass feedstocks (terrestrial and marine; crop residues and biowaste) are used in different biorefinery technology regimes for biofuel and higher-value products such as food, feed, chemicals, plastics, fertilizers, etc., only the final remnants of the biomass would be used for combustion.[21–25]

11.5 Life-cycle analysis and sustainability

Biological processes, products, and solutions are making an important contribution to the more efficient use of natural bioresources, as well as providing the basis for moving from fossil-based to non-fossil-based solutions, processes, and products. However, each new process, product, or solution will have to be evaluated to ensure that regulatory requirements are fulfilled, certification is achieved, and people are reassured that it is truly sustainable, both in the short and long term.

Life-cycle analysis (LCA) is an important part of such an analytical exercise, but standard and stand-alone LCA is not sufficient. The most serious arguments against biofuel are the most valid and acute for developing countries, e.g. when biomass feedstock is grown in a manner that puts serious pressure on food prices and on local biodiversity or when it displaces the production of food and feed for the local population.

Another evaluation criterion is based on the reduction of CO_2 emissions. The production of biofuel, especially in Europe at times, has received low political priority based on not fully valid arguments: it is correct to argue that the combustion of biomass for heat and electricity replaces more fossil carbon (and CO_2 emissions) than the conversion of biomass to biofuel – but that is not the complete picture. What is left out of most calculations is that biofuel is only one of the products obtained from converting biomass to biofuel. Significant amounts of high-value animal feed and combustion and biogas feedstock are produced from the same biomass. If these are included, the overall energy calculation comparing combustion with biofuel looks different. Another factor often left out of LCA calculations is that biofuels are a sustainable alternative in the transportation sector, where no other renewable energy is available. Bioethanol for private cars will, however, most likely be phased out when electrical cars become a reality. Biofuel will primarily be used as the fuel for heavy trucks, cargo ships and most importantly jet planes.

The current focus on carbon emissions is important and well justified but we need to expand the analysis to other natural resources. Evaluations of sustainability must build on several bottom lines, not just CO_2! In a world faced with the challenge of feeding and fueling an expected 9 to 10 billion people under climate change conditions, the following bottom lines are the ones that are important, against which any new processes, products, and solutions should be evaluated and prioritized:

- Replacing fossil fuel: biofuel for transport fills a gap for which no other renewable energy is available.
- CO_2 emissions: second-generation biofuel meets sustainability criteria, but diesel from rapeseed oil and first-generation fuels do not.
- Use of arable land: new sources of animal feed from biorefineries could replace the production of animal feed from feed crops, which take up a large proportion of the total global acreage of arable land.
- Use of freshwater resources: cotton production requires huge amounts of land and water; biorefineries producing textile-relevant microbial polymers and fibers could provide an alternative.
- Improved use of biomaterials: biowaste, including agro-industrial waste streams, post-harvest loss and food wasted in the consumer line, is an interesting avenue with potential for upgrading in biorefineries.
- Impact on biodiversity: forest and marginal land provide shelter for species and support biodiversity. Planning for bioenergy and biorefinery crops should include protection of the biodiversity.
- Food prices: the price of food has become an international issue that is extremely serious. However, the problem of too high food prices will need to be tackled in a comprehensive manner. The production and use of biorefining feedstock, decoupled from land use, should be given priority.
- Creation of more jobs: unemployment – especially among the younger generation – is an extremely serious problem, not only in Europe but globally, e.g., in northern Africa and the Middle East. Biorefinery technologies and a growing bioeconomy sector can provide the basis for an entire spectrum of new knowledge-based industries, creating new skilled jobs. This is true not only within the academic world but very much so for blue-collar jobs as well.

11.6 Future trends

11.6.1 Future global players in biorefineries

Public discussion about the development of bioenergy and biorefineries has focused primarily on the high-tech biotechnology industry and companies in the energy sector. However, this is much too narrow. Biorefinery technologies will become an integral part of many more industrial sectors, and will provide incentives for new joint ventures and mergers between players from different sectors (good examples are collaborations between Danisco and DuPont, and Danisco and Goodyear).

Clarification of who will be the main drivers for the new and growing biorefinery segment of industrial biotechnology is still to be seen. A good bet is that the chemical industry will become very strong in this area. Another trend is that the biomass owners, for example large agro-industrial players, will develop a side branch based on biotech and biorefinery technology, upgrading their own waste streams to higher value. Such developments may also lead to the production of other biotechnology products, as the basic substrate on which microbes are grown develops. Why not produce microbes for other value-adding products that could feed into interesting markets? Europe currently leads in biological production technology, and has for decades. To maintain its leading position, Europe must gather momentum and take advantage of the new options for moving laterally into further biological processes, biological products, and biological solutions worldwide. Climate change, a growing global population, the need for increased resource efficiency and the necessary shift towards renewables are all important drivers, adding to the momentum. Although the momentum is there, the direction, products, geographical distribution, and players are not yet obvious.

11.6.2 Knowledge sharing, intellectual property rights, and targeted technology transfer

The switch from fossil- to non-fossil-based technology and addressing the major global challenges in feeding 9 to 10 billion people under climate change conditions are creating a need and a demand for the fast implementation of new solutions, built on new technologies and new knowledge. The current method of knowledge dissemination is simply not sufficient. It moves too slowly, and has a built-in, inherent trend of keeping new players out for too long.

The characteristic trend of the last few decades has been that universities take out patents and act overall like industrial research departments, but this is not the only way to move forward. We need strong public research, with investment in high risk areas, which hold the potential for adding value and the sustainable transformation of our societies from using fossil-based to non-fossil-based fuels. This includes integrated and mutually inspiring collaborations, disseminating new knowledge to relevant players in both the public and the private sectors. Right now, universities are focused not on disseminating knowledge but on intellectual property rights (IPR), which may lead to new knowledge lying idle in patent applications, filed but not issued and not brought into real use.

We need a new era of knowledge sharing. A stronger open source element of the basics must be developed. Academia on its own, as well as in collaboration with industry and other relevant stakeholders, must agree on sharing the basics with the world, but in a targeted and strategically timely way that allows for patent protection on a level and in a timely manner that really provides the basis for industrial growth, through introducing new, useful, and sustainable products and solutions.

Biotech should learn from the open source solutions in the information and communications technology field. We can share more, move faster, and at the same time stimulate a knowledge-based industry in an even more efficient way. If we spread the basic knowledge to growing economies and developing countries simultaneously sending excellent candidates to our local industries, we will stimulate sustainable development throughout the world, while we also stimulate the economy, including job growth in our own region.

11.6.3 Leadership and diversity management

The need for new and sustainable solutions based on biology is so much in demand that leadership is a necessity. We must ensure that we provide the basis for real diversity management, stimulating growth that is robust because it is based on triple bottom-line judgments. Such leadership is only possible if we include diversity among and within the leadership circles. We need diversity in gender, culture, and competencies – with a good balance between technically knowledgeable leaders and professional business developers without a technical background. This approach should be reflected in education. Problem-based learning and a cross-disciplinary focus, aiming at combining deep insights in individual fields with the competence to interact with neighboring fields, are among the competencies and skills in demand for developing a more sustainable future.

11.6.4 Scientific trends within biorefinery technology

It is beyond the scope of this chapter to review the latest trends in biorefinery technology development. Highly interesting progress has been made recently in, e.g., the role of auxiliary proteins and dehydrogenases, high-temperature stable proteins, synthetic biology, synthesis biology, and metagenomics, which has given a new conceptual understanding of microbial consortia as a means for an even more efficient conversion of biomass. However, most importantly, there is right now a global trend for exploiting the entire range of biomass sources, ending the era where the focus was almost exclusively on biomass conversion of corn stover and wheat straw. Never in history have biological products, biological processes, and biological solutions been more important for the world.

11.7 Sources of further information and advice

- encyclopedia.thefreedictionary.com/biorefinery
- Novozymes: www.novozymes.com
- DuPont/Genencor: www.genencor.com
- Inbicon: www.inbicon.com and www.inbicon.dk
- Terranol: www.terranol.com
- Biogasol: www.biogasol.dk
- Department of Energy, US, DOE: www.energy.gov
- EU: www.climatepolicytracker.eu/findings–2010
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