8.1 Introduction

Biomass combustion influences the environment mainly through emissions to the atmosphere. Depending on the emission component, it influences both the local, regional, and global environment. The local environment is affected mainly by particle emissions and other components caused by incomplete combustion. The regional environment is affected by acid precipitation originating mainly from NO_x and SO_2 emissions, while the global environment is affected by emissions of direct or indirect greenhouse gases and through ozone depletion.

The amount of pollutants emitted to the atmosphere from different types of biomass combustion applications is highly dependent on the combustion technology implemented, the fuel properties, the combustion process conditions, and the primary and secondary emission reduction measures that have been implemented.

Due to the wide diversity of biomass fuels, with highly varying elemental composition, moisture content, density and thermochemical behaviour, many different types of biomass combustion applications have been developed. These biomass combustion applications cover a wide range, from small-scale units for room heating to large-scale power plants. Hence, the air pollution control technologies must be selected with care, and economy will always be a limiting factor. However, implementation of more stringent emission limits forces the development of low emission biomass combustion applications forward.

In general, emission reduction measures developed for combustion of fossil fuels can also be applied for biomass combustion applications. All biomass combustion applications benefit from an optimised combustion process, which reduces emissions from incomplete combustion. However, to reduce the emissions further or to reduce emissions from complete combustion, secondary measures must usually be applied. For small-scale biomass combustion applications secondary emission reduction measures are often not cost-effective, and the emission regulations are therefore usually not as strict as for large-scale biomass combustion applications.

For biomass combustion applications using virgin biomass as fuel, emission regulations are usually applied for emissions from incomplete combustion, such as some kinds of particles and CO. In some cases emission regulations are also applied for NO_x, which to some extent also can be reduced by primary emission reduction measures. However, in special cases it may be necessary to apply secondary NO_x emission reduction measures. Emissions of SO_2 are usually not significant for wood combustion applications due to the low sulphur content in wood. However, for biomass fuels such as miscanthus, grass, and straw, emissions of SO_2 may be significant and SO_2 emission reduction measures must be applied.

In this chapter, the emission reduction measures applicable for biomass combustion applications will be presented, including both emissions from incomplete and complete combustion. However, to give the reader an overview of the environmental aspects of biomass combustion as well, the various emission components are first presented and their sources and impact on climate, environment, and health are indicated. Then an overview of typical emission levels from various biomass combustion applications is given. These emission levels will be very dependent on the emission reduction measures implemented and are only guiding values reflecting today's typical biomass combustion applications, not the emission reduction potential. Following the presentation of primary and secondary emission reduction measures, emission limits for biomass combustion applications in selected IEA member countries will be presented as examples of where the emission limits stand today. However, establishment of emission limits is a dynamic process and emission limits often are adjusted according to the available technology and economic considerations. Finally, the environmental impacts of emissions from biomass combustion applications are analysed and compared with the environmental impacts of combustion of fossil fuels.

Various literature sources dealing with various aspects of air pollution exist. For further reading about air pollution in general the following references are recommended: [199, 200, 201, 202, 203, 204, 205].

8.2 Environmental impacts of biomass combustion

In this subchapter, the environmental impacts of emissions from biomass combustion applications are analysed and compared with the environmental impacts of combustion of fossil fuels. Furthermore, in Section 8.3 options for ash disposal and utilisation and wastewater treatment will be discussed.

The environmental impacts of air pollution from most biomass combustion applications today are far from negligible. However, compared to fossil fuel combustion applications there are several advantages.

First of all, biomass is a renewable fuel, and is considered as being CO_2-neutral with respect to the greenhouse gas balance. However, this is only true if we are able to achieve very low levels of emissions from incomplete combustion [206], and if we do not include our use of fossil fuels in harvesting, and transportation of biomass fuels and our use of electricity produced from fossil fuels.

To evaluate the real environmental impacts of biomass combustion, a Life Cycle Assessment (LCA) should ideally be carried out. This type of evaluation includes the various stages of the life cycle of the biomass, from procurement of the fuel, transportation, storage, and conversion to the discharge and handling of ashes. The construction, operation, maintenance, and decommissioning of the energy converting technology should also be included in the assessment according to the LCA method. The exchanges to the surrounding environment in terms of emissions to air, soil, and water are then inventoried for each stage in the life cycle. These exchanges are added up to environmental impacts such as global warming, acidification, and ozone depletion in the environmental impact assessment.

In [207], an LCA study is presented in which the procurement and conversion of biomass and fossil fuels are compared. The study includes emissions of CO_2 (expressed as CO_2 equivalents), NO_x, and SO_x. It concludes that procurement of biomass fuels, in general, consumes less energy than procurement of fossil fuels. Furthermore, it is concluded that fossil fuels cause the highest emissions for each of the parameters CO_2, NO_x, and SO_x. Many of the activities related to the procurement of fuels involve the use of fossil fuels. Therefore, it is not fully correct to define biomass fuels as CO_2-neutral when considering the complete life cycle. However, from the results in [207] it can be concluded that the gap between the CO_2 impact from biomass and fossil fuels grows bigger when procurement is included in the considerations. The gap is even larger in the case of favourite biomass fuels.

Other aspects of the procurement should ideally be included in the assessment as well, such as for example the use of fertilisers and the release of N_2O during the growth of the biomass. N_2O is a very potent greenhouse gas and can therefore, even in small amounts, change the picture. The handling of the ashes should also be included, whether it is reused/recycled or must be landfilled due to a high content of heavy metals such as cadmium.

The increasing concentration of greenhouse gases in the atmosphere is the main incentive for the substantial increase in the use of biomass for heat and power production in IEA countries today. As a renewable fuel, biomass will be available for heat and power production in substantial amounts, after the fossil fuel resources have diminished. The reserves of oil and natural gas are fast decreasing, while the reserves of coal will be available for much longer. However, as can be seen in Table 8.1, coal is the least attractive fossil fuel for heat and power production due to its high emission levels.

Table 8.1: *Emissions from a typical 2000 MW fossil fuel power station using coal, oil or natural gas [208].*

	Coal, conventional without flue gas desulphurisation [kton/year]	Oil, conventional [kton/year]	Gas, combined cycle [kton/year]
Carbon dioxide	11,000	9,000	6,000
Airborne particulates	7	3	Negligible
Sulphur dioxide	150	170	Negligible
Nitrogen oxides	45	32	10
Carbon monoxide	2.5	3.6	0.270
Hydrocarbons	0.750	0.260	0.180
Hydrochloric acid	5-20	Negligible	Negligible
Solid waste and ash	840	Negligible	Negligible
Ionising radiation (Bq)	10^{11}	10^{9}	10^{12}

NO_x and SO_x emissions from biomass combustion applications are, in general, low compared to coal and oil combustion. Emissions of NO_x from biomass combustion applications mainly originate from the nitrogen content in the fuel, in contrast to fossil fuel combustion applications where nitrogen in the air also contributes, to some extent, to the NO_x emission level. In most cases, the NO_x emission level can be significantly reduced by the use of primary emission reduction measures, and can be further reduced by implementing secondary emission reduction measures. Emissions of SO_x can easily be reduced by secondary emission reduction measures, and in some cases also by primary emission reduction measures. However, for many biomass combustion applications, secondary emission reduction measures for NO_x and SO_x are not cost-effective due to the fact that biomass combustion applications are usually much smaller than fossil fuel combustion applications.

The main disadvantage of biomass combustion applications, especially small-scale applications such as wood-stoves, fireplaces, and wood log boilers, is their high level of emissions from incomplete combustion compared to fossil fuel combustion applications. Many of these small-scale biomass combustion units are based on natural draught and are also operated as batch or semi-continuous systems. In addition, combustion process control systems are usually not cost-effective.

One of the main advantages of biomass combustion for heat and power production is the utilisation of a renewable fuel source, which in most cases is locally available, and which in many cases has a very low or even negative alternative value. Emission reduction measures are known and are available for all harmful emission components; it merely depends on emission limits and cost-effectiveness whether the emission reduction measures are implemented or not. By increasing the size of the biomass combustion applications, improved emission reduction possibilities will become cost-effective. However, local availability of the biomass fuel and transportation costs will usually be a limiting factor for the size of a biomass combustion application. The possibility of co-firing biomass and fossil fuels is promising, both with respect to effective biomass utilisation for heat and power production and for achieving low emission levels.

In short, biomass is an environmentally sustainable fuel for heat and power production that is important today and which will increase in importance in the years to come. By implementing the best available biomass combustion technologies and emission reduction measures, emissions from biomass combustion applications can be minimised. Thus the negative environmental impacts of biomass combustion that exist today can be reduced.

8.2.1 Emission components and their main influencing factors

Emissions from biomass combustion applications can be divided into two major groups: emissions from complete combustion and emissions from incomplete combustion. It should be noted that particle emissions can be a result of both complete and incomplete combustion. They are treated in both sections below.

8.2.1.1 Emissions from complete combustion

The following components are emitted to the atmosphere as a result of complete combustion in biomass combustion applications:

Carbon dioxide (CO_2)

CO_2 is a major combustion product from all biomass fuels, originating from the carbon content in the fuel. However, CO_2 emissions from biomass combustion are regarded as being CO_2-neutral with respect to the greenhouse gas effect and this is considered to be the main environmental benefit of biomass combustion.

Nitric oxides (NO_x)

NO_x emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, both from gas-phase combustion and char combustion. Additional NO_x may be formed from nitrogen in the air given certain conditions. However, these reaction mechanisms are not considered to be of significant importance in most biomass combustion applications. The main nitric oxide emitted is NO, which is converted to NO_2 in the atmosphere.

The possible gas-phase reaction mechanisms for NO_x formation in biomass combustion applications are:

1. **The fuel NO_x mechanism:** [209, 210, 211] Fuel nitrogen is converted to NO (> 90%) and NO_2 (< 10%) through a series of elementary reaction steps called the fuel NO_x mechanism. Important primary nitrogen- containing components are NH_3 and HCN. However, significant amounts of NO and N_2 may also be found in the pyrolysis gas. If sufficient O_2 is available, NH_3 and HCN will mainly be converted to NO through different reaction routes. However, in fuel-rich conditions NO will react with NH_3 and HCN, forming N_2. This is utilised as a primary NO_x reduction measure. By optimising the primary excess air ratio, temperature and residence time, a maximum conversion of NH_3 and HCN to N_2 can be achieved (see Section 8.2.3.7).
2. **The thermal NO_x mechanism:** [212, 213] Nitrogen in the air starts to react with O radicals and forms NO at temperatures above approximately 1300°C. The amount of NO formed increases with increasing temperature, O_2 concentration and residence time. However, in biomass combustion applications the combustion temperatures are, in general, lower than 1300°C. Thermal NO_x is a post-flame problem, meaning that the major formation of thermal NO_x occurs in the post-flame gases, after the main combustion, due to its dependence on O_2 concentration and residence time.
3. **The prompt NO_x mechanism:** [209, 214] Nitrogen in the air may also react with CH, mainly, forming HCN, which then follows the reaction steps of the fuel NO_x mechanism. The prompt NO_x mechanism is less temperature-dependent and much faster than the thermal NO_x mechanism. However, it is only important in fuel-rich conditions and is very dependent on the CH concentration. The prompt NO_x mechanism has not been found to be of significant importance in biomass combustion applications, in contrast to fossil fuel combustion applications.

Additionally, fuel nitrogen is retained in the char and is largely oxidised to NO in the char combustion phase, but may subsequently be reduced to N_2 by a fast heterogeneous reaction with the char [215]. The amount of fuel nitrogen retained in the char relative to the amount of fuel nitrogen released in the devolatilisation phase is determined in part by the thermal exposure of the fuel [216].

The fuel NO_x emissions increase with increasing nitrogen content in the fuel, excess air ratio, and combustion temperature, up to a point where all fuel nitrogen intermediates have been converted to either NO_x, N_2O, or N_2. However, the fraction of fuel nitrogen converted to NO_x decreases with increasing nitrogen content in the fuel, as can be seen in Figure 8.1. This has also been shown by other investigators [217, 218, 219]. Figure 8.2 illustrates the relative importance of the fuel, thermal and prompt NO_x mechanisms as a function of combustion temperature. NO_x emissions may be reduced by both primary and secondary emission reduction measures. Further references: [206, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 267, 272, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 291].

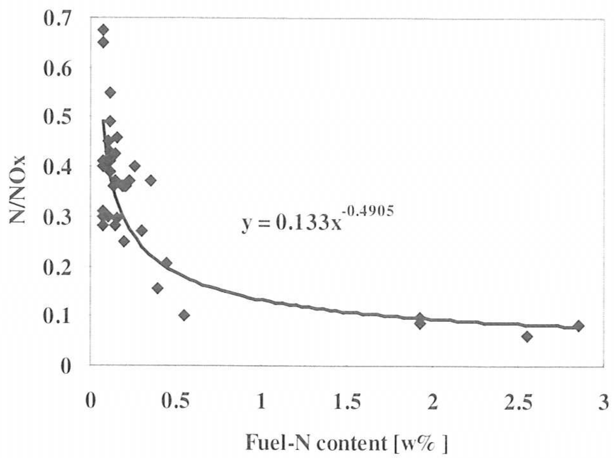

Figure 8.1: *Fraction of fuel nitrogen converted to NO_x for various wood fuels in various wood combustion applications, as a function of fuel nitrogen content, and together with a trend line [229].*

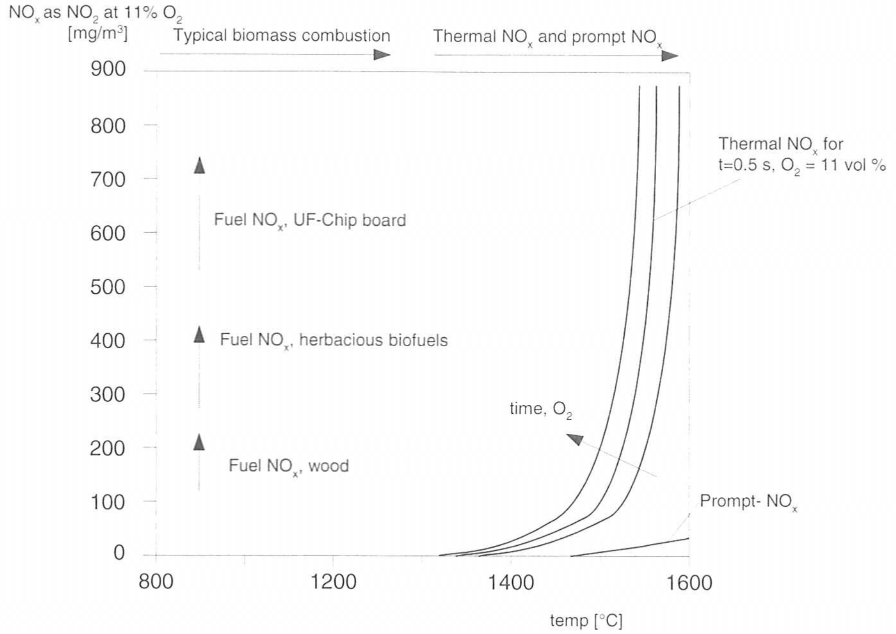

Figure 8.2: *Fuel-NO_x emission levels as a function of temperature and fuel type (fuel-N content), and comparison with thermal and prompt NO_x formation [230].*

Nitrous oxide (N_2O)

N_2O emissions are a result of complete oxidation of fuel nitrogen. However, the N_2O emission levels measured in various biomass combustion applications are very low. This is a result of several influencing factors, which will not be discussed here. Even though the N_2O emission levels from biomass combustion are very low, they do contribute to some degree to the greenhouse gas effect, because of the high GWP (Global Warming Potential) factor of N_2O, and to ozone depletion in the stratosphere. N_2O emissions may be reduced by primary emission reduction measures. Further references: *[219, 231, 232, 233, 234, 235, 236, 237, 238, 291].*

Sulphur oxides (SO_x)

Sulphur oxides (SO_x) are a result of complete oxidation of fuel sulphur. Mainly SO_2 (> 95%) is formed. However, some SO_3 (< 5%) may be formed at lower temperatures. The fuel sulphur will not be completely converted to SO_x; a significant fraction will remain in the ashes while a minor fraction is emitted as salt (K_2SO_4) or as H_2S at lower temperatures. Measurements at two district heating plants in Denmark [239] using straw as fuel showed that 57-65% of the sulphur was released into the flue gas, while the remainder was bound in the ashes. Houmøller and Evald [240] reported nine closed sulphur balances from several full-scale measurements in Denmark, four straw-fired units, three wood-chip-fired units and two pellet-fired units. They found similar results. SO_2 emissions may be reduced by primary measures such as lime or limestone injection or by secondary measures. Further references: *[231, 236, 241, 242, 243, 244, 246, 248].*

Hydrogen chloride (HCl)

Part of the chlorine content in the fuel will be released as HCl. The chlorine content of wood is very low. However, significant amounts of HCl may be formed from biomass fuels containing higher amounts of chlorine, such as miscanthus, grass and straw. The fuel chlorine will not be completely converted to HCl; the main fraction is retained in salts (KCl, NaCl) by reaction with K and Na, while traces are emitted as dioxins and organic chlorine components. HCl emissions may be reduced by washing of the fuel, which is utilised to some extent for straw due to its high chlorine content, and by secondary emission reduction measures. Further references: *[245, 246, 247, 248].*

Particles

Particle emissions originate from several sources. Among those are fly ash, which is a result of entrainment of ash particles in the flue gas, and salts (KCl, NaCl, K_2SO_4) which is a result of reactions between K or Na and Cl or S. The other types of particle emissions are mentioned in the next section on emissions from incomplete combustion. Secondary particle emission reduction measures are utilised to reduce the particle emission level in large-scale biomass combustion applications. By optimal design of combustion chambers, fly ash particles entrained in the flue gas may to some degree be prevented from leaving the combustion chamber, instead falling down to the bottom of the combustion chamber to be removed as bottom ash.

Heavy metals

All virgin biomass fuels contain heavy metals to some degree (most important: Cu, Pb, Cd, Hg). These will remain in the ash or evaporate, and also attach to the surface of particles emitted to the atmosphere or be contained inside fly-ash particles. Contaminated biomass fuels, such as impregnated or painted wood may contain significantly higher levels of heavy metals. One example is the presence of Cr and As in CCA impregnated wood. Heavy-metal emissions can be reduced by secondary emission reduction measures.

8.2.1.2 Emissions from incomplete combustion

Emissions caused by incomplete combustion are mainly a result of either:

- inadequate mixing of combustion air and fuel in the combustion chamber, which produces local fuel-rich combustion zones;
- an overall lack of available oxygen;
- too low combustion temperatures;
- too short residence times;
- too low radical concentrations, in special cases, for example in the final stage of the combustion process (the char combustion phase) in a batch combustion process.

These variables are all linked together through the reaction rate expressions for the elementary combustion reactions. However, in cases in which sufficient oxygen is available, temperature is the most important variable due to its exponential influence on the reaction rates. An optimisation of these variables will, in general, contribute to reduced levels of all emissions from incomplete combustion.
The following components are emitted to the atmosphere as a result of incomplete combustion in biomass combustion applications:

Carbon monoxide (CO)

Conversion of fuel carbon to CO_2 takes places through several elementary steps, and through several different reaction paths. CO is the most important final intermediate. It is oxidised to CO_2 if oxygen is available. The rate at which CO is oxidised to CO_2 depends primarily on temperature. CO can be regarded as a good indicator of the combustion quality. Large-scale biomass combustion applications usually have better opportunities for optimisation of the combustion process than small-scale biomass combustion applications. Hence, CO emission levels are usually lower for large-scale biomass combustion applications. Figure 8.3 shows the CO emission level as a function of excess air ratio for various biomass combustion applications, while Figure 8.4 shows the CO emission level as a function of combustion temperature. For a given system, there exists an optimum excess air ratio: higher excess air ratios will result in a decreased combustion temperature while lower excess air ratios will result in inadequate mixing conditions. In addition, sufficient residence time is important to achieve low CO emission levels, mainly because CO is generally a later intermediate than hydrocarbons.

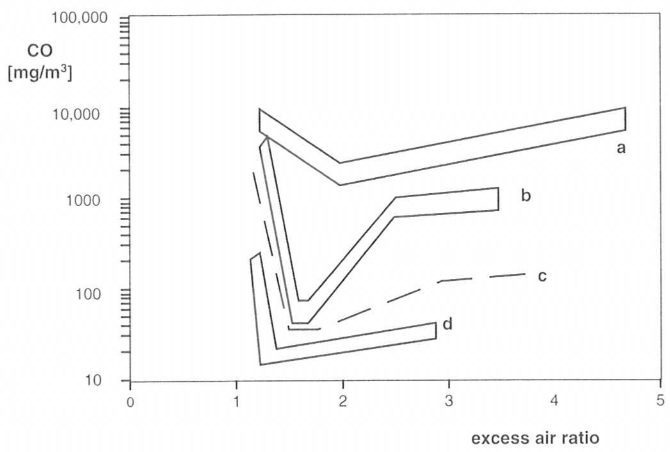

Figure 8.3: *CO emissions in mg/Nm^3 as a function of excess air ratio λ for:*
a) a simple, manually charged wood boiler;
b) a downdraught wood log boiler;
c) an automatic furnace with combustion technology as of 1990;
d) an automatic furnace with enhanced combustion technology as of 1995. Automatic furnaces with appropriate combustion process control can be operated under optimum conditions [230].

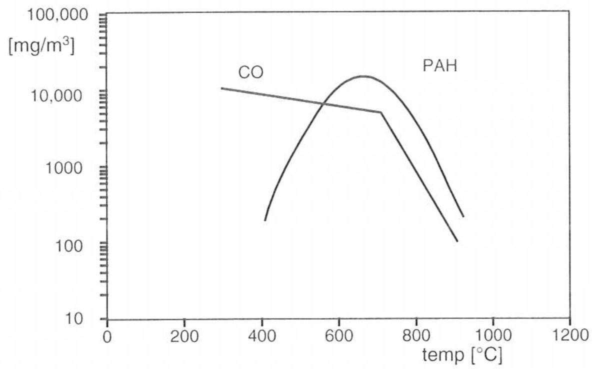

Figure 8.4: *CO emissions in mg/Nm^3 as a function of combustion temperature, together with a qualitative comparison with the influence of combustion temperature on PAH (Polycyclic Aromatic Hydrocarbons) emissions [249].*

Methane (CH_4)

CH_4 is usually mentioned separately from the other hydrocarbons since it is a direct green-house gas. In biomass combustion applications it is an important intermediate in the conversion of fuel carbon to CO_2 and fuel hydrogen to H_2O. As for CO, emissions of CH_4 are a result of too low combustion temperatures, too short residence times, or lack of available oxygen. Hydrocarbons are, in general, earlier intermediates than CO, which means they have lower emission levels.

Non-Methane Volatile Organic Components (NMVOC)
This group includes all hydrocarbons except CH_4, PAH (Polycyclic Aromatic Hydrocarbons) and other heavy hydrocarbons which condense and form particle emissions. They are all intermediates in the conversion of fuel carbon to CO_2 and fuel hydrogen to H_2O. As for CO, emissions of NMVOC are a result of too low combustion temperatures, too short residence times, or lack of available oxygen.

Polycyclic Aromatic Hydrocarbons (PAHs)
PAHs are usually mentioned separately from other hydrocarbons due to their carcinogenic effects. They are all intermediates in the conversion of fuel carbon to CO_2 and fuel hydrogen to H_2O. As for CO, emissions of PAH are a result of too low combustion temperatures, too short residence times or lack of available oxygen. A qualitative comparison of the combustion temperature influence on the PAH and CO emission level was shown in Figure 8.4. Further references: *[250, 251, 252, 253, 254, 258, 260, 263].*

Particles
Particle emissions from incomplete combustion can be found as soot, char, or condensed heavy hydrocarbons (tar). Soot consists mainly of carbon, and is a result of a local lack of available oxygen in the flame zone and/or local flame extinction. Char particles may be entrained in the flue gas due to their very low specific density, especially at high flue gas flow rates. Condensed heavy hydrocarbons are an important, and in some cases the main, contributor to the total particle emission level in small-scale biomass combustion applications such as wood-stoves and fireplaces. As for CO, emissions of particles may be a result of too low combustion temperatures, too short residence times, or lack of available oxygen. However, due to the diversity of particle emission components, reducing particle emission levels by primary measures is not as straightforward as it is for CO, except for particles consisting of condensed heavy hydrocarbons. Secondary particle emission reduction measures are therefore utilised to further reduce the particle emission level in large-scale biomass combustion applications. By optimal design of combustion chambers, particles entrained in the flue gas may to some degree be prevented from leaving the combustion chamber, instead falling down to the bottom of the combustion chamber to be removed with the bottom ash.

Polychlorinated dioxins and furans (PCDD/PCDF = PCDD/F)
Polychlorinated dioxins and furans are a group of highly toxic components. They are found to be a consequence of the de novo synthesis in the temperature window between 180°C and 500°C [230]. Carbon, chlorine, catalysts (Cu), and oxygen are necessary for the formation of PCDD/F. PCDD/F can be formed in very small amounts from all biomass fuels containing chlorine. The emissions of PCDD/F are highly dependent on the conditions under which combustion and flue gas cooling takes place; therefore, wide variations are found in practice. Although herbaceous biomass fuels have high chlorine contents, their PCDD/F emissions are usually very low. This may be explained by their high alkali content, which leads to the formation of salts (KCl, NaCl) and thus to a lower level of gaseous chlorine for the de novo synthesis. Because of the many factors influencing PCDD/F formation, wide variations may appear even within the same biomass combustion installation. In general, the PCDD/F emission level from biomass combustion applications using virgin wood as fuel is well below the health risk limit. PCDD/F emissions can be reduced by primary and secondary emission reduction measures. Further references: *[247, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266].*

Ammonia (NH_3)
Small amounts of NH_3 may be emitted as a result of incomplete conversion of NH_3, formed from pyrolysis/gasification, to oxidised nitrogen-containing components. This occurs in special cases in which the combustion temperature is very low. Additionally, secondary NO_x reduction measures utilising NH_3 injection may contribute to the NH_3 emission level due to NH_3 slippage. NH_3 emissions can be reduced by general primary emission reduction measures for emissions from incomplete combustion, and by optimising the NH_3 injection process.

(Ground level) Ozone (O_3)
O_3 is a secondary combustion product formed from photochemical atmospheric reactions including CO, CH_4, NMVOC, and NO_x. It is a direct greenhouse gas and also influences the local and regional environment. As such, it is a highly unwanted by-product of biomass combustion applications. O_3 emissions can be reduced indirectly by reducing emissions from incomplete combustion, and by primary and secondary NO_x emission reduction measures.

Table 8.2 shows the pollutants from biomass combustion and their impacts on climate, environment, and health.

Table 8.2: *Pollutants from biomass combustion and their impacts on climate, environment and health*

Component	Biomass sources	Climate, environmental and health impacts
Carbon dioxide CO_2	Major combustion product from all biomass fuels.	**Climate:** Direct greenhouse gas. However, CO_2 emissions from biomass combustion are regarded as being CO_2-neutral with respect to the greenhouse gas effect* since biomass is a renewable fuel.
Carbon monoxide CO	Incomplete combustion of all biomass fuels.	**Climate:** Indirect greenhouse gas through O_3 formation. **Health:** Reduced oxygen uptake especially influences people with asthma, and embryos. Suffocation in extreme cases.
Methane CH_4	Incomplete combustion of all biomass fuels.	**Climate:** Direct greenhouse gas. Indirect greenhouse gas through O_3 formation.

Component	Biomass sources	Climate, environmental and health impacts
Non Methane Volatile Organic Components NMVOC	Incomplete combustion of all biomass fuels.	**Climate:** Indirect greenhouse gas through O_3 formation. **Health:** Negative effect on the human respiratory system.
Polycyclic Aromatic Hydrocarbons PAH	Incomplete combustion of all biomass fuels.	**Environment:** Smog formation. **Health:** Carcinogenic effects.
Particles	Soot, char and condensed heavy hydrocarbons (tar) from incomplete combustion of all biomass fuels. Fly ash and salts.	**Climate and environment:** Reversed greenhouse effect through aerosol formation. Indirect effects of heavy-metal concentrations in deposited particles. **Health:** Negative effect on the human respiratory system. Carcinogenic effects.
Nitric oxides NO_x (NO, NO_2)	Minor combustion product from all biomass fuels containing nitrogen. Additional NO_x may be formed from nitrogen in the air under certain conditions.	**Climate and environment:** Indirect greenhouse gas through O_3 formation. Reversed greenhouse gas effect through aerosol formation. Acid precipitation. Vegetation damage. Smog formation. Corrosion and material damage. **Health:** Negative effect on the human respiratory system. NO_2 is toxic.
Nitrous oxide N_2O	Minor combustion product from all biomass fuels containing nitrogen.	**Climate:** Direct greenhouse gas. **Health:** Indirect effect through O_3 depletion in the stratosphere**.
Ammonia NH_3	Small amounts may be emitted as a result of incomplete conversion of NH_3, formed from pyrolysis / gasification, to oxidised nitrogen-containing components. Secondary NO_x reduction measures by NH_3 injection (SNCR, SCR).	**Environment:** Acid precipitation. Vegetation damage. Corrosion and material damage. **Health:** Negative effect on the human respiratory system.
Sulphur oxides SO_x (SO_2, SO_3)	Minor combustion product from all biomass fuels containing sulphur.	**Climate and environment:** Reversed greenhouse gas effect through aerosol formation. Acid precipitation***. Vegetation damage. Smog formation. Corrosion and material damage. **Health:** Negative effect on the human respiratory system, asthmatic effect.
Heavy metals	All biomass fuels contain heavy metals to some degree, which will remain in the ash or evaporate.	**Health:** Accumulate in the food chain. Some are toxic and some have carcinogenic effects.
(Ground level) Ozone O_3	Secondary combustion product formed from atmospheric reactions including CO, CH_4, NMVOC, and NO_x.	**Climate and environment:** Direct greenhouse gas. Vegetation damage. Smog formation. Material damage. **Health:** Indirect effect through O_3 depletion in the stratosphere**. Negative effect on the human respiratory system, asthmatic effect.
Hydrogen chloride HCl	Minor combustion product from all biomass fuels containing chlorine.	**Environment:** Acid precipitation. Vegetation damage. Corrosion and material damage. **Health:** Negative effect on the human respiratory system. Toxic.
Dioxins and Furans PCDD/PCDF	Small amounts may be emitted as a result of reactions including carbon, chlorine, and oxygen in the presence of catalysts (Cu).	**Health:** Highly toxic. Liver damage. Central nervous system damage. Reduced immunity defence. Accumulate in the food chain.

* **The greenhouse gas effect:** The natural greenhouse gas effect keeps Earth's mean temperature at about 15°C. Without the greenhouse gas effect, Earth's mean temperature would be -18°C. Anthropogenic sources of greenhouse gases are generally believed to contribute to an increasing greenhouse gas effect, causing Earth's mean temperature to slowly increase. From 1750 to 1994, the concentration of the three most important greenhouse gases - CO_2, CH_4, and N_2O - increased by 30, 145 and 15%, respectively (contributing to an increasing greenhouse gas effect). However, particles, SO_2 and NO_x contribute, to some degree, to a reversed greenhouse gas effect caused by aerosol formation.

** **Depletion of the ozone layer:** The atmospheric ozone layer is found in the stratosphere, 10-40 km above ground level. Ozone absorbs UV radiation from the sun and prevents damaging radiation from reaching Earth's surface. Ozone in the stratosphere may be reduced by reactions with NO, where NO may be formed from N_2O in a first reaction step. Ground level ozone, however, is a pollutant and a greenhouse gas.

*** **Acid precipitation:** Emissions of NO_x, SO_x and HCl result in acid precipitation through the formation of acids.

8.2.2 Emission data

Emissions from biomass combustion can in general be divided into emissions that are mainly influenced by combustion technology and process conditions, and emissions that are mainly influenced by fuel properties.

The amount of pollutants emitted to the atmosphere from various types of biomass combustion applications is highly dependent on the combustion technology implemented, the fuel properties, the combustion process conditions, and the primary and secondary emission reduction measures that have been implemented. When available, such data generally refer to a single fuel-technology combination. In order to obtain an objective view of emission levels from various biomass combustion applications, it is necessary to collect emission data from a wide range of fuel-technology combinations. However, they will only give an indication of typical emission levels, or ranges of emission levels, from given types of biomass combustion fuel-technology combinations.

A problem in trying to compare emission levels from different biomass combustion applications is that many different denominators are used. Usually the basic data needed to recalculate the emission level into other denominators are not given, and assumptions must be made. Procedures and formulae for converting emission levels between different denominators are given in Chapter 2. Below, selected emission data are presented.

8.2.2.1 Domestic applications

Domestic applications include wood-stoves, fireplaces, fireplace inserts, wood log boilers, heat storing stoves, and pellet stoves. Any of these may in principle be equipped with a catalytic converter. Skreiberg [267] investigated and compared the emission levels from an advanced downdraught staged-air wood-stove, a traditional wood-stove, and a wood-stove equipped with a catalytic converter. The results showed that the traditional stove had significantly higher levels of emissions from incomplete combustion than the staged-air wood-stove and the catalytic stove. The catalytic stove emitted significantly less CO than the staged-air wood-stove, but the difference for C_xH_y and particles was less significant. However, wide variations in the emission levels from the same stove were reported, depending on operating conditions. In many cases, the levels of emissions from incomplete combustion may be many times higher than reported at nominal load, usually increasing exponentially with decreasing load relative to nominal load [268].

In 1994 the Technical University of Munich performed an extensive measuring programme on emission levels from domestic wood applications [269]: wood-stoves, fireplace inserts, heat storing stoves, pellet stoves, and catalytic wood-stoves. The applied test method was DIN 18891/18895. Calculated arithmetic average values of the reported values are shown in Table 8.3.

Table 8.3: *Arithmetic average emission levels in* mg/m^3_0 *at 13%* O_2 *from small-scale biomass combustion applications. The term* m^3_0 *designates volume at standard reference condition; pressure 101,3 kPa and temperature 273 K..*

	Load [kW]	Excess air ratio	CO [mg/m³]	C_xH_y [mg/m³]	Particles [mg/m³]	NO_x [mg/m³]	Temp [°C]	Efficiency [%]
Wood-stoves	9.33	2.43	4,986	581	130	118	307	70
Fire place inserts	14.07	2.87	3,326	373	50	118	283	74
Heat storing stoves	13.31	2.53	2,756	264	54	147	224	78
Pellet stoves	8.97	3.00	313	8	32	104	132	83
Catalytic wood-stoves	6.00		938					

The emission levels of pellet stoves are very low and can be compared to those of oil burners. This is to be expected since pellet stoves are operated as a continuous combustion process, with combustion process control possibilities. The CO emission level for the catalytic wood-stoves is lower than for the other units, except for the pellet stove, which also is to be expected (see Section 8.2.3.9). The heat storing stoves have lower emission levels than the wood-stoves and fireplace inserts. Heat storing stoves usually operate at a high load, which increases the possibilities for reduced emission levels. The fireplace inserts have lower emission levels than the wood-stoves, which is somewhat surprising. However, they operate at significantly higher loads than the wood-stoves. The NO_x emission levels are highly influenced by the fuel nitrogen content, and no specific conclusions can be drawn from this table. Table 8.3 illustrates the main trends that can be expected. However, one must be careful interpreting these results and emission values from domestic biomass combustion applications in general. Also, measured emission levels are highly influenced by the test method (forced or natural draught). The influence of standards, test procedures, and calculation procedures on the emission level of a catalytic wood-stove tested in nine IEA countries, according to their national standards and test procedures, was investigated as a part of the IEA Bioenergy, Task X – Conversion, Combustion activity. The results were published in Biomass and Bioenergy [270].

Skreiberg [271] inventoried emission levels of various biomass combustion applications, both domestic and industrial, and the results are summarised in Table 8.4.

Table 8.4: *Arithmetic average emission values from wood combustion applications. The data were collected from investigations in various IEA countries (Norway, Switzerland, Finland, UK, and Denmark). nm = not measured*

	NO_x as NO_2 [mg/MJ]	Particles [mg/MJ]	Tar [mg/MJ]	CO [mg/MJ]	UHC as CH_4 [mg/MJ]	VOC [mg/MJ]	PAH [µg/MJ]
Cyclone furnaces	333	59	n.m.	38	n.m.	2.1	n.m.
Fluidised bed boilers	170	2	n.m.	0	1	n.m.	4
Pulverised fuel burners	69	86	n.m.	164	8	n.m.	22
Grate plants	111	122	n.m.	1846	67	n.m.	4040
Stoker burners	98	59	n.m.	457	4	n.m.	9
Wood boilers	101	n.m.	499	4975	1330	n.m.	30
Modern wood-stoves	58	98	66	1730	200	n.m.	26
Traditional wood-stoves	29	1921	1842	6956	1750	671	3445
Fireplaces	n.m.	6053	4211	6716	n.m.	520	105

8.2.2.2 Industrial applications

Nussbaumer and Hustad [272] presented typical ranges of emission levels from various automatic wood furnaces (understoker furnaces, grate firings, and dust firings), as can be seen in Table 8.5 and Table 8.6.

Table 8.5: *Emissions that are mainly influenced by combustion technology and process conditions. Comparison between poor and high standard furnace design.*

Emissions at 11% O_2	Poor standard	High standard
Excess air ratio, λ	2 – 4	1.5 – 2
CO (mg/m^3_0)	1000 – 5000	20 – 250
C_xH_y (mg/m^3_0)	100 – 500	< 10
PAH (mg/m^3_0)	0.1 – 10	< 0.01
Particles, after cyclone (mg/m^3_0)	150 – 500	50 - 150 *

* except for dust firings, usually > 150.

Table 8.6: *Emissions that are mainly influenced by fuel properties. Comparison between various fuel types (typical values). Altholz = urban waste wood and demolition wood.*

Emissions at 11% O_2	Fuel type	Typical data
NO_x (mg/m^3_0)	Native wood (soft wood)	100 – 200
	Native wood (hard wood)	150 – 250
	Straw, grass, miscanthus, chip boards	300 – 800
	Altholz	400 – 600
HCl (mg/m^3_0)	Native wood	< 5
	Altholz, straw, grass, miscanthus, chip boards (NH_4Cl)	raw gas: 100 - 1000 with HCl absorption: < 20
Particles (mg/m^3_0)	Native wood	after cyclone: 50 - 150
	Straw, grass, miscanthus, chip boards	after cyclone: 150 - 1000
	Altholz	after bag- or electrostatic filter: < 10
Σ Pb, Zn, Cd, Cu (mg/m^3_0)	Native wood	< 1
	Altholtz	raw gas: 20 - 100 after bag- or electrostatic filter: < 5
PCDD/F (ng TE/m^3_0)	Native wood	typical: < 0.1 range: 0.01-0.5
	Altholtz	typical: 2 range: 0.1 - 20

Table 8.7 presents the emissions of wood-burning installations used in the Netherlands with a capacity between 30 to 320 kW_{th} [269, 273, 274]. As these installations use the same fuel (wood chips), the technologies can be compared. It can be noted that these installations are relatively efficient and have low particle emissions. In all cases, particle emissions are well below the Dutch emission guidelines. The table further indicates that automatic operation and combustion process control drastically reduce the emission of CO and C_xH_y.

Table 8.7: *Emissions from small industrial wood chips combustion applications in the Netherlands [275]. All emission values at 11% O_2..*

Manual/ automatic operation	Combustion principle	Draught control	Capacity [kW]	CO [mg/m^3_o]	C_xH_y [mg/m^3_o]	NO_x [mg/m^3_o]	Particles [mg/m^3_o]	Efficiency [%]
Manually operated	Horizontal grate	Natural, uncontrolled	36	2390	124	156	21	85
		Forced, uncontrolled	34.6	3450	130	172	28.7	83.5
			30	656	21	182	33.7	90
Automatically operated	Understoker	Forced, controlled	~40	66	2.5	118.7	80	85.4
			320	31	3.7	186	51	89.1

Obernberger inventoried emission data from various publications [276], representing capacities ranging from 0.5 to 10 MW_{th}. The fuels used were particle board, wood chips, MDF, and bark. Table 8.8 shows the results.

Table 8.8: *Emissions from industrial wood-fired installations, using particle board, wood chips, MDF, and bark (mg/m^3 at 11% O_2 dry).*

Component	Emission	Number of observations
CO	125 - 2000	25
C_xH_y	5.0 - 12.5	25
PAH	0.0006 - 0.06	unknown
Benzo[a]pyrene	$5{\cdot}10^{-6}$ - $1.0{\cdot}10^{-3}$	4
NO_x (as NO_2)	162 - 337	22
Particles	37 - 312	29
SO_2	19 - 75	17
Cl	1 - 10	12
F	0.25	unknown

It can be seen from the above table that the emissions of SO_2, Cl and F are relatively low. This is due to the low content of these elements in the fuel. The emissions of C_xH_y, PAH and Benzo[a]pyrene are also low. By further optimisation of the combustion process they can be further reduced. Emissions of CO were found to be relatively high, particularly for old combustion installations. CO emissions can be reduced by avoiding intermittent boiler operation through improved combustion process control (see Section 8.2.3.6). NO_x emissions can be further reduced by applying/optimising staged combustion, see Section 8.2.3.7. From a study of the individual measurements carried out in the same study, the following was concluded:

- The emissions usually decrease as the size of the combustion installation increases, due to improved process control possibilities and efficient flue gas cleaning facilities. Combustion installations exceeding 4 MW_{th} often have electrostatic filters or flue gas condensation units in addition to a cyclone, which is usually installed in smaller installations. For smaller combustion installations, such investments are usually not economically viable. However, in Scandinavian installations, economic flue gas condensation has been achieved with boiler installations below 1 MW_{th}.
- NO_x emissions are an exception. The fuel NO_x emissions increase with increasing nitrogen content in the fuel, excess air ratio, and combustion temperature, up to a point where all fuel nitrogen intermediates have been converted to either NO_x, N_2O, or N_2. At low combustion temperatures, the temperature influence is more important than the influence of excess air ratio, resulting in lower NO_x emissions for smaller combustion installations.

8.2.3 Primary emission reduction measures

Reduction of harmful emissions through flue gases and effluents can be obtained by either avoiding creation of such substances (primary measures) or removing the substances from the flue gas (secondary measures).

In this chapter, measures for reducing primarily emissions from incomplete combustion and NO_x are presented. However, SO_x can also be reduced by primary measures, such as lime or limestone injection. N_2O emissions may be reduced by primary measures, but this is not a straightforward process, and these measures will not be presented here due to the low emission levels of N_2O from biomass combustion applications. PCDD/F emissions are a result of incomplete combustion. However, emission reduction measures for PCDD/F deviate from measures related to other emissions from incomplete combustion. It should be mentioned that the main primary emission reduction measures to avoid PCDD/F are complete burnout of the fly ash and an operation of the combustion at low excess air ratio and under stable conditions.

Primary emission reduction measures aim at preventing or reducing formation of emissions and/or reduction of emissions within the combustion chamber. Several possible measures exist. The measures we will discuss here are:

- modification of the fuel composition,
- modification of the moisture content of the fuel,
- modification of the particle size of the fuel,
- selection of the type of combustion equipment,
- improved construction of the combustion application,
- combustion process control optimisation,
- staged-air combustion,
- staged fuel combustion and reburning,
- catalytic converters.

In practice, these measures often are interrelated.

8.2.3.1 *Modification of the fuel composition*

Decreasing the amount of those elements in the fuel that contribute to harmful emissions or operational problems can be carried out to some extent. Several methods have been developed for reducing the sulphur and nitrogen contents in natural gas and oil. Methods also exist for coal, but these are not cost-effective. Virgin biomass fuels are solid fuels, like coal, with limited possibilities of decreasing the amount of specific elements in the fuel. However, washing of straw has been shown to reduce the amount of chlorine and potassium significantly. Washing can either be performed by leaving the straw on the field for some time after the harvest, exposing it to rain, or by controlled washing. Leaching experiments with barley straw performed in Denmark [239] showed that after 150 mm of rain, the chloride content had dropped from 0.49% to below 0.05% and the potassium content had dropped from 1.18% to 0.22%.

Controlled washing of straw has also been carried out in Denmark, by boiling the straw at 160°C and by washing the straw at 50-60°C. The latter is considered the most economic option. So far, straw washing has only been tested at small plants. The energy losses caused by washing, drying, and leaching of organic matter amount to approximately 8% of the calorific value of the straw. This is offset, though, by the prolonged life of the boilers, because corrosion problems are avoided. Washing of straw is also expected to have advantages for the subsequent application of the fly ash, since straw ash that does not contain alkaline salts and other impurities may be used as a filler in building materials in Denmark. As chlorine is needed for formation of dioxins and furans, washing straw will also contribute to reduced dioxin and furan emission levels.

8.2.3.2 *Modification of the moisture content of the fuel*

The moisture content in biomass can vary widely. Wood for energy purposes for instance, may vary in moisture content from approximately 10-60% of water by weight. The first value represents wood residuals from wood industry where drying has been applied, while fresh wood from forest may contain up to 60% of water.

A high moisture content in the fuel makes it difficult to achieve a sufficiently high temperature in the combustion chamber. Often a temperature above approximately 850 °C is desired to ensure a sufficiently low level of CO. If high temperature is not reached, incomplete combustion occurs with high emissions as a result.

In general, unless waste heat from another process can be accessed at a very low cost, the cost of artificial drying is too high to make the drying process itself economically feasible. The design of the combustion chamber is of great importance when biomass with a high moisture content is used. Improvement of the combustion quality can be reached by use of a high amount of ceramic linings and insulation of the combustion chamber. This measure, together with a high pre-heating temperature of the combustion air, may make it possible to utilise fuel with a high moisture content in an environmentally acceptable manner.

Even in cases where improvement of the combustion process is achieved, a certain decrease in the boiler efficiency must be accepted. This is due to the fact that the amount of moisture in the fuel leads to a higher flow of flue gas, including water vapour, from the boiler. This represents an energy loss.

But combustion of wood with high moisture content can be advantageous if combined with a flue gas condensing system, and provided there is a sufficiently low heat sink. Condensation of the water vapour in the flue gas raises the overall efficiency to such an extent that improvement of the overall economy of plant operation may be achieved.

8.2.3.3 Modification of the particle size of the fuel

The fuel particle size is very relevant for the combustion technology selection process. The fuel size in biomass combustion applications may vary from whole wood logs to fine sawdust.

In small-scale biomass combustion applications, such as wood-stoves, fireplaces, and wood log boilers, the fuel generally consists of wood logs with bark, of varying size. Hence, the fuel size has little influence on the selection of combustion technology within this segment of the biomass combustion market. However, by various arrangements of the wood logs inside the combustion chamber, increasing or decreasing the overall active surface area, it is possible to influence the combustion process to some degree. Also by combining large and small wood logs and pieces of bark the combustion process can be influenced.

In large-scale biomass combustion applications with automatic fuel feeding, the fuel size is more decisive. If the fuel consists of both very small and very large pieces, a shredder or chipper can be used to reduce the particle size of the largest particles. In this way, a more homogeneous particle size is obtained. Hence, a wider range of technology options can be used. However, particle size reduction is only attractive if the benefits outweigh the additional investment and energy costs.

8.2.3.4 Selection of the type of combustion equipment

When selecting the combustion technology for a biomass combustion application there are several aspects to be considered, both with respect to the combustion process and to primary and possibly secondary emission reduction measures. Also, the heat/power capacity of the application usually limits the choice of combustion technology, either due to technological or economic considerations.

First of all, fuel characteristics such as fuel composition, moisture content, and particle size are important. For wood fuels only the nitrogen content may limit the choice of combustion technology, if there are NO_x emission limits to be met. The moisture content, however, will be very decisive for wood fuels such as wood chips and bark if drying of the fuel prior to combustion is not an option.

For other types of biomass fuels, additional fuel constituents, such as ash, chlorine, potassium and sulphur may influence the combustion process in such a way that certain preferences should be made when selecting the combustion technology, e.g. for straw combustion.

Secondary emission reduction measures can be bought and fitted to most biomass combustion applications, depending on the emission limits to be met. However, substantial emission reduction can be achieved for emissions from incomplete combustion and NO_x emissions by selection of the best possible combustion technology for a given fuel and by optimising the combustion process, including primary NO_x reduction measures. This may remove the need for secondary emission reduction measures other than for particle removal.

8.2.3.5 Improved construction of the combustion application

In order to obtain optimal combustion, with minimal emissions from incomplete combustion, one has to achieve:

- sufficiently high combustion temperatures,
- sufficiently long residence times,
- optimal mixing of fuel gases and air, also with changing heat and/or power output.

These factors are partly determined by the combustion technology and design of the furnace, and partly by the combustion process operation. Recently, a number of combustion process control systems have been developed for optimisation of combustion processes. These will be mentioned in the next section.

8.2.3.6 Combustion process control optimisation

A process controller aims to govern selected process parameters according to a predefined scheme. The primary aim of a process control device in a biomass combustion application is to adjust the heat production according to the heat demand. In addition to this, the process control device can be programmed for simultaneous optimisation of the combustion process with respect to minimising emissions and maximising thermal efficiency. For biomass combustion, typical process parameters that can be used as process control parameters are the CO, C_xH_y and O_2 concentrations in the flue gas, as well as combustion chamber temperatures and boiler temperature. Process variables that can directly be adjusted to achieve the targets for the mentioned process parameters are typically the amount of fuel fed into the furnace, and the amount of primary and secondary combustion air supplied.

Minimising emissions

The combustion quality can be modified by adjusting the amounts of fuel and primary and secondary air, based on measured concentrations of CO, C_xH_y, O_2 and the combustion chamber temperature.

In the case of direct process control, CO and C_xH_y are measured continuously and the governing variables are adjusted to obtain minimum emissions. Because of process fluctuations, the concentrations of CO and C_xH_y often remain high.

In the case of indirect process control, the ideal excess air ratio (λ) is first established for all expected process conditions (boiler load, fuel moisture content, etc.) to obtain minimum emissions. Then the measured value for O_2 is used as a process control parameter. Control of λ ensures a stable combustion process, but as the actual process parameters often deviate from expected values, emissions are not always minimised in practice.

Direct and indirect process control can also be combined to obtain a stable combustion process with minimised emissions.

Controlling heat output

In addition to minimising emissions, there is a need to control the heat output from the furnace or boiler. This control can be based on using measured temperature difference and mass flow of boiler water. However, the control of the boiler water temperature is more commonly used. The relation between fuel input and the input of primary and