EUROPEAN WOOD-HEATING TECHNOLOGY SURVEY:

AN OVERVIEW OF COMBUSTION PRINCIPLES AND THE ENERGY AND EMISSIONS PERFORMANCE CHARACTERISTICS OF COMMERCIALLY AVAILABLE SYSTEMS IN AUSTRIA, GERMANY, DENMARK, NORWAY, AND SWEDEN

FINAL REPORT 10-01
APRIL 2010

NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY

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Final Report

Prepared for the

**NEW YORK STATE
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Preface

The New York State Energy Research and Development Authority (NYSERDA) is pleased to publish, "European Wood-Heating Technology Survey: An Overview of Combustion Principles, Performance Characteristics of Commercially Available Systems." The report was prepared by BIOENERGY 2020+ GmbH. The principle investigator was DI Dr. Birgit Musil-Schläffer, with collaboration from Aislinn McCarry, BSc, DI Dr. Christoph Schmidl, and DI Dr. Walter Haslinger.

BIOENERGY2020+ GmbH (www.bioenergy2020.eu), formerly the Austrian Bioenergy Centre, is a Competence Center for Excellent Technologies with locations in Graz, Güssing and Wieselburg, Austria. The purpose of the Competence Center is to research, develop, and demonstrate the "Energetic use of Biomass" by partnering with universities, technical and research institutes, government agencies and companies. BIOENERGY 2020+ comprise a staff of 80 researchers with expertise that covers all research and development topics in the field of biomass energy,including small-, medium-, and large-scale biomass combustion and biomass based combined heat and power production (CHP) systems. The overall objective of the work performed is to substantially contribute to the improvement of existing technologies and the development of new technologies, as well as the research and development of the utilization of new biomass fuels.

This report provides a summary of the combustion principles, thermal efficiency and emissions performance of biomass heating technologies of Austria, Germany, Denmark, Norway and Sweden. A key aspect is that the report has presented these performance characteristics in terms of American methodology and units. This information illustrates the technological advances that have been made through technology forcing policies, eco-labeling, and financial incentives. The report therefore provides critical information to assist NYSERDA develop a high-efficiency biomass heating market and assist the U.S. Environmental Protection Agency assess current best demonstrated technology on which to base revisions to the residential wood heater New Source Performance Standard.

NYSERDA's Biomass Heating Program is a joint effort of the Environmental R&D and Building R&D Programs to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance in New York State.

Acknowledgements

This research was supported by the New York State Energy Research and Development Authority. NYSERDA appreciates the guidance of the following: Mr. Gilbert Wood, U.S. Environmental Protection Agency; Ms. Lisa Rector, Northeast States for Coordinated Air Use Management; Dr. Thomas Butcher and Mr. Roger J. McDonald, Brookhaven National Laboratory; and Mr. Raymond J. Albrecht, P.E., Fulton Thermal Corporation.

Abstract

This report provides a summary of the combustion principles, thermal efficiency and emissions performance of biomass heating technologies in Austria, Germany, Denmark, Norway and Sweden. A key aspect is that the report has presented these performance characteristics in terms of American methodology and units. This information illustrates the technological advances that have been made over the last several decades. For example, over the past 30 years, the Austrian boiler technology increased from a thermal efficiency of 55% to more than 90% based on Net Calorific Value. A survey of the boilers in these countries shows those in the Top 25% of thermal efficiency and emissions performance greatly exceed not only the current European Standard (EN 303-5) performance requirements (classes 1, 2, and 3) but also the proposed requirements (classes 4 and 5). Technology forcing policies, regulations, and eco-labelling efforts clearly resulted in greatly improved technology now available in Europe which is expanding into the American wood heating market as well. The report therefore provides critical information to assist NYSERDA develop a high-efficiency biomass heating market and assist the U.S. Environmental Protection Agency assess current best demonstrated technology on which to base revisions to the residential wood heater New Source Performance Standard.

Keywords:

biomass heating, wood boiler, pellet boiler, room heater, masonry heater, thermal efficiency, lower heating value, higher heating value, net calorific value, gross calorific value, particulate matter, total suspended particulate, CO.

Table of Contents

List of Abbreviations

a	Ash in kg/kg
Btu	British Thermal Unit
CHP	Combined heat and power
CO	Carbon monoxide
d.b.	dry basis
FJ-BLT	Franciso Josephinum Wieselburg Biomass Logistics Technology
g	gram
GCV	gross calorific value (upper heating value)
h	hydrogen content of the fuel in kg/kg
HC	Hydrocarbons
J	Joule
lb	pound
m	meter
NCV	net calorific value (lower heating value)
Nm^3	m^3 at normal conditions (1 atm, 32 °F)
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
O_2	Oxygen
OGC	Organic Gaseous Substances
PM	Particulate Matter
P	nominal load in MBtu/h
TSP	Total Suspended Particulates
w	water content of the fuel related to the mass of wet biomass in kg/kg (w.b.)
W	Watt
w.b.	wet basis
η	Efficiency
η_{GCV}	Efficiency based on GCV
η_{NCV}	Efficiency based on NCV

Units and basic conversion factors

Prefixes according to DIN 1301

Abbreviation	*Name*	*Value*
M	*Mega*	10^6
k	*Kilo*	10^3
d	*Deci*	10^{-1}
c	*Centi*	10^{-2}
m	*Milli*	10^{-3}

Example: 1 MW (1 Megawatt) = 10^3 *kW (1,000 Kilowatt) =* 10^6 *W (1,000,000 Watt)*

Custom prefixes for North America (in correlation with Btu)

Abbreviation	*Value*
MBtu	$10^3 \cdot$Btu
MMBtu	$10^6 \cdot$Btu

Calorific value [CV]

[CV] = 1 J/g = 0.43 Btu/lb

Density [ρ]

[ρ] = 1 g/m³ = $6.23 \cdot 10^{-5}$ lb/ft^3

Energy [E]

[E] = 1 Btu = 1055 J

Length [l]

[l] = 1 m = 39.2701 in = 3.28084 ft

Mass [m]

[m] = 1 g = $2.2046 \cdot 10^{-3}$ lb

Power [P]

[P] = 1 W = 3.4121 Btu/h

Volume [V]

[V] = 1 m³ = $1 \cdot 10^3$ l, 1 m^3 = 35.3147 ft^3

Exchange rate Euro – Dollar

1 € = 1.478 US$

Executive Summary

The New York State Energy Research and Development Authority (NYSERDA) is supporting R&D efforts to promote the development of a high-efficiency biomass heating market in New York State. High-efficiency biomass equipment has significantly lower emissions than their low-efficiency counterparts. This is particularly important, considering the United States Environmental Protection Agency (EPA) is currently updating the emissions performance requirments of all residential wood heating technologies. These New Source Performance Standards (NSPS) revisions will require that all newly manufactured heating systems meet emission levels representative of the current best demonstrated technology based on a world-wide survey.

The Europeans, more specifically Austria, Germany, and Scandinavian countries Denmark, Norway, and Sweden, are considered leaders in the development of this technology. BIOENERGY 2020+ prepared this report for NYSERDA to provide a comprehensive overview of biomass technologies in these countries. The report provides critical information to assist NYSERDA with the development of a high-efficiency biomass heating market and to help EPA assess the current best demonstrated technology on which to base revisions to the residential wood heater NSPS.

A key aspect of this study is the description of the European methodology for determining thermal efficiency using the net calorific value (lower heating value) of the wood fuel and the conversion of this value to the gross calorific value (upper heating value) used to determine thermal efficiencies by the U.S. heating industry. Throughout this report thermal efficiency values are converted to the American convention using gross calorific value. The emissions for “dust” or Total Suspended Particulates are converted to pounds per million British thermal unit (lb/MMBtu), the common unit used in the United States. Other emissions are normalized to values at standard conditions at 12% O_2 levels in the flue gas.

Legislative regulations and incentives on national and European levels are used in the European Union to continuously improve the performance of biomass appliances. In the European Standard EN 303-5, which regulates performance requirements for solid fuel boilers, three classes (class 1 to 3) for efficiency requirements and emission limits are defined in order to embrace the diverse technology stages of the EU member states. In the revision of EN 303-5, which is currently under discussion, more stringent classes (class 3 to 5) will be introduced, thereby resulting in the steady increase of the performance of installed biomass appliances. In addition to the EN 303-5, national regulations and eco-labels may request even higher efficiencies and lower emissions. Regional and national financial incentives for the installation of biomass appliances are often linked to eco-label requirements.

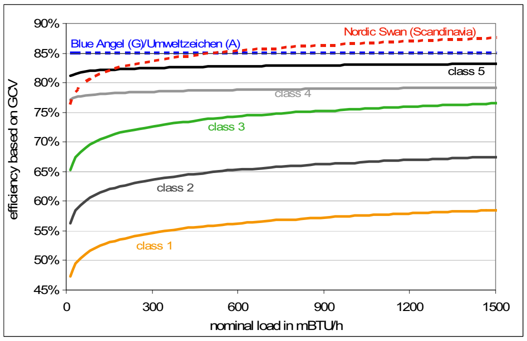

Figure ES-1 efficiency requirements for boilers from EN 303-5 (class 1 to class 5) and efficiency requirements from Austrian, German and Scandinavian eco-labels; efficiencies based on GCV were converted for pellets fuel

Austrian biomass boiler technology is a perfect example of how the improvements in combustion technology can be driven by legislative requirements and incentives. Figure ES-2 shows the technological improvement of boilers for solid wood, wood chips and pellets (starting in 1998) through test data from FJ-BLT. Over the last 30 years average efficiencies of biomass boilers have increased from approximately 55% to more than 90% based on the NCV(net calorific value) and the average CO-emissions have decreased from 15,000 to less than 50 mg/m³ at 13% O_2 in Austria.

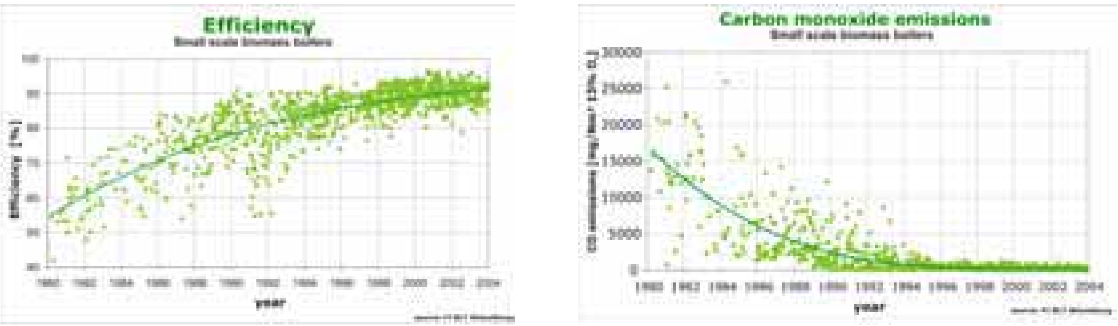

Figure ES-2 Small scale wood combustion systems: Efficiencies and CO emissions measured at the test bench through certification tests since 1980 - data according (FJ-BLT 2005), compilation in (Voglauer 2005)

Modern combustion technology for biomass is based on staged combustion in order to enable maximum burnout rates. In the primary zone located on the grate, drying, devolatilization and solid combustion take place. In the secondary combustion zone, which is situated in the combustion chamber, the volatile gases are burnt with secondary air. In order to minimize emissions, combustion must be as complete as possible in the secondary zone. In Figure ES-3, Figure ES-4 Figure ES-5 and Figure ES-5, the function principles of a solid wood boiler, an underfeed pellet boiler with condensing technology, a pellet boiler with top feed technology, and a pellet boiler with an underfeed burner are illustrated.

Figure ES-3 Under-burning solid wood boiler (Froeling 2005)

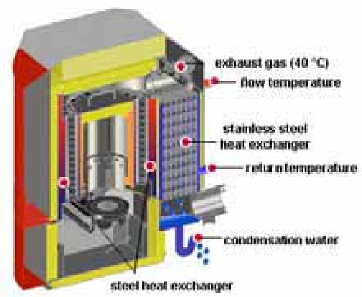

Figure ES-4 Condensing boiler for wood pellets with underfeed burner (Oekofen 2007)

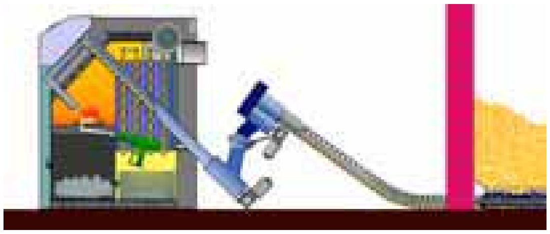

Figure ES-5 Top feed pellets boiler (Evotherm 2010)

Figure ES-6 Underfeed burner or wood chips and pellets (KWB 2007)

The complete combustion of fuel in an optimized 2-stage combustion design results in very low dust (TSP) emissions because it prevents particle formation from unburned hydrocarbons that are absent in the exhaust gas. Figure ES-7 contrasts the chemical composition in an optimized heating appliance and a poorly operated woodstove. The dust from the optimized system is primarily inorganic, while the poorly operated stove emissions are mostly unburned organics and will be a multiple higher in mass than the emissions from the optimized appliance.

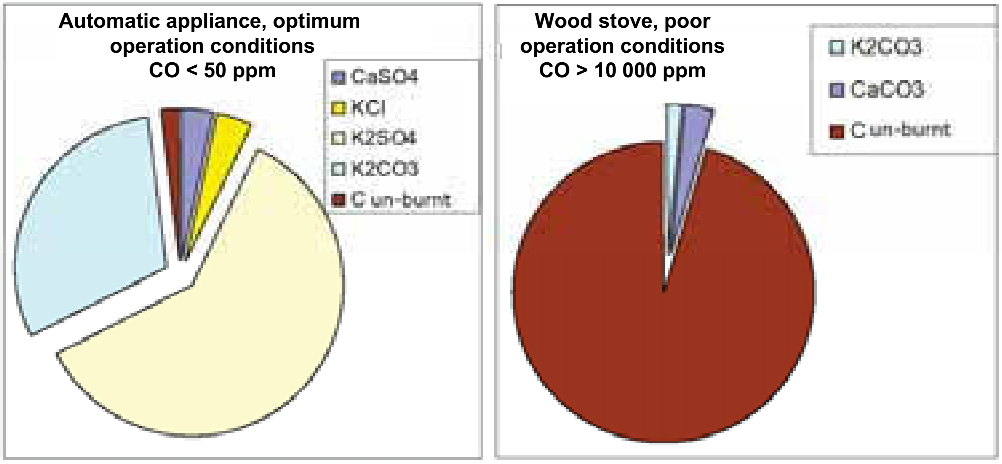

Figure ES-7 chemical composition of dust samples from different biomass appliances and operation conditions (Klippel 2007)

The development of solid bio-fuel standards in Europe is linked to the beginning of wood pellet production. In order to gain a common understanding between the manufacturers and the users, codes of good practice, quality guidelines and later national standards have been developed. For the development of high performing combustion appliances, harmonized fuel properties are advantageous because the optimization of operating conditions is only possible if the fuel properties are known.

The TOP 25% performing biomass appliances that were identified within this study reach high efficiencies and low emissions.

Table ES-1 summary of average efficiency and emission data for TOP 25% performing biomass technologies

technology	fuel	load range (MBtu/h)	data at nominal load			
			ηGCV1) (%)	CO (mg/m^3 12 %O2)	TSP1) (lb/MMBtu)	NOx (mg/m^3 12 %O2)
boiler	pellets	< 55	87	43	0.022	140
		55 - 100	86	39	0.024	136
		100 - 170	87	38	0.023	132
		170 - 340	86	24	0.036	154
		> 340	86	17	0.031	133
	solid wood	< 85	83	174	0.039	139
		85 - 120	83	220	0.044	126
		120 - 170	83	152	0.066	115
		> 170	82	97	0.033	119
	wood chips	< 100	76	60	0.046	157
		100 - 200	79	39	0.027	134
		200 - 340	78	30	0.038	138
		340 - 680	80	22	0.042	125
		> 680	78	34	0.092	131
combined boiler	pellets	50 - 150	82	34	0.027	145
	solid wood		79	252	0.027	120
stove with hot water	pellets	25 - 50	85	117	0.019	143
stove	pellets	< 30	88	164	0.045	88
		> 30	87	180	0.043	110
	solid wood	20 - 130	73	1069	0.050	126

Figure ES-8 clearly exhibits that efficiencies of the TOP 25% performing pellet boilers far exceed the future requirements of EN 303-5, class 5. The same is true for wood chip and solid wood boilers.

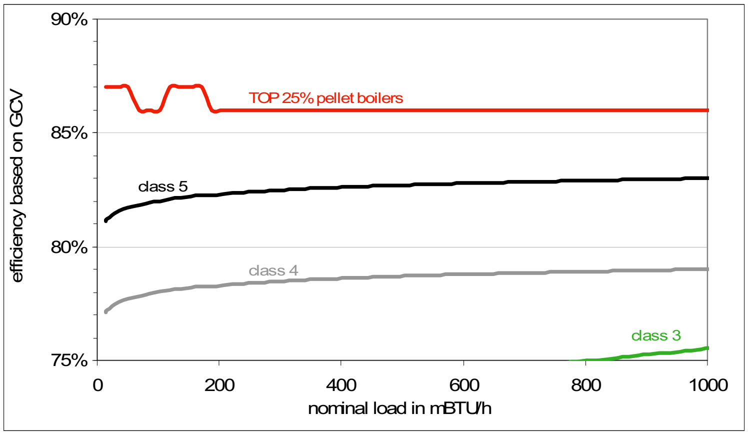

Figure ES-8 average efficiency performance of TOP 25% pellet boilers in comparison to efficiency requirements of EN 303-5, class 3 and future efficiency requirements of EN303-5, class 4 and 5

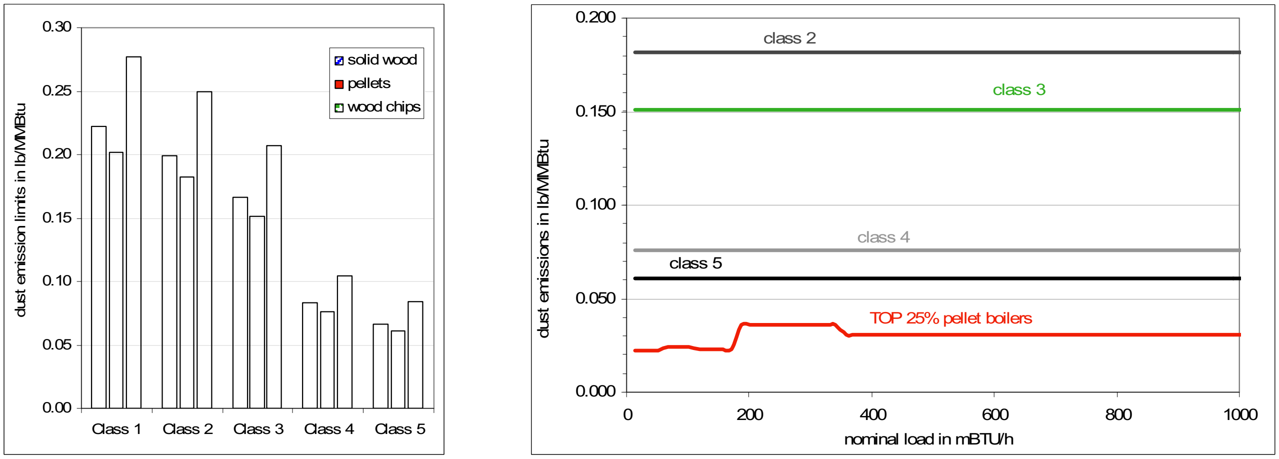

Figure ES-9 dust emission limits for solid wood, wood chips and pellet boilers of EN 303-5, classes 1 to 5 and average dust emissions of the TOP 25% performing pellet boilers.

Figure ES-9 demonstrates that the TOP 25% performing boilers have lower emissions than future EN303-5, class 5 requirements.

Figure ES-10 shows the average efficiencies at nominal and partial load for the TOP 25% performing pellet, solid wood and wood chip appliances. For solid wood boilers partial load equals 50% of nominal load, for pellets and wood chip boilers the partial load is 30% of the nominal load.

Efficiencies for nominal and partial load are almost identical. Solid wood and wood chip boilers sometimes even reach higher efficiencies at partial load operation.

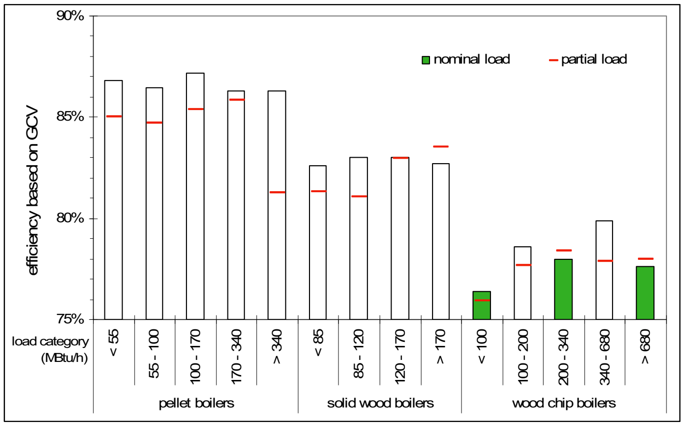

Figure ES-10 average efficiencies based on GCV at nominal and partial heat load for the TOP 25% performing boilers

Although modern solid wood boilers are able to modulate their operation load from 100 to 50%, the use of heat storage is strongly recommended in order to reach high efficiencies and keep emissions low by preventing short cycling. Even though pellet and wood chip boilers can modulate their operation load from 100 to 30%, some studies also recommend the integration of accumulator tanks in these heating systems in order to increase the annual efficiencies of the heating systems. In addition to improved performance, the design of heat storage systems also influences the need for maintenance and the durability of boilers.

Due to their high availability, non-wood biomasses such as grasses and agriculture products are very attractive fuels. They may however have certain general physical and chemical properties that cause problems during combustion. In addition to the possible increase of NO_X, HCl, SO_2, and other emissions in comparison to wood biomass, higher ash contents combined with lower ash melting temperatures and corrosive effects negatively influence the failure rate and durability of the boilers.

Summary

By making careful conversions of conventional methodology and units, the energy efficiency and emissions performance of the European heating systems can be more easily summarized in the context of the American nomenclature. After conversions, differences in evaluation duty-cycle and the emissions sampling and analysis protocols still exist in the regulatory test methods between the European Commission and the U.S. For example, the European Commission evaluation duty cycles do not include operation for the very low burn rates (low heat demand rates) that U.S. evaluations typically require. The U.S. evaluation duty cycles include these low burn rates because many U.S. designs do not always automatically minimize or eliminate idle modes that have poor combustion characteristics. There is considerable interest in the U.S. in this opportunity for much improved performance. Also, the U.S. sampling and analysis typically include condensable particulate matter, which by and large is organic. Such testing is not required in European tests because the high-efficiency designs combust virtually all of the organic precursors to condensable aerosol particles. Instead, the European test measures any residual organic gases in the exhaust stream. Thus one must be careful in comparing results and recognize that not all results are directly comparable. In the case of the Top 25% performing wood boilers in the size range of 120,000 - 170,000 Btu, converting all of the organic gases to particulate matter would result in an increase of approximately 4% of the mass or an output based emission rate of 0.068 lb/mmBtu.

Even considering the differences described above, it is clear that by using improved staged combustion design, fuels with lower water content; only 22.5% for wood chips and 14.5% for solid (cord) wood, requirements for minimum thermal efficiency, and sophisticated controls that optimize combustion and minimize or eliminate idle modes, the top 25% performing commercially available European technologies greatly exceed performance requirements of not only the current classes (1, 2, and 3) of boilers but also the proposed classes (4 and 5) for thermal efficiency and emissions. Technology-forcing policies, regulations, and Eco-labeling efforts have clearly resulted in greatly improved technology now available in Europe, which is expanding into the American wood heating market as well.

1 Introduction

Austria is a leading country in biomass combustion technology due to its long tradition of using biomass for heating purposes as well as the high environmental awareness of its population. Approximately 30 years ago, the first efforts were started towards improving combustion technology for biomass appliances. At this time, the first measurements of efficiencies and CO emissions from boilers were performed by national authorities and a competition was arranged amongst Austrian producers of biomass boilers in order to encourage technology development.

Figure 1-1 shows the technological improvement of boilers for solid (cord) wood, wood chips and pellets (starting in 1998) through test data from FJ-BLT. Over the last 30 years, the average efficiencies of biomass boilers have increased from approximately 55% to more than 90% based on the NCV (net calorific value) and the average CO-emissions have decreased from 15,000 to less than 50 mg/m³.

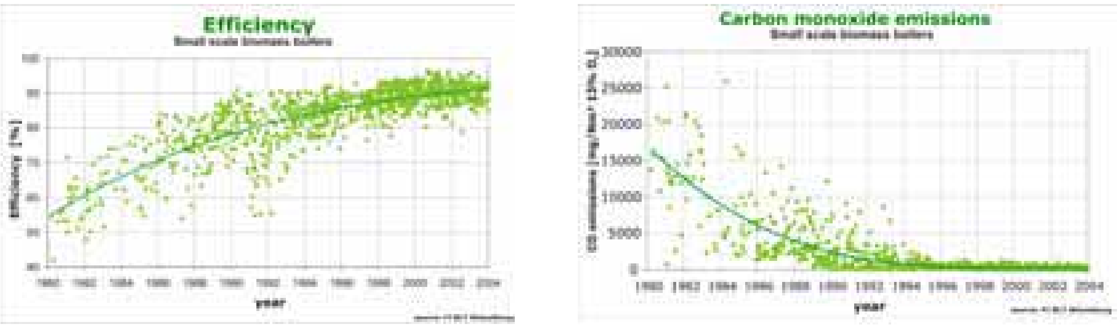

Figure 1-1 Small scale wood combustion systems: Efficiencies and CO emissions measured at the test bench through certification tests since 1980 - data according (FJ-BLT 2005), compilation in (Voglauer 2005)

In the European Union, efficiency requirements and emission limits (CO, OGC and dust) for solid fuel boilers are regulated by one standard: EN 303-5. In order to include the differing technology levels within the EU, different classes are defined for emission limits and efficiency requirements. In the new revision, which is currently under discussion, more stringent efficiency and emission performances will be introduced in order to raise the overall performance of biomass appliances in Europe.

All European Union member states are allowed to introduce additional and more stringent requirements than those given in the European standards for combustion appliances. For example, this is done in Austria, Germany and the Scandinavian Countries. In addition to legal requirements, environmental labels with very high requirments for efficiency and emissions are also introduced by some countries. These eco-labels encourage the population to purchase high performing biomass appliances by giving additional financial incentives.

This report provides a description of:

- combustion principles of modern biomass heating systems and commonly employed designs;
- combustion emission and reduction strategies;
- European test methods for various appliances;
- European regulations for biomass heating systems;
- a survey of current technology performance for commercially available heating systems;
- a summary of the best performing units based on thermal efficiency and CO emissions;
- emission control technology;
- fuel requirements;
- heat storage; and
- heating systems for non-woody biomass fuels.

A key aspect of this study is that it describes the European methodology for determining thermal efficiency using the net calorific value (lower heating value) of the wood fuel and how this is converted to the gross calorific value (high heating value) used to determine thermal efficiencies by the U.S. heating industry. Throughout this report thermal efficiency values are converted to the American convention using gross calorific value. The emissions for "dust" or Total Suspended Particulates are converted to pounds per million British thermal unit (lb/MMBtu), the common unit used in the United States. Other emissions are normalized to values at standard conditions at 12% O_2 levels in the flue gas.

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1.1 Calorific Value and Efficiency

1.1.1 Chemical composition

Biomass is an inhomogeneous raw material. Properties and therefore the composition of biomass influence its combustion behavior. A complete analysis of the biomass fuel would be time extensive and very expensive. For the characterization of the biomass with regard to its combustion behavior, proximate analysis is common, which entails determining the content of water, ash and volatiles in the fuel, as well as, the heating value of the fuel(see afterwards).

Biomass fuel can be divided into combustible and incombustible substances (Figure 1-2). Incombustible components include water and substances which are converted to ash during combustion.

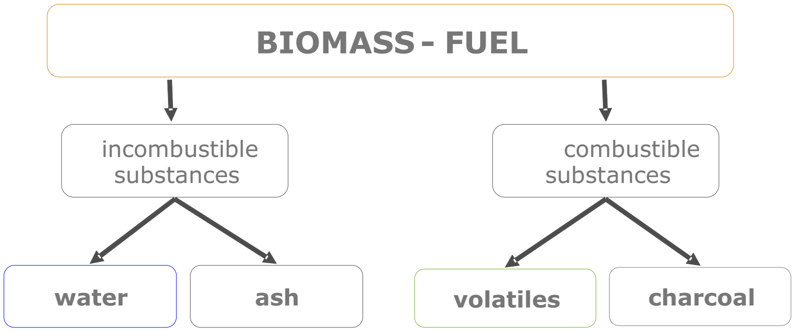


Figure 1-2 classification of biomass fuel with regard to its combustion behaviour (Marutzky, Seeger 1999)

Combustible substances can be divided into volatiles and charcoal (fixed carbon). Volatiles equal the fraction of biomass, which is transferred to gaseous state when the biomass is heated up. The amount of volatile matter in biomass fuels is higher than in coals and usually varies between 76 and 86 wt.% (d.b.). As a result of this high amount of volatiles, the major part of a biomass fuel is vaporized before homogeneous gas phase combustion reactions take place; the remaining char then undergoes heterogeneous combustion reactions. Therefore, the amount of volatile matter strongly influences the thermal decomposition and combustion behavior of solid fuels.

Figure 1-3 shows the mass and energy ratio of ash, volatile matter and charcoal from biomass. From ash forming substances, no energy is gained. Charcoal contributes to the energy quantity in a high degree.

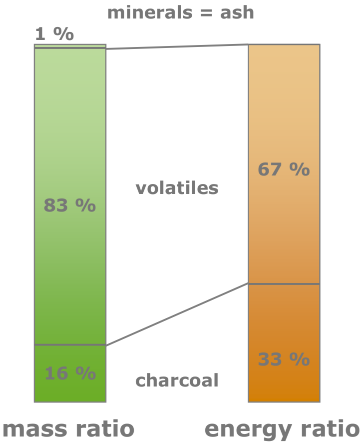


Figure 1-3 Mass and energy ratio of ash, charcoal and volatiles from biomass (Ebert, 1998)

Looking at the elemental composition of biomass, main elements, macro and micro nutrients and others can be identified (Figure 1-4). Figure 1-5 shows the average elemental compositions of plants.

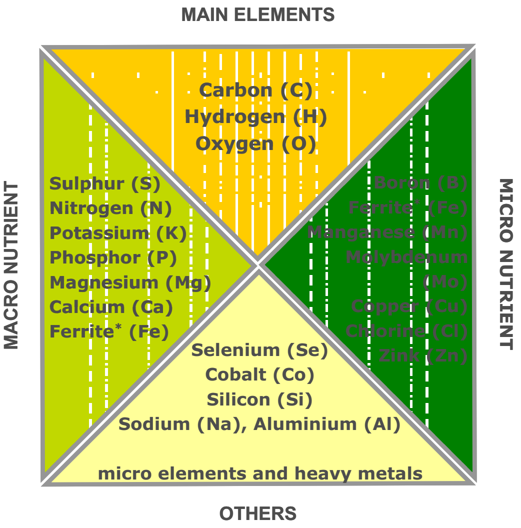
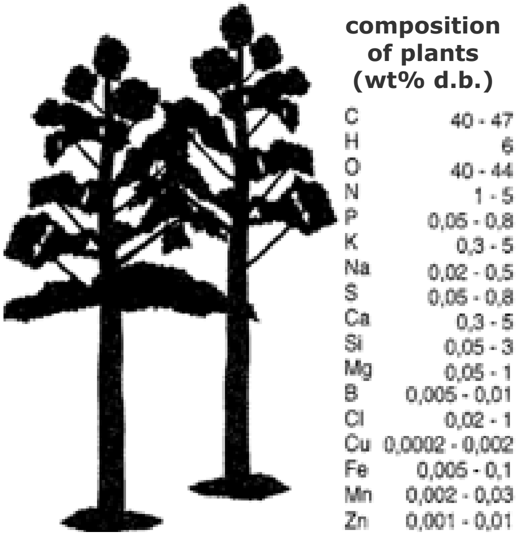


Figure 1-4 concentration and function of elements in biomass (Kaltschmitt, Hartmann 2001)



composition of plants (wt% d.b.)

C	40 - 47
H	6
O	40 - 44
N	1 - 5
P	0,05 - 0,8
K	0,3 - 5
Na	0,02 - 0,5
S	0,05 - 0,8
Ca	0,3 - 5
Si	0,05 - 3
Mg	0,05 - 1
B	0,005 - 0,01
Cl	0,02 - 1
Cu	0,0002 - 0,002
Fe	0,005 - 0,1
Mn	0,002 - 0,03
Zn	0,001 - 0,01

Figure 1-5 average elemental composition of plants (Kaltschmitt, Hartmann 2001)

While the macro and micro nutrients are important for the growth of the plant, they can influence the combustion process negatively. Table 1-1 shows the guiding values and guiding ranges for elements in biomass fuels and biomass ashes for unproblematic thermal utilisation.

Table 1-1 Guiding values and guiding ranges for elements in biomass fuels and biomass ashes for unproblematic thermal utilisation

Element	Guiding concentration in fuel (wt% d.b.)	Limiting parameter	Outside guiding concentration ranges, problems can occur for
N	< 0.6	NO_x emissions	Straw, cereals, grass
	< 2.5		Waste wood, fibre boards
Cl	< 0.1	Corrosion	Straw, cereals, grass
	< 0.1	HCl emissions	Straw, cereals, grass
	< 0.3	PCDD/F emissions	Straw, cereals, grass
S	< 0.1	Corrosion	Straw, cereals, grass
	< 0.2	SOx emissions	Grass, hay
Ca	15 - 35	Ash-melting point	Straw, cereals, grass
K	< 7.0	Ash-melting point, depositions, corrosion	Straw, cereals, grass
	--	Aerosol formation	Straw, cereals, grass
Zn	< 0.08	Ash recycling	Bark, wood chips, sawdust
	--	Particulate emissions	Bark, wood chips, sawdust
Cd	< 0.0005	Ash recycling	Bark, wood chips, sawdust
	--	Particulate emissions	Bark, wood chips, sawdust

Guiding values for ashes related to the biomass fuel ashes according to ISO 1171-1981 at 1022 °F

1.1.2 Calorific Value

1.1.2.1 Measurement and conversion

Gross calorific value (upper heating value)

The wet based GCV is determined by measurement in bomb calorimeter:

- Temperature of fuel before combustion and of combustion products: 77 °F. Before and after combustion all water (water in fuel and formed water by H) is liquid
- complete oxidation of C and S in the fuel (CO_2 and SO_2)
- no oxidation of N in the fuel

$$GCV_{w.b.} = -\frac{(\Delta H_R)}{m} \qquad F\ 1$$

$GCV_{w.b.}$	wet based gross calorific value	Btu/lb
ΔH_R	enthalpy of reaction	Btu
m	fuel mass	lb

In order to calculate the dry based GCV, the moisture content w has to be considered:

$$GCV_{d.b.} = GCV_{w.b.} \cdot \frac{1}{1-w} \qquad F\ 2$$

$GCV_{w.b.}$	wet based gross calorific value	Btu/lb
$GCV_{d.b.}$	dry based gross calorific value	Btu/lb
w	moisture content in the fuel	lb/lb

Net calorific value (lower heating value)
In the NCV the water in the fuel and the formed water by H is gaseous after combustion, but still at a temperature of 77 °F (25 °C). Therefore the difference between NCV and GCV is the evaporation heat of the water amount after combustion at 77 °F. In order to determine the dry based NCV from the dry based GCV, the evaporation heat of the hydrogen in the fuel has to be subtracted:

$$NCV_{d.b.} = GCV_{d.b.} - r \cdot 9 \cdot h_{d.b.} \qquad F\ 3$$

$NCV_{d.b.}$	dry based net calorific value	Btu/lb
$GCV_{d.b.}$	dry based gross calorific value	Btu/lb
r	evaporation heat of water at 77 °F (= 1,050)	Btu/lb
$h_{d.b.}$	dry based hydrogen in the fuel	lb/lb
w	moisture in the fuel	lb/lb

For calculation of the wet based NCV, the mass and the evaporation heat of the moisture in the fuel has to be considered:

$$NCV_{w.b.} = NCV_{d.b.} \cdot (1-w) - r \cdot w \qquad F\ 4$$

$NCV_{w.b.}$	wet based net calorific value	Btu/lb
$NCV_{d.b.}$	dry based net calorific value	Btu/lb
r	evaporation heat of water at 77 °F (= 1,050)	Btu/lb
h	hydrogen in the fuel	lb/lb
w	moisture in the fuel	lb/lb

Conversion from dry based GCV to wet based NCV
If direct conversion of dry based GCV to wet based NCV is wished, combination of F 3 and F 4 result in:

$$NCV_{w.b.} = (GCV_{d.b.} - r \cdot 9 \cdot h_{d.b.}) \cdot (1-w) - r \cdot w \qquad F\ 5$$

$NCV_{w.b.}$	wet based net calorific value	Btu/lb
$NCV_{d.b.}$	dry based net calorific value	Btu/lb
r	evaporation heat of water at 77 °F (= 1,050)	Btu/lb
$h_{d.b.}$	dry based hydrogen in the fuel	lb/lb
w	moisture in the fuel	lb/lb

In Figure 1-6 the relationship of the net calorific value as well as the gross calorific value and the dry based water content is given. Additionally typical water contents for pellets, log wood (seasoned wood) and fresh wood are drawn in.

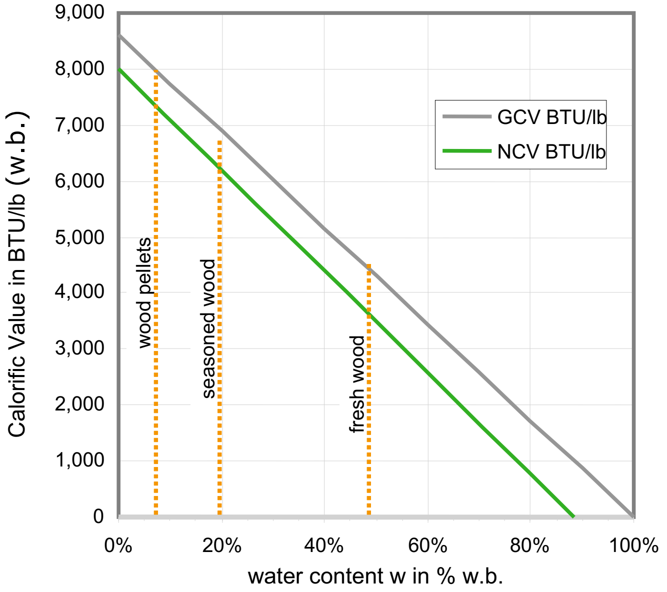


Figure 1-6 relationship of net and gross calorific value and water content

1.1.2.2 Formula from Boie

The heating value can only be determined exactly by measurement. If measurement is not possible or only estimation is requested, the experimentally developed formula from Boie can be used to approximate the heating value of the biomass. Although this formula considers the nitrogen in the fuel, which is hardly oxidized, it still furnishes reasonable results for bio-fuels:

$$\begin{aligned} NCV_{w.b.} \approx\ & 14{,}964 \cdot c_{w.b.} + 40{,}377 \cdot h_{w.b.} - 4{,}644 \cdot o_{w.b.} \\ & + 4{,}515 \cdot s_{w.b.} + 2{,}709 \cdot n_{w.b.} - 1{,}050 \cdot w \end{aligned} \qquad F\ 6$$

$NCV_{w.b.}$	wet based net calorific value	Btu/lb
$c_{w.b.}$	wet based carbon in the fuel	lb/lb
$h_{w.b.}$	wet based hydrogen in the fuel	lb/lb
$o_{w.b.}$	wet based oxygen in the fuel	lb/lb
$s_{w.b.}$	wet based sulfur in the fuel	lb/lb
$n_{w.b.}$	wet based nitrogen in the fuel	lb/lb
w	water content	lb/lb

1.1.3 Conversion factors

For the conversion of efficiencies and emissions, it is necessary to assume the elemental composition, the calorific value and the water content of the considered biofuels. In Table 1-2 the considered values are shown. The elemental composition and the gross calorific value of the biofuels correspond to the standard values that are used for emission calculations by BE2020+, Branch Wieselburg. The average water contents of the fuels from all input data (w_{NCV}) are assumed to be equal to the average water content of each fuel from the FJ-BLT[1] test reports. The water contents of the biofuels for the calculation of the efficiencies based on the GCV (w_{GCV}) were provided by NYSERDA.

Table 1-2 assumed elemental composition, gross calorific value and water content for conversion

	GCV$^{1)}$ *(d.b.)*	*c*$^{1,2)}$	*h*$^{1,2)}$	*a*$^{1,2)}$	$w_{NCV}^{3)}$	$w_{GCV}^{4)}$	*NCV*$^{3)}$ *(w.b.)*	*GCV*$^{4)}$ *(w.b.)*
	Btu/lb	*% (d.b.)*			*%*		*Btu/lb*	
pellets	*8 600*	*50.70*	*6.23*	*0.20*	*7.5*	*5*	*7 300*	*8 200*
solid wood					*14.5*	*20*	*6 700*	*6 900*
wood chips					*22.5*	*40*	*6 000*	*5 200*

$^{1)}$ standard values for emission calculation of BE2020+, Wieselburg
$^{2)}$ c: carbon in the fuel, h: hydrogen in the fuel, a: ash in the fuel
$^{3)}$ averaged from FJ-BLT test reports
$^{4)}$ given from NYSERDA

In the test reports that were used for this study, the efficiencies were based on the lower heating value (net calorific value NCV). These efficiencies were achieved with test fuels having the assumed averaged water content of the test fuels as shown inTable 1-2.

The efficiencies must however be based on the GCV, which is calculated with new water contents of the fuels given by NYSERDA (see Table 1-2). In order to convert the efficiencies based on the GCV values with the new water contents provided in the test reports by NYSERDA, the correlation between the water content of the fuel and the efficiency have to be considered.

In order to calculate the conversion factors, the excess air ratio of the combustion conditions must be determined, whereby it is assumed to equal the average excess air ratio found in the data available from FJ-BLT:

- pellets: $\lambda = 1.50$
- solid wood: $\lambda = 1.42$
- wood chips: $\lambda = 1.43$

Figure 1-7 shows the efficiencies that were reached for water contents of 0, 22.5 and 40% at an excess air ratio of 1.43 (these values correspond to wood chips). In Figure 1-7 only losses by heat in the flue gas are considered. Losses by radiation, un-burnt gases in

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[1] FJ-BLT is the test house for wood boilers in Wieseburg

the flue gas or un-burnt material in the ash are not considered. Theses losses are however small in comparison to the flue gas losses.

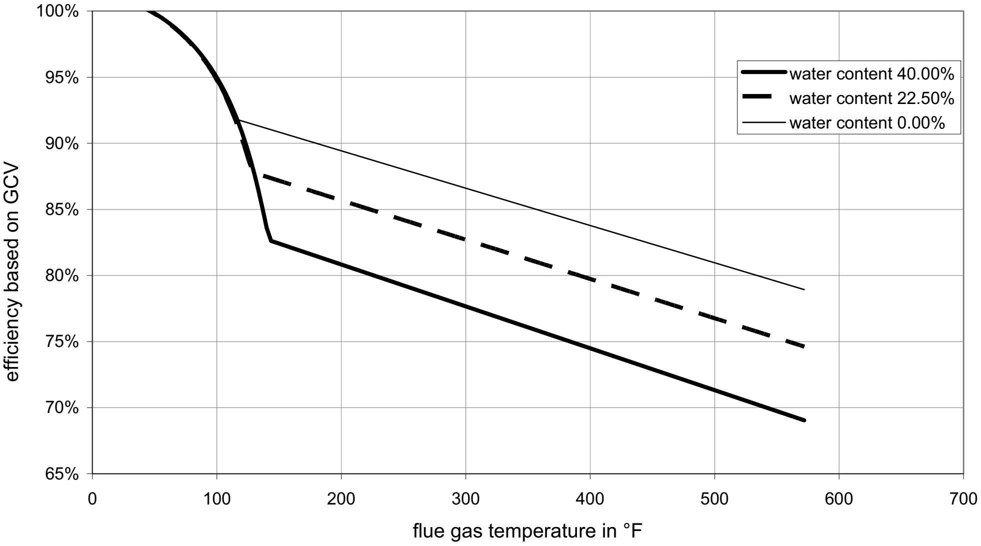


Figure 1-7 correlation between the efficiency and corresponding flue gas temperature for different water contents of the fuel at an excess air ratio of 1.43 (only losses by heat in the flue gas considered)

The effect of water content on efficiency is illustrated in the following example. An efficiency of 85% with a fuel water content of 22.5% will be reduced to 80% if the fuel water content is increased to 40%, assuming that the flue gas temperature stays constant (about 220 °F).

In order to convert the efficiencies based on the NCV and the average water contents of the test fuels to the efficiencies based on the GCV and the water contents provided by NYSERDA, the graphs for each fuel corresponding to Figure 1-8 were determined. Equation F 7 shows the approximated equation that was used for conversion and in Table 1-3 the factors for eqution F 7 are given.

$$\eta_{GCV_{NYSERDA}} = Y_1 - Y_2 \cdot \left(\frac{X_1 - f_{CV} \cdot \eta_{NCV_{BLT}}}{X_2} \right) \qquad F\ 7$$

$\eta_{GCV,NYSERDA}$	efficiency based on GCV and water contents from NYSERDA	-
η_{NCVBLT}	efficiency based on NCV and averaged water contents of the test fuel	-

Table 1-3 factors for conversion from efficiency determined on basis of the NCV and averaged water contents of the test fuels to efficiency based on GCV and water content specified by NYSERDA

fuel	X_1 (-)	X_2 (-)	Y_1 (-)	Y_2 (-)	f_{CV} (-)
pellets	$9.32\cdot10^{-1}$	$5.37\cdot10^{-4}$	$9.36\cdot10^{-1}$	$5.35\cdot10^{-4}$	$9.22\cdot10^{-1}$
solid wood	$9.21\cdot10^{-1}$	$5.21\cdot10^{-4}$	$9.12\cdot10^{-1}$	$5.28\cdot10^{-4}$	$9.11\cdot10^{-1}$
wood chips	$9.07\cdot10^{-1}$	$5.35\cdot10^{-4}$	$8.62\cdot10^{-1}$	$5.70\cdot10^{-4}$	$8.96\cdot10^{-1}$

Figure 1-8 exhibits the resulting conversion functions.

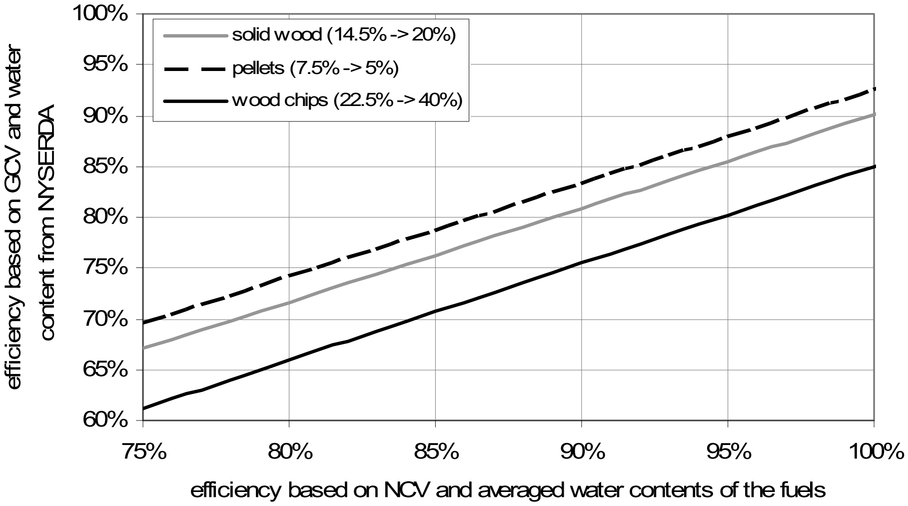


Figure 1-8 conversion function for the conversion of the efficiencies based on the NCV and average water contents of test fuel to efficiencies based on the GCV and average water contents provided by NYSERDA

When converting from NCV with a 7.5% water content pellet to the American convention of GCV with a pellet having 5% water content, a loss of approximately 5% is observed. This loss is mostly due to water formed from the hydrogen in the wood fuel, but also reflects a slight, partly offsetting, efficiency gain that results from lower fuel moisture content. In the case of changing from a wood chip fuel with 22.5% water content to one with 40% water content, not only is the 5% loss of energy from the fuel hydrogen conversion to water accounted for but the loss in energy efficiency of an additional 10% due to the loss of energy required to heat the water in the fuel is also apparent.

2 Biomass combustion technology

2.1 Overview – combustion principles

2.1.1 Staged combustion

Combustion technology for biomass appliances is based on staged combustion in order to enable maximum burnout rates. Figure 2-1 illustrates the stages of biomass combustion that take place in the primary and secondary combustion zones.

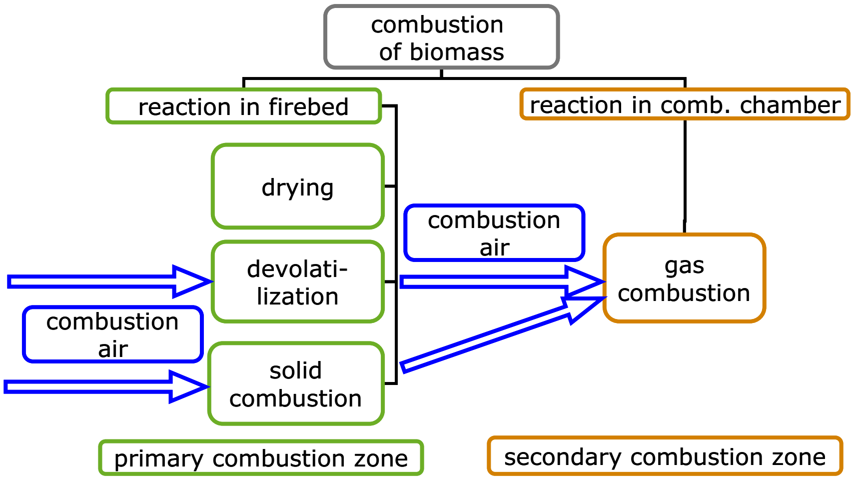


Figure 2-1 primary and secondary combustion zone in biomass combustion

In the primary combustion zone, the bio-fuel is first dried from the heat within the combustion chamber followed by devolatilization, whereby the volatile substances are set free from the solid fuel and ascend to the secondary combustion zone. Finally, the remaining solid charcoal is burnt in the firebed. Primary air is needed for devolatilization and solid combustion.

In the secondary combustion zone, the volatile gases from devolatilization and gases from solid combustion are burnt with secondary air. In order to achieve low emissions, the reaction in the secondary combustion zone must be as complete as possible.

2.1.2 Manual stoking

Manually stoked furnaces can burn logs (from 10 in up to 40 in in length) as well as briquettes. Some log wood furnaces also work with coarse wood chips. There are three common, basic classifications, which are determined by the airflow of the primary air: top burning, through burning or under burning furnace. These designs are illustrated in Figure 2-2. Numerous combinations and modifications of these three principles are available.

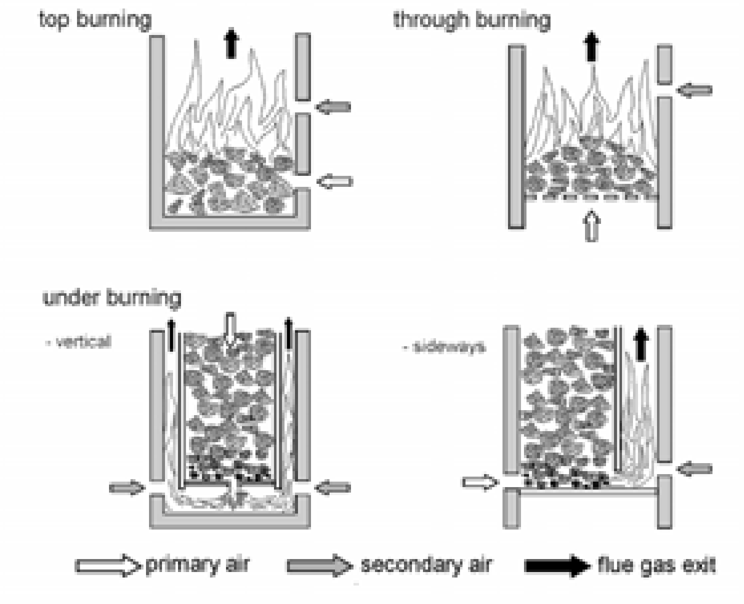


Figure 2-2 Classification of log wood combustion principles (FNR I 2007)

In through-burning systems, the primary air enters the combustion chamber through a grate. The wood logs are then ignited at the bottom of the batch, thus heating the entire stack and commencing the burning. This combustion system is suitable for stoves frequently fed with small batches of log wood. For log wood boilers, this combustion principle is no longer a state-of-the-art technology.

In top burning systems, the primary air enters the combustion zone sideways. The stack is ignited at the top or in the middle and as such, the combustion reactions are slower than those in through-burning systems. The combustion process is nevertheless discontinuous. This combustion system is suitable for small or medium batches of log wood.

Both combustion systems, through and top-burning, are usually operated with natural draught, meaning that no auxiliary ventilation devices are needed.

Under-burning systems are the latest development in log wood combustion technologies. This principle is a state-of-the-art technology for log wood boilers. The fuel is ignited at the bottom and the combustion gases are drawn downwards or sideways, resulting in a relatively continuous combustion process. The continuous combustion process and separation of the primary and secondary combustion zones result in very low emissions; a fan is however necessary to ensure proper operation. This fan is usually placed at the flue gas exit of the furnace.

2.1.3 Automated stoking

Automatically stoking furnaces can be divided into furnaces with fixed bed combustion, fluidised bed combustion and dust combustion. The basic principles of these three technologies are shown in Figure 2-3 (Marutzky, Seeger 1999).

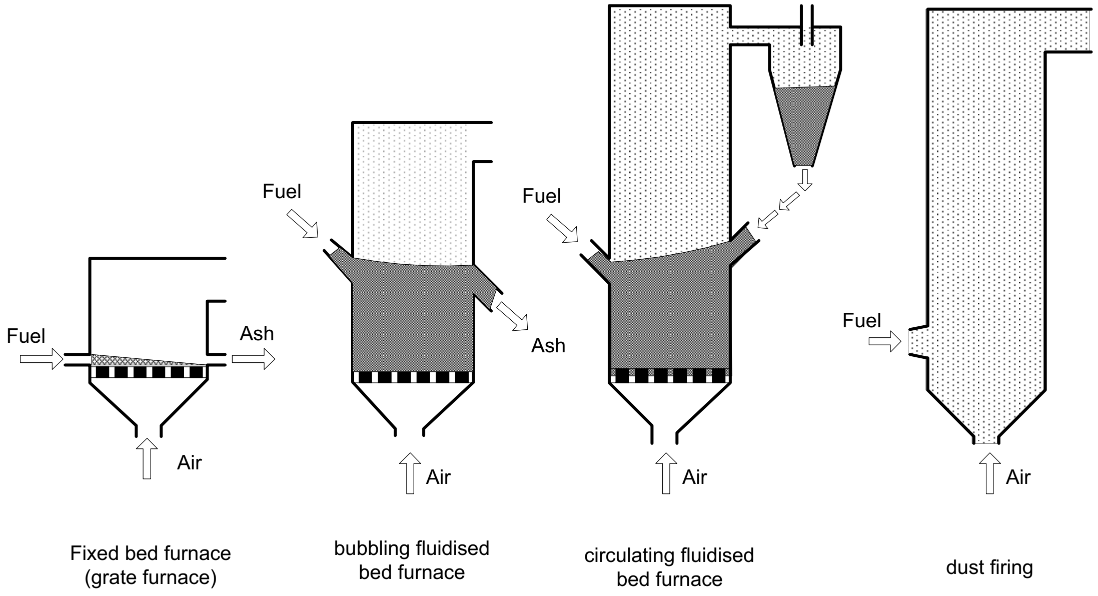


Figure 2-3 Diagram of principle combustion technologies for biomass (Marutzky, Seeger 1999)

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The combustible gases produced are burnt after secondary air addition has taken place, usually in a combustion zone separated from the fuel bed.

Within a fluidised bed furnace, biomass fuel is burnt in a self-mixing suspension of gas and solid-bed material into which combustion air enters from below. The type of combustion can be distinguished depending on the fluidisation velocity, bubbling fluidised bed and circulating fluidised bed

Dust combustion is suitable for fuels available as small particles (average diameter smaller than 0.1 in). For this type of combustion, a mixture of fuel and primary combustion air is injected into the combustion chamber, whereby the combustion takes place while the fuel is in suspension. The gas burnout is achieved after the addition of secondary air.

For small scale appliances, fixed bed combustion technology is used in medium to large scale appliances, inclusive for all technologies.

Small scale appliances - pellets

Existing combustion technologies for wood chips have been adopted for pellet combustion, and a new principle has been developed. The development of small-scale pellet burners has taken place to a great extent in Sweden and Austria. Pellet burners are divided according to the feed direction of the pellets into three main types: top feed, underfeed and horizontal feed (Alakamgas, Paju 2002).

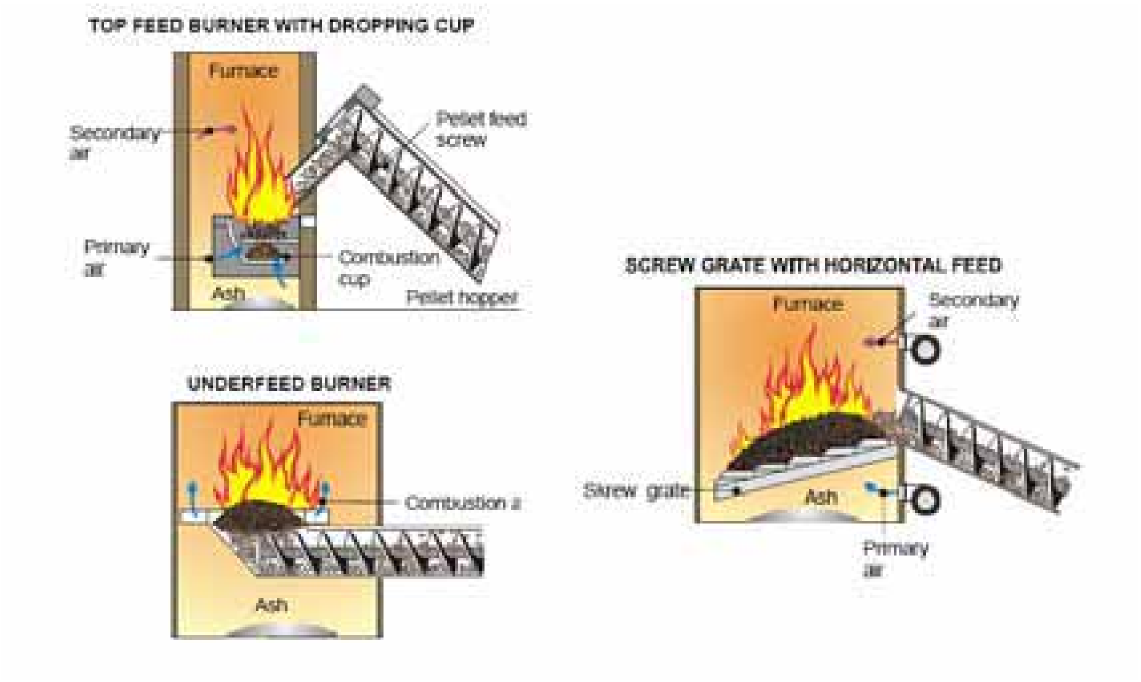


Figure 2-4: Classification of pellet combustion principles (Alakamgas, Paju 2002)

In underfeed burners (underfeed stoker or underfeed retort burners), the fuel is fed into the bottom of the combustion chamber or combustion retort. These burners are best suited for fuels with low ash content (wood pellets, wood chips). They are built for a nominal power between 35 MBtu/h and 8 MMBtu/h or greater.

In horizontal feed burners, the combustion chamber is either fitted with a grate or a pusher plate. The fuel is introduced horizontally into the combustion chamber. During combustion, the fuel is moved or pushed horizontally from the feeding zone to the other side of the pusher plate or the grate. While the fuel is drying, gasification and solid combustion take place; following this the remaining ash drops into an ash container. Horizontal feed burners can burn wood chips and pellets and are built for nominal heat flows from 50 MBtu/h to more than 50 MMBtu/h. Purpose-built horizontal feed systems (with moving grate, and water cooling) are fitted for the use of bark, straw or grain.

Top feed burners have been specifically developed for pellet combustion in small-scale units. The pellets fall through a shaft onto the fire bed consisting of either a grate or a retort. The separation of the feeding system and the fire bed ensures the effective protection against back-burn into the fuel storage. The proper distance between the combustion retort and the feeding system prevents early ignition of pellets in the feeding system (Obernberger, Thek 2002). The ash is removed manually or mechanically by a dumping grate. This feeding system allows very accurate feeding of pellets according to the current heat demand and is thus often used in furnaces with very small nominal heat flows.

Pellet burner systems are always operated with a forced draught. The fan can be placed at the combustion air inlet or at the flue gas exit of the furnace.

2.2 Small scale combustion systems

Common small scale combustion systems for woody biomass are listed in Table 2-1 and are categorized in two groups: Room heaters and boilers. Small scale combustion systems are used in the residential and commercial sectors as well as in district heating systems.

Table 2-1 Types and features of small-scale wood combustions systems, modified from (FNR I 2007)

type	*nominal heat load in MBtu/h*	*combustion principle*	*feature*
ROOM HEATERS			
fireplaces	*0 - 15*	*through- / top burning*	*inappropriate for permanent heating*
pellet stoves	*10 – 35*	*top feed*	*automatically operated, regulated fuel and combustion air input (fan), with or without hot water*
wood stoves	*10 – 40*	*through- / top burning*	*fired from living room* *no water installations*
Masonry heaters	*5 – 60*	*through- / top burning*	*diverse heat storing/release characteristics , with or without hot water, combined technologies with pellets*
BOILERS			
pellet boilers	*≥ 10*	*top feed / horizontally feed / underfeed burner*	*fully automated operation, induced draught*
solid wood boilers	*≥ 35*	*through/ under burning*	*up to 40 in log wood length, natural or induced draught, buffer accumulator is needed*
wood chip boilers	*≥ 35*	*through burning / horizontally feed / underfeed burner*	*fully automated operation possible, induced draught, buffer accumulator advantageous*

2.2.1 Room heaters

Room heaters are intended to heat a space directly, unlike central heating furnaces or boilers, which supply heat to the house through a system of ducts or pipes. Varying concepts for space heaters have been developed and are still in use. Common space heaters are:

- Open and closed fireplaces
- Log wood stoves
- Masonry heaters (Heat storing [tiled] stoves)
- Pellet stoves

2.2.1.1 Fireplaces

Conventional fireplaces have a long history in home heating. They are built from masonry materials such as brick, block and stone. More recently, factory-built models are constructed mainly of steel. Conventional open fireplaces (Figure 2-5, left) do not heat a home efficiently and their use for permanent heating is thus not recommended. In many settlement areas and especially urban areas, the use of open fireplaces is even forbidden.

Factory-built closed fireplaces combine the beauty of an open fire with modern wood stove features, such as controlled and staged combustion air supply, baffle plates, properly dimensioned combustion chambers and fireclay lining. Burnout rate and efficiency clearly exceed those of open fireplaces. Many closed fireplaces provide heat by direct flame radiation and by convection (Figure 2-5, right).

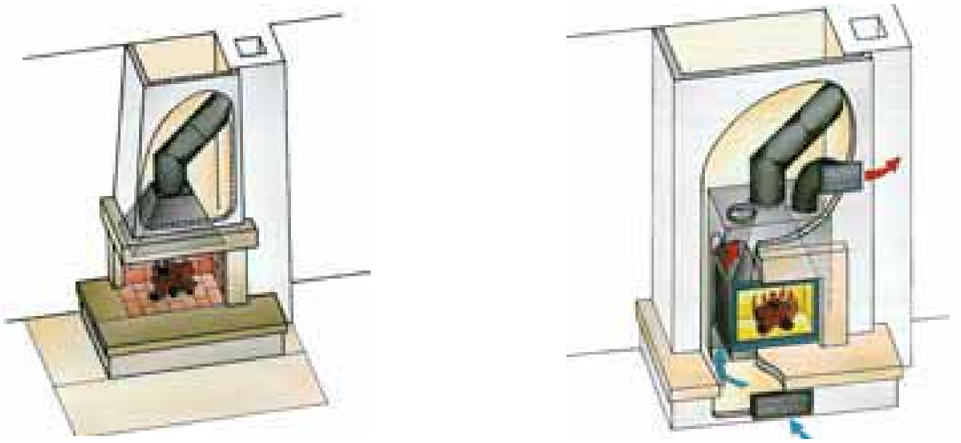


Figure 2-5 Open fireplace (left) and closed fireplace with convection casing (right)(Kachelofenbauerinnung 2007)

Fireplaces will not be considered in this study because they are not an appropriate technology for heating purposes.

2.2.1.2 Pellet stoves

Pellet stoves are suitable for continuous operation; their minimum heat output is usually 30 % of the nominal heat flow. Underfeeding and top feeding are the most common combustion technologies for pellet stoves.

Figure 2-6 shows the principle of a pellet stove with a top feed burner. The pellets are conveyed by the fuel screw into the shaft from where they fall into the combustion retort. The pellets are usually ignited automatically with a glow-plug. The supply of primary and secondary combustion air is controlled by a low-noise fan. External air supply is also possible for some pellet stoves, which is important for houses with controlled ventilation. The storage compartment is placed in the rear of the stove and can hold up to 110 lb of pellets.

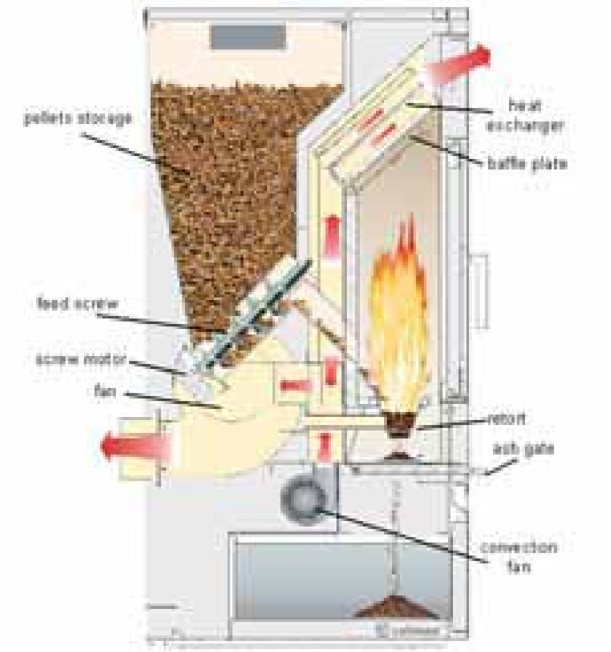


Figure 2-6 Functional principle of a pellet stove with top feed burner (Calimax 2007)

In the latest technological developments, the quality of combustion is regulated by a carbon monoxide sensor which ensures optimal combustion air supply at all times. Excess air ratio sensors are used less often for the control of ventilators in pellet stoves as they are quite expensive. They are however frequently used for control in boiler furnaces.

2.2.1.3 Pellet stoves with hot water production

The heat output of pellet stoves can usually be varied from 30 to 100 %. This enables pellet stoves to produce exactly the heat and, with integrated heat exchangers, also the hot water required. In these pellet stoves up to 80 % of the heat produced can be stored in the water (FNR I 2007).

Figure 2-7 shows an example of a pellet stove with integrated hot water production. The combination of a pellet stove and solar hot water production allows the complete heat and hot water demand of a (low-energy) house to be covered without the need of an additional boiler.

Figure 2-7 Pellet stove with integrated hot water production (Calimax 2007)

2.2.1.4 Wood stoves

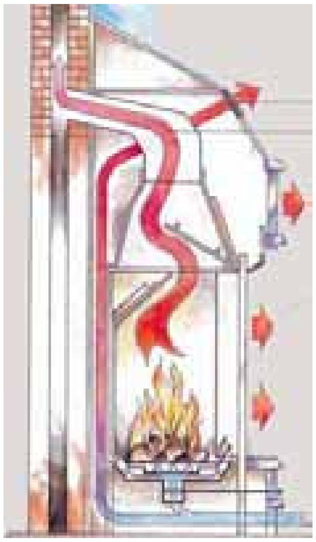


Figure 2-8 Functional principle of a log wood stove (Westfeuer 2005)

Figure 2-9 Example of a log wood stove (Heinz Aberle 2007)

In contrast to fireplaces, log wood stoves are floor mounted (free-standing) in the living room. In general, they are built of cast iron and designed for logs with a length of 10 and 15 in. Wide variations in design, such as doors with or without viewing glass or casings of tiles or soapstone are available. Log Wood stoves are usually based on the through-burning principle. Conventional log wood stoves are equipped with up to three doors; the upper door serves for loading the logs, the middle door is used for manual grate cleaning and the third for ash removal. Combustion air supply can be regulated manually by dampers or push handles. In simple designs, there is no separation of primary and secondary combustion air. *Figure 2-8* and *Figure 2-9* show the functional principle as well as an example of modern log wood stoves based on the through-burning principle. Log wood stoves are still sold without test certification.

2.2.1.5 Masonry heaters

Two different basic types of masonry heaters, the fully handcrafted model and the prefabricated model, can be distinguished. The traditional type of masonry heater, the tiled base stove, is a fully handcrafted heating device. With the exception of the fire door and possibly some parts of the combustion chamber, it is completely built with ceramic materials such as chamotte, soapstone, clay and/or tiles. Due to its large heat storing mass, it is a slow reacting heating system; *Figure 2-10* shows the functional principle of tiled base stoves and *Figure 2-11* shows a design example of a tiled base stove. This stove is fed from another room (mostly from the anteroom).

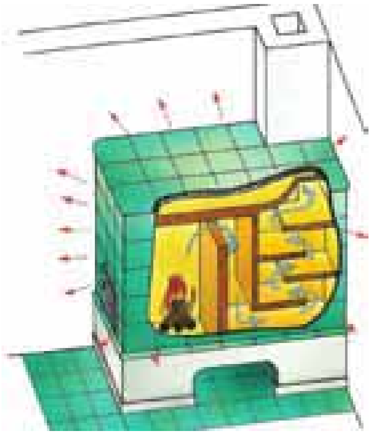


Figure 2-10 Functional principle of a tiled base stove (Kachelofenbauerinnung 2007)

Figure 2-11 Example of a tiled base stove (Kachelofenverband 2007)

The second type of masonry heaters consists of a prefabricated combustion chamber; the combustion gas channel (heat exchangers) can be built by hand or be prefabricated as well. A hot-air tiled stove has only a small heat storage mass. This type of stove consists of a prefabricated heater and optionally, a steel or cast-iron heat exchanger. Most of the heat is transferred by convection. Hot-air tiled stoves can react quickly to changing heat demands, but are not designed for long-lasting heat transfer. Depending on their dimensions, hot-air tiled stoves have similar heating characteristics as conventional wood stoves with convection casings. Combined tiled stoves are a combination of tiled base stoves and hot-air tiled stoves, consisting of a prefabricated heater and a ceramic heat storage unit (Figure 2-12 and Figure 2-13).

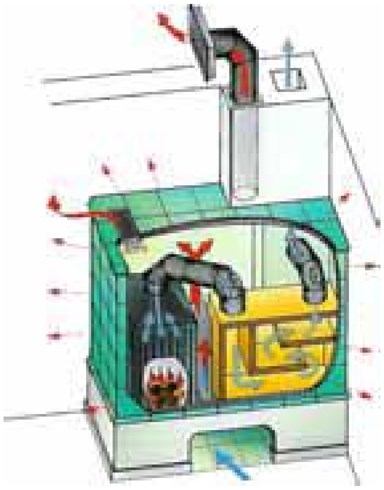


Figure 2-12 Functional principle of a combined tiled stove (Kachelofenbauerinnung 2007)

Figure 2-13 Example of a combined tiled stove (Kachelofenverband 2007)

Masonry heaters are based on the top and through-burning combustion principles. Combustion air is supplied in stages as primary and secondary combustion air.

Combined masonry heaters

Different technologies have been developed for the combustion of pellets in tiled stoves over the past few years. Prefabricated heaters enable the optional combustion of log wood and pellets or have an integrated boiler function; *Figure 2-14* shows a prefabricated heater for pellet combustion in a combined tiled stove. No auxiliary devices such as a fan or motor are needed for operation; *Figure 2-15* shows a fully automated prefabricated heater with an underfeed pellets burner. Both prefabricated heaters can burn log wood as well.

Figure 2-14 Prefabricated heater Pellets Power (Wienerberger Ofenkachel 2007)

Figure 2-15 Prefabricated heater Pellet module (Brunner 2007)

2.2.2 Boilers

In contrast to space heaters, boilers are intended to produce hot water for heating remote rooms. Usually, they are placed in special heating rooms in the cellar, in the garage or even in heating containers outside the house. Modern boilers achieve efficiencies beyond 80 % (based on the upper heating value).

2.2.2.1 Pellet boilers

Pellet boilers operate fully automatically with top feed, underfeed and horizontal feed burners. Manufacturers have typically specialized in a certain technology. Devices exclusively designed for wood pellets are typically used for a heat output range from 25 MBtu/h. For higher heat flows, wood chip furnaces are usually used, which are often approved for wood pellets as well. Figure 2-16 and Figure 2-17 show two different top feed boilers for wood pellets. This combustion principle allows for accurate feeding and is suitable for small heat demands as well as on/off-operation modes. In order to ensure proper operation, the grate must be automatically cleaned. Slagging can occur if low-quality pellets are used (Regionalenergie Steiermark 2005).

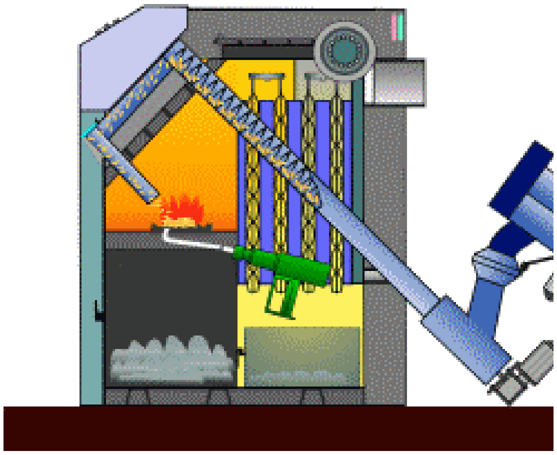


Figure 2-16 Top feed boiler (Evotherm 2010)

Figure 2-17 Top feed boiler (Windhager 2005)

Underfeed boilers are used for small to large heat flows. Underfeed boilers are less sensitive to low-quality pellets than top feed burners (Regionalenergie Steiermark 2005). An example of an underfeed boiler is shown in Figure 2-18. A horizontal feed boiler is demonstrated in Figure 2-19.

Figure 2-18 Underfeed boiler
(Guntamatic 2007)

Figure 2-19 Horizontal feed boiler
(*Hargassner 2005*)

Flue gas condensing
With proper flue gas condensing technology the moisture can be removed from the flue gas to further reduce the exhaust gas temperature, thus achieve **higher efficiencies**. Figure 2-20 shows the functional principle of the first condensing boiler for wood pellets available on the European market. Its efficiency of over 100 % is of course only due to the chosen definition for the determination of the efficiency, which is based on the net calorific value of the used fuel. The measured total dust emissions are very low, most likely due to the effect of the flue gas condensation.

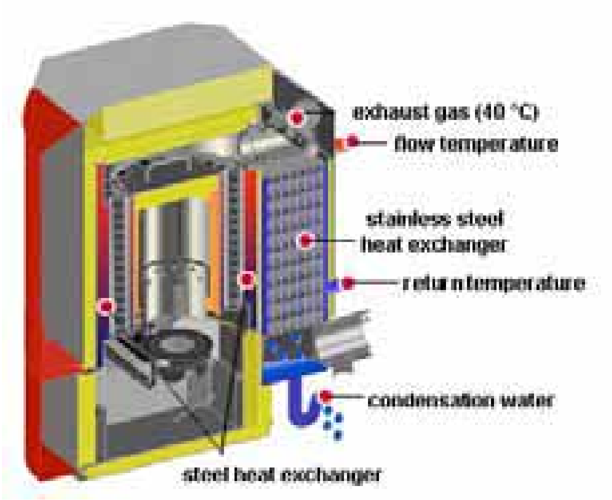


Figure 2-20 Functional principle of a condensing boiler for wood pellets (Oekofen 2007)

2.2.2.2 Solid wood boilers

Log wood boilers with natural draught based on the through-burning combustion principle were a state-of-the-art technology in the 1970s. Modern log wood boilers are based on the under-burning combustion principle and induced draught. Usually a fan, which is placed at the flue gas exit of the boiler, is used to suck primary and secondary combustion air into the corresponding combustion zones. The wood storage compartment may be filled during combustion without the risk of combustion gases leaving the boiler. The high degree of turbulence needed for the mixing of the fuel gas and the combustion air is ensured by the proper design of the combustion air inlet zone and the nozzles; Figure 2-21 and Figure 2-22 show two different log wood boilers with induced draught airflow and flue gas exits on the side and at the top of the boiler.

Log wood boilers are usually designed for a heat output range from 50 to 135 MBtu/h. There are some specialty companies that make systems up to 3 MMBtu/h such as the Lopper company.

Figure 2-21 Under-burning boiler with induced draught, flue gas exit sideways(Buderus 2005)

Figure 2-22 Under-burning boiler with induced draught, vertical flue gas exit (Froeling 2005)

2.2.2.3 Wood chip boilers

For wood chip boilers, underfeed burners and horizontal feed burners with or without a grate are fairly common in various designs. Wood chip boilers are therefore used in a wide nominal power capacity range from 50 MBtu/h up to over 70 MMBtu/h.

Concerning small scale systems, the advantages of wood chip boilers over log wood boilers include automatic operation and low emissions due to continuous combustion. On the other hand, the process of producing, storing and, if necessary, drying wood chips requires more investment in machinery and storage space than is the case for log wood. In comparison to pellets, wood chips are less expensive and can be produced on site. Wood chip boilers are often approved for wood pellets as well; specially designed pellet boilers, however can not be fired with wood chips.

Figure 2-23 shows an example of an underfeed burner for wood chips and pellets. The principle of a horizontal stoker burner is shown in Figure 2-24.

Figure 2-23 Underfeed burner for wood chips and pellets (KWB 2007)

Figure 2-24 Horizontal feed burner for wood chips, pellets and grain (BAXI 2007)

2.2.2.4 Combined boiler technologies

Special boilers have been developed to combine the comfortable combustion system for wood pellets with the combustion system for log wood. In some boilers manual switching is necessary, while others are fully automated. Figure 2-25 shows a combined boiler with a fully automatic switch. When heat is demanded, the pellet burner is started automatically. Any log wood fed into the boiler will be ignited by the pellet flame. As soon as the log wood is ignited, the pellet burner stops and the log wood stack is burnt (under-burning principle). If there is no log wood in the fuel storage compartment, the pellet burner will continue combustion and the log wood compartment is used as secondary combustion zone for pellet combustion.

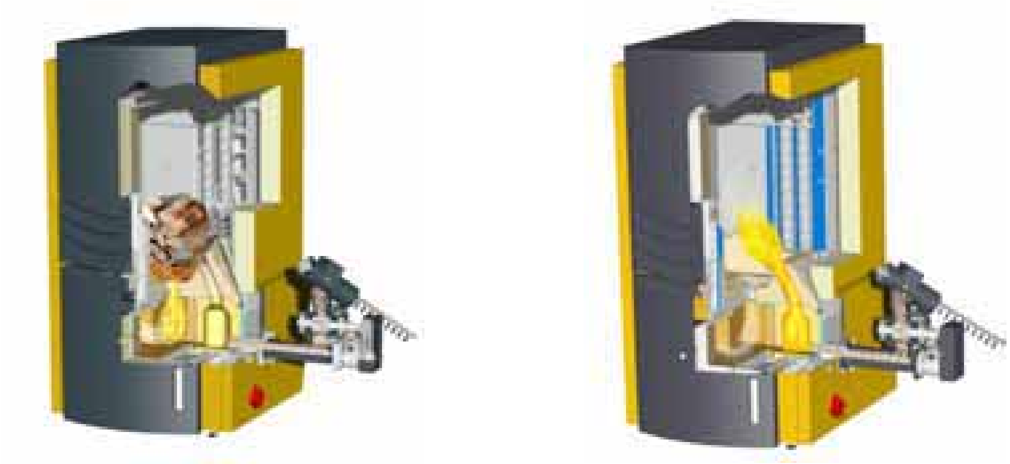


Figure 2-25 Combined boiler technology for pellet and log wood combustion (left: log wood mode, right: pellet mode) (sht 2007)

2.3 Medium to large scale combustion

In Table 2-2 the characteristics of common medium to large combustion technologies for woody biomass are listed.

Table 2-2 Types and characteristics of medium to large combustions systems suitable for woody biomass (FNR II 2007)

Combustion technology	*Stoking*	*Fuel*	*Nominal power*	*Moisture content (% w.b.)*
Underfeed stoker	*Mechanic*	*Pellets and wood chips (ash content ≤1%)*	*35 MBtu/h – 9 MMBtu/h*	*5-40*
Moving grate	*Mechanic*	*All wood fuels (ash content up to 50%)*	*510 MBtu/h – 170 MMBtu/h*	*5-60*
Bubbling fluidised bed combustion	*Mechanic*	*Particle size <3.6 in*	*20 MMBtu/h – 120 MMBtu/h*	*5-60*
Circulating fluidised bed combustion	*Mechanic*	*Particle size <1.5 in*	*50 MMBtu/h- 850 MMBtu/h*	*5-60*
Dust firing	*Pneumatic*	*Particle size <0.20 in*	*1700 MBtu/h- 170 MMBtu/h*	*Usually <20*

2.3.1 Fixed-bed combustion

2.3.1.1 Underfeed stokers

In addition to small scale combustion systems where underfeed stokers are a common technology (see 2.2.2.1 and 2.2.2.3), they are also an inexpensive and operationally safe technology for medium-scale systems up to 20 MMBtu/h. They are suitable for biomass fuels with low ash content (wood chips, sawdust, pellets) and small particle sizes (particle dimension up to 2.0 in). Ash-rich biomass fuels such as bark, straw and grain need more efficient ash removal systems. Moreover, sintered or melted ash particles covering the upper surface of the fuel bed can cause problems in underfeed stokers due to unstable combustion conditions when the fuel and the air are breaking through the ash-covered surface. An advantage of underfeed stokers is their good partial-load behaviour and their simple load control. Load changes can be achieved more easily and quickly than in grate combustion plants because the fuel supply can be controlled more easily (Loo, Koppejan, 2002).

Figure 2-26 Combustion chamber of an underfeed stoker furnace (BINDER 2007)

2.3.1.2 Grate furnaces

There are different grate furnace technologies available: fixed grates, travelling grates, moving grates, rotating grates, vibrating grates etc. All of these technologies have specific advantages and disadvantages depending on the fuel properties; as such careful selection and planning is necessary. Based on the flow directions of fuel and the flue gas, there are different systems for grate combustion plants (Figure 2-27):

- counter-current flow (flame in the opposite direction as the fuel)
- co-current flow (flame in the same direction as the fuel)
- cross-flow (flue gas removal in the middle of the furnace)

Counter-current combustion is most suitable for fuels with low heating values (wet bark, wood chips or sawdust). Co-current combustion is applied for dry fuels such as waste wood or straw, or in systems where pre-heated primary air is used. Cross-flow systems are a combination of co-current and counter-current units and are also especially applied in combustion plants with vertical secondary combustion chambers (Loo, Koppejan, 2002).

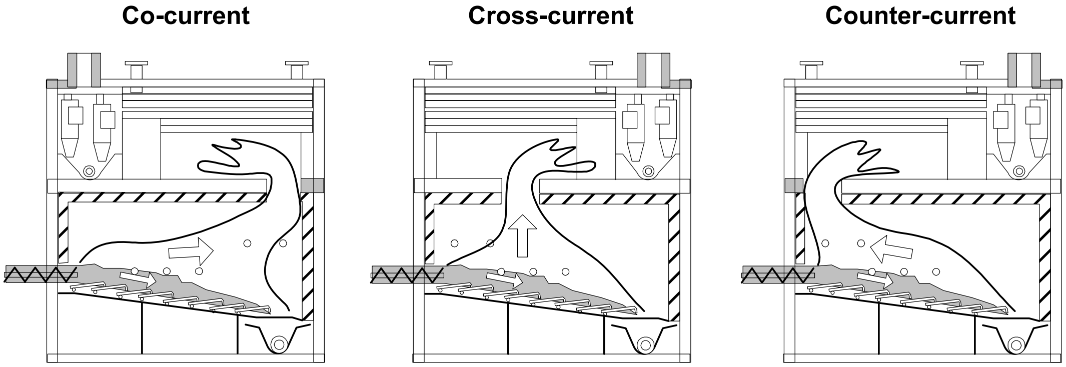


Figure 2-27 Classification of grate combustion technologies: co-current, cross-current and counter-current (Nussbaumer 1995)

Moving grate systems

Moving grate furnaces usually have an inclined grate consisting of fixed and moveable rows of grate bars (see Figure 2-27 and Figure 2-28). They are made of heat-resistant steel alloys and are equipped with small channels in their side-walls for primary air supply. By alternating horizontal forward and backward movements of the moveable sections, the fuel is transported along the grate, whereby un-burnt and burnt fuel particles are mixed and the surface of the fuel bed is steadily renewed. The fuel is evenly distributed over the grate surface (Loo, Koppejan, 2002).

Figure 2-28 Combustion chamber of a moving grate furnace (Polytechnik 2007)

In moving grate furnaces a wide variety of biofuels can be burnt. Air-cooled moving grate furnaces use primary air for cooling the grate and are suitable for wet bark, sawdust and wood chips. For dry biofuels or biofuels with low ash-sintering temperatures, water-cooled moving grate systems are recommended (Loo, Koppejan, 2002).

Travelling grate

Travelling grate furnaces are built of grate bars forming an endless band (like a moving staircase) moving through the combustion chamber. Fuel is supplied at one end of the combustion chamber onto the grate by screw conveyors for example, or it can be distributed over the grate by spreader-stokers injecting the fuel into the combustion chamber (see Figure 2-29). The fuel bed itself does not move, but is transported through the combustion chamber by the grate, contrary to moving grate furnaces where the fuel bed is moved over the grate.

The advantages of travelling grate systems are that they provide uniform combustion conditions and low dust emissions due to the stable and almost unmoving bed of embers. Furthermore, the maintenance or replacement of grate bars is easy to handle. In comparison to moving grate furnaces, however, the fact that the bed of embers is not stoked results in a longer burn-out time (Loo, Koppejan, 2002).

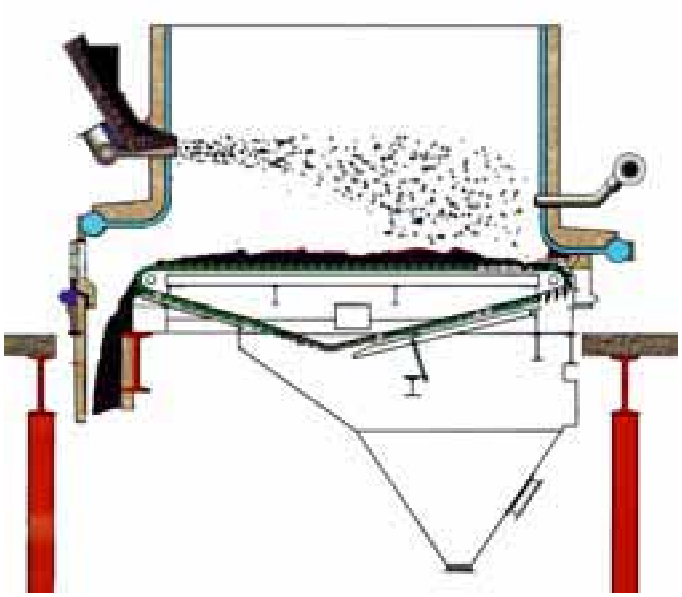


Figure 2-29 Diagram of a travelling grate furnace fed by spreader-stokers (Detroit Stoker Company 1998)

2.3.2 Fluidised bed combustion

Fluidised bed (FB) combustion systems have been applied since 1960 for the combustion of municipal and industrial wastes. Regarding technological applications, bubbling fluidised beds (BFB) and circulating fluidised beds (CFB) have to be distinguished.

Due to the good mixing achieved, FB combustion plants can provide flexibly with different fuel mixtures but are limited in terms of fuel particle size and impurities contained in the fuel. Therefore, an appropriate fuel pre-treatment system covering particle size reduction and separation of metals is necessary for fail-safe operation. Usually a particle size less than 1.6 in is recommended for CFB units and less than 3.1 in for BFB units. Moreover, partial load operation of FB combustion plants is limited due to the need of bed fluidisation.

The low excess air quantities necessary increase combustion efficiency and reduce the flue gas volume flow. This makes FB combustion plants especially interesting for large-scale applications. One disadvantage of FB combustion plants is posed by the high dust loads carried along with the flue gas which make efficient dust precipitators and boiler cleaning systems necessary (Loo, Koppejan, 2002).

2.3.2.1 Bubbling fluidised bed combustion (BFB)

In BFB furnaces (see Figure 2-30) a bed material is located in the bottom part of the furnace. The primary air is supplied over a nozzle distributor plate and fluidises the bed. The bed material is usually silica sand. The advantage of BFB furnaces is their flexibility concerning particle size and moisture content of the biomass fuels. Furthermore, it is also possible to use mixtures of different kinds of biomass or to co-fire them with other fuels. A large disadvantage of BFB furnaces is the difficulties they have at partial load operation, a problem that is solved in modern furnaces by splitting or staging the bed. BFB furnaces are typically used for nominal outputs of more than 17-34 MMBtu/h (Loo, Koppejan, 2002).

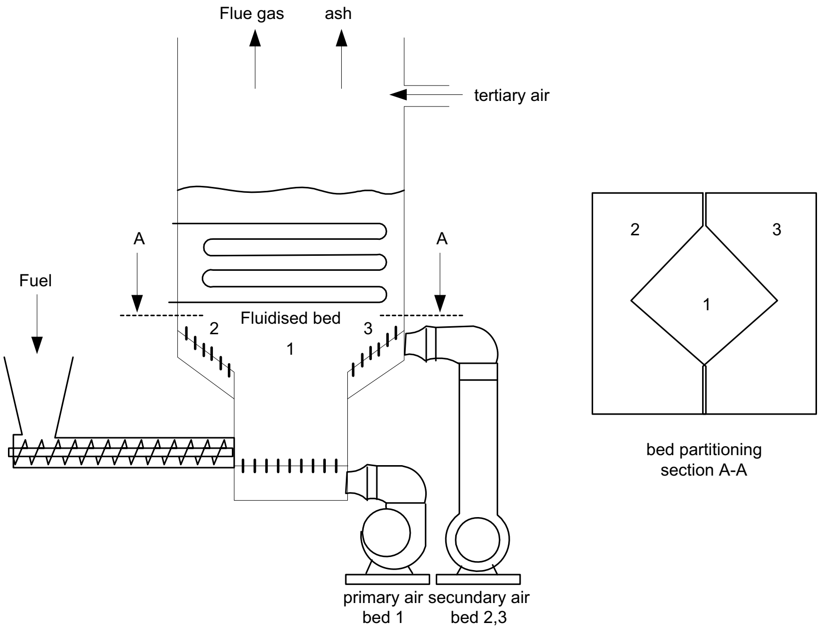


Figure 2-30 Diagram of a BFB furnace (Hein, Schmitz 1995)

2.3.2.2 Circulating fluidised bed (CFB) combustion

By increasing the fluidising velocity to 16 to 33 ft/s and using smaller sand particles (0.008 in to 0.02 in diameter), a CFB system is achieved. The sand particles will be carried with the flue gas, separated in a hot cyclone or a U-beam separator, and fed back into the combustion chamber (see Figure 2-31). The higher turbulence in CFB furnaces leads to a better heat transfer and a very homogeneous temperature distribution in the bed. The disadvantages of CFB furnaces are their larger size and therefore higher price, the even greater dust load in the flue gas leaving the sand particle separator than in BFB systems, the higher loss of bed material in the ash, and the small fuel particle size required (between 0.004 and 1.6 in in diameter). This often causes higher investments in fuel pre-treatment. Moreover, their operation at partial load is problematic. CFB furnaces are usually applied in a power range of more than 100 MMBtu/h (Loo, Koppejan, 2002).

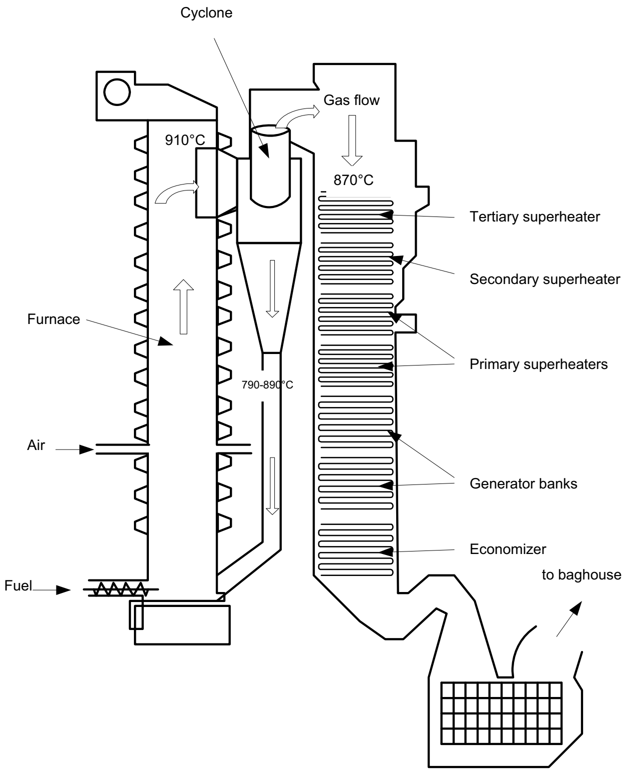
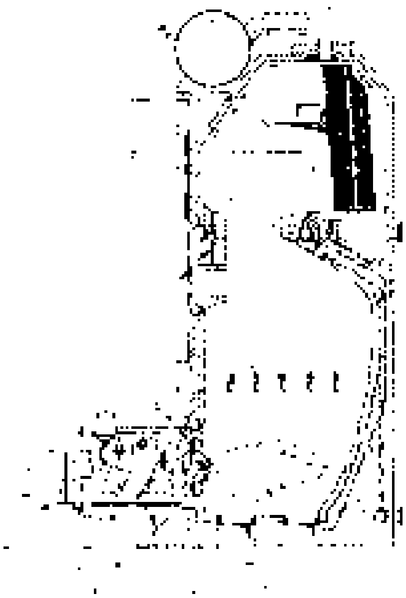


Figure 2-31 Diagram of a CFB furnace (NREL 1996)

2.3.3 Dust combustion

Fuel quality in dust combustion systems has to be quite constant. Fuels such as sawdust and fine shavings are pneumatically injected into the furnace. The transportation air is used as primary air. Start-up of the furnace is achieved by an auxiliary burner. Due to the explosion-like gasification of the fine and small biomass particles, the fuel feeding needs to be controlled very carefully and forms a key technological unit within the overall system. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and an efficient load control can be achieved. Figure 2-32 shows a muffle dust furnace in combination with a water tube steam boiler. This technology is available for thermal capacity between 6.8 and 27 MMBtu/h (Loo, Koppejan, 2002).



1...primary air supply,
2...fuel feed,
3...gasification and partial combustion,
4...flue gas recirculation,
5...ash disposal,
6...secondary air supply,
7...tertiary air supply,
8...water tube boiler.

Figure 2-32 Diagram of a dust combustion plant (muffle furnace) in combination with a water-tube steam boiler (Marutzky, Seeger 1999)

3 Emissions

A short summary of biomass combustion emissions is provided in the following section. Additionally, measurement and reduction methods are summarized. With regard to the reduction methods, primary and secondary measures have to be distinguished: While primary measures are implemented in the combustion process and/or design of the combustion chamber, secondary measures are implemented after combustion process has ended.

More detailed information on formation mechanisms, impacts on health and the environment, and measurement and reduction methods can be found in Nussbaumer 1989, Kaltschmitt, Hartmann 2001, Marutzky, Seeger 1999 or Loo, Koppejan, 2002.

3.1 Conversion factors

Emissions are usually given in a concentration related to a certain O_2-concentration in the flue gas at normal conditions[2] (mg/m³ at 13% O_2 or ppm at 13% O_2); this relation of the emissions to certain O_2-concentrations enables comparability of data. For biomass appliances, the normal O_2-concentrations range from 10 to 13%. Sometimes emissions are related to the fuel input (mg/MJ). Since the measurement of the exact energy input is impractical, especially in medium to large scale appliances, this measurement method is limited to small scale appliances.

The most recent emission limits from the European Commission are usually given in mg/m³ based on 10 % oxygen in the dry flue gas; older regulations refer to 13 % oxygen in the dry flue gas. **In this report, gaseous emissions will be given in mg/m³ at XX % O_2, which always means that emissions are related to the dry volume in m³ at normal conditions (Nm³) at a certain oxygen level in the flue gas (XX % O_2).** According to NYSERDA's specifications, emissions are to be based on an oxygen content of **12 %**. In Table 3-1 the factors for the conversion of the O_2-based emissions in mg/Nm³ for various oxygen levels are shown.

Table 3-1 conversion factors for O_2-based emissions in mg/m³

mg/m³ $_{at\ 10\%\ O2}$	*1*	$0.\dot{9}\dot{0}$	$0.\dot{8}\dot{1}$	$0.\dot{7}\dot{2}$
mg/m³ $_{at\ 11\%\ O2}$	*1.1*	*1*	*0.9*	*0.8*
mg/m³ $_{at\ 12\%\ O2}$	$1.\dot{2}$	$1.\dot{1}$	*1*	$0.\dot{8}$
mg/m³ $_{at\ 13\%\ O2}$	*1.375*	*1.25*	*1.125*	*1*
	mg/m³ $_{at\ 10\%\ O2}$	*mg/m³* $_{at\ 11\%\ O2}$	*mg/m³* $_{at\ 12\%\ O2}$	*mg/m³* $_{at\ 13\%\ O2}$

read the table from the first column to the last row:
Emissions in mg/m³ at 10%O2 · $0.\dot{9}\dot{0}$ *= Emissions in mg/m³ at 11%O2*

The European Commission also provides emission limits for dust in mg/m³ at a certain O_2 level. The factors for the conversion from mg/m³ at 12% O_2 to mg/kg_{fuel} and lb/MMBtu are shown in Table 3-2. For the conversion from mg/m^3 at a certain O_2 level to mg/kg_{fuel}

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[2] pressure of 1 atm and temperature of 32 °F

and lb/MMBtu, the elemental composition and the calorific value of the considered fuels have to be assumed. These assumptions are given in Table 1-2 on page 1-8.

Table 3-2 conversion factors for the conversion of dust emissions from mg/m³ to mg/kg$_{fuel}$ and lb/MMBtu

fuel	$\frac{mg / kg_{fuel}}{mg / m^3_{at12\%O2}}$	$\frac{lb / mmBTU}{mg / m^3_{at12\%O2}}$
pellets	*10.08*	$1.23 \cdot 10^{-3}$
solid wood	*9.31*	$1.35 \cdot 10^{-3}$
wood chips	*8.44*	$1.64 \cdot 10^{-3}$

3.2 Carbon Monoxide (CO)

3.2.1 General

Carbon monoxide emissions can be regarded as the indicator of the combustion quality. Conversion of fuel carbon to CO_2 takes place through several elementary steps, and through several different reaction paths. CO is the most important final derivative. It is oxidized to CO_2 if oxygen is available.

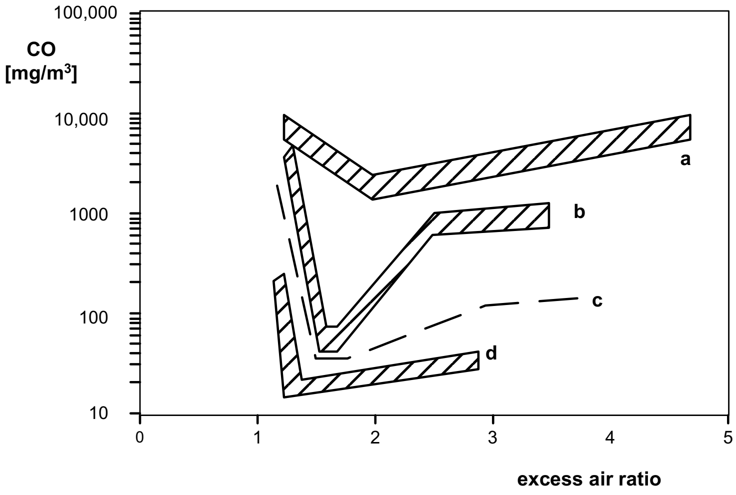
The rate at which CO is oxidised to CO_2 depends primarily on temperature. In addition, sufficient residence time is important to achieve low CO emission levels, mainly because CO is generally a later intermediate than hydrocarbons. Furthermore, enough oxygen must be available and mixed with the fuel for the combustion process.

CO emissions are caused by incomplete combustion, which is mainly a result of:

- inadequate mixing of the combustion air and the fuel in the combustion chamber, producing local fuel-rich combustion zones;
- an overall lack of available oxygen;
- combustion temperatures too low;
- residence times too short;

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.

Figure 3-1 shows the CO emission level as a function of excess air ratio for different biomass combustion applications. For each system an optimum excess air ratio exists: higher excess air ratios will result in a decreased combustion temperature while lower excess air ratios will result in inadequate mixing conditions.



a) simple, manually charged wood boiler;
b) downdraught wood log boiler;
c) automatic furnace with combustion technology as of 1990;
d) automatic furnace with enhanced combustion technology as of 1995

Figure 3-1 CO- emissions - CO vs. excess air ratio (Nussbaumer 1989)

3.2.2 Measurement

CO emissions are measured directly after the flue exit of the appliance in an insulated pipe and results are given in ppm per dry flue volume (m³) at normal conditions. In order to reference the emissions to an oxygen content of 10, 12 or 13 %, the O_2 and/or the CO_2 concentration have to be measured as well.

3.2.3 Reduction

In order to keep CO and correspondingly Organic bound carbon/organic gas (OGC) emissions low, optimal conditions for a high burnout rate of CO must be ensured. These conditions are often summarized as the ***3T-rule*** **(Time, Temperature, Turbulence)** for combustion quality. In addition, the correct amount of **oxygen (air)** must participate in the combustion.

Residence TIME of fuel and oxygen in the combustion zone
Figure 3-2 shows the correlation between CO burnout and residence time in an ideal stirring reactor. The higher the combustion temperature and the oxygen content, the lower residence times are necessary to reach high CO burnout rate.

The residence time is a function of the combustion chamber volume and combustion gas flow. The combustion chamber has to be designed to guarantee high residence times also at high load operation and to avoid undesirable conditions (e.g. dead zones, insufficient mixing, etc.)

High TEMPERATURES of the gases in the combustion zone
The reaction rate of CO to CO_2 depends primarily on temperature if the mixture of fuel and oxygen as well as a certain residence time are given. The temperature of the combustion zone is influenced by the materials used for the combustion chamber. If ceramics are used to line the combustion chamber, temperatures will be higher than if the combustion chamber was built of steel (must be cooled with water).

In addition, the air fuel ratio impacts the combustion temperature, as shown in Figure 3-3. The higher the air fuel ratio, the lower combustion temperatures will be.

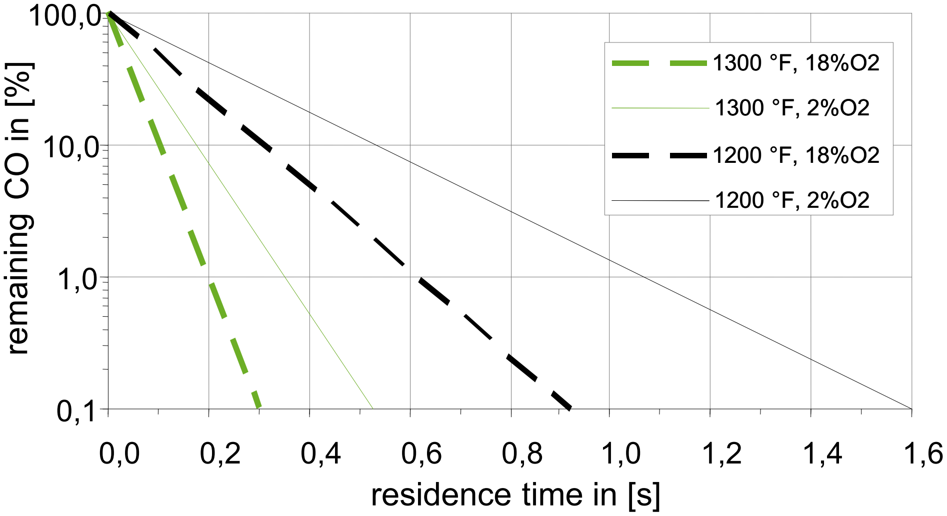


Figure 3-2 CO-rest as function of residence time, combustion temperature and oxygen-concentration in an ideal stirring reactor (Leuckel, Roemer 1979)

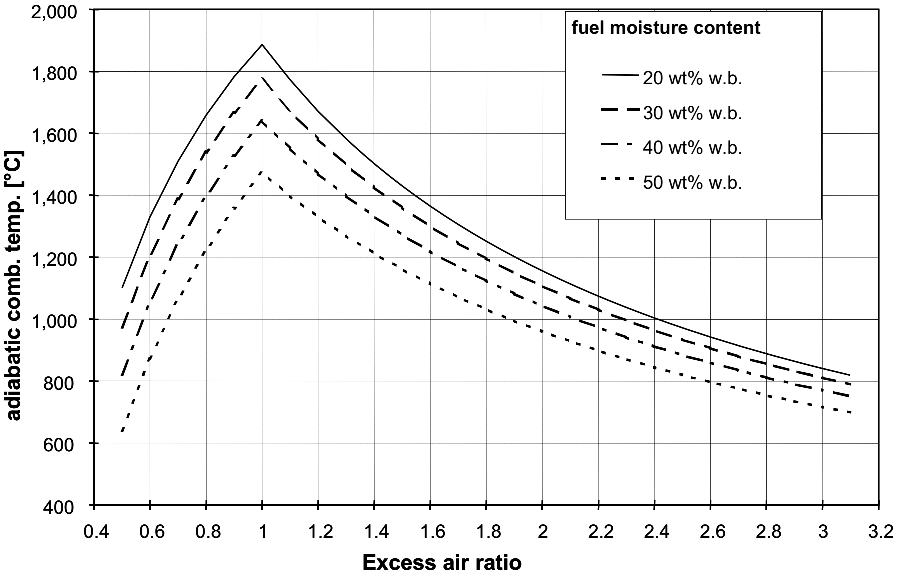


Figure 3-3 Relationship between the adiabatic combustion temperature and the excess air (air fuel) ratio (Nussbaumer 1989)

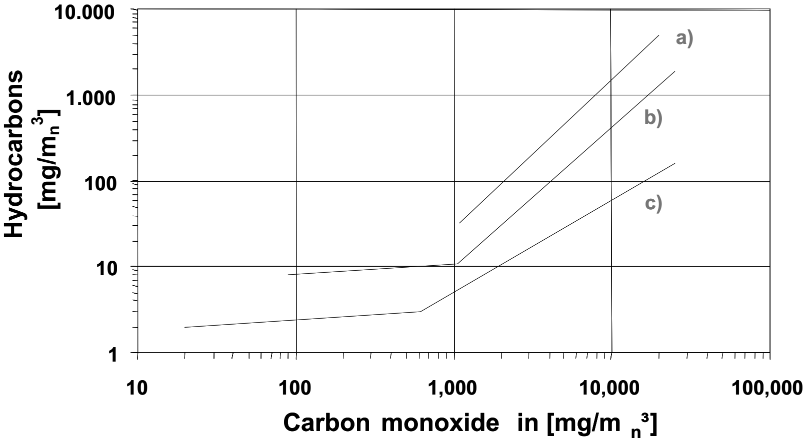
High TURBULENCE in combustion zone

The mixing quality of fuel and oxygen is described by the turbulence in the combustion zone. The turbulence is primarily influenced by the flow velocity of the combustion air. With increasing flow velocities, the mixing of fuel and air becomes increasingly ideal. This again results in lower amounts of air needed for the combustion and thus higher combustion temperatures (see Figure 3-3).

3.3 Total Organic Bound Carbon/Organic Gaseous Substances (OGC)

3.3.1 General

OGC emissions from biomass appliances are directly linked to high CO emissions. In Figure 3-4 the measurement results of the correlation between hydrocarbon and CO-emissions for wood appliances are shown. If CO-emissions are low, hydrocarbon emissions will be 1/100 to 1/10 of the CO-emissions.



a) Wood stove, b) solid wood boiler with underburning technology,
c) Wood chips boiler with horizontal feed

Figure 3-4 Correlation of hydrocarbon and CO-emissions in wood appliances (Nussbaumer 1989)

3.3.2 Measurement

OGC emissions are measured directly after the flue exit of the appliance in an insulated pipe and results are given in ppm. In order to reference the emissions to an oxygen content of 10, 12 or 13 %, the O_2 and/or the CO_2 concentration have to be measured as well.

3.3.3 Reduction

If CO emissions are low, OGC emissions will also be low for biomass combustion processes. Therefore, no separate reduction controls for OGC emissions are necessary for biomass combustion.

3.4 Dust · Particulate Matter (PM) · Totals Suspended Particulate Matter (TSP)

3.4.1 General

Particulates formed during biomass combustion can be divided into bottom ashes and fly ashes. The fly ash fraction typically consists of a coarse and a fine mode. While the coarse mode (particles larger than some µm) is simply due to the ash entrainment from the fuel bed, the formation pathways of the fine mode (so-called aerosols, with a particle diameter <1 µm) are much more complex.

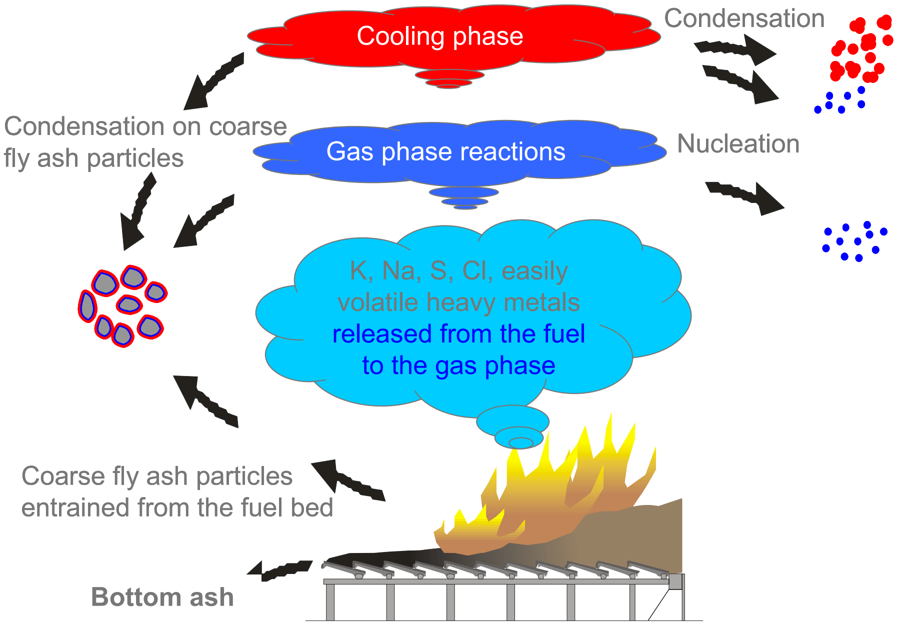


Figure 3-5 Ash and aerosol formation processes during biomass combustion

The basic mechanisms concerning aerosol formation in combustion processes are generally well known from former research work (Friedlander 1977). Volatile ash forming compounds specific to biomass combustion such as K, Na, S and Cl as well as easily volatile heavy metals (Zn and Cd), are released from the fuel into the gas phase and subsequently undergo gas phase reactions. As soon as the vapour pressure of a compound exceeds the saturation pressure, which can happen either due to a high formation ratio of this compound or by cooling of the flue gas, particle formation by nucleation or condensation of these vapours on existing surfaces takes place. Nucleation and condensation are always competing processes, and if enough surface for condensation is available, nucleation can partly or even totally be suppressed. Otherwise, very small (some nm) aerosol particles are formed. As soon as these particles are formed, they start to coagulate with other aerosols or with coarse fly ashes. Figure 3-5 gives an overview of the different ash and aerosol formation processes (for more details see Brunner et al 2004).

Next to the formation path of the fly ash fraction by low volatile minerals, heavy metals and salt, aerosols can also be formed due to incomplete combustion. In this case unburnt carbon, fine wood particles, charcoal, soot, tar, etc. are emitted as dust. Therefore complete combustion (low CO emissions) is necessary to keep dust emissions as low as possible. In Figure 3-6 the chemical compostions of dust samples from an appliance that was operated under optimal conditions (low CO emissions) and from a wood stove that was operated under poor conditions (high CO emissions) are shown.

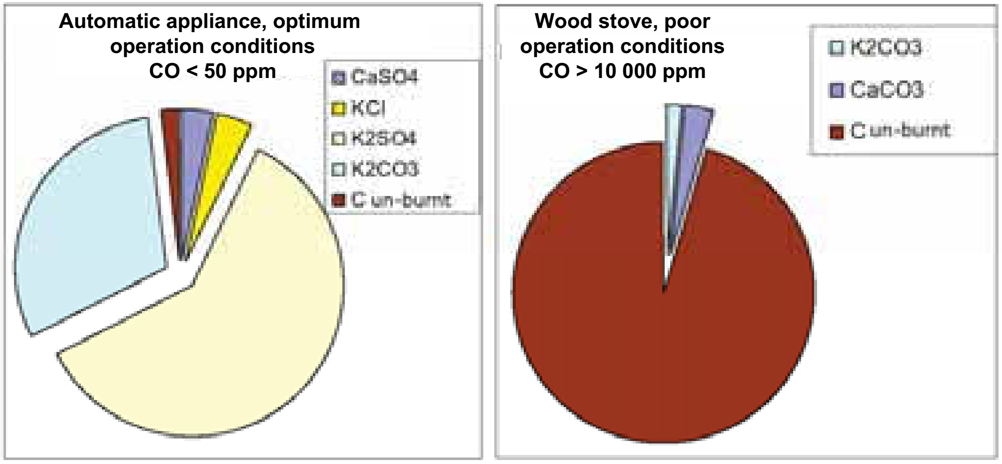


Figure 3-6 Chemical composition of dust samples from different biomass appliances and operation conditions (Klippel 2007)

While the unburned fraction of an automatic appliance under optimum operation conditions is about 2% by weight, the unburned fraction of the wood stove that was operated under poor conditions is about 98% by weight. Considering that the amount of salts is approximately equal for the automatically and the manually stoked appliances, overall dust emissions from the wood stoves will be a multiple higher than those of the automatic system.

Definition and characteristics of coarse fly ashes and aerosols:

- Coarse fly ashes:
    - ashes entrained from the fuel bed
    - particle sizes < 100 µm
    - mainly consist of refractory species such as Ca, Mg, Si as well as smaller amounts of K, Na, Al

- Aerosols:
    - colloidal solid (dust) or fluid (fog) particulate matter in gases
    - formed from condensed ash vapours released from the fuel to the gas phase during combustion
    - particle sizes between 1 nm and 1 µm
    - mainly consist of K, Na, S, Cl, Zn and Pb
- Fly ashes = coarse fly ashes + aerosols

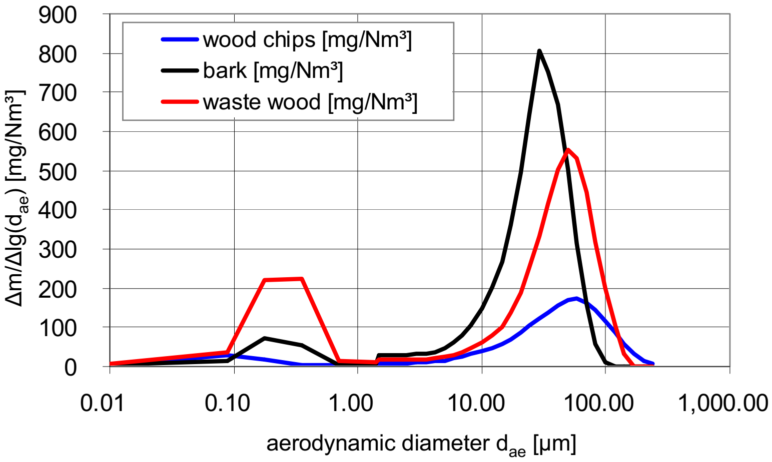


Figure 3-7 Particle size distributions of fly ashes in the flue gas at boiler outlet in dry flue gas at 13% O_2 (Brunner et al 2004)

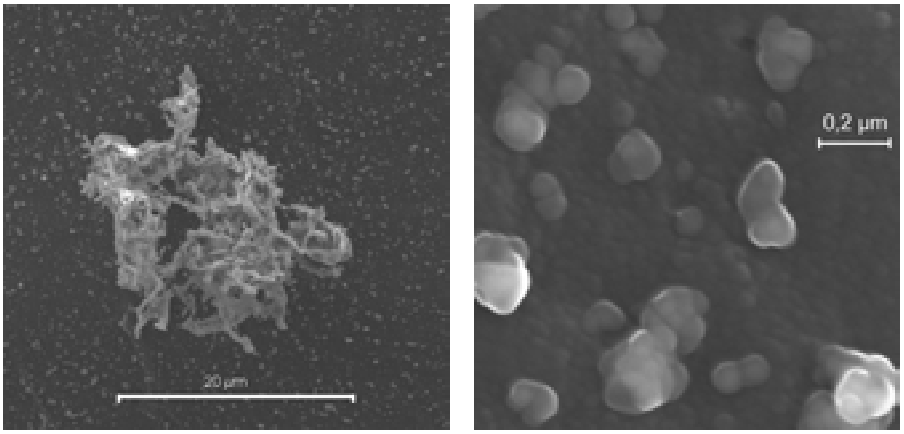
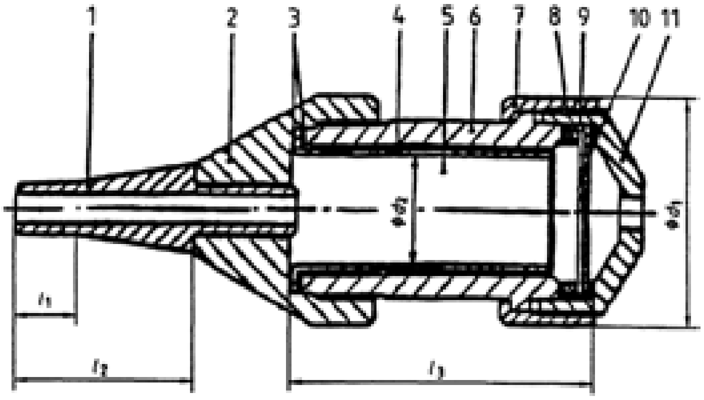


Figure 3-8 SEM images of coarse fly-ash (left) and aerosol particles (right) Description: Samples from wood combustion in a grate furnace; biomass fuel: wood (beech). Equipment used: Scanning Electron Microscopy (SEM) (Brunner et al 2004)

3.4.2 Measurement

The dust content is determined discontinuously (usually over a period of 30 minutes) using a gravimetric or electrostatic method. Suitable test equipment is shown in Figure 3-9.



1. *removable sampling probe*
2. *union nut*
3. *seal*
4. *filtering bush*
5. *quartz wool*
6. *filter housing*
7. *union nut*
8. *clamping ring*
9. *flat filter support*
10. *flat filter*
11. *end case*

Figure 3-9 Tubular filter device for dust measurement

With this method the total coarse and the major fine dust fraction in the flue gas is measured. Filtration efficiencies of 99.5% for 0.3 µm and 99.9% for 0.6 µm respectively are required. In order to avoid the condensing of semi-volatiles, a minimum flue gas temperature of 270 °F is required. More information about measurement methods for dust can be found in VDI 2066, EN 13284-1 or Nussbaumer 2008.

Results are given in mg per dry flue volume (m^3) at normal conditions. In order to reference the emissions to an oxygen content of 10, 12 or 13 %, the O_2 and/or the CO_2 concentration have to be measured as well.

3.4.3 Reduction

3.4.3.1 Primary measures

The study of the primary reduction of dust emissions is a fairly new field of research. Oser, Nussbaumer 2004 developed a **low-particle concept** for biomass appliances:

- operation at very low air-fuel ratio in the firebed (Excess air ratio in firebed: 0.2-0.4)
- gas tightness of combustion and fuel stoking unit
- operation at low overall air-fuel ratio (excess air ratio 1.3-1.6)
- clear staging of secondary air and prevention of backflow of secondary air into the firebed.
- adequately large dimensioned combustion chamber for a high firebed
- high burnout rate of OGC
- sufficiently high temperatures in primary combustion zone

3.4.3.2 Secondary measures

To reduce dust emissions, diverse technologies with different efficiencies and function principles were developed. Since costs for investment, operation and maintenance are, depending on the technology, quite high and limits are given to operating conditions, these technologies were primarily used in large and medium scale appliances. Due to strict dust emission limits in small scale appliances, dust control technologies were recently adopted for the utilization in small appliances as well.

Table 3-3 gives an overview of particle sizes removed and efficiencies reached by medium to large scale dust control technologies.

Table 3-3 summary of typical sizes of particles removed by various particle control technologies

Particle control technology	Particle size (μm)	Efficiency (%)
Settling chambers	> 50	< 50
Cyclones	> 5	< 80
Multicyclones	> 5	< 90
Electrostatic precipitator	< 1	> 99
Baghouse filters	< 1	> 99
Spray chambers	> 10	< 80
Impingement scrubbers	> 3	< 80
Cyclone spray chambers	> 3	< 80
Venturi scrubbers	> 0.5	< 99

3.4.3.2.1 Cyclones

Particle separation in a cyclone is based on the principle of gravity in combination with centrifugal forces. Gas and solid particles are exposed to centrifugal forces, whereby heavy particles experience higher centrifugal forces and therefore hit the wall and slide down into a container. The gas flow into the cyclone can be **tangential** (Figure 3-10) or **axial**. In the second case a fan is necessary to bring the gas into rotation.

The separation efficiency of a cyclone can be improved by increasing the centrifugal force through reduction of the cyclone diameter. In order to prevent the loss of capacity, several cyclones can be used in parallel; this is called a **multicyclone** and is illustrated in Figure 3-11. There are however disadvantages of multicyclones due to design complexities that increase costs. They also require an increased pressure drop, and thus have a higher energy consumption.

Cyclones represent a simple technology which are highly reliable and require little maintenance. The requirements regarding the flue gas quality are low. Cyclones are used at pressure levels from 0.01 to 100 atm and can withstand temperatures of up to 1650 °F. The efficiency from 80 – 90% is quite low and corresponds to dust loads of 0.150 to 0.075 lb/MMBtu when biomass is used. This technology is therefore quite often used as pre-precipitator.

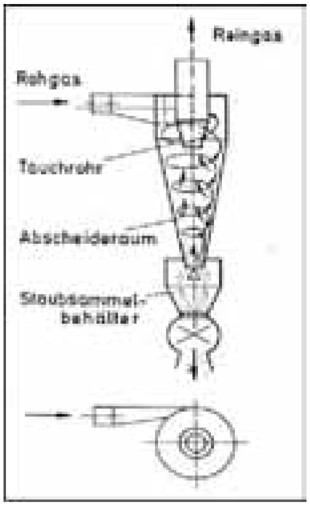


Figure 3-10 Tangential cyclone (Jirkowsky et Al, 2002)

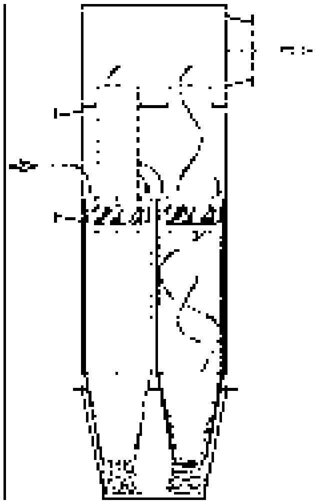


Figure 3-11 Axial multicyclone (Jirkowsky et Al, 2002)

3.4.3.2.2 Electrostatic precipitator

In an electrostatic filter, the particles are first electrically charged and then exposed to an electrical field whereby they are attracted to an electrode. Periodically, this electrode is cleaned through vibration, where the dust falls off the electrode into a collection unit. Efficiencies can be >99%. This operation principle is shown in Figure 3-12.

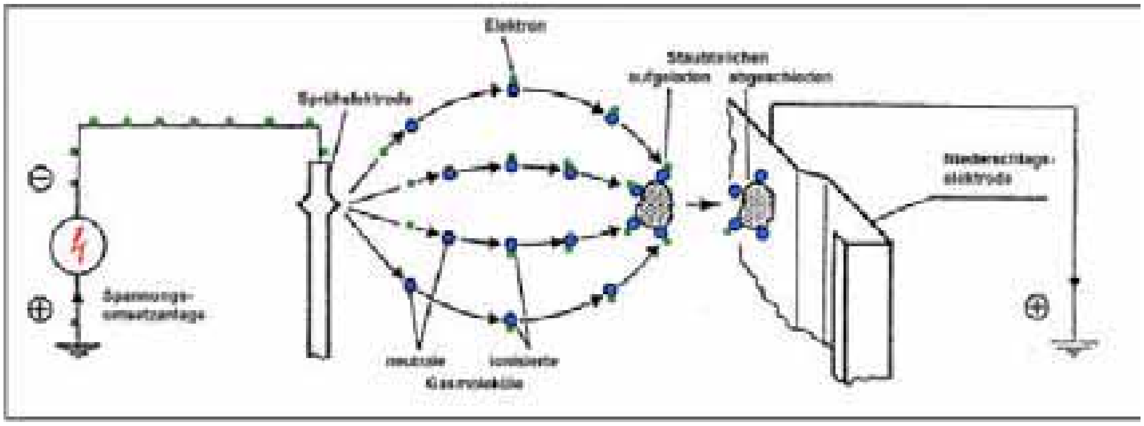


Figure 3-12 Operation principle of electrostatic precipitator (Jirkowsky et Al, 2002)

Different variations of electrostatic precipitators are available:

The **dry electrostatic precipitator** works as illustrated in Figure 3-12. In order to collect the precipitated particles, discontinuous operating rappers are used.

In **wet electrostatic precipitators,** the flue gas is completely saturated before entering the precipitator. This saturation reduces the electrical charging of the particles and increases the efficiency.

Condensing wet electrostatic precipitators are cooled by ambient air, which leads to the cooling of the flue gas and the condensation of water on the inner surface of the precipitator. The condensed water flows down the electrode and cleans it at the same time.

3.4.3.2.3 Baghouse filters

Baghouse filters consist of a filter or cloth tightly woven from special fibres and hung in a closed construction through which flue gas passes. The separation efficiency of bag filters is quite high, even with high flue gas flow rates and high particle content. The first layer of particles actually improves the filtration efficiency. However, as more particles settle on the cloth, the pressure drop increases. The cloth is thus periodically cleaned by vibration or pressurized air (Figure 3-13).

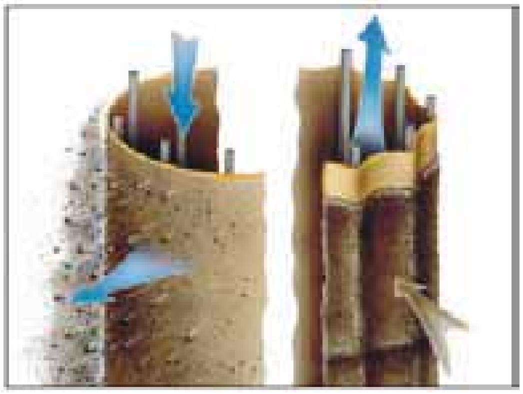


Figure 3-13 Pulse jet baghouse filter (Jirkowsky et Al, 2002)

The operating temperature range is limited to approximately 480 °F; there is a significant risk of fire if this temperature is exceeded or when un-burnt carbon is present in the fly ash. In order to limit the amount of particles settling on the filter and to reduce the chance of fire through sparks, a cyclone can be used. When the operating temperatures are too low, tars present in the flue gas may condense and clog the cloth. In addition, the moisture in the flue gas is limited to a maximum of 20 %.

Baghouse filters reach efficiencies of greater than 99% and therefore reduce the emissions of wood appliances below 0.010 lb/MMBtu.

3.4.3.2.4 Scrubbers

In scrubbers, particles are scrubbed out from the flue gas by water droplets of various sizes depending on the type of scrubber used. The particles are removed by the collision and interception between droplets and particles. Upon impact, the particles are wetted and effectively removed by the water droplet. The more droplets formed, the more efficient the unit will be. The droplets must therefore be small. Smaller diameter spray nozzles will produce smaller droplets, but will also result in higher pressure drops, consuming more energy. Since efficiency increases as the droplet size decreases, the efficiency also increases with increasing pressure drop.

Several types of scrubbers exist. In a **countercurrent scrubber** for example, the flue gas is introduced at the bottom side of the unit and flows upward against the current with respect to the settling of the atomised liquid droplets. In a **cross-flow scrubber**, the flue gas flows perpendicular with respect to the settling of the atomised spray water droplets. Although two sets of sprays atomise the water in horizontal directions, the settling of the resulting droplets is still downward, perpendicular to the direction of the flue gas. A **cyclone spray chamber** (Figure 3-14) is a combination of an ordinary spray and a cyclone. A **venturi scrubber** (Figure 3-14) works with a high pressure nozzle in which the flue gas and the liquid are atomised.

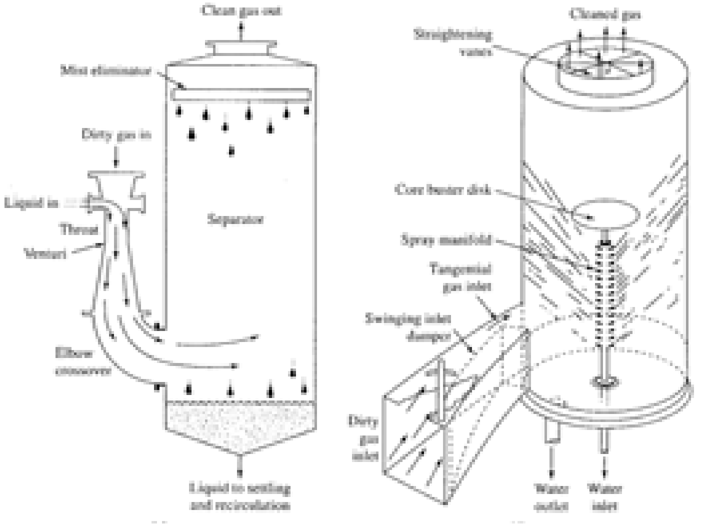


Figure 3-14 Venturi scrubber (left), cyclone spray chamber (right) (Corbitt 1999)

Scrubbers reach efficiencies of up to 99%. They are usually only used if acid components in the flue gas (HCl, SO_2) have to be precipitated as well (FNR 2005). This is necessary for contaminated biomass or for non wood biomass with high chlorine and/or sulphur contents. For medium and large scale wood biomasses appliances this technology is not relevant, but some scrubber systems – always combined with flue gas condensation – have recently been developed for small scale appliances.

3.4.3.2.5 Flue gas condensation

The primary aim of flue gas condensation is the heat recovery from fuels with a high water content. An additional effect of flue gas condensation is that the dust load is precipitated by the condensing water and dust loads can be reduced down to 0.060 lb/MMBtu (FNR 2005). In medium to large scale appliances a cyclone should be used before flue gas condensation. In order to enable flue gas condensation, a return temperature of about 85 °F should be possible.

3.5 Nitroxen Oxides (NO_X)

NO_X emissions from biomass combustion applications are mainly a result of complete oxidation of nitrogen in the fuel. 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. In Figure 3-15 the diverse reaction paths of the nitrogen in the fuel are exhibited. It shows that most of the nitrogen in the fuel is converted to N_2, and some N is bound in the ash, but there is also a fraction of nitrogen in the fuel that is converted to NO and N_2O.

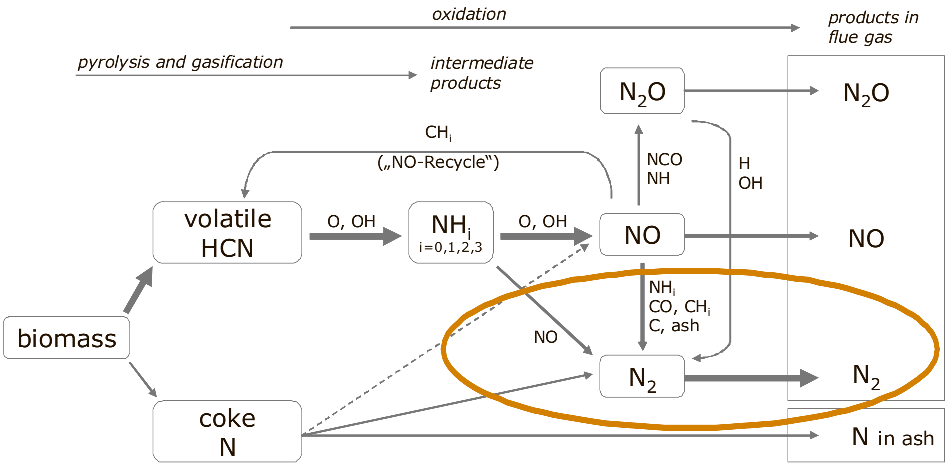


Figure 3-15 Formation paths of biomass fuel nitrogen

Besides the **fuel NO_X mechanism** described in Figure 3-15, two further mechanisms – the **thermal NO_X mechanism** and **the prompt NO_X mechanism -** result in increased NO_X emissions. These two NO_X mechanisms gain relevance at combustion temperatures above 2300 °F (1300 °C), as shown in Figure 3-16. Since these temperatures are hardly ever reached during biomass combustion, the thermal and prompt NO_X mechanisms are not considered to be relevant for biomass combustion. Figure 3-16 also shows that typical NO_X-emissions for wood combustion are in the range of approximately 90 to 250 mg/m³. For herbaceous biofuels, the typical NO_X emissions are between 250 and 550 mg/m³, because the fuel bound nitrogen is generally higher in herbaceous fuels than in wood.

As Figure 3-16 shows, the nitrogen content of the fuel and the NO_X emissions are directly related for biomass combustion, meaning that if the nitrogen content of the fuel is high, the NO_X emissions will be high as well. This relationship is, however, not linear. Conversion rate of fuel bound nitrogen in the fuel to NO_X decreases with increasing nitrogen content.

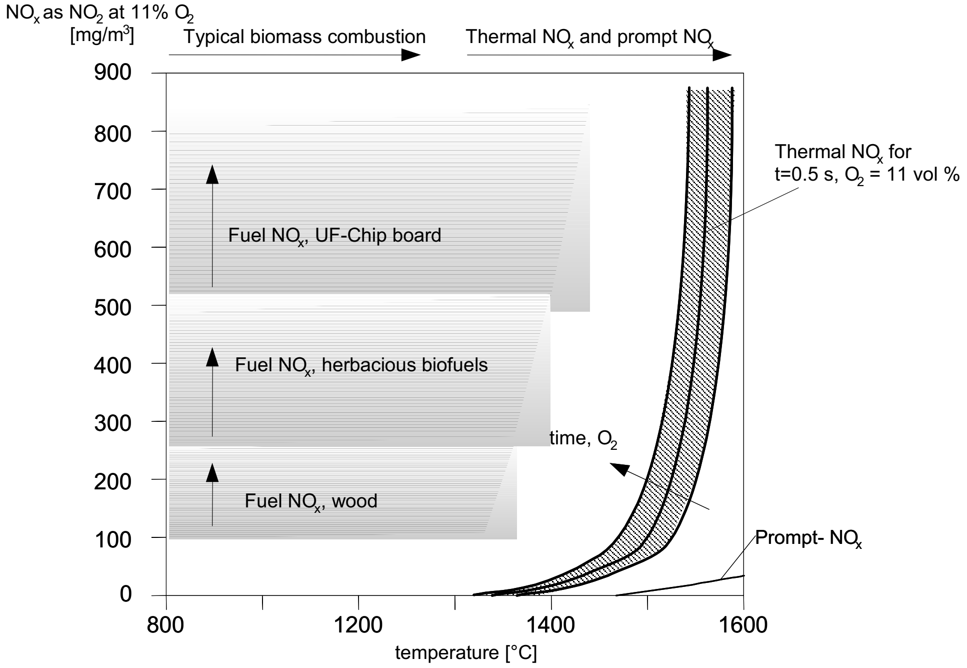


Figure 3-16 NO_X-emissions - dependence on the fuel and the furnace temperature (Nussbaumer 1997)

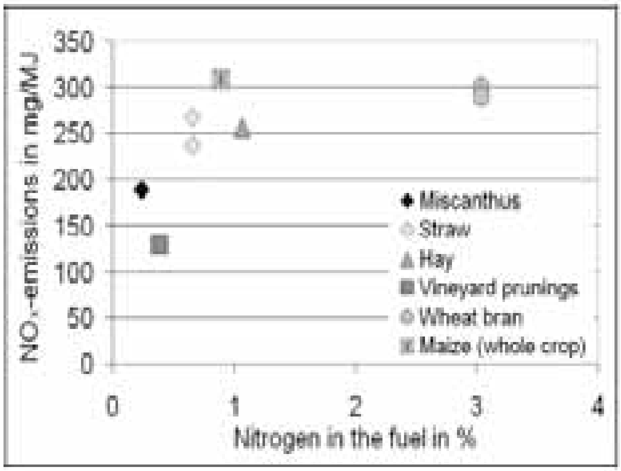


Figure 3-17 Correlation of the nitrogen content of the fuel and NO_X-emissions (Wopienka et al. 2007)

3.5.1 Measurement

NO_X emissions equal the sum of NO and NO_2 emissions. They are measured directly after the flue exit of the appliance in an insulated pipe, and results are given in ppm. In order to refer the emissions to an oxygen content of 10, 12 or 13 %, the O_2 and/or the CO_2 concentration have to be measured as well.

3.5.2 Reduction

3.5.2.1 Primary measures

To reduce NO_X emissions by primary measures, three different concepts are available.

Air staging

Primary and secondary combustion air is injected in clearly separated zones or combustion chambers. Between these zones the NO is reduced in the reduction zone, where an excess air ratio of 0.7 – 0.8 and temperatures from 2000 to 2200 ºF are required. With this technology, a NO_X reduction in the range of 30 – 60% can be reached.

In Figure 3-18 the concept for air staging and flue gas recirculation is shown.

Flue gas recirculation

The recirculation of flue gas is primarily used to reduce or control combustion temperatures and therefore the formation of thermal NO_X. Thermal NO_X is however not considered to be a relevant formation mechanism for biomass combustion (see chapter 0). Some reduction of fuel NO_X is nevertheless achieved by flue gas recirculation.

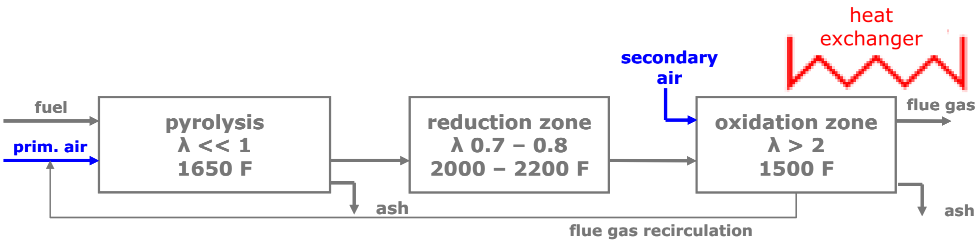


Figure 3-18 Concept of air staging and flue gas recirculation (adapted from Zuberbuehler 2002)

Fuel staging

The concept of fuel staging aims at the same mechanisms as air staging by producing a reduction zone where NO is reduced. In the reduction zone, an excess air ratio from 0.6 – 0.8 is required. Approximately 70% of the fuel is stoked as primary fuel. As secondary fuel, biomass producer gas, shavings, and sawdust, are possible. With this reduction mechanism, a NO_X reduction in the range of 50 to 70% can be achieved. In Figure 3-19 the concept for fuel staging is shown.

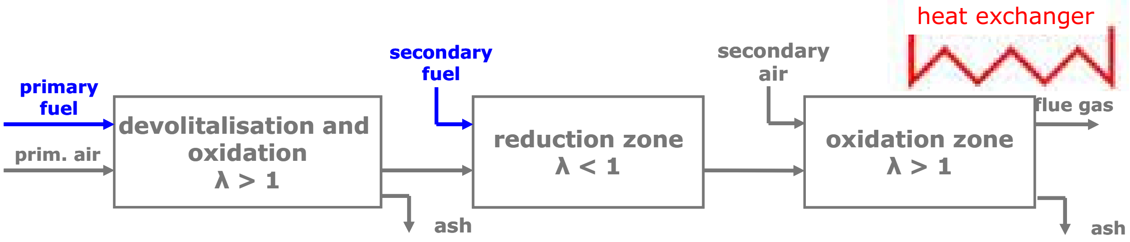


Figure 3-19 Concept of fuel staging for primary NO_X reduction

3.5.2.2 Secondary measures

To reduce NO_X emissions by secondary measures, two different concepts were developed. Both concepts are applied in large scale appliances only because operation requirements and costs are too high for small and medium scale appliances. Figure 3-20 shows typical NO_X emissions for biomasses and the NO_X reduction potential of primary and secondary measures.

For wood biomass combustion, secondary cleaning measures for NO_X are usually not necessary because sufficient NO_X reduction can be achieved by primary measures (FNR 2005).

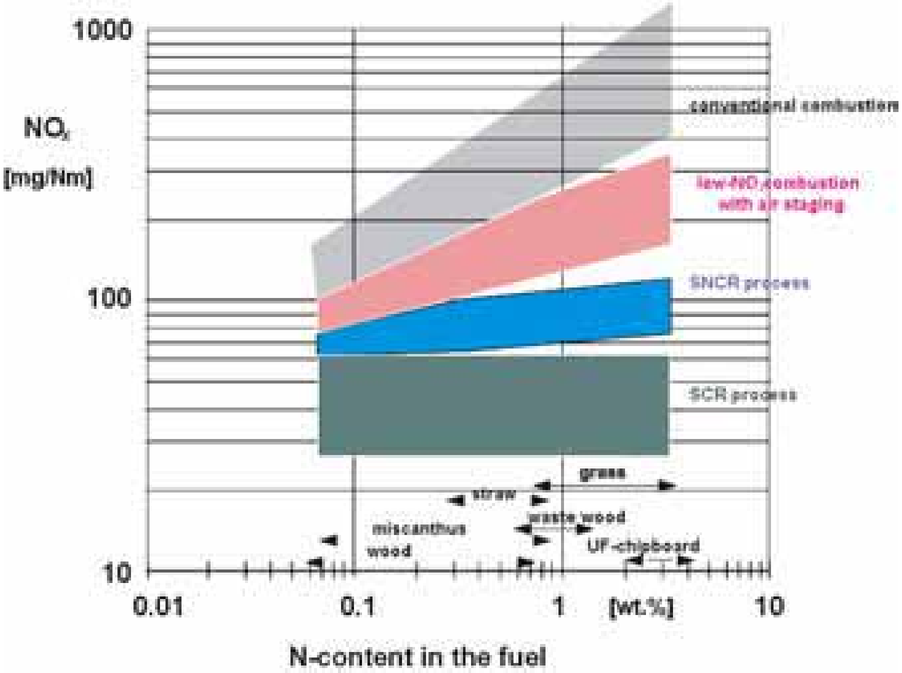


Figure 3-20 NOx-emissions and reduction potential – overview (*Hasler et al. 2000*)

Explanations: NOx calculated as NO_2 and related to the dry flue gas at 11 vol.% O2

SNCR: selective non catalytic reduction

In the SNCR process a reducing agent (ammonia or urea) is injected into the hot flue gas (in the afterburner chamber). The reducing agent reacts with the NO_X to create elemental Nitrogen. The temperature range for optimal reaction is between 1550 and 1750 °F. If the temperature is too low, the reaction will be slow and if temperature is too high, side reactions will become more prominent and NO and N_2O will be formed. To reach the maximum NO_X removal, the reducing agents have to be added hyperstoichiometrically (1.5 for ammonia and 2 for urea). This leads to the emission of ammonia or urea in the flue gas. To keep these emissions low, the reducing agents have to be metered exactly. A NO_X reduction of 60 to 70% can be reached.

SCR: selective catalytic reduction

The SCR process works at the same principle as the SNCR process, but catalysts are used to accelerate the reaction and to keep reaction temperatures lower. Platinum, tungsten, titanium or vanadium oxide based materials are used as catalysts. The optimum temperature level for ammonia is between 430 and 520 °F, and between 750 and 840 °F for urea. Due to the higher reaction rate, the reducing agents can be added nearly stoichiometricly thus resulting in low emissions of ammonia or urea. A NO_X reduction of 80 – 95% can be achieved. A drawback of this technology is, however, the danger of the deactivation of the catalyst by alkaline compounds and heavy metals.

4 European Test Methods

Table 4-1 gives an overview of the European standards for biomass (solid fuel) combustion technologies. These standards consider requirements with respect to materials, design and construction, safety, performance, appliance instructions, marking, evaluation of conformity and type testing of the appliance. The performance requirements include a minimum thermal efficiency as well as limits for CO and optionally for OGC and dust.

Table 4-1 European standards applied for biomass combustion technologies

type	*standard*	*comments*
	BOILERS	
pellets, solid wood, wood chips, combined technologies	*EN 303-5*	*<1000 MBtu/h* *Solid fuels* *max. water temperature: 100 °C,* *max. operating pressure: 6 bar*
boiler also providing direct heat	*EN 12809*	*< 170 MBtu/h* *solid fuels (except for pellets)* *max. operating pressure: 2 bar*
	ROOM-HEATERS	
cook stoves	*EN 12815*	*solid fuels (except for pellets)* *manual stoking* *hot water production also possible*
fireplace insets with or without doors	*EN 13229*	*solid fuels (except for pellets)* *manual stoking* *with or without combustion chamber doors,* *no fan* *hot water production also possible*
masonry heaters (insets)		
wood stoves (continuous or intermitted operation)	*EN 13240*	*solid fuels (except for pellets)* *manual stoking* *with combustion chamber doors* *no fan* *hot water production also possible*
pellet stoves	*EN 14785*	*< 170 MBtu/h* *pellets only* *with or without fan* *closed fire doors only* *hot water production also possible*
masonry heaters (handcrafted)	*EN 15250*	*solid fuels (pellets stoked manually)* *intermittend buring* *no fan* *no boiler function*

4.1 Residential heating systems

4.1.1 EN 303-5: Heating boilers for solid fuels, hand and automatically stoked

Full title: EN 303-5. Heating boilers for solid fuels, hand and automatically stoked, nominal heat output of up to 1025 MBtu - Terminology, requirements, testing and marking

Prepared by/approved/amends: Prepared by CEN TC 57 *Central heating boilers*. Approved on 12 November 1998 and published in April 1999. The standard is to be revised: A first proposal has been elaborated and the discussion at CEN-level started in spring 2008.

Appliances: Boilers for hydronic heating systems up to nominal heat output of 1025 MBtu/h with manual and automatic stoking. Minimum heat loss of boilers has to stay within the requirements of the standard; otherwise the standard does not apply.

Fuels: Wood (logs, chops, briquettes, pellets, sawdust) and fossil fuels (coal, coke, anthracite).

Test Methods: Specifies test methods for heat output, efficiency and emissions (CO, OGC, dust); measurement methods for emissions are not defined.

Availability: Sharing is restricted; English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=70316

Table 4-2 summary of EN 303-5 with regard to testing procedure

MANUALLY STOKED BOILERS	AUTOMATICALLY STOKED BOILERS
TEST DURATION AND NUMBER OF TESTS	
○ Before the tests may begin, the boiler has to be brought to its **normal working condition** using a complete fuel load (up to the maximum filling height). Testing can start when the necessary basic firebed is established. ○ **Test duration** starts immediately after placing the fuel on the basic firebed and ends with the refill. ○ For the **nominal and partial heat loads**, two nominal combustion periods and one combustion period are required respectively.	○ Before the tests may begin, the boiler has to be heated up to its **normal working condition**. Testing can start when the necessary basic firebed is established. ○ For the **nominal and partial heat loads,** test duration has to be at least 6 hours.

<table>
<tr><th>MANUALLY STOKED BOILERS</th><th>AUTOMATICALLY STOKED BOILERS</th></tr>
<tr><td colspan="2">HEAT FLOW - EFFICIENCY</td></tr>
<tr><td colspan="2">o At **nominal heat load** the mean value of the flow temperature has to lie in the range of 155 to 195 °F and the average temperature difference of flow and return has to lie in the range of 50 and 75 °F. In addition, the difference value between the ambient air temperature and the mean value of flow and return temperature has to be not less than 105 °F.
o At **partial heat load** the same conditions as for nominal heat load have to be fulfilled, except for the requested temperature difference of flow and return temperature.
o The **efficiency** is determined on the basis of the net calorific value and has to be calculated with the direct method. The indirect calculation enables control of the measurement accuracy of the test rig and determination of the single losses.</td></tr>
<tr><td colspan="2">EMISSIONS</td></tr>
<tr><td>o At **nominal heat** load, the test period covers two successive combustion periods (including refill), CO_2 or O_2, CO and OGC (and NO_X where appropriate) are measured during the complete test duration.
o At **partial heat load** the test period covers one combustion period, CO_2 or O_2, CO and OGC are measured.
o For the measurement of **TSP** at **nominal heat load,** every combustion period is split into two equal time segments. Measurements start in each case at the beginning of a time segment, with the first measurement beginning immediately after the fuel is placed and the door closed. The suction time per filter is limited to 30 min. The average TSP content is determined from the 4 minimum half-hour values taken at half our intervals.</td><td>o At **nominal heat,** CO_2 or O_2, CO and OGC (and NO_X where appropriate) are measured over the entire test duration.
o At **partial heat load** CO_2 or O_2, CO and OGC are measured over the entire test duration.
o For the measurement of **TSP** at **nominal heat load,** the test period is divided into at minimum 4 equal time segments. The measurements begin in each case at the start of the segment, with the first measurement taken when the test begins. The suction time per filter is limited to 30 min. The average dust content is determined from the 4 minimum values taken at half hour intervals.</td></tr>
<tr><td colspan="2">o For the calculation of the emissions from a combustion period, the measured data sets are first averaged over the complete combustion period. Afterwards transformation to the desired units (mg/m^3 at certain oxygen level or lb/MMBtu) is performed.</td></tr>
</table>

The ambient air temperature during testing procedure has to be between 60 and 85 °F.

Partial load is 50% of nominal heat load for manually stoked boilers and 30% of nominal heat load for automatically stoked boilers.

4.1.2 EN 12809: Residential independent boilers fired by solid fuel

Full title: EN 12809. Residential independent boilers fired by solid fuel – Nominal heat output up to 170 Btu/h – Requirements and test methods.

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 7 April 2001, amends: EN 12809:2001/A1:2004.

Appliances: Hand and automatically fired, manual fuelled solid fuel appliances up to a nominal heat output of 170 MBtu/h for hydronic heating systems also providing direct heat at the place of installation.

Fuels: Solid mineral fuels, peat briquettes, natural or manufactured wood logs or multi-fuel in accordance with the operation instructions of the appliance.

Test Methods: Specifies test methods for total heat output, water heating output, space heating output, efficiency and emissions (CO, dust, OGC); measurement methods for dust and OGC are not defined.

Availability: Sharing is restricted; English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=223590

4.1.3 EN 12815: Residential cookers fired by solid fuel

Full title: EN 12815. Residential cookers fired by solid fuel – Requirements and test methods

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 7 April 2001, amendments: EN 12815: 2001/A1: 2004.

Appliances: Hand fired appliances, of which primary function is to cook and secondary function is direct heating. In case of connecting these appliances to a boiler, they also provide domestic hot water and/or central heating.

Fuels: Solid mineral fuels, peat briquettes, wood logs or multi-fuel in accordance with the operation instructions of the appliance.

Test Methods: Specifies test methods for total heat output, water heating output, space heating output, efficiency and emissions (CO, dust, OGC); measurement methods for dust and OGC are not defined.

Availability: Sharing is restricted; preview is attached, English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=233243

4.1.4 EN 13229: Inset appliances including open fires fired by solid fuels

Full title: EN 13229. Inset appliances including open fires fired by solid fuels – Requirements and testing methods

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 7 April 2001, amendments: EN 13229: 2001/A1: 2003, EN 13229:2001/A2:2004.

Appliances: Freestanding or inset hand fired appliances that have functional modification or inset appliances for fireplaces: recessed and enclosed. Where connected to a boiler, also domestic hot water and/or central heating are provided.

Fuels: Solid mineral fuels, peat briquettes, wood logs or multi-fuel in accordance with the operation instructions of the appliance.

Test Methods: Specifies test methods for total heat output, water heating output, space heating output, efficiency and emissions (CO).

Availability: Sharing is restricted; preview is attached, English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=233241

Table 4-3 shows the categorisations of appliances to EN 13229 and EN 13240.

Table 4-3 Categorisation of appliances (EN 13229 versus EN 13240)

	a) Freestanding or inset appliances without functional modification	b) Freestanding or inset appliances with functional modification	c) Inset appliances for fireplace recess and enclosure
1. Appliances operating with firedoors closed	EN 13240	EN 13229	EN 13229
2. Appliances operating with firedoors closed or open	EN 13240	EN 13229	EN 13229
3. Open fires without firedoors	EN 13229	EN 13229	EN 13229

NOTE: Without functional modification means “modification of the surrounding of an appliance, which only changes the transmission of heat without affecting combustion.”

Table 4-4 summary of EN 13229 with regard to testing procedure

NOMINAL HEAT LOAD	PARTIAL LOAD
TEST DURATION	
o Before tests may begin, the appliance has to be operated until **steady state** is reached; at least one combustion period at nominal heat load is necessary before testing. Prefabricated heaters have to be operated before testing until the ceramic has **completely dried** (usually 10 hours or more). o Testing starts immediately after refilling the fuel onto the firebed and ends when all fuel except the ash is burnt. o At least two tests in two different combustion periods have to be carried out for **nominal heat load**. o Minimum combustion times with closed doors for wood fuel: o 1 hour for continuous operating stoves o 0.75 hours for intermittent operating stoves o 90 (+10/-20) min. for prefabricated heaters	o Before test may begin, the appliance has to be operated at nominal heat load. o Testing starts when operating conditions are stable for not less than 15 min. o For **prefabricated heaters** the test duration ends when an ignitable firebed is left, for **continuous operating stoves** the test is finished when the mass of the firebed equals the mass of the firebed before start of the test. o minimum combustion times with closed doors for wood fuel: o 3 hours for continuous operating stoves o (50 ± 10)% of time at nominal load
HEAT FLOW – EFFICIENCY	
o Efficiency is calculated as the average of the two test periods. o If appliance is equipped with water circulation, flow temperature during test must be 175 ± 40 ºF and flow rate of water has to vary less than ± 5 %.	o If appliance is equipped with water circulation, flow temperature must be below 185 ºF and flow rate of water has to vary less then ± 5 %.
o Efficiency is calculated by the indirect method, considering flue gas loss from heat, un-burnt matter and losses in the ash from un-burnt combustible matter. If appliance has water circulation, the hot water output is considered as well.	
EMISSIONS	
o CO_2 or O_2 and CO are measured during the complete test durations. o For the calculation of the emissions from a combustion period, the measured data sets are first averaged over the complete combustion period. Afterwards transformation to the desired units (mg/m³ at certain oxygen level or lb/MMBtu) is performed.	

4.1.5 EN 13240: Room-heaters fired by solid fuel

Full title: EN 13240. Room-heaters fired by solid fuel – Requirements and test methods

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 7 April 2001, amendments: EN 13240: 2001/A2: 2004.

Appliances: Manually stoked appliances, which are operated with firedoors closed or open, providing direct space heat. Standard also applies to slow heat release appliances that are available as complete units or pre-fabricated parts designed to be built on site.

Fuels: Solid mineral fuels, peat briquettes, wood logs or multi-fuel in accordance with the operation instructions of the appliance.

Test Methods: Specifies test methods for total heat output, water heating output, space heating output, efficiency and emissions (CO, dust, OGC); measurement methods for dust and OGC are not defined.

Availability: Sharing is restricted; preview is attached, English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=233239

Table 4-5 summary of EN 13240 with regard to testing procedure

NOMINAL HEAT LOAD	PARTIAL LOAD
TEST DURATION	
○ Before the test may begin, the appliance has to be operated until **steady state** is reached; minimum combustion times and number of combustion periods for wood fuel are: ○ 1.5 hours / 2 periods for continuous operating stoves ○ 0.75 hours / 3 periods for intermitted operating stoves ○ Testing starts immediate after refilling the fuel onto the firebed and ends when all the fuel except the ash is burnt.	○ Before the test may begin, the appliance has to be operated at nominal heat load or the necessary firebed can be reached within one hour after ignition in the cold appliance. ○ Testing starts when operating conditions are stable for no less than 15 min. ○ Testing is finished for **continuous operating stoves** when the minimum combustion time of 10 hours (or longer time claimed by manufacturer) is reached. The firebed at the end of the test duration has to equal the mass of the firebed before start of the test.
HEAT FLOW – EFFICIENCY	
○ Efficiency is calculated as the average of the two test periods. ○ If appliance is equipped with water circulation, flow temperature during test must be 175 ± 40 ºF and flow rate of water has to vary less than ± 5 %.	○ If appliance is equipped with water circulation, flow temperature must be below 185 ºF and flow rate of water has to vary less than ± 5 %.
○ Efficiency is calculated by the indirect method, considering flue gas loss from heat and un-burnt matter and losses in the ash from un-burnt combustible matter. If appliance has water circulation, the hot water output is considered as well.	

EMISSIONS
○ CO_2 or O_2 and CO are measured during the complete test durations. ○ For the calculation of the emissions from a combustion period, the measured data sets are first averaged over the complete combustion period. Afterwards transformation to the desired units (mg/m³ at certain oxygen level or lb/MMBtu) is performed.

4.1.6 EN 14785: Residential space heating appliances fired by wood pellets

Full title: EN 14785. Residential space heating appliances fired by wood pellets – Requirements and test methods

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 3 May 2006.

Appliances: Residential space heaters fired by wood pellets. Appliances may be freestanding or inset appliances and provide direct heat. They can be operated by either a natural draught or fan-assisted combustion air. Where combined with a boiler, they also provide domestic hot water and/or central heating. These appliances are only operated with fire-doors closed.

Fuels: wood pellets

Test Methods: Specifies test methods for total/nominal/reduced heat output, water heating output, space heating output, efficiency and emissions (CO, dust, OGC); measurement methods for dust and OGC are not defined.

Availability: Sharing is restricted, English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=221785

Table 4-6 summary of EN 14785 with regard to testing procedure

<table>
<tr><th>NOMINAL HEAT LOAD</th><th>PARTIAL HEAT LOAD</th></tr>
<tr><td colspan="2">TEST DURATION</td></tr>
<tr><td>o Before the tests may begin, the appliance has to be de-ashed and operated for at least 30 min. in its steady state (normal working conditions). Steady state is reached when flue temperature varies less than ± 40 °F.
o Test starts with the refill of the appliance and has to last for at least 3 hours. If manufacturer claims a longer combustion period, the test has to be prolonged according to the manufacturer’s declaration.
o At least two tests in two different combustion periods have to be carried out.</td><td>o Before the tests may begin, the appliance has to be operated at nominal heat load. After de-ashing, the appliance has to be operated at partial load for at least one hour in steady state. Refill of appliance is possible before start of test.
o Test duration has to last at least 6 hours.
o No partial heat load tests are carried out, if the appliance works in the on/off – mode only.
o One test is required.</td></tr>
<tr><td colspan="2">HEAT FLOW - EFFICIENCY</td></tr>
<tr><td>o Efficiency is calculated as the average of the two test periods.
o If appliance is equipped with water circulation, flow temperature during test must be 175 ± 40 °F and flow rate of water has to vary less than ± 5 %.</td><td>o If appliance is equipped with water circulation, flow temperature must be below 185 °F and flow rate of water has to vary less than ± 5 %.</td></tr>
<tr><td colspan="2">o Efficiency is calculated by the indirect method, considering flue gas loss from heat and un-burnt matter and losses in the ash from un-burnt combustible matter. If appliance has water circulation, the hot water output is considered as well.</td></tr>
<tr><td colspan="2">EMISSIONS</td></tr>
<tr><td colspan="2">o CO_2 or O_2 and CO are measured during the complete test durations.
o For the calculation of the emissions from a combustion period, the measured data sets are first averaged over the complete combustion period. Afterwards transformation to the desired units (mg/m^3 at certain oxygen level or lb/MMBtu) is performed.</td></tr>
</table>

4.1.7 EN 15250: Slow heat release appliances fired by solid fuel

Full title: EN 15250. Slow heat release appliances fired by solid fuel – Requirements and test methods

Prepared by/approved/amends: Prepared by CEN TC 295 *Residential solid fuel burning appliances*, approved on 13 January 2007.

Appliances: Manually stoked, intermittent burning, slow heat release appliances with thermal storage capacity. Appliances are always built on site, either completely hand crafted or assembled with pre-fabricated parts. This standard specifies the minimum time period within which the maximum differential surface temperature may be reduced to half of its original value.

Fuels: Solid mineral fuels, peat briquettes, wood logs or multi-fuel in accordance with the operation instructions of the appliance. Manually stoked wood pellets can also be burnt either on the existing grate on in special insets.

Test Methods: Specifies test methods for total heat output, efficiency and emissions (CO, dust, OGC); measurement methods for dust and OGC are not defined

Availability: Sharing is restricted, preview is attached, English version purchasable: https://www.on-norm.at/shopV5/search/Details.action?showDetails=&dokkey=278524

Table 4-7 summary of EN 15250 with regard to testing procedure

<table>
<tr><th>NOMINAL HEAT LOAD</th><th>PARTIAL HEAT LOAD</th></tr>
<tr><td colspan="2">TEST DURATION</td></tr>
<tr><td>o The test is to be started cold without a pre-test period, whereby ignition is to be performed either according to the manufacturer’s instructions or using kindling of mass of 500g or 10% of the fuel load, whichever is greater. Any bottom air entry is to be open during ignition.
o The adding of further batch charges should not exceed 3 hours.
o Any batch charges shall not be less than 20% of the total fuel loading.
o The test is over once 25% of the mean maximum differential surface temperature of the appliance’s external surfaces has been reached.
o One test is required.
o A Temperature Safety Test is also required.</td><td>o The test is to be started cold without a pre-test period, whereby ignition is to be performed either according to the manufacturer’s instructions or using kindling of mass of 500g or 10% of the fuel load, whichever is greater. Any bottom air entry is to be open during ignition.
o Any batch charges shall not be less than 20% of the total fuel loading.
o The adding of further batch charges should not exceed 3 hours.
o Any batch charges shall not be less than 20% of the total fuel loading.
o One test is required.
o A Temperature Safety Test is also required.</td></tr>
<tr><td colspan="2">HEAT FLOW - EFFICIENCY</td></tr>
<tr><td>o If the test fuel is wood logs, the combustible constituents of the residue need not be measured, but can be taken as 0.5 % points of efficiency.</td><td>o If the test fuel is wood logs, the combustible constituents of the residue need not be measured, but can be taken as 0.5 % points of efficiency.</td></tr>
<tr><td colspan="2">o Efficiency is calculated by the indirect method, considering the heat losses determined from the mean value of the flue gas and room temperature, the flue gas composition and the combustible matter in the residue.</td></tr>
<tr><td colspan="2">EMISSIONS</td></tr>
<tr><td colspan="2">o CO_2 or O_2 and CO are measured during the complete test duration.
o For the calculation of the emissions from a combustion period, the measured data sets are first averaged over the complete combustion period. Afterwards transformation to the desired units (mg/m^3 at certain oxygen level or lb/MMBtu) is performed.</td></tr>
</table>

4.2 Commercial heating systems

For commercial heating systems > 1025 MBtu, no European standards are defined. These plants undergo individual commissioning procedures. An example of a commissioning report is added in the annex.

4.3 Summary

Table 4-8 summary of standards for residential heating systems

	303-5	12809	12815	13229	13240	15250	14785
Full title	Heating boilers for solid fuels, hand and automatically stocked, nominal heat output of up to 300 kW - Terminology, requirements, testing and marking	Residential independent boilers fired by solid fuel – Nominal heat output up to 50 kW – Requirements and test methods	Residential cookers fired by solid fuel – Requirements and test methods	Inset appliances including open fires fired by solid fuels – Requirements and testing methods	Room-heaters fired by solid fuel – Requirements and test methods	Slow heat release appliances fired by solid fuel – Requirements and test methods	Residential space heating appliances fired by wood pellets – Requirements and test methods
Appliance	Boilers for hydronic heating without direct space heating output	Residential independent solid fuel fired boilers with heat direct to living room	Cookers (with or without water circulation)	Freestanding or inset appliances	Room-heaters (with or without water circulation)	Hand fuelled intermittent burning slow heat release appliances	Residential space heating appliances fired by wood pellets (with and without water circulation)
Fuel	wood and fossil fuels	Solid mineral fuels, peat briquettes, natural or manufactured wood logs or multi-fuel in accordance with the operation instructions of the appliance					wood pellets
Heat Output	determined on the basis of water flow and temperatures	total heat output: based on efficiency, fuel input and calorific value hot water output: based on water flow and temperatures space heating output: difference of total heat output and hot water output				on the basis of efficiency, fuel input and calorific value	see 12809
Efficiency	Direct method: Quotient of heat output and heat input. Indirect method for control purposes only	Indirect method: flue gas loss from heat, un-burnt matter and losses in the ash from un-burnt combustible matter					
Emissions	CO_2 or O_2, CO, OGC, TSP (NO_X where appropriate)	CO_2 or O_2 and CO					

5 Regulations for biomass installations

Performance regulations for biomass installations (emission limits and thermal efficiency requirements) aim at increasing the number of newly installed, state-of-the-art appliances, thus decreasing the number of old technologies in operation. The end result is thereby the continuous improvement in performance of biomass appliances in operation.

These regulations have to consider the different performance levels of appliances in Europe and at the same time encourage all countries to improve their technologies, regardless if the country is leading or lagging behind in combustion technology. In order to embrace all technology stages in the European Union, different emission and efficiency classes are defined for boilers in EN 303-5. Additionally, national requirements and eco labeling programs also encourage technology development to increase performance levels.

Figure 5-1 shows efficiency requirements for boilers in the EN 303-5 (classes 1 to 3 are currently in practice and classes 3 to 5 are under discussion) and efficiency requirements from Austrian, German and Scandinavian eco-labels. A continuous increase of efficiency requirements is one major driving force for technology developments.

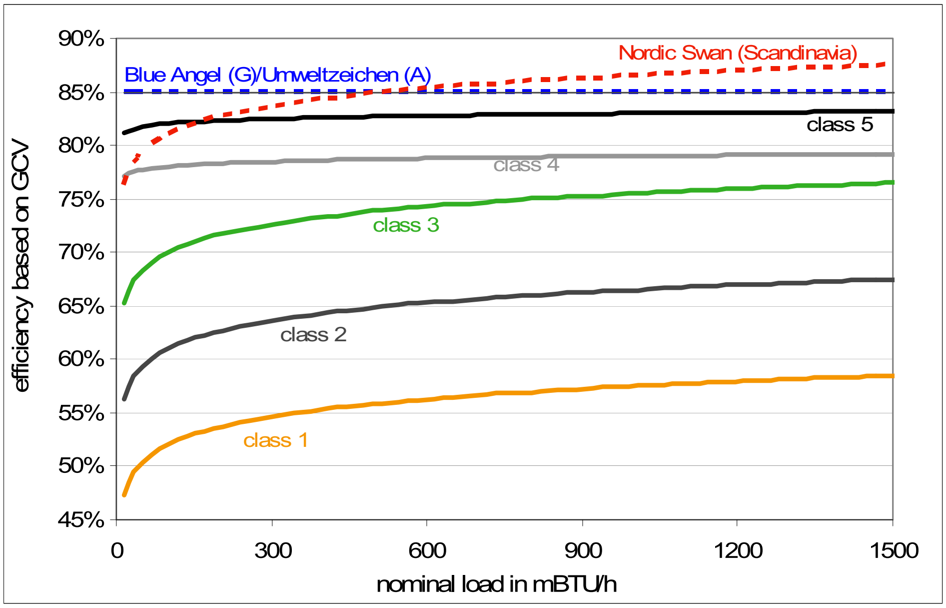


Figure 5-1 efficiency requirements for boilers from EN 303-5 (class 1 to class 5) and efficiency requirements from Austrian, German and Scandinavian eco-labels; efficiencies based on GCV were converted for pellets fuel

5.1 European level

5.1.1 Regulations for boilers

EN 303-5 sets the standards for solid fuel boilers with a nominal heat load up to 1025 MBtu/h. In EN 303-5 emission limits for CO, OGC and dust as well as thermal efficiency requirements for solid fuel boilers are specified. In order to embrace the diverse combustion standards from EU member states, three different emission and efficiency classes were defined. Table 5-1 shows the emission limits for wood fuel and fossil fuel boilers in the valid standard.

Table 5-1 emission limits for biogenic fuels in EN 303-5

Stoking	Nominal heat load in MBtu/h	Emission limits at 12% O_2								
		CO in mg/m³			OGC in mg/m³			Dust[3] in mg/m³ (and lb/MMBtu)		
		class 1	class 2	class 3	class 1	class 2	class 3	class 1	class 2	class 3
Manual[1]	≤ 170	20455	6545	4090	1635	245	120	165 (0.22)	145 (0.20)	125 (0.17)
	170 - 510	10227	4090	2045	1230	165	80	165 (0.22)	145 (0.20)	125 (0.17)
	510 - 1025	10227	1635	980	1230	165	80	165 (0.22)	145 (0.20)	125 (0.17)
Automatic[2]	≤ 170	12270	4090	2455	1430	165	80	165 (0.20)	145 (0.18)	125 (0.15)
	170 - 510	10230	3680	2045	1020	120	65	165 (0.20)	145 (0.18)	125 (0.15)
	510 - 1025	10230	1635	980	1020	120	65	165 (0.20)	145 (0.18)	125 (0.15)

[1] Based on the higher heat value (GCV) and the heat value for solid wood (dust values only)

[2] Based on the higher heat value (GCV) and the heat value for pellets (dust values only)

[3] Dust emission limits are identical for automatical and manual systems in EN 303-5, conversion from mg/m³ to lb/MMBtu results in higher emission limits for manually stoked appliances, though (see Table 3-2 on page 2)

The emission limits for fossil fuels will be identical to the emission limits for biogenic fuels, except for dust – emissions (brown coal fuel assumed):

- class 1: 145 mg/m at 12% O_2 and 0.185 lb/MMBtu
- class 2: 125 mg/m at 12% O_2 and 0.160 lb/MMBtu
- class 3: 100 mg/m at 12% O_2 and 0.130 lb/MMBtu

The efficiency requirements from EN 303-5 are calculated as follows (based on the GCV):

- 41 + 5.5·log P_n for class 1
- 50 + 5.5 log P_n for class 2
- 59 + 5.5 log P_n for class 3

where P_n is the nominal heat load of the boiler in MBtu/h.

A revision of the EN 303-5 is currently in progress and new emission classes (class 4 and 5) are being discussed. Class 1 and 2 will be phased out as more stringent class 4 and 5 are phased in. The actual status of the discussion regarding wood fuel boilers is shown in Table 5-2. In addition to lower emission levels, the future standard will be valid for higher loads (1025 – 1700 MBtu/h) as well.

Table 5-2 proposed future emission limits for biogenic fuels in EN 303-5

Stoking	Nominal heat load in MBtu/h	Emission at 12% O_2								
		CO limits in mg/m³			OGC limits in mg/m³			Dust3) in mg/m³ (and lb/MMBtu)		
		class 3	class 4	class 5	class 3	class 4	class 5	class 3	class 4	class 5
Manual1)	≤ 170	4090	820	410	125	60	40	125 (0.17)	60 (0.08)	50 (0.07)
	170 - 510	2045	615	245	80	40	25	125 (0.17)	60 (0.08)	50 (0.07)
	510 - 1025	980	410	205	80	10	10	125 (0.17)	60 (0.08)	50 (0.07)
	1025 – 1710	980	410	205	80	10	10	125 (0.17)	60 (0.08)	50 (0.07)
Automatic2)	≤ 170	2455	820	410	80	60	40	125 (0.15)	60 (0.08)	50 (0.06)
	170 - 510	2045	615	245	65	60	40	125 (0.15)	60 (0.08)	50 (0.06)
	510 - 1025	980	410	205	65	40	20	125 (0.15)	60 (0.08)	50 (0.06)
	1025 – 1710	980	410	205	65	40	20	125 (0.15)	60 (0.08)	50 (0.06)

1) Based on the higher heat value (GCV) and the heat value for solid wood (dust values only)

2) Based on the higher heat value (GCV) and the heat value for pellets (dust values only)

3) Dust emission limits are identical for automatical and manual systems in EN 303-5, conversion from mg/m³ to lb/MMBtu results in higher emission limits for manually stoked appliances, though (see Table 3-2 on page 2)

The emission limits for fossil fuels will be identical to the emission limits for biogenic fuels, except for dust – emissions (brown coal fuel assumed):

- class 4
    - manual stoking: 60 mg/m at 12% O_2/0.075 lb/MMBtu
    - automatic stoking: 50 mg/m at 12% O_2/0.060 lb/MMBtu
- class 5: 40 mg/m at 12% O_2/0.050 lb/MMBtu

In the future EN 303-5, the following efficiency requirements are being discussed for classes 4 and 5 (based on the GCV):

- 76 + log P_n for class 4
- 80 + log P_n for class 5

where P_n is the nominal heat load of the boiler in MBtu/h.

5.1.2 Regulations for room heaters

For room-heaters a number of standards apply, providing efficiency requirements and limits for CO-emission. In Table 5-3 a summary of efficiency and emission requirements of these standards are given. This summary shows the broad range of emission limits and efficiency requirements for diverse room-heating technologies.

Table 5-3 Summary of efficiency and CO-requirements in standards for room-heating appliances

Type of appliance	*Standard*	*Minimum efficiency[1] in %*	*CO limits in mg/m³ at 12% O_2*
cookers	*EN 12815*	*55[2]*	*14065*
slow heat release inset	*EN 13229*	*65[2]*	*280*
fireplace insets (closed doors)		*25[2]*	*1410*
room-heater	*EN 13240*	*for closed doors* *class 1: 60[2]* *class 2: 55[2]* *class 3: 45[2]*	*class 1: 420* *class 2: 1410*
pellet stove	*EN 14785*	*nominal load: 70* *partial load: 65*	*nominal load: 565* *partial load: 845*
slow heat release appliances	*EN 15250*	*60[2]*	*4220*

[1] related to higher heating value (GCV)
[2] based on heat value for solid wood

5.2 National levels

All EU member states are allowed to introduce stricter and additional requirements for combustion appliances than provided in the standards. In the following section, national regulations for emissions and efficiencies of biomass appliances are shown for Austria, Germany and the Scandinavian countries. Regulations for small scale (residential) appliances and, if available, for medium to large scale (commercial) appliances are quoted.

Additional legal requirements and environmental labels, which are often linked to additional financial incentives, are also being introduced by some countries.

5.2.1 Austria

Currently, two regulations apply to the emission limits and energy-efficiency requirements of residual small combustion installations:

- The Vereinbarung gemaeß Art. 15a B-VG ueber Schutzmaßnahmen betreffend Kleinfeuerungen sets emission limits for combustion units < 1365 MBtu/h.
- In the *Vereinbarung gemaeß Art. 15a B-VG ueber die Einsparung von Energie* minimum efficiency requirements are defined for combustion installations < 1365 MBtu/h.

The regulation for combustion units of < 1365 MBtu/h makes a distinction between manually and automatically stoked appliances as well as fossil fuels and biofuels. The Austrian limits for these installations are in any case lower than the emissions levels in EN 303-5, class 3. There are also additional limits set for NO_X.

Emission limit values for appliances < 1365 MBtu/h are presented in Table 5-4.

Table 5-4 Austrian emission limits for installations < 1365 MBtu/h (Vereinbarung Art. 15a B-VG)

Stoking and fuel types		*Emission limits in mg/m³ 12 % O_2*				*Dust in lb/MMBtu*
		CO	*NO_X*	*OGC*	*dust*	
Manual	***Biogenic solid fuels*[2]**	***1840*[1]**	***2510***	***135***	***100***	***0.135***
	Fossil solid fuels[3]	*1840*	*185*	*135*	*100*	*0.125*
Automatic	***Biogenic solid fuels*[4]**	***8470***	***2540***	***70***	***100***	***0.125***
	Fossil solid fuels[3]	*8470*	*185*	*70*	*75*	*0.095*

[1] of partial load (30 %) the limit may be exceeded by 50 %

[2] solid wood fuel assumed

[3] brown coal fuel assumed

[4] pellets fuel assumed

The adoption of these emission limits due to improved combustion technologies and an increasing variety of biomass fuels is currently under discussion. The present status of this discussion is shown in Table 5-5.

Table 5-5 Future Austrian emission limits for installations < 1365 MBtu – present status of discussion

Fuel types and appliances		*Emission limits in mg/m³ 12 % O_2*				*Dust in lb/MMBtu*
		CO	*NO_X*	*OGC*	*dust*	
wood fuels	*room-heaters[1)]*	*1840*	*250*	*145/85*	*100/60*	*0.135/0.080*
	boilers[2)]	*850*	*250/170*	*85/50*	*85/50*	*0.105/0.060*
other standardised biog. fuels[2)]	*< 170 mBUT/h*	*1860*	*505*	*85*	*100/60*	*0.125/0.075*
	> 170 mBUT/h	*850*	*500*	*50*	*100/60*	*0.125/0.075*
fossil fuels[3)]	*< 170 mBUT/h*	*2020*	*185*	*145*	*90/65*	*0.115/0.080*
	> 170 mBUT/h	*920*	*185*	*55*	*90/65*	*0.115/0.080*
XX/YY: values valid from coming into force/values valid from 2015 *1) solid wood fuel assumed* *2) pellet fuel assumed* *3) brown coal fuel assumed*						

Regulations for the minimum efficiency distinguish between room-heating appliances and boilers. **For room heating appliances the minimum efficiency is 70 %, whereas it is 62 % for cookers.** For boilers, the minimum efficiency depends on the type of stoking and the nominal heat load, as shown in Table 5-6.

Table 5-6 minimum efficiency requirements for boilers < 1365 MBtu/h (Vereinbarung Art. 15a B-VG)

Stoking	*Nominal heat load in MBtu/h*	*Efficiency[1)] in %*
Manual stoking[3)]	*< 35*	*65 %*
	35 – 680	*(57 + 7.1 log P_n[2)]) %*
	> 680	*75 %*
Automatic stoking[4)]	*< 35*	*70 %*
	35 – 680	*(60 + 7.1 log P_n) %*
	> 680	*80 %*

[1)] related to the higher heating value (GCV)
[2)] nominal heat load in MBtu/h
[3)] based on the heat value for solid wood
[4)] Based on the heat value for pellets

Environmental label – Umweltzeichen

The *Umweltzeichen (environmental label)* was introduced by the Austrian Government. For wood appliances (boilers and room heaters) the Environmental Label number 37 specifies emission and efficiency requirements.

In Table 5-7 the emission limits for boilers and room heaters according to the Environmental Label are shown.

Table 5-7 Austrian Environmental Label emission limits for boilers and room-heaters (Umweltzeichen)

Appliance	*fuel*	*Emission limits in mg/m³ at 12 % O_2*				*Dust in lb/MMBtu*
		CO/OGC (nominal load)	*CO/OGC (partial load[2])*	*NO_X*	*dust*	
Boiler	*pellets*	*100/5*	*230/5*	*170*	*25*	*0.030*
	wood chips	*250/10*	*495/15*	*200*	*50*	*0.080*
	solid wood	*420/50*	*1250*	*200*	*50*	*0.070*
Room-heater	*pellets*	*205/10*	*450/20*	*170*	*35*	*0.042*
	solid wood	*1170/85*	*-/-*	*200*	*50*	*0.070*

1) related to the lower heating value (NCV)

2) for pellets and wood chips: 30% of nominal load, for solid wood: 50% of nominal load

Table 5-8 shows the efficiency requirements for boilers and room-heaters according to the Austrian Environmental Label.

Table 5-8 Austrian Environmental Label efficiency requirements for room-heaters and boilers (Umweltzeichen)

Stoking	*Efficiency in % related to upper heating value (GCV)*	
	Boilers	*Roomheaters*
Manual[2)]	*62 + 7.1 log P_n[1)]*	*70*
Automatic[3)]	*85*	*85*

1) nominal heat load in MBtu/h

2) based on heat value for solid wood

3) based on the heat value for pellets

In addition to these requirements, the losses due to radiation of the boilers are also limited:

- up to 340 MBtu/h: maximum losses of 2.5 % by radiation
- 340 – 1365 MBtu/h: maximum losses of 1.5 % by radiation

Medium to large scale (commercial) applications

The *Feuerungsanlagen-Verordnung, BGBl. II Nr. 331/1997,* which came into force on June 1st 1998, covers residential installations with a nominal heat capacity > 1365 MBtu/h as well as commercial combustion units > 170 MBtu/h. Table 5-9 and Table 5-10 show the emission limits for CO, dust, NO_X and HC for biomass appliances and emission limits for CO, dust, NO_X and SO_2 for coal and coke appliances according to the Feuerungsanlagenverordnung.

Table 5-9 Austrian emission limits for commercial biomass appliances according to the Feuerungsanlagenverordnung (FAV)

Installation heat load in MBtu/h	*Emission limits in mg/m³ at 12% O_2*						*Dust lb/MMBtu*
	CO	*HC*	*NO_X*			*dust*	
			fuel1	*fuel2*	*fuel3*		
170 – 340	*900*[1]	*55*	*340*	*280*	*565*	*170*	*0.210*[3]
340 – 1195	*900*	*55*	*340*	*280*	*565*	*170*	*0.210*[3]
1,195 – 6,830	*280*	*25*	*340*	*280*	*565*	*170*	*0.275*[4]
6,830 – 17,075	*280*	*25*	*340*	*280*	*565*	*55*[2]	*0.090*[2], [4]
17,075 – 34,150	*115*	*25*	*340*	*280*	*395*	*55*	*0.090*[4]
> 34,150	*115*	*25*	*340*	*225*	*395*	*55*	*0.090*[4]

[1] *at 30 % load limit may be exceeded by 50 %*

[2] *from 1st January 2010*

fuel1: beech, oak, non-treated bark, brushwood, cones

fuel1: other non-treated wood

fuel1: derived timber products (no heavy metals or halogen organic compounds in binder, hardener and coating)

[3] *Based on the higher heat value (GCV) of the fuel, pellets assumed*

[4] *Based on the higher heat value (GCV) of the fuel, wood chips assumed*

Table 5-10 Austrian emission limits for commercial coal and coke appliances according to the Feuerungsanlagenverordnung (FAV)

Installation heat load in MBtu/h	*Emission limits in mg/m³ at 12% O_2*				*Dust*[1] *lb/MMBtu*
	CO	*NO_X*	*SO_2*	*dust*	
170 – 340	*1125*	*-*	*-*	*170*	*0.215*
340 – 1195	*1125*	*450*	*-*	*170*	*0.215*
1,195 – 6,830	*170*	*450*	*-*	*170*	*0.215*
6,830 – 17,075	*170*	*450*	*-*	*55*	*0.070*
17,075 – 34,150	*170*	*395*	*450*	*55*	*0.070*
> 34,150	*170*	*115*	*225*	*55*	*0.070*

[4] *Based on the higher heat value (GCV) of the fuel, brown coal assumed*

In the Feuerungsanlagenverordnung, a minimum **efficiency** of **75 %** based on the GCV for automatically stoked solid fuel appliances used for room heating or domestic hot water production is required.

5.2.2 Germany

In Germany, the 1. *BImSchV* (*Bundes Immissions Schutz Verordnung fuer Kleinfeuerungsanlagen*) regulates the Emissions for small scale installations. It was implemented in 1988 and has since then been revised twice (in 1997 and 2003) and is currently undergoing a third revision. In Table 5-11 the valid emission limits for biomass combustion appliances with nominal heat loads > 50 MBtu/h is shown.

Table 5-11 German emission limits for biomass combustion appliances according to the valid 1st BImSchV (1st BImSchV)

fuel	nominal heat load in MBtu/h	emissions in mg/m³ at 12 % O_2		dust in lb/MMBtu
		CO	dust	
non-treated wood in pieces, i.e. shavings, and straw or other plant products	50 – 170	4500	170	0.230[1]
	170 – 510	2250	170	0.230[1]
	510 – 1705	1125	170	0.275[2]
	> 1705	565	170	0.275[2]
painted, coated or laminated wood, plywood and chipboards	50 – 340	900	170	0.275[2]
	340 – 1705	565	170	0.275[2]
	> 1705	340	170	0.275[2]

[1] based on the higher heat value (GCV) of the fuel, solid wood assumed

[2] based on the higher heat value (GCV) of the fuel, wood chips assumed

No specific efficiency requirements are given in the *1. BImSchV* for biomass boilers.

Table 5-12 future German emission limits for biomass boilers according to the 1st BImSchV (1st BImSchV – Draft from July 2009)

Fuel	Installation built after 1st BImSchV came into force				Installations built after 2014[1]			
	nominal heat load (MBtu/h)	E-limits in mg/m³ at 12% O_2		dust in lb/ MMBtu	nominal heat load (Btu/h)	E-limits in mg/m³ at 12% O_2		dust in lb/ MMBtu
		CO	dust			CO	dust	
non treated wood[2]	15 – 1705	1125	115	0.185[7]	≥ 15	450	25	0.040[7] 0.030[8] 0.030[9]
	> 1705	565	115	0.185[7]				
pellets[3]	15 – 1705	900	70	0.085[8]				
	> 1705	565	70	0.085[8]				
coal	15 – 1705	1125	100	0.125[9]				
	> 1705	565	100	0.125[9]				
pre treated wood[4]	170 – 340	900	115	0.185[7]	170 – 1705	450	25	0.040[7]
	340 – 1705	565	115	0.185[7]				
	> 1705	340	115	0.185[7]	> 1705	340	25	0.040[7]
straw	15 - 340	1125	115	-	15 – 340	450	25	-

[1] solid wood emission limits instated in 2017

[2] non-treated wood (pieces, shavings), straw or other plant products – wood chips assumed for dust emissions

[3] pressed untreated wood (briquettes, pellets, etc.)

[4] painted, varnished or coated wood; plywood, chipboards, fibre boards (no reservatives used, no heavy metals of halogen organic compounds – solid wood assumed for dust emissions

[5] straw and similar plant materials

[6] all dust emissions based on the higher heating value (GCV)

[7] based on the higher heat value (GCV) of the fuel, wood chips assumed

[8] based on the higher heat value (GCV) of the fuel, pellets assumed

[9] based on the higher heat value (GCV) of the fuel, brown coal assumed

Table 5-12 shows the recent status of the discussion for the new emission (and efficiency) requirements for biomass boilers.

No specific efficiency requirements are given in the draft version of the *1st BImSchV* for biomass boilers.

Table 5-13 shows the recent discussion status for new emission (and efficiency) requirements for room-heaters.

Room-heaters that were installed before the future *1st BImSchV* was implemented are only allowed to be operated, if

- dust emissions are < 0.228 lb/MBtu (150 mg/m³ at 13% O_2) and
- CO-emissions are < 6.090 lb/MBtu (4000 mg/m³ at 13% O_2)

Otherwise they must be upgraded with emission control technology or placed out of operation corresponding to a time schedule.

Table 5-13 future German emission and efficiency requirements for room-heaters according to 1st BImSchV (1st BImSchV – Draft)

Type of appliance	*Standard*	*Installation built after 1st BImSchV came into force*				*Installations built after 2014*		
		Efficiency 1) (%)	*Emission in mg/m³ limits at 12% O_2*		*Dust in lb/ MMBtu*	*Emission in mg/m³ limits at 12% O_2*		*Dust in lb/ MMBtu*
			CO	*dust*		*CO*	*dust*	
room heater (intermittent operation)	*EN 13240*	*65*	*2250*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
room heater (continuous operation)		*60*	*2810*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
slow heat release appliances	*EN 15250*	*65*	*2250*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
closed inset	*EN 13229*	*65*	*2250*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
slow heat release inset (intermittent)		*70*	*2250*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
slow heat release inset (continuous)		*70*	*2815*	*115*	*0.150 2)*	*1405*	*45*	*0.061*
cookers	*EN 12815*	*60*	*3375*	*115*	*0.150 2)*	*1690*	*45*	*0.061*
cookers (with room heater function)		*65*	*3940*	*115*	*0.150 2)*		*45*	*0.061*
pellet stove	*EN 14785*	*80*	*450*	*55*	*0.070 3)*	*280*	*35*	*0.040*
pellet stove with boiler		*85*	*450*	*35*	*0.040 3)*	*280*	*25*	*0.030*

1) related to the higher heating value (GCV)

Environmental Label – The Blue Angel

The Blue Angel label is sponsored and administered by the German Federal Environmental Agency and the Quality Assurance and Product Labeling Institute *RAL Deutsches Institut fuer Guetesicherung und Kennzeichnung e.V.* This label provides additional emission and efficiency requirements for pellet stoves and pellet boilers (Table 5-14).

Table 5-14 Emission limits for the German Blue Angel label (Blue Angel)

appliance	*Efficiency (%)[1]*	*Emission limits in mg/m³ at 12% O_2 for nominal/partial load*				*dust in lb/mmBtu*
		CO	*NO_X*	*TOC*	*dust*	
pellet stove	*≥ 85*	*200/450*	*170/-*	*10/20*	*30/-*	*0.035/-*
pellet boiler		*100/225*	*170/-*	*5/5*	*25/-*	*0.030/-*

[1] related to the higher heating value (GCV)
XXX/YYY: values for nominal load/values for partial load

Medium to large scale applications

In the TA Luft, emission limits for CO, dust, NO_X and OGC are given for medium to large scale appliances. The emission limits for non treated and pretreated biomass are given in Table 5-15. The installation heat load for installations that burn pretreated wood is limited to 170 MMBtu/h.

Table 5-15 German emission limits for medium to large scale appliances according to the TA Luft

Fuel	*Heat load in MMBtu/h*	*Emission limits in mg/m³ at 12 % O_2*				*Dust[3] lb/MMBtu*
		CO	*OGC*	*NO_X*	*dust*	
non treated biomass	*≤ 8.5*	*135[1]*	*10*	*225*	*90*	*0.150*
other biomass[2]		*135[1]*	*10*	*360*	*45*	*0.075*
non treated biomass	*8.5 – 17*	*135*	*10*	*225*	*45*	*0.075*
other biomass[2]		*135*	*10*	*360*	*45*	*0.075*
non treated biomass	*> 17*	*135*	*10*	*225*	*20*	*0.030*
other biomass[2]		*135*	*10*	*360*	*20*	*0.030*

[1] emission limit only valid for nominal load
[2] painted, varnished or coated wood; plywood, chipboards, fibre boards (no preservatives used, no heavy metals or halogen organic compounds)
[3] based on heat value for wood chips

For non treated biomass appliances, TA Luft requires continuous measurement of dust emissions:

- from 17 to 85 MMBtu/h: qualitative measurement
- from 85 MMBtu/h: measurement of mass concentration

In addition, the continuous measurement of CO-emissions for heat loads > 9 MMBtu/h is required. No efficiency requirements are specified in the TA Luft.

For fossil solid fuels emission limits are identical to the emission limits for “other biomass” in Table 5-16. Additionally emission limits for SO_2 are requested:

- fluidised bed combustion: 315 mg/m³ at 12% O_2
- other combustion technology
    - mineral coal: 1170 mg/m³ at 12% O_2
    - other fossil fuels: 900 mg/m³ at 12% O_2 (TA Luft)

5.2.3 Denmark

The Danish *Guidelines for Air Emission Regulation* (Environmental Guidelines no. 1, 2002) apply to all emitting installations, while the Statutory Order, regulating air pollution from wood burners and boilers and certain other fixed energy producing installations applies to combustion installations with a total input of < 1025 MBtu/h. Handcrafted masonry heaters are excluded from this regulation. In Table 5-16 the Danish emission limits for biomass boilers are shown.

Table 5-16 Danish emission limits for biomass boilers (according to EN 303-5, Class 3) (Statutory Order)

Appliance and fuel types		*Nominal heat load MBtu/h*	*Emission limits in mg/m³ at 12% O_2*			*Dust in lb/MMBtu*
			CO	*OGC*	*dust*	
Manual stoking	*Biomass*[1]	< 170	4090	125	125	0.165[3]
		170 – 510	2045	80	125	0.165[3]
		510 – 1025	980	80	125	0.165[3]
	Fossil[2]	< 170	4090	125	100	0.125[4]
		170 – 510	2045	80	100	0.125[4]
		510 – 1025	980	80	100	0.125[4]
Automatic stoking	*Biomass*[1]	< 170	2455	80	125	0.150[5]
		170 – 510	2045	65	125	0.125[5]
		510 - 1025	980	65	125	0.125[5]
	Fossil[2]	< 170	2455	80	100	0.210[4]
		170 – 510	2045	65	100	0.210[4]
		510 – 1025	980	65	100	0.210[4]

[1] *wood, plant seed and other residual products*

[2] *fixed carbon or coal*

[3] *based on the higher heat value (GCV) of the fuel, solid wood assumed*

[4] *based on the higher heat value (GCV) of the fuel, brown coal assumed*

[5] *based on the higher heat value (GCV) of the fuel, pellets assumed*

In addition, the efficiency requirements according to EN 303-5 are requested (based on the GCV):

- $\eta_{GCV} \geq 59 + 5.5 \log P_n$

where P_n is the nominal heat load of the boiler in MBtu/h.

For room-heaters, dust emissions are limited depending on the method of measurement:

- Measurement in dilution tunnel:

    0.16 oz/lb (10 g/kg) fuel; max. 0.32 oz/lb (20 g/kg) fuel in the individual testing intervals

- Measurement in the flue gas pipe (according to EN 13240):

    0.115 lb/MMBtu (75 mg/m³ at 13 % O_2)

Efficiency and emissions requirements for room heaters according to EN 13240:

- $\eta_{GCV} \geq 44$ % (class 3)
- CO < 1405 mg/m^3 at 12 % O_2 (class 2)

Environmental label – The Nordic Swan

The Nordic Swan was introduced by the Nordic Council of Ministers and it is a common system for **Sweden, Norway**, **Denmark** and **Finland**. It provides criteria for closed fireplaces and solid biomass boilers.

Table 5-17 presents efficiency and emission requirements for (closed) room-heaters.

Table 5-17 Nordic Swan efficiency and emission requirements for closed room-heaters (Nordic Swan)

Appliance	*Efficiency$^{1)}$ (%)*	*Emission limits in mg/m³ at 12 % O_2 at nominal load*		*Dust in g/kg_{fuel} and (lb/MMBtu) at nominal load/ partial load/ for each individual test*
		CO	*OGC*	
slow heat release appliance$^{2)}$	*70*	*170*	*2250*	*1/-/- (0.020/-/-)*
inset (manual stoking)$^{2)}$	*65*	*170*	*2815*	*3/8/15 (0.050/0.120/0.230)*
stove (manual stoking)$^{2)}$		*170*	*2815*	*3/5/10 (0.045/0.080/0.150)*
stove (automatic stoking)$^{3)}$	*70*	*55*	*1125*	*2/5/10 (0.030/0.070/0.135)*

$^{1)}$ related to the lower heating value (NCV)
$^{2)}$ based on heat value for solid wood
$^{3)}$ based on heat value for pellets
XXX/YYY/ZZZ: values for nominal load/values for partial load/values for each individual test

In Table 5-18 emission requirements for boilers are exhibited.

Table 5-18 Nordic Swan emission requirements for boilers (Nordic Swan)

Stoking	*Nominal heat load in kW*	*Emission limits in mg/m³ at 12 % O_2*				*Dust in lb/MMBtu*
		CO	*NO_2*	*OGC*	*dust*	
Automatic	*1025*	*330*	*280*	*20*	*35*	*0.040$^{1)}$*
Manual	*≤ 340*	*1640*	*280*	*60*	*55*	*0.080$^{2)}$*
	340 - 1025	*820*	*280*	*40*	*55*	*0.080$^{2)}$*

$^{1)}$ based on heat values for pellets
$^{2)}$ based on heat values for solid wood
Dust and NO_X emissions are tested only at nominal load
Testing procedure for OGC and CO-emissions:

- *nominal heat load for manually stoked boilers*
- *nominal load and partial load for automatically stoked boilers*

Efficiency requirements for boilers are shown in Table 5-19.

Table 5-19 Nordic Swan efficiency requirements for boiler (Nordic Swan)

Stoking	Efficiency[1] in %
Manual[3]	at nominal load: 65 + 5.5 log P_n[2]
Automatic[4]	at nominal load: 70 + 5.5 log P_n[2] and $\eta x \geq 80$ % where $\eta x = (\eta 20 + \eta 40 + \eta 60)/3$ with η20, η40, η60 are measured efficiencies at 20, 40 and 60% load

[1] related to the higher heating value (GCV)

[2] nominal heat load in MBtu/h

[3] based on heat values for pellets

[4] based on heat values for solid wood

Medium to large scale appliances

For medium to large scale appliances, efficiency and fuel quality requirements are defined, but there are no requirements for emissions. Medium to large scale appliances have to reach efficiencies larger than 68% based on the GCV (Brønnum 2009).

5.2.4 Finland

In Finland, a proposal for the regulation of *emissions and efficiencies for heating appliances using wood fuels* has been in the works, under discussion and review since 2006. This regulation will apply to new biomass installations that provide heat, domestic hot water or other energy services with a nominal heat load up to 1025 MBtu/h. The proposal distinguishes primary and secondary heating systems. Primary heating systems provide all required heat/hot water on their own, while secondary heating systems have another (main) heat source. Table 5-20 shows the suggested emission and efficiency requirements for Finland.

Table 5-20 Proposed Finnish emission and efficiency requirements for biomass boilers < 1025 MBtu/h kW (EuP Lot 15, Task1)

Heating system	Nominal heat load (MBtu/h)	Efficiency[1] (%)	Emission limits in mg/m³ at 12% O_2	
			CO	OGC
primary	170	59+ 5.5 log P_n[2]	2455	80
	170 – 510		2045	65
	> 510		980	65
secondary	170	59 + 5.5 log P_n[2]	4090	125
	170 – 510		2045	80
	> 510		980	80

[1] related to the higher heating value (GCV), based on heat value for solid wood

[2] nominal heat load in MBtu/h

In Table 5-21 the Finnish emission and efficiency requirements for fireplaces (room heaters) is shown. Fireplaces that do not fulfill the requirements are still allowed, but they have to be marked as useable only for decorative purposes.

Table 5-21 Proposed Finnish emission and efficiency requirements for fireplaces (room-heaters) (EuP Lot 15, Task1)

Heating system	*Nominal heat load (MBtu/h)*	*Efficiency[1] (%)*	*CO (mg/m³) at 12% O_2*
primary	*170*	*60*	*2455*
secondary			*4220*

[1] related to the higher heating value (GCV), based on heat value for solid wood

Medium to large scale appliances

For medium to large scale applications, national dust requirements are given:

- 3.4 – 17 MMBtu/h: < 0.465 lb/MMBtu
- 17 – 170 MMBtu/h: < 0.200 - $^4/_3 \cdot (P_n - 0.01)$ lb/MMBtu

Additionally, emission limits can be requested by local authorities for heating plants > 17 MMBtu/h. For appliances > 170 MMBtu/h approval is needed by even higher authorities and these limits are open to public (Oravainen 2009).

Environmental label – The Nordic Swan

5.2.5 Sweden

In Sweden emission limits for small scale solid fuel appliances are included in the building regulation (BFS 2006:12). The regulation applies to solid fuel installations with nominal heat loads < 1025 MBtu/h. The emission limits for solid fuel appliances are shown in Table 5-22. The CO requirements do not apply to open fireplaces, tiled stoves (masonry heaters) and cook stoves.

Table 5-22 Swedish emission limits for solid fuel appliances < 1025 MBtu/h (EuP Lot 15, Task1)

Stoking	*Nominal heat load (MBtu/h)*	*OGC in mg/m³ at 12% O_2*
manual	*≤ 170*	*125*
	170 – 1025	*80*
automatic	*170*	*80*
	170 – 1025	*65*

For secondary heating systems (another main heat source is used), limits for CO-emission are given:

- for stoves and fireplaces inserts: CO < 3300 mg/m³ at 12% O_2
- for pellet stoves: CO < 440 mg/m³ at 12% O_2

These CO requirements do not apply to open fireplaces, tiled stoves (masonry heaters) and cook stoves.

For efficiency requirements only recommendations are given:

- for stoves: η > 53 % (on GCV basis)
- for fireplace inserts: η > 44 % (on GCV basis)
- for pellet stoves: η > 65 % (on GCV basis)

Environmental label – The Nordic Swan

6 Performance of biomass installations

Technology forcing efforts of regulations, technology cluster investment, competition among manufacturers and Eco-labeling efforts have resulted in commercially available technologies with performance far exceeding regulatory requirements. This chapter describes the top performing biomass technologies based on thermal efficiency, CO , NO_X and dust (fine particles) emissions.

For selection of the TOP 25% performing technologies in each size category, thermal efficiency and CO data at full load is used due to the availability of this information. Recall that for many technologies, especially boilers the thermal efficiency curve is linear down to very low part loads with these technologies (Figure 6-1).

6.1 Introduction

6.1.1 Data sources

Before installation of biomass appliances is allowed, they have to pass the efficiency and emission requirements of the current European standards as well as the national/regional regulations. Small scale appliances are usually type-tested by certified testing houses. Results of these tests are property of biomass appliances' manufacturer and are therefore not usually publicly available. However, some local and national organisations collect and publish test data which they collect from manufacturers or from test houses. In order to receive test data of biomass appliances in the considered countries, the following sources were used:

- Web site of FJ-BLT (http://www.josephinum.at), an Austrian testing laboratory
- Publications of the *Fachagentur Nachwachsende Rohstoffe* (FNR) on biomass boilers and pellet stoves available on the German market
- Web page of Teknologisk Institut (http://www.teknologisk.dk), a Danish testing house
- Web page of the Danish Environmental Protection Agency (http://www.mst.dk)
- Written information of the Teknikfoeretagens Branschgrupper AB, the Swedish Heating Boilers and Burners Association (contact person: Magnus Davidsson)
- Web site and written information of the HKI Industrieverband Haus-, Heiz und Kuechentechnik e.V., the German heat technology association (contact person: Frank Kienle)
- Written information of following manufacturers of biomass appliances:
    - Veljekset Ala-Talkkari (Finland)
    - Nunnauuni Oy (Finland)
    - Rika (Austria)
    - Calimax (Austria)

Information from these sources about test data varies from the simple statement that the appliances have passed the efficiency and emission requirements to detailed data on efficiency and emissions at nominal and partial load as well as investment costs.

6.1.2 Selection method for TOP 25% performing appliances

For the selection of the TOP 25% performing biomass appliances, the efficiency and CO-emissions at full load (nominal heating load) were considered:

- The **efficiency** of an appliance provides information regarding the extent the fuel input is used to produce hot water and/or room heat. It is therefore one of the most important quality criteria.
- **CO-emissions** are the prime indicators of the combustion quality of biomass appliances (chapter 4). If CO-emissions are low, the emissions of OGC as well as the organic fraction of the TSP (total suspended particulate matter) will also be low. NOx-emissions depend primarily on the nitrogen content of the fuel; therefore, they are not considered for the selection of the TOP 25% performing appliances.
- The **full load** range is chosen for the selection method, because most data is available at this load.

The appliances with the highest efficiencies and CO-emissions lower than the average CO-emissions of the considered technology and load range represent the TOP 25% performing appliances.

6.2 Stoves/room-heaters

6.2.1 Pellet stoves

The European pellet stove market is quite manageable, because pellets combustion technology is a relatively young technology. Manufacturers of pellet stoves are used to having their products tested and are usually willing to publish their test data. As a result, a very broad database was able to be compiled for this study. Therefore, the data given in the list of the TOP 25% performing pellet stoves is considered to be representative of the current market.

Table 6-1 shows a summary of the minimum, maximum and average efficiency and emission values at full load for all the considered pellet stoves and Table 6-5 shows a summary of the minimum, maximum and average efficiency and emissions values at full load for the TOP 25% pellet stoves with and without water circulation equipment.

A total of 79 data sets were recorded, of which 53 were not identical. Identical data sets are a result of manufacturers producing two or more appliances, which are identical in terms of all technical aspects and combustion systems, but have different designs for the housing as well as different model names. However, due to the identical technical design, separate performance tests are not necessary.

Table 6-1 summary of extreme and averaged values for all considered pellet stoves

water circulate		no		yes
load range (MBtu/h)		< 30	> 30	all
No. of all test data		34	18	27
No. of unequal test data		17	16	19
No. of top 25% appliances		4	4	5
nominal load (MBtu/h)	min.	8	30	25
	max.	29	132	51
	avg.	**23**	**66**	**38**
η_{GCV}[1] at full load (%)	min.	86	85	84
	max.	89	87	85
	avg.	**87**	**86**	**84**
CO at full load (mg/m^3 $_{12\%O2}$)	min.	75	153	39
	max.	844	1316	460
	avg.	**249**	**449**	**174**
TSP[1] at full load (lb/MMBtu)	min.	0.011	0.027	0.014
	max.	0.104	0.082	0.087
	avg.	**0.040**	**0.052**	**0.031**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	15	92	84
	max.	259	213	162
	avg.	**101**	**139**	**119**
avg. retail price (US$)		5262	3757	8820

[1] related to the Gross Calorific Value (upper heating value)

Pellet stoves with and without water circulation equipment are built in a load range from approximately 10 to 130 MBtu/h, whereby the efficiency of these appliances is 86% on average. Pellet stoves with hot water production attain slightly lower efficiencies.

The measured CO-emissions exhibit a very broad range from 75 to 1350 mg/m³ at 12% O_2 . This broad variation is due to different combustion chamber materials and diverse control concepts used for the stoves:

- If ceramics are used in the combustion chamber, the combustion temperature will be higher than if steel only is used – the combustion temperature is the most important indicator for low CO-emissions.
- If the control concept of the stove involves CO or air ratio-measurement, CO emissions can be minimized more easily than if only the combustion gas temperature is measured. If no concepts for combustion condition optimisation are implemented, the control of the stove is not able to adopt to the operation mode.

The measures for the reduction of CO described above will however result in an increase in cost of the stoves. This is clearly shown in a comparison of the CO emissions in relation to the costs of stoves without water installations having heat loads of <30 and >30 MBtu/h. The average pellet stove with a heat load of < 30 MBtu/h emits approximately 250 mg/m³ CO at 12% O_2 and costs approximately 5250 US$. On the other hand, the average pellet stove with a heat load > 30 MBtu/H emits nearly twice as much CO (450 mg/m³ at 12% O_2), but costs one quarter less (3750 US$).

Emissions of TSP vary from 0.015 to 0.100 lb/MMBtu. This broad range can be attributed to the same factors mentioned above. A low combustion temperature will result in a high organic fraction of TSP and the (control) concept for the air supply influences the amount of fly ash.

NO_X emissions range from 100 to 360 mg/m³ at 12% O_2 and the average value is approximately 120 mg/m³ at 12% O_2. These are typical values for wood combustion.

Table 6-2 summary of extreme and averaged values for TOP 25% performing pellet stoves

water circulate		no		yes
load range (MBtu/h)		< 30	> 30	all
No. of all test data		34	18	27
No. of unequal test data		17	16	19
No. of top 25% appliances		4	4	5
nominal load (MBtu/h)	min.	8	30	25
	max.	29	34	51
	avg.	**21**	**32**	**38**
η_{GCV} [1] at full load (%)	min.	88	86	85
	max.	89	87	85
	avg.	**88**	**87**	**85**
CO at full load ($mg/m^3{}_{12\%O2}$)	min.	86	153	39
	max.	236	234	169
	avg.	**164**	**180**	**117**
TSP [1] at full load (lb/MMBtu)	min.	0.033	0.035	0.014
	max.	0.072	0.050	0.025
	avg.	**0.045**	**0.043**	**0.019**
NOx at full load ($mg/m^3{}_{12\%O2}$)	min.	88	106	125
	max.	88	114	162
	avg.	**88**	**110**	**143**
avg. retail price (US$)		8113	4820	9843

[1] related to the Gross Calorific Value (upper heating value)

The TOP 25% performing pellet stoves reach average efficiencies from 85 to 87% based on the GCV. Their CO-emissions vary from 40 to 240 mg/m³ at 12% O_2 and the average CO emissions are approximately 155 mg/m³ at 12% O_2. The difference between the CO emissions from pellet stoves without water circulation having heat loads of < 30 MBtu/h and those with heat loads of > 30 MBtu/h still exists, but is definitely smaller.

The average dust emissions range from 0.020 to 0.045 lb/MMBtu, a range which is slightly smaller than the average dust emissions calculated from all of the collected data. The NO_X emissions from the TOP 25% performing pellet stoves are essentially no different than those from all the other pellet stoves collected for this study.

For pellet stoves without water circulation having heat loads of < 30 MBtu/h in particular, a quite notable increase in price for the TOP 25% is observed in comparison to the average price of all the collected data.

6.2.2 Solid wood stoves

The solid wood stove market is extremely broad and diverse as manufacturers come from many different backgrounds (masonry heater industry, steel industry, biomass boiler industry, etc.) and as such define the main purposes for their products differently (e.g., efficient heating, stove design, lifestyle product, etc.). Moreover, many uncertified products, which do not conform to the standard EN 13240 are also offered on the market.

The publishing of test data is not common for wood stoves. The fact that the emissions from wood stoves are difinitively higher those from pellet stoves or biomass boilers discourages manufacturers from publishing test data.

For these reasons, only a small group of wood stoves data could be collected and evaluated.

Table 6-3 and Table 6-4 show the minimum, maximum and average efficiency and emissions values at full load for all analysed wood stoves and for the TOP 25% performing wood stoves.

A total of 51 data sets were recorded, of which 40 were not identical.

Table 6-3 summary of extreme and average values for selected wood stoves

No. of all test data		51
No. of unequal test data		40
No. of top 25% appliances		10
nominal load (MBtu/h)	min.	25
	max.	128
	avg.	**57**
η_{GCV}[1] at full load (%)	min.	64
	max.	76
	avg.	**71**
CO at full load (mg/$m^3_{12\%O2}$)	min.	776
	max.	2535
	avg.	**1521**
TSP[1] at full load (lb/MMBtu)	min.	0.009
	max.	0.128
	avg.	**0.059**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	59
	max.	225
	avg.	**139**
avg. retail price (US$)		-

Table 6-4 summary of extreme and average values for TOP 25% performing wood stoves

No. of all test data		51
No. of unequal test data		40
No. of top 25% appliances		10
nominal load (MBtu/h)	min.	25
	max.	128
	avg.	**57**
η_{GCV}[1] at full load (%)	min.	71
	max.	76
	avg.	**73**
CO at full load (mg/$m^3_{12\%O2}$)	min.	776
	max.	1340
	avg.	**1069**
TSP[1] at full load (lb/MMBtu)	min.	0.020
	max.	0.081
	avg.	**0.050**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	59
	max.	197
	avg.	**126**
avg. retail price (US$)		-

[1] *related to the GCV*

The heat loads of the wood stoves vary from 25 to 130 MBtu/h and achieve an average efficiency of 71 % based on the GCV.

CO emissions fall into a rather wide range between 750 to 2550 mg/m³ at 12% O_2. Since dust emissions are related to CO emissions due to un-burnt particles in the fly ash fraction, dust emissions also widely vary from 0.010 to 0.130 lb/MMBtu.

The average NO_X emissions are approximately 140 mg/m³ at 12% O_2, which is a typical value for wood combustion.

The TOP 25% performing wood stoves reach efficiencies of approximately 73% and emit on average 1050 mg/m³ CO at 12% O_2, a 33% reduction with respect to the entire data set. The dust emissions still show quite broad variations from 0.020 to 0.080 lb/MMBtu; however, the average data changes marginally in comparison to the entire data set.

Altogether, the average data of the TOP 25% performing wood stoves does not exhibit significant improvements in comparison to the entire data set.

Detailed performance data of all considered wood stoves is given in the annex. This summary should give an idea of the average emissions as well as the performance of wood stoves. It does not imply that test data from other manufacturers is better or worse than the given data.

6.2.7 Masonry heaters

The masonry heater market is similar to that of wood stoves. Data from only two manufacturers (LEDA and Brunner) could be collected. For this reason, performance and emission data will not be summarized for masonry heaters.

6.3 Boilers

The European biomass boiler market is quite large. A very competitive environment and local/national grant schemes for biomass appliances (see diverse environmental labels) lead to a high transparency of performance and emission data. Test data can be found on web pages from national authorities. It is estimated that approximately 90% of Austrian and German boilers were collected for this study. Therefore, the data given in the list of the TOP 25% performing technologies is considered to be an accurate representation of the current market.

A total of 954 data sets were recorded, of which 787 were not identical. These identical data sets are a result of manufacturers producing two or more appliances, which are identical in terms of all technical aspects and combustion systems, but have different designs for the housing as well as different model names. Due to the identical technical design, a separate performance test is not necessary.

6.3.1 Pellet boiler

Table 6-5 shows a summary of the minimum, maximum and average efficiency and emission values at full load for all the considered pellet boilers and Table 6-6 shows test data of the TOP25% performing appliances at the defined load ranges.

A total of 433 data sets were recorded, of which 362 were not identical.

Table 6-5 overview of extreme and averaged values for all considered pellet boilers

load range (MBtu/h)		< 55	55 - 100	100 - 170	170 - 340	> 340
No. of all test data		124	142	83	52	32
No. of unequal test data		102	130	66	45	29
No. of top 25% appliances		26	33	17	11	7
nominal load (MBtu/h)	min.	26	55	99	171	342
	max.	54	98	169	338	997
	avg.	**45**	**78**	**134**	**254**	**568**
η_{GCV} 1) at full load (%)	min.	78	73	80	81	81
	max.	89	88	89	88	88
	avg.	**85**	**84**	**85**	**85**	**85**
CO at full load (mg/m^3 $_{12\%O2}$)	min.	7	1	3	4	1
	max.	371	603	281	338	543
	avg.	**91**	**116**	**76**	**66**	**62**
TSP 1) at full load (lb/MMBtu)	min.	0.003	0.008	0.006	0.014	0.004
	max.	0.069	0.348	0.377	0.377	0.058
	avg.	**0.023**	**0.028**	**0.030**	**0.047**	**0.031**
NOx at full load (mg/m$^3_{12\%O2}$)	min.	84	12	63	63	63
	max.	398	365	378	293	247
	avg.	**154**	**168**	**144**	**151**	**133**
avg. retail price (US$)		11359	12149	16052	24795	30244

1) related to the Gross Calorific Value (upper heating value)

Pellet boilers are built for heat loads starting at 25 MBtu/h and reach high efficiencies independent of their load, in the range of 73 to 89 %. The average efficiency for these boilers is 85 %.

CO emissions vary from very small amounts to elevated values of 600 mg/m^3 at 12% O_2. The average CO-emissions for all load ranges are, however, below 120 mg/m^3 at 12% O_2. Higher loads give rise to lower CO emissions, a fact that can be attributed to the higher combustion temperatures reached in larger appliances as a result of the favourable relationship between combustion chamber volume and combustion chamber surface as well as the better materials that are used. It can be stated that CO-emissions are generally low in pellet boilers.

TSP-emissions vary from 0.003 to 0.377 lb/MMBtu; the average emissions are in the range of 0.025 to 0.045 lb/MMBtu, which are very low values.

NO_X-emissions fall within a range of 60 to 400 mg/m^3 at 12% O_2; the average value is approximately 150 mg/m^3 at 12% O_2, which can be considered normal NO_X-emissions for wood fuel.

Table 6-6 overview of extreme and average values for TOP 25% performing pellet boilers

load range (MBtu/h)		< 55	55 - 100	100 - 170	170 - 340	> 340
No. of all test data		124	142	83	52	32
No. of unequal test data		102	130	66	45	29
No. of top 25% appliances		26	33	17	11	7
nominal load (MBtu/h)	min.	27	55	102	171	342
	max.	53	92	169	331	885
	avg.	**44**	**78**	**141**	**258**	**524**
η_{GCV} [1] at full load (%)	min.	86	85	86	86	85
	max.	89	88	89	88	88
	avg.	**87**	**86**	**87**	**86**	**86**
CO at full load ($mg/m^3{}_{12\%O2}$)	min.	7	1	5	4	5
	max.	77	105	73	59	41
	avg.	**43**	**39**	**38**	**24**	**17**
TSP[1] at full load (lb/MMBtu)	min.	0.008	0.010	0.006	0.014	0.008
	max.	0.043	0.056	0.057	0.053	0.056
	avg.	**0.022**	**0.024**	**0.023**	**0.036**	**0.031**
NOx at full load ($mg/m^3{}_{12\%O2}$)	min.	95	39	63	105	118
	max.	230	260	183	198	171
	avg.	**140**	**136**	**132**	**154**	**133**
avg. retail price (US$)		12221	13659	16844	23537	0

[1] related to the Gross Calorific Value (upper heating value)

The TOP 25% performing pellet boilers exhibit average efficiencies 2% higher than that of the entire data set. The CO emissions are 50% less than of all considered appliances, and varying from nearly no CO emissions to 105 mg/m³ at 12% O_2.

The average dust emissions are slightly lower than the emission values of the entire data and range from 0.02 to 0.035 lb/MMBtu.

Detailed performance data of the TOP 25% performing pellet boilers is given in the annex.

6.3.2 Solid wood boiler

Table 6-7 shows a summary of the minimum, maximum and average efficiency and emission values at full load for all the considered solid wood boilers. Table 6-8 shows test data of the TOP25% performing appliances for the defined load ranges.

A total of 279 data sets were recorded, of which 229 were not identical.

Table 6-7 overview of extreme and average values from all considered solid wood boilers

load range (MBtu/h)		< 85	85 - 120	120 - 170	> 170
No. of all test data		69	81	72	57
No. of unequal test data		65	64	54	46
No. of top 25% appliances		16	16	14	12
nominal load (MBtu/h)	min.	40	85	120	171
	max.	82	116	167	348
	avg.	**63**	**98**	**141**	**199**
η_{GCV} 1) at full load (%)	min.	62	73	73	73
	max.	84	85	84	84
	avg.	**80**	**81**	**81**	**81**
CO at full load ($mg/m^3{}_{12\%O2}$)	min.	64	20	18	44
	max.	3912	4137	2878	2009
	avg.	**612**	**417**	**399**	**308**
TSP 1) at full load (lb/MMBtu)	min.	0.008	0.009	0.008	0.012
	max.	0.175	0.189	0.324	0.166
	avg.	**0.034**	**0.035**	**0.041**	**0.036**
NOx at full load ($mg/m^3{}_{12\%O2}$)	min.	20	57	34	75
	max.	206	225	242	199
	avg.	**129**	**133**	**135**	**149**
avg. retail price (US$)		8436	9683	11965	14104

1) related to the Gross Calorific Value (upper heating value)

Solid wood boilers are built for heat loads starting at 50 MBtu/h and reach efficiencies from 60 to 85 %. The average efficiencies are approximately 81%, which is 3% lower than the efficiencies reached by pellet boilers.

CO-emissions vary from 20 to 4140 mg/m³ at 12% O_2, which exhibits a very broad variation. This may be attributed to the broad range of control (or no control) concepts[3] for solid wood boilers as well as the materials used in the combustion zone. The average values are approximately 400 mg/m³ at 12% O_2 and decrease with higher load ranges. This can be attributed to the same phenomenon discussed for the pellet boilers.

Dust emissions range from 0.010 to 0.325 lb/MMBtu, whereby the average emissions are approximately 0.035 lb/MMBtu, which is nearly as low as the dust emissions from pellet boilers.

The average NO_X-emissions are approximately 130 mg/m³ at 12% O_2 and thus lie in the normal range for wood combustion.

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[3] The solid wood boiler is the oldest biomass boiler technology. There are thus a large number of traditional manufacturers who use very traditional design concepts without proper control concepts, resulting in a broad variation.

Table 6-8 overview of extreme and average values from TOP 25% performing solid wood boilers

load range (MBtu/h)		< 85	85 - 120	120 - 170	> 170
No. of all test data		69	81	72	57
No. of unequal test data		65	64	54	46
No. of top 25% appliances		16	16	14	12
nominal load (MBtu/h)	min.	40	85	123	171
	max.	75	116	167	239
	avg.	**63**	**97**	**143**	**189**
η_{GCV}[1] at full load (%)	min.	82	82	82	81
	max.	84	83	84	84
	avg.	**83**	**83**	**83**	**82**
CO at full load (mg/m$^3_{12\%O2}$)	min.	64	40	50	44
	max.	353	298	343	282
	avg.	**174**	**220**	**152**	**97**
TSP[1] at full load (lb/MMBtu)	min.	0.014	0.014	0.021	0.015
	max.	0.175	0.189	0.324	0.076
	avg.	**0.039**	**0.044**	**0.066**	**0.033**
NOx at full load (mg/m$^3_{12\%O2}$)	min.	90	100	34	75
	max.	182	186	181	194
	avg.	**139**	**126**	**115**	**119**
avg. retail price (US$)		10116	10319	12672	14089

[1] related to the Gross Calorific Value (upper heating value)

The TOP 25% performing solid wood boilers reach average efficiencies which are 2% higher than the average values from the entire data set.

The variation of CO emissions is significantly lower and varies from 40 to 350 mg/m³ at 12% O_2. The average CO emissions decrease by 50 to 75% and range from 100 to 220 mg/m³ at 12% O_2. A decrease of CO emissions with higher loads can also be observed for the TOP 25% performing appliances.

Surprisingly and also inconsistent with the statement that low CO emissions result in low dust emissions, the dust emissions of the TOP 25% performing appliances are higher than the dust emissions for the entire data set. This could be attributed to quality variations of the dust measurement methods.

Detailed performance data of the TOP 25% performing solid wood boilers is given in the annex.

6.3.3 Wood chip boiler

Table 6-9 shows a summary of the minimum, maximum and average efficiency- and emission values at full load of all considered wood chip boilers and Table 6-10 shows test data for the TOP25% performing appliances at the defined load ranges.

A total of 213 data sets were recorded, of which 174 were not identical.

Table 6-9 overview of extreme and averaged values from all considered wood chip boilers

load range (MBtu/h)		< 100	100 - 200	200 - 340	340 - 680	> 680
No. of all test data		35	65	44	39	30
No. of unequal test data		26	49	42	33	26
No. of top 25% appliances		7	12	11	8	7
nominal load (MBtu/h)	min.	34	102	205	342	683
	max.	96	188	340	666	5123
	avg.	**74**	**150**	**265**	**444**	**1459**
η_{GCV}1) at full load (%)	min.	73	68	69	70	46
	max.	86	86	86	86	86
	avg.	**77**	**77**	**76**	**77**	**75**
CO at full load ($mg/m^3_{12\%O2}$)	min.	22	4	7	3	6
	max.	489	649	641	368	369
	avg.	**128**	**117**	**106**	**74**	**86**
TSP1) at full load (lb/MMBtu)	min.	0.011	0.009	0.011	0.004	0.024
	max.	0.134	0.258	0.237	0.127	0.460
	avg.	**0.058**	**0.051**	**0.052**	**0.048**	**0.106**
NOx at full load ($mg/m^3_{12\%O2}$)	min.	91	45	51	45	45
	max.	438	394	411	371	235
	avg.	**180**	**145**	**146**	**150**	**122**
avg. retail price (US$)		15921	21887	26468	32373	54890

1) related to the Gross Calorific Value (upper heating value)

Wood chip boilers are available from a nominal load of 35 MBtu/h. The efficiencies vary from 70 to 86% and the average is approximately 77%, meaning that their performance is 4% lower than that of the solid wood boilers.

The CO-emissions range from very small amounts to 650 mg/m³ at 12% $O_{2;}$ the average value is approximately 100 mg/m³ at 12% O_2. Due to the continuous operation conditions, these emission values are similar to the CO-emissions of pellet boilers. It can also be observed that the CO-emissions decrease as the load range increases.

TSP-emissions vary from 0.004 to 0.460 lb/MMBtu; the average is approximately 0.052 lb/MMBtu. Emissions in the largest load range (> 680 MBtu/h) are significantly higher, which can be attributed to the small amount of appliance data. Overall, the TSP-emissions are slightly higher than the TSP-emissions for solid wood boilers, which may be due to the characteristics of the fuel as wood chips have more fine parts and are more inhomogeneous than pellets.

The NO_X-emissions fall into the range of 50 to 440 mg/m³ at 12% O_2; the average value is approximately 150 mg/m³ at 12% O_2. This value is slightly higher than the NO_X-emissions from pellets and solid wood stoves, which can be attributed to the characteristics of wood chips (bark).

Table 6-10 overview of extreme and averaged values from TOP 25% performing wood chip boilers

load range (MBtu/h)		< 100	100 - 200	200 - 340	340 - 680	> 680
No. of all test data		35	65	44	39	30
No. of unequal test data		26	49	42	33	26
No. of top 25% appliances		7	12	11	8	7
nominal load (MBtu/h)	min.	51	102	205	342	751
	max.	96	171	340	666	2220
	avg.	**78**	**147**	**276**	**449**	**1322**
η_{GCV}[1] at full load (%)	min.	73	75	77	77	76
	max.	78	81	80	86	79
	avg.	**76**	**79**	**78**	**80**	**78**
CO at full load (mg/$m^3_{12\%O2}$)	min.	28	10	7	9	15
	max.	108	93	87	40	68
	avg.	**60**	**39**	**30**	**22**	**34**
TSP[1] at full load (lb/MMBtu)	min.	0.017	0.009	0.020	0.009	0.053
	max.	0.110	0.053	0.075	0.072	0.156
	avg.	**0.046**	**0.027**	**0.038**	**0.042**	**0.092**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	91	90	106	45	90
	max.	185	179	180	180	178
	avg.	**157**	**134**	**138**	**125**	**131**
avg. retail price (US$)		14350	25504	31581	34056	65180

[1] related to the Gross Calorific Value (upper heating value)

The TOP 25% performing wood chip boilers reach efficiencies of approximately 78%, which is 1% higher than the average emissions of the entire data set.

In comparison to the CO emissions of the entire data set, decreases of 50 – 70% can be observed in that the average CO emissions are very low at approximately 35 mg/m³ at 12% O_2. Dust emissions are approximately 20% lower than the emissions of the entire data set. The average dust emissions are approximately 0.040 lb/MMBtu/h.

Detailed performance data of the TOP 25% performing wood chip boilers is given in the annex.

6.3.4 Combined technologies

Table 6-11 shows a summary of the minimum, maximum and average efficiency- and emission values at full load of all considered combined technology boilers (pellets & solid wood) and Table 6-12 shows test data of the TOP 25% performing appliances at the defined load ranges.

A total of 29 data sets were recorded, of which 22 were not identical.

Table 6-11 overview of extreme and average values from all considered combined technology boilers (pellets & solid wood)

fuel		pellets	solid wood
No. of all test data		29	
No. of unequal test data		22	
No. of top 25% appliances		6	
nominal load (MBtu/h)	min.	51	51
	max.	205	205
	avg.	**80**	**92**
η_{GCV} 1) at full load (%)	min.	79	72
	max.	89	87
	avg.	**84**	**80**
CO at full load (mg/$m^3_{12\%O2}$)	min.	1	158
	max.	294	1384
	avg.	**109**	**367**
TSP 1) at full load (lb/MMBtu)	min.	0.008	0.021
	max.	0.139	0.079
	avg.	**0.036**	**0.035**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	92	96
	max.	218	174
	avg.	**131**	**135**
avg. retail price (US$)		15675	

1) related to the Gross Calorific Value (upper heating value)

Combined boilers are built in load ranges from 50 to 200 MBtu/h. For pellet mode and solid wood mode, average efficiencies of 84% and 80% respectively are achieved.

CO emissions in pellet mode are approximately 110 mg/m³ at 12% O_2, meaning that CO emissions are similar to the emissions from pellet boilers. In solid wood mode, CO emissions are approximately 370 mg/m³ at 12% O_2. These emissions are comparable to emissions from solid wood boilers.

Dust emissions range from 0.010 to 0.140 lb/MMBtu and are approximately 0.036 lb/MMBtu on average. These values also correspond closely with emission data from pellets and solid wood boilers.

NOx emissions are approximately 130 mg/m³ at 12% $O_{2,}$ which can be considered normal NO_X-emissions for wood fuel.

Table 6-12 overview of extreme and average values from TOP 25% performing combined technology boilers (pellets & solid wood)

fuel		pellets	solid wood
No. of all test data		29	
No. of unequal test data		22	
No. of top 25% appliances		6	
nominal load (MBtu/h)	min.	51	51
	max.	126	153
	avg.	**75**	**88**
η_{GCV} 1) at full load (%)	min.	79	72
	max.	84	83
	avg.	**82**	**79**
CO at full load (mg/$m^3_{12\%O2}$)	min.	6	158
	max.	104	530
	avg.	**34**	**252**
TSP 1) at full load (lb/MMBtu)	min.	0.017	0.023
	max.	0.040	0.038
	avg.	**0.027**	**0.027**
NOx at full load (mg/$m^3_{12\%O2}$)	min.	92	96
	max.	218	150
	avg.	**145**	**120**
avg. retail price (US$)		16870	

1) related to the Gross Calorific Value (upper heating value)

The emissions and efficiencies of the TOP 25% performing appliances correspond to the increase of efficiency and decrease of CO and TSP emissions as discussed for the pellets and solid wood boilers.

Detailed performance data of all combined technology boilers is given in the annex.

6.3.5 Summary

In Figure 6-1 and 6-2 the deviations of the average efficiencies and dust emissions of the TOP 25% performing appliances from the requirements given in EN 303-5 are summarized. The efficiency requirements in EN 303-5 are illustrated in Figure 5-1 and the dust emission limits are shown in Figure 6-2

Figure 6-1 and Figure 6-2 clearly show that the average performance of the TOP 25% performing appliances identified in this report greatly exceed the efficiency requirements and are mostly below the dust emission limits of class 5 from EN 303-5 (currently still under discussion and has not yet been introduced). At present, class 3 represents the most stringent requirements for biomass boilers.

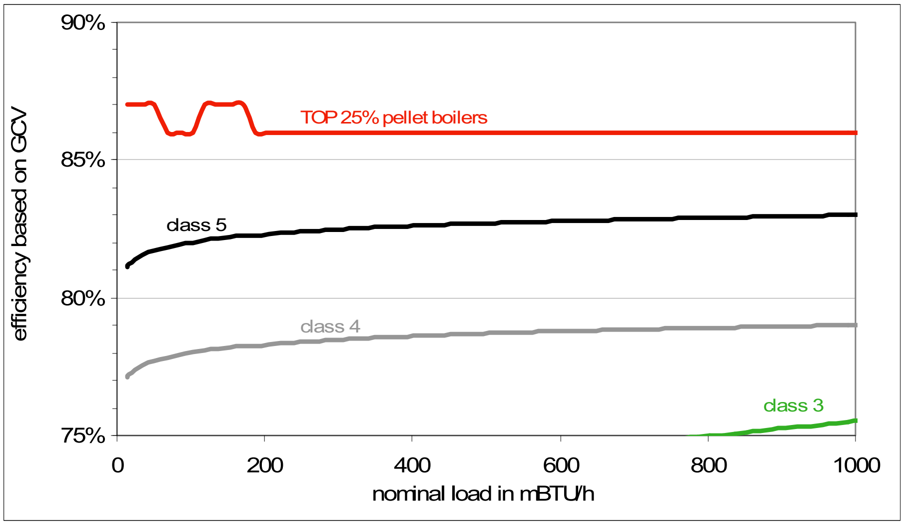


Figure 6-1 average efficiency performance of TOP 25% pellet boilers in comparison to efficiency requirements of EN 303-5, class 3 and future efficiency requirements of EN303-5, class 4 and 5

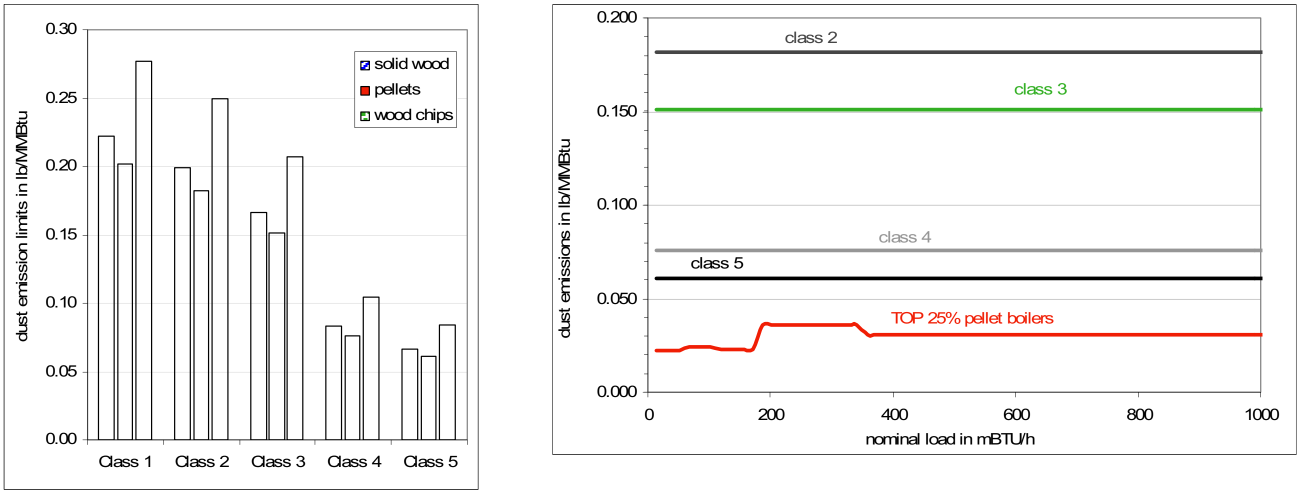


Figure 6-2 dust emission limits for solid wood, wood chips and pellet boilers of EN 303-5, classes 1 to 5 and average dust emissions of the TOP 25% performing boilers.

Figure 6-3 shows the efficiencies from the TOP 25% performing boilers for nominal and partial loads. For pellet and wood chips boilers partial load equals 30% of nominal load, for solid wood boilers partial load is 50% of nominal load.

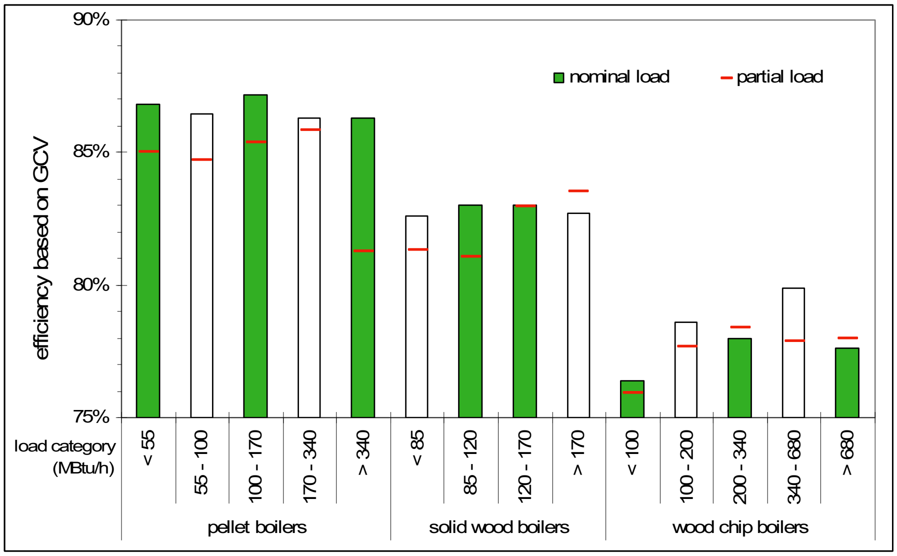


Figure 6-3 average efficiencies based on GCV at nominal and partial heat load for the TOP 25% performing boilers

Efficiencies that are reached at nominal and partial load are nearly identical, solid wood and wood chip appliances sometimes even reach higher efficiencies at partial load.

6.4 Commercial biomass installations

Medium to large scale commercial biomass installations undergo individual commissioning, meaning that these plants are dimensioned and built individually with respect to the technical requirements of the buyer. Commisioning is performed in order to guarantee that the emission and efficiency requirements are met. Depending on the local regulations, emissions and efficiencies have to be controlled periodically by consulting engineers. Results of these measurements are usually not published; therefore, no database on emissions and efficiencies of medium commercial biomass appliances is available.

In order to give an idea of emissions and efficiencies of medium scale biomass plants, results from various studies on this topic will be cited in this section. In addition, national emission factors for biomass combustion units shall show which average emissions are assumed for the Austrian biomass plants.

6.4.1 Data collection of Austrian medium scale biomass appliances (Musil et al. 2006)

Emission data for Austrian biomass combustion and CHP plants was collected directly from the operators of medium scale biomass units using a standard questionnaire. In addition, the measurement results of one consulting engineer were used for the estimation of emissions from medium scale biomass appliances. Approximately 100 data sets in total were collected, all appliances were operated with wood chips, saw shavings or wood residues.

In Figure 6-4 the average emission results for TSP and NO_X assigned in three load ranges are shown.

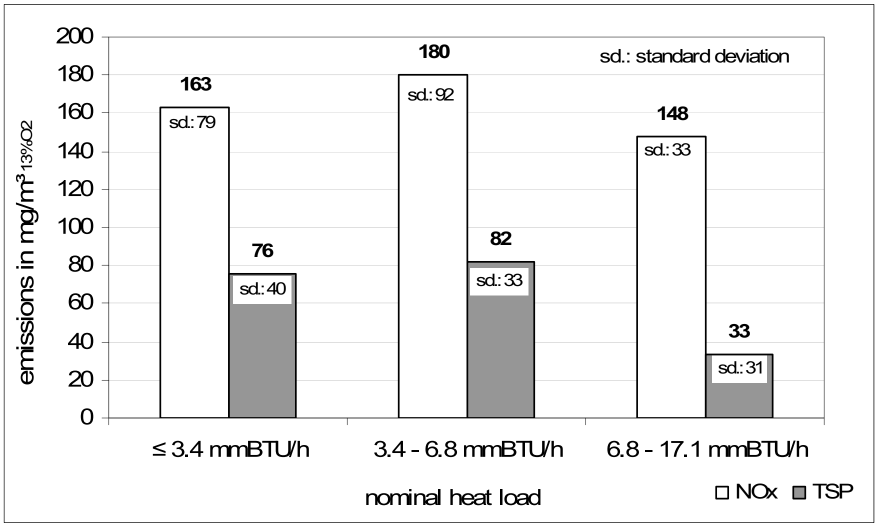
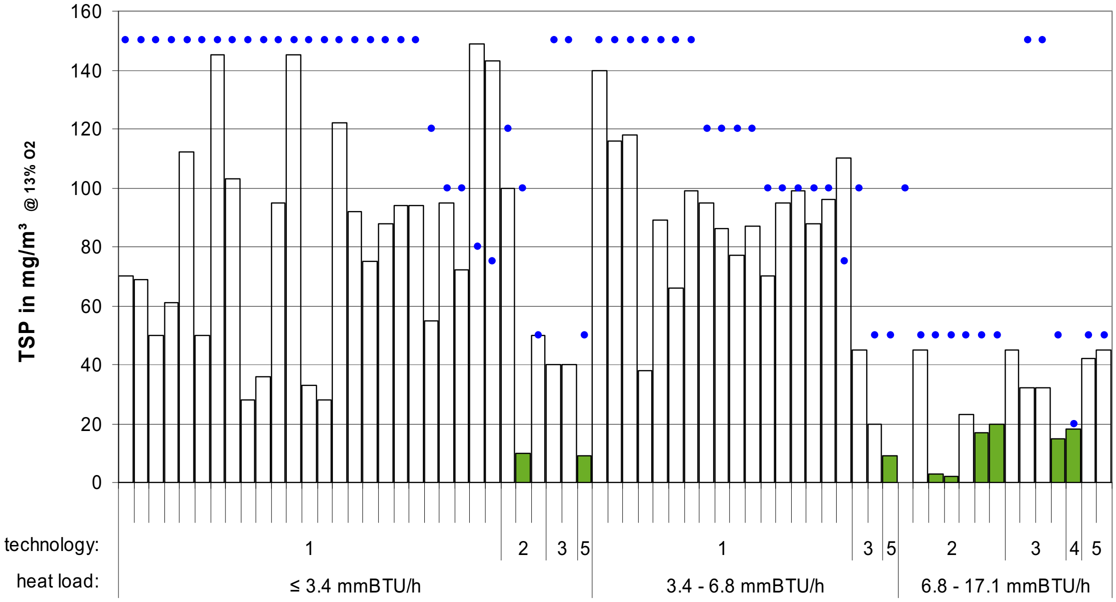


Figure 6-4 TSP and NOx emissions of medium scale biomass appliances in Austria

While the NO_X emissions were quite constant for these load categories (from 170 – 205 mg/m³ at 12% O_2), dust emissions decreased significantly with increasing load because of stricter emission limits for loads from 6.9 MMBtu/h. Up to a load range of 6.8 MMBtu/h, TSP emissions were found to be around 80 mg/m³ at 13% O_2 (0.150 lb/MMBtu), TSP emissions for higher loads are around 35 mg/m³ at 13% O_2 (0.065 lb/MMBtu).

Figure 6-5 shows the TSP emissions and the emission limits of the analysed biomass appliances in more detail including the utilized emission control technology.



blue dots: emission limits for the appliance

technology 1: cyclone

technology 2: cyclone + electrostatic precipitator

technology 3: cyclone + flue gas condensation

technology 4: cyclone + flue gas condensation + electrostatic precipitator

technology 5: electrostatic precipitator

Figure 6-5 dust emissions and emission limits of Austrian medium scale biomass appliances (Musil et al. 2006)

For appliances of up to 6.8 MMBtu/h, cyclones are the most commonly used emission control technology. This is due to the relatively high emission limits of 150 mg/m at 13% O_2 (0.275 lb/MMBtu) in comparison to emission limits for combustion units 6.8 MMBtu/h (50 mg/m³ at 13% O_2 and 0.090 lb/MMBtu). Next to cyclones, electrostatic precipitators combined with cyclones are the second most common. No bag-house filters were used for appliances of this load range.

6.4.2 Data collection of Swiss automated biomass appliances (Hasler et al. 2000)

In a large data survey, approximately 1000 measurement results of 250 biomass appliances installed in Switzerland were collected and analyzed. Untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c) and urban waste wood (Altholz) were used. For comparison, a small number of data from solid wood appliances (LRV Kat. a) were also considered.

Figure 6-6 shows the number of the considered wood chip appliances by heat load and fuel category.

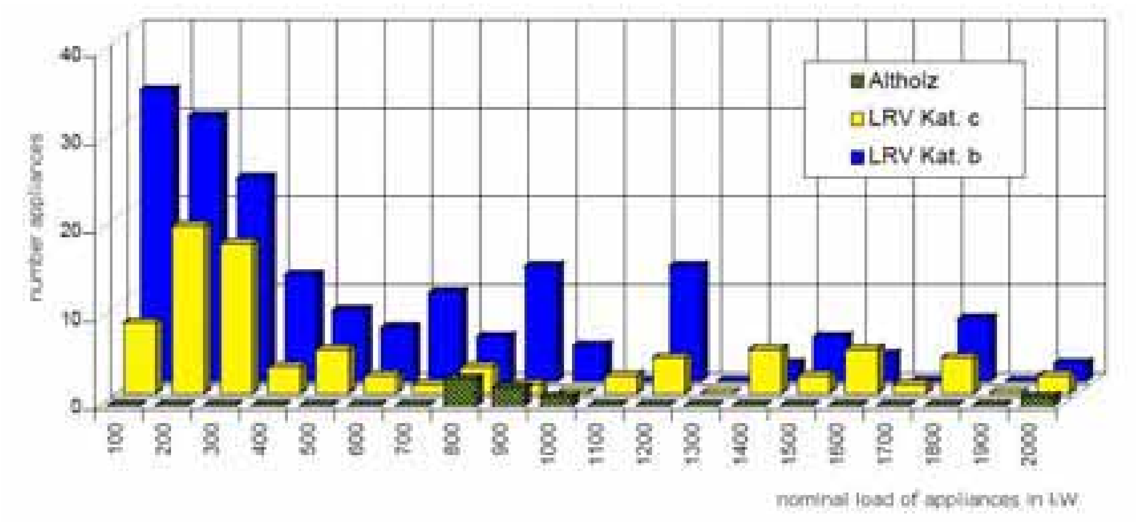


Figure 6-6 number of considered wood chip boilers by heat load and fuel category from 100 to 2000 kW (340-6820 MBtu/h); fuels: untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c) and urban waste wood (Altholz)
how to read the graph: the first range of values (1st field of the X-axis) includes all appliances in the range from 0 to 100 kW (0-340 MBtu/h)
(Hasler et al. 2000)

Figure 6-7 shows the CO emissions and the excess air ratio of the considered boilers with untreated wood chips fuel (LRV Kat. b).

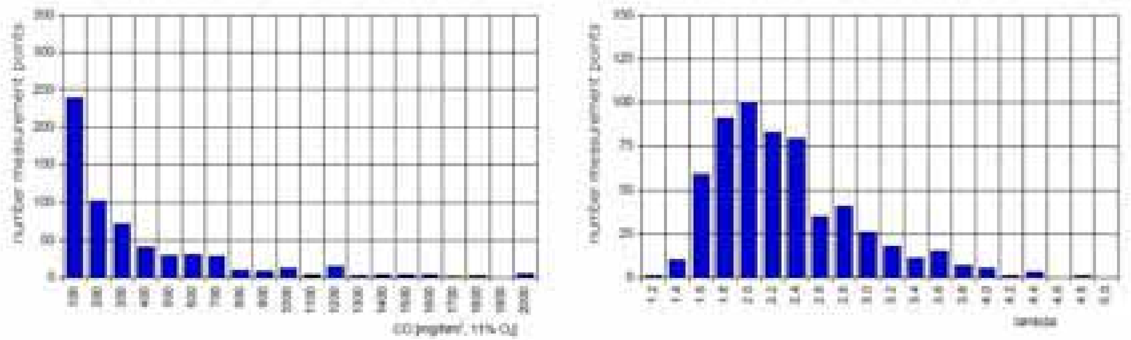


Figure 6-7 CO emissions in mg/m³ at 11%O2 and the excess air ratio of the considered boilers with untreated wood chips fuel (LRV Kat. a) (Hasler et al. 2000)
How to read the graph: the first range of values (1st field of the X-axis) includes all measurement points in the range from 0 to 100 mg/m³ at 11%O_2 (0 to 90mg/m^3 at 12%O_2) respectively 0 to 1.2

Two thirds of the considered appliances have CO emissions < 250 mg/m³ at 11% O_2 (225 mg/m³ at 12% O_2); CO emissions > 1000 mg/m³ at 11% O_2 (900 mg/m³ at 12% O_2) are only measured in appliances with heat loads below 500 kW (1706 MBtu/h). The excess air ratio shows broad variations from $1.2 < \lambda < 5$. Most of the appliances reach excess air ratios between 1.8 and 2.4 and about one third of the appliances are operated with excess air ratios > 2.4.

Figure 6-8 shows the NO_X emissions of all considered wood chip appliances (untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c) and urban waste wood (Altholz)).

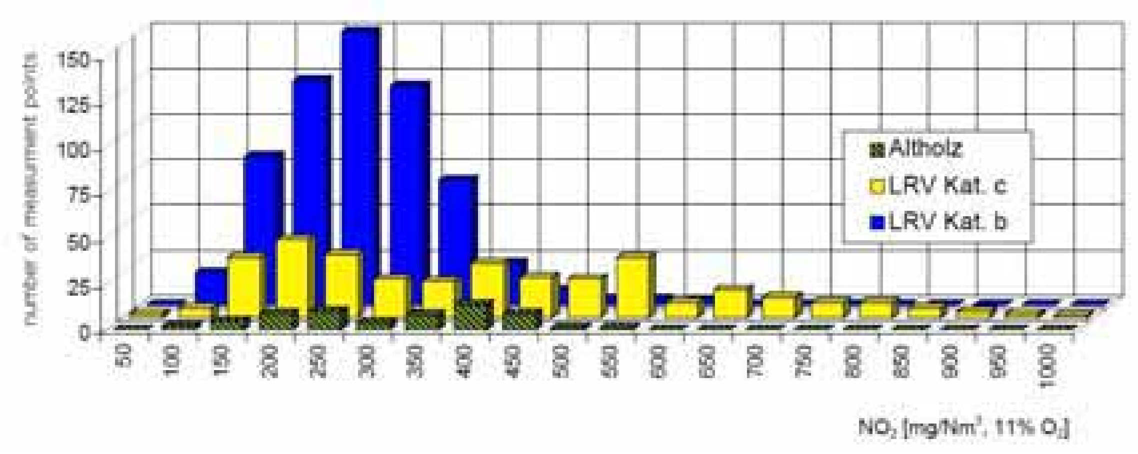


Figure 6-8 NO$_X$ -emissions from wood chip appliances (fuels: untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c) and urban waste wood (Altholz)) (Hasler et al. 2000)
How to read the graph: the first range of values (1st field of the X-axis) includes NO$_X$ emissions in the range from 0 to 50 mg/m³ at 11% O_2 (45 mg/m³ at 12% O_2)

NO$_X$ emissions from untreated wood chips (LRV Kat. b) exhibit a nearly Gaussian distribution in the range from 100 to 400 mg/m³ at 11% O_2 . For urban waste wood, NO$_X$ emissions fall into a similar range. NO$_X$ emissions from wood residues (LRV Kat. c) fall into a broader range of up to 850 mg/m³ at 11% O_2 due to higher N contents in some wood residues appliances.

Figure 6-9 shows the TSP/dust emissions of wood chip appliances (untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c) and of solid wood appliances (LRV Kat. a)).

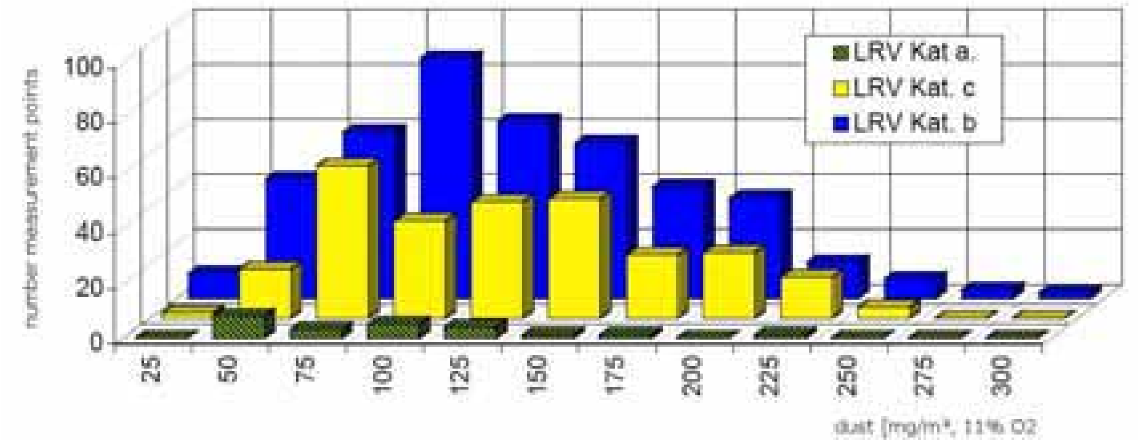


Figure 6-9 TSP/dust emissions from wood chips and solid wood appliances (fuels: solid wood (LRV Kat. a) untreated wood chips (LRV Kat. b), wood residues (LRV Kat. c))
How to read the graph: the first range of values (1st field of the X-axis) includes dust emissions in the range from 0 to 25 mg/m³ at 11% O_2 (0-0.030 lb/MMBtu for solid wood and 0-0.037 lb/MMBtu)
(Hasler et al. 2000)

For all solid wood appliances (LRV Kat. a) the dust emissions are below 150 mg/m³ at 11% O_2 (0.185 lb/MMBtu); most dust loads are in the range from 25 to 50 mg/m³ at 11% O_2 (0.030 – 0.060 lb/MMBtu). For untreated wood chips (LRV Kat. b) and wood residues (LRV Kat. c) the averaged dust emissions are between 100 and 150 mg/m³ at 11% O_2 (0.150- 0.220 lb/MMBtu).

6.4.3 Emission factors

While measurement results of emissions are related to the input load, emission factors are related to the annual energy use. Therefore a direct conversion from emissions to emission factors is not possible.

Emission factors are used to calculate the national annual overall emissions of CO_2, CO, NO_X and other pollutants.

Calculation methods for emission factors vary from country to country and depend strongly on the available data sources. Emission factors are supposed to represent the average annual emissions of the considered appliance type, including start and stop emissions as well as summer and winter operation modes. Emission factors are derived as a function of plant size and fuel type and are combined in different classes which differ from country to country. To calculate the annual overall emissions, the shares of the diverse emission classes in the total energy consumption has to be determined.

In order to estimate nationwide emissions of diverse facilities, emission factors are specified for diverse facilities and fuels. Each country identifies emission categories on its own, which means that emissions from biomass combustion units are often mixed with emissions from other combustion units.

Table 6-13 shows emission factors from Austria, Germany and Switzerland.

Table 6-13 Austrian, German and Swiss emission factors

	CO (lb/MMBtu)	*TSP (lb/MMBtu)*	*NO_X (lb/MMBtu)*
AUSTRIA (SOURCE: BOEHMER ET AL. 2007)			
biomass district heating/CHP facilities < 170 MMBtu/h wood chips including bark and wood residues	*0.115*	*0.050*	*0.215*
GERMANY (SOURCE: STRUSCHKA ET AL. 2008)			
manual boilers > 170 MBtu/h	*1.400*	*0.145*	*0.200*
pellet boilers > 170 MBtu/h	*0.255*	*0.075*	*0.230*
wood chip boilers > 170 MBtu/h	*2.305*	*0.150*	*0.370*
SWITZERLAND (SOURCE: HASLER ET AL. 2000)			
solid wood (LRV Kat. a)		*0.105*	*0.235*
untreated wood chips (LRV Kat. b)		*0.205*	*0.375*
wood residues (LRV Kat. c)		*0.215*	*0.665*
urban waste wood (Altholz)		*0.005*	*0.485*

Table 6- clearly shows that each country looks at different combustion systems and fuel categories in order to calculate the national emission factors. Therefore, the comparability of these emission factors is limited.

CO emissions vary from 0.100 to 2.300 lb/MMBtu. While wood chip appliances are considered to reach low CO emissions in the Austrian study, very high emissions are considered in the German study.

Except for the Swiss emission factors for urban waste wood (0.005 lb/MMBtu), TSP emissions vary from 0.050 to 0.220 lb/MMBtu. Since TSP emissions depend on the emission control system installed, this variation seems reasonable due to different TSP control concepts and/or limits.

For medium scale biomass appliances, emission controls for NO_X are usually not installed. Since NO_X emissions result primarily from nitrogen in the fuel and the fuel quality is quite constant, NO_X emission factors should be very similar. This is true for the emission factors shown in Table 6-13 where NO_X emission factors are within the range of 0.200 to 0.375 lb/MMBtu. Since wood residues and urban waste wood usually contain more nitrogen than the other biomass fuels, NO_X emissions are thus higher for these appliances.

6.4.4 Summary

In two studies, emission data from medium scale biomass appliances were collected and analysed, whereby an emphasis was placed on NO_X and dust emissions. In the Austrian study (Musil et al. 2006), biomass district heating/CHP facilities with heat loads of up to 17 MMBtu/h were analysed, while the Swiss study (Hasler et al. 2000) considered all sizes of biomass appliances from residential stoves up to 17 MMBtu/h. In addition, emission factors are presented for Austria (Boehmer et al. 2007), Germany (Struschka et al. 2008) and Switzerland (Hasler et al. 2000). Since emission factors are based on the annual heat demand, they cannot be directly compared with measured average emission values.

CO emissions were only analysed in the study from Hasler et al. 2000. It was shown that two thirds of the appliances emit CO < 225 mg/m³ at 12% O_2. Emission factors for CO show very broad variations from 0.100 to 2.300 lb/MMBtu (≈ 70 to 1400 mg/m³ at 12% O_2).

While the Austrian study shows averaged dust emissions (the following values are based on those for pellets) of about 0.097 lb/MMBtu for appliances < 6830 Btu/h and about 0.060 lb/MMBtu for appliances > 6830 Btu/h, the Swiss study results in averaged dust emissions of 0.150 – 0.200 lb/MMBtu for all fuels. Emission factors for dust vary from 0.050 to 0.220 lb/MMBtu. Since dust emissions depend greatly on the installed emission control technology, variations of these emissions may be attributed to different technologies.

Average NO_X emissions that were given in the studies vary from 150 to 220 mg/m³ for untreated wood. For wood residues the NO_X emissions can be higher due to a higher nitrogen content of the wood fuel. Also the emission factors for NO_X show high correlation. They are in a range from 0.200 to 0.375 lb/MMBtu (≈ 120 to 230 mg/m³ at 12% O_2) for untreated wood. For urban waste wood and wood residues, higher emission factors were fixed because of the higher nitrogen content of these fuels.

7 Emission control technologies

For biomass appliances, emission control technologies usually aim at the reduction of CO, OGC, dust and NO_X emissions. Two different concepts for emission reduction, both primary and secondary measures have to be considered. While primary measures are implemented in the combustion process and/or design of the combustion chamber, secondary measures are implemented after combustion process has ended, mostly adjacent to the boiler. Table 7-1 gives a summary indicating what reductions measures are available for small and medium to large scale biomass appliances.

Table 7-1 overview of primary and secondary emission control technologies for biomass appliances

scale	*small*		*medium to large*	
measures	*primary*	*secondary*	*primary*	*secondary*
CO/OGC	***X***	**-**	***X***	**-**
PM/dust	***X***	***X***	***X***	***X***
NO_X	**-**	**-**	***X***	*X*[1)]

[1)] in biomass appliances NO_X emissions are usually below the limit by primary measures

7.1 Emission control technology for PM/dust

Secondary measures for emission control in biomass appliances usually aim at the reduction of dust emissions. CO/OGC and NO_X emissions are reduced below the limits by primary measures, as was shown above.

7.1.1 Small scale appliances

Due to stricter dust emission limits for small scale appliances, special solutions for dust reduction in this load range were recently developed. These developments were mostly performed by small companies (business start-ups) and manufacturers of small scale appliances, who were aware of this need. Small scale dust emission control is based on the technology of scrubbers and electrostatic precipitators. For heat loads > 650 MBtu/h, baghouse filter systems were also developed. Scrubber systems are always combined with flue gas condensation.

Table 7-2 gives an overview of commercially available secondary dust reduction technology for small scale appliances.

Table 7-2 commercial small scale dust control technologies (summarised from Bischof 2008)

name	heat load in MBtu/h	effi-ciency in %	life time in years	market launch	sold systems	price in US$	producer
SCRUBBER/CONDENSATION							
Hydrocube	50 – 3400	≤ 70	15 - 20	2007	250	7400	Schraeder Abgastechnologie
Power Condenser	≤ 85	75[1]	20	2008	20	2500	Powerkondens AG
	≤ 170					3700	
Carbonizer	75 - 1700	≤ 86	> 20	2003	500	2100[2] 7400[3]	Bschor GmbH
Profitherm	50 - 500	50	> 20	-	-	3400[4] 6600[3]	BOMAT Heiztechnik GmbH
ELECTROSTATIC PRECIPITATOR							
Zumik®on	≤ 120	60 - 90	15 - 20	2006	> 140	1600	Rueegg Cheminée AG
Trion	≤ 120 ≤ 170 ≤ 12000	90	15-20	2005	300 - 400	1500 - 3000[5]	Trion Luftfiltersysteme GmbH
OekoTube	≤ 240	90	15	2008	0	2000	OekoSolve AG
Airbox	≤ 50	> 60	-	2008	10	2100	Spartherm
BAGHOUSE FILTER							
Keramik-filter	> 680	99	15 - 20	-	-	-	Herding GmbH Filtertechnik
Koeb Winkel	680 - 2000	< 10 mg/m³	-	-	-	-	Koeb & Schaefer GmbH

[1] 50 without scrubber (condensing only)
[2] 75 MBtu/h
[3] 340 MBtu/h
[4] 70 MBtu/h
[5] depends on length

As Table 7-2 shows, dust removal technologies for small scale appliances were not introduced to the market before 2003. Furthermore, the number of systems sold shows that this is a very young technology. A large number of prototypes are currently being tested.

Scrubbers with flue gas condensing and electrostatic precipitators are available for very small heat loads. In general, electrostatic precipitators are less expensive and reach higher efficiencies. While for scrubber technology low return temperatures of about 85 °F are necessary for flue gas condensation, electrostatic precipitators have a maximum energy demand of 100 Btu/h (Bischof 2008).

7.1.2 Medium scale appliances

For medium to large scale appliances, industrial solutions for emission control are used. These technologies are usually produced by plant or system manufacturers who are either specialists of flue gas cleaning technology or build complete (energy) plants. Emission control technologies for medium and large scale appliances are individually fit to the design data of the biomass appliance.

For medium scale biomass appliances the cyclones for dust removal are usually built by the boiler manufacturers themselves. Table 7-3 shows important European manufacturers of dust emission control technologies for medium scale biomass appliances including their special fields.

Table 7-3 European manufacturers for dust control technologies for medium scale biomass appliances(Brunner 2009, Lundgren 2009, Oravainen 2009)

company	cyclone	scrubber	electrostatic precipitator	baghouse filter
Beth			**X**	**X**
Scheuch GmbH	**X**	**X**	**X**	**X**
VAS - Verfahrenstechnik & Anlagensysteme			**X**	
JM Stoftteknik AB	**X**			**X**
Jaernforsen Energi System AB			**X**	
Dust Control Systems Oy		**X**		**X**

Table 7-4 an overview of prices for the dust removal technologies is given.

technology	*heat load in MMBtu/h*	*costs in US$/MBtu/h*
multicyclone	*0.3 – 1.7*	*7 – 11*
	1.7 – 6.8	*4 – 7*
baghouse filters or electrostatic precipitators	*3.4 – 6.8*	*20 - 30*
	6.8 - 17	*15 - 22*
	17 - 68	*9 - 18*
flue gas condensation	*3.4 - 17*	*20 - 30*

Table 7-4 prices for medium to large scale dust control technologies (FNR 2005)

8 European Biomass Fuel Requirements

8.1 General remarks

The development of solid bio-fuel standards in Europe is linked to the beginning of wood pellet production, which started in Sweden in the late 1980s. Other countries such as Finland, Denmark and Austria followed in the early 1990s.

In order to gain a common understanding between the manufacturers and the users, codes of good practice, quality guidelines and later national standards have been developed. In Europe the first national standards on pellet quality were developed in Sweden and Austria in 1998 – other countries followed.

In general these fuel quality standards should:

- guarantee a common, official, national quality of a certain bio-fuel
- ensure legal compliance and security for all involved market participants by defining responsibilities and duties
- help to avoid problems at interface-points along the supply chain by defining quality standards and threshold values
- inform the consumers about quality characteristics and therefore support the dissemination of a new biomass fuel to the market.

In addition to the national efforts, the development of quality guidelines was also pushed on the European level. The Technical Committee 335 (TC335) of the European Committee for Standardization (CEN) developed the European standards *CEN/TC 14558:2003 Solid bio-fuels – Terminology, definitions and descriptions as well as CEN/TC 14961:2005 Solid bio-fuels – Fuel specifications and classes* that allow a differentiation of terminologically defined solid bio-fuels by means of defined parameters.

Additionally, a series of technical standards dealing with determination methods of specific fuel properties or sampling methods have been worked out by the TC335. Table 8-1 lists all standards developed by this technical committee.

Moreover, national standards for wood pellets logistics and storage have been developed. The definition of quality parameters for logistics and storage was also found to be important so as to avoid any problems along the supply chain. Furthermore, the end-user should have a clear guideline of how to ensure product quality and user safety during the storage of bio-fuels.

Table 8-1 List of standards developed by CEN/TC 335

STANDARD REFERENCE	TITLE
CEN/TS 14588:2004	Solid bio-fuels - Terminology, definitions and descriptions
CEN/TS 14774-1:2004	Solid bio-fuels - Methods for determination of moisture content - Oven dry method - Part 1: Total moisture - Reference method
CEN/TS 14774-2:2004	Solid bio-fuels - Methods for the determination of moisture content - Oven dry method - Part 2: Total moisture - Simplified method
CEN/TS 14774-3:2004	Solid bio-fuels - Methods for the determination of moisture content - Oven dry method - Part 3: Moisture in general analysis sample
CEN/TS 14775:2004	Solid bio-fuels - Method for the determination of ash content
CEN/TS 14778-1:2005	Solid bio-fuels - Sampling - Part 1: Methods for sampling
CEN/TS 14778-2:2005	Solid bio-fuels - Sampling - Part 2: Methods for sampling particulate material transported in lorries
CEN/TS 14779:2005	Solid bio-fuels - Sampling - Methods for preparing sampling plans and sampling certificates
CEN/TS 14780:2005	Solid bio-fuels - Methods for sample preparation
CEN/TS 14918:2005	Solid Bio-fuels - Method for the determination of calorific value
CEN/TS 14961:2005	Solid bio-fuels - Fuel specifications and classes
CEN/TS 15103:2005	Solid bio-fuels - Methods for the determination of bulk density
CEN/TS 15104:2005	Solid bio-fuels - Determination of total content of carbon, hydrogen and nitrogen - Instrumental methods
CEN/TS 15105:2005	Solid bio-fuels - Methods for determination of the water soluble content of chloride, sodium and potassium
CEN/TS 15148:2005	Solid bio-fuels - Method for the determination of the content of volatile matter
CEN/TS 15149-1:2006	Solid bio-fuels - Methods for the determination of particle size distribution - Part 1: Oscillating screen method using sieve apertures of 3,15 mm and above
CEN/TS 15149-2:2006	Solid bio-fuels - Methods for the determination of particle size distribution - Part 2: Vibrating screen method using sieve apertures of 3.15 mm and below
CEN/TS 15149-3:2006	Solid bio-fuels - Methods for the determination of particle size distribution - Part 3: Rotary screen method
CEN/TS 15150:2005	Solid bio-fuels - Methods for the determination of particle density
CEN/TS 15210-1:2005	Solid bio-fuels - Methods for the determination of mechanical durability of pellets and briquettes - Part 1: Pellets
CEN/TS 15210-2:2005	Solid bio-fuels - Methods for the determination of mechanical durability of pellets and briquettes - Part 2: Briquettes
CEN/TS 15234:2006	Solid bio-fuels - Fuel quality assurance
CEN/TS 15289:2006	Solid Bio-fuels - Determination of total content of sulphur and chlorine
CEN/TS 15290:2006	Solid Bio-fuels - Determination of major elements
CEN/TS 15296:2006	Solid Bio-fuels - Calculation of analyses to different bases
CEN/TS 15297:2006	Solid Bio-fuels - Determination of minor elements

STANDARD REFERENCE	TITLE
CEN/TS 15370-1:2006	Solid Bio-fuels - Method for the determination of ash melting behavior - Part 1: Characteristic temperatures method

8.2 European Bio-fuel standards

The technical standard EN14961 from 2005 defines the fuel quality classes and specifications for solid bio-fuels originating from the following sources:

- Products from agriculture and forestry,
- Vegetable waste from agriculture and forestry
- Vegetable waste from the food processing industry,
- Wood waste, with the exception of wood waste that may contain halogenated organic compounds or heavy metals as a result of treatment with wood preservatives or coatings
- Waste originated from construction and demolition waste
- Fibrous vegetable waste from virgin pulp production and from production of paper from pulp, if it is co-incinerated at the place of production and heat generated is recovered.
- Cork waste

NOTE: Demolition wood is not included in the scope of this standard. Demolition wood is defined as “used wood arising from demolition of buildings or civil engineering installations” (CEN/TS 14588).

8.2.1 Origin of Bio-fuels

The first step in the classification of solid bio-fuels according to En14961 is based on the bio-fuel origin and source. In the hierarchical classification system, the main origin-based solid bio-fuel groups are:

- Woody biomass
- Herbaceous biomass
- Fruit biomass
- Blends and mixtures

Each group has several subdivisions to allow for a more detailed specification.

8.2.2 Specification of solid bio-fuels based on traded forms and properties

Solid bio-fuels are traded in many different forms (sizes and shapes). The European standard EN14961:2005 distinguishes between solid bio-fuel trading forms, listed in Table 8-2.

Table 8-2 Trading forms of solid bio-fuels and their preparation methods according to EN14961:2005.

FUEL NAME	TYPICAL PARTICLE SIZE	COMMON PREPARATION METHOD
Briquettes	Ø>25 mm	Mechanical compression
Pellets	Ø<25 mm	Mechanical compression
Fuel powder	<1 mm	Milling
Sawdust	1 – 5 mm	Cutting with sharp tools
Wood chips	5 – 100 mm	Cutting with sharp tools
Hog fuel	Varying	Crushing with blunt tools
Logs	100 – 1000 mm	Cutting with sharp tools
Whole wood	>500 mm	Cutting with sharp tools
Small straw bales	0.1 m³	Compressed and bound to squares
Big straw bales	3.7 m³	Compressed and bound to squares
Round straw bales	2.1 m³	Compressed and bound to cylinders
Bundle	Varying	Lengthways oriented & bound
Bark	Varying	Debarking residue from trees Can be shredded or unshredded
Chopped straw	10 – 200 mm	Chopped during harvesting
Grain or seed	Varying	No preparation or drying
Shells and fruit stones	5 – 15 mm	No preparation
Fiber cake	Varying	Prepared from fibrous waste by dewatering

The specifications of properties of these different forms are given in the annex.

8.2.3 Revision of EN14961:2005

Currently the EN14961 is under revision. The revised standard will not only define the specification of properties of solid bio-fuels, but also include definite properties such as threshold values for different quality classes. The main intention of this step is to simplify the acquisition of appropriate fuels for end users. To cover all kinds of solid biomass fuels as well as industrial fuels with lower quality requirements, a general section (part 1 of the revised EN14961) will be included in the revised standard. The structure of prEN 14961-part 1 is very similar to the first version of the standard from 2005 (see chapter 0):

EN14961-1: Scope and general requirements of solid bio-fuels

Parts 2 – 6 of the new standard will define fuel quality classes and specifications explicitly for non-industrial bio-fuels:

- EN14961-2: Fuel quality classes and specifications of wood pellets
- EN14961-3: Fuel quality classes and specifications of wood briquettes
- EN14961-4: Fuel quality classes and specifications of wood chips
- EN14961-5: Fuel quality classes and specifications for firewood
- EN14961-6: Fuel quality classes and specifications of non-woody pellets

8.3 European countries with national pellet standards

As previously mentioned, some European countries developed national quality standards for solid bio-fuels – mainly for wood pellets – long before a European standard was available. Some of these national standards do not only regulate the declaration of solid bio-fuels as the existing European standard EN14961:2005, but set definite specifications of properties (e.g. threshold values for contaminants) for high quality fuels. If the revised European Standard for solid bio-fuels is implemented, the national standards will be discarded.

8.3.1 Austria

In Austria, three standards referring to pellets product quality, logistic quality and storage quality are available:

- OeNORM M 7135 - Compressed wood in natural state or bark in natural state – pellets and briquettes - requirements and test specifications
- OeNORM M 7136 - Compressed wood in natural state - Wood pellets quality assurance in the field of logistics of transport and storage
- OeNORM M 7137 - Compressed wood in natural state - Wood pellets – Requirements on pellets storage at the end-consumer

8.3.1.1 OeNORM M 7135

This product standard covers wood pellets as well as briquettes. Pellets or briquettes must be made of virgin wood; up to 2 % of natural binding agents are allowed. Physical and chemical property requirements for the highest quality class are listed in Table 8-3.

The process of quality management includes internal and external audits. Manufacturers must perform internal quality assurance continuously, at least once a week by testing abrasion, water content, unit density and pressing aids. External audits include an initial inspection of the production plant and the sampling for laboratory tests, the control of the internal quality assurance system as well as the control of the labeling. Periodic, unannounced supervision is done once a year.

8.3.1.2 OeNORM M 7136

In order to assure the quality of wood pellets produced according to OeNORM M 7135 during transport and storage, certain requirements are specified under the OeNORM M 7136.

Specifications encompass transportation and temporary storage. These specifications are intended to assist pellet manufacturers, haulers and traders in avoiding mistakes to ensure customer satisfaction along the logistic chain.

8.3.1.3 OeNORM M 7137

This standard refers to the storage of wood pellets produced according to OeNORM M 7135. It defines specifications and requirements of wood pellet storage for the end user. The standard addresses the end users of wood pellets as well as the manufacturers of pellets storage units.

8.3.2 Germany

In Germany there exist two standards, DIN 51731 for common pellets and briquettes and Din *plus* with higher requirements, especially for the use in automatically stoked pellet boilers.

8.3.2.1 DIN 51731

The German standard defines the physical and chemical property requirements such as shape, unit density and the chemical composition of wood pellets. Specifications of the highest pellet quality class according to DIN 51731 are listed in Table 8-3.

8.3.2.2 DIN *plus* Standard

The DIN plus certification programme is used for high quality pellets intended for use in small scale household appliances. The specifications are mainly based on the Austrian standard OeNORM M7135, extended by the threshold requirements for minor elements from the DIN 51731. External auditing is performed once a year and is unannounced. Specifications of the DIN plus pellet quality label are listed in Table 8-3.

8.3.2.3 Certification of pellet logistics

"DIN-Gepruefter Fachbetrieb – Pelletlogistik" (DIN tested qualified enterprise pellet logistics) monitors the transport to the end-customer. The test criteria for suppliers include specifications for the storage depot, employees, internal and external monitoring and transport vehicles. The requirements are very similar to the Austrian standard OeNORM M 7136.

DIN CERTCO developed a new standard for the storage of pellets for end consumers based on the Austrian standard OeNORM M7137: "DIN gepruefte Pelletlagerung" ("DIN certified pellet storage").

8.3.3 Sweden

The Swedish standard SS187120: "Bio-fuels and peat—Fuel pellets—Classification" for wood pellets specifies properties and threshold values for three different wood pellet quality classes. Specifications are listed in Table 8-3.

8.3.4 Italy

The Italian standard for solid bio-fuel CTI - R 04/5 was published in March 2004 and specifies the requirements for biopellets for energetic purposes and is related to the technical specification defined by CEN/TC335 (EN14961:2005).

This standard classifies four categories of pellets and includes the origin of the raw material.

Categories A1 and A2 (with / without additives) determine the fuel quality classes and specifications for pellets originating from virgin wood, by-products and residues from the wood processing industry as well as chemically untreated used wood. Categories B and C encompass non-woody pellets produced from herbaceous biomass, fruit biomass and biomass blends and mixtures. Specifications of the CTI - R 04/5 are listed in Table 8-3.

8.3.5 United Kingdom

The Department of Trade and Industry of the UK published "Codes of Good Practice" for Bio-fuel pellets. These codes were adopted by British BioGen members as a standard for products and services. The Codes of good practice will be superseded by the European standards for solid bio-fuels once they are published. Specifications of the British code are listed in Table 8-3.

8.4 Additional environmental or quality labels

In addition to the official national standards, additional environmental or quality labels for pellets have been published. In some countries these quality labels act as a substitute for the lack of a national standard, while in others they function as a supplement to the national standard indicating the best available product quality or special ecological products. Figure 8-1 shows logos of environmental and quality labels for solid bio-fuels.

Figure 8-1: Environmental labels for solid bio-fuels

Austria – "Umweltzeichen (Environmental Label)": The Federal Ministry for the Environment has devised a special environment label for biomass fuels, where only raw materials from natural wood are allowed.

Nordic Ecolabeling – "Nordic Swan": The Swan-labeling of pellets includes requirements on manufacturing methods, transportation and storage. The aim is to identify the top-grade quality from an environmental perspective. The quality of the pellets shall mean that they are easy to use and thus meet the end-users' wishes when converting to a renewable energy source that reduces the emission of greenhouse gases. In addition, the energy required to manufacture the pellets is limited to ensure the energy efficiency. Finally, the combustion shall not entail a health or environmental risk. Specifications of "Swan labeled" pellets are summarized in Table 8-3.

Italy – "Pellet Gold" (*Pelletgold 2009*): is the highest Italian wood fuel quality standard. The certification system is based on clear operation rules to determine that the product satisfies the requirement indicated in the reference documents.

The requirements of Pellet Gold are based on CEN/TS 14961, DINplus, OeNORM M 7135 and the limits introduced by the American Pellet Fuels Institute (PFI).

An additional element in the Pellet Gold standard which is not present in other European certification systems was introduced by AIEL (Associazione Italiana Energie Agroforestali): the Formaldehyde content (HCHO) which is fundamental to verify the presence of health hazardous materials such as glue and varnish (see Table 8-3).

8.5 Summary of European and national property specifications for bio-fuels

Table 8-3 Comparison of European and national wood pellet/briquette standards and environmental labels

		Austria	EU		Germany		Great Britain S	Italy		weden	
Property class	Unit	OeNORM M 7135	EN 14961:2005 Best pellet categories	prEN 14961-2 A1-class	DIN 51731	DIN plus	BioGen - Code of good practice	CTI – R 04/5	Pellet Gold	SS 187120	Nordic Ecolabelling – Swan Label
Diameter, D and Length, L	in	0.16 ≤ D ≤ 0.39	D06 0.24 ± 0.02	D06 0.24 ± 0.04	0.16 ≤ D ≤ 0.39	0.16 ≤ D ≤ 0.39	D 0.16 – 0.79	D 0.24 – 0.31	-	D -L ≤ 4 D	0.24 ± 0.02
Moisture, M	as received, w-%	≤ 10	M10 ≤10	M10 ≤10	≤ 12	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10
Ash, a	w-% dry	≤ 0.5	A0.7 ≤ 0.7	A0.5 ≤ 0.5 A0.7 ≤ 0.7	≤ 1.5	≤ 0.5	≤ 1.0	≤ 0.7	≤ 1.0	≤ 0.7	≤ 0.5
Mechanical durability, DU or abrasion (100 – DU)	as received, w-%	≥ 97.7	DU97.5 ≥ 97.5	DU97.5 97.5	-	97.7	-	≥ 97.7	97.7	-	≥ 97.5
Fines at factory gate in bulk transport Fines in small bags at factory gate (at packing) Fines in small	w-%	-	F1.0 ≤ 1.0	F1.0 ≤ 1.0 F0.5 ≤ 0.5	-	-	≤ 0.5	-	-	≤ 0.8	≤ 1.0

		AUSTRIA	EU		GERMANY		GREAT BRITAIN S	ITALY		WEDEN	
bags (at delivery to end-user)				F1.0 ≤ 1.0							
Additives	w-%	≤ 2	Type and amount to be stated	Type and amount to be stated	none	≤ 2	-	none	≤ 2	Type and amount to be stated	-
Net calorific value, Q	as received, MBtu/lb	7.74	-	Q16.5 ≥ 7.10	7.53 – 8.39	≥ 7.74	7.27	≥ 7.27	7.27	≥ 7.27	7.35
Gross density	lb/oz	≥ 0.073	-	-	0.065 – 0.091	0.073	-	-	0.075	-	-
Bulk density, BD	10^3·lb/oz	-	-	BD600 ≥ 39.0	-	-	39.0	40.3-746.8	≥ 39.0	39.0	D6: 39.0-45.5 D8: 45.5-50.7
Nitrogen, N	w-% dry	≤ 0.3	N0.3 ≤ 0.3	N0.3 ≤ 0.3	≤ 0.3	≤ 0.3	-	≤ 0.3	≤ 0.3	-	≤ 0.3
Sulphur , S	w-% dry	≤ 0.04	-	S0.05 ≤ 0.05	≤ 0.08	≤ 0.04	≤ 0.03	≤ 0.05	≤ 0.05	≤ 0.08	≤ 0.04
Chlorine, Cl	w-% dry	≤ 0.02	Cl0.03 ≤ 0.03	Cl0.02 ≤ 0.02	≤ 0.03	≤ 0.02	≤ 0.08	≤ 0.03	≤ 0.03	≤ 0.03	≤ 0.02
Arsenic, As	mg/kg dry	-	-	≤ 1	≤ 0.8	≤ 0.8	-	-	≤ 0.8	-	-
Cadmium, Cd	mg/kg dry	-	-	≤ 0.5	≤ 0.5	≤ 0.5	-	-	≤ 0.5	-	-
Chromium, Cr	mg/kg dry	-	-	≤ 10	≤ 8	≤ 8	-	-	≤ 8	-	-
Copper, Cu	mg/kg dry	-	-	≤ 10	≤ 5	≤ 5	-	-	≤ 5	-	-
Lead, Pb	mg/kg dry	-	-	≤ 10	≤ 10	≤ 10	-	-	≤ 10	-	-

		Austria	EU		Germany		Great Britain S	Italy		weden	
Mercury, Hg	mg/kg dry	-	-	≤ 0.1	≤ 0.05	≤ 0.05	-	-	≤ 0.05	-	-
Nickel, Ni	mg/kg dry	-	-	≤ 10	-	-	-	-		-	-
Zinc, Zn	mg/kg dry	-	-	≤ 100	≤ 100	≤ 100	-	-	≤ 100	-	-
Sodium; Na	w-% dry	-	-	-	-	-	-	-	≤ 0.03	-	-
EOX (extract. org. halogens)	mg/kg dry	-	-	-	≤ 3	≤ 3	-	≤ 1	-	-	-
Formaldehyde	mg/100g dry	-	-	-	-	-	-	-	≤ 1.5	-	-
Ash melting behavior, DT	°F	-	-	DT1200 ≥ 2190	-	-	-			Tempera-ture to be stated	IT ≥ 2370 HT 2550

9 Heat storage (accumulator tank)

9.1 Introduction

Function

An accumulator tank is a heat-insulated steel tank in which a heat carrier (mostly water) circulates when it is loaded. Temperature stratification results from the density difference between cold and hot water (cold water has a higher density than hot water). Hot water from the boiler is introduced into the buffer accumulator at the top. The design of the inlet ensures that turbulence is low and that the temperature stratification is not destroyed. High flow temperatures result in good temperature stratification and high heat storage capacity.

Types

Different types of buffer accumulators are available depending on the use of the buffer accumulators as heat storage devices with or without integrated hot service water storage and/or integration of additional heating sources, e. g. solar energy (Figure 9-1).

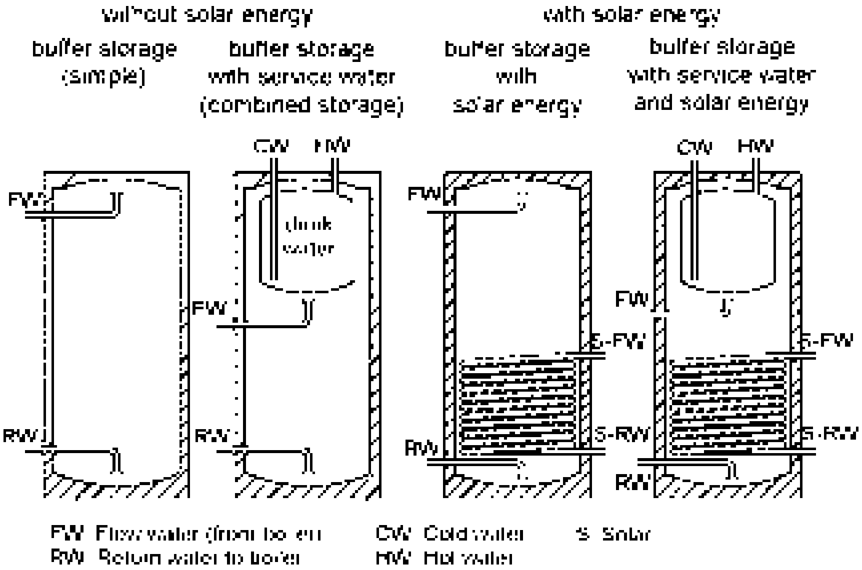


Figure 9-1 Different types of buffer (adapted from FNR I 2007)

The capacity of the tank installations can be reduced when using a combined storage unit for heating and hot water. Major drawbacks are however the reduction of the volume of the buffer accumulator and energy losses in summer, when only hot water is needed.

Application area

Although modern solid wood boilers are able to modulate their operation load from 100 to 50%, the use of heat storage is strongly recommended by manufacturers of the boilers, by R&D institutions and authorities.

Pellet and wood chip boilers can even modulate their operation load from 100 to 30%. Nonetheless, some manufacturers recommend the integration of accumulator tanks in these heating systems as well in order to increase the annual efficiencies of the heating systems.

The research field on annual efficiencies in residential homes is quite young in Europe; there are however some ongoing research activities. BE 2020+ for example is currently working on the development of a test stand method for the determination of system efficiency and emission factors of small-scale biomass combustion systems.

9.2 Dimensioning

9.2.1 General aspects

The necessary volume of the accumulator tank is influenced by several factors:

- range of capacity of the boiler (only full load of variable heat load)
- volume of the fuel storage in the boiler (for manually stoked boilers)
- nominal heat load of the boiler
- calorific value and energy density of fuel
- effective temperature difference in the heat storage
- demand for convenience

In Table 9-1 the benefits and disadvantages of large and small heat storage vessels are summarized.

Table 9-1 benefits and drawbacks of large and small heat storages (adapted from FNR III 2007)

	benefits	disadvantage
large heat storage (one fuel charge can be accumulated)	o boiler can always be operated at full load (low emission operation) o reduction of combustion intervals o one combustion period with maximum fuel charge covers heat demand for a couple of days in spring/autumn	o high investment costs for large heat storage o heat losses by accumulator tank (even if tank is well insulated)
small heat storage	o low investment costs	o boiler will be operated in part load (which means higher emissions) o emergency shut-downs may occur if heat load of boiler is larger than heat demand (which results in very high emissions for a short time) o reduction of boiler durability

In general, the dimensioning of the accumulator tank is an optimisation function of investment costs and boiler performance.

9.2.2 Sizing guidelines

For the sizing of heat storage vessel for solid wood boilers, many guidelines can be found in literature. These guidelines are related to the nominal heat load of the boiler and vary from approximately 10 to 30 l/MBtu/h and 2.7 to 7.9 gal/MBtu/h respectively (FNR II 2007, Struschka et al. 2004…).

Struschka et al. 2004 analysed the emissions of solid wood boilers with heat loads of 100 MBtu/h that were operated with and without accumulator tanks in field tests. Table 9-2 and Figure 9-2 show the major results of this study.

Table 9-2 average annual CO emission factors for solid wood boilers (adapted from Struschka et al. 2004)

control concept:		modulated	nominal load only
volume of heat storage		average annual CO emissions in mg/MBtu	
0 l	0 gal	4 384	4 384
750 l	200 gal	1 431	1 444
1 500 l	400 gal	1 110	1 003

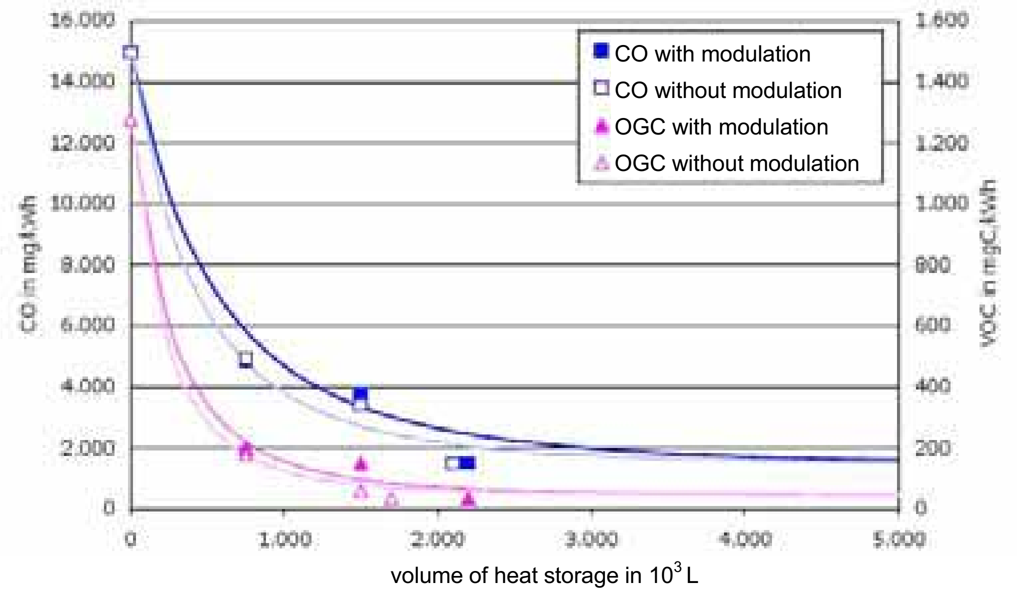


Figure 9-2 development of CO and OGC emissions depending on the volume of the heat storage

Heat storage vessels with larger dimensions give rise to lower annual emission factors and solid wood boilers, which are operated solely at nominal load, emit less than modulated boilers. The characteristics of the curve in Figure 9-2 shows that significant reductions of emissions will be reached for storage volumes between 0 to 2,500 l (650 gal).

The authors of this study identify 2,250 l (600 gal) to be the optimum volume for the heat storage vessel, which corresponds to 20 l/MBtu/h and 5.9 gal/MBtu/h respectively.

In spite of these common guidelines, FNR III 2007 recommends to dimension the heat storage vessel according to the volume of the fuel storage of the boiler and not according to the heat load of the boiler due to the fact that the volume of the fuel storage vessel determines the amount of heat that is produced during a combustion cycle, and not the nominal heat load of the boiler.

9.2.3 EN 303-5

The EN 303-5 requests manufacturers for boilers with manual stoking to specify how the amount of heat generated can be dissipated. The most probable solution is to install a heat storage vessel.

For the sizing of a heat storage vessel for manual fed boilers, the following equation is given:

$$V_{AT} = 4.5 \cdot T_B \cdot Q_N \cdot \left| 1 - 0.3 \frac{Q_H}{Q_{\min}} \right|$$

V_{AT}	*Accumulator tank capacity*	*l*
Q_N	*Nominal heat output*	*MBtu/h*
T_B	*Burning period*	*h*
Q_H	*Heating load of the premises*	*MBtu/h*
Q_{min}	*Minimum heat output*	*MBtu/h*

In order to convert the volume of the heat storage vessel from liter to gallons, a factor of 0.264 must be multiplied with V_{AT}.

10 Energy from non-Woody Biomass Fuels

10.1 Emissions and efficiencies of solid non wood biomasses

Carvalho et al. 2007 summarized the main challenges of using agricultural fuels in residential boilers as follows:

"… agricultural fuels have, in general, certain physical and chemical properties that may induce problems during combustion. In addition to their low heating value, on average 5% to 10% lower than wood, they have higher ash contents, lower melting points of the ash and higher concentrations of nitrogen, sulphur and chlorine than typical wooden fuels (Werther et al. 2000). Large ash quantities in connection with low ash melting points can cause disturbances by the formation of deposits or slags in combustion systems not prepared for agricultural fuels. High concentrations of sulphur, nitrogen and chlorine, intensify the emissions of SO_2, NO_x and chlorine compounds respectively (Werther et al. 2000). Chlorine and sulphur, besides promoting the formation of deposits, are also involved in corrosion reactions of metals (Bryers 1996, van Loo, Koppejan 2002)."

In extensive tests, combustion behavior of diverse agricultural pelletized biomasses was analyzed by the BE 2020+. Results of these tests are discussed afterwards.

10.1.1 Fuels & fuel properties

For the analysis of the combustion behavior of agricultural pellets, most relevant biomasses for the Austrian market were chosen. Altogether, 6 different fuels – hay, maize, miscanthus, straw, vineyard pruning and wheat bran – were considered. In Table 10-1 the fuels and their most relevant properties with regard to combustion are shown as well as average properties of wood fuels.

Table 10-1 fuel properties of the investigated pellets and average values for wood fuel (Wopienka et al. 2007)

fuel	*diameter (in)*	*GCV d.b (MBtu/lb)*	*water (%)*	*ash (%) d.b.*	*volatile matter (%) d.b.*	*nitrogen (%) d.b.*	*sulfur (%) d.b.*	*softening temperature (°F)*
wood (spruce)		*8.6*		*0.20*		*0.10*	*0.04*	*2480*
hay	*0.236*	*7.5*	*7.5*	*7.40*	*73.1*	*1.08*	*0.13*	*2085*
maize (whole crop)	*0.236*	*8.2*	*8.7*	*3.39*	*80.2*	*0.89*	*0.09*	*1670*
miscanthus	*0.236*	*8.2*	*8.7*	*3.26*	*82.9*	*0.24*	*0.03*	*1850*
straw	*0.236*	*8.0*	*7.9*	*5.71*	*74.8*	*0.66*	*0.10*	*1470*
vineyard pruning	*0.236*	*9.0*	*8.4*	*2.70*	*-*	*0.39*	*-*	*1465*
wheat bran	*0.315*	*8.3*	*13.7*	*5.70*	*76.8*	*3.04*	*0.24*	*1780*

The ash content of agricultural pellets is 10 to 20 times higher than the ash content of wood pellets, the nitrogen content is 5 to 10 times and the sulfur content is even 10 to 30 times higher. In comparison to average wood fuels, the softening temperature of agricultural fuels is 550 to 1100 °F lower.

These differences clearly influence the combustion process and therefore emissions and efficiencies.

10.1.2 Emissions

In Figure 10-1 the average CO emissions and their deviations are shown for the analyzed bio-fuels and Figure 10-2 exhibits the average dust emissions including deviations for these fuels.

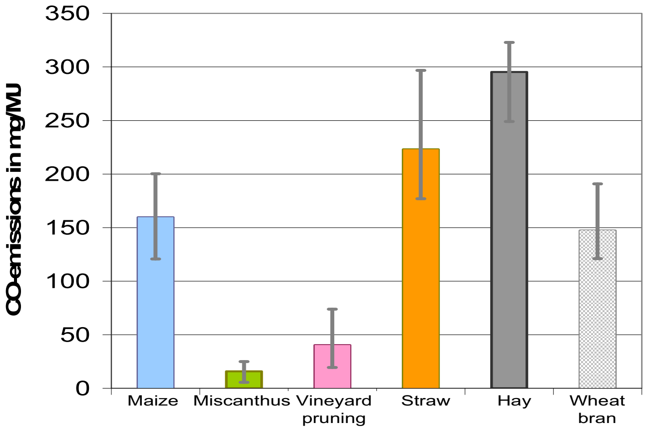


Figure 10-1 average CO emissions including their deviation of the investigated fuels (1 mg/MJ ≈ 1.5 mg/m² at 12% O_2)(Wopienka et al. 2007)

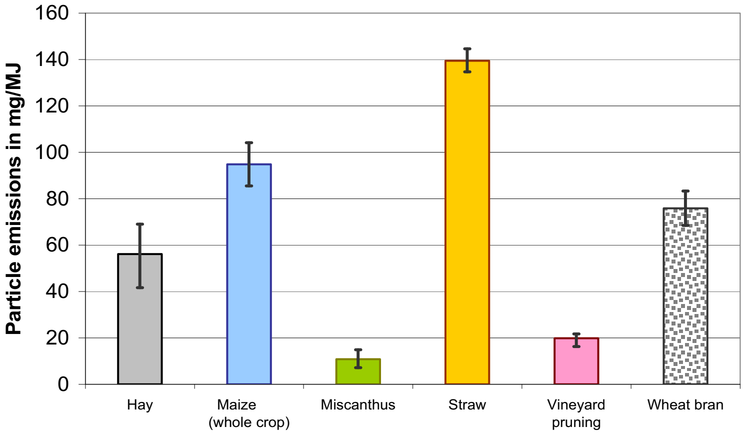


Figure 10-2 average dust emissions including their deviation of the investigated fuels; 1 mg/MJ = 0.0023 lb/MMBtu (Wopienka et al. 2007)

The emission values of Figure 10-1 and Figure 10-2 show a week correlation of CO and dust emissions. If CO emissions are low, dust emissions will also be rather low. Miscanthus and vineyard pruning, which have a quite low ash content (Table 10-1), reach the lowest dust and CO emissions. Hay exhibits the highest ash content. It reaches the highest CO emissions, but its dust emissions are relatively low. A simple and reliable correlation of fuel properties and CO- and dust emissions could not be found.

Figure 10-3 exhibits the NO_X and SO_2-Emissions of the considered bio-fuels depending on the nitrogen and sulfur content of the fuels.

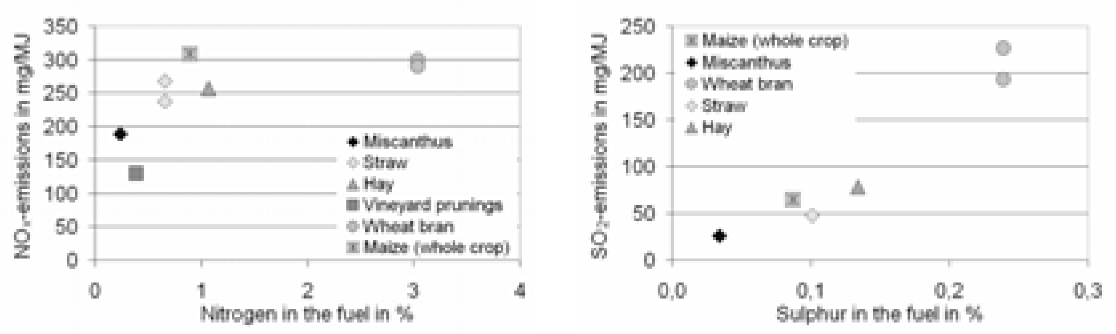


Figure 10-3 NO_X and SO_2 emissions depending on the nitrogen respective sulphur content of the investigated biomasses (Wopienka et al. 2007)

In this case, quite clear correlations can be found: if the nitrogen and sulphur content is low, NO_X and SO_2 emissions will be low as well and vice-versa.

10.1.3 Efficiencies

In Figure 10-4 the CO-excess air ratio characteristic of the investigated fuels for the test boiler is shown. The CO-excess air ratio characteristic shows at which range of excess air the minimum CO emissions are reached in the test boiler.

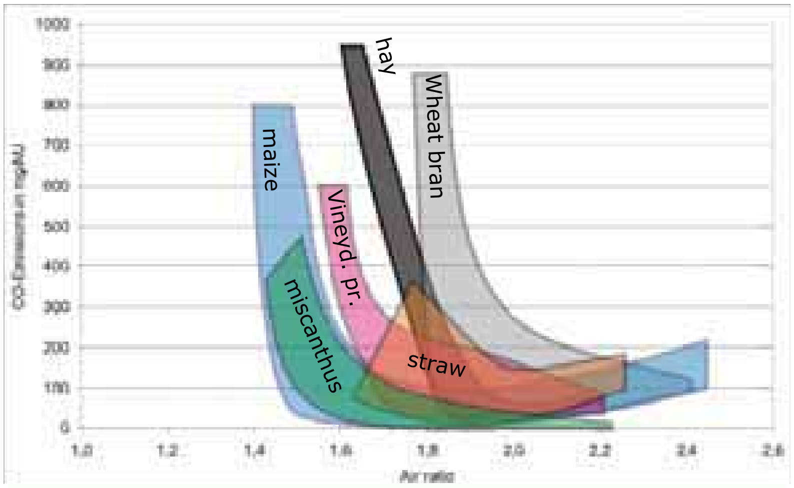


Figure 10-4 correlation of CO emissions and excess air ratio for the considered fuels (Wopienka et al. 2007)

The optimum excess air ratio varies from approximately 1.5 for maize to approximately 1.9 for wheat bran. Straw shows a very broad characteristic.

If the fuels are burnt at optimum conditions (low CO), different excess air ratios are needed. The higher the excess air ratio, the lower the efficiency of the boiler, because more combustion air is sucked through the boiler and heat losses in the flue gas are increased. Hence, the boiler will reach higher efficiencies with maize than with wheat bran, if it is operated at optimum combustion conditions.

10.1.4 Slagging & Corrosion

If non wood bio-fuels are used for combustion, the slagging behavior of these bio-fuels has to be considered. Otherwise molten ash or slag can lead to an emergency shutdown of the combustion unit and cause severe damage in the primary combustion chamber (grate, lining, etc.).

Figure 10-5 ash (left) and ash lumps (right) from combustion of agricultural fuels

In Figure 10-6 the slagging tendency of the considered fuels (except for hay) is shown. In order to evaluate the slagging tendency, a mash analysis of the ash was carried out to determine the fraction of all particles in the ash with a diameter > 5.6 mm (0.22 in).

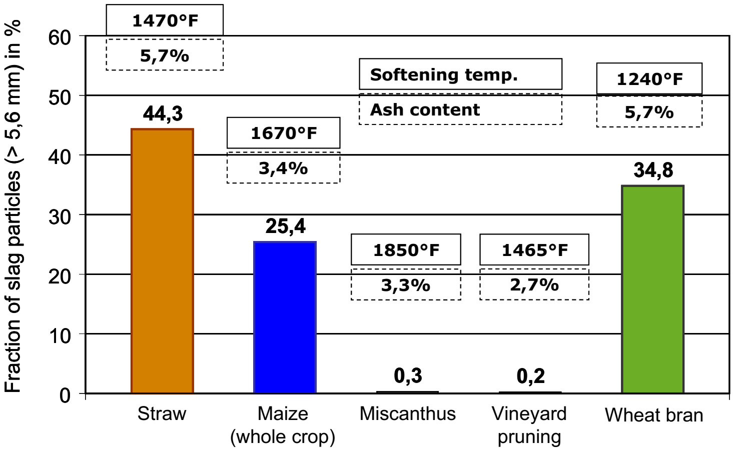


Figure 10-6 Slagging tendency of the investigated fuels (Wopienka et al. 2007)

Straw, wheat bran and maize showed a higher slag forming tendency than miscanthus or vineyard pruning pellets. From the combustion of hay almost no slag was found in the ash. Basically, fuels with higher ash content combined with lower softening temperature tend to form a bigger fraction of molten lumps.

Next to the slagging phenomena, corrosion of the boiler (heat exchanger, ceramics, grate, combustion chamber) has to be considered when burning non wood bio-fuels.

Chlorine and sulphur are involved in corrosion reactions, therefore the combustion conditions (temperature, atmosphere) have to be observed. Figure 10-7 shows two examples of corrosion attacks while burning agricultural fuels.

Figure 10-7 corrosive attack of refractory materials after operation with grain (left) and corrosion of metal after straw combustion

10.2 Summary

Due to their high availability, non-wood biomasses are very attractive fuels. They may however have certain general physical and chemical properties that may cause problems during combustion. In addition to the possible increase of NO_X, HCl, SO_2, and other emissions in comparison to wood biomass, higher ash contents combined with lower ash melting temperatures and corrosive effects negatively influence the failure rate and durability of the boilers.

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B. Annex

1. Test details of biomass appliances
    1.1. TOP 25% models – solid wood boilers
    1.2. TOP 25% models – pellet boilers
    1.3. TOP 25% models – wood chip boilers
    1.4. All models – combined technology boilers
    1.5. All models – pellet stoves
    1.6. All models – solid wood stoves

Solid wood boilers - TOP 25%

load range	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$	TSP mg/kg$_{fuel}$	TSP lb/MMBtu	NO$_X$ mg/m$^3_{12\%}$	$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$
< 85 MBtu/h	A	65	35	84	353	189	0.027	153	81	479
	B	72		83	142	94	0.014	118	77	107
	C	50		83	161	94	0.014	131		
	D	58		83	69	115	0.017	132		
	E	58		83	90	109	0.016	90	84	56
	F	51		83	219	314	0.046	104	82	258
	F	68		83	312	314	0.046	104	82	258
	D	68		83	131	115	0.017	170	81	259
	A	73	49	83	347	168	0.024	164	83	560
	A	56	35	82	199	199	0.029	168	81	479
	G	68		82	160	262	0.038	140	83	200
	H	75		82	105	346	0.050	128	81	216
	I	72	34	82	64	210	0.030	146	79	1069
	J	40	68	82	137	1205	0.175	182		
	K	68		82	137	157	0.023	182		
	L	68		82	164	419	0.061	110	82	116
85 - 120 MBtu/h	M	92		83	248	283	0.041	100		
	I	92		83	293	189	0.027	132		
	A	96	49	83	192	199	0.029	177	83	560
	N	89		83	137	110	0.016	186	85	538
	B	89		83	183	147	0.021	120	78	203
	O	89	44	83	183	1299	0.189			
	F	85	51	83	262	314	0.046	104	82	258
	P	102		83	262	304	0.044	113	81	258
	F	85		83	287	314	0.046	104	82	258
	Q	102		83	40	210	0.030			
	C	116		83	298	178	0.026	125	80	
	B	109		82	241	220	0.032	124	77	203
	P	85		82	287	283	0.041	101	81	258
	R	116	58	82	298	178	0.026	125		
	D	102		82	189	566	0.082			
	E	106		82	115	94	0.014			104
120 - 169 MBtu/h	F	137	120	84	50	524	0.076	107	83	162
	P	137		84	158	356	0.052	81	83	162
	I	123		83	343	168	0.024	131		
	I	167		83	300	157	0.023	144		
	G	137		83	68	157	0.023	131	84	206
	D	150		83	155	681	0.099	181		
	E	161		83	95	189	0.027		83	110
	H	154		82	124	346	0.050	155	81	419
	S	157	58	82	78	262	0.038	110	82	294
	D	137		82	96	199	0.029	111		
	T	123		82	207					
	U	137		82	71	148	0.021	75	83	147
	O	137	68	82	232	2232	0.324	34		
	B	137		82	315	314	0.046	127	80	467

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Solid wood boilers - TOP 25%

load range	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO mg/$m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_X mg/$m^3_{12\%}$	$\eta_{,GCV}$ %	CO mg/$m^3_{12\%}$
> 170 MBtu/h	F	171	120	84	50	524	0.076	107	83	162
	P	171		84	50	388	0.056	100	83	162
	I	205		83	282	147	0.021	150		
	E	171	137	83	95	189	0.027		84	110
	G	171		83	68	157	0.023	131	84	206
	D	171		82	95	168	0.024	123		
	U	205		82	44	105	0.015	75	84	135
	G	205	69	82	68	157	0.023	131		
	S	178	58	82	78	262	0.038	110	82	294
	U	171		82	71	148	0.021	75	83	147
	I	208		81	64					
	K	239		81	195	283	0.041	194		

pellet boilers - TOP 25%

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load range	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$	TSP mg/kg$_{fuel}$	TSP lb/MMBtu	NO$_X$ mg/m$^3_{12\%}$	$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$
< 55 MBtu/h	V	50	13	89	47	204	0.025			151
	W	41	9	88	29	136	0.017	165	85	37
	W	27	8	88	43	91	0.011	159	85	37
	X	48	17	88				95	86	
	Y	48	14	88	47	68	0.008	137	86	128
	I	51	15	88	35	193	0.024	120	83	228
	W	51	10	88	25	113	0.014	159		35
	I	48	13	87	68	147	0.018	127	83	167
	Z	32	9	87	73	283	0.035	152	86	48
	X	34	13	87	32	91	0.011	105	86	164
	X	48	14	87	35	91	0.011	107	86	169
	AA	50	14	87	37	107	0.013	120	84	179
	Z	41	12	87	30	170	0.021	164	85	113
	Z	41	9	87	77	181	0.022	159	84	53
	G	51	15	87	7	159	0.019	156	89	33
	G	28	8	86	15	102	0.012	124	83	151
	Z	32	9	86	72	283	0.035	154	84	53
	AB	48	10	86	59	317	0.039	230	85	95
	H	51	15	86	42	204	0.025	110	86	199
	AC	53	15	86	32	198	0.024	108	87	88
	AD	51	15	86	55	351	0.043	159	87	
	Z	51	14	86	7	113	0.014	125	84	37
	AE	41	14	86	71	323	0.040	153	86	234
	AE	51	14	86	57	272	0.033	159	86	234
	AF	51	17	86	66	170	0.021	122	83	359
	G	38	8	86	11	136	0.017	134	83	151
55 - 100 MBtu/h	Z	85	26	88	17	170	0.021	128	86	180
	X	85	24	88				124	87	
	I	85	26	88	30	283	0.035	122	85	137
	Z	57	17	87	32	147	0.018	149	86	44
	F	85		87	15	91	0.011		87	57
	AB	88	24	87	38	317	0.039	260	87	55
	AA	92	25	87	48	115	0.014	133	87	79
	AC	85	23	87	15	91	0.011	157	87	57
	Z	75	20	87	45	170	0.021	135	86	108
	X	79	24	87	54	102	0.012	111	86	200
	G	89	24	87	11	79	0.010	115	84	77
	AG	85	25	87	8	193	0.024	139	84	35
	AH	92	24	87	47	107	0.013	128	80	362
	AG	70	21	87	105	193	0.024	151	83	276
	AI	70	21	87	105	193	0.024	151	83	276
	AB	85	17	86					85	
	W	82	7	86	72	453	0.056	151	86	35
	A	68	18	86	9	215	0.026	164	84	160
	AJ	72	17	86	28	148	0.018	160	86	209
	G	85	24	86	59	272	0.033	167	86	72
	AF	85	27	86	61	147	0.018	119	83	338
	I	68	17	86	12	227	0.028	137	82	314

pellet boilers - TOP 25%

load range	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$	TSP mg/kg$_{fuel}$	TSP lb/MMBtu	NO$_X$ mg/m$^3_{12\%}$	$\eta_{,GCV}$ %	CO mg/m$^3_{12\%}$
	AF	55	15	86	104	136	0.017	119	84	97
	AG	68	20	86	1	272	0.033	145	85	42
	AG	68	20	86	12	272	0.033	145	85	42
	AK	68	19	86	27	215	0.026	114	83	68
	AL	88	26	86	53	125	0.015		83	168
	AG	85	25	85	21	306	0.037	93	83	114
	AM	65	19	85	30	165	0.020	124	82	218
	AN	68	41	85	41	306	0.037	39		48
100 - 170 MBtu/h	Y	169	48	89	20	79	0.010	125	85	68
	Z	143	42	89	11	193	0.024	179	87	53
	AG	102	29	88	5	113	0.014	133	84	29
	AO	167	51	88	73	465	0.057	63	85	7
	Z	167	42	88	12	227	0.028	183	87	53
	AP	120	28	87	70	96	0.012	181	89	
	G	109	32	87	27	45	0.006	104	84	95
	Z	120	26	87	37	238	0.029	126	86	180
	AB	137	41	87					87	
	A	154	40	87	34	295	0.036	131	88	73
	X	102	28	87	62	102	0.012	115	86	212
	X	137	33	87	73	102	0.012	115	86	219
	Z	169	39	87	42	249	0.031	131	84	99
	G	167	48	87	23	204	0.025	117	86	86
	AQ	133	38	86	20	115	0.014	105	80	587
	AR	126	35	86	47	198	0.024	176	85	162
	AL	167	48	86	59	295	0.036		83	82
170 - 340 MBtu/h	Z	198	42	88	38	431	0.053	183	87	53
	AL	236	68	87	20	113	0.014		84	127
	AF	219	63	87	59	159	0.019	167	84	156
	G	324	97	86	9	272	0.033	119	87	74
	AS	331	33	86		363	0.044			
	AT	286	79	86	4	289	0.035	105	85	26
	AU	296	79	86	12	387	0.047	198		113
	A	205	40	86	32	419	0.051	144	88	73
	AG	280	83	86	42	204	0.025	164	85	91
	AR	290	86	86	4	313	0.038	193	88	273
	Y	171	47	86	23	283	0.035	109	85	281
> 340 MBtu/h	AV	885	161	88	41	453	0.056		82	477
	D	355	89	87	7	68	0.008	122	86	23
	Z	350	112	87	19	215	0.026	126	85	77
	Z	731	204	86	14	261	0.032	171	55	66
	Z	529	150	86	18	272	0.033	128	86	27
	G	478	119	85	16	181	0.022	118	87	16
	AR	342	102	85	5	305	0.037		88	200

wood chip boilers - TOP 25%

load range	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_X $mg/m^3_{12\%}$	$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$
< 100 MBtu/h	G	68	20	78	35	114	0.022	185	78	176
	G	89	26	78	28	85	0.017	180	78	102
	AW	96	27	77	71	85	0.017	91	77	96
	AG	51	17	77	108	275	0.053	153	73	747
	AG	85	25	76	38	332	0.064	171	76	609
	Z	85	27	76	72	199	0.039	149	76	181
	I	68	18	73	68	570	0.110	173	72	527
100 - 200 MBtu/h	D	171	44	81	13	76	0.015	104	78	72
	Y	126	38	81	93	133	0.026	179	79	37
	A	166	45	80	46	275	0.053	159	80	111
	D	102	24	79	22	95	0.018	99	77	322
	AP	126	38	79	93	133	0.026	176	77	37
	D	169	47	79	49	152	0.029	159	75	194
	W	102	28	78	22	57	0.011	127	78	109
	Z	157	44	78	47	266	0.052	159	78	81
	W	137	28	78	10	47	0.009	131	77	109
	AO	167	51	78	28	209	0.040	117	77	183
	W	169	47	77	28	47	0.009	90	78	74
	AP	169	51	77	16	199	0.039	116	76	39
200 - 340 MBtu/h	D	256	97	80	36	361	0.070	136	80	87
	Y	340	106	80	87	114	0.022	151	80	239
	AX	205	59	79	33	161	0.031	161	78	38
	W	273	81	78	15	104	0.020	133	78	106
	AO	256	68	78	28	209	0.040	117	77	183
	AU	205	58	78	33	387	0.075		76	349
	D	323	92	78	7	142	0.028	169	81	101
	AT	292	77	78	17	186	0.036	119	77	266
	AY	290	87	77	39	108	0.021	106	77	77
	AX	256	70	77	15	133	0.026	109	80	33
	AG	338	100	77	21	256	0.050	180	78	177
340 - 680 MBtu/h	D	342	97	79	36	361	0.070	136	80	87
	AY	376	113	79	9	47	0.009	91	77	11
	G	656	190	86	19	142	0.028	110	79	7
	AZ	666	190	78	19	142	0.028	110	79	7
	AX	342	96	77	9	152	0.029	45	75	199
	W	512	143	77	40	247	0.048	168	79	38
	AU	354	85	86	20	373	0.072	159	77	233
	AG	345	100	77	21	256	0.050	180	77	177
> 680 MBtu/h	AB	820	246	79	34	408	0.079	134	78	124
	AB	1025	246	79	68	541	0.105	149	78	124
	AX	1708	490	78	35	399	0.077	177	79	213
	AX	2220	490	78	35	807	0.156	100	79	213
	BA	1708	427	77	15	275	0.053	92	79	11
	A	751	184	77	16	294	0.057	90	76	43
	BA	1025	256	76	33	598	0.116	178	77	19

combined technology boilers

Data	manufacturer	pellets									solid wood								
		nominal load MBtu/h	partial load MBtu/h	nominal load					partial load		nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_x $mg/m^3_{12\%}$	$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$			$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_x $mg/m^3_{12\%}$	$\eta_{,GCV}$ %	CO $mg/m^3_{12\%}$
TOP 25%	BB	51		79	104	227	0.028	92		17	51								4838
	T	51	10	81	23	136	0.017	162		17	51		72						8775
	U	85	25	81	45	193	0.024	218		34	102	34	81	158	157	0.023	96		17102
	G	85	25	84	12	329	0.040	152		34	102	51	81	160	262	0.038	140		16711
	U	51	14	84	17	215	0.026	99		23	68	34	81	158	157	0.023	96		16799
	T	126	37	84	6	215	0.026	147		50	153		83	530	157	0.023	150		
rest	G	51	15	84	1	136	0.017	159											
	BB	68		79	104	227	0.028	92		28	85								6188
	AZ	85	26	84	12	329	0.040	152		34	102	51	81	160	262	0.038	140		16711
	AZ	51	15	84	1	136	0.017	159		23	68	34	82	160	262	0.038	140		16387
	BB	68		79						36	109								6975
	BC	51		80	225	1133	0.139			17	51	27	76						8189
	BC	68		81	225	567	0.069			28	85	41	76						9190
	BC	68		81	225	567	0.069			34	102	61	76						9190
	H	68	15	83	294	204	0.025	111	77										
	BD	68	24	83	118	147	0.018	141		34	102	51	80	1384	220	0.032	141	87	8303
	BE	51	15	84	195	102	0.012	138	67	17	51	15							9449
	BF	51	14	84	45	68	0.008	95	88	17	51	14	76						11588
	H	86	15	84	225	193	0.024	114		34	102		84	316	293	0.043	122		11711
	S	51	15	84	248	215	0.026	120	74	17	51		79	377	545	0.079	174		11509
	S	85	26	84	248	215	0.026	120	74	34	102		79	377	545	0.079	174		11509
	H	85	15	84	248	215	0.026	120	74										
	I	102	22	86	11	329	0.040	141		30	92		83	293	189	0.027	132		13322
	BC	79	14	86	225	1133	0.139			26	79	14	76						8399
	I	75	22	87	21	261	0.032	141		30	92		83	293	189	0.027	132		13136
	I	205	60	88	19	193	0.024	114		68	205		83	282	147	0.021	150		18225
	I	137	36	88	36	204	0.025	124		41	123		83	343	168	0.024	131		14587
	I	167	47	88	36	204	0.025	124		55	167		83	300	157	0.023	144		18225
	H	52	15	89	90	176	0.022	104		18	54		87	576	157	0.023	104		11374

combined technology boilers

Data	manufacturer	wood chips									solid wood								
		nominal load MBtu/h	partial load MBtu/h	nominal load					partial load		nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				η,GCV %	CO $mg/m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_X $mg/m^3_{12\%}$	η,GCV %	CO $mg/m^3_{12\%}$				CO $mg/m^3_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_X $mg/m^3_{12\%}$	η,GCV %	CO $mg/m^3_{12\%}$
all data	AO	167	51	80	73	389	0.075	63	33	55	167	51	85	96	430	0.062	63	39	
	AO	335	68	80	73	389	0.075	63	33	77	232	68	85	96	430	0.062	63	39	
	AO	249	73	73	56	275	0.053	92		86	262		78	96	105	0.015	134		

red data: CO emission > averaged CO emissions

water circulate	load range	Data	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
						$\eta_{,GCV}$ %	CO $mg/m^3{}_{12\%}$	TSP mg/kg_{fuel}	TSP lb/MMBtu	NO_X $mg/m^3{}_{12\%}$	$\eta_{,GCV}$ %	CO $mg/m^3{}_{12\%}$
without	< 30 MBtu/h	TOP 25	BG	27	7	89	236	306	0.037	88		414
			V	8	17	88	167	589	0.072		86	186
			BG	20		88	86	272	0.033			309
			BH	29		88	169	306	0.037			628
		rest	BI	27	7	88	236	306	0.037	88		414
			BG	27		88	236	306	0.037			414
			BG	27		88	261	272	0.033			498
			BG	27		87	261	272	0.033			498
			BG	27		87	261	272	0.033			498
			BG	27		87	261	272	0.033			498
			BG	27		87	261	272	0.033			498
			BJ	27		87	266					520
			BK	20	7	87	261	272	0.033	77		498
			BL	17	8	87	470	714	0.087	70		410
			BG	20	7	87	261	272	0.033	77		498
			BG	20	7	86	261	272	0.033	77		498
			BG	20	7	86	261	272	0.033	77		498
			BI	20	7	86	261	272	0.033	77		498
			BI	20	7	86	261	272	0.033	77		498
			BI	20	7	86	261	272	0.033	77		498
			BI	20	7	86	261	272	0.033	77		498
			BG	20	7	86	261	272	0.033	77		498
			BM	27	8	86	196	91	0.011			318
			BN	24	8	86	231	351	0.043	123	89	989
			BL	24	8	86	231	351	0.043	123	89	989
			BL	24	8	86	231	351	0.043	123	89	989
			BO	24	8	86	231	351	0.043	123	89	989
			BL	24	8	86	231	351	0.043	123	89	989
			BN	20		86	75	147	0.018	15		174
			BP	27	9	86	261	272	0.033	77		498
			BP	27	8	86	171	91	0.011			233
			BP	20	8	86	77					370
			BQ	28	10	86	169	533	0.065	259	77	788
			BM	20	17	88	844	850	0.104	225		
	> 30 MBtu/h	TOP 25	BH	30		87	169	340	0.042			563
			BP	31	6	87	153	283	0.035	106		398
			BR	32	9	87	164	374	0.046	114		1168
			BL	34	11	86	234	408	0.050	110	87	375
		rest	BN	34	11	86	234	408	0.050	110	87	375
			BL	34	11	86	234	408	0.050	110	88	375
			BR	31	9	86	293	363	0.044	213		914
			BL	34	11	86	516	397	0.049	92	83	405
			BL	34	11	86	234	408	0.050	110	87	375
			BH	38		85	281	340	0.042			271
			BL	41	11	85	234	408	0.050	110		375
			BS	67			159	223	0.027			
			BT	113		85	664	533	0.065	192		
			BT	120		85	612	567	0.069	168		
			BT	123		85	803	567	0.069	162		
			BT	128		85	900	601	0.074	197		
			BT	131		85	1316	669	0.082	187		
			BT	132		85	881	329	0.040	105		

with	all loads	TOP 25%	V	51	13	85	39	113	0.014			189
			H	25	8	85	104	136	0.017	125	87	628
			BG	38	10	85	141	136	0.017	162	88	408
			BI	44	10	85	169	204	0.025	158	88	408
			H	31	10	85	133	193	0.024	128	87	488
		rest	BG	44	10	85	169	204	0.025	158	88	408
			BI	38	10	85	141	136	0.017	162	88	408
			BG	38		85	141	136	0.017			268
			BG	44		84	169	204	0.025			268
			BI	31	10	84	174	113	0.014	158	88	408
			BI	34	7	84	185	204	0.025	90	88	380
			BG	34	7	84	185	204	0.025	90	88	380
			BI	34	7	84	185	204	0.025	90	88	380
			BK	34	7	84	185	204	0.025	90	88	380
			S	39	11	84	231	272	0.033	137	86	703
			BP	31	7	84	81	261	0.032	95	88	605
			BM	34	7	84	124	306	0.037	117	88	605
			BU	41	13	84	460	544	0.067	111	88	701
			BU	41	13	84	460	544	0.067	111	88	701
			BL	34	9	84	132	714	0.087	100	88	277
			BP	41	12	84	162	249	0.031	131	87	345
			H	41	12	84	162	249	0.031	131	87	345
			BI	34	7	84	73	170	0.021	84	84	439
			BG	34	7	84	73	170	0.021	84	84	439
			BL	34	12	84	167	385	0.047	108	87	424
			BJ	45	15	84	184	320	0.039			540
			BH	44		84	267	238	0.029			744

red data: CO emission > averaged CO emissions

data	manufacturer	nominal load MBtu/h	partial load MBtu/h	nominal load					partial load	
				$\eta_{,GCV}$ %	CO mg/m^3$_{12\%}$	TSP mg/kg$_{fuel}$	TSP lb/MMBtu	NO$_X$ mg/m^3$_{12\%}$	$\eta_{,GCV}$ %	CO mg/m^3$_{12\%}$
TOP 25%	BT	123		76	1055	524	0.076	162		
	BT	128		74	1182	555	0.081	197		
	BP	25		73	1077	210	0.030	72		
	BT	113		73	872	492	0.072	192		
	BV	33	16	72	1065	156	0.023	85	71	1689
	BV	29	14	72	795	280	0.041	137	70	1766
	BP	30		72	1253	524	0.076	119		
	BV	29	12	72	1340	312	0.045	129	70	1400
	BV	31	15	71	1278	140	0.020	109	76	1776
	BP	26	14	71	776	225	0.033	59	73	
rest	BV	33	16	72	1065	156	0.023	85	71	1689
	BV	29	12	72	1340	312	0.045	129	70	1400
	BP	21		74	2535	870	0.126	142		
	BT	131		73	1729	618	0.090	187		
	BV	26	12	72	2401	732	0.106	120	70	1723
	BV	25	12	72	1691	265	0.038	122	75	1810
	BV	23	11	72	1742	748	0.109	119	75	1790
	BM	*17*		*72*	*1847*	*419*	*0.061*	*225*		
	BM	*20*		*72*	*1847*	*419*	*0.061*	*225*		
	BM	*24*		*72*	*2216*	*786*	*0.114*			
	BV	32	16	71	1287	234	0.034	82	73	1246
	BV	33	15	71	1048	530	0.077	99	71	1656
	BV	22	11	71	2135	732	0.106	95	70	1823
	BT	120		71	804	524	0.076	168		
	BT	132		71	1157	304	0.044	105		
	BP	34		71	1971	482	0.070	95		
	BP	27	14	71	2355	178	0.026	133		
	BP	23	13	71	1085	309	0.045	112	73	933
	BV	32	16	71	1158	62	0.009	135	72	1683
	BK	30	15	71	1197	421	0.061	147	71	1279
	BP	28	22	70	1359	147	0.021	127	71	1895
	BV	27	14	70	1346	171	0.025	135	74	1836
	BV	25	12	70	2078	467	0.068	139	72	1805
	BV	28	13	70	1169	405	0.059	144	70	1808
	BV	26	12	70	1270	296	0.043	140	73	1708
	BV	26	13	70	1059	93	0.014	115	70	1724
	BV	28	14	70	1070	156	0.023	140	71	1810
	BP	27	14	70	1921					
	BP	19		69	2102	241	0.035	163		
	BM	*20*		*67*	*1847*	*419*	*0.061*	*225*		
	BM	*27*		*67*	*2216*	*786*	*0.114*	*225*		
	BP	28		64	1884	880	0.128	107		
	BP	20		64						
	BP	26		64						

kursive data: only minimum efficiency and maximum emissions were given

red data: CO emission > averaged CO emissions

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