

## 5.2 Conversion of biomass to heat and electricity

[D. Hein, J. Karl]

### 5.2.1 Introduction

Energy from biomass is renewable and – due to a balance between  $\text{CO}_2$  consumption and release – commonly entitled “ $\text{CO}_2$  free”. Combustion of biomass naturally produces carbon dioxide ( $\text{CO}_2$ ), but it produces only the same amount that has been accumulated from the atmosphere during the growth of a plant. Forests are therefore short time accumulators for  $\text{CO}_2$  and – in contrast to fossil feedstock – regenerative sources.  $\text{CO}_2$  consumption and release are also in balance in case that energy crops or biogeneous wastes – in particular agricultural wastes and wastes from wood and food-processing industries – are used.

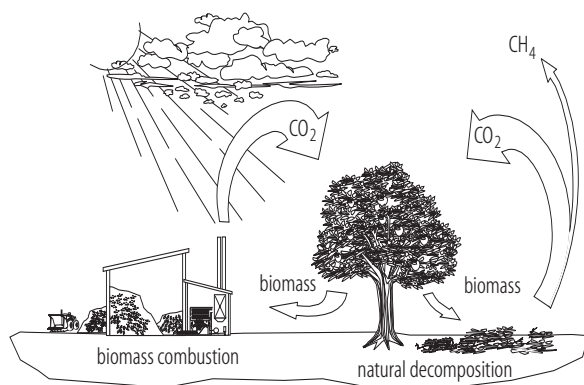
Decomposition of any biomass after its lifecycle releases not only approximately the same amount of  $\text{CO}_2$  that would develop during combustion; it also releases methane, which is a much more hazardous greenhouse gas than  $\text{CO}_2$ . Hence, combustion of biomass not only substitutes fossil fuel, but additionally reduces the emission of methane and other problematic gases during uncontrolled decomposition.

Another reason that makes energy from biomass residues particularly attractive comes from its economical prospects. Huge amounts of agricultural residues are available and can substitute costly fossil fuels. Disposal of these wastes is becoming more and more costly in many industrialized countries, which makes their usage for energy production additionally attractive.

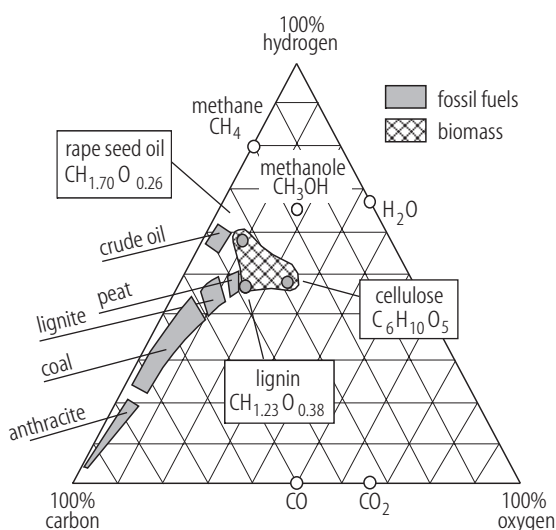
Substitution of natural gas, oil, lignite or hard coal with specialized energy crops like miscanthus or triticale will become competitive only with high funding or if the prices of fossil fuel increase severely for example due to governmental restrictions, political crisis or shortening of fossil resources within the next decades. In contrast to biogeneous wastes, specialized energy crops are still too expensive and are not expected to become competitive within the next years.

### 5.2.2 Fuel properties

Presently, extensive usage of biomass fails not only due to economical restrictions, but also due to technical matters. The fuel properties, namely the diversity and inhomogeneity of biomass, cause severe technical challenges. Well-known technologies arising from coal combustion need to improve and to consider the special properties of biomass – in particular its morphology, its varying composition and its chemical and physical properties.



**Fig. 5.2.1.**  $\text{CO}_2$  balance of biomass combustion. Combustion of biomass (energy crops and biogeneous residues) releases only the same amount of the greenhouse gas carbon dioxide as has been accumulated during its growth and furthermore reduces emissions of the more hazardous green house gas methane.



**Fig. 5.2.2.** Composition of biomass and fossil feedstock. Biomass has a higher hydrogen and oxygen content than usual fossil fuels.

Biomass is mainly classified into herbaceous and woody biomass. The structure of herbaceous biomass is mostly determined by cellulose ( $C_6H_{10}O_5$ ). Lignin (sum formula  $CH_{1.23}O_{0.38}$ ) leads to a slightly increased carbon proportion in woody biomass (see Fig. 5.2.2). Other energy crops of major importance are oilseed crops, in particular oilseed rape, sunflowers and sugar rich energy crops like sugar cane, sweet sorghum or grain.

Further special applications include the combustion of animal biomass (i.e. meat, fat and bone meal) and microorganisms, as well as the conversion of residues with high ash content (i.e. sewage sludge) and contaminated fuels (i.e. demolition wood).

The most considerable differences between coal and biomass are the significantly reduced heating value of biogenic fuel and the higher content of volatile components, hydrogen and oxygen.

### 5.2.2.1 Heating value and energy density

The heating value of dry biomass is comparable to that of lignite although the heating value of wet and newly-harvested biomass may be lower (see [Table 5.2.1-5.2.4](#)). The main characteristic value which influences the economic performance of biomass conversion is not the commonly used mass-based heating value, but the volumetric heating value – the energy density. Dry biomass may have quite high mass-based heating values between 16000 and 20000 kJ/kg – but its energy density (heating value in [kJ/m<sup>3</sup>]) is orders of magnitudes smaller than the energy density of coal or any kind of liquid fuel (see [Table 5.2.5](#)).

The logistic effort of handling wood chips increases by a factor of ten compared to that of handling coal. The transportation of the equivalent energy content of a single wagon of coal requires up to thirty wagons of straw bales. The reduced density increases not only the costs for transportation, but also the required storage capacity and the performance of the fuel feeding and handling systems. This typically limits the collection area and the thermal input for heating and power plants to approx. 100 megawatts. This power range already demands a mean transportation distance of more than 25 km for wood chips [[98Sch](#)]. Biomass conversion is therefore particularly attractive for decentralized applications. Consequently the most common are heating, both household and district.

### 5.2.2.2 Inhomogeneity and diversity

Another outstanding property of the biomass fuel is its huge diversity. Combustion of herbaceous biomass requires a fundamentally different design of the combustion system than combustion of woody biomass. Even the moisture content and morphology of standardized fuels like wood chips vary so immensely that an efficient and environmentally friendly combustion demands a high technical effort.

Special technical challenges for the fuel feeding system result from the inhomogeneous morphology and moisture of solid biomass. Inhomogeneities and contamination with inorganic materials are the main reasons for operational failures and damages of fuel feeding systems. Particularly important for the combustion and gasification are the ash melting behavior (see [Sect. 5.2.4.3](#)) and the chlorine content (see [Sect. 5.2.4.4](#)).

Another important feature of biomass is its high content of volatile components, especially in herbaceous biomass. These volatile components lead to a significantly enhanced combustion velocity and require an adapted layout of the furnace.

Emissions, in particular  $\text{NO}_x$  and  $\text{SO}_2$ , are usually in a range comparable to the emissions from coal and lignite fired furnaces. Special regard should be paid to the emission of dioxin, heavy metals and aromatic hydrocarbons. Emission values for these systems vary largely with fuel and combustion conditions.

There are several ongoing national and international attempts to reduce technical problems by means of standardization of biofuel [\[01FNR\]](#). The main criteria to achieve comparable fuel classes for a reliable fuel treatment are a classification of physical properties (size, morphology, moisture content, heating value) and origin.

### 5.2.2.3 Heating values of solid biomass

Experimental data usually provide the higher heating value (HHV)  $H_h$  of dry biomass in [kJ/kg]. The lower heating value (LHV)  $H_{l,db}$  of the dry feedstock (“dry base”) in [kJ/kg] takes into account the amount of water vapor which results from combustion of the hydrogen:

$$H_{l,db} = H_h - h \cdot \frac{18}{2} \cdot 2440, \quad (5.2.1)$$

where  $h$  denotes the mass fraction of hydrogen of the *dry* biomass (“dry base”), in [wt-%]. The lower heating value (LHV)  $H_{l,ar}$  of the wet feedstock (“as received”) in [kJ/kg] additionally considers the amount of water vapor which comes from evaporation of its water content  $w$ :

$$H_{l,ar} = H_h \cdot (1 - w) - 2440 \frac{\text{kJ}}{\text{kg}} \cdot w - h \cdot \frac{18}{2} \cdot 2440 \frac{\text{kJ}}{\text{kg}} \cdot (1 - w). \quad (5.2.2)$$

The water content  $w$  of the *wet* biomass (“as received”), measured in [ $\text{kg}_{\text{water}}/\text{kg}_{\text{wet biomass}}$ ], is related to the moisture  $u$  of the *wet* biomass (“as received”), measured in [ $\text{kg}_{\text{water}}/\text{kg}_{\text{dry biomass}}$ ], by

$$w = \frac{u}{1 + u}. \quad (5.2.3)$$

For values for  $H_h$ ,  $H_l$ ,  $h$  and  $w$  see [Table 5.2.1-5.2.4](#) and Fig. 5.2.3. The conversion between “wet” and “dry” lower heating value results from

$$H_{l,ar} = H_{l,db} \cdot (1 - w) - 2440 \frac{\text{kJ}}{\text{kg}} \cdot w. \quad (5.2.4)$$

Common empiric equations for heating values (i.e. “Verbandsformel” [\[99Ste\]](#)) are valid only for fossil feedstock and do not provide sufficient accuracy for a calculation of heating values of any kind of biomass. Two empirical correlations deduced from experimental data have been suggested for woody and

herbaceous biomass [97Obe]. Insertion of an average higher heating value  $H_h = 20$  MJ/kg and an average hydrogen mass fraction  $h$  of 6% for woody biomass and an average higher heating value  $H_h = 18.6$  MJ/kg and an average hydrogen mass fraction  $h$  of 5.5% for herbaceous biomass yields

$$H_{l,ar} = 18.7 - 21.1 \cdot w$$

in [MJ/kg] for woody biomass, and

$$H_{l,ar} = 17.4 - 19.8 \cdot w$$

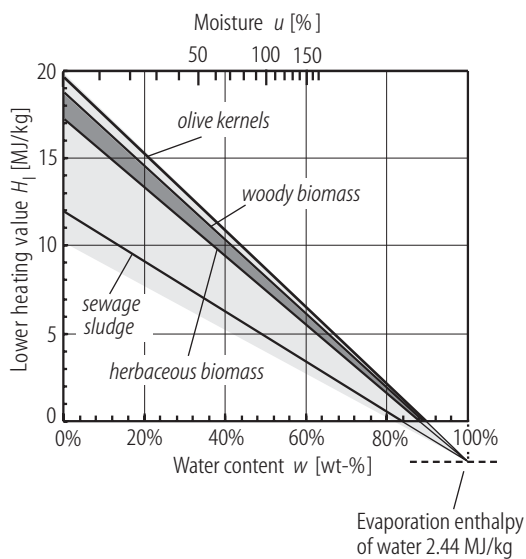
in [MJ/kg] for herbaceous biomass.

## 5.2.3 Generation of heat and power from biomass

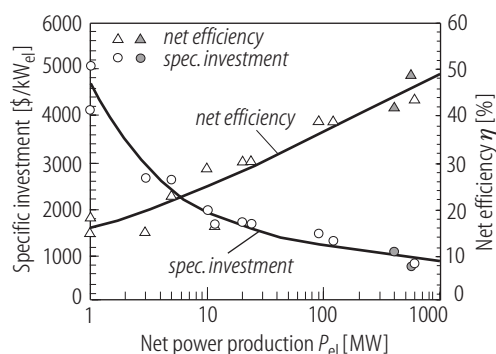
### 5.2.3.1 Generation of heat

Household heating is traditionally the most common application of biofuels. Generation of heat is the most efficient conversion of biomass to energy, but it wrecks all its “working ability”, its exergy.

There are generally two alternatives for heat generation. Small ovens are used for single households and require user-friendly systems and clean fuels. Pellets and wood log furnaces in the power range of a few kilowatts are therefore widespread systems. The main disadvantages for these small-scale systems are the necessity to use rather clean fuel and – if comfort is wanted – the high specific investment costs. An alternative is the installation of heating grids for district heating. This concept allows enhanced flue gas treatment and use of less expensive biomass. The main disadvantages are additional heat losses during distribution. These losses depend on size and loading of the grid and usually range between 10 and 30% of the total energy input ([97Obe], see Table 5.2.12).



**Fig. 5.2.3.** Lower heating value  $H_l$  with respect to the water content  $w$  and fuel moisture  $u$ .



**Fig. 5.2.4.** Specific investment costs and net efficiencies with respect to the plant size for large scale power plants for solid fuels (white symbols: steam cycles, grey symbols: IGCC plants) [99Cam].

### 5.2.3.2 Large scale power plants

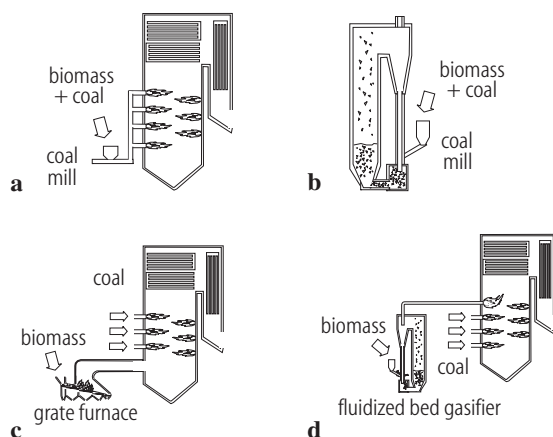
The traditional power plants for generation of electricity with solid fuels are steam power plants. An efficient and economical operation of these plants requires large units. Modern coal fired steam power plants with electrical power of several hundred megawatts achieve net efficiencies between 40 and 45%. Small-scale power plants with an electrical output of few MW only achieve net efficiencies around 20-30%. The investment costs for these relatively small units rise inadequately as shown in Fig. 5.2.4.

The low energy density and the low volumetric heating value of energy crops limits the maximum thermal input due to inadequate high costs for transportation and logistics. Conventional biomass fired steam power plants will operate economically only as combined heat and power (CHP) plants and therefore require adequate heat consumers.

An alternative to classic steam power plants within the large-scale range are combined cycle power plants – a combination of gas and steam turbines. However, this type of power plant requires liquid or gaseous fuel and therefore demands gasification or liquefaction of solid energy crops. Integrated gasification combined cycle (IGCC) plants reach high efficiencies but they suffer from high investment costs.

### 5.2.3.3 Co-combustion

The most efficient concept using large amounts of biomass with a high net efficiency is co-combustion in large, existing coal fired power plants. Substitution of 10 to 20 percent of the coal is not only the easiest and most cost effective way to use huge amounts of biomass with relatively small investment, but it presently is the only way to produce power from biomass with net efficiencies above 40 percent. Figure 5.2.5 shows the available concepts for using biomass in existing coal fired power plants.



**Fig. 5.2.5.** Available options for co-combustion of biomass in large-scale coal fired power plants.

(a) Entrained flow combustion. (b) Co-combustion in circulating fluidized beds. (c) External combustion (grate furnace). (d) External gasification (fluidized bed gasifier).

The simplest concept is mixing the biomass with the coal (see Fig. 5.2.5a and 5.2.5b). This option requires small biomass particles, like saw dust and sewage sludge, or pulverization of the biomass. Biomass can be added to the coal mills and blown into coal burners together with the coal. Especially fluidized bed furnaces are well suited for co-combustion of various feedstocks without pretreatment. This version requires only negligible investment.

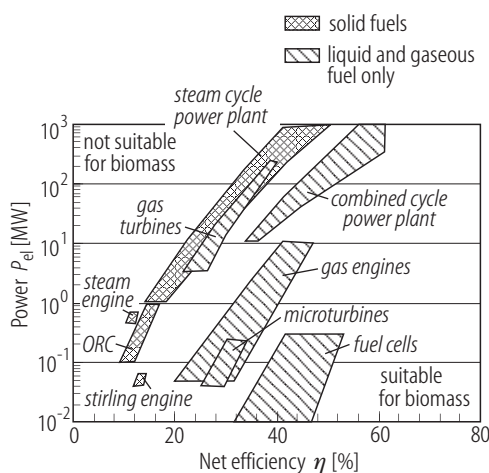
Due to its bad grinding behavior most biomass fuels require external combustion or gasification. External combustion, i.e. with grate furnaces (see Fig. 5.2.5c), allows an adaptation of the furnace system to the needs of the biomass fuel. The hot flue gas finally gets into the steam generator of the large-scale power plant and passes its flue gas path and gas cleanup system. The main technical challenge of this concept is that large openings must be cut into the walls of the steam generator and may cause flow instabilities, especially with once-through steam generators. An uneven flue gas composition and an inhomogeneous temperature distribution may initiate fouling on the evaporator and superheater surfaces. Reduced radiation heat transfer changes the heat balance in the steam generator and may increase the heat flux to the superheater and economizer.

A third concept for co-combustion has been demonstrated in Zeltweg, Austria [01Kal]. An autothermal fluidized bed gasifier generates low calorific wood gas (see Fig. 5.2.5d). This gas is burned in specially adapted gas burners, which are integrated in the combustion chamber of an existing coal fired power plant. This version negligibly affects the operation of the steam generator, but causes comparatively high investment costs.

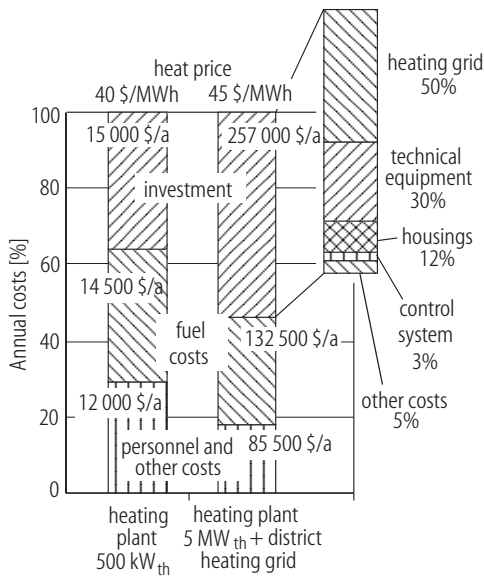
#### 5.2.3.4 Decentralized generation and combined heat and power production (CHP)

Decentralized applications with combined heat and power generation (CHP) are only suitable with small-scale working engines with sufficiently high efficiencies. Common power plant concepts – like steam cycle power plants – do not match the demand for small unit size and high efficiency (see Fig. 5.2.6). There are only few small-scale systems which may be combined with a common combustion system for solid fuels. Stirling engines and small-scale steam engines are not expected to become economically competitive within the next years. Attractive, but still expensive options are Organic Rankine Cycle plants (ORC). They are particularly promising due to their low requirements for maintenance and supervision.

All other working engines require liquid or gaseous fuel and therefore a digestion or gasification of solid biomass. Internal combustion engines are the most convenient machines within the power range between several kW and few MW. Their efficiency depends on the power range and reaches 42% for units with an electrical output of several MW. Standardized gas turbines are also adequate for these processes, but they require fuel gases with heating values above 10 MJ/kg or a specially adapted design of the



**Fig. 5.2.6.** Power range and efficiencies for usual working machines. Biogeneous fuels require particularly small scaled and efficient aggregates which are only available for gaseous fuels.



**Fig. 5.2.7.** Cost structure (annual costs) of a heating plant 500 kW<sub>th</sub> without heating grid and a district heating plant 5 MW<sub>th</sub> (2 MW<sub>th</sub> biomass, 3 MW<sub>th</sub> oil) with district heating grid (Bank rate 6%, depreciation time 15 years, 2000 full load hours per year (heating plant 500 kW) and 4500/800 full load hours per year (biomass/oil), fuel costs biomass 12.5 \$/MWh, oil 15 \$/MWh, German data, base 1999, [00Jah]).

combustor. Interesting alternatives for very small applications with acceptable efficiencies are so-called microturbines (small-scale gas turbines with flue gas recuperator) with net efficiencies of approximately 30%. Fuel cells will probably offer the best compromise between system size and efficiency in some years. However, fuel cells require an extremely high quality of the fuel gas.

All concepts with an acceptable relation between system size and system efficiency require either liquid or gaseous fuels. Fermentation and small-scale gasification systems are therefore key technologies for biomass based CHP systems.

### 5.2.3.5 Economical aspects

The main parameters for the economic performance of large-scale power plants are the net efficiency and annual operation time. The net efficiency determines the fuel costs, and the annual operation time the specific investment  $s_1$  per MWh. The break-even electricity selling price therefore mainly depends on the investment and fuel costs. Personnel costs are of minor importance for large-scale plants.

The economical boundary conditions for small-scale applications are completely different. The end user price for electricity contains to a large extend costs for distribution and backup capacities. Consequently it is significantly higher than the break-even electricity selling price of a power producer. This means that revenues for electricity from decentralized CHP plants are identical to the end user price and therefore considerably higher than the break-even electricity selling price for large scale plants.

Another important aspect originates from the different cost structure of small-scale applications. Whereas fuel and investment costs dominate the annual costs of large-scale applications, personnel costs govern the annual costs of small-scale applications. Automation and high reliability of the fuel feeding and of the combustion system are therefore essential for these applications. On the other hand, this cost structure offers advantages for small-scale combined heat and power applications. Due to the fact that only 30 percent of the investment (16 percent of the total annual costs, see Fig. 5.2.7) come from technical equipment, in particular fuel feeding, combustion and flue gas cleaning, additional costs for gasification and an additional working engine do not necessarily affect the annual costs unacceptably.



The most significant parameter for small-scale applications is the annual operation time per year, expressed as “annual full load hours”  $z$  [98Ort]:

$$z = \frac{\dot{Q}_H}{\dot{Q}_{\text{peak}}}, \quad (5.2.5)$$

where  $\dot{Q}_H$  is the annual heat production of the heating plant in [MWh/a] and where  $\dot{Q}_{\text{peak}}$  is the thermal output (peak load) of the heating plant in [kW] (see Table 5.2.9).

The return of investments for decentralized applications crucially depends on the continuity of the heat demand and on the consumer structure. Hospitals and industrial processes are particularly good consumers; residential areas, development areas and school buildings are less adequate.

## 5.2.4 Combustion of biomass

### 5.2.4.1 Combustion efficiency

The efficiency of biomass combustors depends mainly on the mass flow, the composition and the temperature of the exhaust flue gas. Neglecting further losses (incomplete combustion, radiation losses, ash losses) leads to a simplified correlation for the efficiency of a combustion system:

$$\eta_B = \frac{\dot{Q}_H}{\dot{m}_F(H_1 + c_F t_F) + \dot{m}_A c_{p,A} t_A} \approx 1 - \frac{t_{\text{out}}}{t_{\text{ad}}}, \quad (5.2.6)$$

where  $\dot{Q}_H$  in [kW] denotes the thermal power of the boiler,  $\dot{m}_F$  and  $\dot{m}_A$  the mass flow of fuel and air in [kg/s],  $t_F$  and  $t_A$  the temperature of fuel and air,  $t_{\text{out}}$  in [°C] the exhaust temperature and  $t_{\text{ad}}$  in [°C] the adiabatic combustion temperature given by

$$t_{\text{ad}} = \frac{H_{1,\text{db}} \cdot (1 - w) - 2440 \frac{\text{kJ}}{\text{kg}} \cdot w}{\frac{44}{12} \cdot c \cdot c_{p,\text{CO}_2} + \left(\frac{18}{2} \cdot h + w\right) \cdot c_{p,\text{H}_2\text{O}} + 0.232 \cdot (\lambda - 1) \cdot l_{\text{min}} \cdot c_{p,\text{O}_2} + 0.768 \cdot \lambda \cdot l_{\text{min}} \cdot c_{p,\text{N}_2}}. \quad (5.2.7)$$

$c_F$  and  $c_p$  are specific heat capacities in [kJ kg<sup>-1</sup> K<sup>-1</sup>] of fuel, air and flue gas components. A combustion calculation provides the minimum specific air quantity  $l_{\text{min}}$  in [kg<sub>air</sub>/kg<sub>fuel,db</sub>] for complete combustion as

$$l_{\text{min}} = \frac{1}{0.232} \cdot (2.664 \cdot c + 7.937 \cdot h + 0.998 \cdot s - o), \quad (5.2.8)$$

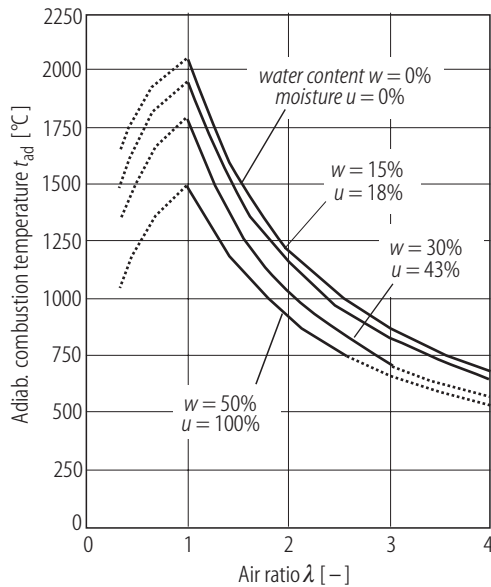
which also defines the excess air ratio  $\lambda$  of the combustion process,

$$\lambda = \frac{l}{l_{\text{min}}}, \quad (5.2.9)$$

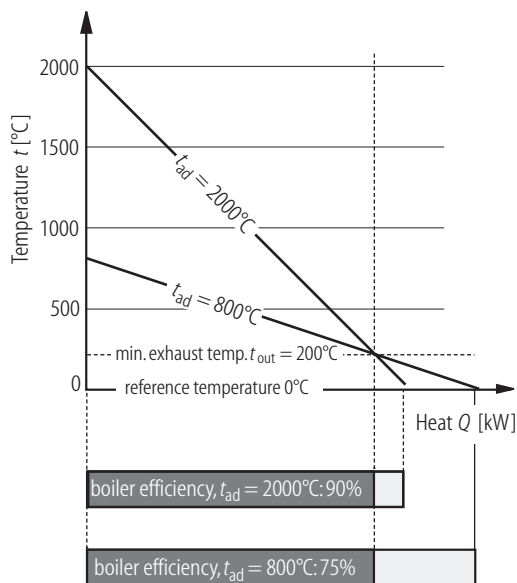
for a certain specific air quantity  $l$  in [kg<sub>air</sub>/kg<sub>fuel,db</sub>] and a given fuel composition with water content  $w$  in [wt-%] (as received), the mass fraction of hydrogen  $h$ , carbon  $c$ , sulfur  $s$  and oxygen  $o$  in [wt-%] (dry base) (see Table 5.2.1-5.2.4). Hence, the main influence on the combustion efficiency comes from the excess air ratio  $\lambda$  and the water content  $w$  of the fuel. They limit the adiabatic flue gas temperature  $t_{\text{ad}}$  and reduce the boiler efficiency as shown in Fig. 5.2.8 and Fig. 5.2.9.



A common way for enhancing the boiler efficiency, especially with high fuel moistures, is flue gas condensation – the condensation of the water vapor content of the flue gas. Lowering of the flue gas temperature  $t_{\text{out}}$  to at least 30–60°C reduces flue gas losses and enables usage of the latent heat of the water vapor. This concept is quite usual, especially for district heating plants, because flue gas condensation avoids swaths and therefore increases their public acceptance.



**Fig. 5.2.8.** Adiabatic combustion temperature  $t_{\text{ad}}$  for different water contents  $w$  and moistures  $u$  for the combustion of wood chips.



**Fig. 5.2.9.** Influence of the adiabatic combustion temperature  $t_{\text{ad}}$  on the boiler efficiency.

### 5.2.4.2 Emissions

Combustion calculation also provides the flue gas composition and emission rates

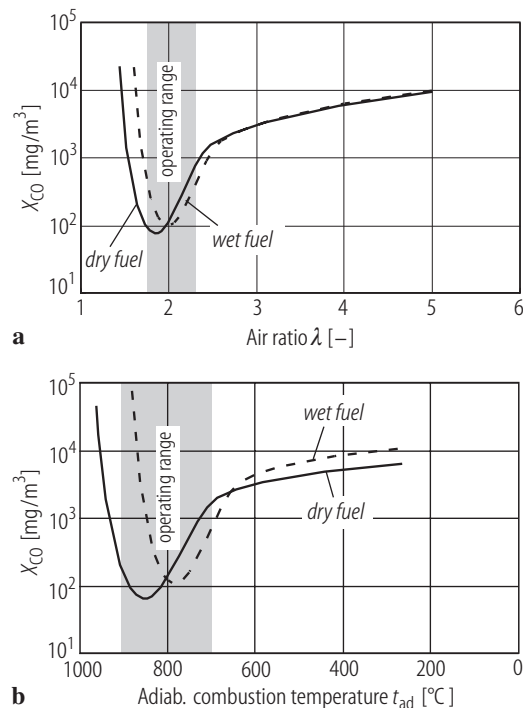
$$x_{\text{CO}_2} = \frac{\frac{11}{3} \cdot c}{\lambda \cdot l_{\text{min}} + (1-a)} \quad \text{in} \left[ \frac{\text{kg}_{\text{CO}_2}}{\text{kg}_{\text{fluegas}}} \right],$$

$$x_{\text{H}_2\text{O}} = \frac{9 \cdot h + w}{\lambda \cdot l_{\text{min}} + (1-a)} \quad \text{in} \left[ \frac{\text{kg}_{\text{H}_2\text{O}}}{\text{kg}_{\text{fluegas}}} \right],$$

$$x_{\text{SO}_2} = \frac{2 \cdot s}{\lambda \cdot l_{\text{min}} + (1-a)} \quad \text{in} \left[ \frac{\text{kg}_{\text{SO}_2}}{\text{kg}_{\text{fluegas}}} \right].$$

Actual SO<sub>2</sub> emissions are often significantly lower due to the formation of sulfates in the ash.

The CO and NO<sub>x</sub> emissions mainly depend on combustion conditions, in particular the combustion temperature (see Fig. 5.2.10). NO<sub>x</sub> formation occurs not only due to oxidation of the nitrogen content in the biomass, but also due to oxidation of nitrogen from the combustion air. Extremely high temperatures should be avoided because they generate thermal NO<sub>x</sub>. The common way for reducing local high temperatures and NO<sub>x</sub> formation is staged combustion. Combustion with an excess air ratio  $\lambda < 1$  reduces the temperature on the grate and in fluidized beds. Secondary air completes the combustion and prevents unacceptable CO emissions. Staged combustion is also an adequate method to reduce NO<sub>x</sub> emissions coming from the combustion of biomass with exceptionally high nitrogen content, like meat and bone meal.



**Fig. 5.2.10.** Influence of (a) air ratio, (b) combustion temperature and fuel moisture on CO emissions of grate furnaces for wood chips [97Obe].

### 5.2.4.3 Ash melting behavior

Ash content and ash melting behavior have crucial influence on the selection of an appropriate firing system. The sintering temperature is a common measure that characterizes the ash melting temperature. It varies between 700 and 800°C for several herbaceous biomasses and is more than 1200°C for woody biomass (see [Table 5.2.7](#)). The main ash components that reduce the ash melting behavior are alkali metals and earth alkali metals, especially potassium.

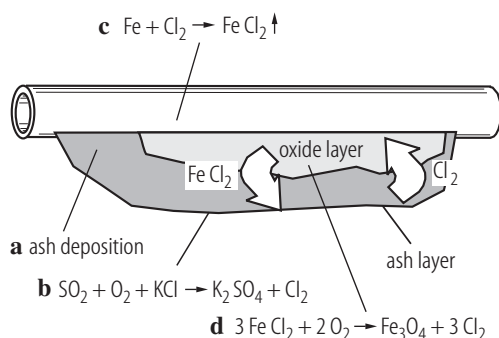
Low ash melting temperatures cause slagging in grate and under stocker furnaces. In particular inhomogeneous fuels or uneven loading of the grate often leads to hot zones in the fuel bed. These “hot spots” cause temperatures above 1000°C and thus – due to the exceeding of the ash softening temperature – cinder formation. Individual grate elements stick together if the cinder solidifies which usually causes an outage of the plant and expensive repairs.

Fluidized-bed combustion systems operate with combustion temperatures around 800-900°C. No local overheating has to be expected due to an ideal mixing of the bed. Additional problems result from the fact that ashes with particularly high alkali content form low melting eutectics with the particles of the bed material. Especially quartz sand ( $\text{SiO}_2$ ) and potassium chloride (KCl) form eutectics with softening temperatures below 800°C. Softened ash mixtures cover the particles of the bed material (coating) and cause them to stick together as large agglomerates. This agglomeration finally brings the fluidization to a standstill. The agglomeration occurs particularly often near surfaces with reduced mixing and fluidization. The most simple and effective way to avoid bed agglomeration is to use only bed materials which do not form low melting eutectics with the ash components (i.e. olivine ( $\text{Fe}_x\text{Mg}_{2-x}\text{SiO}_4$ ), calcined dolomite  $\text{CaO}^x\text{MgO}$ , magnesite  $\text{MgO}$ , mullit sand  $2\text{SiO}_2 \cdot 3\text{Al}_2\text{O}_3$ , zirconium sand  $\text{ZrSiO}_4$  [[98Zin](#)]).

Another widespread reason for the agglomeration of bed particles are unburned coke or fuel particles which remain in the bed after power-off of the furnace. Small amounts of air lead to a local oxidation of these particles and thus to very high temperatures. The released heat cannot be dissipated without fluidization and melts even ashes with high melting temperatures.

### 5.2.4.4 Chlorine corrosion

Especially herbaceous fuels often have an extraordinarily high chlorine content. The chlorine content depends not only on the biomass species itself, but also on its origin and storage. Corrosion in combustion systems caused by chlorine is well known from waste incineration plants. High temperature chlorine corrosion damages especially superheater surfaces, even within few thousand operation hours. An easily removable, multi-layered oxide coating with a thickness of 0.1 to 0.3 mm, usually covered by a thin ash deposit, typically indicates high temperature chlorine corrosion. The wall thickness loss of the affected heat exchanger surface is usually much higher than the thickness of the formed oxide coating.



**Fig. 5.2.11.** Mechanism of the high temperature chlorine corrosion. **(a)** Deposit formation. **(b)** Sulfatization of alkali and alkaline-earth chlorides. **(c)** Formation and evaporation of  $\text{FeCl}_2$ . **(d)** Formation of  $\text{Fe}_3\text{O}_4$  and regeneration of elementary chlorine.

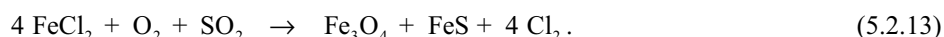
The dominating mechanisms take place in four steps [97Rei], [97Obe]: Alkali chlorides such as NaCl and KCl develop during combustion and leave the furnace with the flue gas due to their high evaporability. Cooling of the flue gas leads to condensation of the alkali chlorides at fine dust particles and heat exchanger surfaces (see Fig. 5.2.11, 1st step). The second step, sulfatisation of alkali and alkaline-earth chlorides, forms elementary chlorine: Flue gas contains SO<sub>2</sub> which produces alkali sulfates and releases elementary chlorine within the deposit layer:



This elementary chlorine creates iron perchloride, which evaporates from the metallic surface due to its extremely high partial pressure at temperatures above 500 °C (3rd step):



Regeneration of iron perchloride by the formation of iron oxides releases again elementary chlorine:



This means that the chlorine regenerates during formation of Fe<sub>3</sub>O<sub>4</sub> in the fourth step and continuously affects the heat exchanger surface again. The developing ferric oxide forms an easily removable oxide layer. The corrosion process can only be stopped by removing the ash and oxide deposits.

Crucial for developing the high temperature chlorine corrosion is the SO<sub>2</sub> concentration in the flue gas, the quantity of alkali chloride (e.g. NaCl and KCl) in the aerosol particles delivered from the furnace and the temperature of the heat exchanger surfaces. Reducing the live steam temperature in steam generators to 400-420°C prevents the danger of high temperature chlorine corrosion.

In waste incineration plants mechanical devices ceramic half shells or ceramic shaped bricks are used for the protection of the heat exchangers at particularly endangered spots. A very expensive way to avoid corrosion is to use more corrosion-resistant materials (AC66, Incoloy 625, Incoloy 825).

Particularly remarkable is the unexpected occurrence of the chlorine corrosion in lignite fired circulating fluidized-bed combustions even with very low chlorine contents (0.035 per cent). This means that even small amounts of SO<sub>2</sub> and chlorine in the flue gas are sufficient to initiate high temperature chlorine corrosion. At this point, the sulfur content of the fuel plays a major role. Low sulfur proportions cause an insufficient sulfatisation of alkali chlorides in the furnace itself and lead to an intensified formation of alkali and alkaline-earth chlorides in the flue gas. Hence, internal desulphurization increases the risk of high temperature chlorine corrosion and should be avoided even when fuels with low chlorine contents are used.

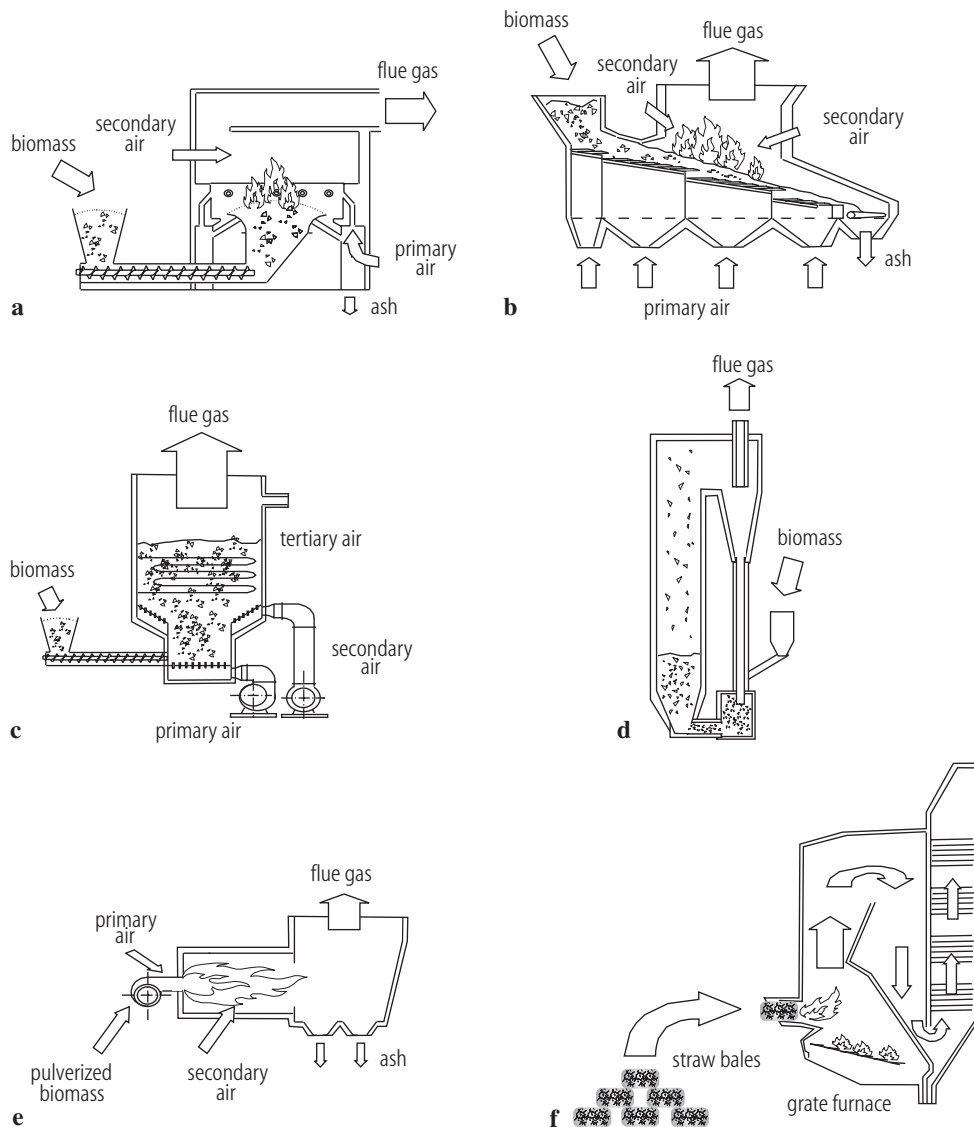
#### 5.2.4.5 Combustion systems

Combustion systems for biomass are comparable to furnaces used for coal. Commonly in use are under stocker furnaces, grate furnaces, entrained flow combustion and fluidized bed furnaces. Each technology requires modifications and adaptations to the needs of biogeneous feedstock. The specific requirements of herbaceous fuels led to the development of specially designed systems like Hesston bale furnaces

Air staging is a common principle for all available systems. Biomass combustion systems are mainly hot water generators because steam generators are only needed for large power plants. Crucial criteria for the selection of the firing system are thermal output, fuel composition and consistency of the fuel.

### 5.2.4.5.1 Under stocker furnaces

Under stocker furnaces (Fig. 5.2.12a) are quite usual in particular for small-scale applications within a power range below 6 MW<sub>th</sub> with low ash content. A stocker pushes the fuel from the bottom into the furnace and creates a small fuel bed. The investment costs are moderate, but these furnaces require rather homogenous fuel, preferably wood chips or wood shavings. Main problems are ash removal and the creation of a homogeneous bed in order to avoid channeling which causes hot zones and slagging.



**Fig. 5.2.12.** Commonly used systems for biomass combustion. **(a)** Under stocker furnace. **(b)** Grate furnace. **(c)** Bubbling fluidized bed furnace (BFB). **(d)** Circulating fluidized bed furnace (CFB). **(e)** Entrained flow burner (jet burner). **(f)** Hesston bale furnace.

#### 5.2.4.5.2 Grate furnaces

The grate furnace (Fig. 5.2.12b) is common mostly in the medium power range between 1 and 30 MW thermal input. It is particularly suitable for homogeneous fuels like wood chips and bark. Combustion of woody biomass is unproblematic in general. However, the combustion of herbaceous fuels like hay, straw and other energy crops on grates causes severe problems because of their low ash melting temperature and a high chlorine content. Exceeding the ash softening or the ash melting temperature leads to slagging and may damage the grate. Water-cooled grates and flue gas recirculation are therefore state-of-the-art for the combustion of woody biomass – in particular combustion of biomass mixtures and contaminated biomass like demolition wood and bark. Grate firing systems for the combustion of hay and straw are either staged systems for the co-combustion of wood-chips and straw or specially designed furnaces with extremely low combustion temperatures and correspondingly high CO emission values.

#### 5.2.4.5.3 Fluidized bed combustion systems

Fluidized bed combustion systems are primarily applied for large-scale boilers. The combustion air is blown vertically through a bed of small inert particles, for example quartz sand. The airflow lifts the sand particles and creates a state which comes close to the state of liquids (“fluidization”). An external gas burner preheats the sand bed for start-up. The combustion temperature is around 800-900°C. The fuel particles are fed into the bed and release the heat of combustion to the sand particles. The turbulent mixing within the bed creates a very even temperature distribution. Similar to coal fired applications, there are circulating (CFB) and bubbling (BFB) fluidized bed applications (see Fig. 5.2.12c and Fig. 5.2.12d).

A main advantage of fluidized bed systems is the excellent heat transfer behavior of the fluidized bed. High heat transfer rates allow an effective cooling of the bed and therefore an operation at moderate temperature with low excess air ratios. The bed normally operates with an excess air ratio  $\lambda$  between 0.6-0.8. Addition of secondary air to the freeboard results in exceptionally low air ratios between 1.2-1.4. Other important features are the particularly high heat content of fluidized beds, which allows combustion of rather inhomogeneous fuels with changing moisture and particle sizes as well as the possibility to apply additives for in-situ desulphuration. Hence, fluidized bed combustion systems are particularly common for waste incineration plants, especially in Japan.

A significant problem in the application of fluidized beds to biomass combustion comes from a particularly low fuel density and from low ash melting temperatures (see [Sect. 5.2.4.3](#)). In contrast to coal particles the density of biomass is normally lower than the mean density of the sand bed. This causes the fuel particles to swim predominantly on the bed surface instead of mixing in the bed itself. This reduces the heat release to the bed particles and has to be taken into account for the boiler design. Possible options to increase the heat release to the fluidized bed consist of an operation with high expansion of the bed and of applying circulating or internally circulating fluidized bed systems.

#### 5.2.4.5.4 Special designs

The huge variety of biomass led to the development of rather specialized combustion systems. Quite popular, especially in Denmark, are Hesston bale furnaces (“cigar furnaces”, see Fig. 5.2.12f) which are designed for the combustion of large straw bales [[01Kal](#)]. Hay and straw have an extraordinary high content of volatile components and extremely low ash softening temperatures. Thereupon combustion of straw requires a distinct staged combustion in order to avoid slagging. Combustion of straw on grates leads to entrainment of light straw particles and an incomplete combustion. This causes high CO emissions and enhances the proportion of organic carbon in the fly ash. Not even extreme air staging is sufficient to avoid high CO emissions with normal bale firing systems. For this reason, straw combustion systems are often combined with the combustion of wood chips.

Another concept especially designed for rather inhomogeneous fuel like demolition wood and biomass wastes are rotating cone combustion systems [[99Bur](#)]. A rotating cone creates an endless grate furnace and therefore realizes largely varying residence times.

### 5.2.5 Gasification of biomass

#### 5.2.5.1 Definition

The production of combustible gases from biogeneous solid fuels becomes particularly evident if the biomass shall be used in small-scale decentralized CHP plants. Hereby, the high proportion of volatile components and hydrogen in the biomass is particularly advantageous for gas generation.

There are three different ways of producing liquid or gaseous fuels from solid biomass – digestion, pyrolysis and thermal gasification. Nowadays the most common process is anaerobic digestion or fermentation of biogeneous wastes and residues. Agricultural residuals together with solid and liquid manure are converted into a methane-rich gas in large fermenters. In most cases so called co-substrates like fat, kitchen trash, leftovers or spent hops are added. Anaerobic fermentation also allows the use of herbaceous biomass. In this case the cellulose should be hydrolyzed in order to enhance the conversion rate in the fermenter.

Anaerobic fermentation is presently not suitable for the conversion of ligneous fuels and all kind of woody biomasses. Development of microorganisms which are able to produce ethanol from ligneous biomass is under progress, but such microorganisms are not yet available. The success of these developments depends to a large extent on the achievable conversion rates and the resistance and robustness of the microorganisms. Conversion of ligneous biomasses therefore particularly demands thermal processes. Fast pyrolysis and flash pyrolysis aim at producing storable liquid fuels. Higher hydrocarbons develop at temperatures over 500°C. Producing pyrolysis oil requires extremely high heating rates up to 500 K/s. Rapid condensation of the hydrocarbons afterwards avoids thermal cracking of large molecules and the development of gaseous components. The major technical challenge is the permanent preservation of these oils to allow storage and transportation.

Thermal gasification of carbon-containing fuels starts at temperatures above 700°C. One thereby differentiates autothermal gasification and allothermal gasification. Gasification is an endothermal process and requires heat at high temperatures.

Partial oxidation within the reactor produces the necessary heat of reaction during autothermal gasification. The main drawback of this concept comes from the fact that partial oxidation forms flue gas which dilutes the product gas. A high CO<sub>2</sub> and H<sub>2</sub>O proportion and above all the high nitrogen proportion seriously reduce the heating value of the product gas.

Allothermal gasification means that the heat of reaction is supplied to the reactor totally or partly from an external source. This avoids a dilution of the product gas with flue gas and nitrogen and results in substantially higher heat values of the product gas. A special form of allothermal gasification is steam gasification or so-called steam reforming. High heat values and a particularly high hydrogen content characterize its product gas. Steam reforming of biomass is therefore an interesting option for the production of synthesis gas for fuel cells and methanol synthesis.

A common measure for comparing gasifiers is the cold gas efficiency  $\eta_{cg}$ :

$$\eta_{cg} = \frac{\dot{m}_{cg} \cdot H_{l,cg}}{\dot{m}_F \cdot H_{l,F}}, \quad (5.2.14)$$

where  $\dot{m}_{cg}$  indicates the product gas flow,  $H_{l,cg}$  the lower heating value of the cold product gas,  $\dot{m}_F$  the fuel mass flow and  $H_{l,F}$  the heating value of the fuel. The main disadvantage of allothermal gasifiers comes from the fact that their cold gas efficiencies  $\eta_{cg}$  are significantly lower than the efficiencies of autothermal gasifiers, as a part of the product gas has to be used to heat the reactor.



### 5.2.5.2 Digestion

The production of fermentation gas is quite common in agricultural farms. Solid and liquid manure are the main fuel components for anaerobic digestion in large fermenters. A certain measure of herbaceous residuals such as hay, grass cut or verge grass are added in most cases. Other usual co-substrates are sewage sludge, food wastes and frying fat. The produced fermentation gas is stored in gas tanks and finally used in internal combustion engines mostly for combined heat and power production. The high methane proportion of up to 75% and the associated high heat value of about 20000 kJ/m<sup>3</sup> are favorable for the use in gas engines and even allow combustion in microturbines. The use of leftovers and kitchen wastes require pasteurization, a brief heating up to 70°C before digestion. Due to a usually high H<sub>2</sub>S content in the product gas, the gas engines require a desulphuration, for example with active coal filters.

One differentiates between mesophile and thermophile microorganisms. Mesophile bacteria permit a very stable fermentation at temperatures around 35-38°C and retention times between 25 and 40 days. Thermophile microorganisms (fermentation temperature 60-75°C) permit a more rapid digestion, but they demand more accurate and stable process conditions [99Amo], [01Kal].

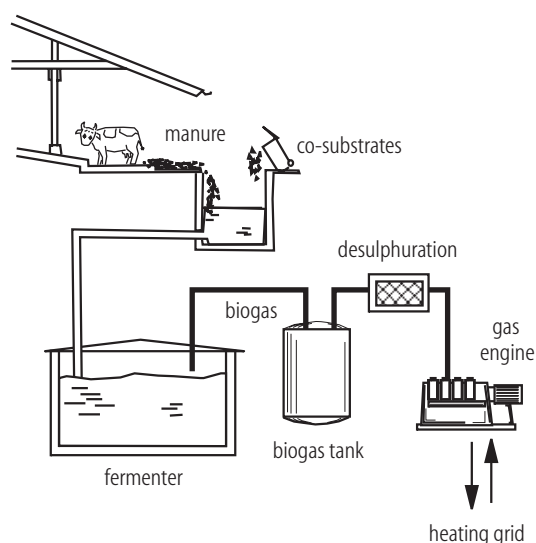
The fermentation process converts only up to 50 percent of the cellulose [98Beh]. As a result, the anaerobic compost contains significant amounts of unconverted cellulose and lignin. The gas yield

$$y_{\text{CH}_4} = \frac{\dot{V}_{\text{CH}_4}}{\dot{m}_{\text{ODM}}} = \frac{\dot{V}_{\text{CH}_4}}{x_{\text{ODM}} \cdot \dot{m}_{\text{Sub}}} \quad (5.2.15)$$

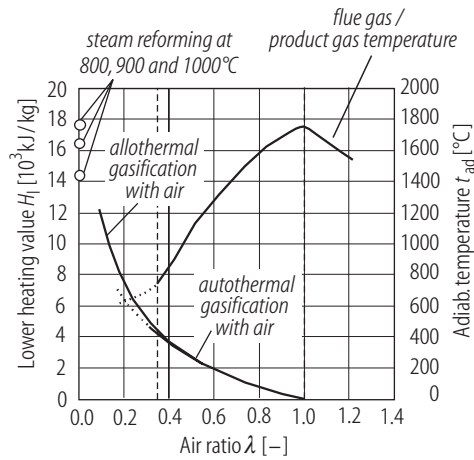
designates the amount of methane gas  $\dot{V}_{\text{CH}_4}$  in [m<sup>3</sup>/s] produced from an organic dry material mass flow  $\dot{m}_{\text{ODM}}$  in [kg/s] and thus the efficiency of the fermentation process. Values for the proportion of organic material  $x_{\text{ODM}}$  of the dry substrate mass flow  $\dot{m}_{\text{Sub}}$  in [kg/s] of are given in [Table 5.2.8](#).

### 5.2.5.3 Thermal gasification

Thermal gasification of organic residues and biomass basically corresponds to coal gasification. The main difference to the gasification of coal is a significantly higher proportion of volatile components of biomass, which produces a significantly higher tar content. The fuel gas contains H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> and a certain amount of higher hydrocarbons and unconverted tars.



**Fig. 5.2.13.** Process scheme for typical digestion plants with gas engine.



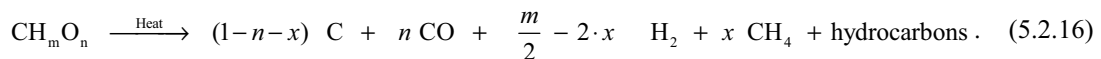
**Fig. 5.2.14.** Influence of the gasification temperature on the lower heating value  $H_1$  of the product gas (gasification of wood chips with  $w = 20\%$ ).

Autothermal gasifiers are normally air-blown gasifiers. Reducing the air ratio  $\lambda$  to values between 0.2 and 0.6 leads to an incomplete combustion, an enhanced formation of carbon monoxide and increased heating values. The incomplete combustion results in lower temperatures and reduced conversion rates.

Steam reforming provides highest heating values (see Fig. 5.2.14). The equilibrium composition depends on the pressure, temperature, fuel and the gasification agent, but the final gas composition mainly depends on reaction kinetics, i.e. on the residence time in the reactor and the activity of the used catalysts.

Thermal conversion of the biomass takes place in three steps, namely fuel drying, pyrolysis and the actual gasification. The slowest and thus speed-determining step is the drying of the fuel particles. Due to the low heat conductance of the fuel particles, the heating up of the fuel occurs very slowly. Evaporation of the water and its diffusion to the particle surface delays the reaction rate, too.

Pyrolysis, an outgasing of volatile constituents, starts with approx. 250°C. It begins with the depolymerisation of large molecule chains and a formation of low-molecular hydrocarbons. Outgasing of these hydrocarbons, in particular methane and other low-molecular species, starts above approx. 350°C. Temperatures above 600°C finally lead to the cracking of the lignin structure. Thermal cracking predominantly produces aromatic hydrocarbons like benzene, toluene, naphthalene and higher hydrocarbons, the main components of the so-called tar [01Sch]. Thus, the pyrolysis gas contains carbon monoxide (CO), hydrogen ( $H_2$ ), methane ( $CH_4$ ) and higher hydrocarbons. Fixed carbon remains as charcoal:



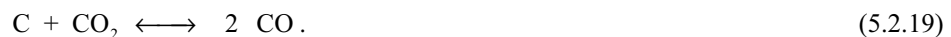
The actual gasification reactions require temperatures above 700°C for achieving sufficiently high reaction rates. One thereby differentiates between heterogeneous (gasification of fixed carbon) and homogeneous gasification reactions (conversion of gaseous carbon monoxide and hydrocarbons). Fixed carbon (charcoal) partially oxidizes and forms carbon monoxide

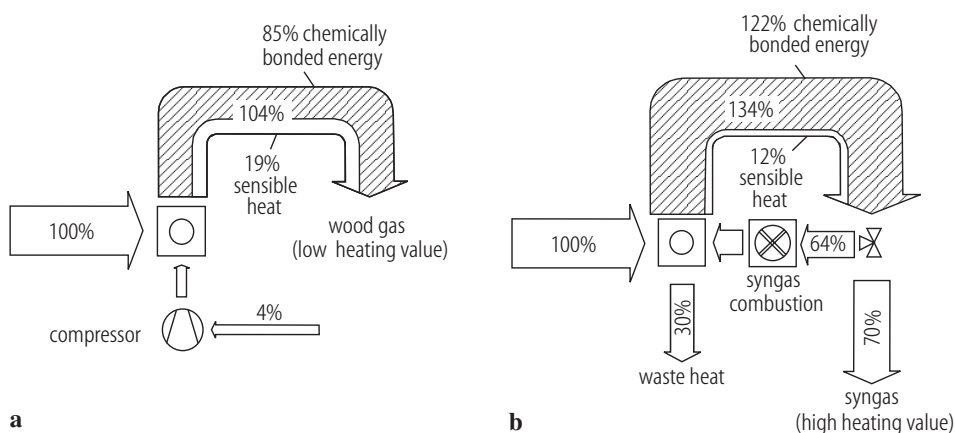


Additional CO and  $H_2$  develop from the reaction with water vapor (heterogeneous steam carbon reaction),



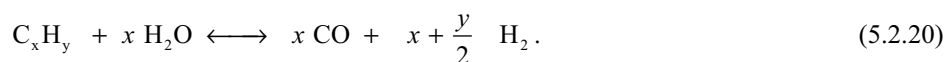
and carbon dioxide according to the “Boudouard equilibrium”:





**Fig. 5.2.15.** Energy balance for (a) autothermal and (b) allothermal gasification.

Water vapor plays the main role in homogeneous gasification reactions. Hydrocarbons and tars are either partially oxidized or form CO and H<sub>2</sub> with water vapor (“reforming”):



Essential for achieving a high hydrogen content are the reforming of methane,



and the “shift reaction”



The theoretically achievable gas composition depends on the thermodynamic equilibria of these reactions and therefore on the reaction conditions (pressure, temperature, see Fig. 5.2.18).

The fuel composition and moisture determine the energy demand for the endothermic reactions. It amounts up to 30-35 % of the total energy input for allothermal gasification (see Fig. 5.2.15). This heat demand and the waste heat of the heat source significantly reduce the cold gas efficiency of allothermal gasifiers ([Table 5.2.15](#)).

#### 5.2.5.4 Autothermal gasification

Autothermal gasifiers provide the energy for the endothermic reactions by means of partial oxidation within the gasification reactor. The product gas contains flue gas in this case and – in case that air is used as gasification agent - large quantities of nitrogen. This so called “autothermal gasification” provides only low calorific gases with heating values below 6000 kJ/kg for air-blown gasifiers and below 11000 kJ/kg for gasification with pure oxygen.

Small-scale gasification systems are usually autothermal, atmospheric fixed bed reactors aiming at the combination with cold gas filtering (see [Sect. 5.2.5.6](#)) and internal combustion engines. Such up-draft (counter current) or down-draft (co-current) gasifiers have been tested in various versions for many decades without significant success. The main dilemma is still the tar problem, which inhibits a successful implementation of autothermal gasification systems with internal combustion engines. Hydrocarbons and

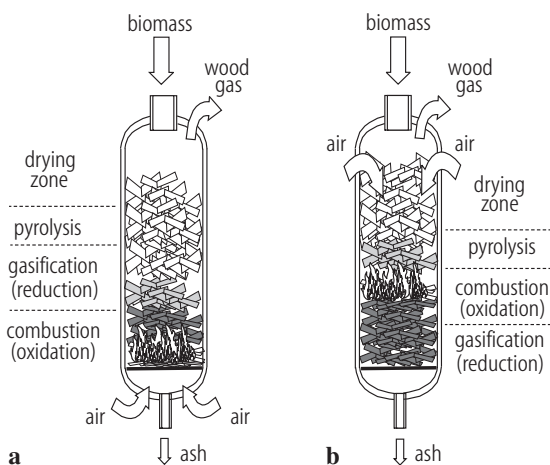
tars condense at temperatures below 200–250°C forming tar layers in the piping or in the engine. Conventional internal combustion engines require fuel gas inlet temperatures below 100°C, whereby the condensation of the tars cannot be avoided. Engine manufacturers specify tar contents below 10 or 100 mg/m<sup>3</sup>.

Small-scale air-blown fixed bed gasifiers combined with gas engines have been quite common in motor vehicles during the Second World War. A high tar load limited the availability of the vehicles and allowed only short-term operation. These gasifiers were up-draft (counter current) gasifiers (Fig. 5.2.16a). The gas flow first passes the combustion zone and then the gasification, pyrolysis and drying zone. The hot flue gas transfers heat effectively from the combustion to the gasification zone. Regrettably, the gas passes the pyrolysis zone immediately before leaving the reactor. Thus the tar load exceeds several thousand mg/m<sup>3</sup>. Down-draft (co-current) gasifiers (Fig. 5.2.16b) produce gases with much lower tar load. Tars and hydrocarbons from the pyrolysis zone have to pass the combustion and gasification zone. This concept allows reducing the tar load to less than 100 mg/m<sup>3</sup> for small units. The poor heat transfer from the combustion zone into the pyrolysis and drying zone results in rather large and more costly reactors.

Alternatives to internal combustion engines are gas turbines with hot gas cleaning, based upon the idea of keeping tars in the gaseous phase. A main inherent problem of gas turbines systems with air-blown gasification is that these systems require pressurized gasifiers and that the low heating value demands gas turbines with specially adapted combustors. Another important problem is that the power consumption for air compression drastically affects the process efficiency. Gasification plants with gas turbines are commonly large-scale units with bubbling or circulating fluidized bed gasifiers, in particular integrated gasification combined cycle (IGCC) power plants like the Bioflow-IGCC plant in Värnamo, Sweden [98Sta]. Entrained flow gasifiers require pure oxygen, which means costly air fractioning plants. They are therefore only feasible for very large coal fired IGCC plants.

#### 5.2.5.5 Allothermal gasification

Allothermal gasification necessitates bringing heat from an external heat source into the gasifier in order to avoid a dilution of the produced gas and to realize lower heating values  $H_l$  of above 10 MJ/kg. The main technical challenge for allothermal gasifiers is the heat transfer into the fluidized bed. Allothermal gasification and steam reforming require transferring up to 30 percent of the total thermal input into the gasifier by means of external heating. This demands large heat fluxes at high temperatures and reduces the cold gas efficiency of the gasification process.



**Fig. 5.2.16.** Fixed bed gasifier systems. **(a)** Up-draft gasifier. **(b)** Down-draft gasifier.

Allothermal gasifiers provide heating values up to 18000 kJ/kg or 12000 kJ/m<sup>3</sup>, a high hydrogen content and low tar rates. Two principal concepts are discussed to solve the heat transfer problem:

- The first idea is to circulate hot solids (i.e. fluidized bed material) from a combustion zone to a gasifier zone. The most popular concept is the Batelle gasifier (Vermont Gasification Project, see Fig. 5.2.17) [99Ans]. It consists of two connected fluidized bed reactors – one for gasification and one for combustion. The bed material circulates between the combustion chamber and the gasifier to transfer heat without mixing of flue gas and product gas. TU Vienna's "Fast Internal Circulating Gasifier" [97Hof] follows the same principle. DMT suggests to circulate hot steel balls between a pyrolysis chamber and a furnace combined with an external reformer ("Staged Reforming") in order to solve the heat transfer problem [01Kal].
- A second concept suggests indirectly heated fluidized bed gasifier systems with integrated heat exchanger tubes. The main problem with indirect heating is the generation of sufficiently high heat fluxes of the heat carrier gas, i.e. flue gas, into the fluidized bed. The heat transfer between the fluidized bed and the heat exchanger tubes is excellent, but the inner heat transfer between the tube wall and the gaseous heat carrier is normally quite poor. The DMT modification of the classical Winkler gasifier uses pressurized hot helium as heat carrier because of its excellent heat transfer characteristics [79Hee]. [99Chu] suggests to increase the heating value of the product gas additionally by pre-heating the fluidizing gas (steam/flue gas mixture) to high temperatures and to separate the steam content of the product gas in an external condenser. Usage of common flue gas as heat carrier demands either extremely high temperatures or special concepts to enhance the gas – solid heat transfer inside the heat exchanger tubes. A quite promising concept is to use pulse combustors to enhance this heat transfer [97Lar].

Existing allothermal systems are only applicable for large units. Especially systems with circulation of hot solids are more complicated than indirectly heated systems. A new approach, the so-called heat-pipe reformer, aims at using heat-pipes to transfer heat from an external fluidized bed combustor into a fluidized bed gasifier. Sodium acts as a heat carrier and as working liquid inside the heat pipe. Thus evaporation and condensation determine the heat exchange resistances inside the tubes and enable significantly higher heat transfer rates [01Sch]. An extraordinary efficient concept to provide a particularly high H<sub>2</sub>-content in the syngas is the Absorption-Enhanced-Reforming (AER) process [04Spe]. A CO<sub>2</sub>-absorbent in the fluidized bed reformer removes CO<sub>2</sub> from the product gas and shifts the chemical equilibrium towards H<sub>2</sub>, away from CO, hydrocarbons, soot and tar. The process thus yields a gas containing > 80 vol-% H<sub>2</sub>.

The substantial disadvantage of allothermal gasification in large-scale IGCC installations arises from the fact that a part of the fuel gas must be branched off before reaching the gas turbine in order to supply the heat for the gasification process. Allothermal gasification offers substantial advantages with high temperature fuel cells. Using the waste heat of a solid oxide fuel cell (SOFC) for indirect heating of an allothermal gasifier allows an internal recuperation of heat, leading to highest cycle efficiencies [05Kar].

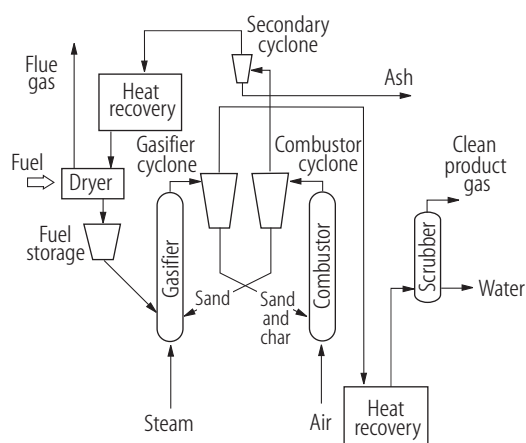
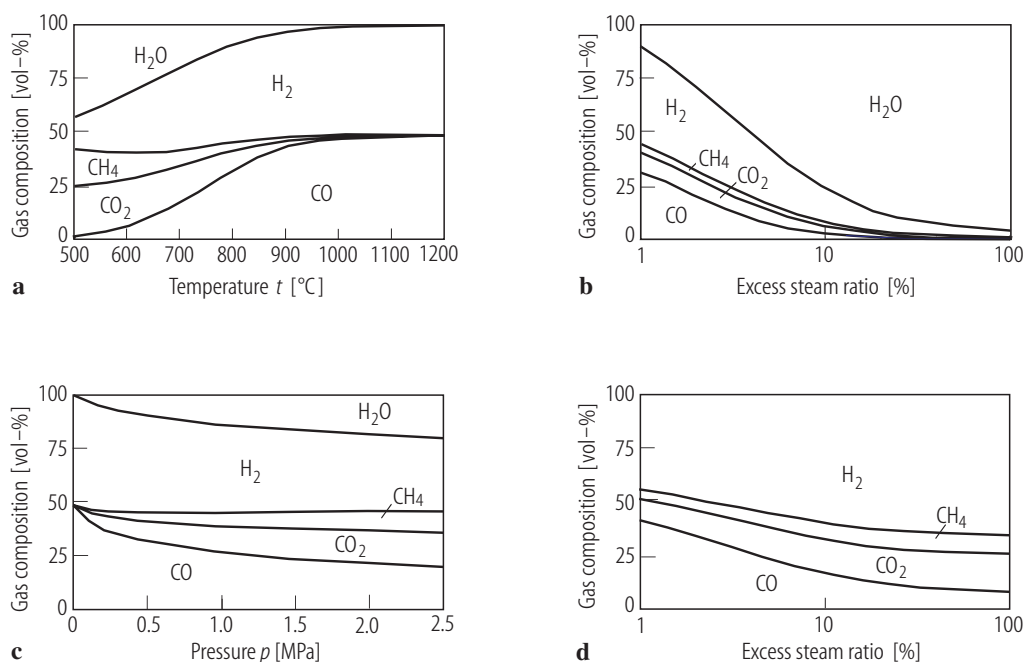


Fig. 5.2.17. Batelle gasifier, Vermont Gasification Project.



**Fig. 5.2.18.** Theoretically achievable gas composition (thermodynamical equilibria) for steam reforming of wood chips with different reaction conditions. **(a)** Temperature influence (atmospheric pressure, without excess steam). **(b)** Pressure influence (800 °C, without excess steam). **(c)** Influence of the excess steam ratio (800 °C, atmospheric pressure), without product gas drying. **(d)** Influence of the excess steam ratio (800 °C, atmospheric pressure), with product gas drying.

### 5.2.5.6 Gas cleaning and process integration

Gas cleaning is a key technology for upcoming systems with integrated gasification. Applications with internal combustion engines have to focus mainly on tar removal and thus on scrubbing technologies and catalyst design. Current research aims at reducing the tar content by means of catalytic cracking and gas scrubbing, either with aqueous or organic solvents [01Sch, 01Kal]. Scrubbing with water produces highly loaded wastewater, which causes substantial disposal problems. Furthermore, cooling of the product gas for the gas cleaning strongly affects the system efficiency and condensing tars cause severe technological and economical problems. Hence, minimizing the amount of wastewater is essential for the economic operation of such systems. A main advantage of organic solvents is the option to dispose the polluted solvent in the gasifier. Biogeneous solvents such as rapeseed oil or rape methyl ester (RME) consequently provide ecological sustainable systems.

Hot gas filtering technologies offer new perspectives for innovative concepts with gas turbines and high temperature fuel cells. Filtering at high temperatures avoids quenching of the hot product gas and thus enhances the system's performance and efficiency.

A main problem for gas turbine systems are the high dust loads of the product gas, which might create deposits on the turbine blades. High temperature gas cleaning for gas turbines is already quite well developed. Ceramic filter systems are available for a temperature range up to 600 °C. Commercial systems, for example at the IGCC plant in Värnamo, Sweden [98Sta], operate at 350–400 °C in order to guarantee the condensation and removal of alkali vapors at fine dust particles and due to the maximum operation temperature of the gas turbine control valves.

For fuel cell applications special regard has to be spent on the removal of hydrogen sulfur, dust, hydrocarbons and tars. Hydrogen sulfur reduces the catalyst activity at the anode and has to be removed.

High temperature desulphuration processes are available for temperatures up to 450°C [98Mei]. High temperature fuel cells like molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) allow internal reforming of hydrocarbons and tars. This internal reforming might cause carbon deposits at the anode. Investigation of the mechanism and preventing carbon formation caused by internal reforming of methane is a major focus of recent SOFC research activities worldwide. Especially aromatic hydrocarbons and tars favor the development of carbon deposits. The carbon formation depends on the operating conditions like temperature, steam content and tar composition. The allowable tar content in the fuel gas is one of the key questions for upcoming fuel cell concepts with integrated biomass gasification.



## 5.2.6 Tables

### 5.2.6.1 Elementary composition and heating values

Given data for biomass composition should be used carefully because the biomass composition varies largely due to the origin of a plant, different fertilization procedures and different chemical analyzing methods. A large data base with more detailed information (statistics, variation, ash composition) is available online at [[98Rei](#)].

<i>c</i>	Mass fraction carbon of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>h</i>	Mass fraction hydrogen of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>o</i>	Mass fraction oxygen of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>n</i>	Mass fraction nitrogen of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>s</i>	Mass fraction sulfur of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>cl</i>	Mass fraction chlorine of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>a</i>	Mass fraction ash of the <i>dry</i> biomass (“dry base”) in [wt-%];
<i>w</i>	Water content of the <i>wet</i> biomass (“as received”) in [kg <sub>water</sub> /kg <sub>wet biomass</sub> ];
<i>H<sub>l,db</sub></i>	Lower heating value (LHV) of the <i>dry</i> biomass (“dry base”) in [kJ/kg];
<i>H<sub>h</sub></i>	Higher heating value (HHV) in [kJ/kg].

#### 5.2.6.1.1 Woody biomass

**Table 5.2.1.** Composition and heating values of woody biomass.

Biomass	<i>lat:</i> Latin term <i>ger:</i> German term <i>fr:</i> French term	<i>c</i>	<i>h</i>	<i>o</i>	<i>n</i>	<i>s</i>	<i>cl</i>	<i>a</i>	<i>w</i>	<i>H</i> <sub>l,db</sub> [kJ/kg]	<i>H</i> <sub>h,db</sub> [kJ/kg]	Lit.
					[% ab]				[% ar]			
ailanthus	<i>lat:</i> <i>Ailanthus altissima</i> <i>ger:</i> <i>fr:</i>	49.5	6.2	42.3	0.3			1.7			19000	<a href="#">98Rei</a>
alder, log	<i>lat:</i> <i>Alnus glutinosa</i> <i>ger:</i> <i>Erle</i> <i>fr:</i> <i>aulne</i>									17978		<a href="#">98Rei</a>
almond	<i>lat:</i> <i>Prunus amygdalus</i>	48.55	5.33	40.74	0.81	0.01	0.06	4.5			19136	<a href="#">87Dom</a>
almond, hulls	<i>ger:</i> <i>Mandel</i>	47.12	5.97	40.07	1.19	0.06	0.04	5.55			18872	<a href="#">98Rei</a>
almond, shells	<i>fr:</i> <i>amandes</i>	48.04	5.79	42.32	0.72	0.04	0.03	3.06			19096	<a href="#">98Rei</a> <sup>1</sup>
almond shells		49.8	6.0	42.3	0.00	0.00	0.00	1.16	8.8			<a href="#">97Rap</a>
ash, log	<i>lat:</i> <i>Fraxinus sp</i>									17815		<a href="#">98Rei</a>
ash, white ash	<i>ger:</i> <i>Esche</i> <i>fr:</i> <i>frêne</i>	49.73	6.93	43.04				0.3		19200	20800	<a href="#">98Rei</a>
aspen wood	<i>lat:</i> <i>ger:</i> <i>Espenholz</i> ( <i>Zitterpappel</i> ) <i>fr:</i> <i>bois de tremble</i>	51.6	6.3	39.5	0.47	0.02	0.00	2.15				<a href="#">97Bla1</a>
bark	<i>lat:</i>	50.4	5.64	40.06	0.55	0.03	0.02	3.3		15500	16900	<a href="#">98Rei</a>
bark	<i>ger:</i> <i>Rinde</i>	52.5	5.7	41.3	0.4	0.03	0.02					<a href="#">93Nor</a>
bark, mixed	<i>fr:</i> <i>écorce</i>	48.83	4.6	41.04	0.33	0.08	0.04	5.08		19023	19936	<a href="#">98Rei</a>
beech	<i>lat:</i> <i>Fagus sp</i>	49.69	6.07	42.8	0.41	0.02		1.01		17547	19507	<a href="#">98Rei</a> <sup>1</sup>
beech, chips	<i>ger:</i> <i>Buche</i>	48.26	5.82	45.06	0.22	0.03		0.61		17388	18659	<a href="#">98Rei</a>
beech, red beech, log	<i>fr:</i> <i>hêtre</i>	48.4	6.2							17530		<a href="#">98Rei</a>
beech, with bark		47.9	6.2	44.7	0.22	0.02	0.01	0.50		18400		<a href="#">00Har</a>

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
					[% db]				[% ar]			
birch	lat: <i>Betula sp.</i>	49.85	6.72	42.54	0.1	0.5		0.29		18700	19965	<a href="#">98Rei<sup>1</sup></a>
birch	ger: <i>Birke</i>	49.0	6.1	44.5	0.1	<0.01		0.4		19300		<a href="#">99Che</a>
birch ,log	fr: <i>bouleau</i>	48.5	5.9							18866		<a href="#">98Rei</a>
birch and maple, chips		50.48	5.94	42.8	0.16	0.05	0.03	0.54			19619	<a href="#">98Rei</a>
cherry tree	lat: <i>Prunus avium</i>	49.52	5.81	42.97	0.31	0.02	0.02	1.35			19565	<a href="#">98Rei</a>
cherry tree, log	ger: <i>Kirschbaum</i> fr: <i>cerisier</i>	49.7	6							17850		<a href="#">98Rei</a>
chestnut, log	lat: <i>Castanea sativa</i> ger: <i>Kastanie</i> fr: <i>marron</i>									18840		<a href="#">98Rei</a>
cotton	lat: <i>Gossypium sp</i>	39.53	5.1	41.54	1.22	0.49		12.12			17137	<a href="#">98Rei<sup>1</sup></a>
cotton, husks	ger: <i>Baumwolle</i>	48.48	6.12	41.48	0.97	0.1		2.85			19393	<a href="#">98Rei</a>
cotton, cotton waste	fr: <i>coton</i>	49.04	4.7	35.0	1.45	0.36		9.36			17964	<a href="#">98Rei</a>
cotton stalks, Greece		44.3	5.3	44.50	1.2	0.8	0.1	3.7		16838		<a href="#">96Gad</a>
cotton stalks, Austr.		45.6	5.2	41.5	1.4	0.6	0.2	5.3		16847		<a href="#">96Gad</a>
douglas fir	lat: <i>Pseudotsuga</i>	52.3	6.3	40.32	0.1			0.98		19700	21062	<a href="#">98Rei<sup>1</sup></a>
douglas fir, bark		56.2	5.9	36.7				1.2			22107	<a href="#">98Rei<sup>1</sup></a>
douglas fir, log	ger: <i>Douglasie</i> fr: <i>pin d'Oregon</i>									19180		<a href="#">98Rei</a>
elm	lat: <i>Ulmus sp</i>	50.35	6.57	42.34				0.74		19000	20500	<a href="#">98Rei</a>
elm, stick	ger: <i>Ulme</i> fr: <i>orme</i>									18500		<a href="#">98Rei</a>
eucalyptus	lat: <i>Eucalyptus sp</i>	48.5	5.89	44.43	0.28	0.01	0.14	0.75			19355	<a href="#">98Rei</a>
eucalyptus /chips	ger: <i>Eukalyptus</i> fr: <i>eucalyptus</i>	50.43	6.01	41.53	0.17	0.08	0.02	1.76			19611	<a href="#">98Rei</a>
fir	lat: <i>Abies sp</i>	50.35	6.14	43.18	0.05			0.28		19084	21101	<a href="#">98Rei<sup>1</sup></a>
fir, whole tree	ger: <i>Tanne</i>	48.52	5.81	44.66	0.25	0.04		0.72		17649	18901	<a href="#">98Rei</a>
fir, white fir	fr: <i>sapin</i>	49	5.98	43.91	0.05	0.01	0.01	1.04			19973	<a href="#">98Rei<sup>1</sup></a>
fir; fir char, bark		49.9	4	24.5	0.1	0.1		21.4			19221	<a href="#">98Rei<sup>1</sup></a>
hazelnut, seedcoat	lat: <i>Corylus avellana</i>	51	5.4	40.5	1.3			1.8			19300	<a href="#">98Rei</a>
hazelnut, shell	ger: <i>Haselnuß</i> fr: <i>Noisette</i>	52.9	5.6	38.7	1.4			1.4			19300	<a href="#">98Rei</a>
hemlock fir	lat: <i>Tsuga heterophylla</i>	50.4	5.8	41.4	0.1	0.1		2.2		18800	20100	<a href="#">98Rei</a>
hemlock fir; west- ern hemlock fir	ger: <i>Schierling</i> fr: <i>ciguë</i>	50.4	5.8	41.4	0.1	0.1		2.2			20059	<a href="#">98Rei</a>
hickory	lat: <i>Carya sp</i> ger: <i>Hickorynusbaum</i> fr: <i>hickory</i>	49.7	6.5	43.1				0.7		18700	20112	<a href="#">98Rei<sup>1</sup></a>
larch, log	lat: <i>Larix sp</i>	52.1	6.4							18715		<a href="#">98Rei</a>
larch, chips	ger: <i>Lärche</i> fr: <i>mélèze</i>	50.9	6.4	42				0.7			17581	<a href="#">98Rei</a>
macadamia	lat: <i>Macadamia sp</i> ger: <i>Macadamianussb.</i> fr: <i></i>	54.41	4.99	39.67	0.36	0.01		0.56			21034	<a href="#">98Rei</a>
maple	lat: <i>Acer sp</i>	50.6	6	41.7	0.3			1.4		18600	20057	<a href="#">98Rei<sup>1</sup></a>
maple, chips	ger: <i>Ahorn</i> fr: <i>érable</i>	49.54	6	43.84	0.1	0.02		0.5			19328	<a href="#">98Rei</a>
oak	lat: <i>Quercus sp</i>	49.89	5.98	42.57	0.21	0.05	0.01	1.29			19992	<a href="#">98Rei<sup>1</sup></a>
oak, chips	ger: <i>Eiche</i>	48.99	5.93	42.58	0.33	0.05	0.02	2.1			19355	<a href="#">98Rei</a>
oak, log	fr: <i>chêne</i>	49.5	6							17769		<a href="#">98Rei</a>
oak, American red oak		49.49	6.62	43.74				0.15		18700	20200	<a href="#">98Rei</a>
oak, black oak; American		48.78	6.09	44.98				0.15		17700	19100	<a href="#">98Rei</a>

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{i,db}$ [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
					[% ab]				[% ar]			
oak, oak charcoal; 1060F		64.6	2.1	15.5	0.4	0.1		17.3			23061	<a href="#">98Rei</a>
oak, oak charcoal; 820F-1185F		67.7	2.4	14.4	0.4	0.2		14.9			24806	<a href="#">98Rei</a>
oak, red oak, chips		49.74	5.96	42.56	0.23	0.01	0.03	1.47			19540	<a href="#">98Rei</a>
oak, tan oak		47.81	5.93	44.12	0.12	0.01	0.01	2			18951	<a href="#">87Dom</a>
oak, white oak		49.48	5.38	43.13	0.35	0.01	0.04	1.61			19442	<a href="#">87Dom</a>
oak, white oak; American		50.44	6.59	42.73				0.24		19000	20500	<a href="#">98Rei</a>
oak; Alabama, wood waste		49.5	5.7	41.3	0.2			3.3			19235	<a href="#">98Rei</a>
olive wood	lat: ger: Olivenholz fr: bois olive	45.1	6.1	39.7	0.00	0.00	0.00	1.06	15.5	18160		<a href="#">00Zab</a>
pine	lat: <i>Pinus sp</i>	52.13	6.36	41.01	0.07	0.05	0.01	0.37			21323	<a href="#">98Rei</a> <sup>1</sup>
pine, bark	ger: <i>Kiefer</i>	52.3	5.8	38.76	0.2	0.03	0.01	2.9		19700	20431	<a href="#">98Rei</a> <sup>1</sup>
pine, chips	fr: <i>pin</i>	51.85	6.21	41.23	0.13	0.14	0.02	0.42			20440	<a href="#">98Rei</a>
pine, log										18580		<a href="#">98Rei</a>
pine, sawdust		52.49	6.24	40.45	0.15	0.03	0.04	0.6		19030	20846	<a href="#">98Rei</a> <sup>1</sup>
pine, eastern white pine		52.55	6.08	41.25				0.12		19300	20700	<a href="#">98Rei</a>
pine, lodgepole		53.6	6.2	35.41	0.1			4.69			18867	<a href="#">98Rei</a>
pine residues												
pine, pitch pine		59	7.19	32.68				1.13		24700	26400	<a href="#">98Rei</a>
pine, yellow pine		52.6	7.02	40.07				0.31		20800	22400	<a href="#">98Rei</a>
pine; Corsican		50.1	6	38.17	0.1			5.63			18243	<a href="#">98Rei</a>
pine; mixed		48.4	6.31	44.23	0.21	0.03		0.82			19147	<a href="#">98Rei</a>
pistachio	lat: <i>Pistacia vera</i>	48.79	5.91	43.41	0.56	0.01	0.04	1.28			19282	<a href="#">87Dom</a>
pistachio, shell	ger: <i>Pistazie</i> fr: <i>pistaches</i>	47.66	4.55	45.79	0.57	0.18	0.01	1.24			19663	<a href="#">98Rei</a>
poplar	lat: <i>Populus sp</i>	49.93	6.1	42.26	0.29	0.05	0.01	1.36		19400	20293	<a href="#">98Rei</a> <sup>1</sup>
poplar	ger: <i>Pappel</i>	49.1	6.0	44.3	0.48	0.01	0.10	0.00	50.0	24400		<a href="#">97Faa</a>
poplar (with bark)	fr: <i>peuplier</i>	47.5	6.2	43.1	0.42	0.03	0.004	1.90		18500		<a href="#">00Har</a>
poplar, black										17288		<a href="#">98Rei</a>
poplar, log												
robinia, log	lat: <i>Robinia sp</i>	49.2	5.9							17828		<a href="#">98Rei</a>
sequoia	lat: <i>Sequoiadendron</i>	53.5	5.9	40.3	0.1			0.2		19800	21100	<a href="#">98Rei</a>
sequoia, redwood	ger: <i>Mammuthbaum</i>	53.5	5.9	40.15	0.1	0.03	0.02	0.3			21036	<a href="#">98Rei</a> <sup>1</sup>
sequoia	fr: <i>séquoia</i>											
sequoia, redwood		75.6	3.3	18.4	0.2	0.2		2.3			28855	<a href="#">98Rei</a>
sequoia charcoal; 790F-1020F												
sequoia, redwood		78.8	3.5	13.2	0.2	0.2		4.1			30484	<a href="#">98Rei</a>
sequoia charcoal; 860F-1725F												
spruce	lat: <i>Picea abies</i>	51.06	5.75	42.29	0.11	0.01	0.01	0.77		18806	20058	<a href="#">98Rei</a> <sup>1</sup>
spruce	ger: <i>Fichte</i>	50.3	5.8	43.5	0.4	0.04	0.02			18700		<a href="#">96Gad</a>
spruce, bark	fr: <i>sapin rouge</i>	52.27	5.18	39.49	0.45	0.04	0.02	2.55		18966	20525	<a href="#">98Rei</a> <sup>1</sup>
spruce, chips	fr: <i>épicéa</i>	49.53	5.77	44.01	0.19	0.01	0.01	0.48		17161	18803	<a href="#">98Rei</a> <sup>1</sup>
spruce, log		50.1	6							19160		<a href="#">98Rei</a>
spruce, bark		49.5	5.5	40.8	0.46	0.09	0.02	3.80		19.2		<a href="#">96Gad</a>
spruce, with bark		49.7	6.3	42.3	0.13	0.02	0.01	0.60	50	18.8		<a href="#">00Har</a>

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	H <sub>i,db</sub> [kJ/kg]	H <sub>h,db</sub> [kJ/kg]	Lit.
					[% ab]				[% ar]			
spruce; sitka		50.2	5.9	41.14	0.2			2.56			18798	<a href="#">98Rei</a>
spruce, whole tree												
spruce; thinning residues, whole tree		48.46	5.84	44.88	0.21	0.01		0.6		17508	18784	<a href="#">98Rei</a>
spruce; thinning residues without needles, whole tree		48.05	5.81	45.24	0.08	0.03		0.79		17302	18572	<a href="#">98Rei</a>
spruce + beech		49.73	5.95	43.4	0.22	0.02	0.01	0.67		18248	19525	<a href="#">98Rei</a> <sup>1</sup>
walnut	lat: <i>Juglans regia</i>	49.98	5.71	43.35	0.21	0.01	0.03	0.71			20203	<a href="#">87Dom</a>
walnut, black	ger: <i>Walnußbaum</i>	49.8	5.82	43.25	0.22	0.01	0.05	0.85			19852	<a href="#">87Dom</a>
walnut	fr: <i>noix</i>											
walnut, English		49.72	5.63	43.14	0.37	0.01	0.06	1.07			19652	<a href="#">87Dom</a>
walnut												
willow	lat: <i>Salix sp</i>	47.66	5.72	44.7	0.43	0.03	0.01	1.45		18420	19153	<a href="#">98Rei</a> <sup>1</sup>
willow	ger: <i>Weide</i>	48.1	6.2	0.4	43.9		0.036	2.5		19200		<a href="#">99Che</a>
willow	fr: <i>saule</i>		48.4	5.9	45.1	0.5	0.06	0.01			18.37	<a href="#">93Nor</a>
willow			49.7	6.2	41.4	0.6	0.00	0.00	2.1		18.41	<a href="#">96Gad</a>
white willow										17850		<a href="#">98Rei</a>
willow, with bark		47.1	6.1	43.2	0.54	0.05	0.01	2.20		18400		<a href="#">00Har</a>
wood		51.38	5.88	42.22	0.1	0.1	0.02	0.3			20478	<a href="#">98Rei</a>
wood		50.9	6.3	42.1	0.1	0.10	0.00	0.5		18980		<a href="#">96Gad</a>
wood		51.1	6.3	41.4	0.4	0.03		0.8		18770		<a href="#">96Gad</a>
wood, bark		53.1	6.1	39	0.2			1.6			20500	<a href="#">98Rei</a>
wood, briquette		50.98	6.2	42.23	0.18	0.01		0.4		18816	20174	<a href="#">98Rei</a> <sup>1</sup>
wood, chips		50.63	6.02	41.52	0.35	0.03	0.02	1.43		19152	20263	<a href="#">98Rei</a> <sup>1</sup>
wood waste, compost, bark		49.84	5.24	38.64	0.37	0.03	0.01	5.87		18678	19831	<a href="#">98Rei</a>
wood waste, driftwood		30.4	3.6		0.5		0.02			18500	19600	<a href="#">98Rei</a>
wood waste, forest residue; Finnish, chips		51.3	6.1	40.84	0.4	0.02	0.01	1.33		19340	20670	<a href="#">96Wil</a>
wood waste, forest residue; Swedish, chips		51	5.8	38.2	0.9	0.04	0.01	4.05		19270	20540	<a href="#">96Wil</a>
wood waste, mixed softwood residues		52.73	7.1	36.42	0.2	0.4		3.15			18787	<a href="#">98Rei</a>
wood, compressed wood briquettes, pellets		49	6	44.4		0.1		0.5		18000		<a href="#">98Rei</a>
wood, forest wood, chips + bark		48.94	5.77	42.96	0.18	0.02		2.13		17211	18537	<a href="#">98Rei</a>
wood, forest wood chips, whole tree		48.76	5.9	44.35	0.1	0.02		0.87		19661	20771	<a href="#">98Rei</a>
wood, hardwood		47.1	5.52	36.92	0.43	0.07	0.02	9.94			18123	<a href="#">98Rei</a> <sup>1</sup>
wood, hardwood, bark		50.35	5.83	39.62	0.11	0.07	0.03	3.99			19556	<a href="#">98Rei</a>
wood, hardwood, chips		50.48	6.04	42.43	0.17	0.08	0.02	0.78			19526	<a href="#">98Rei</a>
wood, lumped hardwood		49	6	44.6		0.1		0.3		18000		<a href="#">98Rei</a>
wood, lumped softwood		50	6	43.6		0.1		0.3		19000		<a href="#">98Rei</a>
wood, mixed hardwood, chips		50.09	5.94	42.3	0.26	0.05	0.05	1.31			19592	<a href="#">98Rei</a>
wood, mixed wood, chips		49.49	5.82	43.18	0.19	0.05	0.02	1.25			19484	<a href="#">98Rei</a>
wood, plywood scraps		54.74	6.13	37.25	0.31	0.04	0.03	1.5			21370	<a href="#">98Rei</a>
wood, sawdust		49	6	44.4		0.1		0.5		18000	20510	<a href="#">98Rei</a> <sup>1</sup>
wood, sawdust, pellets		47.2	6.5	45.3				1			20510	<a href="#">98Rei</a> <sup>1</sup>
wood, softwood		52.1	6.1	39.9	0.2			1.7			20000	<a href="#">98Rei</a>

<sup>1</sup>) Mean values.

## 5.2.6.1.2 Herbaceous biomass

**Table 5.2.2.** Composition and heating values of herbaceous biomass.

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
		[% <sub>db</sub> ]							[% <sub>ar</sub> ]			
alfalfa	lat: <i>Medicago sativa</i>	45.92	5.21	36.72	2.46	0.18	0.37	9.14		17290	18433	<a href="#">98Rei</a> <sup>1</sup>
alfalfa, stems	ger: <i>Lucern</i> fr:	43.01	5.47	43.52	2.55	0.18	0.46	4.81				<a href="#">98Rei</a>
barley, straw	lat: <i>Hordeum vulgare</i> ger: <i>Gerste</i> fr: <i>orge</i>	42.88	5.53	45.48	0.56	0.25	0.35	4.95			19235	<a href="#">98Rei</a> <sup>1</sup>
barley straw		47.5	5.8	39.2	0.46	0.08	0.40	4.80		17500		<a href="#">00Har</a>
barley, summer		46.86	5.31	40.12	0.73	0.12	0.98	5.88		17400	18568	<a href="#">98Rei</a>
barley, straw												
barley, winter		46.79	5.53	41.94	0.41	0.06	0.41	4.86		17563	18780	<a href="#">98Rei</a>
barley, straw												
barley; Finnish, straw		46.2	5.7	41.27	0.6	0.08	0.27	5.88		17430	18680	<a href="#">96Wil</a>
banagrass		48.1	5.5	41.2	0.60	0.10	0.58	3.94	65.6			<a href="#">97Tur</a>
cane, Italy	lat: <i>Arundo donax</i> ger: fr: <i>canne</i>	47.7	6	41.65	0.5	0.16	0.29	3.7		16750	18060	<a href="#">96Wil</a>
cereals, Austria	lat: <i>Poaceae</i>	45.2	5.1	42.8	1.5	0.1	0.2	5.1		16720	18439	<a href="#">98Rei</a> <sup>1</sup>
cereal	ger: <i>Getreide</i> fr: <i>céréales</i>	47.0	5.3	41.3	0.5	0.07	0.49	5.4				<a href="#">00Har</a>
corn (maize)	lat: <i>Zea mays</i>	44.6	5.4	39.6	0.4	0.05	1.48	8.5				<a href="#">00Har</a>
corn straw (maize)	ger: <i>Mais</i> fr: <i>maïs</i>	45.7	5.3	41.7	0.65	0.12	0.35	6.70		17700		<a href="#">00Har</a>
erica arborea		50.7	6.2	41.6	0.99	0.00	0.00	0.60	26.0			<a href="#">00Zab</a>
flax	lat: <i>Llinum</i>	46.6	5	42.92	0.6	0.16	0.32	4.4		17270	18750	<a href="#">98Rei</a>
flax, shive	<i>usitatissimum</i>	50.3	6.1	41.08	0.6	0.07	0.04	1.81		18860	20190	<a href="#">96Wil</a>
flax, straw	ger: <i>Flachs</i> fr: <i>lin</i>	48.24	5.62	41.23	0.88	0.12	0.23	3.68		18169	19401	<a href="#">98Rei</a> <sup>1</sup>
grass		45.8	5.1	36.2	2.2	0.18	0.88	9.58				<a href="#">00Har</a>
grass, hay		45.1	5.9	38.4	1.26	0.17	0.76	7.10		17100		<a href="#">00Har</a>
grass, field grass	lat: ger: <i>Feldgras</i> fr: <i>herbe de champ</i>	46.31	5.2	35.82	2.37	0.2	0.75	9.35		17249	18412	<a href="#">98Rei</a>
grass, grass straw char		51	3.7	19.7	0.5	0.8		24.3			19314	<a href="#">98Rei</a> <sup>1</sup>
grass, intensive grass	lat: ger: <i>Landschaftsheugras</i> fr:	45.11	4.9	36.81	2.01	0.15	1.09	9.93		17053	18130	<a href="#">98Rei</a>
grass, knotgrass	lat: <i>Paspalum distichum</i> ger: <i>Knöterichgras</i> fr: <i>herbe de renouée</i>	47.07	5.41	39.9	1.08	0.12	0.48	5.94		17305	18495	<a href="#">98Rei</a>
grass, summer switch grass	lat: <i>Panicum virgatum</i> ger:	41.21	5.03	51.07	0.31	0.04	0.01	2.33				<a href="#">98Rei</a>
grass, switch grass	fr:	47.76	5.77	37.91	0.7	0.11	0.09	7.66			18071	<a href="#">98Rei</a>
grass, switch grass; Dakota		41.45	5.02	49.63	0.65	0.07	0.03	3.15				<a href="#">98Rei</a>
hay		45.5	6.1	39.2	1.14	0.16	0.31	5.70		17400		<a href="#">00Har</a>

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
		[% <sub>db</sub> ]							[% <sub>ar</sub> ]			
hemp	lat: <i>Cannabis sativa</i>	45.12	5.14	43.21	0.85	0.08	0.22	5.38		16743	17917	<a href="#">98Rei<sup>1</sup></a>
hemp	ger: <i>Hanf</i>		44.8	5.2	42.0	1.0	0.07	0.16	6.86			<a href="#">00Har</a>
hemp straw	fr: <i>chanvre</i>	46.1	5.9	39.2	0.74	0.10	0.20	4.80		17000		<a href="#">00Har</a>
lupine	lat: <i>Lupinus sp</i> ger: <i>Lupine</i> fr: <i>lupin</i>	41.22	4.39	37.5	1.25	0.33	0.57	14.74		16064	17030	<a href="#">98Rei</a>
maize (corn), stems	lat: <i>Zea mays</i> ger: <i>Mais</i>	47.09	5.97	44.42	0.74		0.05	1.73			4377	<a href="#">98Rei</a>
maize, straw	fr: <i>maïs</i>	46.91	5.47	42.78	0.56	0.04	0.25	3.99		17271	18474	<a href="#">98Rei</a>
maize, whole crop		44.62	5.37	39.57	0.41	0.05	1.48	8.5		16509	17690	<a href="#">98Rei</a>
maize, corncob		47.79	5.64	44.71	0.44	0.01	0.21	1.2			17895	<a href="#">98Rei<sup>1</sup></a>
miscanthus	lat: <i>Miscanthus sp</i>	47.5	6.2	40.7	0.73	0.15	0.22	3.90		17800		<a href="#">00Har</a>
miscanthus	ger: <i>Chinaschilf</i>	47.9	6.3	43.8	0.7	0.11		2.8		17000		<a href="#">99Che</a>
miscanthus	fr:	48.0	5.4	43.0	0.4	0.1	0.2	2.7		18070	18875	<a href="#">98Rei<sup>1</sup></a>
miscanthus; three annual		48.49	5.42	41.81	0.56	0.05	0.21	3.46		17970	19165	<a href="#">98Rei</a>
miscanthus; two annual		47.67	5.46	41.38	0.49	0.06	0.25	4.69		17856	19063	<a href="#">98Rei</a>
oats, straw	lat: <i>Avena sativa</i> ger: <i>Hafer</i> fr: <i>avoine</i>	46.32	4.9	38.66	0.69	0.11	1.5	7.82		17011	18089	<a href="#">98Rei</a>
rape	lat: <i>Brassica napus</i>	37.82	4.61	53.22	0.76		0.04	3.55			19380	<a href="#">98Rei</a>
rape	var	48.5	5.9	35.1	1.9	0.45	0.62	7.6				<a href="#">00Har</a>
rape, straw	ger: <i>Raps</i>	33.73	3.85	58.39	0.67		0.06	3.3			19740	<a href="#">98Rei<sup>1</sup></a>
rape, whole crop	fr: <i>colza</i>	50.46	6.26	33.63	2.07	0.53	0.45	6.6		20170	21546	<a href="#">98Rei</a>
rape straw		47.1	5.9	37.1	0.84	0.27	0.47	6.20		17100		<a href="#">00Har</a>
rape; summer		44.66	5.13	37.8	1.4	0.3	0.98	9.73		16481	17610	<a href="#">98Rei</a>
rape, straw												
reed canary grass	lat: <i>Phalaris</i>	45	5.7	38.85	1.4	0.14	0.06	8.85		17130	18370	<a href="#">96Wil</a>
reed canary grass	arundinacea	45	5.7	47.27	1.1	0.19	0.74			17017		<a href="#">93Nor</a>
reed canary grass	ger: <i>Schilfgras</i>	44	5.8	49.14	0.8	0.15	0.11			16.595		<a href="#">93Nor</a>
reed canary grass	fr: <i>roseau</i>											
rice	lat: <i>Oryza sativa</i>	37.86	4.75	33.48	0.23	0.31		23.37			17383	<a href="#">98Rei</a>
rice, hull	ger: <i>Reis</i>	38.68	5.14	37.45	0.41	0.05	0.12	18.15		14516	15381	<a href="#">98Rei<sup>1</sup></a>
rice, straw	fr: <i>riz</i>	39.65	4.88	35.77	0.92	0.12	0.5	18.16			15351	<a href="#">98Rei<sup>1</sup></a>
rice, rice hull char		35.99	1.81	9.37	0.22	0.1		52.51			14195	<a href="#">98Rei<sup>1</sup></a>
rye, straw	lat: <i>Secale cereale</i>	47.57	5.89	42.4	0.42	0.09	0.23	3.4		15881	17220	<a href="#">98Rei<sup>1</sup></a>
rye straw	ger: <i>Roggen</i>	46.6	6.0	39.8	0.55	0.08	0.39	4.80		17500		<a href="#">00Har</a>
whole crop rye	fr: <i>seigle</i>	48.0	5.8	40.9	1.14	0.11	0.16	4.20		16500		<a href="#">00Har</a>
sorghum, sweet	lat: <i>Sorghum</i>	45.81	5.26	41.02	0.97	0.06	0.31	6.57		16830	17990	<a href="#">98Rei</a>
sorghum	saccharatum											
sorghum, sweet	ger: <i>Hirse</i>	47.3	5.8	41.37	0.4	0.09	0.3	4.74		17650	18910	<a href="#">96Wil</a>
sorghum; Italy	fr: <i>petit mil</i>											
sugar cane	lat: <i>Saccharum</i> officinarum ger: <i>Zuckerrohr</i> fr: <i>canne à sucre</i>	44.8	5.35	39.55	0.38	0.01	0.12	9.79			17350	<a href="#">87Dom</a>
sunflower, husk	lat: <i>Helianthus an-</i>	50.92	6.31	37.82	1.12	0.17	0.04	3.62		19300	20400	<a href="#">98Rei<sup>1</sup></a>
sunflower, residue	nus ger: <i>Sonnenblume</i>	57.56	6.48	30.85	1.65	0.13	0.1	3.23		22703	24150	<a href="#">98Rei</a>
sunflower, straw	fr: <i>Tournesol</i>	44.62	5.1	37.15	1.1	0.11	0.72	11.2		16289	17408	<a href="#">98Rei</a>
sunflowers		51.3	5.8	33.0	1.6	0.14	0.40	7.8				

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [% <sub>ar</sub> ] [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
tobacco, leaf	lat: <i>Nicotiana</i>							17.2			15000	<a href="#">98Rei</a>
tobacco, stalk	ger: <i>Tabak</i> fr: <i>tabac</i>							2.4			17700	<a href="#">98Rei</a>
triticale, grain		43.5	6.4	45.3	1.68	0.11	0.07	2.10		16900		<a href="#">00Har</a>
triticale, whole crop		44.0	6.0	43.2	1.08	0.19	0.07	4.40		17300		<a href="#">00Har</a>
triticale, straw		43.9	5.9	42.4	0.42	0.05	0.26	6.00		17100		<a href="#">00Har</a>
verge grass	lat: <i>Strassenbegleitgrün</i> ger: <i>paturage routier</i>	44.6	5.9	38.9	1.74	0.13	0.36	8.40	60.0			<a href="#">97Faa</a>
wheat	lat: <i>Triticum aestivum</i>	42.29	5.05	37.15	1.83	0.15	0.28	13.25			16873	<a href="#">87Dom</a>
wheat, grain	ger: <i>Weizen</i>	45.8	5.05	41.05	0.34	0.06	0.43	7.27		17039	18150	<a href="#">98Rei</a>
wheat, stems	fr: <i>blé</i>	39.07	4.77	50.17	0.58	0.08	0.37	4.96				<a href="#">98Rei</a>
wheat, straw		44.33	5.32	42.93	0.57	0.14	0.5	6.21		16534	17821	<a href="#">98Rei</a> <sup>1</sup>
wheat, whole crop		46.71	5.5	41.21	1.23	0.09	0.33	4.93		17159	18353	<a href="#">98Rei</a>
wheat, straw		44.2	79.5	35.9	0.77	0.07	0.09	1.63				<a href="#">97Bla1</a>
wheat, straw		40.9	5.8	40.9	0.48	0.08	0.19	5.70		17200		<a href="#">00Har</a>
wheat + rye, straw		47.49	6.07	41.3	0.48	0.11		4.55		14317	15723	<a href="#">98Rei</a>
wheat, whole crop		45.2	6.4	41.7	1.41	0.12	0.09	4.10		17600		<a href="#">00Har</a>

<sup>1</sup>) Mean values.

### 5.2.6.1.3 Other biomass

**Table 5.2.3.** Composition and heating values of other biomass.

Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [% <sub>ar</sub> ] [kJ/kg]	$H_{h,db}$ [kJ/kg]	Lit.
bagasse	lat: <i>Bagasse</i>	48.2	5.6	42.3	0.14	0.08	0.00	3.61				<a href="#">97Tur</a>
bagasse, sugar bagasse	ger: <i>Bagasse</i>	46.95	5.47	40.95	1.71	0.09		4.83			18950	<a href="#">98Rei</a>
cellulose	lat: <i>Zellulose</i> ger: <i>cellulose</i>	44.4	6.2							17520		<a href="#">98Rei</a>
coal, anthracite	lat: <i>Kohle</i>	54	4	36		1		5		28980		<a href="#">98Rei</a>
coal, bitumen. coal	ger: <i>charbon naturel</i>	75	4	14		2		5		28000		<a href="#">98Rei</a>
coal, brown coal	fr: <i>lignite</i>	30	4	44		2		20		12500		<a href="#">98Rei</a>
coal, charcoal		80.3	3.1	13	0.2			3.4			31112	<a href="#">98Rei</a>
coal, coke		90	0.5	1.5		1		7		28000		<a href="#">98Rei</a>
coal, lignite coal		64	4.2	19.2	0.9	1.3		10.4			24927	<a href="#">98Rei</a>
coal, low temp coke		78	3	10		2		7		28500		<a href="#">98Rei</a>
cocoa, hull	lat: <i>Theobroma cacao</i> ger: <i>Kakao</i> fr: <i>cacao</i>	48.23	5.23	33.19	2.98	0.12		10.25			19060	<a href="#">87Dom</a>



Biomass	lat: Latin term ger: German term fr: French term	c	h	o	n	s	cl	a	w	$H_{l,db}$ [% ar]	$H_{h,db}$ [kJ/kg]	Lit.
		[% db]										
coconut, fibre	lat: <i>Cocos nucifera</i> ger: Kokosfaser fr: fibre de noix de coco	50.29	5.05	39.63	0.45	0.16	0.28	4.14			20073	<a href="#">87Dom</a>
cotton waste	lat: <i>Gossypium sp</i> ger: Baumwolle fr: coton	49.04	4.71	35.08	1.45	0.36		9.36			17964	<a href="#">98Rei</a>
humus	lat: ger: Humus fr: humus	32.4	3.8	26.9	1.21	0.65	0.39	34.64	12.5			<a href="#">97Jen</a>
olive, stone	lat: <i>Olea europaea</i>	51.38	6.32	40.02	0.45	0.08	0.06	1.69			21599	<a href="#">98Rei</a> <sup>1</sup>
olive kernel	ger: Olivenkern	42.6	5.6	47.9	0.00	0.00	0.00	3.90	21.5	19300		<a href="#">00Zab</a>
olive wastes	fr: noyaux d'olive	47.5	5.7	41.3	0.00	0.00	0.00	4.75	7.1			<a href="#">00Zab</a>
olive wastes		47.5	5.7	41.3	0.00	0.00	0.00	4.75	7.1			<a href="#">00Zab</a>
paper	lat: ger: Papier fr: papier	43.4	5.8	44.3	0.3	0.2		6			17620	<a href="#">98Rei</a> <sup>1</sup>
peach, stone	lat: <i>Prunus persica</i>	53	5.9	39.14	0.32	0.05		1.59			20843	<a href="#">87Dom</a>
peach, stone	ger: Pfirsich fr: noyaux de pêche	46.91	5.16	32.83	0.95	0.0			13.24	17560		<a href="#">99Aze</a>
peanut, shell	lat: <i>Arachis hypogaea</i> ger: Erdnußschale fr: coques d'arachides	45.77	5.46	39.56	1.63	0.12		7.46			18660	<a href="#">87Dom</a>
peat	lat: ger: Torf fr: tourbe		54.6	5.6	33.2	1.7	0.41		4.5		20.71	<a href="#">96Gad</a>
rape seed	lat: <i>Brassica napus var</i>	53.3	13.5	18.7	2.55	0.38			16.0	25800		<a href="#">99Hov</a>
rape seed	ger: Raps	48.1	5.9	42.03	0.8	0.21	0.1	2.86		18040	19330	<a href="#">96Wil</a>
rape seed oil	fr: colza	57.8	20.2	8.2	2.76				17.0	37400		<a href="#">99Hov</a>
rape oil filter cake		50.2	6.86	30.79	5.05	0.77	0.03	6.3		20300	22000	<a href="#">98Rei</a>
rape methyl ester		55.6	19.4	11.7	2.65				9.0	43500		<a href="#">99Hov</a>

<sup>1</sup>) Mean values.

#### 5.2.6.1.4 Wastes

**Table 5.2.4.** Composition and heating values of biogeneous wastes.

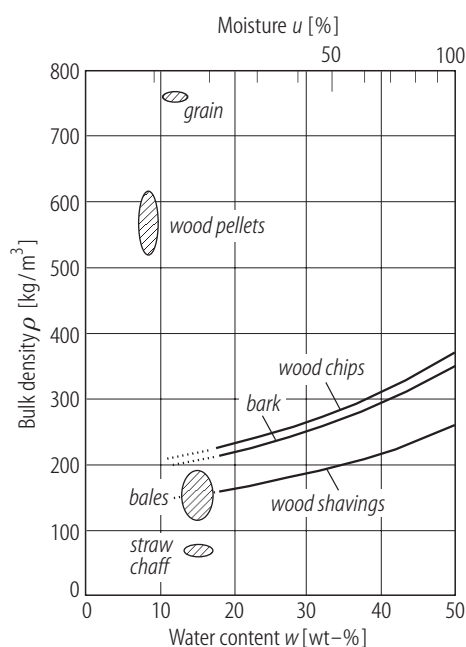
Biomass	c	h	o	n	s	cl	a	w	$H_{l,db}$ [% ar]	$H_{h,db}$ [kJ/kg]	Lit.
	[% db]										
animal waste	42.7	5.5	31.3	2.4	0.3		17.8			17173	<a href="#">98Rei</a> <sup>1</sup>
animal waste char	34.5	2.2	11.7	1.9	0.9		48.8			12682	<a href="#">98Rei</a> <sup>1</sup>
cartoon-plastic-aluminum packing	54	7.79	34.41	0.16	0.08	0.06	3.5				<a href="#">98Rei</a>
compost	39.1	4.44	27.89	1.23	0.18	0.46	26.7		14700	16000	<a href="#">98Rei</a>
domestic organic waste from municipal collection	48.1	5.91	40.74	0.69	0.04	0.02	4.5		15900	17300	<a href="#">98Rei</a>
meat and bone meal, Germany	40.83	5.9	23.0	7.7	0.6		22.03	4.6	21426		<a href="#">01Not</a>
meat and bone meal, Germany	36.3	5.1	20.0	7.3	0.3		31.00	7.53	20082		<a href="#">01Not</a>

Biomass	<i>c</i>	<i>h</i>	<i>o</i>	<i>n</i>	<i>s</i>	<i>cl</i>	<i>a</i>	<i>w</i>	$H_{l,db}$	$H_{h,db}$	Lit.
				[% db]				[% ar]	[kJ/kg]	[kJ/kg]	
meat and bone meal, Ireland	47.3	6.9	11.2	10.6	0.4		23.60	2.2	20695		<a href="#">01Not</a>
meat and bone meal, Portugal	37.2	7.7	18.9	5.8	0.5	0.50	29.40	18.9	22367		<a href="#">01Not</a>
municipal solid waste	47.6	6	32.9	1.2	0.3		12			19887	<a href="#">98Rei</a> <sup>1</sup>
municipal solid waste char	54.9	0.8	1.8	1.1	0.2		41.2			18663	<a href="#">98Rei</a> <sup>1</sup>
organic domestic waste	42.1	5.4	31.4	1.78	0.41	0.24	18.90	54.0			<a href="#">97Faa</a>
pulp & paper mill sludge				0.88	0.47						<a href="#">98Rei</a> <sup>1</sup>
rejects from waste paper preparation	55.1	6.37	32.19	0.31	0.07	0.76	5.2				<a href="#">98Rei</a>
sewage sludge	35.2	6.9	26.0	6.08	0.00	0.00	25.80	84.5			<a href="#">97Ino</a>
sewage sludge	32.6	4.5	18.9	4.38	1.69	0.12	37.50	85.0			<a href="#">97Faa</a>
sewage sludge	28.3	4.07	17.55	2.96	1.25	0.07	45.8		10600	12100	<a href="#">98Rei</a>
sewage sludge from waste paper production	44.6	5.1	15.99	0.71	0.18	0.72	32.7				<a href="#">98Rei</a>
sugar beet	44.5	5.9	42.78	1.84	0.13	0.05	4.8		16600	17700	<a href="#">98Rei</a>
tallow									39000		<a href="#">01Not</a>
tea waste	48.6	5.5	44	0.5			1.4			17100	<a href="#">98Rei</a>
waste from brewing-industries	51.1	6.87	32.52	4.66	0.44	0.01	4.4		20500	22200	<a href="#">98Rei</a>
waste from malt-industries	45.1	6.24	36.93	4.69	0.36	0.68	6		17500	19000	<a href="#">98Rei</a>
waste material	48.3	5.7	40.8	0.7			4.5			17100	<a href="#">98Rei</a>
waste paper	47.94	6.79	36.75	0.38	0.1	0.04	8			21368	<a href="#">98Rei</a>
waste wood	48.29	5.61	39.27	0.81	0.14	0.06	5.82				<a href="#">98Rei</a> <sup>1</sup>
waste wood, birch furn. ply.	51.25	5.94	38.78	3.48	0.01	0.16	0.38			19347	<a href="#">98Rei</a>
waste wood, demolition wood	48.0	5.2	44.8	0.15	0.03	0.08	0.90	20.0			<a href="#">97Faa</a>
waste wood, demolition wood	48.85	5.8	44.58	0.18	0.01		0.58		17635	20186	<a href="#">98Rei</a>
waste wood, furniture waste	50.88	6.13	40.23	1.6	0.02	0.06	1.08			19626	<a href="#">98Rei</a>
waste wood, lacquered waste wood	49.4	6.08		0.35	0.18	0.01					<a href="#">98Rei</a>
waste wood, laminated wood	49.71	6.08	39.04	3.36	0.05	0.25	1.51			19521	<a href="#">98Rei</a>
waste wood, mixed waste wood	50.7	5.91	40.09	1.68	0.06	0.16	1.4		16000	17600	<a href="#">98Rei</a>
waste wood, particle board; s. hardwoods	51.83	5.81	38.8	2.96	0.03	0.33	0.24			19361	<a href="#">98Rei</a>
waste wood, particle board; s. pine coarse	53.51	5.92	35.92	3.5	0.08	0.12	0.95			20832	<a href="#">98Rei</a>
waste wood, particle board; s. pine fine	52.99	6.09	37.26	2.95	0.03	0.13	0.55			20588	<a href="#">98Rei</a>
waste wood, particle board; s. pine medium	55.01	5.65	35.58	3.16	0.03	0.18	0.39			20897	<a href="#">98Rei</a>
waste wood, particle boards; partly impregnated	48.6	6.08	39.65	3.92	0.06	0.39	1.3		16800	18300	<a href="#">98Rei</a>
waste wood, particle boards; pressed	49	5.89	38.14	5.93	0.13	0.01	0.9		17200	18600	<a href="#">98Rei</a>
waste wood, plywood scraps	54.74	6.13	37.25	0.31	0.04	0.03	1.5			21370	<a href="#">98Rei</a>
waste wood, railroad ties	54.06	6.05	37.86	0.43	0.11	0.05	1.44		17400	20483	<a href="#">98Rei</a> <sup>1</sup>
waste wood, salt impregnated wood	51	6.24	41.22	0.26	0.01	0.07	1.2		16800	18400	<a href="#">98Rei</a>
waste wood, telephone poles	55.65	6.02	34.51	0.44	0.56	0.41	2.41			21922	<a href="#">98Rei</a>
waste wood, uncontaminated waste wood	49.6	6.1	42.36	0.38	0.02	0.06	1.48				<a href="#">98Rei</a>
waste wood, waste wood containing particle boards	49.8	6.05	39.43	1.04	0.15	0.03	3.5				<a href="#">98Rei</a>
waste wood, wood residues containing adhesives	49.2	6.12	41.45	2.21	0.02	0.1	0.9		16500	18000	<a href="#">98Rei</a>
waste wood; fir treated	50.19	6.24	40.44	1.89	0.01		1.23			19279	<a href="#">98Rei</a>
waste wood; pressure treated waste wood	53.07	6.15	38	0.24	0.03	0.1	2.41			20621	<a href="#">98Rei</a>

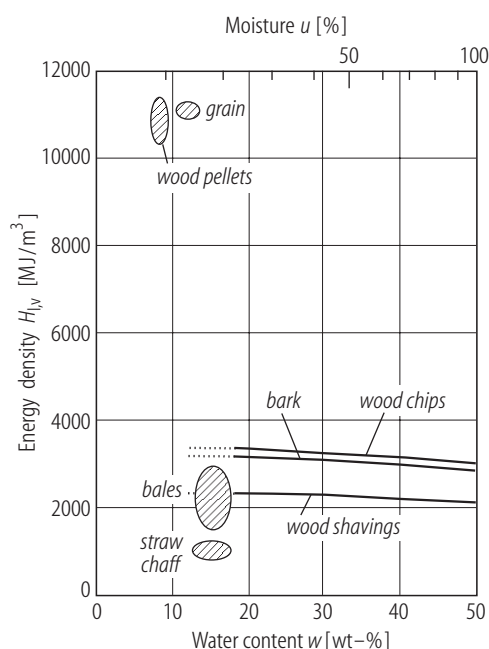
### 5.2.6.2 Energy density

**Table 5.2.5.** Volumetric heating value  $H_{l,v}$  (energy density) of solid biomass ( $w = 15\%$ ) [00Har], [97Obe], [98Obe].

	Bulk density $\rho$ [kg/m <sup>3</sup> ]	Energy density $H_{l,v}$ [10 <sup>3</sup> MJ/m <sup>3</sup> ]	Reference factor
heating oil	840	36.0	1 (reference)
coal	870	27.8	1.3
wood logs	300 - 475	4.7 - 7.4	4.9 - 7.7
wood chips	195 - 260	3.0 - 4.0	8.9 - 11.9
bark	205 - 320	3.2 - 5.0	7.2 - 11.3
saw dust	110 - 170	1.7 - 2.6	13.6
wood shavings	90 - 153	1.4 - 2.4	15.1
cuboid bales, straw, hay, miscanthus	120 - 160	1.7 - 2.3	15.6 - 20.8
round bales	85 - 104	1.2 - 1.5	24.0 - 29.4
cuboid bales, whole crop	190 - 216	2.7 - 3.1	11.6 - 13.1
round bales, whole crop	144	2.1	17.3
straw chaff	59 - 65	0.8 - 0.9	38.4 - 42.3
whole crop chaff	150	2.2	16.6
grain	760	10.9	3.3
pellets	500 - 650	9.2 - 12.0	3.0 - 3.9



**Fig. 5.2.19.** Influence of the water content  $w$  on the bulk density of different biomass fuels.



**Fig. 5.2.20.** Influence of the water content  $w$  on the energy density of different biomass fuels.

### 5.2.6.3 Gaseous fuels

**Table 5.2.6.** Lower heating value  $H_l$  for gaseous fuel [99Ste], [99Ans], [98Cio], [98Fer], [01Kal].

	Lower heating value $H_l$ [kJ/kg]	Volumetric lower heating value $H_{l,v}$ (1.013 bar, 0°C) [kJ/ m <sup>3</sup> ]
methane CH <sub>4</sub>	50010	35880
hydrogen H <sub>2</sub>	119980	10780
carbon monoxide CO	10100	12630
biogas (digestion)	18000 - 22000	18000 - 20000
autothermal gasification with air	2000 - 5000	2000 - 5000
autothermal gasification with air, preheated air (400°C)	6000 - 7500	6000 - 7500
autothermal gasification with pure oxygen	6000 - 11000	6000 - 11000
allothermal gasification, steam reforming (dry product gas)	12500 - 15000	11000 - 14000
allothermal gasification, steam reforming (wet product gas)	7000 - 1200	5000 - 10000

### 5.2.6.4 Ash melting behavior

**Table 5.2.7.** Ash melting temperatures (DIN 51730).

Biomass	Sintering temperature [°C]	Softening temperature [°C]	Hemisphere temperature [°C]	Melting temperature [°C]	Lit.
alfalfa	716	740	1323	1668	<a href="#">98Rei</a> <sup>1</sup>
amaranth	980	1286	1673	1738	<a href="#">98Rei</a>
bark	1100	1250	1270	1270	<a href="#">98Rei</a>
bark, mixed	1250	1320	1340	1410	<a href="#">98Rei</a>
barley, summer barley, straw	720	760	1010	1080	<a href="#">98Rei</a>
barley, winter barley, straw	900	1000	1110	1180	<a href="#">98Rei</a>
barley; Finnish, straw	750			1050	<a href="#">96Wil</a>
beech	1140	1260	1310	1340	<a href="#">98Obe</a>
cane; Italy	1040	1050	1065	1070	<a href="#">96Wil</a>
cereals, grain	710	740	800	850	<a href="#">00Har</a>
cereals, whole crop	850	870	1040	1080	<a href="#">00Har</a>
field grass	850	920	1160	1210	<a href="#">00Har</a>
flax, straw	1147	1020	1710	1677	<a href="#">98Rei</a> <sup>1</sup>
grass	830-1130	950-1230	1030-1280	1100-1330	<a href="#">98Obe</a>
grass, field grass	930	987	1077	1170	<a href="#">98Rei</a>
grass, intensive grass	775	935	990	1055	<a href="#">98Rei</a>
grass, knotgrass	740	760	1660	1690	<a href="#">98Rei</a>
grass, reed canary grass	1455	1530	1585	1605	<a href="#">96Wil</a>
hay	1020	1060	1240	1240	<a href="#">00Har</a>

Biomass	Sintering temperature [°C]	Softening temperature [°C]	Hemisphere temperature [°C]	Melting temperature [°C]	Lit.
hemp	1300	1750	1800	1800	<a href="#">98Rei<sup>1</sup></a>
kenaf; Italy	1585			1610	<a href="#">96Wil</a>
lupine	880	925	1485	1530	<a href="#">98Rei</a>
maize, straw	880	1005	1085	1135	<a href="#">98Rei</a>
maize, whole crop	920	1040	1140	1200	<a href="#">98Rei</a>
miscanthus	820-980	820-1160	960-1290	1050-1270	<a href="#">98Obe</a>
miscanthus	860	970	1100	1170	<a href="#">00Har</a>
miscanthus; Italy	835	1005	1020	1220	<a href="#">96Wil</a>
miscanthus; three annual	823	912	1079	1152	<a href="#">98Rei</a>
miscanthus; two annual	894	1051	1127	1205	<a href="#">98Rei</a>
oats, straw	910	930	950	970	<a href="#">98Rei</a>
pine, bark	1340	1525	1650	1650	<a href="#">98Rei<sup>1</sup></a>
pine, sawdust	1150	1180	1200	1225	<a href="#">98Rei<sup>1</sup></a>
poplar	1280	1340		1480	<a href="#">00Har</a>
rape, rape oil filter cake	1000	1120	1140	1140	<a href="#">98Rei</a>
rape, whole crop	1140	1505	1650	1705	<a href="#">98Rei</a>
rape; summer rape, straw	920	1380	1460	1530	<a href="#">98Rei</a>
rapeseed	1500			1600	<a href="#">96Wil</a>
rye, straw	860	985	1150	1210	<a href="#">98Rei<sup>1</sup></a>
sorghum, sweet sorghum	1020	1111	1171	1157	<a href="#">98Rei</a>
sorghum, sweet sorghum; Italy	975	1090	1257	1340	<a href="#">96Wil</a>
spruce	1197	1543	1693	1737	<a href="#">98Rei<sup>1</sup></a>
spruce	1110-1340	1410-1640	1630->1700	>1700	<a href="#">98Obe</a>
spruce	1190	1430	1600	1600	<a href="#">00Har</a>
spruce, bark	1398	1615	1700	1725	<a href="#">98Rei<sup>1</sup></a>
spruce, bark	1250-1390	1320-1680	1340->1700	1410->1700	<a href="#">98Obe</a>
spruce, bark + impurities	1020	1100	>1700	>1700	<a href="#">98Obe</a>
spruce, chips	1340	1410	1700	1700	<a href="#">98Rei<sup>1</sup></a>
spruce + beech	1140	1260	1310	1340	<a href="#">98Rei<sup>1</sup></a>
straw	930	960	1170	1210	<a href="#">00Har</a>
sunflower, husk	980	1180	1240	1240	<a href="#">98Rei<sup>1</sup></a>
sunflower, residue	1060	1140	1525	1570	<a href="#">98Rei</a>
sunflower, straw	685	738	1178	1208	<a href="#">98Rei</a>
waste wood, mixed waste wood	990	1180	1230	1250	<a href="#">98Rei</a>
waste wood, particle boards; partly impregnated	1140	1180	1300	1380	<a href="#">98Rei</a>
waste wood, particle boards; pressed	1160	1180	1230	1240	<a href="#">98Rei</a>
waste wood, railroad ties	1200	1220	1250	1260	<a href="#">98Rei<sup>1</sup></a>
waste wood, salt impregnated wood	1110	1130	1500	1700	<a href="#">98Rei</a>
waste wood, wood residues containing adhesives	1030	1120	1140	1160	<a href="#">98Rei</a>
waste, cartoon-plastic-aluminum packing	1210	1360	1700	1700	<a href="#">98Rei</a>
waste, compost	1060	1170	1220	1220	<a href="#">98Rei</a>
waste, domestic organic waste from the municipal collection	1000	1210	1280	1300	<a href="#">98Rei</a>
waste, rejects from waste paper preparation	1140	1160	1210	1230	<a href="#">98Rei</a>
waste, sewage sludge	1120	1180	1290	1320	<a href="#">98Rei</a>
waste, sewage sludge from waste paper production	1180	1210	1300	1310	<a href="#">98Rei</a>

Biomass	Sintering temperature [°C]	Softening temperature [°C]	Hemisphere temperature [°C]	Melting temperature [°C]	Lit.
waste, sugar beet	1000	1200	1600	1670	<a href="#">98Rei</a>
waste, waste from brewing-industries	1100	1540	1700	1700	<a href="#">98Rei</a>
waste, waste from malt-industries		815			<a href="#">98Rei</a>
wheat, grain	870	1000	1120	1220	<a href="#">98Rei</a>
wheat, straw	848	956	1107	1241	<a href="#">98Rei</a> <sup>1</sup>
wheat, whole crop	987	1020	1140	1213	<a href="#">98Rei</a>
willow	1490				<a href="#">98Rei</a> <sup>1</sup>
winter wheat, cereals	970-1010	1020	1120-1170	1180-1220	<a href="#">98Obe</a>
winter wheat, straw	800-860	860-910	1040-1150	1080-1290	<a href="#">98Obe</a>
wood waste, compost, bark	1180	1200	1220	1220	<a href="#">98Rei</a>
wood waste, driftwood	1100	1170	1200	1200	<a href="#">98Rei</a>
wood waste, forest residue; Finnish, chips	1175	1205	1230	1250	<a href="#">96Wil</a>
wood waste, forest residue; Swedish, chips	1180	1190	1205	1235	<a href="#">96Wil</a>
wood, chips	1210	1225	1250	1275	<a href="#">98Rei</a> <sup>1</sup>

### 5.2.6.5 Biomass digestion efficiency

**Table 5.2.8.** Gas yield of biogas from dry biomass substrates, see equation (5.2.15) [[98Beh](#)].

Substrate	$x_{\text{ODM}}$ [%]	$y_{\text{CH}_4}$ [m <sup>3</sup> /kg <sub>ODM</sub> ]
chicken manure	77	0.2 - 0.4
pig manure	77 - 85	0.2 - 0.3
clover	80	0.4 - 0.5
apple slops	86	0.3 - 0.4
spent grain	87 - 90	0.6 - 0.7
vegetables	76	0.7 - 0.7
bread waste	96 - 98	0.7 - 0.75
potato slops	90	0.55
rape seed slops	97	0.58 - 0.62
leftovers	90 - 95	0.5 - 0.6
fat	96	0.7 - 1
meat meal	90	0.5 - 0.8
grass	76 - 80	0.45 - 0.5

### 5.2.6.6 Economical data

The specific heat price in [\$/MWh] from heating plants and combined heat and power plants (CHP plants) results from specific investment costs  $s_I$ , fuel costs  $s_F$  and other costs  $s_O$  which are in particular personal costs. Power revenues  $s_{el}$  reduce the specific heat price:

$$s_H = s_I + s_F + s_O - \sigma \cdot s_{el}.$$

The specific costs  $s$  and the annual heat production  $Q_H$  yield the annual costs  $S_a$  in [\$/a] for each cost component (investment costs, fuel costs other costs):

$$S_{a,H} = S_{a,I} + S_{a,F} + S_{a,O} - \sigma \cdot S_{a,el} = s_H \cdot Q_H.$$

The following definitions are used throughout this section:

$\sigma = P_{el}/\dot{Q}_H$	Power-to-heat ratio [kW/kW];
$Q_H$	Annual heat production of the heating plant [MWh/a];
$s_{el}$	Power revenues [\$/MWh];
$p$	Bank rate [-];
$a = \frac{p \cdot (1+p)^n}{(1+p)^n - 1}$	Annuity [-];
$n$	Depreciation time [a];
$I$	Total investment [\$];
$z$	Full load hours per year [h], see (5.2.5) and <a href="#">Table 5.2.9</a> ;
$\dot{Q}_{peak}$	Thermal output (peak load) of the heating plant [kW];
$S_I = I / \dot{Q}_{peak}$	Specific equipment costs [\$/kW], see <a href="#">Table 5.2.10</a> ;
$s_I = a \cdot \frac{S_I}{z} = \frac{p \cdot (1+p)^n}{(1+p)^n - 1} \cdot \frac{S_I}{z}$	Specific investment costs [\$/MWh];
$s_F = \frac{Q_H \cdot S_F}{\eta_g \cdot \eta_b \cdot H_L}$	Specific fuel costs [\$/MWh];
$S_F$	Mass specific fuel costs [\$/kg]
$s_O$	Other costs [\$/MWh] (insurance, personal, ash disposal etc.), see Table 5.2.13;
$\eta_b$	Efficiency of a biomass combustion system, see (5.2.6);
$\eta_g = Q_H / (Q_H + \Delta q_g \cdot l)$	Grid efficiency;
$\Delta q_g$	Specific grid losses [MWh/m], see <a href="#">Table 5.2.12</a> ;
$l$	Grid length [m].

**Table 5.2.9.** Typical full load hours per year  $z$  (German data, VDI 2067) [99Ewu].

Consumer	$z_{\min}$ [h]	$z_{\max}$ [h]
Multiple dwellings, apartment houses	1600	2000
One family houses, terraced house	1200	1600
Hotels	1800	2200
Industrial companies (chemical and food industries)	2500	8000
Industrial companies (mechanical industries etc.)	1500	3000
Hospitals	3000	5000
School buildings	1000	1500
Swimming halls	3000	4500

**Table 5.2.10.** Specific equipment costs  $S_I = I / \dot{Q}_{\text{peak}}$  in [\$/kW] (German and Austrian data) [00Jah], [00Sta], [99Ewu], [97Obe], [00Ruc].

Technical equipment, without building	$S_{I,\min}$ [\$/kW]	$S_{I,\max}$ [\$/kW]
Boiler <sup>1</sup> oil/natural gas 100 kW	219	374
Boiler <sup>1</sup> oil/natural gas 500 kW	108	224
Boiler <sup>1</sup> oil/natural gas 1000 kW	65	95
Boiler <sup>1</sup> oil/natural gas 2000 kW	28	36
Boiler <sup>1</sup> oil/natural gas 5000 kW	22	30
Boiler <sup>1</sup> oil/natural gas 10000 kW	18	24
Boiler <sup>1</sup> biomass 500 kW	255	510
Boiler <sup>1</sup> biomass 5000 kW	204	408
Steam boiler plant, (oil) 10 MW	99	
CHP plant, 10 MW <sub>th</sub> (biomass combustion, steam turbine 1.5 MW <sub>el</sub> )	395	

Complete plant (including building, planning costs etc.), without heating grid	$S_{I,\min}$ [\$/kW]	$S_{I,\max}$ [\$/kW]
Heating plant <sup>1</sup> (oil/natural gas), 1 MW	102	153
Heating plant <sup>1</sup> (oil/natural gas), 5 MW	112	153
Heating plant <sup>1</sup> (biomass + oil/natural gas), 500 kW	540	962
Heating plant <sup>1</sup> (biomass + oil/natural gas), 1 MW	255	765
Heating plant <sup>1</sup> (biomass + oil/natural gas), 10 MW	255	714
Heating plant (biomass + oil/natural gas), 5 MW	225 <sup>1</sup>	721 <sup>2</sup>
Steam boiler plant, (oil/ natural gas) 10 MW	153	204
Steam boiler plant, (biomass) 10 MW	561	714
CHP plant, 40-100 kW <sub>th</sub> (biomass digestion, gas engine 20-50 kW <sub>el</sub> )	2500	3700
CHP plant, 1.5-3 MW <sub>th</sub> (digestion, gas engine 0.9-1.9 MW <sub>el</sub> )	4000	5000
CHP plant, 14 MW <sub>th</sub> (oil/natural gas, steam turbine 2 MW <sub>el</sub> )	255	547
CHP plant, 14 MW <sub>th</sub> (biomass, steam turbine 2 MW <sub>el</sub> )	620	765

<sup>1</sup>) Hot water.



**Table 5.2.11.** Specific investments for district heating (diameter 25-250 km, cost per meter main route) [00Jah], [00Sta], [99Ewu].

Application	$S_I$ , min [\$/m]	$S_I$ , max [\$/m]
Simple installation, rural areas	175	400
Costly laying, residential areas	300	500
Very costly laying, residential areas, high sensitivity of building, rocky underground		Up to 1200

**Table 5.2.12.** Specific grid losses  $\Delta q_g$  in [MWh/m].

	Minimum	Maximum
Specific grid losses $1 - \eta_g$	15%	25%
Specific grid losses per $\Delta q_g$ [W/m]	15	20
Annual grid losses $\Delta q_g$ [MWh/a-m]	0.13	0.18

**Table 5.2.13.** Other costs for heating plants (German data).

	Minimum	Maximum
Supervision hours per year [h/a], oil/natural (VDI 2067)	1000	2000
Supervision hours per year [h/a], oil/natural (VDI 2067)	1500	3500
Ash disposal costs per ton [\$/t] <sup>1,2</sup>	50	200
Insurance costs per year	0.15% of investment	1% of investment
Maintenance costs per year	1% of investment	1.5% of investment

<sup>1)</sup> Depends on ash composition: High heavy metal loads (i.e. with fly dust ashes) may cause significantly higher disposal costs.

<sup>2)</sup> Ashes must not be disposed with carbon yields of more than 5% in Germany after 2005.

**Table 5.2.14.** Boiler efficiency  $\eta_b$ , see (5.2.6).

	Specified efficiency	Mean annual efficiency <sup>1</sup>
Oil/natural gas furnace	90 - 95 %	85%
Condensing boiler	95 - 105 %	
Biomass furnace	80- 90 %	70-80%

<sup>1)</sup> Includes off design operation, power-on/off losses.

**Table 5.2.15.** Gasifier cold gas efficiency  $\eta_{cg}$ , see (5.2.14).

	$\eta_{cg}$
Autothermal gasifier	up to 85%
Allothermal gasifier, steam reformer	up to 70%

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