Wood Fuel User Manual

Baltic ForBio

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2020

Foreword

Wood has long been humanity's most important renewable energy source, accounting for about 10% of global energy production, being the main source of energy for more than two billion people. Although burning wood fuel emits carbon into the atmosphere, then as the forest grows, it also sequesters carbon - one cubic meter of wood sequesters an average of 800 kilograms of carbon dioxide. As a result, wood is considered a renewable fuel, and the use of wood as a fuel means a reduction in greenhouse gas emissions.

The use of wood fuel helps to combat climate change, increases the security of the energy supply, and ensures energy security, all of which are objectives of the EU energy policy. However, wood can only make a limited contribution to solving energy problems, which is why other renewable energy technologies need to be developed and energy needs to be used efficiently (e.g., the energy efficiency of buildings and equipment). Conscious consumption and sustainable forest management, which takes into account the balanced volume of felling and forest growth, ensure the necessary timber reserves and the long-term and stable use of forest resources.

The Wood Fuel User Manual seeks to provide a comprehensive overview of the entire wood-based energy value chain, from wood resources to various heating solutions, environmental requirements, and cost-effectiveness calculations. The book focuses on expanding the use of wood fuel as well as its residues-free and more efficient use – to make sure that there will be enough forest all of us!

This Wood Fuel User Manual is intended primarily for local and corporate building management professionals who are exposed to the design, construction, and operation of heating solutions for buildings, groups of buildings, and small settlements in their daily work. The handbook could also be suitable for experts, consultants, and students in the fields of renewable energy, energy supply, and planning.

This manual consists of eleven chapters and appendices. The first chapter of the book provides an overview of forest resources and their use in different Baltic Sea countries. The subsequent chapters focus on the classification of wood fuel, their properties, quality classes, and relevant standards. Chapter 5 provides an overview of fuel storage. Chapters 6 and 7 describe the basics of wood fuel combustion and different combustion technologies. The subsequent chapters provide an overview of the types of heat supply, such as district heating, local heating, room heating, and combined heat and power. The final chapters focus on the planning of heating solutions, environmental emission requirements, equipment selection methodology, and cost-benefit analysis.

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Martin Kikas
CEO of Tartu Regional Energy Agency

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1. Energy and Forestry

1.1. Wood as an Energy Source

Wood has been used as a fuel by humans for thousands of years. The energy released by burning wood has been used to produce heat and light, prepare food, but also to protect oneself from dangerous animals or other humans. In the old days, where there were abundantly more resources per person, it was not very important to pay attention to the efficient use of wood as a resource – it was expedient for a person to just burn down the whole forest to turn the land freed from it into fields. Unfortunately, the same behavior is still encountered in some parts of the world today. In developed countries, however, wood has become a valuable resource, with every stage of processing from planting to use and burning becoming increasingly efficient.

Although wood is generally no longer used directly to obtain light, the use of wood for heat production is still important in many countries, and cogeneration is becoming more common as an added value.

Wood has always been considered a renewable energy source, i.e., carbon released during the combustion process is sequestered during photosynthesis as a new forest grows. Recently, the question has been raised as to whether the intensive use of wood is carbon neutral, as a mature forest that is left to grow would still sequester carbon. Reducing fossil fuel consumption is crucial to achieving climate goals and curbing climate change. Wood, as a renewable energy source (in the case of sustainable forest management), should play a role in this process, and the use of wood with energy potential as fuel should remain in use by mankind for a long period of time.

However, the main value of wood is not its energy production, which is actually the least value-added process. In certain assortments of wood material, from the forest and wood processing industry, burning is the most viable, cost-effective, and environmentally friendly way of use. Wood raw material should be handled more efficiently at each stage of its use. The same applies to wood with energy potential, one of the most efficient uses of which is combustion in cogeneration plants.

In addition to the security of the energy supply and energy security, which meeting our energy needs with local resources can be considered, and in terms of common economic space or state borders, energy efficiency, sustainable use and the reduction of environmental impact in production has from words and distant promises increasingly turned into becoming part of everyday life and politics. Optimizing energy production and use, reducing fossil fuel consumption, and switching to renewable energy sources are part of both international agreements as well as agreements of environmental policy within the EU (including Estonia).

In addition to political agreements, support, restrictions, and rule-making, economic benefits are a catalyst for greening the energy economy. Environmental and resource savings go hand in hand to a certain extent, and saving resources through more efficient combustion also ensures the expected environmental savings, so it is important to continuously improve the use of wood fuel.

1.2. Forest Resources, Renewable Energy Production, and Future Prospects

37.9% or 160 million hectares of the **European Union's** (EU28) land area is forest land. According to Eurostat, roundwood production has grown year on year, reaching 501 million cubic meters[1] in 2018, which is 72 million more than in 2010. The percentage of firewood felling has increased the most (25%), while in absolute numbers,

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[1] all volumes of wood in cubic meters are given in solid cubic meters, unless otherwise stated

the volume of sawn timber has increased with its 32 million m^3 of felling volume (17%). Assessing the volume and increment of timber and determining the resulting felling volume has an important role to play in ensuring sustainable forest management. The INTERREG Baltic Sea Program project Baltic ForBio developed a web-based GIS platform for the six participating countries, which allow users to assess the potential of wood resources and energy wood spatially.

According to EurObservER's annual publication Solid Biomass Barometer, the amount of primary energy from solid biomass in Europe in 2017 was 1101 TWh. In the same year, electricity production (gross) was 95 TWh, and heat production 929 TWh. In the same year, the share of renewable energy in the total final energy consumption of the European Union (EU28) was 18%; in district heating and cooling, the share of renewable energy in final consumption was 20% and in final electricity consumption 31%. Subsequent brief overviews of the forest sector of the Baltic ForBio countries mainly use summaries prepared by Eurostat and the 2019 edition of the annual EU Energy in Figures, solid biomass summaries prepared by EurObservER and summaries prepared within the framework of the Baltic ForBio project of the INTERREG Baltic Sea Program project.[1, 2, 3, 4, 5]

More than half of **Estonia's** land area, or 51.4%, is forest land; in 2019, it was 2.33 million hectares. The most common stands are pine forests (31%) and birch forests (29%). The annual felling volume has been between 10 and 13 million m^3 in recent years. In 2018, industrial timber accounted for 7.4 million m^3 of and firewood 4.7 million m^3 of the annual felling volume. Most of the wood used for energy comes from clear-cutting. The share of forest harvesting residues in the volume of timber marketed for regeneration felling was 15%, i.e., 1.3 million m^3 per year.

Biomass is in Estonia, where renewable energy makes up 29.2% of final consumption, the most common type of renewable energy, with primary energy production of 17.3 TWh, accounting for over 63% of total renewable energy production in 2017. In Estonia, a large number of district heating boiler houses have switched to chopped wood with their main boilers. This has been due to investment subsidies to encourage the replacement of fossil fuels. In 2017, the heat produced from renewable energy sources accounted for 52% of total heat production.

The goals of the Estonian National Energy and Climate Plan envisage a 70% reduction in greenhouse gas emissions by 2030 compared to the 1990 level. The share of renewable energy must be 50% or 16 TWh of final energy consumption, including 4.3 TWh of renewable electricity (2018 – 1.8 TWh), 11 TWh of renewable heat (2018 – 9.5 TWh), and 0.7 TWh of transport fuels (2018 – 0.3 TWh). It is also important to ensure energy security by keeping the use of local fuels as high as possible, and the main measures include the further development of efficient cogeneration of electricity and heat and the development of heat management. The Forestry Development Plan states that the use of wood as a renewable raw material and a renewable energy source is preferable to higher carbon and non-renewable energy sources.

There is still potential for biomass and peat cogeneration plants in cities and smaller settlements. Low-quality wood and wood industry residues play an important role in the production of both heat and combined heat and power.

Finland is the country with the largest share of forest land in Europe, 73.1% of the land or 22.2 million hectares is covered with forest. The dominating tree species is pine, and pine forests make up 67% of the total forest area. Pine forests are followed by spruce and birch forests, occupying 22 and 10%, respectively. [6] The annual felling volume in Finland has been over 60 million m^3 in recent years, increasing to 68.3 million m^3 in 2018. The main increase has been due to the increase in the volume of industrial wood, sawn timber, and paper wood. The volume of firewood has remained at the same level for years, i.e., 7 – 8 million m^3 per year. The energy potential of logging residues is between 4.0 and

6.6 million m^3, and that of stumps is between 1.5 and 2.5 million m^3 per year.

In 2017, a total of 100 TWh of energy was produced from wood fuels, which accounted for 27% of total energy consumption and three-quarters of renewable energy production in Finland. Twenty million m^3 of woody biomass was used to produce heat and electricity. The most densely populated settlements in Finland have wood-fired cogeneration plants, and 41% of final energy consumption (gross) and 55% of final heat and cooling consumption, respectively, are based on renewable fuels.

Total energy consumption in Finland has remained at the same level as at the beginning of the century, but the production of heat and electricity from cogeneration plants has decreased significantly compared to ten years ago. The use of wood fuel has been pressured by the integrated economic environment, emissions trading, competing fossil fuels, improved energy efficiency, and the recent mild winters. Major investment decisions require a long-term commitment from the government to support renewable energy and CO_2 emissions trading policies.

Through its activities, the state supports the sustainable management and use of forests, while the increasing emphasis is placed on the conservation of biological diversity. However, woody biomass will be seen as the fastest growing renewable energy source over the next ten years. As the by-products of the wood industry have been fully utilized in Finland, the additional volumes of wood fuel can only come from woodchips. The consumption volume of woodchips is growing significantly more than the felling volume of trees. The consumption volume of domestic woodchips is estimated at 12.7 – 14.2 million m^3 in 2030, which can only be achieved by using logging residues and also by using stumps. According to the baseline scenario of the energy and climate strategy, combined heat and power production in 2030 would be 29 TWh, which would correspond to 14.5 million m^3 of woodchips.

Forests cover almost 33% of **Germany's** land area, extending to 11.4 million hectares. The main tree species in Germany are spruce (26%) and pine (23%), followed by beech (16%) and oak (10%).[7]. The volume of wood used as fuel has doubled in the last two years compared to the previous decade. In 2018, 21.9 million m^3 of wood fuel was used, which, together with the increase in the volumes of sawn timber and veneer, has increased the felling volume from the previous stable 48 – 55 million m^3 to 66 and 72 million m^3 in 2017 and 2018.

Germany is also the country with the highest final energy consumption and renewable energy production in the European Union, but the share of renewable energy is only 16%. The number of cogeneration plants operating on biomass has increased more than 14 times since the beginning of the century, reaching more than 700 plants. The amount of primary energy from biomass in 2017 was 139 TWh, and it accounted for 7% of the total primary energy supply (TPES).

In the conditions of growing felling volume, more investments have been made in sustainable forest management and supplying forest with nutrients. Forest management development (growth and quality) and nature protection have become a public interest issue. National and regional forest policies focus on forest conservation, an adaptation of forestry to climate change, and nature conservation issues. The government strongly promotes the use of wood fuel for household heating. From the beginning of 2020, investments will be funded in modern small scale heating systems using woody biomass.

The planned felling volume will decrease in the future and will be in the range of 23 – 35 million m^3 per year in 2020 – 2050, of which the share of logging residues will be 5 – 12 million m^3.

Latvia has both the largest share of forest land and the area of forest land in the Baltics, 54%, and 3.36 million hectares, respectively. Pine forests make up 29% of the forest land, followed by birch and spruce forests with 28% and 17%, respectively. [8] In Latvia, the volume of felling has remained stable for years between 12 and 13 million m^3, the vast majority of which, or 10 to 11.5 million m^3, has been made up of industrial logs. Based on the forest inventory (2004 – 2008), the theoretical felling volume of thinning was found to be 4.9 million m^3 (biomass, 4 cm, and thicker trees), of which 1.8 million m^3 can be considered economically usable for energy production.

Latvia has the third-largest share of renewable energy sources in energy production in the EU. In 2017, renewable resources were used for 39% of final energy consumption. The amount of primary energy from biomass was 23.7 TWh, and the energy produced on its basis accounted for 55% of the total renewable energy consumed. In 2017, there were 204 combined heat and power plants in Latvia, of which 24% used woodchips as the main raw material for energy production. The share of renewable energy in heat production was 55%.

Latvia is very close to its target of 40% of final energy consumption by 2020 in terms of the share of renewable energy. The national climate and energy plan envisages achieving a 50% share of renewable energy in final consumption. The baseline scenario of the National Energy and Climate Plan envisages an increase in the share of energy produced from biomass in final consumption – 13% by 2030 compared to 2015. In order to meet the renewable energy target, measures have been approved to promote the use of biomass in electricity and heat production. At the same time, no increase in biomass production is planned in Latvia.

In **Lithuania**, forest land accounts for 33.5% of the country's area. As of 2017, there were 2.19 million hectares of forest land. The most common stands are pine forests (33%), birch forests (21%), and spruce forests (20%). Annual felling volumes, averaging 6.8 million m^3, have remained stable over the last decade. Approximately 25 – 30% of the amount of Roundwood marketed are stumps, logging residues, young trees, and currently, 15 – 20% of logging residues are collected and used. Of the annual felling volume, firewood accounts for about 1.8 million m^3. The potential of woodchips collected from the forest is 2.5 million m^3

In 2017, renewable energy sources accounted for almost 26% of final energy consumption in Lithuania. In 2016, there were 332 biofuel boiler houses with 990 MW installed boilers in Lithuania. District heating accounts for more than 50% of heat consumption. The main measure to support the production of renewable electricity is the feed-in tariff, which is based on a commitment to purchase renewable electricity at a fixed price. In Lithuania, electricity generation from wind, biomass, solar, and hydropower plants with a capacity of up to 10 MW is encouraged.

The national target is to produce at least 38% or 5 TWh of electricity consumed in Lithuania in 2025 from renewable energy sources, of which at least 15% are biofuels.

In **Sweden**, the share of forest land is 68.9%, the forest grows on 28.1 million hectares. In terms of the share of forest land, Sweden lags behind Finland, and together, they are vastly ahead of other EU countries. In absolute terms, Sweden is the most forested country in the European Union. The main tree species are spruce and pine. The felling volume has been 73 – 75 million m^3 per year in recent years. 6 – 7 million m^3 have gone from the felling volume directly to firewood. The rest of the wood is evenly divided into lumber and paper wood.

Bioenergy accounts for the largest share of final energy consumption in Sweden, where final energy consumption is around 370 TWh per year. In 2017, 111 TWh of energy was produced from solid biomass, of which 19.5 TWh was primary forest fuels, and about 9.5 TWh was wood fuels used for heating private houses (stoves). The volume of utilization of logging residues can be increased from 8.5 TWh to 29 TWh in the period 2020 – 2029.

The installed capacity of biofuels boiler is 4.3 TW, and the potential for district heating in Sweden is almost entirely used, but there are still more options for the construction of smaller local heating systems.

2. Wood as Fuel

2.1. General

Biomass is one of the most important renewable energy sources worldwide and covers all terrestrial and aquatic vegetation and all organic residues. The biomass of green plants is formed from carbon dioxide in the air during photosynthesis under the influence of sunlight. Photosynthesis typically uses less than 1% of the available sunlight, which is stored as chemical energy in biomass. Biomass has always been an important source of energy for humankind, and its share of the world's energy supply is currently estimated to be 10 – 14%.

When biomass is converted either chemically or biologically, the energy stored in the chemical bonds is released, and when combined with oxygen, carbon is oxidized to CO_2 and returns to the atmosphere. The process is cyclical, as air CO_2 is again used to form new biomass (Figure 2.1).

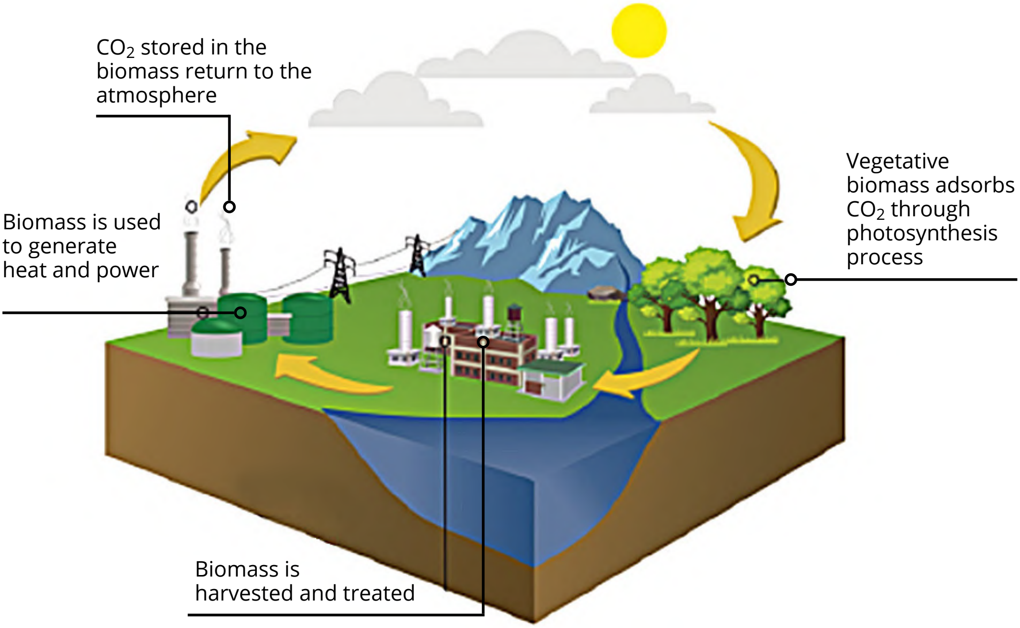


Figure 2.1. Carbon cycle on growth and use of biomass [9]

2.2. Classification of Biomass

Biomass is the world's fourth-largest source of fuel energy after coal (including brown coal and lignite), oil, and natural gas. Biomass materials are characterized by their enormous diversity, which makes them quite difficult to characterize as a whole.

European Union standards CEN/TS 14961:2005 [10] provides the following hierarchical breakdown by the origin of solid biofuels:

- woody biomass,
- herbaceous biomass,
- fruity biomass,
- aquatic biomass,
- blends and mixtures.

2.3. Biomass Fuel – Woody Biomass – Wood Fuel

2.3.1. General

In forest-rich countries with a traditional forest industry wood fuel as a predominant type of biomass has been used for heating and cooking for centuries. Wood is used less and less for heating new single-family houses (private houses) (the same trend is observed elsewhere in Europe). The main reasons are the labor-intensive use of traditional firewood (production and burning) and the lack of automation.

In recent decades, a number of so-called 'upgraded wood fuels' - pellets (wood pellets), charcoal and sawdust briquettes – have been introduced, as well as technologies and high-efficiency equipment for burning them. The implementation of new equipment and technologies will also make it possible to drastically reduce emissions from heating stoves in small houses (particulate matter, CO_2, etc.), which has now become one of the main air pollutants in many places. The development of the wood fuel industry and terminals would make it possible to create a large number of jobs, especially in rural areas.

As a preliminary work for the development and introduction of wood fuel terminals, combustion plants, and technologies, it is necessary to know more precisely the types and properties of wood as heating material. The properties of wood make it an environmentally friendly fuel, and it is used in the European Union's energy systems to produce both heat and electricity.

Typically, woody biomass used for energy and fuel production comes from four main sources:

- production waste and residues;
- non-commercial wood residues;
- post-consumer wood residues (e.g., construction and demolition wood);
- urban, agricultural, and horticultural residues and scrap (e.g., twigs, bushes).

Woody biomass is currently the most important renewable energy source in the world. In 2010, about 30 EJ of woody biomass was used for energy purposes worldwide, of which 16 EJ was used in households and 14 EJ in large industrial equipment.[11].

2.3.2. Wood Plant Composition

Wood, as a lignocellulosic material, is the main part of the stem and branches of woody plants (trees, bushes), which consists mainly of woody cells. The shell of wood cells consists mainly of cellulose, hemicellulose, and lignin (Figure 2.2). Lignin gives wood mechanical strength. The dry basis of pine, spruce, and birch wood contains 40 – 45% cellulose, 25 – 40% hemicellulose (Figure 2.3, Table 2.1). The lignin content in the dry basis of coniferous is 24 – 33%, in broadleaf trees 16 – 25%. About 40% of the calorific value of wood falls on lignin.

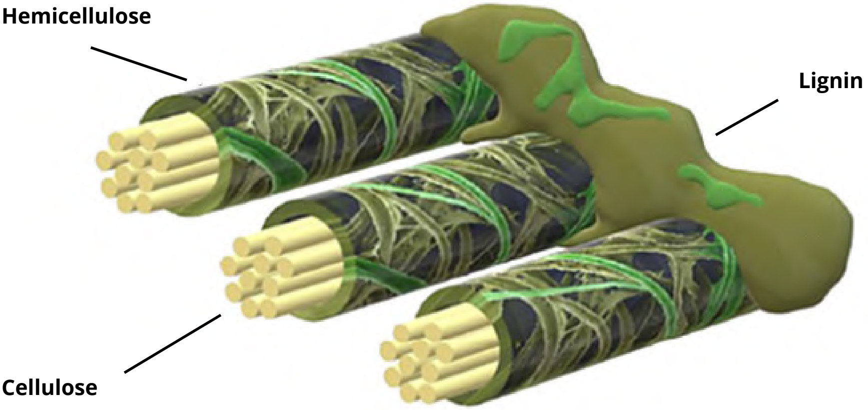


Figure 2.2. Structure of lignocellulosic biomass (including woody biomass) [9]

2.3.3. Distribution of Woody Plant Biomass

A growing tree consists of a stem, branches, and foliage. When producing fuel from woody biomass, it is not expedient to use higher quality stemwood, but above all, logging debris (branches, tops).

It is estimated that the above-ground biomass of adult coniferous is about 73 ±10% of the stem, 10 ±5% of the branches, 5 ±3% of the bark and the same amount (5 ±3%) of the needles. The useful stem part in broadleaf trees is usually about 5 – 10% less, as many broadleaf trees have branched stems (Table 2.2).

Table 2.1. Wood composition [13]

Ingredient	Coniferous	Broadleaf
Cellulose	40 – 45%	40 – 50%
Hemicellulose	24 – 37%	22 – 40%
Lignin	25 – 30%	20 – 25%

The size of the different parts of the tree, of course, varies not only by the individual tree and the tree species but also by the age of the tree and the season (Figure 2.4). Data on the dry basis weight of the stumps and the related energy content depending on the stump diameter and tree species are given in the figure (Figure 2.5). Young trees and/or thin branches probably have more bark compared to the coarse stem tree, broadleaf trees have fewer leaves in winter (or no leaves at all) than in summer, and so on. The ratio may differ for trees growing in different climate zones (Figure 2.4, Figure 2.6 and Table 2.2) [14]

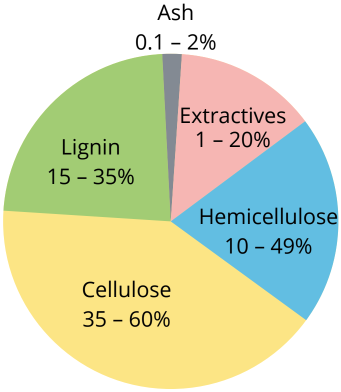


Figure 2.3. Wood fuel composition [12]

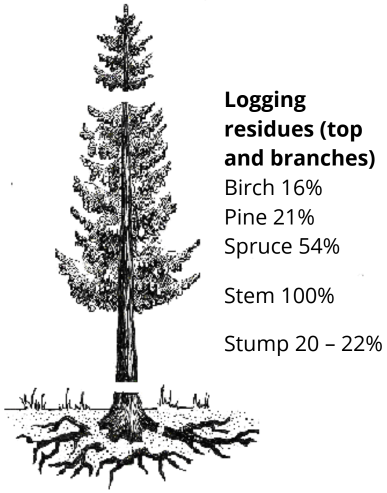


Figure 2.4. Distribution of woody biomass, [15]

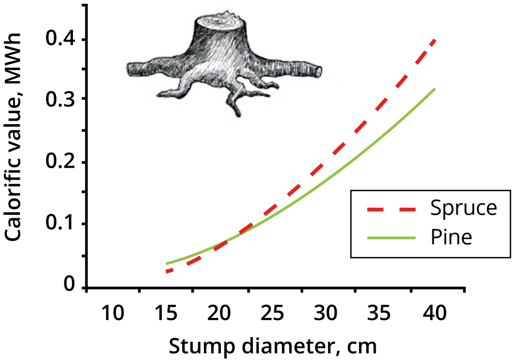


Figure 2.5. Dry basis mass and calorific value of stumps depending on stump diameter, [15]

Table 2.2. Distribution of parts of pine and spruce, %

Part of a tree	Biomass distribution, %			
	Pine		Spruce	
Stem	100	69	100	59
Top, branches	23	16	45	27
Stump, roots	22	15	24	14
Total	145	100	169	100

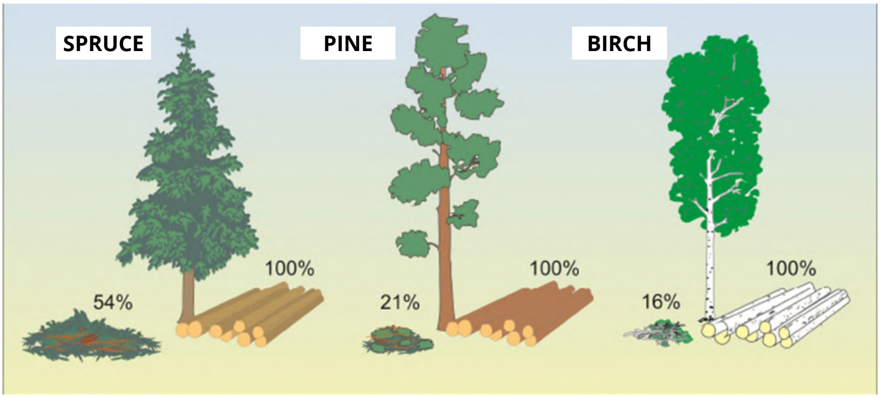
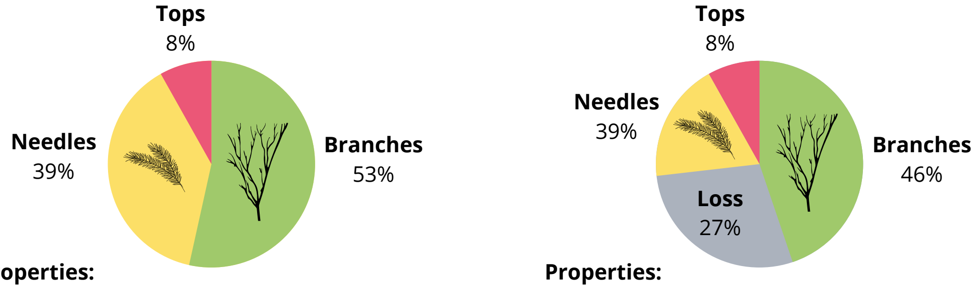


Figure 2.6. Biomass yield of regeneration sites (clear-cutting) (top weight/stem weight, %) [16]

Table 2.3. Biomass (t/10 m^2) and biomass energy (MWh/10 m^2) of different parts of broadleaf trees (broadleaf) [17], [18]

Indicator	Stem wood	Stem bark	Fresh branches	Branches	Leaves	Roots	Total
Biomass, t/10 m^2	38.47	6.30	0.26	10.23	3.74	24.62	**83.90**
Percentage, %	46.18	7.51	0.30	12.20	4.46	29.34	**100**
Biomass energy, MWh/10 m^2	203.24	33.18	1.39	54.66	20.38	128.26	**441.09**
Percentage, %	46.08	7.52	0.32	12.39	4.62	29.08	**100**

The biomass distribution of individual spruce stands is shown in the following figure (Figure 2.7).



Properties:
Moisture content: 55 w-%
Calorific value: 0.78 MWh/l m^3
Yield per hectare: 60 m^3/ha

Properties:
Moisture content: 35 w-%
Calorific value: 0.88 MWh/l m^3
Yield per hectare: 45 m^3/ha

Figure 2.7. Composition of spruce logging residues (raw on the left, dry on the right) [19]

The most important properties of logging residue chips for energy use are the dry mass per loose m^3, as well as the moisture content (moisture), the calorific value of the fuel, and the particle size distribution. Moisture affects the lower calorific value, as evaporation of water requires energy. The higher the dry basis content per m^3 of woodchips and the lower the moisture, the higher the energy yield from the wood. [16]

In a growing tree, the minerals and nutrients – that is, the ingredients that make up the actual ash – are carried on the outer layer of the stem and the lower layer of the bark. From there, minerals and nutrients are transferred through the branches and shoots to the green parts, needles, and leaves, where photosynthesis takes place.

From this, it becomes clear that the actual ash content of the outer layer of the stem and the lower layer of bark and foliage is higher than, for example, in the middle parts of the tree stem. This also applies to fine branches and shoots. Not only is the ash content higher, but so are the main nutrients. The main problem is nitrogen, as it promotes the formation of nitrogen oxides during combustion.

2.4. Classification of Woody Biomass

Woody biomass is classified according to the standard “Solid biofuels. Fuel specifications and classes. Part 1: General requirements (EN ISO 17225-1:2014. In Estonian: EN ISO 17225-1: 2014), and the types are as follows. [20]

Forest, plantation and other virgin wood

Wood belonging to the group of forests, plantations, and other virgin wood may be treated to reduce the size, peeled, dried, or moistened. The group of forests, plantations, and other virgin wood include timber from forests, parks, plantations, and short rotation coppice forests and reforestation.

By-products and residues from wood industry

This group includes wood processing by-products and residues. These biofuels may be chemically untreated (for example, residues from peeling, sawing or cross-cutting, mold processing, pressing) or residues from the treatment of chemically treated wood, tiles and furniture (glued, painted, coated, varnished or otherwise treated), provided that it does not contain heavy metals or halogenated organic compounds from wood treatment with wood preservatives or coatings.

Used wood

This group includes wood residues from consumer / social use; natural or slightly mechanically treated wood which may be contaminated only with insignificant quantities of substances not normally found in the natural state (for example, pallets, transport supports, boxes, wood bales, cable drums, construction timber). The same treatment criteria apply as for "wood by-products and residues": i.e., the wood used must not contain heavy metals or halogenated organic compounds from the impregnation or coating of the wood.

Blends and mixtures

The term ‘blends and mixtures’ (Table 2.4) means fuels of different origins in this column of the classification table, which are present at four levels. This includes woody biomass blends mixtures, according to Chapters 1.1 to 1.3 (Table 2.4). Blending can be either intentional (blends) or unintentional (mixtures).

Second level classification (Table 2.4) describes fuels from different sources in the main groups that first determine whether biomass is unprocessed, a by-product of processing, or industrial waste.

Groups Table 2.4 are further subdivided into subgroups. The purpose of the table is to provide an opportunity to differentiate and define biofuel materials according to their origin in as much detail as necessary.

Table 2.4. Origin and classification of wood-based biomass [20]

1.1. Forest, plantations and other virgin wood	
Subgroup I	**Subgroup II**
1.1.1. Whole trees without roots	1.1.1.1. Broadleaf 1.1.1.2. Coniferous 1.1.1.3. Short rotation coppice 1.1.1.4. Bushes 1.1.1.5. Blends and mixtures
1.1.2. Whole trees with roots	1.1.2.1. Broadleaf 1.1.2.2. Coniferous 1.1.1.3. Short rotation coppice 1.1.2.4. Bushes 1.1.2.5. Blends and mixtures
1.1.3. Stemwood	1.1.3.1. Broadleaf with bark 1.1.3.2. Coniferous with bark 1.1.3.3. Broadleaf without bark 1.1.3.4. Coniferous without bark 1.1.3.5. Blends and mixtures
1.1.4. Logging residues	1.1.4.1. Fresh/green, broadleaf (including leaves) 1.1.4.2. Fresh/green, coniferous (including needles) 1.1.4.3. Stored, broadleaf 1.1.4.4. Stored, coniferous 1.1.4.5. Blends and mixtures
1.1.5. Stumps/roots	1.1.5.1. Broadleaf 1.1.5.2. Coniferous 1.1.5.3. Short rotation coppice 1.1.5.4. Bushes 1.1.5.5. Blends and mixtures
1.1.6. Bark (from forestry operations)	
1.1.7. Segregated wood from gardens, parks, roadside maintenance, vineyards, fruit orchards and driftwood from freshwater	
1.1.8. Blends and mixtures	

1.2. By-products and residues from wood processing industry	
Subgroup I	**Subgroup II**
1.2.1. Chemically untreated wood by-products and residues	1.2.1.1. Broadleaf tree with bark 1.2.1.2. Coniferous tree with bark 1.2.1.3. Broadleaf tree without bark 1.2.1.4. Coniferous tree without bark 1.2.1.5. Bark (from industry operations)
1.2.2. Chemically treated wood by-products, residues, fibres and wood constituents	1.2.2.1. Without bark 1.2.2.2. With bark 1.2.2.3. Bark (from industry operations) 1.2.2.4. Fibers and wood constituents
1.2.3. Blends and mixtures	
1.3. Used wood	
Subgroup I	**Subgroup II**
1.3.1. Chemically untreated used wood	1.3.1.1. Without bark 1.3.1.2. With bark 1.3.1.3. Bark
1.3.2. Chemically treated used wood	1.3.2.1. Without bark 1.3.2.2. With bark 1.3.2.3. Bark
1.3.3. Blends and mixtures	
1.4. Blends and mixtures	

2.5. Types of Wood Fuel

Most biomass-based materials, including woody biomass, require some form of treatment before being used as a biofuel. Treatment processes can range from simple chopping and drying (logwood) to more complex processes such as granulation (mechanical treatment, pressing). The method of processing biomass-based raw materials is important as it determines the possible field of and options for application, as well as the choice of combustion plants, fuel feed, and storage equipment. The most commonly used solid wood fuels are characterized in Table 2.5.

Table 2.5. Main fuels in biomass heating projects

Type of fuel	Usage
Log woods	Most used in small heating systems (<50 kW – from households to small industrial installations), requires daily refueling.
Chipped/crushed wood	Conventional fuel for automatic wood fuel systems with a capacity of 150 kW or more
Wood pellets	It is mostly used in boiler houses of small residential houses and in small industrial systems of less than 150 kW, where the higher energy density of pellets compensates for their higher price compared to wood chips. Wood pellets are also used in relatively large boiler houses of up to 5 MW and, thanks to support for renewable energy in cogeneration plants and co-combustion in existing coal-fired power plants.
Wood industry residues/sawdust	Some combustion plants are designed to burn wood industry by-products (e.g., very dry furniture industry residues and sawdust).
Energy grain	In some wood fuel boilers, grain residues (e.g., spoiled oats and husks) can be burned either neat or mixed with wood fuel.

Solid biofuels, including solid wood fuels, are classified on the basis of commercial forms and properties. Solid biofuels are marketed in several different piece sizes and in many forms. The size and shape of the piece affect both the handling of fuels and the choice of combustion technology. Wood fuels are usually supplied in the commercial forms described in the standard ([20], Table 4.1).

2.6. Units for Measuring and Quantifying Woodfuel

Several units are used to measure the quantities of wood fuel (presented together with their English and Finnish equivalents, as there is a great deal of wood fuel literature available to us in these languages):

Solid cubic meter or cubic meter solid volume – solid m^3 s m^3.

Cubic meter loose or bulk volume – loose m^3) or l m^3, is used to measure wood chips.

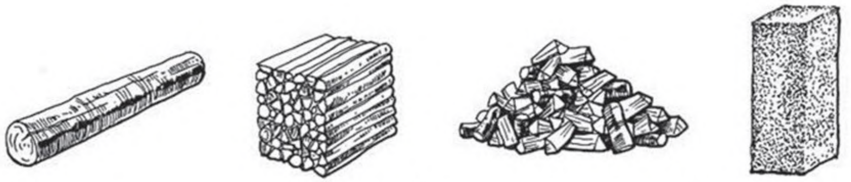
Cubic meter stacked volume piled cubic meter – stacked m^3 or st m^3 (sometimes named piled m^3).

The conversion factors between units of different types of wood fuel are given in the table (Table 2.6). It should be emphasized that the conversion factors may not be exactly the same in different countries and literature sources, but vary by a few percent, and fortunately, these deviations are not very significant in practice. Conversion factors for sawmill residue (wood residues) are given below (Table 2.7).

The ratio of the amounts of different types of wood fuel is also characterized by Figure 2.8. [21]

Table 2.6. Roundwood/log woods/woodchips conversion rates

Assortments	Round-wood	One-meter log woods	Chopped log woods		Wood chips	
			Stacked	Bulked	Fine (G30)	Medium (G50)
	s m^3	st m^3	st m^3	l m^3	l m^3	
1 solid m^3 roundwood	1	1.4	1.2	2.0	2.5	3.0
1 stacked m^3 one-meter log woods	0.7	1	0.8	1.4	(1.75)	(2.1)
1 stacked m^3 chopped log woods	0.85	1.2	1	1.7		
1 bulk m^3 chopped log woods	0.5	0.7	0.6	1		
1 bulk m^3 forest chips fine (G30)	0.4	(0.55)			1	1.2
1 bulk m^3 forest chips medium (G50)	0.33	(0.5)			0.8	1



1 solid m^3 roundwood ≈ 1,4 stacked m^3 one-meter log woods ≈ 2 bulk m^3 chopped log woods ≈ 3 bulk m^3 forest chips medium (G50)

Figure 2.8. Roundwood conversion rates [21]

Table 2.7. Sawmill industry residues and residues conversion rates [21]

Assortment	Transition factor	
1 stacked m^3 of splinters in a bundle	= 0.65 s m^3	Roundwood
1 bulk m^3 of sawn wood chips G50 (P50)	= 0.33 s m^3	
1 bulk m^3 of fine sawdust (≤5 mm)	= 0.33 s m^3	
1 bulk m^3 of planer shavings	= 0.20 s m^3	
1 bulk m^3 of bark	= 0.30 s m^3	

Note: G50 (P50) – particle size of the main fraction in the range $3.15 \text{ mm} < P \leq 50 \text{ mm}$

3. Properties of Solid Wood Fuel

3.1. Moisture

Wood moisture consists of external or mechanical and internal or hygroscopic moisture. External moisture is released from the wood by natural drying in the air. Internal moisture is completely released when the wood is dried at temperatures above 100 °C. The internal moisture of the wood is about 15%. The moisture content of wood fuel can vary widely. The moisture content of raw wood is in the range of 40 – 60%.

Factors affecting moisture are season, location, wood type, and age. The relative moisture of residues from the furniture industry is 8 – 12%, but the moisture of logging residues is 45 – 55%.

The moisture content of wood dried in the open air is 20 – 25%, and the moisture content of wood dried under the roof is 15 – 20%. For smaller combustion plants, the wood is usually dried before use, but for larger wood fuel boilers, this is usually not done. The difference in moisture between the different parts of wood is illustrated in Table 3.1 and moisture data for various wood fuel in Table 3.2.

Table 3.1. Moisture content of different parts of trees, M%. [22]

Part of a tree	Pine	Spruce	Birch	Alder	Aspen
Stem	45 – 50	40 – 60	45 (35 – 50)	54	47
Branches	50 – 60	42 – 46	41 (39 – 44)	57.5	45
Top	60	60			
Bark					
outer bark			(15 – 20)		
bast			(50)		
The whole tree			47	55	48

Table 3.2. Relative moisture content of wood fuels, M% [19]

Wood fuel	Moisture content, %
Log wood, raw	45
Log wood, been in a stack for one summer	25
Log wood, been in a stack for two summers	20
Fine stem chips, raw	50
Fine stem chips, air-dried for one year	25 – 30
Wood chips from logging residues, raw pine	60
Wood chips from logging residues, raw spruce	50 – 57
Wood chips from dried trees	35

Wood fuel	Moisture content, %
Wood chips from willow	35 – 40
Raw sawdust	50 – 55
Sawdust from dried wood	5 – 15
Planing shavings, air dry	15 –20
Conifer bark, dry	40 – 50
Conifer bark, raw	60 – 70
Broadleaf bark, dry	40 – 50
Broadleaf bark, raw	65 – 70

Moisture affects not only the calorific value of the wood fuel but also storage conditions, combustion temperature (Table 3.3), and flue gas volume. The moisture content of the wood can be expressed in terms of wet weight (i.e., the fuel entering the boiler house) and the dry mass of the wood. Wood is sometimes divided into three categories according to moisture:

- air dry – 20 (25), %,
- semi-dry – 21 – 33 (26 – 50), %,
- raw – more than 33 (more than 50), %,

where the first number indicates the relative moisture per fuel and the second (in brackets) per dry basis.

Table 3.3. Effect of moisture of logwood on flame temperature [23]

Moisture of wood fuel, %	Flame temperature in the ignition phase, °C	Flame temperature in the final stage of combustion when the furnace has warmed, °C
10	660	1010
15	640	990
20	610	960
25	580	930
30	550	900
35	520	870
40	490	840

The relative moisture on dry basis (U) is calculated by the formula:

$$U = \frac{M_1 - M_0}{M_0} \cdot 100 \qquad (3.1.)$$

The relative moisture on wet basis (M) is given by the formula (water content in some sources):

$$M = \frac{M_1 - M_0}{M_1} \cdot 100, \qquad (3.2.)$$

where M_1 – mass of wet wood (fuel), kg,

M_0 – mass of dry wood (wood dry basis), kg.

Of these, the first term (U) is more applicable in wood science and mechanical processing of wood, while the second (M) is found in energy and the pulp and paper industry.

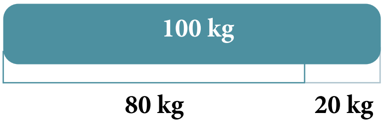
Assuming that the weight of freshly chopped fresh wood is half water and half wood, the weight of the wood (fuel) is 50% relative moisture (M) and 100% moisture (U) 100 % per dry basis (Table 3.4).

Table 3.4. Moisture and water content conversion rate[24]

M, %	15	20	25	30	35	40	45	50	60
U, %	18	25	33	43	54	67	82	100	150

U, %	15	20	30	40	50	65	80	100	150
M, %	13.0	16.7	23.1	28.6	33.3	39.4	44.4	50.0	60.0

The following is a practical example of calculating moisture, where 20 kg of 100 kg of wood is made up of water.

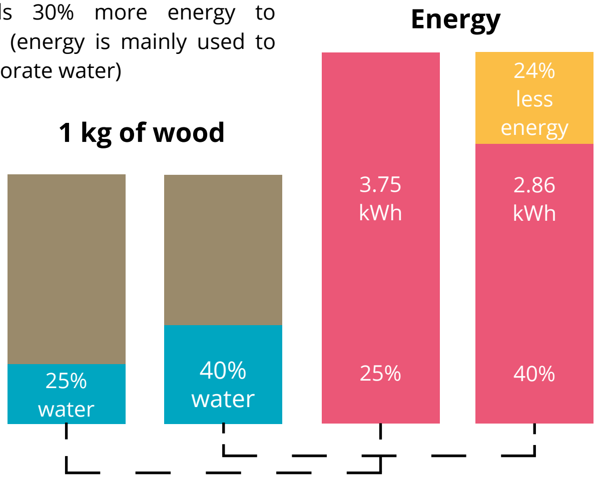


$$M = \left(\frac{20}{100}\right) \cdot 100 = 20\%$$

Moisture is a harmful part of the fuel, which causes additional costs during both transport and storage. In winter, damp wood chips can freeze, and transport from the warehouse to the boiler house can be difficult. Moisture lowers the calorific value of the fuel, increases the volume of combustion gases, and raises the dew point temperature. The higher the moisture of the fuel being burned, the more heat is required to evaporate it (Figure 3.1). If a flue gas condenser is used after the boiler, it is possible to put some of the heat used to evaporate the moisture to good use (direct it to heat the water in the district heating network or to preheat the boiler feed water).

In the figure (Figure 3.2), wood fuel moisture, volatiles (volatiles content), and solid or bound carbon are expressed in the form of a bar graph.

Wood fuel with 40% moisture needs 30% more energy to burn (energy is mainly used to evaporate water)

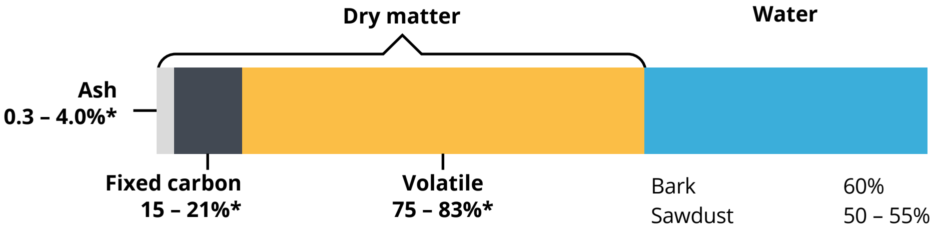


On burning 10 kg of birch wood, it is necessary to evaporate:

- 2.5 kg of water when the relative humidity of the wood is 25%
- 4 kg if the wood moisture is 40%

Figure 3.1. Effect of firewood moisture on energy content

To evaporate 1 kg of water (from 0 °C to 100 °C) it takes 2680 kJ of heat or 0.744 kWh, of which ~ 85% is used to evaporate the water to heat the rest of the water (moisture in the wood) to 100 °C.



Carbon (C)	49 – 51%*
Hydrogen (H)	6.0 – 6.2%*
Oxygen (O)	38 – 42%*
Nitrogen (N)	0.1 – 0.4%*
Sulphur (S)	0.01 – 0.05%*

Bark	60%
Sawdust	50 – 55%
Fresh wood	50 – 60%
Forest residue	35 – 50%
Stemwood	30 – 45%
Firewood	20 – 25%
Wood pellet	8 – 10%

*of dry matter, %

Figure 3.2. Wood composition and average moisture of different wood fuels [16]

3.2. Effect of Drying on Wood Fuel

Drying of sawn and broken logs depends on the initial moisture of the source wood, storage location, and weather conditions. The most important climatic factors are relative moisture, precipitation, temperature, and wind conditions. In a normal summer, the drying of sawn and broken logs from raw wood with a moisture content of 40 – 50% to the level of moisture in the open air undercover in the wind takes at least two months, during which time the moisture content can decrease to 20 – 25%. Fresh sawn and cut logs shrink by 6 – 7% in size. The shrinkage only starts at a moisture level of 23 – 25%, i.e., at the saturation point of the so-called wood fibers (when a constant moisture level corresponding to the drying conditions has been reached). Storing wood in winter, e.g., in a shed, does not significantly reduce the moisture content of the wood, as the most favorable time for drying wood is the summer season from April to early September (Figure 3.3 and Figure 3.4).

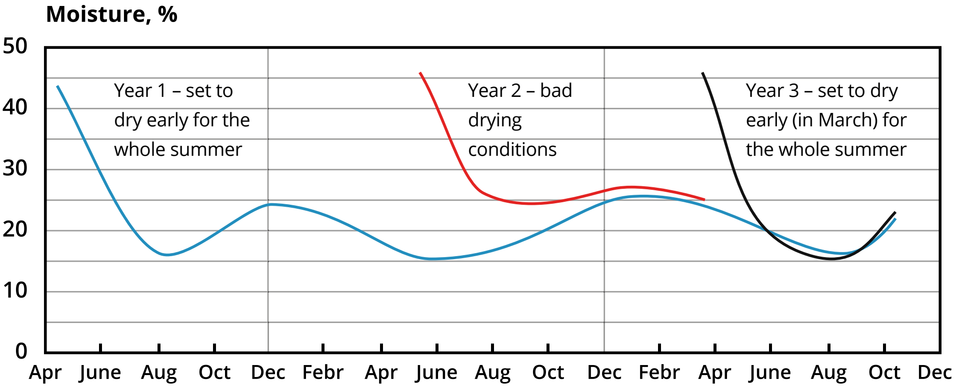


Figure 3.3. Sawn and cut logs drying in a covered wire cage and seasonal differences in their moisture [16]

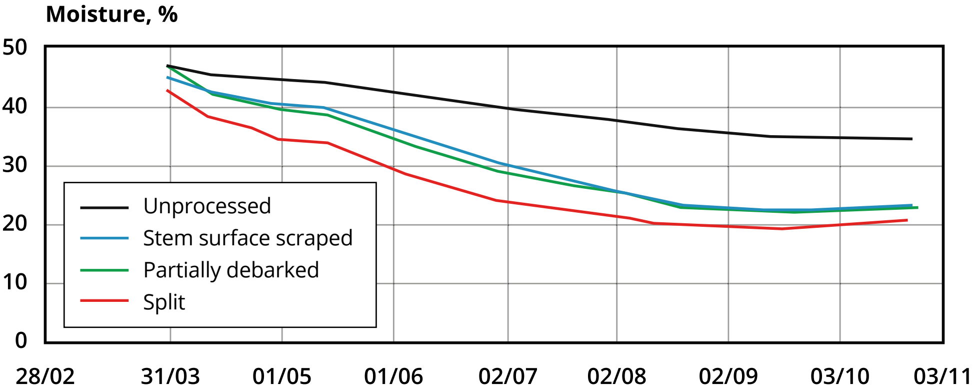


Figure 3.4. Effect of bark scraping (peeling) on drying of birch bunches in a covered pile (2007)[16]

The moisture content of fresh logging residues is 50 – 60% by weight of the total weight of wood chips. However, the moisture content of wood chips produced from logging residues is 25 – 65%. Moisture depends on factors such as the season and storage conditions. The moisture value can be reached below 30% in the summer if the source material of wood chips is left to dry on-site (on or near the felling site), but in the same way up to 65% moisture can be measured in winter when the wood chips mix with snow and ice (Figure 3.5). Moisture has a significant effect on the energy content (density) of wood chips. In practice, the energy content of logging residues chips is 0.6 – 1.0 MWh/l m^3 (2.16 – 3.6 GJ/l m^3). [16]

It is relatively common to cover piles of logging residues (long piles) with kraft paper developed for this purpose. The paper only protects against getting wet, which means that chipping can be performed even in bad weather conditions. The paper can be passed through the chipper with the chipping residue so that it is not left in the storage area. Figure 3.5 is an example of a VTT study on the moisture content of logging residues on the cutting area in a covered and uncovered pile. Moisture is given in both weight percentages and kilograms (H_2O)/l m^3. Based on the results, the moisture content of logging residues stored in covered piles was 7 – 10 percentage points lower than in uncovered piles. According to these studies, drying of logging residues was most efficient at the beginning of the storage period, as logging residues dried by 14 – 20 percentage points during the first two months. Evaporation exceeded the precipitation by more than 100 mm during this period. Moisture started to increase again in October due to higher rainfall (Figure 3.5). [16] [24]

Woodchips should not be stored in small (less than 200 m^3) uncovered piles, except for a short time, as they may be completely saturated with water due to rain. However, relatively dry (<30% by weight) wood chips can be stored throughout the heating period if they can be placed in covered piles.[25]

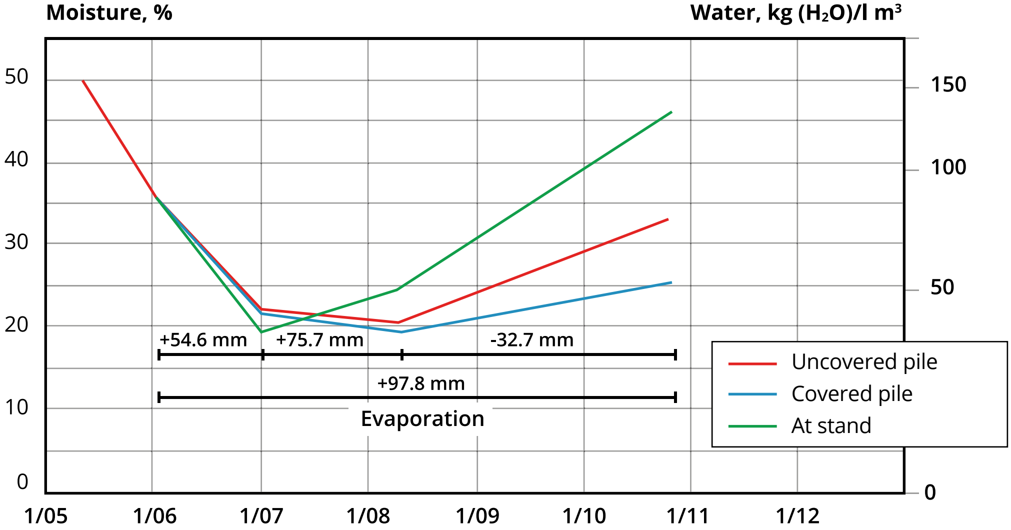


Figure 3.5. Moisture of logging residues in uncovered and covered piles at the felling site (line diagram shows the ratio of evaporation to precipitation, mm) [26]

3.3. Calorific Value and Energy Content

The calorific value is the amount of heat released under predetermined conditions by the complete combustion of one unit of fuel. The calorific value is given per 1 kg of solid fuel under normal conditions. A distinction is made between the *gross* calorific value (q_{gr}, GCV) and the net calorific value (q_{net}, NCV). The gross calorific value also includes the heat of condensation of the water vapor in the combustion gas. [27]

As the temperature of the combustion gas emitting from the combustion plant is generally higher than the condensing temperature (dew point) of the water vapor contained in it, then in practice the net calorific value is mainly used. For appliances using flue gas condensers (scrubbers), the gross calorific value may also be used to calculate the efficiency. In the case of wood as a low-sulfur fuel, the use of flue gas condensing heat is technically easy. Today, flue gas condensers are installed in almost all district heating boiler houses for boilers over 4 MW using wet wood fuel.

The technological solution of combustion plants and the practical range of capacities are greatly influenced by the moisture content of the fuel, to some extent, also by the type of wood. In small heating systems (e.g., heating systems in private houses), the moisture of wood fuel should not exceed 25 percent. If it is higher, the combustion temperature will fall below the ideal range (Table 3.3), which leads to increased heat loss and emissions and can damage the chimney.

The amount of water vapor in the combustion gas depends on the moisture and hydrogen content of the fuel. The heat of condensation per kg of water vapor is 2.442 MJ at 25 °C, and the combustion of 1 kg of hydrogen produces 8.94 kg of water vapor.

The net calorific value of wood fuel depends mainly on moisture and ash content and can be calculated using the formula:

$$q_{net,ar} = q_{net,daf} - 21.4M_{ar}/100 - 18.9A_{ar}/100, \quad (3.3)$$

where $q_{net,daf}$ – is the net calorific value of the wood fuel, J/kg [16, 22]

M_{ar} – moisture of the fuel, %;

A_{ar} – ash content of the fuel, %.

The wood fuel consists of so-called ballast material (moisture + ash) and combustible material.

The calorific value is usually expressed in MJ/kg or kJ/kg, and the mass can be either wet (as received), dry or dry ash free fuel mass. If the hydrogen content of the dry fuel, in percentage H_d, is known, the net calorific value ($q_{net,d}$) of the dry mass of the wood fuel can be calculated from the net calorific value of the dry basis ($q_{gr,d}$):

$$q_{net,d} = q_{gr,d} - 2.442 \cdot 8.94 \cdot H_d/100, \text{ MJ/kg} \quad (3.4)$$

If only the moisture content of the wood fuel is used to calculate the net calorific value of the fuel, the following formula applies:

$$q_{net,ar} = q_{net,d}\,(1 - M_{ar}/100) - 2.44M_{ar}/100, \quad (3.5)$$

MJ/kg,

where $q_{net,d}$ – net calorific value of the dry basis, MJ/kg (Table 3.5).

Table 3.5. Average net calorific value of dry basis of different parts of the most common tree species in Estonia $q_{net,d}$, MJ/kg [14, 16]

Type of tree	Stem-wood	Bark	The whole stem	Tops	Leaves, thorns	The whole tree	Stumps
Pine *(Pinus Sylvestris)*	19.31	19.53	19.33	20.23	21.00	19.53	22.36
Spruce *(Picea abies)*	19.05	18.80	19.02	19.77	19.22	19.29	19.18
Downy birch *(Betula pubescens)*	18.62	22.75	19.19	19.94	19.77	19.30	18.61
Silver birch *(Betula pendula)*	18.61	22.53	19.15	19.53	19.72	19.21	18.50
Gray alder *(Alnus incana)*	18.67	21.57	19.00	20.03	20.57	19.18	19.27
Black alder *(Alnus glutinosa)*	18.89	21.44	19.31	19.37	20.08	19.31	18.91
Aspen *(Populus tremula)*	18.67	18.57	18.65	18.61	19.18	18.65	18.32

The tables (Table 3.5, Table 3.6, Table 3.7) present the calorific values of wood fuel and the calorific values of wood fuel depending on moisture and ash for technical calculations. Table 3.3 indicates the extent to which the moisture content of the wood fuel affects the flame temperature.

The mass of the top consists mainly of leaves or needles. On regeneration felling sites in southern Finland, needles make up 26% of the weight of pines and 39% of spruce. The lower calorific value of the dry basis of pine branches with no needles is 20.09 MJ/kg, and that of spruce branches is 19.41 MJ/kg (see ratio Table 3.1). The net calorific value of the needle dry basis is 21.04 and 19.19 MJ/kg, respectively. In other words, the lower calorific value of pine needles is higher than the rest of the mass of the top, but the difference between the calorific value of spruce needles and branches is smaller. The falling of the needles thus affects the average lower calorific value of the pine more than in spruce. It is concluded that although the net calorific value of logging residues decreases due to dropping of needles, rot, and extraction of extractives, the average calorific value of the dry basis remains the same, as does the carbon to hydrogen ratio during storage. Moisture is, therefore, the only factor influencing the net calorific value of the fuel [16].

Table 3.6. Calorific value and ash content of some wood fuels [10, 24]

Parameter	Unit	Wood of coniferous trees		Wood of broadleaf trees	
		Typical value	Typical range	Typical value	Typical range
Ash, A_d	w-% d	0.3	0.2 – 0.5	0.3	0.2 – 0.5
Gross calorific value, $q_{gr,daf}$	MJ/kg$_{daf}$	20.5	20.2 – 20.8	20.2	19.5 – 20.4
Net calorific value, $q_{net,daf}$	MJ/kg$_{daf}$	19.2	18.8 – 19.8	19.0	18.5 – 19.2
		Coniferous bark		**Broadleaf bark**	
Ash, A_d	w-% d	4	2 – 6	5	2 – 10
Gross calorific value, $q_{gr,daf}$	MJ/kg$_{daf}$	21	20 – 23	21	20 – 23
Net calorific value, $q_{net,daf}$	MJ/kg$_{daf}$	20	19 – 21	20	19 – 21
		Coniferous forest residues		**Broadleaf forest residues**	
Ash, A_d	w-% d	2	1 – 4	1.5	0.8 – 3
Gross calorific value, $q_{gr,daf}$	MJ/kg$_{daf}$	21	20.8 – 21.4	20	19.7 – 20.4
Net calorific value, $q_{net,daf}$	MJ/kg$_{daf}$	20	19.5 – 20.0	19	18.4 – 19.1
		Coniferous		**Boradleaf**	
Ash, A_d	w-% d	2.0	1.1 – 4.0	2.0	1.5 – 2.5
Gross calorific value, $q_{gr,daf}$	MJ/kg$_{daf}$	20.3	20.0 – 20.6	20.2	20.0 – 20.4
Net calorific value, $q_{net,daf}$	MJ/kg$_{daf}$	18.8	18.4 – 19.2	18.8	18.6 – 19.1

Note: w-% d is the percentage of mass on dry basis; daf - (dry ash-free)

Table 3.7. Dependence of wood energy content on moisture and ash content of the fuel [28]

Moisture, M, %	Energy content E_{ar}, kWh/kg ($q_{net,daf}$=19.2 MJ/kg) according to the ash content of the consumer substance A_{ar}, %				
	1	2	3	4	5
25	3.79	3.75	3.71	3.67	3.63
30	3.49	3.46	3.42	3.38	3.34
35	3.19	3.16	3.13	3.09	3.06
40	2.90	2.86	2.83	2.80	2.77
45	2.60	2.57	2.54	2.51	2.48
50	2.30	2.27	2.25	2.22	2.19
55	2.00	1.98	1.96	1.93	1.91
60	1.71	1.68	1.66	1.64	1.62
65	1.41	1.39	1.37	1.35	1.33
70	1.11	1.09	1.08	1.06	1.05

While the calorific value is usually determined and reported in manuals per unit of mass, it is often useful to express the calorific value per unit of mass used in the boiler house to account for the incoming fuel. In the case of chopped wood, this unit is often a bulk m^3 or a m^3. In order to correlate the calorific values reported per unit mass and volume, it would be necessary to know the specific gravity and density of the respective fuel.

As the calorific value of a fuel is usually given per unit mass of wet fuel, it can cause significant inaccuracy in the event of fluctuations in the moisture content of the fuel. Another possibility is to express the calorific value per kilogram of dry basis. In the typical range of moisture content of wood fuel (up to 50%), the effect of an error in the measurement of moisture on the calorific value reported per mass of dry basis is significantly smaller (Figure 3.7) as the calorific value given for the wet mass of the fuel (Figure 3.6).

In view of the above, it is useful to know that the dry basis content of both a m^3 of wood and a bulk m^3 of wood chips is practically independent of moisture. Thus, by measuring the amount of fuel (e.g., wood chips) entering the boiler house in units of volume and knowing the calorific value of the dry basis contained in the unit of volume, the energy content of the fuel can be determined relatively accurately and there is no urgent need to determine moisture very accurately. Weighing the accepted fuel and determining the moisture content accurately and operatively is therefore not the only way to determine the energy content of the fuel, and the installation of expensive weighing equipment for fuel trucks is not necessarily necessary for proper settlement with fuel suppliers.

The accuracy of the calorific value calculation per unit mass of wood chips dry basis at moisture of 35% with a possible error of ±5% is less than 1.7% and per unit mass of the same fuel 9.24% [14].

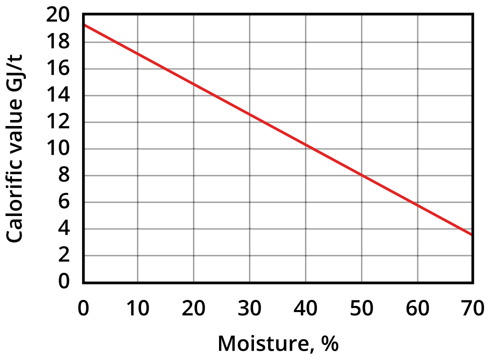


Figure 3.6. Dependence of net calorific value GJ/t of wood chips consumable on moisture, *M* [29]

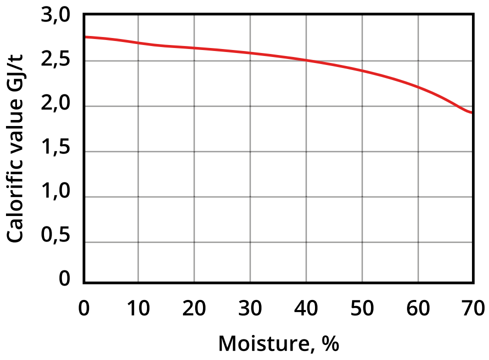


Figure 3.7. Dependence of the net calorific value GJ/s m^3 of wood chips on moisture *U* (per dry basis) [29]

3.4. Energy Density (Energy Content) of the Fuel

In practice MWh is used as a unit of heat, but the energy unit in the SI system is Joule (J) and its multiples. Instructions for converting energy units are given in the Annex (Table 13.1 and Table 13.2).

For small heating appliances (boiler houses) and households, fuel is usually sold by volume, and the energy content (net calorific value) is therefore expressed in megawatt-hours (MWh) per bulk volume. Bulk density and moisture are either measured or evaluated.

The energy density of fuel can be calculated using the following formula:

$$E_{ar} = \frac{1}{3600} \cdot q_{net,ar} \cdot BD_{ar}, \qquad (3.6.)$$

where E_{ar} – energy density of wood fuel (wet fuel), (MWh/l m^3);

$q_{net,ar}$ – net calorific value per fuel (constant pressure), MJ/kg;

BD_{ar} – bulk density of wood fuel as received (kg/l m^3);

1/3600 – is the conversion factor of energy units from megajoules (MJ) to megawatt-hours (MWh).

The result of the energy density calculation shall be rounded to the nearest 0.01 MWh/l m^3 per m^3 of bulk volume.

GJ/t, MWh/t, kWh/kg or MWh/kg for solid fuels and MWh/m^3 or kWh/m^3 for gaseous and liquid fuels are used as the unit of energy density (energy content in some sources) for wood fuels (Table 3.8). In the case of wood fuels, MWh/l m^3 or MWh/st m^3 are also often used.

In table 3.8, in addition to moisture, the ash content of the fuel has been taken into account in finding the energy density.

Table 3.8. Energy density (energy content) and bulk density of the fuel (1 MJ=0.278 kWh and 1 GJ=277.8 kWh) [30]

Fuel	Energy density by mass, GJ/t	Energy density by mass, kWh/kg	Bulk density, kg/m^3	Energy density by volume, $MJ/l\ m^3$	Energy density by volume, $kWh/l\ m^3$
Woodchips (highly moisture dependent)	7 – 15	2 – 4	175 – 350	2000 – 3600	600 – 1000
Logwood (stacked – air dry, 20% moisture)	15	4.2	300 – 550	4500 – 8300	1300 – 2300
Wood (dried)	18 – 21	5 – 5.8	450 – 800	8100 – 16 800	2300 – 4600
Wood pellets	18	5	600 – 700	10 800 – 12 600	3000 – 3500
Chinese silver grass, baled (25% moisture)	17	4,7	120 – 160	2000 – 2700	560 – 750
Coal (from lignite to anthracite)	20 – 30	5.6 – 8.3	800 – 1000	16 000 – 33 000	4500 – 9100
Fuel oil	42	11,7	830	36 500	10 200
Natural gas (Russian) by gross calorific value by net calorific value	53 48	14.9 13.4	0.7	37.4 33.8	10.4 9.4

3.5. Mineral Part, Ash, Ash Content, Ash Fusibility

A solid fuel consists of a combustible component, a mineral component, and moisture (water) (Figure 3.8). The combustible part of the fuel, in turn, consists of organic matter (in the case of wood, e.g., cellulose, hemicellulose, lignin, and extractives) and pyritic sulfur (absent in wood, wood contains a small amount of organic sulfur in organic molecules). Sulfur is an undesirable component in the fuel that is harmful to combustion plants and provides much less heat than carbon when burned. Other important elements in wood fuel are carbon, hydrogen, and oxygen (and some nitrogen) [27].

Compared in the table are concentrated chemical or elemental composition of different types of biomass, as well as moisture, ash, fly ash, and coke (Table 3.9).

Table 3.9. Typical chemical composition (elemental composition) of different types of biomass, volatile matter and fixed carbon, moisture and ash in the consumable in % by weight [31]

Biomass group	C*	O	H	S	N	VM	FC	M	A
Woody biomass	49 – 57	32 – 45	5 – 10	≤1	≤1	30 – 80	6 – 25	5 – 63	1 – 8
Herbaceous biomass	42 – 58	34 – 49	3 – 9	≤1	<1 – 3	41 – 77	9 – 35	4 – 48	1 – 19
Aquacultural biomass	27 – 43	34 – 46	4 – 6	1 – 3	1 – 3	42 – 53	22 – 33	8 – 14	11 – 38
Residual biomass of animal and human origin	57 – 61	21 – 25	7 – 8	1 – 2	6 – 12	43 – 62	12 – 13	3 – 9	23 – 34
Biomass blendes and mixtures	45 – 71	16 – 46	6 – 11	<1 – 2	1 – 6	41 – 79	1 – 15	3 – 38	3 – 43

* Abbreviations: carbon (C), oxygen (O), hydrogen (H), nitrogen (N), volatile matter (VM), fixed carbon or coke (FC), moisture (M), and ash (A).

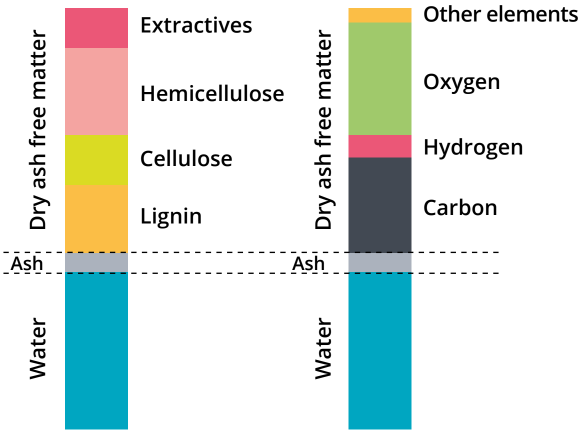


Figure 3.8. Wood fuel components (left) fuel elemental composition (right) [32]

The mineral part of the fuel is formed by the combination of mineral compounds present in the fuel in the primary form (SiO_3, CaO, Al_2 O_3, etc. Table 3.10). During combustion, the constituents of the mineral part are transferred, in whole or in part, to the ash, either in their original form, modified or in the form of new minerals [27]. The mineral part of the fuel is divided into internal and external. The internal mineral part has got into the woody plants from the soil during the growing process, therefore, depending on the mineral composition of the soil, the composition of the mineral part on the woody plants grown in different places is slightly different. The external mineral part has been transferred into the wood from the external environment, mainly during the acquisition, transport, and storage of the wood. The durability of combustion plants using wood fuel, the need for and methods of cleaning, and environmental emissions depend on the content and composition of minerals.

Ash is a solid residue from the combustion of a fuel, consisting mainly of the mineral part of the fuel, but to which some organic matter may be added as a result of complex chemical processes. Therefore, the ash from combustion cannot be equated with the mineral component of the fuel, either in composition or in quantity, although this is often erroneously done.[27] If the wood fuel did not receive the required amount of air (oxygen) during combustion, some of the carbon will not burn and may be transferred as soot to the boiler reheating surfaces, flues, and chimneys or remain in the ash (ash is dark gray or even black).

Table 3.10. Chemical composition of mineral part of wood fuel, % [22]

Component	Quantity, %	Component	Quantity, %
CaO	37 – 58	K_2O	3 – 29
P_2O_5	1 – 8	MgO	5 – 16
Fe_2O_3	1 – 5	SiO_2	3 – 22
Na_2O	0.5 – 3	SO_3	1 – 4

Table 3.11. Dry ash content of different wood species A_d, % [22]

Tree species	Stem	Bark	Branches, roots
pine	0.2 – 0.7	1.4 – 2.2	0.3 – 0.7
spruce	0.2	2.3	0.3 – 0.4
birch	0.2 – 0.4	2.4	0.3 – 0.6
aspen	0.2 – 0.3	2.7	0.3

The **ash content** of a fuel sample is determined by a laboratory method during the combustion of the fuel. The amount and properties of the ash depend on the combustion conditions (they are standardized), in particular the temperature. As a general rule, the wood fuel sample is ashed in a muffle furnace at 550 ±10 °C in an air atmosphere, and the result is expressed as a percentage of dry basis (see Figure 3.2). Ash data for parts of different tree species are presented in Table 3.11.

An important indicator in the characterization of any fuel is the **fusibility of the ash.** The melting points of the ash are determined by a standardized method, observing the behavior of an ash sample of a certain geometric shape in a heating medium. During the observation, the characteristic temperatures are determined by the external deformation of the shape of the specimen (Figure 3.9). Melting rates depend on the chemical composition of the ash, SiO_2, CaO, Al_2 O_3, and iron compounds have the greatest effect on the fusibility of the ash.[27]

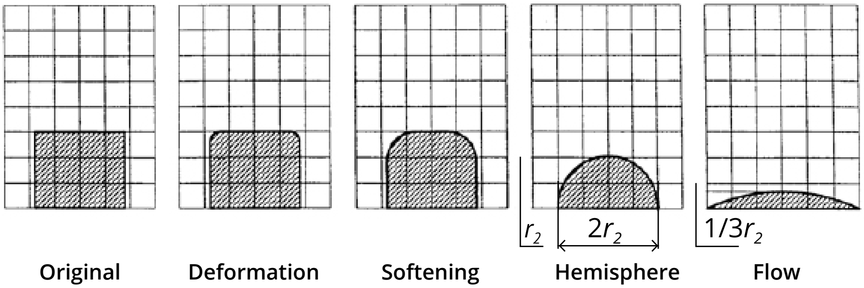


Figure 3.9. Characteristic changes in the shape of a cylindrical or cubic specimen when determining the melting characteristic [22]

The melting of the ash is characterized by the following temperatures (melting characteristics), which in the case of wood ash according to various literature sources remain in the range shown in Table 3.12:

Deformation temperature (onset of deformation – the first signs of melting of the sample and change in the upper part of the specimen, mainly rounding of the edges or expansion of the specimen), international symbol DT = 1150 – 1490 °C,

softening temperature (upper edges of the specimen rounded), ST = 1180 – 1525 °C,

hemispherical temperature (the specimen has reached the shape of a hemisphere, the height being ½ of the original diameter of the specimen), HT=1230 – 1650 °C,

flow temperature (i.e. the temperature at which the liquid ash starts to flow), FT = 1250 – 1650 °C.

Table 3.12 . Average melting characteristics of wood ash [33]

Fuel	Melting characteristics, °C			
	DT	ST	HT	FT
Whole wood chips, pine	1210	1225	1250	1275
Logging residue wood chips	1175	1205	1230	1250
Sawdust, pine	1150	1180	1200	1225
Bark, spruce	1405	1550	1650	1650
Bark, pine	1340	1525	1650	1650

Although the ash content of wood fuel as well as other solid biofuels is low (up to a few percent), the melting characteristics of the ash directly affect the operation of the boiler. Melting of the ash can cause the furnace to slag and strong deposits to form on convective heating surfaces. While in the case of bark, the ash softening temperatures are usually quite high (above 1500 °C) and do not generally cause slag of the furnace and the grate, the much lower softening temperatures of sawdust and wood chips require careful monitoring of combustion regimes to prevent slag. The melting of the ash depends on its mineral composition, and even small differences in composition can significantly alter the melting characteristics. In practice, it is not possible to reliably predict the melting of ash based on the composition of fuel and ash. [14]

The ash on the grate undergoes physical changes during the combustion process: as the temperature rises, the ash softens, up to the state where the ash particles are completely stuck together. The use of fuels with a low ash melting characteristic increases the risk of slag formation on the grate. Slag (combustion residue) melting on the furnace grate interferes with the combustion process, as it prevents the air (primary pressure) supplied from under the grate from being evenly distributed throughout the grate. This can cause the grate metal to overheat and corrode.

However, problems with slag formation can be solved, for example, by cooling the grate, arranging the flue gas circulation, installing mechanical systems for automatic cleaning of heating surfaces or using calcium supplements when burning grain with a particularly low melting point (e.g., oats have FT = 750 °C). The addition of Ca and Mg usually raises the melting point of the ash. The melting point of pure wood and bark is relatively high (1300 – 1400 °C), and therefore there are no critical ash melting problems when burning these fuels. However, the melting point of herbaceous plants is often below 1000 °C, and, as a result, slag may be formed during their combustion.[24].

Caution should also be exercised when burning different biofuel blends, especially co-combustion of herbaceous biomass (straw, meadow grass) and wood. In contrast, co-combustion of wood fuel and peat (when adding peat 10 – 15% by weight) often helps to prevent ash deposits in fluidized bed boilers.

The ash generated during combustion in the boiler can be divided into two:

Bottom ash (furnace ash) – this considerable part of the ash collects either under the grate or in a cavity at the end and is usually sent from there to a container with a screw conveyor. The density of bottom ash is 1.3 t/m^3.

Fly ash – this is the ash that flies from the furnace together with the combustion gas, is trapped in flue gas purification equipment, and can be further divided into cyclone ash, electrostatic precipitator or bag filter ash. Their properties and composition differ slightly. The density of fly ash is 0.8 – 0.9 t/m^3.

Bottom ash from clean wood fuels (furnace ash) is allowed to be used to add minerals to fields. The use of fly ash in agriculture is not recommended due to the heavy metals contained in it (e.g., it is prohibited in Sweden).

3.6. The Volatiles, Fixed Carbon and Elemental Composition of the Fuel

Upon heating, the molecules of the organic matter in the solid fuel decompose into simpler compounds, i.e., thermal decomposition takes place, during which part of the organic matter enters the gas phase and flies. This part is volatile, and the individual components of the part of the volatile are volatile components (Table 3.9 and Figure 3.2). The most important compounds in the volatile are hydrocarbons. The dry basis that remains in the solid-state after thermal decomposition is **fixed or solid carbon.**

One of the indicators of the thermal stability of the organic part of the fuel is the decomposition onset temperature, which is determined by the composition and structure of the organic matter. The more oxygen rich the fuel (but also the younger the fuel), the lower the onset temperature of thermal decomposition. Wood and peat are young and oxygen-rich fuels, and the initial temperature of thermal decomposition of wood and peat is 100 – 160 °C (wood has a lower temperature). It is not possible to quantify the volatile of the fuel unambiguously, as its amount depends on the heating temperature and time and the determination conditions. Both the volatile matter and the amount of bound carbon are given by the mass of the fuel (kg/kg), less often by the total mass of the fuel [27].

The elemental composition of wood fuels is dominated by three chemical components: carbon (C), hydrogen (H), and oxygen (O), which together make up about 99% of the dry basis. (Figure 3.2, Table 3.13) The nitrogen content (N) is usually less than 0.2%, and the sulfur content (S) less than 0.05% of the dry basis. The sulfur content of the fuel is of particular interest in terms of sulfur emissions, but higher sulfur content can also affect low-temperature corrosion in smoke passages and in the metal chimney. As chlorine can also cause corrosion of heating surfaces, it is important to know the chlorine content of the fuel. The chlorine content can cause problems, for example, when burning coniferous wood chips if the proportion of needles in the fuel is high.

Although the content of heavy metals in the wood mass is not dangerously high, their content must also be taken into account in the case of stricter environmental requirements (Table 3.14). The various parts of the wood contain small amounts of nickel, arsenic, cadmium, chromium, copper, mercury, lead, and zinc.[14].

The last two columns of Table 3.13 and Table 3.14 show the main and minor elements of different wood fuel and wood parts. For example, data from the analysis of willow on the content of heavy metals in the dry basis, mg/kg: As < 4, Cd 0.7–2.9, Cr < 2.5, Cu 2.5–3.8, Pb < 4, Zn 11–64, and Ni < 1.5 [34]

Table 3.13. Elemental composition of different types of wood fuel,% [33]

Wood fuel	**Element content on dry basis,%**					
	C	**H**	**N**	**O**	**S**	**Cl**
Whole wood (wood pulp)	48 – 50	6.0 – 6.5	0.5 – 2.3	38 – 42	0.05	<0.01
Whole wood chips, pine	51.8	6.1	0.3	41.2**	0.01	0.0042
Forest residues wood chips	51.3	6.1	0.4	4.08**	0.02	0.0076
Coniferous wood chips					0.02 – 0.045	0.011 – 0.031
Broadleaf wood chips					0.02 – 0.09	
Barkless pine sawdust	51.0	6.0	0.08	42.8**	0	<0.0050
The whole willow	49.7	6.1	0.4	42.6**	0.03 –0.05	0.0037
Pine bark	52.5 54.5	5.7 5.9	0.4 0.3	39.7** 37.7**	0.03	0.0085
Spruce bark	49.9 50.6	5.9 5.9	0.4 0.5	41.4** 40.2	0.03	0.0279
Birch bark	56.6	6.8	0.8	34.2		

* Data obtained from different sources,
** Oxygen (O) is calculated as the difference (O = 100 – other elements,%)

Table 3.14. Mineral content of different parts of coniferous and broadleaf trees in dry basis [33]

Tree species and part of the tree	Main elements, %				Minor elements, mg/kg				
	P	K	Ca	Mg	Mn	Fe	Zn	B	Cu
Coniferous									
Stem	0.01	0.06	0.12	0.02	147	41	13	3	2
Stem bark	0.08	0.29	0.85	0.08	507	60	75	12	4
Branches	0.04	0.18	0.34	0.05	251	101	44	7	4
Thorns	0.16	0.60	0.50	0.09	748	94	75	9	6
Whole tree	0.03	0.15	0.28	0.05	296	85	30	6	4
Broadleaf trees									
Stem	0.02	0.08	0.08	0.02	34	20	16	2	2
Stem bark	0.09	0.37	0.85	0.07	190	191	131	17	13
Branches	0.06	0.21	0.41	0.05	120	47	52	7	4
Thorns	0.21	1.17	1.10	0.19	867	135	269	21	10
Whole tree	0.05	0.21	0.25	0.04	83	27	39	6	5

3.7. Bulk Density

Density is the ratio of the mass of a given type of wood fuel to the actual volume. It varies from 1050 to 1350 kg/m^3 in exotic trees, but in typical European species, it is ~400 kg/m^3 in coniferous (e.g., spruce and pine), ~ 800 kg/m^3 in broadleaf trees (oak) and up to 1200 kg/m^3 in wood pellets. The density of stemwood depends on the type of wood, moisture, and the expansion (swelling) factor. The wood shrinks on average by 10 – 20% when dry and expands on average 0.1% along with the fiber, 3 – 5% radially, and 6 – 10% tangentially when wet. Density has a strong effect on wood fuel storage and transportation.

The following terms are used to describe the density of wood:

- density at standard moisture, i.e., 12% absolute humidity – ρ_{12}, kg/m^3,
- density of woody cells (substance) equal in all tree species – ρ = 1530 kg/m^3,
- density of absolutely dry wood – ρ_0, kg/m^3,
- density of wet wood fuel) ρ_{ar}, kg/m^3.

The density of different wood species at normal moisture, as well as the density of absolutely dry wood, are given in Table 3.15, and the bark density of some tree species is given in Table 3.16.

Table 3.15. Density of stemwood of different tree species, kg/m^3 [22]

Tree species	ρ_0, absolutely dry wood	ρ_{12}, at standard moisture
Larch	630	660
Pine	470	500
Oak	650	690
Maple	650	690
Birch	600	630
Alder	490	520
Aspen	470	495
Linden	470	495
Willow	430	455
Pear	670	710

Table 3.16. Bark density of some tree species, kg/m^3 [22]

Tree species	ρ_0, absolutely dry bark	ρ_{12}, at standard moisture
Pine bark	652	680
Spruce bark	715	730
Birch bark	736	745

In the case of wood fuel, it should also be specified whether the density refers to the density of individual particles or to the density of the volume of the material and whether it contains the weight of water.

Different units of measurement (kg/m^3, kg/s m^3, kg/l m^3, kg/st m^3) can be used to express the density of wood fuel.

The base density is considered to be the ratio of the dry mass of the fuel to the volume (volume of wood without air gaps), kg/s m^3.

Bulk density is the weight of the solid fuel in bulk, divided by the volume of the measuring container filled with that bulk part in accordance with ISO 1213-2:2016). It is used for wood fuel piles (logwood and wood chips) where, between the pieces of wood, there are gaps that can be larger or smaller, depending on the size and shape of the pieces of fuel. It is expressed either in kilograms per m^3 stacked (kg/st m^3) or in kilograms per m^3 of bulk (l m^3), depending on whether the heap is stacked or in bulk (Table 3.17).

Particle density is the density of a single particle (kg/m^3).

The size and shape of a single wood particle have an important effect on the determination of the bulk density (Figure 3.10). Loose logwood (left) and woodchips (middle) have a similar bulk density, but pellets (right) have a higher bulk density due to their small and uniform size.

Figure 3.10. Logwood, wood chips, and pellets in bulk [32]

Table 3.17. Densities of some tree species as roundwood, stacked and in bulk [24]

Moisture, *M*%	Beech			Oak			Spruce			Pine		
	RWE, s m^3	Fw, st m^3	Cw, l m^3	RWE, s m^3	Fw, st m^3	Cw, l m^3	RWE, s m^3	Fw, st m^3	Cw, l m^3	RWE, s m^3	Fw, st m^3	Cw, l m^3
Mass or bulk density, kg per unit volume												
0	680	422	280	660	410	272	430	277	177	490	316	202
10	704	437	290	687	427	283	457	295	188	514	332	212
15	716	445	295	702	436	289	472	304	194	527	340	217
20	730	453	300	724	450	298	488	315	201	541	349	223
30	798	495	328	828	514	341	541	349	223	615	397	253
40	930	578	383	966	600	397	631	407	260	718	463	295
50	1117	694	454	1159	720	477	758	489	312	861	556	354

1 m^3 of roundwood (s m^3) is considered here to be equivalent to 2.43 l m^3 of wood chips (0.41 s m^3/l m^3)
For clarification: RWE – roundwood; Fw – sawn and cut logwood (33 cm, stacked); Cw – woodchips.

If the quantities of fuel entering the boiler house are accepted on the basis of the bulk volume, it is expedient to determine the bulk volume according to the volume of the fuel truck and the load capacity before unloading. It should be noted that the density of the load may increase somewhat during transport, i.e., the bulk density of the fuel after loading the fuel onto the truck is slightly lower than on arrival at the boiler house.

Quantities of both timber and wood fuel are usually reported in solid cubic meters (s m^3). The ratio of m^3 to bulk m^3 is given in the table above (Table 3.17) calculated at 0.41 s m^3/l m^3, but this ratio is approximate and fluctuates somewhat.

4. Wood Fuel Quality Classes, Standards

The European Committee for Standardization (CEN) organizes the development of technical specifications for solid biofuels (including wood fuel). The technical conditions harmonize:

- terminology and definitions;
- technical conditions and quality classes of fuels;
- fuel sampling;
- determination of mechanical, physical, and chemical properties.

The need to establish technical conditions stems from the expansion of the use of solid biofuels and from many types of fuels becoming subject to international trade (e.g., pellets). Fuel quality classes facilitate communication between the buyer and the seller of the fuel and the conclusion of the contract, as both parties have to use the same terms defined in the technical specifications and indicate all the required fuel characteristics.

As a boiler fuel, a wide variety of wood-based fuels are used in practice. **Woody biomass** is biomass from trees or bushes, which can be obtained directly from the forest or plantation (so-called energy forest), wood industry residues, reusable biomass, etc.

Wood fuel can be chemically treated and contain impurities and chemicals that affect the use of these materials as fuel. Examples of impurities in reusable wood are nails, metal for electrical wires and resins and adhesives (demolition wood), resins and adhesives for wood industry residues, etc. The content of such impurities must be classified with particular precision on the basis of environmental hazards.

Wood fuel is produced, marketed, and used in a wide variety of so-called commercial forms, typical examples of which are given in Table 4.1.

Depending on the type of wood fuel, indicators are used to classify fuels in two categories:

- normative or mandatory indicators;
- informative indicators, the provision of which is desirable but not mandatory.

Fuel performance indicators for classification (either normative or informative) may include: [14]

- the origin and source of the fuel;
- the commercial form of fuel (Table 4.1);
- fuel moisture (M_{ar});
- the ash content of the fuel (A);
- fuel particle size distribution (P);
- fuel particle density (DE);
- fuel bulk density (BD);
- mechanical stability of pellets (DU);
- the carbon (C), hydrogen (H) and nitrogen (N) content of the fuel;
- content of water-soluble chloride (Cl), sodium (Na) and potassium (K);
- total sulfur content (S) and chloride content (Cl);
- content of chemical elements (Al, Ca, Fe, Mg, P, K, Na, and Ti). This group includes those chemical elements whose content is usually above a certain minimum level;
- trace element content (As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, V, and Zn). The content of these chemical elements is low but may be required due to environmental protection requirements.

Wood fuel is marketed in several different unit sizes and in many forms. The size and shape of the piece affect both the handling of the fuels and the combustion properties.

Table 4.1. Typical examples of commercial forms of wood fuel [20]

Name of fuel	Typical particle size	Common method of preparation
Whole tree	>500 mm	No preparation or delimbed
Wood chips	5 mm to 100 mm	Cutting with sharp tools
Hog fuel	Variable	Cutting with blunt tools
Stemwood/roundwood	>100 cm	Cutting with sharp tools
Logwood	50 cm to 100 cm	Cutting with sharp tools
Firewood	5 cm to 100 cm	Cutting with sharp tools
Slabs and offcuts	Variable	Cutting with sharp tools
Bark	Variable	Debarking residue from tree (shredded or unshredded)
Bundles	Variable	Lengthwise oriented and bound
Fuel powder	<1 mm	Milling
Sawdust	1 mm to 5 mm	Cutting with sharp tools
Shavings	1 mm up to 30mm	Planing
Briquettes	Ø >25 mm	Mechanical compression
Pellets (granules)	Ø ≤25 mm	Mechanical compression
Bales		
Small square bales	$0.1\ m^3$	Compressed and bound to squares
Large square bales	$3.7\ m^3$	Compressed and bound to squares
Round bales	$2.1\ m^3$	Compressed and bound to cylinders
Charcoal	Variable	Charcoal is prepared by the destructive distillation and pyrolysis of biomass.
Thermally treated wood (torrefaction)	Variable	Mild pre-treatment at 200 to 300 °C for a short time period (e.g., 60 min)

According to the standards, [20] for all fuel properties, the lowest possible class should be indicated, except for bulk density, particle density, and mechanical stability, for which the highest possible class must be indicated. Only one class needs to be defined.

Additional parts of ISO 17225 (e.g., ISO 17225-2, ISO 17225-3, etc.) have been developed to describe classified solid biofuel products. These international product standards are recommended for small appliances used in, for example, households, small commercial, and public buildings. Pellets, briquettes, wood chips and firewood (logwood) are the commercial forms commonly used for small appliances. ISO 17225-2 also deals with specifications for industrial classified pellets.

Indicators provided for the definition of solid biofuels (e.g., wood chips) express normative and informative properties (Table 4.2). In this table, wood chips are defined by quality classes.

When defining a property class, it is necessary to decide to which class the fuel belongs on the basis of the average numerical value of the total amount of fuel or a specified portion of fuel (for example, a shipload, truckload, or bag).

For example, in Table 4.2, moisture class M25 (≤ 25%) means that the moisture (M) must not be higher than 25% in order to belong to this class.

For the classification of the most commonly used biofuels, most fuel quality indicators are divided into ranges within which the respective property of the fuel may vary within insignificant limits for the consumer. For example, the moisture class M20 of wood chips indicates that the moisture content of the consumable fuel must not exceed 20%. The next moisture class M30 sets the humidity limits for consumer fuel at 20 – 30%. Other fuel property classes are used on the same principle.

Table 4.2. Specifications for the properties of wood chips and hog fuel

	Origin according to the table (Table 2.1)			Woody biomass	
	Traded form according to the table (Table 4.1)			Wood chips or hog fuel [a]	
	Dimensions (mm) ISO 17827-1				
	Main fraction [b] (at least 60 w %), mm		**Coarse fraction, w-% (particle length, mm)**	**Maximum particle length [c], mm**	**Maximum cross-sectional area [d], cm^2 of the coarse fraction**
Normative	P16S	3.15 mm < P ≤ 16 mm	≤ 6% > 31.5 mm	≤ 45 mm	≤ 2 cm^2
	P16	3.15 mm < P ≤ 16 mm	≤ 6% > 31.5 mm	≤ 150 mm	
	P31S	3.15 mm < P ≤ 31.5 mm	≤ 6% > 45 mm	≤ 150 mm	≤ 4 cm^2
	P31	3.15 mm < P ≤ 31.5 mm	≤ 6% > 45 mm	≤ 200 mm	
	P45S	3.15 mm < P ≤ 45 mm	≤ 10% > 63 mm	≤ 200 mm	≤ 6 cm^2
	P45	3.15 mm < P ≤ 45 mm	≤ 10% > 63 mm	≤ 350 mm	
	P63	3.15 mm < P ≤ 63 mm	≤ 10% > 100 mm	≤ 350 mm	
	P100	3.15 mm < P ≤ 100 mm	≤ 10% > 150mm	≤ 350 mm	
	P200	3.15 mm < P ≤ 200 mm	≤ 10% > 250mm	≤ 400 mm	
	P300	3.15 mm < P ≤ 300 mm	To be specified	To be specified	
	Fine fraction, F (<3,15 mm w-%), ISO 17827-1				
	F05	≤ 5%			
	F10	≤ 10%			
	F15	≤ 15%			
	F20	≤ 20%			
	F25	≤ 25%			
	F30	≤ 30%			
	F30+	> 30 (maximum value must be shown)			

Normative	**Moisture, M** [e] (w-% as received ISO 18134-1, ISO 18134-2		
	M10	≤ 10%	
	M15	≤ 15%	
	M20	≤ 20%	
	M25	≤ 25%	
	M30	≤ 30%	
	M35	≤ 35%	
	M40	≤ 40%	
	M45	≤ 45%	
	M50	≤ 50%	
	M55	≤ 55%	
	M55+	> 55% (maximum value to be stated)	
	Ash, A (w-% of dry basis) ISO 18122		
	A0.5	≤ 0.5%	
	A0.7	≤ 0.7%	
	A1.0	≤ 1.0%	
	A1.5	≤ 1.5%	
	A2.0	≤ 2.0%	
	A3.0	≤ 3.0%	
	A5.0	≤ 5.0%	
	A7.0	≤ 7.0%	
	A10.0	≤ 10.0%	
	A10.0+	> 10.0% (maximum value to be stated)	
Normative/informative	**Nitrogen, N** (w-% of dry basis) ISO 16948		
	N0.2	≤ 0.2%	Normative: Chemically treated biomass (1.2.2; 1.3.2) Informative: All fuels that are not chemically treated (see the exceptions above)
	N0.3	≤ 0.3%	
	N0.5	≤ 0.5%	
	N1.0	≤ 1.0%	
	N1.5	≤ 1.5%	
	N2.0	≤ 2.0%	
	N3.0	≤ 3.0%	
	N3.0+	> 3.0% (maximum value to be stated)	
	Väävel, S (w-% of dry basis) ISO 16994		
	S0.02	≤ 0.02%	Normative: Chemically treated biomass (1.2.2; 1.3.2) Informative: All fuels that are not chemically treated (see the exceptions above)
	S0.03	≤ 0.03%	
	S0.04	≤ 0.04%	
	S0.05	≤ 0.05%	
	S0.08	≤ 0.08%	
	S0.10	≤ 0.10%	
	S0.10+	> 0.10% (maximum value to be stated)	

Normative/informative	**Chlorine, Cl** (w-% of dry basis) ISO 16994		
	Cl0.02	≤ 0.02%	Normative:
	Cl0.03	≤ 0.03%	Chemically treated biomass (1.2.2, 1.3.2)
	Cl0.05	≤ 0.05%	Informative:
	Cl0.07	≤ 0.07%	All fuels that are not chemically treated
	Cl0.10	≤ 0.10%	(see the exceptions above)
	Cl0.10+	> 0.10% (maximum value to be stated)	
Informative	**Net calorific value, Q** (MJ/kg or kWh/kg of fuel) or **energy density, E** (MJ/l m^3 or kWh/l m^3) ISO 18125		Minimum value to be stated
	Bulk density (BD) (kg/m^3 per fuel) ISO 17828		
	BD150	≥ 150	Recommended to be stated if traded on a volume basis
	BD200	≥ 200	
	BD250	≥ 250	
	BD300	≥ 300	
	BD350	≥ 350	
	BD400	≥ 400	
	BD450+	> 450 (minimum value to be stated)	
	Melting characteristics of ash [f] (°C) CEN/TS 15370–1		To be stated

[a] Sometimes the raw material of hog fuel or wood chips has a high content of stones, such as stumps/roots or wood from gardens/parks.

[b] The numerical values of the dimensions (class P) correspond to the particle size (at least 60 w-%) passing through a sieve with round holes of appropriate size (ISO 17827-1).

[c] Length and cross-sectional area need only be determined for particles found in the coarse fraction. A maximum of 2 pieces in a sample of about 10 l may exceed the maximum length if their cross-sectional area is <0.5 cm^2.

[d] For measurement of the cross-sectional area, it is recommended to use a transparent grid, place the particle perpendicularly behind the grid and estimate the maximum cross-sectional area of the particle using a cm^2 grid.

[e] The lowest possible property class must be indicated.

[f] Particular attention must be paid to the ash melting characteristics of some biomass-based fuels, such as eucalyptus, poplar, and short rotation coppice.

Every consumer group and type of combustion plants need or prefer fuels with certain properties. The smaller the combustion plants, the higher quality fuel it would be necessary or expedient to use there.

The fuel performance requirements for district heating boiler houses and other major fuel consumers depend on the design features and use of the combustion plants, conveyors, and storage used. For example, if, as a general rule, in case of a household consumer, the driest possible fuel is the most suitable, whereas, in the boiler house, a boiler can be installed, the construction of which requires the use of moist fuel.

A very important indicator of untreated natural wood fuels is the range of fuel particle sizes, which is already reflected in the name of the commercial form of the fuel and largely determines the combustion technology.

A typical class of wood chips in terms of particle size can be considered to be class P45, in which case the distribution of particles in the fuel would be as follows:

- fine fraction – less than 5% by weight of the fuel has a particle size of up to 1 mm;
- main fraction – at least 80% by mass of the fuel has a particle size range of 3.15 mm ≤ P ≤ 45 mm;
- coarse fraction – less than 1% by weight of particles may be larger than 63 mm.

As can be seen from the breakdown, the classification defines the content of fine fraction and large pieces in the fuel, as both deviations from the main fraction affect the operation of the fuel conveyors as well as the combustion of the fuel in the furnace.[14]

5. Storage and Preparation of Fuels for Combustion

5.1. General

Storage is generally necessary to ensure uniform fuel supply in energy conversion plants (power plants, boiler houses, industrial plants, etc.), to improve the quality of wood fuel (e.g., to allow natural drying and falling of leaves/needles) and to optimize the logistical system. Storage is essential where the wood resource is only available outside the consumption period, such as in the Alpine countries, where the felling was conducted in the summer and heating in winter.

Some techniques also improve the storability of forest industry residues. For example, logging residues can be compressed into round bales, which reduces transport and storage volumes. In most cases, such logging residues are compressed to supply fuel to large combustion plants, as large chippers are required to break round bales. Due to the high transport volume, the transport distance of bulk logging residues (Figure 5.1) must be as short as possible.

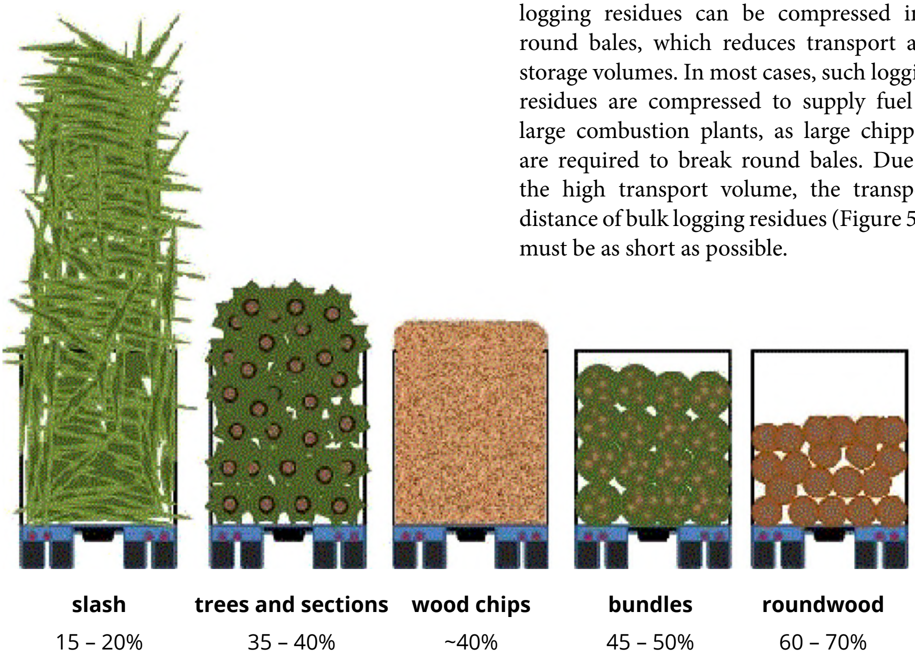


Figure 5.1. Bulk density of different types of forest-derived raw fuel compared to solid wood density (100%) and its effect on transport (truckload capacity) efficiency [32]

If, from a logistical point of view, the chopping (or crushing) of raw materials should be performed as early as possible in the supply chain (e.g., at the point of origin), in terms of quality, the opposite is right. Chopping should be done immediately before using biomass (wood fuel) in combustion plants. This is due to the fact that whole trees, stems, or even branches are protected from microbial attack by the bark, and their exposed area is quite small (only cut points), while the exposed area of refined woody biomass is extremely large. As a result, for example, in the case of storage of uncrushed logging residues or wood industry residues, the natural drying process is much faster than the decline in biomass quality due to the biological activity of microbes. One of the advantages of chopping just before combustion is that logging residues of evergreen species (coniferous, olives, eucalyptus, etc.) lose their leaves and needles during storage (standing). This improves the quality of the biomass and restores the nutrients contained in the leaves and needles in the forest storage site. On the contrary, chopped logging residues is rapidly attacked by fungi, which can cause biomass loss in large piles of wet (moist) material (up to 30% of the original biomass). In addition, the bark protects the adsorption of rainwater (snow, rain) on the entire material, while the bare wood fibers of chips are quite hygroscopic and moisten easily when stored uncovered (Table 5.1).

High humidity (M) is the main cause of fungal growth, so the best way to maintain the quality of the chopped wood pulp is to dry it (M = 30 – 35% or less) and keep it in a covered and ventilated place. Storage sites should be paved to prevent contamination of the fuel by soil. The risk of fuel spoilage and spontaneous combustion depends on the size and moisture of the stored fuel pile. In some countries, the size of the woodchip pile is considered a direct risk factor, and in the case of larger piles (e.g., 5000 m^3 in Italy) the presence of a fire-fighting device and a permanent check of the condition of the pile are required, which of course involves additional costs.

Table 5.1. The main factors influencing the storage of wood chips [32]

Factor	Effect of the factor on losses during storage	
Moisture	High moisture	Low moisture
Pile size (height)	Large (high)	Small (low)
Particle (piece) size	Small pieces	Coarse material
Losses	Large	Small

In Sweden, insurance companies have agreed to set upper limits for the height and storage time of wood fuel (wood chips) according to the following table (Table 5.2), which distinguishes between chips from compacted piles (e.g., with a tractor) and loosely compacted (or uncompacted) piles. The table shows the maximum pile heights in meters and the maximum storage time in months for the different types of wood chips, with the bottom two rows indicating industrial waste. The limiting factor is the risk of spontaneous combustion, and it must be borne in mind that the warmer the climate, the greater the risk. Thus, in southern Europe and in warm summers, even in northern Europe, the permissible pile heights and storage times may even be lower than shown in the table.

In order to ensure the security of wood fuel supply (especially for large boiler houses and cogeneration plants), it is crucial to store sufficient fuel stocks in a way that allows the quality of the fuel to be maintained or improved (including by reducing moisture by natural drying). Figure 5.2 shows the drying dynamics of woody biomass with the change in energy content and total weight during drying. The drier the stored material, the higher its energy content.

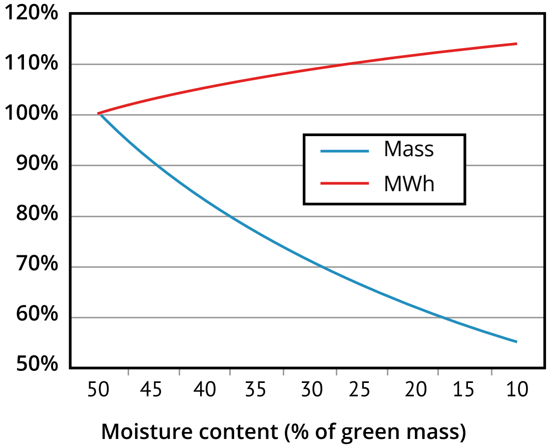


Figure 5.2. Change in mass and energy content of wood fuel during natural drying (percentage decrease in moisture on the ordinate axis and percentage increase in energy content from 100%) [32]

Table 5.2. Restrictions of Swedish insurance companies for storing woodchips in piles [32]

Raw material of woodchips	Stored in bulk		Compressed or baled	
	Maximum height, m	Maximum time, month	Maximum height, m	Maximum time, month
Stemwood without bark	10	12	16	9
Stemwood with bark	15	9	12	6
Whole tree – broadleaf tree	12	9	9	6
Whole tree – coniferous tree	10	9	7	6
Logging residues	7	6	NOT ALLOWED	
Bark	7	3	4	3
Sawdust	15	6	12	4
Sawmill residues	8	6	6	4

Storage is an essential step in any solid biomass supply chain. Storage problems are mainly related to the biodegradation of biomass. Degradation processes begin as soon as the tree is felled or the biomass is harvested, and this is generally unavoidable. However, there are some factors that are conducive to degradation, and such factors should be eliminated or avoided where possible.

In general, two main types of biodegradation can be distinguished:

- Aerobic degradation. Aerobic degradation occurs when molecular oxygen (i.e., air) can easily access the woody biomass, and as a result, the woody biomass is completely converted to carbon dioxide and water vapor. Popularly, this process can also be called rotting or composting.
- Anaerobic degradation. Anaerobic degradation can occur when the wood fuel pile is more or less airtight because it is so compact that access of air (oxygen) is impeded, there is no ventilation, or it is kept in a closed compartment.

To initiate both processes, it is necessary that the simplest sugar compounds in the cell fluid be readily accessible to the microorganisms. The first favorable condition for biodegradation during storage is the presence of chopped and moist (wet) woody biomass.

Typically, both biodegradation processes begin with the entry of mold into the material. Mold is tolerant of a wide range of moisture and oxygen content, and because mold spores are ubiquitous, mold formation begins within a few days of the wood fuel pile being built. Depending on the material stored and the climate, mold types may vary, but this has little effect on the degradation process.

Molds cannot usually digest lignin but feed mainly on starch, sugars, cellulose, and hemicellulose. However, some species produce an enzyme that breaks down lignin into simple sugars. The formation of mold has several consequences in the storage pile:

1. Heat is released. The release of heat creates a natural draft in the material. If the pile is porous, the draft can be large enough to maintain a relatively high oxygen concentration in the middle of the pile and also cool so that the temperature remains low. If the pile is more compact, the inside of the pile may be oxygen-free, and the temperature may rise there.
2. As the temperature rises, the water evaporates, and the middle parts of the pile become drier. At the same time, it must be remembered that fungi generate new water vapor as a result of their activities, so not only drying but also moisture recovery takes place. The relatively high vapor pressure in the middle of the pile, in turn, leads to a redistribution of moisture, so that the moisture (water content) in the outer and cooler parts of the pile increases.
3. The part of the organic material that is rapidly absorbed by the fungi is consumed (decomposes).

The above processes gradually change the living conditions in the material, and new species of fungi and bacteria are gradually developing. It is also clear from the first point above that, depending on the porosity of the material, the conditions can change from aerobic to anaerobic. At the same time, the water content in the outer layers of the pile increases.

Depending on the type of material stored, increasing moisture content combined with rising temperatures can provide good living conditions for fungi and bacteria that cause rot. Rot usually affects not only the cellulose and hemicellulose content of woody biomass, but micro-organisms also consume lignin and other more complex substances.

In order to minimize degradation during storage, it is important that the material is stored in a form that promotes ventilation, i.e., that the temperature rise referred to in point 1 is kept to a minimum. For some types of wood fuel, such as tree branches, this is easy to do by simply storing the material in its original form. For some types of biomass (such as grass), pores cannot be formed unless some bases are installed or it will stay to dry as a thin layer on the mowing site.

If the high porosity of the pile cannot be achieved, the piles must be low enough to allow a natural draft. In the case of wet wood chips, mixed fractions, including bark, the height may be up to 6 – 7 m, in the case of pure wood chips without bark, the height may be up to 15 m. Compact piles of crushed wet bark can reach a height of about 3 – 4 m, as can piles of most agricultural residues.

To minimize losses during storage, it is important to keep the different woody biomass fractions separate throughout the supply chain. Different fractions are usually attractive to different types of microorganisms and offer different types of advantages. Thus, one type of biomass can provide easily digestible sugars, while another assortment can provide higher moisture. Mixing the two fractions creates an environment with high levels of both easily digestible sugars and water, and these improved living conditions attract macro-organisms and increase biological degradation and loss.

Although proper storage of wood fuel can result in a loss of combustible material – i.e., a reduction in total energy content – of less than 1% per month, improper storage can lead to a total loss of the order of 10% per month or even more.

5.2. Self-Ignition of Wood Fuel

During storage, fresh lignocellulosic biomass heats up due to the respiration processes of parenchymal cells that are still alive. Such processes stop when the temperature reaches 40 °C. A further increase in the temperature of the wood pulp can be associated with fungal and bacterial metabolism. If the fungi are able to survive at a temperature of about 60 °C, the activity of thermophilic bacteria begins at a temperature of 75 – 80 °C. In special cases, the warming of the wood pulp can even reach a temperature of about 100 °C; however, the reasons for the further rise in temperature have not yet been clarified. Above 100 °C, thermochemical conversion processes begin, which can lead to spontaneous combustion, although this is very rare. Such phenomena usually occur in the case of very fine (fine sawdust) wood and wood with moist bark. Under optimal conditions for the growth of bacteria and fungi (e.g., M = 40%), the wood starts to warm up after only a few seconds. On the contrary, micro-organisms do not activate at persistently low temperatures (winter) unless they have been activated previously (Figure 5.3 and Figure 5.4).

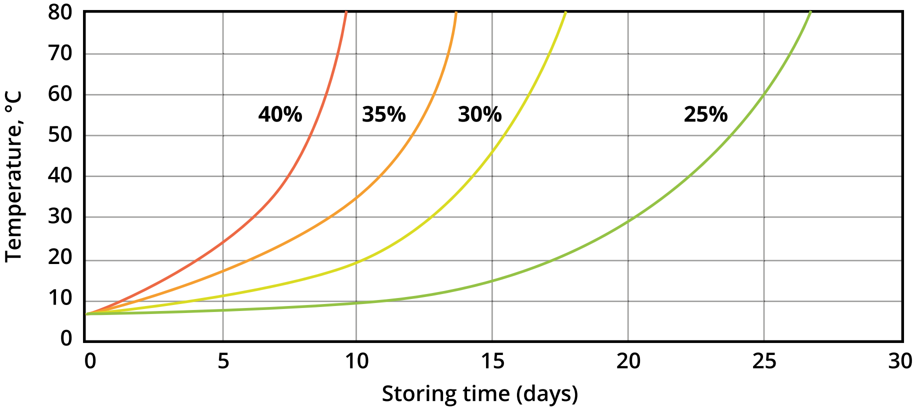


Figure 5.3. Temperature changes inside a pile of wood chips with different levels of moisture. The higher the humidity level, the faster the pile heats up [21]

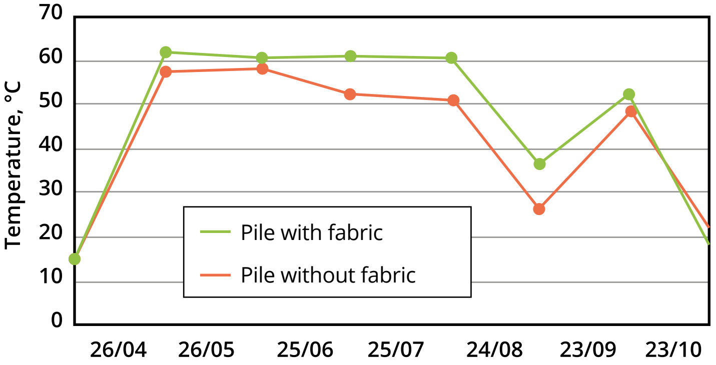


Figure 5.4. Temperature change (from April to November) in two heaps of wood chips, uncovered and covered with breathable fabric TOPTEX [21]

5.3. Loss of Wood

Due to the intensification of the metabolic activity of fungi and bacteria, the timber decomposes, and as a result, the organic mass of the fuel is lost. To minimize such losses, biological activity should be controlled as much as possible. Below is a list of measures to be taken, especially with woodchips and bark, as these fuels are most often affected by such problems.

- Keep the material with as little moisture as possible and keep it away from rain;
- Prefer natural ventilation: it accelerates heat and water loss;
- Remember that rough, coarse and regular size promotes internal ventilation of the pile;
- Use sufficiently sharp blades (normal size) when chopping;
- Reduce the presence of needles and leaves that are easily attacked by microorganisms;
- Minimize storage time;
- Choose the perfect height for the pile.

It is not always possible to implement all the above measures/recommendations, so a certain loss of wood timber must be taken into account. Some recommended values are given in the following table (Table 5.3).

The loss of dry basis can be at least partially offset by a reduction in the moisture of the material at the storage site; this leads to an increase in the calorific value of the fuel. Even when dried with heated air, the total dry basis loss is estimated at about 4%. If forced ventilation (with unheated air) is used for a certain period of time, which allows the wood mass to self-heat, the loss is doubled to 7 – 8%.

Table 5.3. Loss of wood for different types of stored wood fuel [21]

Timber/method of storage	Annual loss (dry mass),%
Fresh logging residues chips, uncovered	20 – 35
Fine logging residues chips, held covered during storage	2 – 4
Coarse fresh logging residues chips (7 – 15 cm), covered	4
Fresh bark, uncovered	15 – 22
Logwood (beech, spruce), kept undercover for 2 years	2.5
Logwood (beech, spruce), kept uncovered for 2 years	5 – 6
Fresh logwood (spruce, fir), uncovered	1 – 3
Young whole tree (poplar, willow), uncovered	6 – 15

5.4. Preparation of Logwood for Storage

Logwood lose water in winter, but most disappear in March (about 10%). Especially in hot summers (e.g., summer 2003, Figure 5.5), fresh logwood sawn and chopped in December and laid under over can reach a moisture content of 20% (M20) by June, which are suitable for sale as 'oven-ready' logwood. In wetter summers, the value of M 20% is obtained only a month later. From May, spruce dries faster than beech (oak, ash in Estonia), although the latter initially appears to be drier than spruce due to both lower moisture and faster water loss. In any case, it takes more or less the same time for both species to reach M20. In April, the maximum amount of water has evaporated from the wood, the maximum being about 90 liters per m^3 stacked per month [90 l/(st $m^3 \cdot$ month)]. From September, the moisture in the wood will start to recover at the expense of moisture from the air and rain; it is estimated that the moisture content of the wood will increase by 5 l/(st $m^3 \cdot$ month) from October to December (Figure 5.6).

Logwood stored under cover or in shelter dry somewhat faster during the early winter months. The advantage of covered wood is compensated by uncovered wood during the summer months. However, the presence of a woodshed, especially in very rainy places, is recommended as it helps to limit re-wetting in the next autumn-winter period. A suitable construction of a woodshed is with a rain-proof roof and walls that allow adequate ventilation (walls with gaps). Compared to sawn and chopped logwood, unchopped logwood do not reach the M20 moisture until two months later. Therefore, in order to be sure that the moisture reaches M20 and that such a moisture level is maintained, it is recommended to chop Roundwood logs thinner than 10 cm in diameter into logwood before storage.

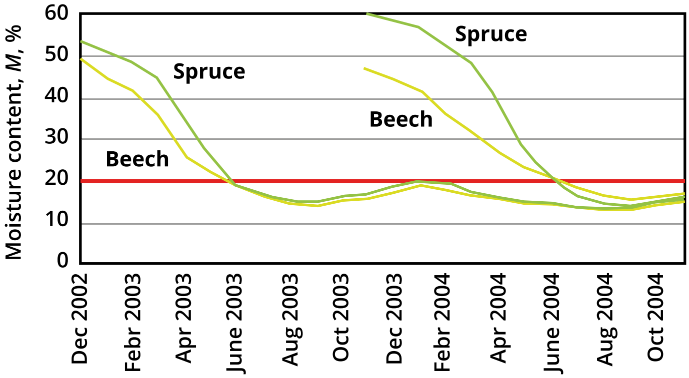


Figure 5.5. Drying process of sawn, chopped and stacked logwood, stored outdoors and covered [21]

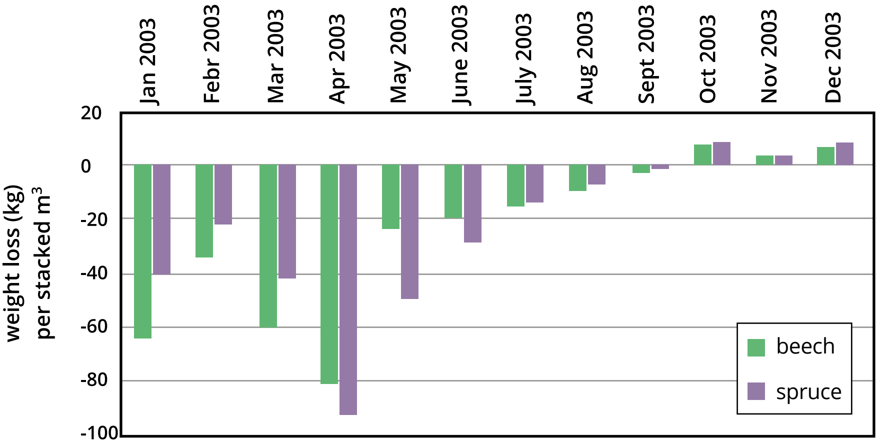


Figure 5.6. Drying rate of sawn and chopped 1 m long firewood per month when stored outdoors and covered [21]

5.5. Storage of Wood Chips

For the production of wood chips of suitable quality for use in low or medium capacity (fixed grate) boilers, the following raw timber is used: unbranched coniferous tree stems with a diameter of at least 5 cm, shavings and slabs of coniferous and broadleaf trees, stems of broadleaf trees (with or without branches) and logging residues. By avoiding finer raw materials, we limit the ash content of the fuel, because the ash content in the bark is higher than in wood.

The material, as such, may be temporarily stored on the edge of the forest or by the road (Figure 5.7), on a hard slope before being transported for chopping or chopped on-site in late summer or autumn. If this is not possible, the material must be transported to the logistics area where it is kept under cover (Figure 5.8) and later chopped (Figure 5.9).

Figure 5.7. Stored undelimbed smallwood, (photo P. Muiste)

Figure 5.8. Logging residues stored under waterproof paper, (photo P. Muiste)

Figure 5.9. Chipping of logging residues into a truck bed, (photo P. Muiste)

Outdoor storage should take place in summer, as free solar and wind energy promote the natural drying of the wood. The moisture loss of the leaves during storage usually varies between 40 and 50%. When trees are felled in May, the leaves accelerate the natural drying of the wood. The same applies to coniferous (spruce and fir) which are felled from late autumn to December and which are subsequently placed in a heap on the storage site.

If the dried timber is placed in a pile outside the forest in the sun, the freshly felled trees will reach 30% moisture by the end of the summer and are ready to be chopped (Figure 5.10). The value of M 30% is defined as suitable for storage; below this limit, wood chips are classified as suitable for storage without biological stability problems (Austria ÖNORM M 7133).

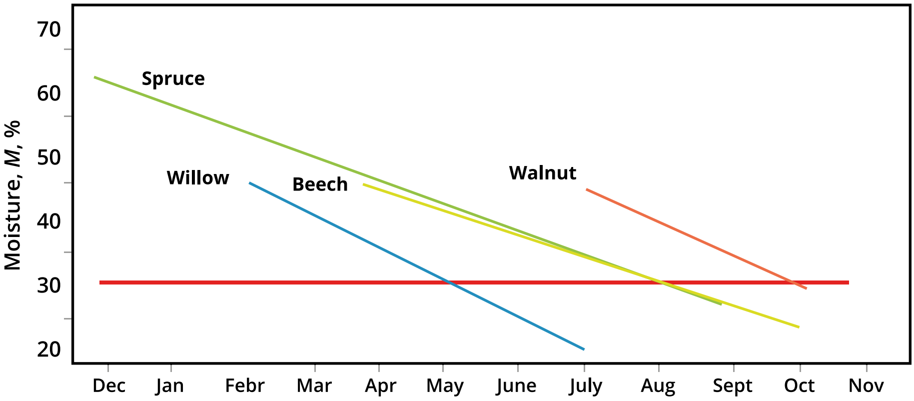


Figure 5.10. Drying process of various tree species (drying dynamics) [21]

5.6. Wood Chips' Storages and Delivery Methods

Chipped wood storages can be conditionally divided into:

- interim storage (fuel storage) – to hold approximately 5 – 7 days of fuel supply, and
- main storage – for storing up to 24 hours of fuel supply and for automated refueling of the boiler.

The interim storage of larger boiler houses and CHP plants is often an uncovered concrete or asphalted open field, but in this case, the fuel is unprotected from the weather (Figure 5.11). Often the interim storage and the main storage are located in the same building, for example, in a gable hall with a concrete floor (Figure 5.12). The interim storage can also be located in a separate covered building.

In automated boiler houses with higher capacity, a grab crane with an automatic finder is used to fill the main storage. In smaller boiler houses, a bulldozer or a wheel loader tractor is also used to transport fuel from the interim storage to the main storage (Figure 5.13).

In the case of a woodchip boiler house with a capacity of up to a few megawatts and regular fuel transport, it is possible to limit oneself to compact so-called hopper storage. The hopper storage takes up less space, and the fuel is well protected from the weather.

Hopper storage can be, even partially, drive-in storages – by opening one wall or roof of the hopper. Unloading the truck from the platform or an additional receiving device is also used. In the first case, the truck drives to a platform or elevation and tilts the fuel into the hopper from above. This option is mainly used when the truck tilts to the side. In the second case, the truck is tilted to the rear or equipped with a horizontal conveyor to empty the truck bed. A third option is to empty the truck from ground zero to a recessed hopper or to transport the fuel poured on the ground to an above-ground hopper with an additional conveyor. The use of dredged hopper storage is mostly problematic in Estonia due to the high level of groundwater.

As a general rule, the hopper must have vertical walls or expand at the bottom. Otherwise, there is a high probability of emerging of a fuel arch above the hopper emptying device. To prevent freezing of the wet fuel onto the walls and bottom of the hopper, the hopper railings are covered with waterproof (slippery) plywood. In the case of a clean and dry piece of fuel (pieces thinner than 20 mm less than 5%, moisture less than 33%), the risk of vaulting is low and therefore the warehouse may be narrowing at the bottom. The walls of such a warehouse outside the building must be insulated and also heated. The size of this warehouse is limited and must be limited to stock of one step less (for example, one day instead of three days).

Figure 5.11. Transport of wood chips by container truck or special truck adapted for the transport of wood chips, (photo P. Muiste)

Figure 5.12. Fuel storage – interim storage, (photo Ü. Kask)

6. Basics of Wood Fuel Combustion

6.1. Combustion Reactions

Combustion is a rapid oxidation reaction with intense heat release, a sharp rise in the temperature of the reaction products, and usually light phenomena (flame). In most cases, the combustion is such an oxidation reaction, which is a rapid association with atmospheric oxygen in the atmosphere, takes place.

In short, the combustion process is usually the oxidation of a fuel substance in the presence of oxygen with the release of heat and light.

The combustion process can take place in two ways: in the form of a flame and or glow. The gaseous components of the fuel burn in the room with a flame, but the combustion of carbon takes place as a glow.

The complete reaction of the fuel carbon, hydrogen, and sulfur with oxygen produces CO_2, H_2O, and SO_2, respectively. Stoichiometric (theoretical) equations can be used to determine the theoretical amount of oxygen and air required to form these combustion products, which is the minimum required for complete fuel combustion. A mass balance is drawn up according to which the mass of the reactants must be equal to the mass of the reaction products.

The stoichiometric equation for the complete combustion of carbon is:

$C + O_2 = CO_2$ + emits heat (405.8 kJ), mass balance is as follows:

12 kg C + 32 kg O_2 = 44 kg CO_2 and the same per 1 kg of carbon:

1 kg C + 2,67 kg O_2 = 3,67 kg CO_2

From this, we can see that 2.67 kg of oxygen is needed for the complete combustion of 1 kg of carbon, and 3.67 kg of carbon dioxide is produced after complete combustion. If we know the densities of the gaseous components, we can find out how much oxygen is needed to burn 1 kg of carbon and how much CO_2 is produced.

Similarly, stoichiometric equations for the combustion of hydrogen and sulfur can be described, and their mass balances compiled.

$2\ H_2 + O_2 = 2H_2O$ + heat (241 kJ) and 1 kg H_2 + 8 kg O_2 = 9 kg H_2O;

$S + O_2 = SO_2$ + heat and 1 kg S + 1 kg O_2 = 2 kg SO_2

Although the combustion of sulfur also releases heat, sulfur is a highly undesirable element in the fuel due to environmental influences and the risk of damaging heating surfaces (corrosion).

With the theoretically necessary amount of air, it is not really possible to ensure complete combustion of the fuel. The theoretical burning time of the fuel/air (oxygen) mixture would be very long and would require large-scale combustion plants, and it is difficult to obtain a uniform mixing of air and fuel (especially in the case of solid fuel) throughout the combustion chamber. Thus, in order to burn the fuel completely, it is necessary to supply an excess of air (oxygen) to the combustion chamber. This is where one important concept is introduced into boiler technology – excess air factor.

6.2. Excess Air Factor

Excess air factor (λ)[2] is the ratio of the theoretically (stoichiometrically) required air volume involved in the combustion process:

$$\lambda = V/V_0, \tag{6.1}$$

where V – the amount of air actually supplied to the furnace and

V_0 – the amount of air theoretically required for combustion.

---

[2] The letter α is also used in a number of literature sources to denote the excess air factor.

In case of stoichometric relationship between fuel and air the value of excess air factor is $\lambda = 1$. The air sucked into the gas flue ducts of combustion plants from the external environment is called false air (false air leaks occur in combustion units operating under reduced pressure). In combustion plants, the value of the excess air factor is generally kept above 1, and the value of the false air factor is kept below 1. The actual values of the excess air factors and the false air factors are determined during the thermal tests of the combustion plants. The design shall be based on the relevant manuals or product specifications (Table 6.1)

Table 6.1. Recommended values for excess air factor in the combustion of wood fuels

Furnace, boiler	Excess air factor, λ	O_2 in dry flue gas,%
Open furnace	>3	>14
Wood fuel stove (air-dried logwood)	2.1 – 2.3	11 – 12
District heating boiler (wood chips of logging residues)	1.4 – 1.6	6 – 8
District heating boiler (wood pellets)	1.2 – 1.3	4 – 5
Combined Heat and Power (CHP) plant, wood dust	1.1 – 1.2	2 – 3

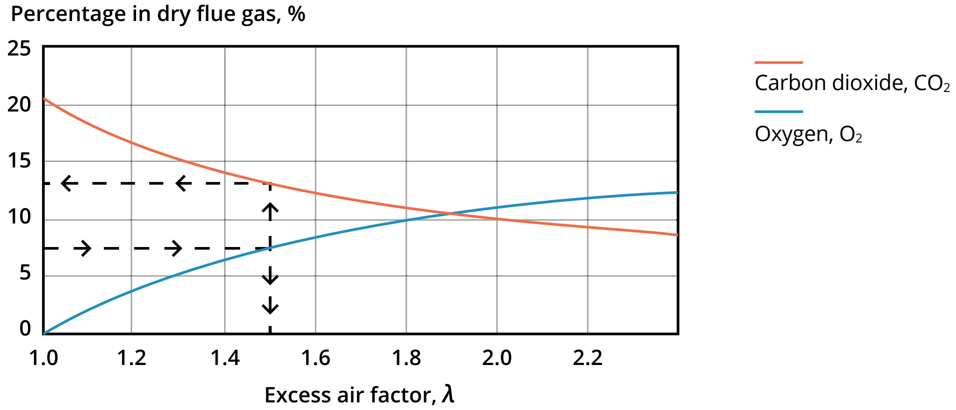


Figure 6.1. Dependence of excess air factor on O_2 and CO_2 content in dry flue gases when burning wood fuel [35]

The table and figure above show that the ideal combustion of wood chips takes place in the excess air factor range of 1.4 – 1.6. The percentage of oxygen in the dry flue gas is 7.5%. The curve shows that the percentage of CO_2 is then about 13% and the excess air factor 1.5 (Figure 6.1).

6.3 Fuel Combustion in the Furnace

The combustion of fuels in the furnace of a boiler is a physio-chemical process in which the fuel is brought into contact with an acidifier, which is usually atmospheric oxygen, and heat is released.

Fuel combustion in the furnace depends on many parameters, the most important of which are:

- the properties of the fuel to be burned (moisture, calorific value, volatile matter content, fuel particle size, etc);
- combustion method (bed combustion, dust combustion, fluidized bed combustion, and their subtypes);
- aerodynamic conditions in the furnace (ensuring even distribution of combustion air);
- temperature conditions in different zones of the process.

The heat released during combustion is needed both to dry the fuel and to remove the volatile matter (pyrolysis). As the moisture of the fuel (especially in the case of wood chips) can vary greatly, it is necessary to control and manage the temperature regime, aerodynamics, and heat exchange of the furnace.

6.4. Combustion Zones and Stages

In the combustion of solid fuels (wood fuels), combustion processes take place both in the furnace grate (combustion of solid carbon) and in the combustion chamber (combustion of the volatiles). When burning in a high-temperature environment containing oxygen, the wood particle goes through several stages or phases: heating, drying (takes place at ~100 °C), partitioning of the volatile or pyrolysis (takes place at ~150 – 160 °C in the case of wood), ignition and combustion of the volatile (the time of burning of the volatile makes up about 10% of the total fuel particle combustion time) and the longest stage is the combustion of solid (or bound) carbon.

The stages of combustion are shown in a simplified manner in Figure 6.2.

Heating, drying, and the release of the volatile are based on the transfer of heat from the surrounding environment to the particle. The volatile matter is released during the thermal decomposition of the organic part, i.e., pyrolysis, as a result of which the simpler compounds are ignited and burned as a flame at a sufficient oxygen concentration. After thermal decomposition of fuel, solid carbon remains.

The combustion of solid carbon begins after most of the volatile has been released. Despite the high volatile content of wood fuel, the longest of the combustion stages

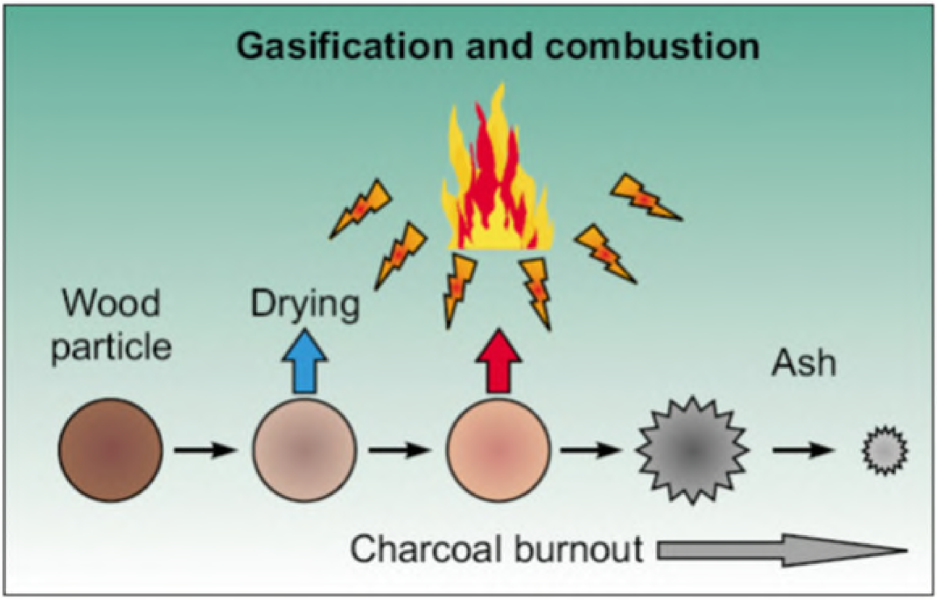


Figure 6.2. Conversion of wood particles as a result of combustion [35]

listed is the burning of solid carbon. In the combustion of a volatile (in a flame), the intensity of combustion is determined on the one hand by the rate of their release from the fuel particles, and on the other hand, by the reaction rate of the released volatile with oxygen. The burning intensity of a solid carbon particle depends on the rate of reaction of oxygen on the surface of the particle and the rate of diffusion on the surface of the particle.

The combustion of moist wood fuel can be considered from the example of burning on the grate, where some processes take place in the fuel bed and part in the combustion chamber (zones) and where the following processes or ongoing stages take place on the grate (Figure 6.3):

- drying begins as soon as the fuel enters the top of the grate, as the temperature of the bed begins to rise due to the uncooled sloping wall and flame radiation opposite the bed. In the case of preheating of the primary pressure below the grate, it also provides a certain amount of additional heat to the fuel layer;
- when the fuel temperature reaches 100 – 105 °C, pyrolysis begins, and the volatile matter (especially hydrocarbons) is released. The structure of the fuel particles becomes porous as a result of this process. Depending on the type of fuel, the fuel ignites at temperatures between 220 – 300 °C (conifer at 220 °C, broadleaf up to 300 °C and dry peat at 225 –280 °C);
- the combustion of the carbon ends at a temperature of 800 – 900 °C, and the ash falls from the grate down to the ash room;
- the processes on the grate are divided into endothermic (heat-absorbing) (drying and pyrolysis) and exothermic (heat-generating) (combustion);
- the wetter the fuel, the more heat is needed to dry the fuel and heat it to the ignition temperature. Thus, there are no heating surfaces (i.e., surfaces that can be cooled) in the furnace intended for burning wet fuel, or their share is small. The constant high temperature of the hot ceramic furnace walls is necessary for the drying zone to remain within the desired limits at the upper end of the grate and for the fuel to ignite in time;
- when burning dry fuel, cooling the furnace walls may be necessary, as opposed to burning wet fuel. In the case of dry fuel, little heat is required to dry and heat the fuel, and hot radiating surfaces and flame radiation can raise the temperature of the fuel bed to a level where the ash becomes sticky or melts. The melting of the ash clogs and damages the grate, in addition, the temperature of the ceramic furnace surfaces can reach dangerously high, and the ceramic does not withstand it and can start to melt. Thus, the design of each furnace is designed to burn fuels with a certain moisture content;
- the main part of the heat from wood is released not in the fuel bed, but in the combustion chamber because the fly ash content of wood fuels is high. The combustion of the gaseous volatile as a result of pyrolysis begins in the combustion chamber at the temperature of 500 – 600 °C. The required temperature is needed for the volatile to ignite, and in addition, fresh oxygen-rich air must be provided to the combustion chamber. While the combustion air supplied under the grate is commonly referred to as the primary pressure, the additional air required to burn the volatiles is called the secondary pressure, the need for secondary pressure being higher than the need for primary pressure when burning these fuels. It is advisable to preheat at least the secondary pressure so as not to cool the combustion zone of the volatile. The grate is, in turn, divided into sections, and each section is given a suitable amount of air. In the case of wet fuel, more air is given to the beginning of the grate to dry the fuel bed, and in the case of dry fuel, more air is given to the middle of the grate. For each different boiler, the air volumes in all sections should be determined during the thermal tests of the boiler to ensure efficient combustion. The volatile richer the fuel, the higher the volume of the furnace above the grate should be so that the whole volatile can be well mixed with the air

and so that the particles have room to burn to the end;

- in addition to the secondary pressure, some boilers are supplied with tertiary pressure to ensure perfect combustion of the volatile. It is very important that the fuel particle stays in the combustion zone for as long as possible, then one can be sure that the fuel can be completely oxidized. For this purpose, tangential direction of the secondary pressure to the zone is used to create cyclonic motion of the combustible gases. [14]

During the operation of the boiler at rated load, all processes take place on the grate (or in volume) continuously and simultaneously.

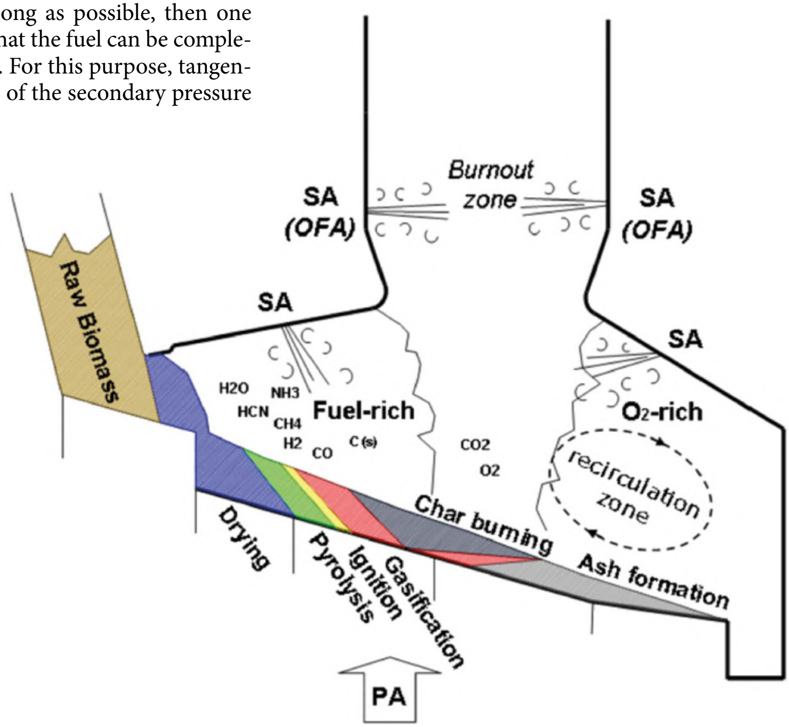


Figure 6.3. Stages, combustion zones and air distribution of wood fuel in a grate furnace (stratified combustion) in a boiler [36]

The nature and ratio of the processes in the grate in the fuel bed and in the combustion chamber directly affect the temperature regime of the furnace. The main heat-generating reaction on the grate is the combustion of carbon. However, the hot carbon dioxide formed as a result of the reaction may give off some of the oxygen and cool the bed when it comes into contact with the glowing coals in the oxygen-poor zone. A secondary bed cooling reaction can take place between the water vapor contained in the combustion air and released as the fuel dries and the glowing coal. The result of the last two reactions is that the generated carbon monoxide (CO) and hydrogen gas (H_2) increase the heat release in the combustion chamber because, in addition to the combustion of the volatile matter (hydrocarbons), carbon monoxide is burned into carbon dioxide and hydrogen. In summary, the amount of heat spent on the grate to form carbon monoxide and hydrogen is released in the furnace chamber.

The role of the endothermic reactions that cool the fuel bed in shaping the bed temperature can be increased by directing flue gases under the grate. This technique is called flue gas recirculation and can be used to burn drier fuel or fuel with a higher calorific value, but also a lower volatile matter content, in a furnace targeted for wet fuel. The main purpose of regulating the temperature of the grate and the fuel bed burning on the grate is to prevent the ash from melting and clogging the grate. If the furnace is used alternately to burn, for example, sod peat and wood chips, the use of flue gas circulation in peat heating proves to be a very suitable technique to prevent the grate from overheating and the ash from melting. Organizing the flue gas circulation also helps to reduce the formation of nitrogen oxides, as lower temperatures in the fuel bed reduce the oxidation of atmospheric nitrogen.

6.5. Combustion Losses and Combustion Efficiency

The calculation of heat loss during combustion can be based on the results of either wet or dry flue gas analysis. Losses are considered here on the basis of a methodology based on dry flue gas analysis, as this method is compatible with modern measurement techniques and makes it possible to highlight the role of fuel moisture and the water vapor generated in the combustion of hydrogen.

Combustion heat losses include:

- heat loss from the physical heat of the dry flue gas;
- heat loss from the content of carbon monoxide (CO), hydrocarbons (C_mH_n), and other combustible gaseous components in the dry flue gas. Loss is heat lost from chemically incomplete combustion;
- heat loss with ash and fly ash, which consists of two parts – the physical heat of the ash and the heat lost due to the unburned carbon contained in the ash;
- heat loss with water vapor contained in flue gases (water vapor sources are both water vapor released during drying of fuel and hydrogen vapor generated during combustion).

Water vapor is usually present in flue gases in the form of overheated steam, so this loss component is the energy content of the water vapor (more precisely, the heat of condensation and the heat of overheating of water vapor) and is taken into account when calculating the combustion efficiency based on the gross calorific value of the fuel. The heat of evaporation could be usefully used, for example, to preheat the feedwater or water returning from the district heating network in a flue gas condenser (scrubber).

The so-called indirect heat balance method is used to determine combustion efficiency:

efficiency = 100 – (minus) total losses, where total losses and efficiency are expressed as a percentage. This efficiency can be determined from the boiler balance tests.

Combustion heat losses must not be equated with boiler and boiler house heat losses, as the latter also includes several additional losses, such as boiler external cooling losses (often called radiation losses), steam boiler blow-off losses, in the case of several boilers, the flow of air (sometimes also water) through the boiler in reserve, loss of hot equipment and piping in the boiler house, etc. [14]

6.6. Possibilities for Improving the Combustion Process

Flue gas analysis directly determines the flue gas temperature, the CO_2 or O_2 content and the CO content, on the basis of which the main part of the heat loss can be easily calculated and which, in practice, people usually limit themselves to.

The greatest heat loss is usually the loss of physical heat in the flue gas, and it depends not only on the temperature but also on the excess air factor λ (in some sources α), which is defined as the ratio of actual to theoretical combustion air and is used as one of the most important combustion characteristics. Based on the flue gas analysis, the following simplified relationship is more appropriate to determine the excess air factor:

$$\lambda = CO_{2,max}/CO_{2,measured}, \qquad (6.2)$$

where $CO_{2,max}$ indicates the maximum possible carbon dioxide content for a given fuel, and its values depend on the type of fuel and, in terms of some fuels, are provided in Table 6.2.

Table 6.2. $CO_{2,max}$ values for some fuels

Fuel	$CO_{2,\,max}$, %
Coal	18.8
Fuel oils	15.9
Wood	20.2
Peat	19.6
Natural gas	12.1

Many gas analyzers do not directly measure the carbon dioxide content, but calculate it from the oxygen content:

$$CO_{2,measured} = CO_{2,max} \cdot (1 - O_2/20{,}94) \qquad (6.3)$$

The value of a practical excess air factor depends strongly on both the combustion technology and the fuel, but must always be greater than 1 for complete combustion. When burning wood and peat fuels, it is relatively difficult to ensure a very even distribution of the combustion air throughout the combustion zone, and therefore an excess air factor of 1.4 is often required to achieve complete combustion. At the same time, when burning liquid and gaseous fuels, the optimal excess air factor is usually in the range of 1.02 – 1.1.

Heat loss due to chemically imperfect combustion can be determined with high accuracy by the CO content of the flue gases. The high CO content (from 0.5%) also indicates the possible content of unburned carbon particles (soot) in the flue gases, which is easily noticeable due to the dark color of the smoke. Although here we regard only the relationship between CO content and losses, many countries also limit CO emissions due to health and environmental requirements.

Nowadays, the work of the boiler equipment is controlled by computers and the programs installed in them, but it is recommended to order special boiler emissions and balance measurements once a year or every few years. As a result, you get a good overview of the efficiency of the boiler and the possibilities to increase its efficiency. Based on the test results, the boiler work program and air and fuel supply settings can also be adjusted.

6.7. Combustion Products, Emissions, Their Effect on Boiler Operation

6.7.1. General

Research and development related to biomass combustion are progressing rapidly, partly due to the similarities with coal combustion and the many years of experience and knowledge in coal combustion. For example, the mechanisms of air emissions, ash formation, precipitation, and corrosion in biomass combustion may be somewhat similar to those in coal combustion. However, there are many types of biomass fuels, and they have different chemical and physical properties, which not only require different combustion conditions and do not cause different emissions (gaseous and solid), but also cause different problems during combustion in different plants.

In the combustion process, in case of incomplete combustion (if there is too little air) CO, C_x H_y, polycyclic aromatic hydrocarbons and tar (pitch) are formed. Oxidation produces NO_x and N_2O. The second part of the emissions is caused by inorganic compounds in biomass (incl. wood). Particulate matter (PM5 and PM10) in fly ash is volatile and harmful to respiratory organisms, and in many respects chlorine (Cl) and sulfur (S), which are present in small amounts in the form of HCl, SO_x and salts (KCl) in wood fuel boiler flue gases, are also harmful.

6.7.2. Particulate Emissions

Solid emissions from combustion in the boiler can be conditionally divided into bottom ash and fly ash. When burning wood fuel, the bottom ash falls to the bottom of the furnace (below the end of the grate) and is usually collected and transported to the collection hopper by a screw conveyor or a chain scraper conveyor. Fly ash is the part of the ash that is carried with flue gases through the boiler's flue ducts to the chimney. Fly ash is collected from under the trapping equipment (multicyclones, electrostatic precipitators, bag filters), but it should be disposed of separately as it is not recommended for use in agriculture. The use of bottom ash in agriculture is not directly restricted, as its heavy metal content is negligible.

The total amount of particulate emissions depends directly on the ash of the fuel used. The ash content of wood chips and wood pellets is generally less than 1%. The ash content of pure wood chips (debarked wood) can also be less than 0.3%. When using lower quality raw materials (contains more bark and may be contaminated with soil), the ash content can also be higher: even more than 5%, and it depends significantly on the season of fuel storage. When storing and disposing of ash, both its quantity and composition must be taken into account.

Ash formation in the combustion of biomass (incl. Wood fuel) in a grate furnace has been shown in Figure 6.4. Some of the inorganic compounds in the fuel can be released and form inorganic gaseous compounds and particulate matter (PM, fly ash and aerosols), but the rest remains in the bottom ash. It can be seen from the figure that solid particles are formed in two different ways, which causes a characteristic bimodal particle size distribution (fine particles and coarse particles). The main path for the formation of fine particles are the formation of nuclei and condensation from the gas phase. Fine particles usually consist of aerosols with a diameter between 30 and 300 nm. The second part is coarse particles, which consist mainly of non-volatile ash waste and result in fly ash particles with a diameter of $1\ \mu\text{m} < d < 10\ \mu\text{m}$. Of all the ash streams, bottom ash makes up the majority of the ash produced by grate furnace boilers burning wood fuels. The amount of bottom ash varies depending on a number of factors, such as the type of grate furnace boilers, operating conditions and fuel properties.

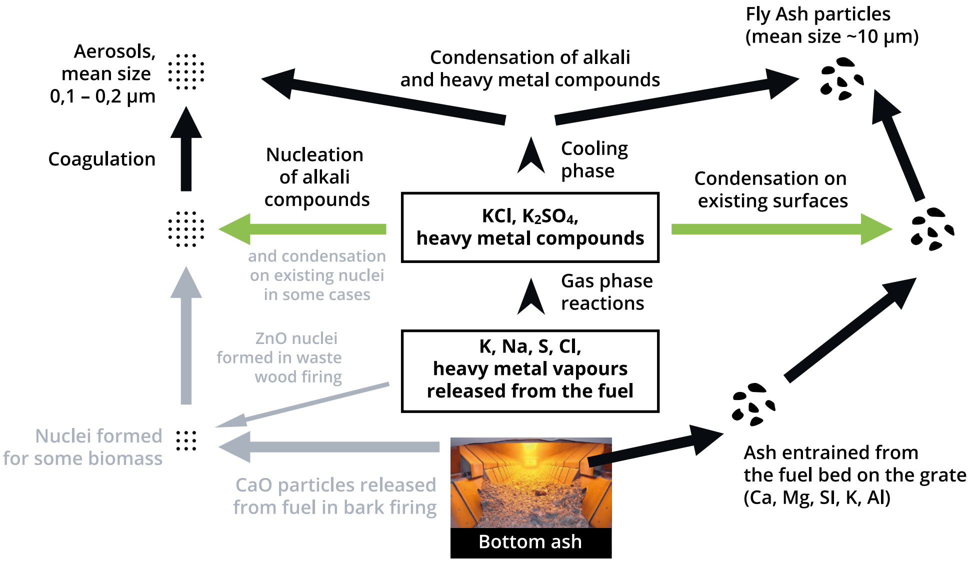


Figure 6.4. Basic scheme of ash generation when burning biomass (incl. wood fuel) with a grate furnace [36]

In grate furnace boilers, the most volatile metals in the wood fuel (e.g., Hg, Th, and Se) evaporate completely and can then be released into the atmosphere with flue gas or condensed on the surfaces of aerosols and fly ash particles.

Bottom ash from wood-burning grate furnace boilers is relatively less problematic in terms of the concentration of toxic leaching elements and can be used directly for fertilization/liming of fields or forests or sent to landfill. Compared to bottom ash, fly ash aerosols and ash particles cause more problems. First, they have a significant effect on the formation of slag and deposits on the heat transfer surfaces of grate furnace boilers, which reduces heat transfer and causes corrosion problems.[36] Secondly, aerosols increase ambient air pollution and also have a detrimental effect on health. Inhalation of aerosols from biomass combustion has been found to cause significantly more lung damage in mice than inhalation of aerosols from coal combustion, probably due to the zinc content of aerosols from biomass combustion.

The mechanism of aerosol and fly ash generation when burning wood fuel in a grate furnace boiler can also be seen in Figure 6.4.

Contamination and corrosion problems on boiler heating surfaces are one of the main manifestations that should be minimized in the design and operation of combustion plants.

6.7.3. Possible Solutions to the Problems of Deposits Formation and High-Temperature Corrosion

Both high-temperature corrosion and the formation of deposits can be mitigated during the combustion of wood fuels by the use of additives or, for example, by co-combustion with peat, coal, or sludge. High-temperature corrosion can be alleviated by the use of new tubular metal alloys or also ceramic composite coatings or by lowering the surface temperature of superheaters. The first solution is the use of additives at the melting point of the ash (in the case of wood fuels is generally not necessary). When biomass burns, some impurities prevent the release of gaseous KCl or react with KCl to form the less corrosive components. The lower the surface temperature of the ash and/or the more volatile the calcium or chlorine compounds, the greater the risk of problems due to the ash. Raising the melting point of the ash clearly increases the potential for the use of biomass fuels. Additives that raise the melting temperature of the ash in grate furnace boilers above normal temperatures are Al_2O_3, CaO, MgO, $CaCO_3$, $MgCO_3$. and kaolin. [36]

6.7.4. Gaseous Emissions

Harmful gaseous emissions include, in particular, sulfur emissions (SO_2), nitrogen emissions (NO_x)[3], carbon monoxide and unburnt hydrocarbons (C_xH_y) and carbon dioxide CO_2.

Separate treatment should be given to carbon dioxide emissions, the increase in which in the atmosphere contributes to global warming. At the same time, as biomass grows, photosynthesis absorbs as much carbon dioxide from the atmosphere as is released after subsequent combustion. On the other hand, the decomposition of biomass in nature also releases carbon dioxide into the atmosphere. If biomass is burned to the extent of its natural growth, the carbon dioxide emitted during the combustion of biomass does not affect its content in the atmosphere, and this carbon dioxide is also not taken into account as a greenhouse gas under international agreements. Another important aspect of using wood fuels is the associated land-use change.[4]

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[3] The symbol NO_x is used to denote the oxides of nitrogen NO and NO_2, in addition, nitrogen emissions may also contain laughing gas N_2O

[4] ASince 2008, the European Union has been monitoring emissions from the LULUCF (*Land Use, Land Use Change and Forestry*) sector. In order to meet the European Union's 2030 climate targets, the European Commission proposed in 2016 to include emissions from land use, land use change and forestry in the reduction of GHGs, which had so far been left out of monitoring. The Paris Climate Agreement also highlighted the critical role of land use in tackling climate change. As a result of the Kyoto Protocol, the carbon cycle from forest growth, deforestation and management is currently being monitored. However, this is only a matter of monitoring, no binding agreements have yet been reached. The exact rules for the calculation of LULUCF emissions and their implementation in the period 2021-2030 are still being negotiated between Member States.

Incomplete combustion is likely to be a major problem in the operation of grate furnace boilers and small heating installations, especially older installations, compared to, for example, a circulating fluidized bed boiler. Incomplete combustion products can also cause other pollutants. For example, the incompletely burned carbon (soot) in fly ash may, at relatively high excess air factor, even when burning wood fuel in grate furnace boilers, cause increased levels of dioxins and furans (the PCDD / PCDF or *polychlorinated dibenzo-p-dioxin/dibenzofuranes*). The situation becomes especially dangerous when, for example, solid combustible municipal waste (plastic, chemically treated or contaminated wood, etc.) is added to wood fuel. The relatively poor mixing with air in both the fuel bed and the furnace volume is the main cause of incomplete combustion in grate furnace boilers. Improved air supply systems and optimized grate systems (sectioned air distribution) can significantly improve mixing, reduce excess air consumption, improve the combustion process, and reduce pollutant generation. Another very important aspect that influences emissions is the residence time of combustible particles in the combustion zone. The more evenly the air and fuel mix and the longer the particle can remain in the combustion zone, the more likely it is to burn completely and no CO, $C_x H_y$, polyaromatic hydrocarbons, dioxins, furans and tar (pitch) are formed.[36]

As the combustion temperatures in the grate furnaces are relatively low, good mixing of the fuel with air and sufficient residence time in the higher temperature range are also particularly important for improving the combustion process. If the boiler has a water-cooled grate, relatively little primary pressure is required for cooling. As a result, combustible gases leave the fuel bed at a lower rate, and less flammable particles are removed from the fuel bed. If an improved secondary pressure supply system is used in the same boiler, which can be optimized to improve the mixing of air and combustible gases, thus improving combustion volume in the furnace, incomplete combustion emissions are reduced to a minimum. Residence time is considered sufficient if the particle can be in the combustion zone at a high temperature of above >850 °C for at least >1.5 s, and the excess air factor should be the minimum recommended for the respective boiler grate set and furnace.

Sulfur, chlorine, and nitrogen emissions depend on both their content in the fuel and the combustion process. Most biofuels do not have very high nitrogen, and sulfur content and the capture of these compounds from flue gases in biofuel combustion plants is not very common, although some measures are taken to prevent their formation.

During grate combustion, the chlorine (Cl) in the fuel mainly forms gaseous compounds (HCl) or alkaline chlorides (e.g., KCl and NaCl) and sulfur (S) mainly forms gaseous compounds (SO_2) and alkaline compounds as well as sulfates (chlorine and sulfur are mainly present in needles and bark). Due to the cooling of the flue gas leaving the furnace, a large part of the chlorine-containing salts condenses on the boiler post-heating surfaces (superheater, economizer, air preheater) or is bound to the flue gas with the remaining ash particles.

HCl and SO_2 emissions from biomass grate combustion can be regulated in different ways. The most common measures used in power plants are the installation of flue gas purification systems (however, only in large boiler houses or cogeneration plants), and the addition of pulverized limestone to flue gases or dry sorption with $Ca(OH)_2$. HCl and SO_2 emissions can also be reduced to some extent by dry sorption on the textile surfaces of a bag filter (sock filter) installed to catch fly ash.

NO_x emissions from a combustion plant are the result of various processes. Due to the relatively low combustion temperatures of biomass combustion grate furnace boilers, the percent of thermal NO_x (by combining with high oxygen at atmospheric oxygen) can be considered small or insignificant, and the main source of NO_x is the nitrogen in the fuel.

7. Combustion Technologies and Equipment

Combustion plants are used for various technological purposes:

- in boiler plants for heat production;
- in combined heat and power plants;
- for other purposes of heat production (e.g., industrial furnaces, small furnaces).

This handbook pays more attention to wood-fired boilers used in district heating boiler houses, but also briefly discusses heating appliances (boilers, stoves, heat pumps and solar collectors) targeted for heating of individual buildings and combined heat and power systems.

Boiler combustion plants can be grouped by capacity as follows:

- less than 0.1 MW – micro-combustion plants;
- 0.1 to 5 MW – small combustion plants;
- 5 to 50 MW – medium combustion plants;
- over 50 MW – large combustion plants.

The next chapter (8. Heat supply methods, systems used) deals in more detail with a number of energy converters: mainly combustion plants, but also briefly heat pumps and solar collectors used to supplement combustion plants in the heat supply of buildings.

Technological solutions for solid fuel (incl., wood fuel) combustion plants vary mainly in terms of the interaction between fuel particles and the gaseous environment. A distinction is made between layer combustion, dust combustion, cyclone combustion, and fluidized bed combustion. Solid fuel combustion technologies can also be divided into high and low-temperature technologies. Dust combustion takes place at a high temperature and fluidized bed combustion at low temperatures. [37]

- Layer or grate combustion/burning. If the fuel layer is on the grate of the furnace, it is grate burning. Grate combustion technology includes solutions with very different grate designs, which are usually divided into two main groups – technological solutions with stationary (fixed) and mechanical (mobile) grate.
- In the case of dust combustion wood fuel, used in individual cases, such as burning wood grinding dust with (or without) liquid fuel.
- In the case of cyclone combustion, intense vortex movement of fuel and air takes place in a cylindrical furnace.
- Fluidized bed combustion – either a so-called bubbling bed or a circulating fluidized bed is used.
- Fuel gasification – the generated gas is burned in either a liquid or gaseous fuel boiler, and it can also be used as fuel for a gas engine or gas turbine.

7.1. Layer Combustion

Layer combustion is historically the oldest solid fuel combustion technique, but it has not lost its importance today. For wood fuel boilers with a capacity of less than 10 MW, this is the predominant technology, which does not mean that it will not be used for wood fuel boilers with a higher capacity.

There is no movement between the fuel particles during layer combustion. Combustion air and the formed combustible gas move in the gaps between the particles. Typically, the gravity of the particles exceeds the aerodynamic drag of the combustion air from under the grate, but if some particles are very small (e.g., a fine fraction in wood chips), such particles may be carried out of the bed with combustion gas, such as ash particles emerging as a result of combustion. The fuel layer itself can be stationary (planar grate) or movable (mechanical slope grate) relative to the walls and grate of the furnace.

One of the important parameters of the layer furnace (grate furnace) is the area of the grate, the size of which determines the thermal capacity of the combustion plant. Restrictions on increasing the grate area hinder the increase of the capacity of layer combustion units. The need to increase the capacity of a combustion plant, especially in power plants, has led to the development of dust combustion technology and the creation of appropriate dust combustion boilers. Layered combustion has continued to be useful in smaller units.[37]

Of the combustion engineering solutions, grate furnaces are the most common in the range of medium and small capacities. Historically, grate furnaces were divided into manually operated and automatically fed furnaces. At present, the share of manually operated furnaces has remained minuscule, and even the boilers of single-family houses are increasingly using automatic fuel supply with suitable fuel (e.g., pellets), however, in the case of low ash wood fuels, ash removal can still be done manually for even quite large (up to 100 kW) boilers.

Although there are many types of grates, they can be divided as follows:

- fixed grate;
- mechanical rotating grate
- traveling grate
- special grates for the combustion of fuels with special properties, such as municipal waste (not covered here).

7.1.1. Furnaces with Fixed Grate

In most cases, the fixed grate is placed in the furnace at an angle that ensures that the fuel drops along the grate from the drying zone downwards to the solid carbon (coke) combustion zone. The angle of inclination of the hearth with a fixed rotating grate is approximately equal to the falling angle of the fuel used. Depending on the fuel and the design of the grate elements, the following grate inclinations are recommended [14]:

- rotating grate with bars for burning wood chips and air-dried sod peat: 32 – 36 °C;
- step grate for burning sawdust: 38 – 40 °C.

The rotating grate of barbs consists of grate elements in the direction of fuel flow, and the step grate consists of steps perpendicular to the direction of fuel flow.[38] Step grates were used in Estonia in the middle of the last century, mainly for burning wet sawdust at sawmills. The fuel supplied sinks downwards on the grate by gravity until it burns to the end, and the ash falls over the edge of the grate into the corresponding collection bin.

The rotating grates typically have a large active area (the ratio of air passages to the total grate area), and therefore the air velocity through the grate remains low, and the air distribution is uneven. To ensure a sufficient amount of combustion air throughout the grate, the excess air factor must be kept relatively high, and this reduces the combustion efficiency. In modern boilers with a moving grate furnace, the active area of the grate is only a few percent, the air distribution is relatively even, and therefore the efficiency is higher.

In addition to single-sided rotating grates, conical rotating grates (Figure 7.1) are used, to which the fuel is supplied either by a snail feeder from below or by gravity from above. The conical grate can be either stationary or rotating grate floors (Figure 7.3).

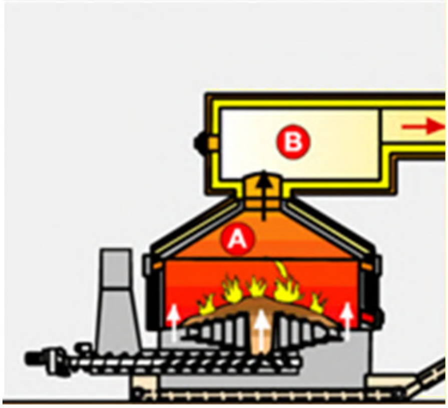

Figure 7.1. A. Primary combustion chamber with a rotating grate rate

B. Secondary combustion chamber. [39]

7.1.2. Furnaces with Moving Grate

Compared to fixed grate combustion chambers, the movement of grate elements allows better control of the movement of the fuel bed, more even distribution of fuel and air on the grate, and ultimately more efficient combustion and reduction of harmful emissions, especially carbon monoxide (CO) content in flue gases. One combined solution is a two-part grate, the upper side of which is a stationary grate part with a drying and pyrolysis zone, and the lower side is a combustion zone with less rotating movable elements.

The grate links of a furnace with a moving grate are moved either over a row (one row of grate links is immobile, the next is mobile, etc.), in a chessboard composition, where the links in the same row move over one or the grate rows are moved alternately, first some rows, then different rows (Figure 7.2. Moving the grate elements ensures an even thickness and smoother advancement of the fuel bed.

In the case of very moist fuel, the walls of the furnace are, as a general rule, without cooling and made of ceramic materials (Figure 7.3), the operating temperature of which is high enough that the radiation from the heated walls provides sufficient heat to dry the fuel, remove the volatiles and create suitable combustion conditions both on the grate and in the combustion zone of the volatiles. If dry fuel is burned in such a non-cooled furnace, even for a short time, the temperature will start to rise rapidly both in the fuel bed and in the furnace chamber. The results can be melting of the ash, slagging of the grate and its air vents, as well as damage or even melting of the masonry of the furnace.

Figure 7.2. Moving grate for burning wood fuel [40, 41]

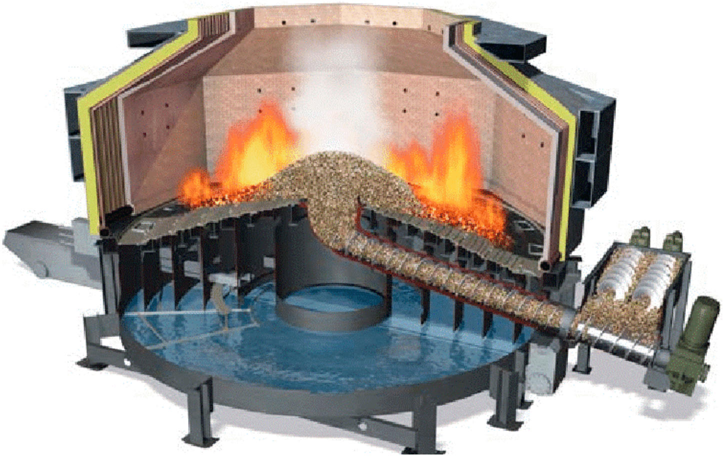

Figure 7.3. Wärtsilä's patented combustion chamber BioGrate with a conical grate fed from below [42]

Wärtsilä's patented combustion chamber with conical grate allows the burning of fuel with both extremely low and high (up to 65%) moisture (Figure 7.3). With BioGrate combustion technology, the fuel is fed to the center of the conical grate with a snail feeder, from where it flows down the surface of the cone. Practically any biofuel that can be fed to the furnace with a snail feeder can be used.

The conical grate consists of concentric circles or floors, where the stationary and rotating floors alternate, and every second rotating grate floor moves in a different direction, i.e., one counterclockwise and the other clockwise. The movement of the BioGrate grate ensures a particularly even fuel over the entire circumference and surface of the grate. Hydraulic drives are used to move the grate floors. The ash and slag that have dropped from the grate enter the under-grate chamber filled with water, from which it is removed through a wet ash removal system.

The key to high combustion efficiency and minimum emissions is a system of efficient air distribution and control that includes air fans with adjustable speed. In addition, adjustable flue gas recirculation (circulation) is used, which allows regulating the heat release of the fuel bed in the zone of volatile emissions and ensures clean combustion with low NOx and CO emissions in a very wide range of fuels.

The outer diameter of the conical grate depends on the capacity of the furnace, with a diameter of 4.15 m for the smallest capacity of 3.5 MW and 9.5 m for the largest capacity of 20 MW.

If furnaces suitable for burning wood fuels are designed as pre-furnaces, they must be connected to a suitable boiler in the boiler house. Many manufacturers design and supply the furnace and boiler as a single unit, especially for lower power units. In such devices, it is easier to organize, for example, ash removal from under the grate, from vertical flues and from under flue gas purification devices. In the 1990s, when Estonia urgently needed to switch from imported heavy oil to domestic fuels, the existing oil-gas boilers were used, and pre-furnaces were installed for burning wood fuels and also peat.

If it is recommended to burn dry fuel in the boiler, the walls of the furnace must be cooled by means of the heating surfaces placed there. The type and the level of moisture of fuel that can be burned in this furnace depend directly on the cooling conditions of the furnace walls. In the case of burning dry fuel, such as pellets or furniture industry residues, the furnace temperature is kept within suitable limits, in particular by cooled furnace walls, and it may be necessary to design the volatile combustion zone so that the flame radiation does not fall completely on the fuel bed.

When burning moist fuel in such a cooled furnace, the temperatures on the grate remain low because the drying conditions of the fuel are not sufficient. The result is unburned fuel particles entering the ash, and incomplete combustion of the volatiles, which dramatically reduces the combustion efficiency and the ingress of soot and unburned gases into the chimney, as well as the heating surfaces and flues can get pitched.

Combustion air ducts can be located in the walls of the furnace, which cool the walls to some extent, but at the same time, the combustion air is pre-heated, and it improves the combustion conditions of wet fuel. Such furnaces are very common and are well suited for the combustion of moderately moist fuels, such as forest chips (logging residues chips) with a typical moisture range of 35 – 55%. [14]

7.1.3. Furnaces with Traveling Grate

Traveling grate is in (Figure 7.4), and a furnace with a traveling grate boiler is shown in the figure (Figure 7.5).

The fuel is directed from the hopper directly to the closed-surface traveling grate, which consists of individual links. The layer height can be adjusted with the layer damper. By changing the speed of the traveling grate, it is possible to very flexibly control the advancement speed of the fuel from the drying zone to the complete combustion of carbon and the removal of fuel-free ash. When switching from one fuel to another, for example, from wood chips to coal, the speed of the grate and the amounts and ratios of combustion air must be changed. The main thing is that the grate is so-called drop-proof, which prevents the finer particles of fuel from dropping through the grate into the air distribution boxes below.

As the grate moves horizontally, the fuel dries and heats up, ignites, burns (the layer thins), and the remaining ash and slag flow over the end of the grate into the ash hopper. The air supplied under the grate is sectioned (separated so-called air boxes) because the intensity of fuel combustion is not uniform throughout the grate. The combustible gases leaving the fuel layer burn at the expense of the secondary air supplied to the furnace chamber.

Traveling grates are well suited for burning several fuels in the same furnace at higher capacities. If the main fuel is wood chips, it is also possible to use peat and coal.

7.2. Pulverized Combustion

The first attempts to burn solid fuel in pulverized form were made more than a hundred years ago. This combustion technique is particularly common in boilers for high-power energy equipment. In the case of the largest ones (steam at supercritical parameters), the thermal capacity of the boiler reaches up to 3000 MW. High parameters allow achieving 40 – 43% efficiency of the power plant with such boilers. Pulverized combustion boilers are rarely used to burn wood fuel, and then their capacity is lower than on the combustion of coal and lignite. Large-scale boilers can also be used for co-combustion of coal and biofuels.

In the furnace of a pulverized boiler, solid fuel (coal, lignite, oil shale, etc.) is burned in a particularly finely ground form, as so-called dust fuel (Figure 7.6). The median particle diameter characterizing the granulometric composition of dust is in the range of 30 – 60 μm. The pulverized heating furnace or chamber furnace is equipped with burners and shielded (surrounded by heat exchange surfaces) with a square or rectangular cross-section. The heat of the combustible fuel and combustion gas is transferred to the heat exchange surfaces covering the inside of the furnace walls, i.e., to the furnace screens (pipes).

Depending on the particle size of fuel entering the power plant, the fuel may first be crushed by roller or jaw crushers, and the fuel passed through them is directed to mills (ball mill, hammer mill) where the desired fineness of dust is achieved. Grinding can also be done in special fans. Fuel dust travels from the mills by the primary air through the burners to the furnace. A high-temperature flame is formed in the furnace, in the core of which the temperature can reach 1400 – 1700 °C. The ash stream is divided into slag (bottom ash and slag) precipitating at the bottom of the furnace and fly ash, leaving with the combustion gas.

Combustion of pulverized fuel leads to significant problems, such as intensive contamination of heating surfaces (especially in the case of ash-rich fuels), the intensive formation of nitrogen oxides from atmospheric nitrogen, and relatively complex flue gas purification.

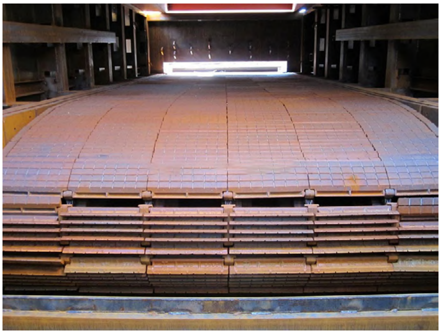

Figure 7.4. Traveling grate [43]

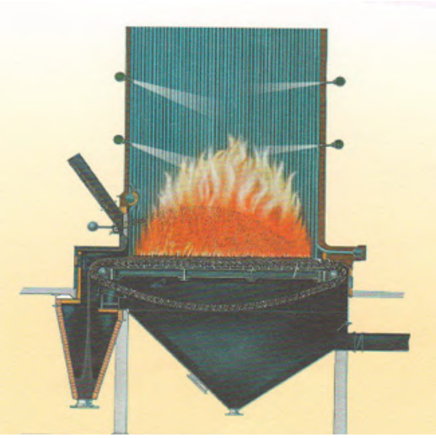

Figure 7.5. Boiler furnace with traveling grate [44]

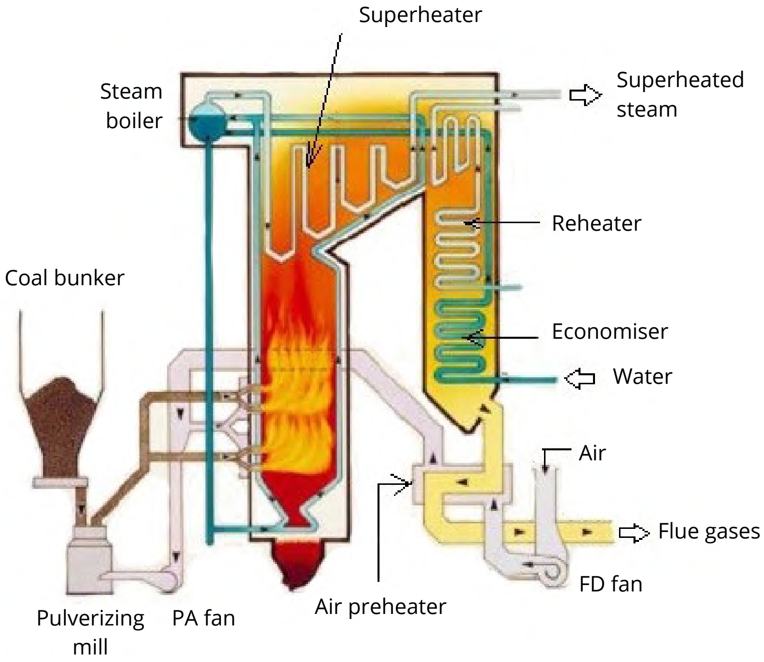

Figure 7.6. Dust fuel (coal) boiler (the part of the steam boiler furnace and heating surfaces is delimited by a brown line) [45]

7.3. Cyclone Combustion

The cyclone furnace is an internally lined ceramic cylinder in which the primary air and fuel are directed axially, from the center of the burner to the beginning of the furnace and the high-speed secondary air is directed tangentially, creating an intense vortex in which the fuel and air mix well (Figure 7.6.). The more suitable diameter of the fuel particles is usually 4 – 6 mm. The cylindrical part can be uncooled or cooled, i.e., shielded by water pipes. The temperature in the furnace depends on the properties of the fuel being burned but is usually not below 1600 °C. Combustible gas heats the pipes, and the heat is transferred to the water, which evaporates. The peculiarity of this type of furnace is that due to the high combustion temperature, the slag melts, sinks to the bottom of the furnace, and leaves the furnace as a liquid. The furnace is placed at a small angle so that the liquid slag can spill out. The combustion gas leaving the furnace proceeds to the post-combustion chamber, to which tertiary air is also added to ensure more complete combustion, from where the remaining molten ash parts of the combustion gas precipitate out. The proportion of fly ash leaving the boiler is small. [37]

A wide variety of fuels can be burned in a cyclone furnace: bituminous coal, lignite, mineral-rich anthracite, wood chips, petroleum coke and old tires. Although the combustion method is not very widespread, all the listed fuels have been burned in this way.

Four advantages have been taken into account in the design and construction of cyclone furnaces:

- lower fuel preparation time and costs (compared to dust combustion);
- small and compact furnace;
- small amount of fly ash, as most of the ash is removed as liquid slag;
- flexibility in fuel use.

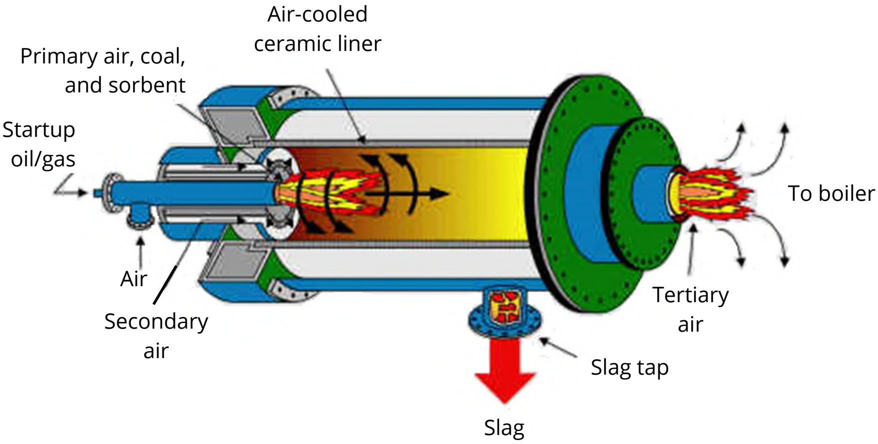

Figure 7.7. Horizontally placed cyclone furnace [46]

7.4. Fluidized Bed Combustion

The beginning of the fluidized bed technique is considered to be 1921, when Fritz Winkler (Germany), who passed the combustion gas through the coke particles in the grate, noticed that in the case of a balance between the gravity of the particles and the aerodynamic drag of the fuel bed, the fuel particles do not escape from the fuel bed but form a floating state similar to that of boiling liquid. It was called a fluidized bed, which can also be considered a pseudo-liquid (a complex hydrodynamic system - suspended solids in a gas stream). The velocity of the gas flow or air must not exceed the speed of the pneumatic transport of the particle, because then the particles would be carried out of the bed together with the gas flow. [37]

Solid fuel fluidized bed combustion technology, in its diversity, has found widespread use today and is constantly evolving and improving. Boilers using this combustion technology have a power range of a few megawatts to 1500 MW. The latter has a circulating fluidized bed. The range of fuels that can be burned in these boilers is also wide, from biofuels to anthracite. Nowadays, fluidized bed boilers (with a capacity of 50 – 150 MW) are mostly installed in medium-capacity combined heat and power plants using wood fuels.

The reason for the increasing spread of fluidized bed technologies is the possibility to use different low-quality fuels in the same furnace. Another great advantage of these boilers is that they make it easier to meet increasingly stringent emission limits, especially for sulfur dioxide and nitrogen oxides. When burning sulfur-rich coal, sulfur compounds can be bound with ash by adding sorbent (limestone) (oil shale ash contains sorbent, and it does not need to be added.

NO_x from atmospheric nitrogen is low in fluidized bed combustion because the temperature in the fluidized bed furnace is much lower than in a pulverized combustion furnace and, in most cases, ranges from 750 to 900 °C. The lower temperature of the range is determined by the stable combustion of the fuel and the upper by the sintering of the ash. [37]

One of the good properties of the fluidized bed is the high concentration of solid particles and the resulting high heat capacity, which exceeds the heat capacity of the gas by more than 1000 times. Also, considering the intense heat transfer between the particles and the gaseous medium, the temperature distribution in the fluidized bed is very uniform.

An important structural element of the fluidized bed furnace is the grate at its lower part (which can also be only air nozzles), through which the air necessary for burning fuel and also keeping the boiling bed in a floating state is supplied to the furnace. It differs from the grate of a boiler with a grate furnace in terms of simplicity of construction and considerably smaller free cross-section. This grate forms a pre-resistance to the air, which is necessary for a more even distribution of air across the cross-section of the furnace. By gradually increasing the velocity of the combustion air supplied to the fuel bed, it is possible to reach a situation where the fuel bed is lifted by the air, the fuel particles begin to float in the airflow and are constantly relocated in the floating bed. It looks like the layer starts to boil. The described floating fluidized bed is called a stationary fluidized bed, or due to the nature of the process, a bubbling fluidized bed, and moisture, released volatile matter and ash are removed from the fuel layer by airflow, as well as a small amount of fine fuel particles which burn together with the volatile in the furnace chamber above the fluidized bed (Figure 7.8, B). [14]

As the velocity further increases, a turbulent layer with a uniform structure begins to form, and the number of particles emitted from the layer increases. The turbulent layer is characterized by the formation of particle colonies and gas cavities and their reciprocating motion. The layer has an upper limit, but it is not clearly identifiable, and a definition - turbulent fluidized bed is used for it.

By using an even higher air velocity, combustible fuel particles are entrained in the airflow. In the cyclone separator, the solids are separated from the air and gas flow and returned to the furnace. As the burning fuel is circulated between the furnace and the separator, the term "circulating fluidized bed," is used for this type of combustion (Figure 7.8 C). [14]

According to the speed of air, fluidized bed combustion technologies are divided into subtypes:

- classic or bubbling, slow fluidized bed;
- turbulent or fast fluidized bed;
- circulating fluidized bed.

The first two of these are the so-called stationary fluidized bed.

The bubbling fluidized bed is well suited for burning biofuels, peat, and residues, the circulating fluidized bed is better suited for coal and oil shale, but biofuels can also be burned together with the main fuel.

The general requirement for fluidized bed technology for fuels is a relatively uniform piece size. When burning biofuels and peat, a bubbling fluidized bed is formed of an inert material, usually of quartz sand, which is heated to about 600 °C by gas or liquid fuel burners when the furnace is started before the base fuel bed is applied. The main fuel supplied to the bed then ignites, the temperature of the bed begins to rise, and the auxiliary burners used for ignition are switched off. Both the sand pad and the fuel bed burning above it float. If the sand particles wear out during friction, their finer fraction is transferred out of the furnace with the combustible gas, and at the same time, new sand is added from time to time.

There are several ways to feed fuel into the bubbling fluidized bed:

- feeding the fuel through a vertical pipe from above to the fluidized bed, sometimes with the additional mechanical injection of fuel over the cross-section of the furnace;
- feeding fuel through a horizontal channel into the fluidized bed by either pneumatic transport or screw conveyor.

Unlike grate hearths, which are difficult to operate at low capacities, a bubble fluidized bed furnace with a sand bed can operate efficiently over a very wide range of capacities, due to the high heat capacity of the sand bed and ash for a short time even without a load.

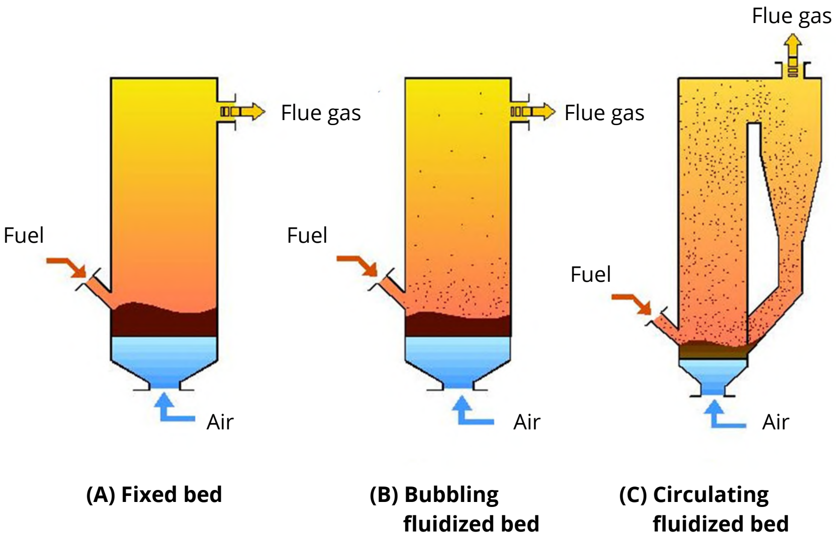

Figure 7.8. Furnaces with fixed bed (A), bubbling fluidized bed (B) and circulating fluidized bed (C) [47]

One practical example of the application of fluidized bed technology is the fluidized bed boiler of the Finnish company Putkimaa OY, the scheme of which is given in Figure 7.9. [14]

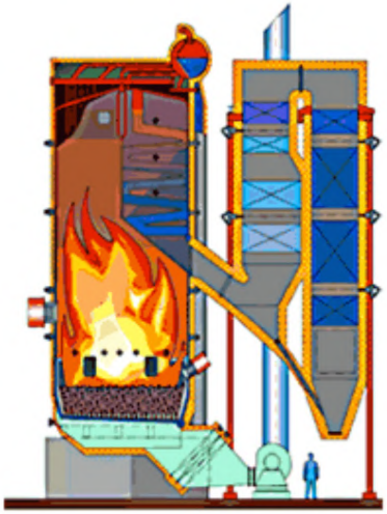

Figure 7.9. Fluidized bed boiler (Putkimaa Oy).

7.5. Gasification of Solid Fuels

Thermal gasification is an endothermic (heat-absorbing) thermal fuel conversion technology in which solid (or liquid) material, e.g., wood, is converted into a combustible gas (gaseous fuel, generator gas, syngas). This process takes place at high temperatures with the limited participation of free or bound oxygen (air, water vapor, etc.). Unlike the treatment of fuels without access to air (combustion, pyrolysis, cracking), almost all the fuel contained in the fuel becomes gases (CO, H_2, CO_2, partly also oil) during gasification.

Biomass gasification is a complex process consisting of several successive stages (Figure 7.10):

- thermal conversion of biomass to gas, condensable vapors, and coal;
- subsequent thermal cracking of the vapor into gas and coal;
- gasification of coal with steam or carbon dioxide,
- partial oxidation of combustible gases, vapors, and coal.

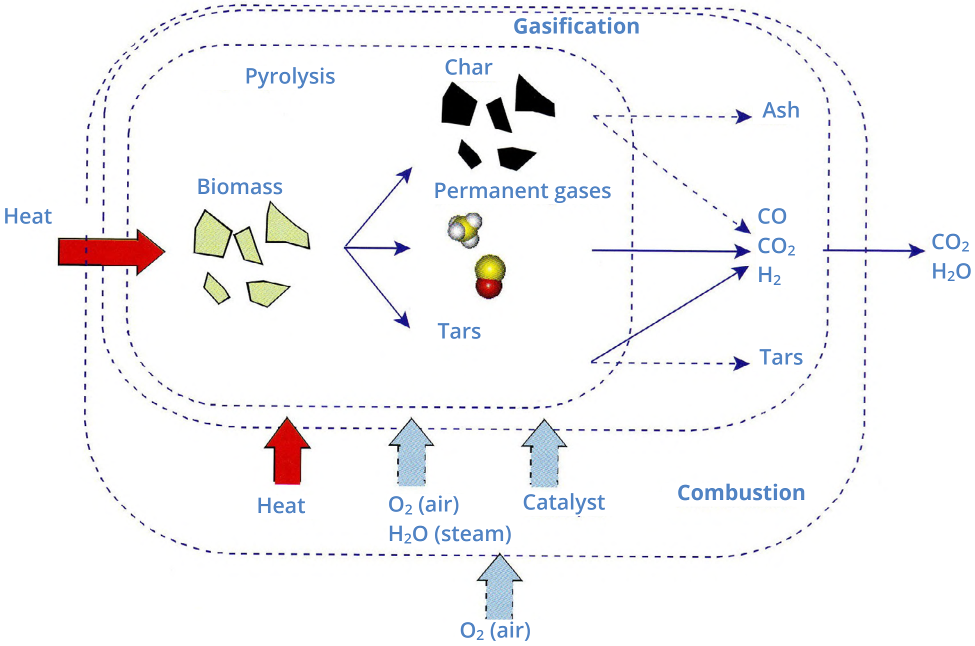

Figure 7.10. Schematic diagram of the biomass gasification process [48]

The gasification takes place in a reactor (gasifier), the types of which differ in the direction of fuel and gas flow. In the reactor shown in Figure 7.11, the fuel moves from top to bottom into the reactor, first dries, then undergoes pyrolysis, followed by combustion and finally reduction, resulting in a final product of gas mix with an average of 22% carbon monoxide (CO), 18% hydrogen (H_2), 3% methane (CH_4) and out of non-combustible, 6% carbon dioxide (CO_2) and 51% nitrogen (N_2). The resulting gas mix is cooled, purified of particulates, and then fed to a gas engine or gas turbine. If the resulting gas is burned in a boiler, the purity requirements for the gas are less stringent.

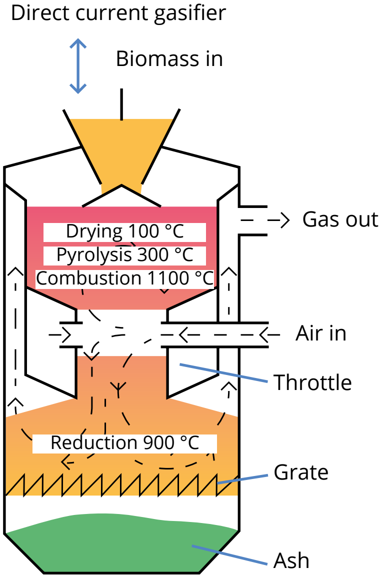

Figure 7.11. Schematic diagram of a wood gas generator (gasification reactor)

The gas obtained from the thermal gasification of biomass is a so-called medium quality gas with a calorific value in the range of 10 – 18 MJ/nm^3 (2.8 – 5 kWh/nm^3). This gas can be burned directly in boilers and, after purification, also in internal combustion engines and gas turbines, which are part of cogeneration units (Figure 8.29 – Figure 8.31) or operate heat pump compressors, but also vehicles. The purified gas obtained from the gasification of biomass can also be used as a motor fuel for vehicles (buses). The gas from the gasifiers can also be converted to, for example, methanol.

The principles of biomass gasification were already known at the end of the 18th century, at first, this technology was used to supply gas lamps with combustible gas, but later, during the Second World War, also to produce motor fuel. The next major wave of the use of this technology came during the oil crises of the 1970s and 1980s when it was necessary to replace the oil fuels that had undergone a sharp rise in prices.

There are two main types of gasification equipment; with a stationary bed (fixed fuel bed) and fluidized bed reactors. Stationary gasifiers are traditional and are distinguished by the direction of airflow: upstream, downstream, and cross-flow reactors. Depending on the direction of fuel and gas flow, the gasifiers operate according to either a forward or reverse flow scheme. The energy content of the resulting gas is about 75% of the calorific value of the original precursor, but it is important that the moisture content of the fuel to be gasified (e.g., wood) should be as low as possible and not more than 15 – 20% for downstream gasifier producing a cleaner gas. Most gasifiers use air and steam to carry out the process.

The capacities of gasification equipment with a fixed fuel bed are up to 10 MW in the case of a downstream scheme and up to 20 MW in the case of an upstream scheme. For even higher capacities (10 – 100 MW), fluidized bed gasifiers are used.

From gasification reactors in local heating boiler houses and district heating boiler houses, the gas is fed to the post-combustion chamber and the recovery boiler (Figure 7.12). Recently, biomass gasification reactors have also found wider use in combined heat and power plants (Figure 7.13).

Higher capacity gasification reactors are usually either stationary fuel and gas countercurrent reactors or fluidized bed reactors. In the countercurrent scheme, the gases contain tar, soot, and ash from the pyrolysis (gasification) process, while this technology also allows the gasification of low-quality, i.e., moist and ash-rich, fuel. The resulting gas is suitable for combustion, but the gas ducts must be cleaned periodically. If the resulting gas is cooled and purified, it can also be used as a fuel for internal combustion engines and, thus, also in gas-fired CHP plants. Downstream gasification reactors provide tar-free hot gas, but it still requires purification from ash and soot, and this type of reactor requires the use of relatively dry fuel with low ash content.

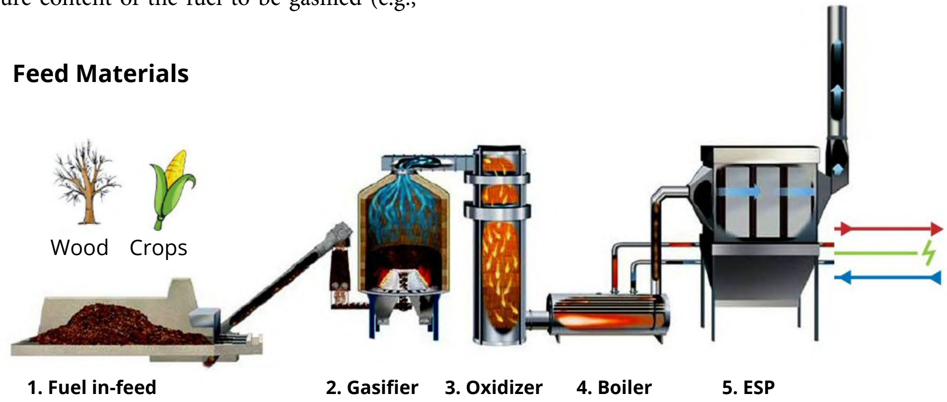

Figure 7.12. Scheme for heat production with a gasification reactor used in district heating boiler houses [49]

Figure 7.13. Combined heat and power plant (left) with a wood gas generator (right) [50]

7.6. Solid Fuel Burners

To burn solid fuel in chamber furnaces, a so-called solid fuel burner has been developed, which is a compact furnace, either with a fixed or movable grate, often lined with ceramic tiles. Fuel is fed to it by screw conveyors, and the primary and secondary air is generally supplied by separate fans (Figure 7.14). Lower capacity burners are practically only suitable for burning wood pellets. Pellets are a high-quality homogeneous fuel, the transport, storage, transmission, and even combustion of which are almost as convenient and easily automated as the combustion of light liquid fuel. In addition to pellets, woodchips and sod peat can also be burned in solid fuel burners, but it must be borne in mind that the fuel used in such burners is of uniform sod size and preferably dry (at least in local heating boiler houses).

Based on the fuel feeding system, these burners can be classified into burners with upper, horizontal, and lower feeding system. **The burner with an upper feeding system** has the simplest design (Figure 7.15, A) because it does not have an auger feeder (screw conveyor). The pellets fall on the grate through a vertical feed pipe. As a general rule, boiler capacity is less than 50 kW when using such technology (Figure 7.15, B).

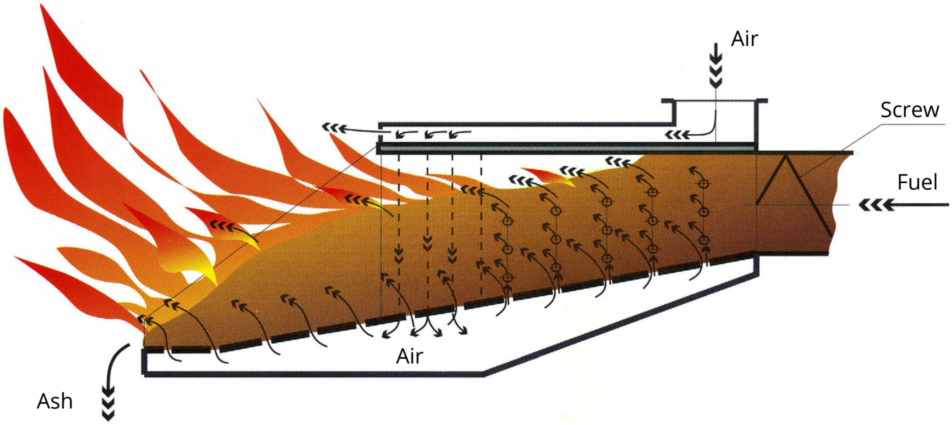

Figure 7.14. Scheme of a solid fuel burner for dry fuel developed at Tallinn University of Technology [14]

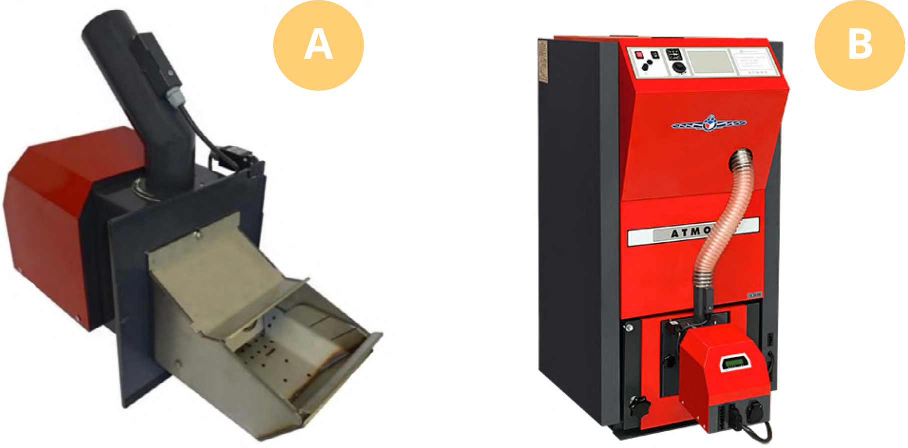

Figure 7.15. Solid fuel burner Atmos with upper feeding system, 45 kW (A) and boiler D25PX (B) equipped with it [51]

Figure 7.16. Solid fuel burner HakeJet with a horizontal feeding system. [52]

Figure 7.17. Solid fuel burner BioMultiJet with a horizontal feeding system. [52]

The housing of a burner with a horizontal feeding system has an auger feeder that delivers fuel (pellets or wood chips) to the grate. Although this type of burner is more complex than the previous one, it ensures a more even feed to the grate and better control of the boiler load. It is also not as sensitive to fuel quality as the previous type. Larger burners of this type have a capacity of 1.5 – 2.0 MW and can also burn wetter fuel (Figure 7.16and Figure 7.17).

Solid fuel burner HakeJet (Figure 7.16) with a horizontal feeding system has a fixed grate and holes for both primary and partially secondary air. Above the semicircular grate part is a ceramic semicircular heating element, which accelerates the drying of the fuel and the separation of the volatile. Externally, the burner head looks like a tube from which a flame comes out. These types of burners can also be installed instead of oil or gas boiler burners. The HakeJet solid fuel burner is designed primarily for burning wood chips, which does not mean that pellets cannot be burned. The capacity range of the produced equipment is from 40 kW to 400 kW.

BioJetMulti burner (Figure 7.17) is also fitted with a fixed grate and well-arranged air distribution, partly lined with ceramics on the inside. Capacity from 60 kW to 1500 kW. Larger boilers can be fitted with two burners and designed for burning various biofuels, also suitable for wetter wood chips. Suitable for installation on older liquid fuel boilers when converting them to biofuel (e.g., "Kiviõli" type boiler produced in Estonia).

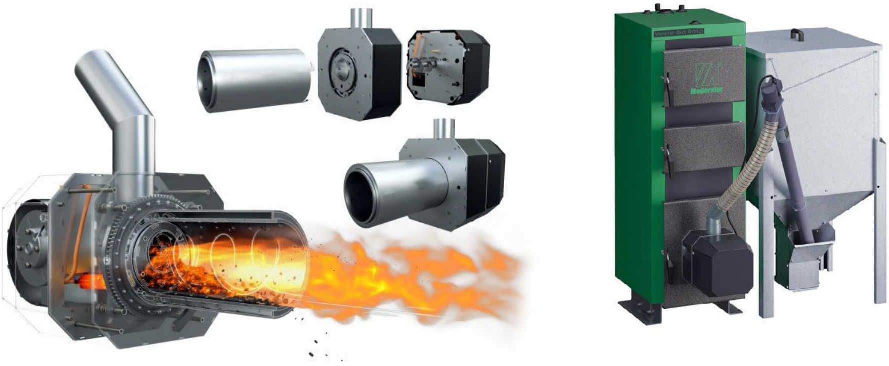

Figure 7.18. Burner Vento Bio Roto with rotating burner head (A) and corresponding boiler (B) [53]

Burner Vento Bio Roto (Figure 7.18, (A) is a technically advanced solid fuel burner with upper feeder system, the combustion chamber (cylindrical part) of which rotates during operation, thus removing ash and slag and not requiring separate cleaning. Thanks to this solution, the burner works very efficiently, ensuring capacity stability and not clogging. It is also possible to burn biofuels with more complex composition and any quality (herbaceous and fruit biomass also from peat). Vento BIO ROTO burner with boiler (Figure 7.18, B) is well suited for burning pellets in single-family houses.

In the following figure (Figure 7.19), we also see a developed solid fuel burner MultiJet with a horizontal auger feed, which has a movable grate and ceramic side plates. Primary air is supplied through holes in the grate links and secondary air from the sides and ends. This allows a fairly high specific load on the grate in such burners, and a variety of biofuels and peat of different qualities can be burned. The capacity classes are as follows: 40 – 150 kW; 200 – 500 kW and 700 – 1500 kW.

Figure 7.19. The MultiJet burner is suitable for various biofuels and peat [52]

The burner with lower fuel feed is even more sophisticated than the previous, but all the more efficient. The fuel is also directed by a horizontal auger feeder to a circular burner head grate, which forms a fuel layer that is ignited by either an electrical resistor or hot air. Burned fuel ash and slag fall over the edge. More modern burners have a circular perforated rotating grate through which the primary air is conducted and which is equipped with knives that guide the ash over the edge of the grate, but can also cut off the sintered ash layer from the grate. The secondary air is directed through a separate flame-retardant pipe (Figure 7.20, A). Tertiary air may also be provided to ensure virtually complete combustion. Boilers equipped with such a burner generally have a capacity between 40 and 200 kW. Figure 7.20, Easyfire boilers shown in B are produced for private houses in the power range of 10, 15, 20 kW, but Powerfire boilers, in the capacity range of 130 – 300 kW are suitable for local boiler houses and smaller district heating boiler houses.

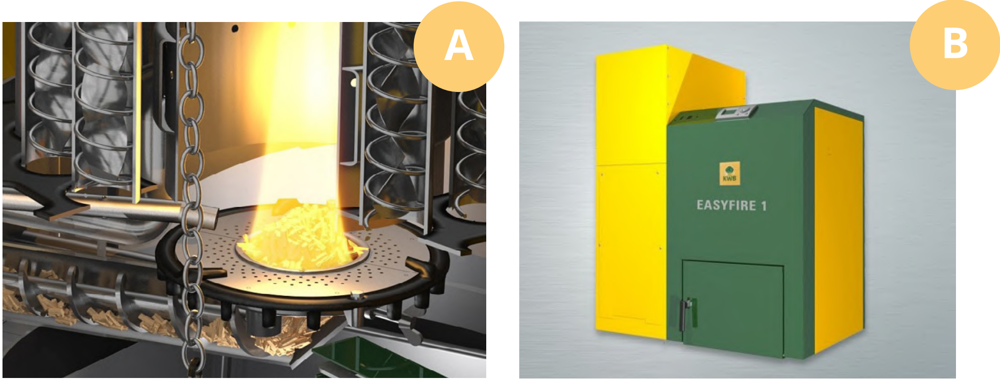

Figure 7.20. Solid fuel burner EasyFire with lower fuel feeder system, rotating grate, and slag cutting knives (A). KBW pellet boiler (B) with the above burner [54]

7.7. Capacity Ranges Suitable for Combustion Technologies

For each combustion technology, a range of capacities has been developed at which its application is either technically or economically feasible. In Finland, wood-fired boilers with a capacity of up to 5 MW have been built, usually with a grate furnace; at higher capacities, fluidized bed furnaces are preferred, although others are also built (Table 7.1). The second-order grate furnace fuel boilers of the Tallinn Power Plant located in Väo have a capacity of 20 MW.

Table 7.1. Typical equipment capacities for different combustion methods [55]

Combustion technology	Minimum capacity, MW	Typical capacity, MW
Fixed grate	0.01	0.05 – 1
Solid fuel burner	0.01	0.04 – 2
Moving grate	0.8	2 – 20
Stationary (bubbling) fluidized bed	1	>5
Circulating fluidized bed	7	>20
By pre-gasification of the fuel		
• small boilers	0.02	0.1
• large appliances	0.3	2 – 15, up to 150
• CHP equipment	0.01	0.04 – 0.2

Unlike Finland and other Scandinavian countries, fluidized bed technology in the Baltic States has not been used much for burning wood fuels for equipment smaller than 10 MW, however, it has been used for larger wood fuel boilers, mostly with a capacity of more than 50 MW. Typical capacities for wood-fired boilers and more preferred technological solutions with a level of automation that takes into account the specificities of the sector have developed for each application (Table 7.2).

Table 7.2. Distribution of wood fuel boilers by capacity according to the field of use [55]

Area of application of boilers	Typical capacities
Boilers for single-family houses	15 – 40 kW
Boilers for large buildings (local heating)	40 – 400 kW
Boilers for district heating boiler houses	0.4 – 20 MW
Industrial boilers	1 – 80 MW

8. Heat Supply Methods, Equipment Used

8.1. Heat Supply Methods

The types of heat supply to buildings are classified into three [56]

- "district heating" means a heat supply system serving several consumers or buildings in a settlement or area;
- local heating – building-centered heat supply (e.g., boiler in the basement of an apartment building or in a private house, ground source heat pump in a private house, etc.);
- room heating – room-based heat supply (e.g., stoves, storage fireplace, fireplace, air heat pump, etc.).

In the case of different heat supply for buildings, heating, heat supply of ventilation equipment, and production of domestic hot water on the basis of either district heating or local heating energy source may be arranged. In the case of local heating, each energy source usually has its own purpose: the stove and the air-to-air heat pump heat the room, a stove, and a storage fireplace can also be used to prepare domestic hot water.

8.2. District Heating and District Heating Boiler Houses, Their Basic Equipment

8.2.1. Definition of District Heating System

The definition of district heating as a heating method is given in the District Heating Act [57]. **District heating** is the production and distribution of heat through the network to supply heat to consumers through a district heating system. **A district heating system** is a technical system for the production, distribution, and consumption of heat, consisting of technical equipment for the production, distribution, and consumption of heat and related buildings.

Thus, more generally, district heating is a way of supplying heat to buildings through a pipeline located outside the building (compiler's definition). It can also be said that district heating is considered to be the supply of heat to two or more buildings from a central heat source across the boundary of a property through the piping, if the commercial-monetary relationship takes place upon the heat transfer, i.e., the heat is sold.

8.2.2. A Brief Historical Overview of the Development of District Heating in the World and in Estonia

Although the roots of district heating date back to the Roman Empire, when saunas and greenhouses were heated on this principle, Sir William Cook showed in 1745 the potential of steam heat to heat buildings, [58] when he installed a coiled tubing system in his home in Manchester, England. The first water heating system was installed in an American building in the United States in 1830, and in 1844 steam was used for the first time to heat a large building – the Eastern Hotel in Boston, Massachusetts. The first commercial district heating network was built in the United States, where the district heating network was installed and commissioned in Lockport, New York, in 1877, and Birdsill Holly, a hydraulic engineer who designed the system, is considered the creator of modern district heating networks.

In contrast, European countries developed a significant amount of hot water district heating systems in the same period, mainly in the Scandinavian countries, especially in Denmark.

After gaining independence and the transition to a market economy, the former socialist countries, some of which have now joined the EU, still have to contend with the modernization and efficiency of district heating systems in order to meet ever-increasing environmental and energy saving requirements.

Kohtla-Järve must be considered the birthplace of district heating in Estonia, where residential heating was started in this way in 1949. In 1959, the first main section of the district heating network was completed in Tallinn, and from 1960 onwards, the development of district heating networks was started in several Estonian settlements. The first district heating networks were created in the production cycle of combined heat and power plants to transfer the remaining heat for heating buildings. This enabled more efficient use of primary energy and increased efficiency of power plants.

In the 1960s and 1970s, a method of heating, nowadays called district heating, but at one-time central heating, was used to supply heat to industrially produced apartment buildings throughout the USSR. This method of heating later spread from the cities to the central settlements of the former collective farms and to other small towns with apartment buildings. The construction of combined heat and power plants in the modern sense gained momentum in Estonia only in the second half of the 2000s.

The share of district heating varies from country to country and is influenced by many factors, including climatic conditions, environmental requirements, the availability of heat sources, and the economic and legal framework. The basic scheme of the city district heating system is presented in Figure 8.1. You can see the boiler house, the waste heat source (factory), the district heating main and distribution pipeline, and consumers.

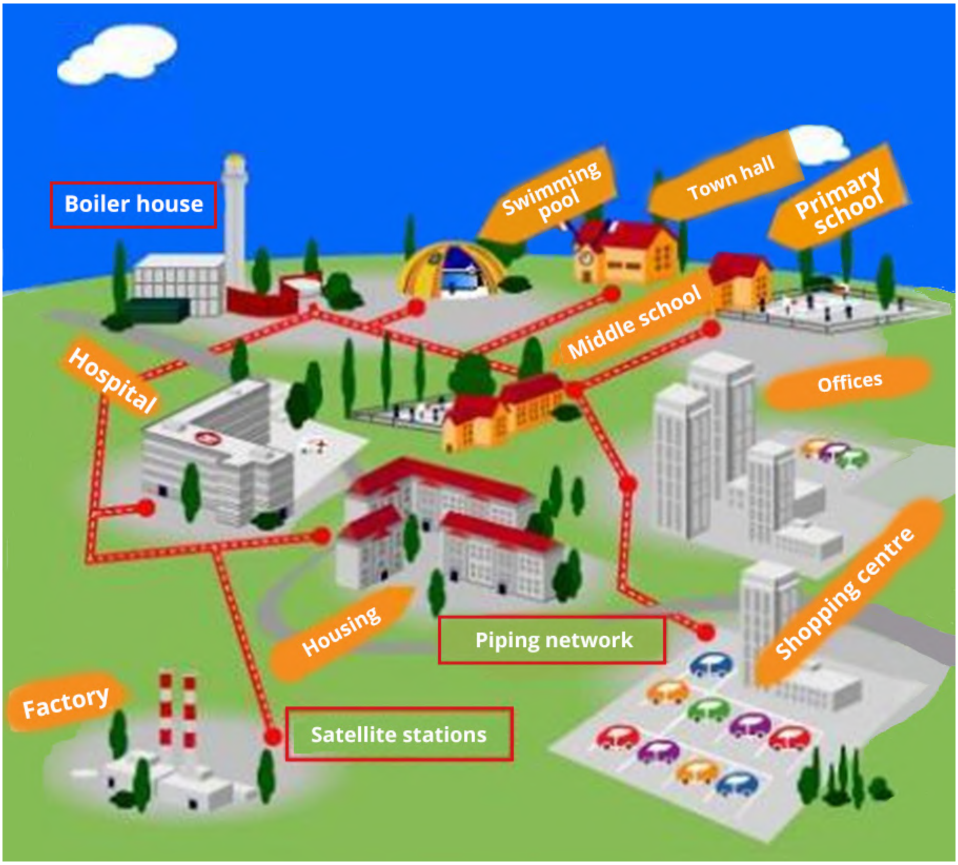

Figure 8.1. Basic scheme of the city district heating network [59]

District heating systems currently serve around 60 million EU citizens to meet their heat needs. District heating systems are so far only able to partially supply heat to the inhabitants of the cities where the district heating networks are located. Cities with at least one district heating system have a total population of 140 million, and around 57% of the EU population lives in settlements with at least one district heating system. Thus, district heating networks would be able to serve more people in the future if they expand their service areas.

8.2.3. District Heating Energy Sources

District heating energy sources can be various fuels (e.g., in Estonia oil shale, oil shale oil, natural gas, sod peat and wood fuels from biofuels, straw, meadow grass, and biogas), residues heat from industry and electricity generation, geothermal heat, solar heat and environmental heat (mainly by geothermal heat pumps). In the last two EU funding periods (2007 – 2020), Estonian district heating boiler houses have been massively converted mainly to wood fuels, and combined heat and power plants have been built.

Figure 8.2 provides a good overview of the historical development of district heating, the energy sources used, the supply and return water temperatures, and the efficiency of the systems.

To get an overview of the amount of energy used for a purpose (e.g., heating a building), the whole energy supply chain should be considered from the receipt of the fuel (energy) to the final consumption. Then we get a comprehensive picture of losses and energy efficiency. The use of efficiency measures helps to reduce both the losses and costs associated with energy conversion and the environmental impact. It should be emphasized here that increasing energy efficiency means activities from the beginning of the energy conversion chain all the way to the consumer, sustainable use (so-called energy saving, implementation of saving measures) starts with the consumer.

The procurement, processing, storage, and transport of locally produced, renewable biomass fuels also require energy, mainly fossil energy. It is necessary to spend 10 – 15% of its energy content on the production and transport of wood briquettes. If moist wood chips are used in district heating boiler houses to produce heat without pre-treatment and drying, only 4% of its energy content is needed for storage and transport costs (14% for fuel oil and natural gas). If water vapor condensation from flue gases is used in the boiler house, the efficiency of the boiler house (in this case, a conditional indicator) can be 100% and more calculated according to the net calorific value. In modern densely populated areas (cities, villages), where the district heating network piping is pre-insulated from pipes and optimally dimensioned, the relative heat loss of the pipelines is within 10% (in many places even less, but may be higher if many small distributed consumers are connected to the district heating network). Thus, from the receipt of the wood chips to the transfer of the heat obtained in the process of conversion in the district heating system to the consumer, only 10 – 15% is lost, and the consumer can receive 85 – 90% of the primary energy of the wood as heat.

8.2.4. District Heating Boiler Houses and their Basic Equipment

High-capacity district heating boiler houses (100 – 200 MW) are built to generate heat for larger cities or districts and are generally economically viable. [61] This concentration of heat loads allows the use of large equipment and technical solutions. This ensures low specific fuel consumption and efficient use of low-quality fuels and offers a number of advantages over district heating systems with small and medium-sized boiler houses. In any district heating system, it is necessary to make a choice in terms of the fuels to be used. It is easier to use natural gas; the transport of wood fuels may require very heavy traffic of large trucks. Due to the latter, larger district heating heat sources are usually built, whenever possible, in the suburbs of settlements, where the flow of trucks is less disturbing for the residents.

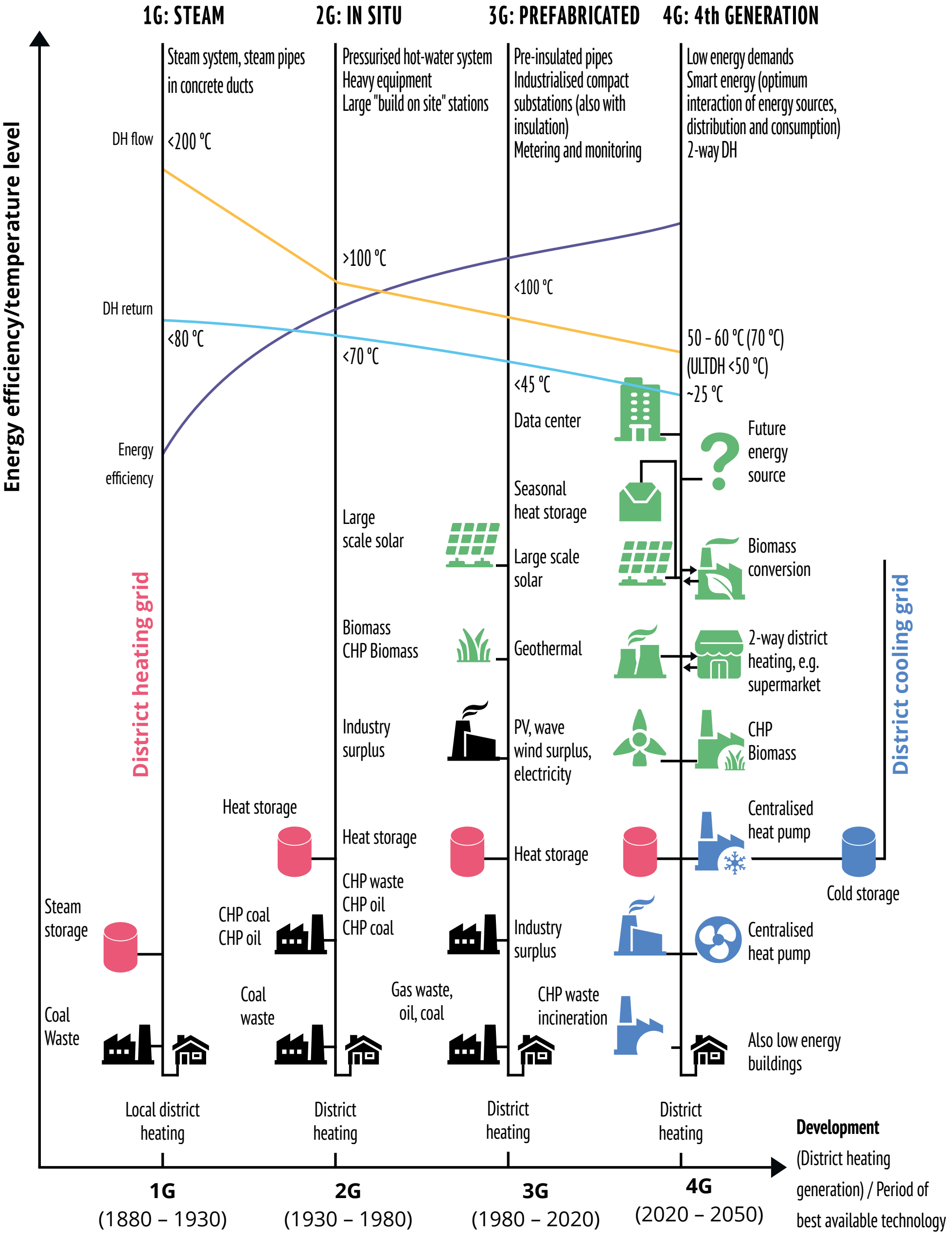

Figure 8.2. Four different generations of district heating systems, their energy sources, efficiency, and temperature schedule [60])

Hot water or steam is used to transfer heat from the boiler house or CHP to consumers through a system of pipelines (heating networks), which are complex engineering and technical facilities. The length of district heating pipelines can range from a few hundred meters to a few kilometers in small settlements and up to hundreds of kilometers in large cities. The diameter of the pipes can reach 1.5 m. District heating network pipelines are divided into main pipelines (main network), which go from the boiler house (CHP) to the consumption areas of the settlement, and distribution pipelines (distribution network), which branch from mains to individual buildings and other consumers. More complex district heating networks are designed in an annular shape (e.g., around a settlement) and can be connected to several heat sources, which alone (during periods of low consumption, e.g., in summer) or together (during peak hours in winter) provide all consumers with standard quality heat supply (water temperature and pressure of the district heating system) at all times.

The efficient operation of heat supply systems requires a sound management structure and work organization. The most successful organization of the heat supply system is a hierarchical structure, in which the whole system is divided into several levels, each of which has its own function, the value decreases from the upper levels to the lower ones. The upper hierarchical level is formed by heat sources (boiler houses, CHPs); the next level is the backbone networks; the lower level is distribution networks with consumer inputs. Such a heat supply system enables its controllability and performance, as well as a high-quality heat supply at all times.

Heat is most needed to heat buildings (up to 40% of the energy used in the EU). The heating load changes with changes in the outdoor temperature. To ensure the quality of the heat supply to consumers, central control in heat sources, and additional automatic control in consumer heat units are used. The flow rates in district heating systems are constantly changing, and the hydraulic and temperature mode of the heating networks is adjusted automatically to maintain a stable heat supply. At the same time, the water temperature in the pipes should be stable and correspond to a predetermined temperature schedule.

There are high demands on equipment installed in district heating systems. All parts of the system must be reliable and provide the necessary security. Increasing attention is being paid to the ongoing maintenance of district heating networks and also to meet the requirements of increasingly stringent sanitary standards.

Despite the advantages of district heating systems, they have a number of disadvantages, such as the considerable length of the heating networks and the associated heat losses, the need for major investments to modernize and reconstruct its components, and to expand the district heating network.

District heating boiler houses are classified according to the fuel used, capacity, and configuration. Solid, liquid and gas fuel boiler houses, small boiler houses (150 kW – 1 MW), medium-sized boiler houses (1 MW – 50 MW), and large boiler houses with a capacity exceeding 50 MW in Estonian conditions are known. The boiler house can operate fully automatically controlled from somewhere in the center, but it can also be manned around the clock. A distinction is made between main boiler houses, which operate practically all year round (at least during the so-called heating period), and reserve and peak load boiler houses, which operate either during very cold periods in winter, in case of other boiler house accidents or for some other reason.

Boilers using cheaper fuel (wood fuels), which are themselves more expensive than, for example, gas or liquid fuel boilers, are generally installed in main boiler houses. Equipment for reserve and peak load boiler houses, as they have a shorter operating time and the need to start operating, may emerge suddenly, must be able to be started quickly and automatically, and operate efficiently (they are generally unmanned). They mainly use liquid and gaseous fuels or electricity (currently, there are no electric peak load boilers in district heating boiler houses in Estonia; however, there are some in Sweden, for example). Independent electricity sources (diesel generators) have recently been installed in the main boiler houses in case the electricity connection to the distribution network is interrupted.

The main equipment of wood-fired district heating boilers includes fuel storage (may be open and semi-closed or closed warehouses, main and interim warehouses), fuel transfer and supply equipment and interim hoppers or main hoppers (using pellets), boilers, flue gas purification equipment, and chimney(s), ash removal equipment and collection hoppers. Some boiler houses also use flue gas condensing devices that provide additional heat. In addition, boiler houses have much auxiliary equipment that helps to ensure efficient combustion and removal of flue gases from the furnace, chemical, and thermal treatment of boiler water and heat transfer to the district heating network (heat exchangers, piping and pumps). Electrical automation equipment is also required to ensure the smooth and trouble-free operation of the entire boiler house.

As a rule, at least larger wood-fired boiler houses have a reserve or peak load boilers running on liquid or gaseous fuel. Depending on the capacity of the boiler house, some equipment may not be installed (e.g., electric filters, flue gas condenser, reserve boiler, etc.). A three-dimensional diagram of one wood-fired boiler house is presented in Figure 8.3. You can see the bottom of the fuel storage with moving grates, fuel feeder equipment, boiler, flue gas purification equipment, chimney, accumulation tank, and reserve boiler with liquid fuel tank (yellow, outside the boiler house). The exterior and interior views of the modern woodchip boiler house in Tapa can be seen in Figure 8.4.

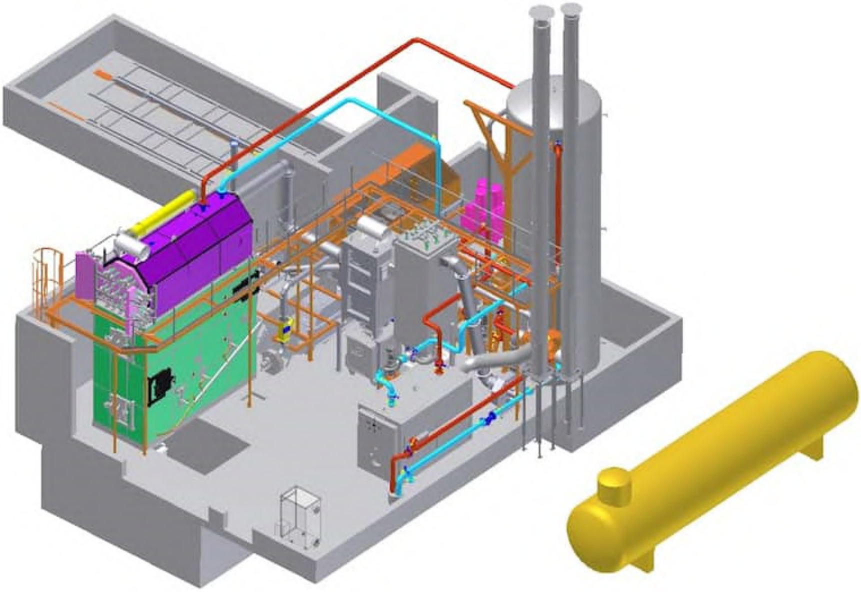

Figure 8.3. Wood fuel boiler house equipment [62]

Figure 8.4. Modern woodchip boiler house inside and out (Tapa city). Photo Ü. Kask

8.2.5. Combined Heat Sources for District Heating

Nowadays, non-fuel energy sources have also been used in district heating systems, such as heat pumps that receive energy from the ground, energy wells, or deep wells with the depth of 100 meters or more or from water (incl., wastewater from wastewater treatment plants, seawater, etc.).

The reasons for the increasing use of heat pumps in district heating are the decline in average electricity prices, increased regulatory requirements to increase the share of renewable energy sources, uncertainty about future fuel prices and future heat supply, technological development of heat pumps, and success of past investments and projects. Heat pumps make efficient use of low-temperature heat sources and low-temperature waste heat from industrial plants. For example, the use of heat pumps makes it possible to mitigate the risks of fluctuations in electricity and fuel prices and to enable a combination of district heating and cooling.

The use of heat pumps in a district heating system also has a positive effect on the environment, which in turn depends on how the electricity consumed by the heat pump is produced and what the low-temperature heat source is. The use of heat pumps increases the proportion of renewable energy in heat production in the district heating system, does not cause local emissions, and generally creates a more positive and environmentally friendly image of district heating. The most profitable is the use of heat pumps in a district heating system in a situation where there is a surplus of electricity produced from renewable energy sources (for example, with electric wind turbines), and the price of electricity is low. If the low price of electricity during such a period is exploited and heat is produced for large storage (including seasonal storage), this heat could be used at a time when the prices of other district heating energy sources are high. [63]

Low-temperature heat sources used in district heating systems through heat pumps can be divided into four categories: industrial waste (residual) heat, ambient water, sewage, and other heat sources. Industrial waste heat is the recovery of low-temperature heat of the range of 15 and 40 °C generated by industrial processes. The ambient water is mainly represented by saline seawater, lake, and river water and, to a lesser extent, groundwater and water pumped out of mines. The ambient water temperature varies between 2 and 14 °C depending on the seasons. The temperature of the wastewater from the treatment of effluents generated by human activity is between 8 and 20 °C. Other heat sources can be classified as heat from flue gas condensation and heat from a district cooling plant, the temperature of which is raised by the heat pump, and which is directed to the district heating network, with the cooled water going to the district cooling network.

When installing heat pumps in district heating systems, a number of factors must be taken into account, on which the profitability of the investment depends. Good access to and proximity to a low-temperature heat source, such as a sewage treatment plant, water bodies (river, sea, lake), industrial plants with a more or less constant heat surplus with an even temperature level, must be ensured. The heat from a heat source should be free or at a very low price. The investment is reasonable only if the installation of the heat pump does not involve significant investments in strengthening the electricity network. The profitability of the investment is further enhanced by the fact that the heat storage (storage tank) already exists or its construction does not require significant additional investments, and even better if the heat pump could be used for district cooling in addition to district heating.

Large hot water tanks with a heat storage capacity of 60 – 80 kWh/m^3 are used for seasonal heat storage. Energy from any heat source is fed into the heat exchanger, either directly or via a heat pump, and later, if the temperature or price of the heat source used by the heat pump is not economically viable for district heating, the energy stored in the heat exchanger can be used to transmit district heating.

One example is a calculation where a heat pump produces heat for a district heating network and covers a base load of 60 MW. If seawater in the bottom layer of the Gulf of Finland is used as a heat source, the price of heat would be about 26 €/MWh, and the annual heat production would be about 525 GWh. If the same amount of heat is produced at the expense of the residues heat of the server park, the price of heat should be about 19 €/MWh. [63]

Large heat pumps are mainly used in district heating networks in the Nordic countries (Sweden, Norway, Finland, Denmark), to a lesser extent elsewhere.

Solar collectors have been installed near district heating boiler houses, on or near buildings connected to the district heating network (Figure 8.6.). If heat accumulators of a suitable capacity are also installed in the district heating system, practically all the heat load required for heating domestic hot water in this network could be covered with solar energy (Figure 8.7.).

Figure 8.5. Installation of solar panels at the Pühajärve wood-fired district heating boiler house. (Photo Ü. Kask)

In summary, a district heating system with combined heat sources uses a wide range of heat sources, including wood-fired boilers, fast-start gas and electric boilers, waste heat from industrial processes, heat pumps, solar panels and heat accumulators (Figure 8.6).

By the end of 2016, a solar district heating plant, the largest in the world, had been installed in the Danish city of Silkeborg (Central Jutland), which has a population of 44,000. 12,436 large solar panels were installed in agricultural areas near the city. The total area of the completed station is 156,694 m^2. The solar panel field should produce 80,000 MWh of heat per year, the rated thermal input of the station is 110 MW, and it should be able to cover 20% of the heat demand of the Silkeborg district heating network (the rest was produced on the basis of natural gas) and the entire summer load. Despite its size, the station does not include a seasonal heat accumulator. As a result, heating costs are particularly low, and thanks to a sufficiently high summer heat load in the city of Silkeborg, all the solar heat produced is used up immediately. [64]

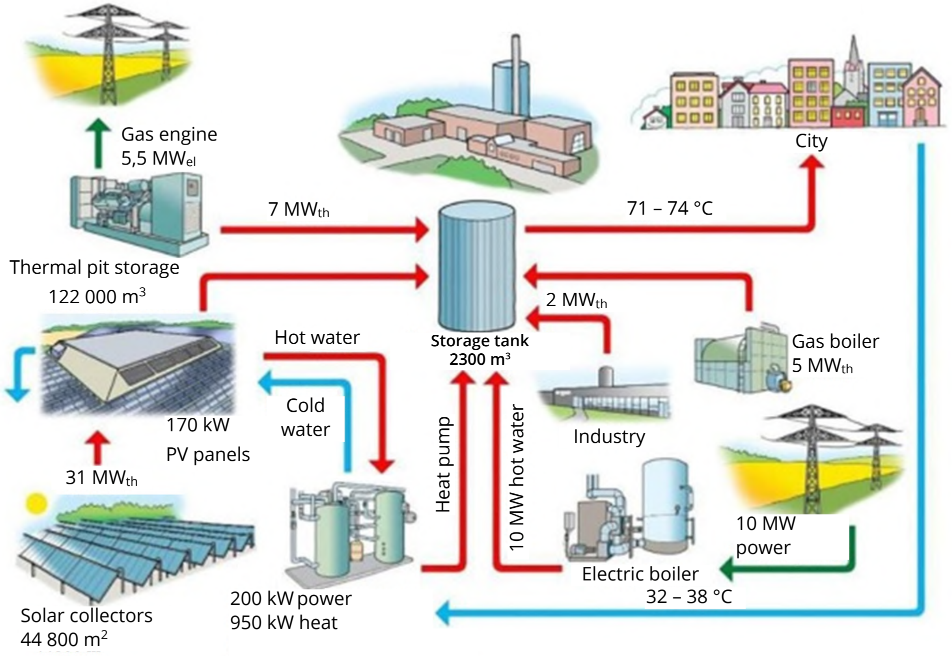

Figure 8.6. Large-scale solar district heating plants in the smart district heating network in Gram, southern Denmark (annual heat production 28,000 MWh) [65]

8.3. Local Heating Boiler Houses and Equipment

If district heating is primarily a method of heating in densely populated areas, then in the case of sparsely populated areas, the construction of a district heating network is either not economically feasible or even impossible. Unlike a district heating boiler house, a local heating boiler house is located directly at the consumer, usually has a much lower capacity, and supplies heat to only one building or a group of buildings.[5] The local heating heat source can be located, for example, in the basement of a building, in an outbuilding, or even on the roof (e.g., gas boilers). Local heating appliances should operate automatically and require minimal maintenance, which places restrictions on the fuels used. Heat sources located directly at the consumer should be as small as possible, operate quietly and, in the case of combustion plants, provide very clean flue gas.

Strict requirements for local heating systems can be met by using the most environmentally friendly technology and fuel possible. Therefore, gas and liquid fuel boilers, heat pumps, as well as electric heating and solar collectors as an additional heat source are often used for local heating.

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[5] According to Estonian legislation, district heating is not considered to be heating of several buildings from one heat source if the buildings are managed by one institution or person, i.e., there is no purchase and sale of heat. [57]

As biofuels ensure relatively clean combustion, the use of wood pellets, wood briquettes, and dry wood, for example, in local heating systems is perfectly suitable. Historically, logwood have been the main source of energy in small households and are still suitable for that purpose today, despite the fact that some manual work is unavoidable and that the firewood requires a fairly large storage space. The use of pellets in small appliances requires very minimal maintenance and pellet burners can be fitted to most previously used solid fuel boilers as well as gas and liquid fuel boilers.

The basic scheme of the local heating boiler house and building heating system is given in Figure 8.7. In the diagram shown, the circuits of the boilers and the heating system are separated by a heat exchanger, which allows the circuits of boilers and the heating system to maintain a different temperature regime. The temperature of the water supplied to the heating system is regulated by the outside air temperature and is variable. The boiler circuit is usually maintained at a constant temperature, as the temperature of the water entering the wood fuel boilers must be kept at a relatively high level (above 65 °C), which prevents the formation of dew points and the resulting condensation and pitch on heating surfaces.

The accumulation tank of the heating system helps to even out the uneven consumption.

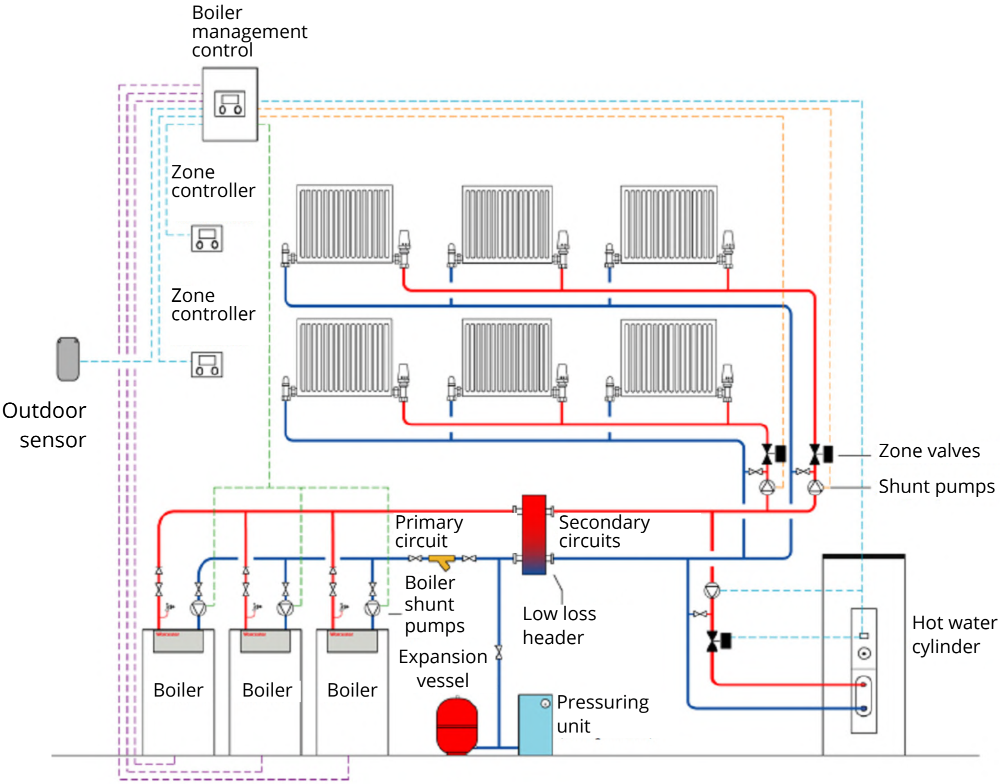


Figure 8.7. Schematic diagram of a local heating boiler house and heating system [66]

Natural wood log boilers suitable for block boiler houses and private houses can be divided into three basically according to the principle of operation:

- top fired boiler (Figure 8.8);
- bottom fired boiler (Figure 8.9);
- reverse fired or so-called gasification boiler (see Figure 8.10).

The disadvantage of a top fired boiler is the need to add fuel often, but the fuel quality requirements are not very strict. The operating cycle of a bottom fired boiler can reach 5 – 8 hours, while it is necessary to use dry and uniformly sized logwood. The reverse fired so-called gasification boiler is a further development of the bottom-fired boiler, where cleaner combustion, better controllability, and higher efficiency are ensured.

Billet boilers usually operate intermittently and should, therefore, be equipped with an accumulation tank (water tank). The size of the accumulation tank depends on the operating principle, adjustability, and capacity of the boiler, and the capacity of the boiler must correspond to the heat load of the building.

Wood-fired boilers can have a capacity of up to 500 kW, small wood-fired boilers start at around 100 kW and require high-quality chips with a uniform unit size of less than 35% moisture. The capacity range of pellet boilers is wide, typically 20 kW – 4 MW. Wood briquettes can also be used as fuel in billet fired boilers.

The set of pellet boilers and woodchip boilers used for local heating includes fuel storage and feed equipment, ash handling equipment, often also an accumulation tank (heat accumulator), and if necessary, flue gas purification equipment (Figure 8.11, Figure 8.12, Figure 8.13). In smaller boiler houses, there is an ash collection vessel in the boiler room next to the boiler, and the ash is removed from the boiler by hand or with a screw conveyor. In larger boiler houses (which also have fly ash traps (Figure 8.12, B.) may be located at the outer wall of the building so that it can be emptied or moved mechanically. The choice of auxiliary boiler equipment is rich, and they can be used to assemble a boiler house with minimal maintenance.

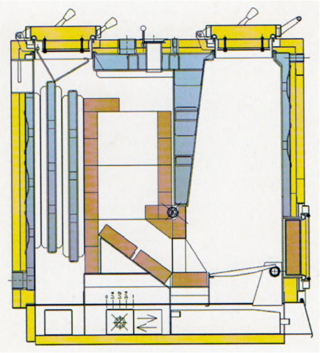


Figure 8.9. Bottom fired wood boiler [22]

Figure 8.8. Rapla Metall OÜ top fired wood boilers with a capacity of up to 500 kW. [67]

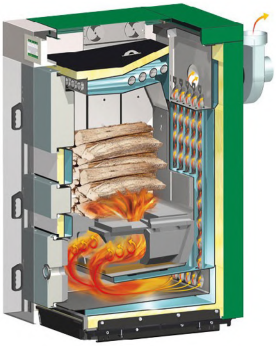
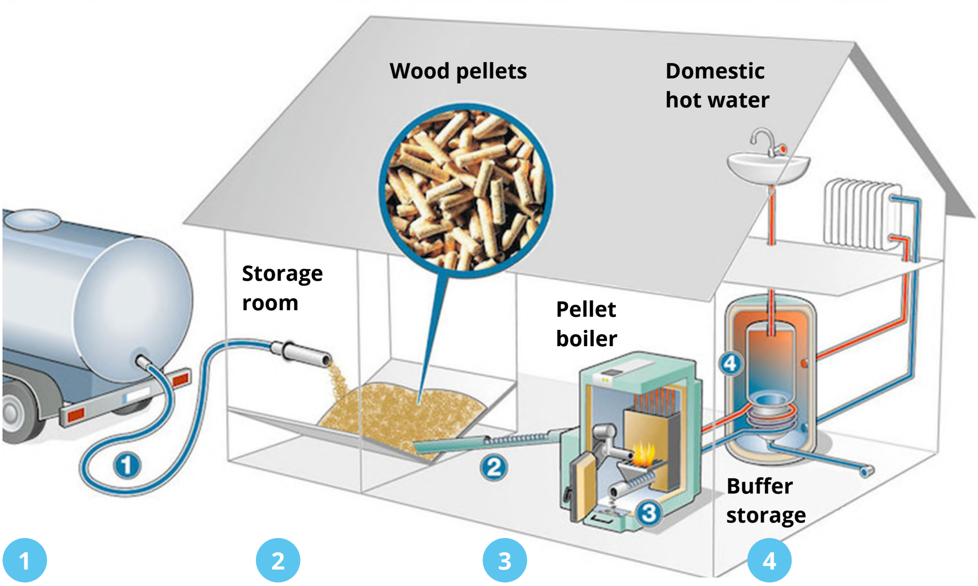


Figure 8.10. Reverse fired wood boiler with a capacity of up to 40 kW [68]



1 Once or twice a year the pellets are delivered by a silo tanker. A loaded storage room of 4,5 m^2 is enough to keep a single-family house warm for one year.

2 The pellets are carried from the storage room to the boiler by a fully automatic pellet feed.

3 After the burning process all that's left is ash - with a weight of only 0,5 per cent of the original pellet. The ash can be disposed of with the domestic waste.

4 If the pellet boiler is interconnected with a buffer storage, emissions can be reduced and efficiency increased.

Figure 8.11. Local heating boiler of a private house with fuel storage [69]

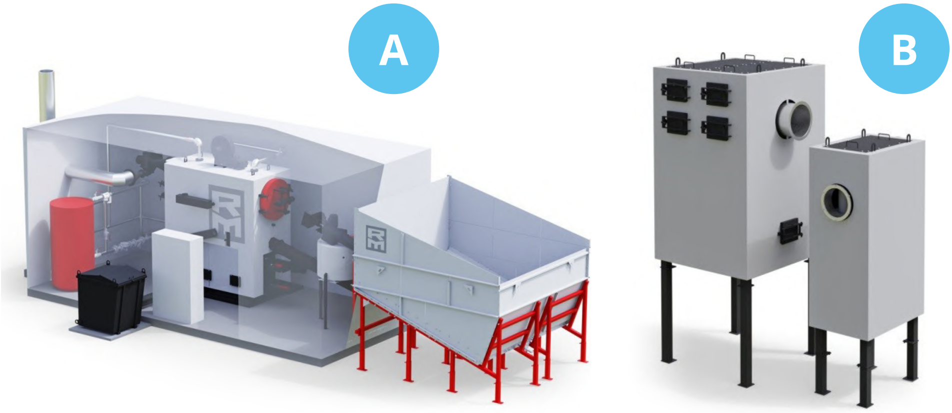


Figure 8.12. A. 120 kW pellet fueled boiler house of a kindergarten with AS Rapla Metall boiler and feed equipment. B. Flue gas purification equipment [67]

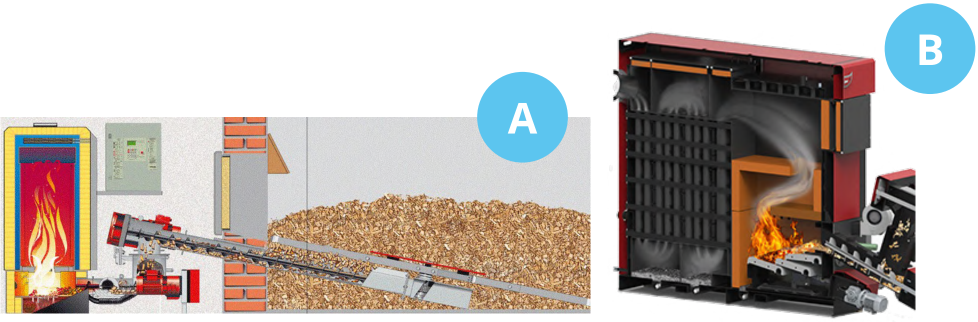


Figure 8.13. A. Local heating boiler house operating on wood chips and fuel storage (cross-section). B. EasyLife wood chip boiler [70]

8.3.1. Local Hybrid Heating Systems, Equipment, and Technologies

In addition to, or without traditional heating equipment, (boilers) non-combustible renewable energy sources, such as heat pumps (using the heat of ventilation air, sewage water, ground or outside air), solar collectors or even fuel cells, can be used in block boiler houses.

In domestic applications, there are hybrid solutions based on renewable energy sources, mainly in the heating sector. Hybrid heating systems (Figure 8.14), which are based on a variety of energy sources, such as natural gas, wood fuel, electric heaters, heat pumps, solar panels, etc., have recently been increasingly installed in detached houses and apartment buildings, especially outside district heating networks. On the other hand, district heating networks with hybrid heat sources are also being added (see section 8.2.3).

In hybrid heating solutions based on renewable energy sources, the use of wood fuels in combination with heat pumps (3 main types: geothermal heat pump, air-to-water, and air-to-air heat pump) is more common; in many places, solar panels have also been added to wood heating systems to provide domestic hot water if the heat pump has not been intended or has not been possible to install. In Germany, for example, in 60% of cases, owners of pellet boilers and stoves have also installed solar heaters in their households. Both geothermal heat pumps and wood heating equipment are both suitable for covering the main heat load of a building all year round. Although most of the annual heat load of a private house could be covered by air-to-water heat pumps, other heating devices must be used during very cold periods (below −20 °C). The air-to-air heat pump is mainly used in local heating solutions.

Solar collectors have also been integrated into wood-fired block boiler houses so as not to operate boilers only for domestic hot water in summer. This is particularly efficient when using underfloor heating and pool water heating to heat some rooms or terraces, garages (Figure 8.15). At Estonian latitudes, almost the entire heating and hot water supply of the building could be secured with appropriately selected solar heating equipment and the size (volume) of the heat accumulator starting from March. During this period, it would be practically unnecessary to operate other heating sources, but for a few days.

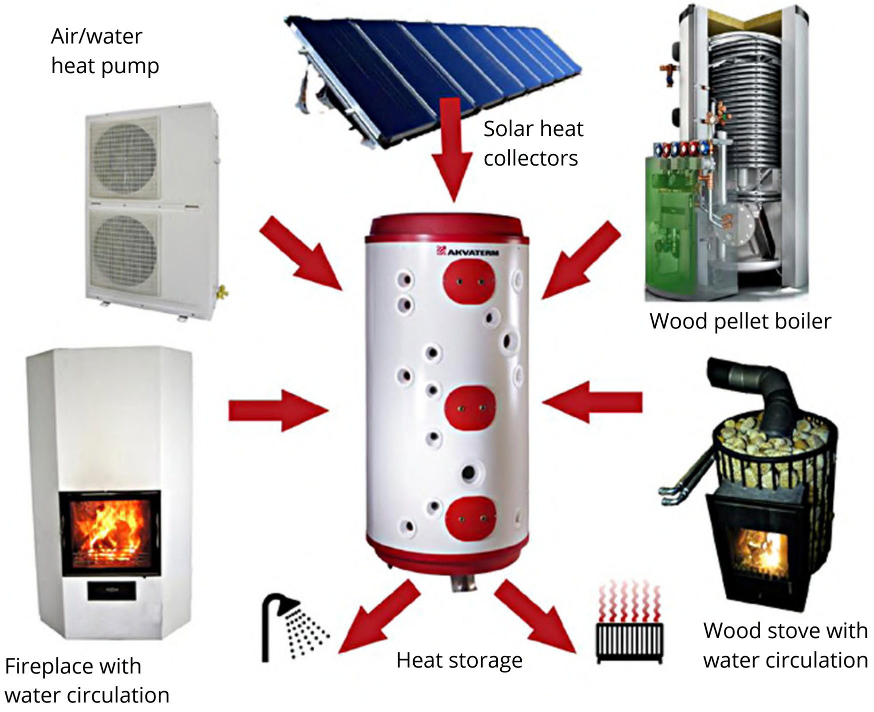


Figure 8.14. Main heat sources of a hybrid local heating system [71]

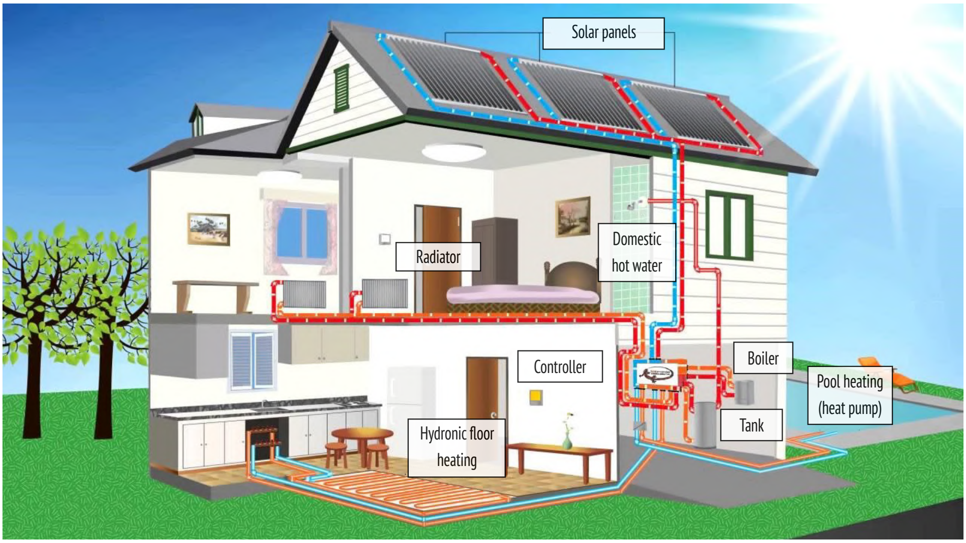


Figure 8.15. Residential heating with boiler and solar panels (The Solamander System) [72]

If a detached house or a locally heated apartment building has been renovated to the level of energy class C or built, taking into account the requirements of energy class A or B, a low heating schedule could be used. In such cases, the use of a heat pump as a basic heating device can be fully justified, as it is one of the most convenient and efficient heating solutions. There is no need for a separate room for storing pellets or other solid fuels or for weekly cleaning and maintenance.

8.3.2. Room Heating Systems and Equipment

Room heating is prevalent mainly in private houses, but also in older apartment buildings and public buildings of local governments (e.g., manor schools, community centers, libraries, etc.). Room heating is generally intended for heating one room, but it is also possible to heat two or more rooms with one oven, depending on the location of the heater (e.g., oven) in the building and its thermal capacity. The share of room heating has gradually decreased compared to other heating methods, but it probably lasts the longest in private houses. As with district heating and local heating, the equipment and technology of boiler houses are constantly evolving in the case of room heating. Higher efficiency ovens, heat-storing fireplaces but also air heaters such as air-to-air heat pump, have appeared. If it heats several rooms in one building (e.g., the entire second floor of a private house), it can also be conditionally considered as a local heating device. Often, room heaters complement each other. Nowadays, a scheme is common where the air-to-air heat pump(s) is/are used for heating until late autumn and heating starts in early spring, and in cold weather, it is supported by stoves or heat-storing fireplaces. Some rooms that are not in constant use (e.g., community centers) are kept at the minimum permissible indoor air temperature with an air-to-air heat pump, but if necessary, the oven is also heated, or electric heaters are switched on. When the outside air temperature drops below −20 °C, the air-to-air heat pump provides more or less the same amount of heat (kWh) as it consumes electricity (kWh). In summer, these heat pumps (if they are reversible) can be used to cool rooms.

One of the common sources of energy for room heating is electricity, which is the most expensive but also the highest quality type of energy to use in a household. There are many types of electric heaters (radiators, convectors, heat emitters, underfloor heating cables, ceiling heating panels, wall panels, and skirting boards, etc.), and they can be combined with other local heating devices, including stoves and fireplaces, using modern automation and control systems. The control unit, which is able to monitor the price of electricity, starts the electric heaters during the low price period (whereby the price threshold can be predetermined), otherwise, the stove or fireplace is heated. Nowadays, fully automatic pellet fireplaces are available, the operation of which can be controlled according to predetermined indoor air temperature. If the electricity becomes more expensive than desired and if the room air starts to cool below the set temperature due to the electric heater being switched off, the pellet fireplace will start operating, the warm air emanating from it will continue to heat the room. Such hybrid room heating systems can be quite economical and ensure room air quality.

As a rule, room heating appliances are small appliances, rarely exceeding 5 – 6 kW in terms of heat output, the larger ones up to 10 kW (stove, pellet fireplace).

In addition to heat separation, room heating devices (especially fireplaces, stoves) also perform another important function – they are also elements of interior design, a design, and environmental value that help to create coziness and a peaceful mood in the room. If the dwelling has central heating, then often a wood-burning fireplace has also been installed, and especially rather for creating a cozy feeling and pleasure and not so much for heating.

The most common room heating devices today are: stoves (Figure 8.16), fireplaces, stoves with hot walls (Figure 8.17) and air heaters (air-to-air heat pumps, Figure 8.21). Pellet fireplaces, (Figure 8.18), Bullerjan ovens or air heaters (Figure 8.19) and some air heating fireplaces (Figure 8.20), through whose air ducts the air heats up and is directed to one or more rooms can also be classified as air heaters. Bullerjan type air heaters are especially suitable for heating those workshops where there are clean wood residues (blocks, sticks, board edges, etc.) left, as well as warehouses, shops and other buildings and premises.

Room heating appliances are linked by one important aspect, they need high-quality fuel, i.e., the drier and more uniform the material and the lower the ash content, the more efficiently they work and the less they need to be serviced on a daily basis (especially in terms of ash removal).

Figure 8.16. Crucible oven with high storage capacity (Photo Ü. Kask)

Figure 8.17. Stove with a hot wall (Photo Ü. Kask)

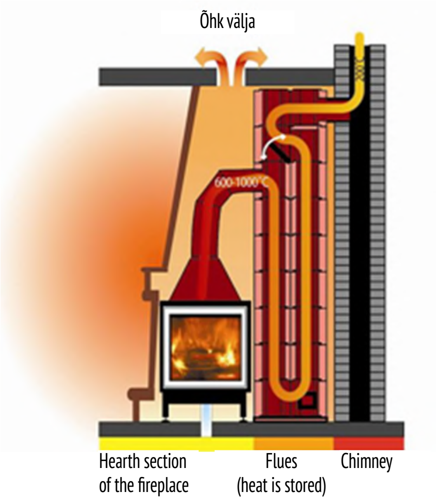


Figure 8.18. Heat-storing air heating fireplace

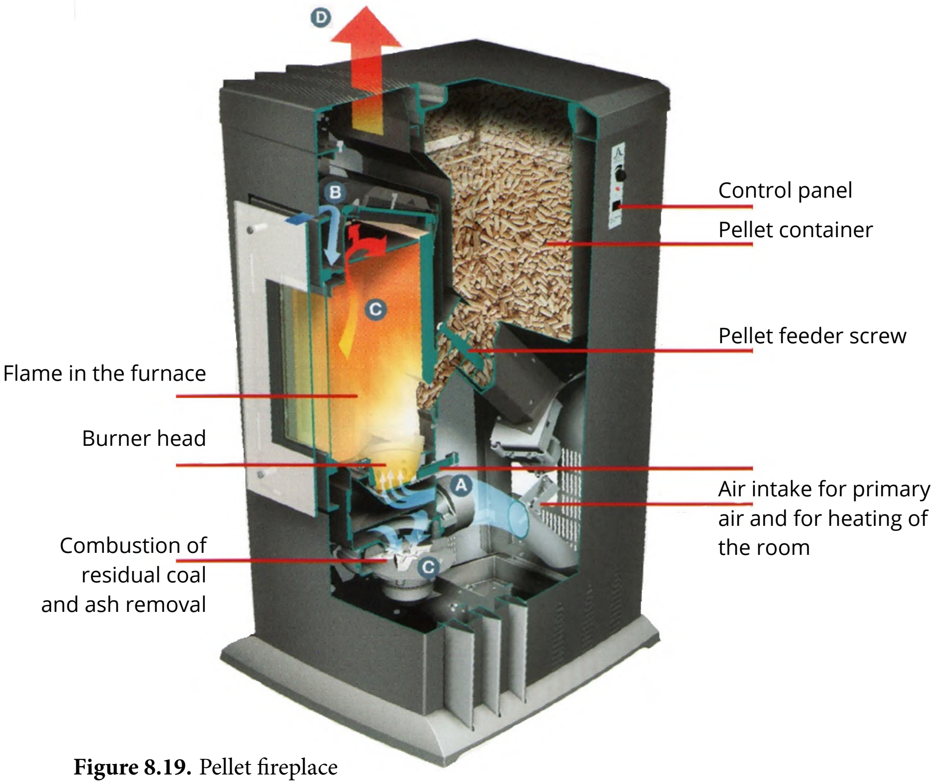


Figure 8.19. Pellet fireplace

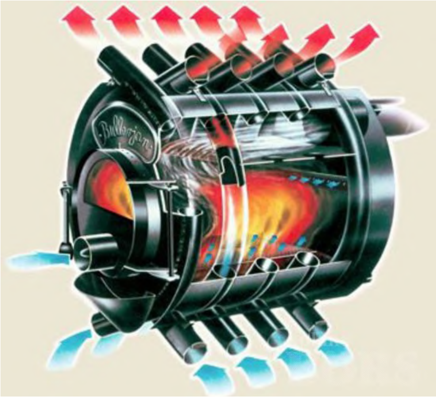


Figure 8.20. Air heater, the so-called Bullerjan oven or air heater Bulder [73]

Figure 8.21. Air-to-air heat pump (above outdoor part, below room unit) [74]

In modern airtight rooms with wood heating and ventilation equipment, it must be taken into account that the average burning of one kilogram of wood requires an average of 10 m^3 of air. At the same time, it is necessary that there is sufficient ventilation in the room. In case of insufficient ventilation, a vacuum is created when using the heater in the room, and the combustion in the furnace is disturbed. The first solution is to open a window or door in the room. In fact, in airtight dwellings, separate combustion air should be supplied to or near the heater. The combustion air duct must be insulated and equipped with a separate shut-off valve.

8.4. Combined Heat and Power

Combined heat and power (CHP) is a technological process of energy conversion in which two types of energy are output from one device. Thus, the outputs of the process are:

- heat that can be used in technological processes, district or local heating. Heat from cogeneration is also used to run cooling processes in district cooling systems;
- mechanical energy, which is usually converted into electricity, but can also be used to drive pumps, compressors, and other equipment directly.

The aim of combined heat and power (i.e., cogeneration for short) is to reduce primary energy (fuel) consumption and emissions of harmful compounds compared to the production of electricity and heat in separate installations. Many of the technological processes used in cogeneration can also be used only for electricity generation, but in this case, part of the heat generated in the process remains unused. With maximum use of heat, the total cost-effectiveness of the cogeneration process (efficiency indicators for cogeneration are discussed in Chapter 11.1) may extend to around 86%.

The most commonly used technological equipment used in cogeneration are:

- back pressure steam engines;
- steam power units turbines with extraction steam turbines;
- gas turbines;
- combined gas-steam cycle equipment;
- internal combustion engines;
- fuel cells.

In addition to the listed cogeneration equipment, a number of other technological solutions have been introduced, the equipment created on the basis of which will also be briefly described in the following sections of the Handbook.

According to the focus of the Handbook, the main emphasis is on equipment and solutions that can use biofuels as fuel, and in particular, wood fuels.

Table 8.1 provides a partial overview of the different technologies of cogeneration, fuels used, typical capacities, and other characteristic parameters.

Table 8.1. Indicative parameters for cogeneration technologies [75]

Technology	P_{el}/P_{th}*	Fuel used	Efficiency, %		Power, MW_{el}	Expected investment, €/kW_{el}	Estimated maintenance costs, €/kW_{el}
			Total	Electric			
Steam turbine	0.1 – 0.5	all	60 – 80	7 – 20	0.5 – >1000	1000 – 2000	0.003
Gas turbine	0.2 – 0.8	liquid fuels, biogas, natural gas	65 – 87	25 – 42	0.25 – >50	450 – 950	0.0045 – 0.0105
Combined cycle gas turbine	0.6 – 2.0	natural gas	65 – 90	35 – 55	3 – >300	450 – 951	0.0045 – 0.0106
Diesel engine	0.8 – 2.4	natural gas, biogas, liquid fuels	65 – 90	35 – 45	0.05 – 20	340 – 1000	0.0075 – 0.015
Internal combustion engine	0.5 – 0.7	liquid fuels, biogas, natural gas	70 – 92	25 – 43	0.03 – >6	600 – 1600	0.0075 – 0.015

* P_{el}/P_{th} - the ratio of electrical to thermal power

8.4.1. Cogeneration with Steam Power Devices

Steam power generation is based on the Rankine cycle, which usually uses water vapor as a working thermodynamic body, but other substances, including organic compounds, can also be used.

Steam power units can use any fuel (including wood fuel) and can have a capacity of up to about 1000 MW_{el} (see Table 8.1). In both thermal power plants and combined heat and power plants, steam cycle energy conversion has long been the most important energy technology.

The working principle of a back-pressure steam turbine cogeneration unit is explained in Figure 8.22, whereas the operation of the condensing unit used only for electricity generation differs from the operation of the backpressure device only in that instead of the district heating water heat exchanger shown in the figure, the steam leaving the turbine is condensed at the lowest possible pressure, and the low-temperature heat released during condensation goes to nature with cooling water or air. A comparison of the heat balances of the Rankine cycle condensing plant and the cogeneration unit is shown in Figure 8.23.

In a typical high-capacity condensing power plant, the steam with high parameters generated at the steam boiler expands (temperature 510 – 565 °C, pressure 9 – 26 MPa) in a steam turbine to a deep vacuum pressure of 2 – 5 kPa. Due to the low temperature, the heat of the steam leaving the turbine cannot be used, the steam is cooled (condensed) in a condenser, and its heat is transferred to nature with cooling water. As it is shown in Figure 8.23, almost half of the heat of the fuel is given off with the cooling water.

In a back-pressure turbine, the expansion of steam is stopped at a higher final pressure (and correspondingly at the higher temperature) than in a condensing turbine, and this makes it possible to use the heat of condensation of the back-pressure steam to heat district heating water, sometimes for conducting technological processes.

The higher the temperature of the water supplied to the district heating network, the higher the backpressure of the turbine must be, and the lower the amount of electricity produced on the basis of heat load. As Figure 8.23 shows, the electrical efficiency in the back-pressure turbine unit decreases by about one third, compared to a condensing station with the same steam parameters, i.e., from 40.8% – 27.6%. The ratio of the amount of electricity and heat from the backpressure device and the values of electrical and thermal efficiency also strongly depend on the steam parameters in front of the turbine (see also chapter 11.1 and Figure 11.1).

A significant disadvantage of a device with a backpressure turbine is the fact that the production of electricity is directly dependent on the heat load, and in its absence, the device must be shut down. In the case of a steam extraction turbine, there is a condenser after the turbine, which enables the production of electricity with better efficiency in the absence of heat load in the same way as in the case of a condensing unit. Higher pressure steam from turbine extraction is used to heat district heating water.

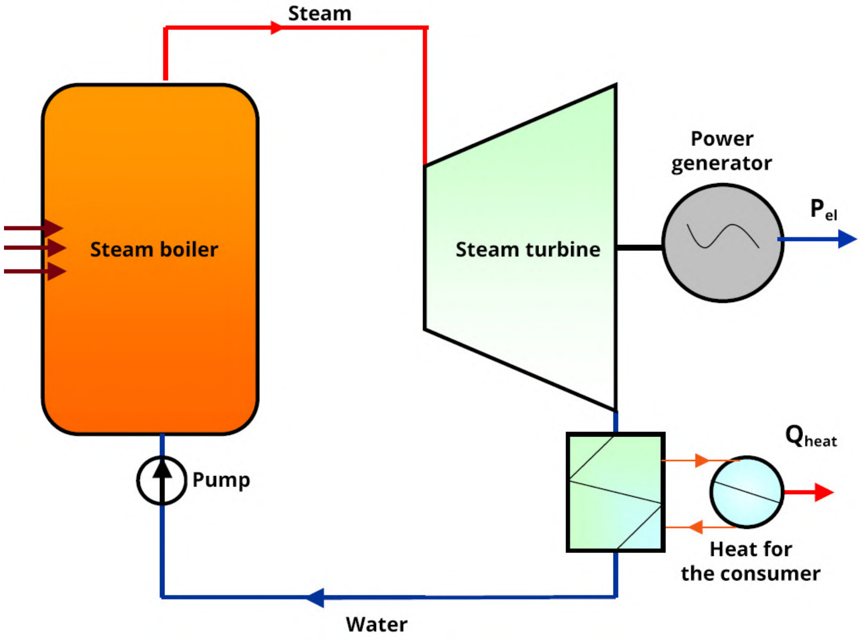


Figure 8.22. Schematic diagram of a cogeneration unit with backpressure turbine

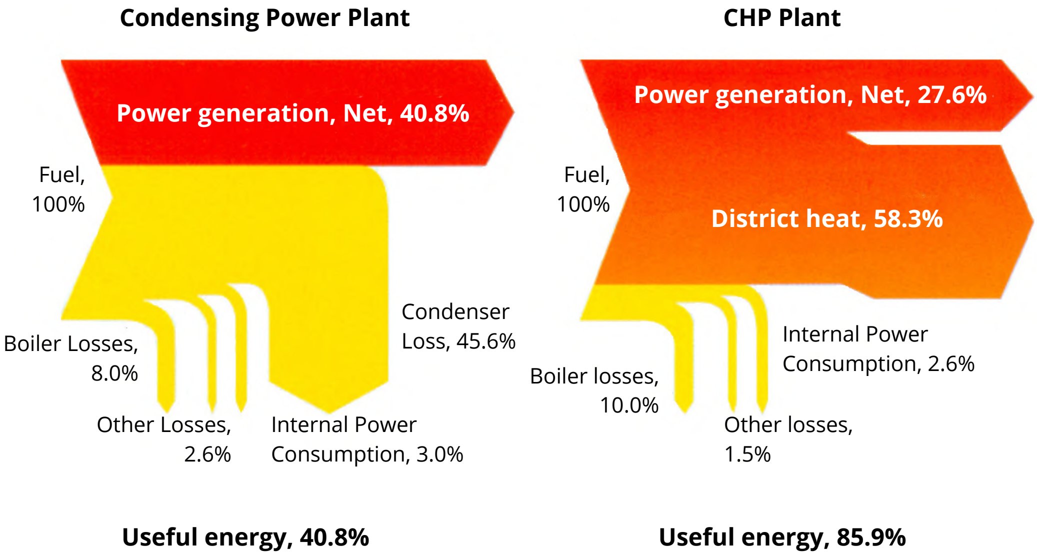


Figure 8.23. Comparison of energy balances of a high-capacity back-pressure turbine CHP plant and a condensing power plant [76]

In Estonia, biofuel (mainly wood fuel) cogeneration plants with a steam cycle backpressure turbine have been installed at OÜ Utilitas in The Tallinn Power Plant, in the Tartu, Pärnu and Paide power plants, etc. The thermal capacity of the fluidized bed boilers in Väo, Tallinn (Figure 8.24), Tartu and Pärnu cogeneration plants is in the range of 50 – 70 MW_{th}, and the total electrical capacity of the plants (generator capacity) is 24 – 25 MW_{el}. Väo II power plant in Tallinn uses three grate furnace boilers with a total thermal capacity of 76 MW_{th} and one turbo generator with an electrical capacity of 21 MW_{el}. In these cogeneration plants, the parameters of fresh steam are in the range: pressure 10 – 12 MPa and temperature 500 – 550 °C. In addition, flue gas condensers are used, which increases the thermal output of the plants.

Back-pressure turbine cogeneration units are particularly suitable for use in the presence of a uniform heat load; systems with steam extraction turbines and condensers are more practical in case of a largely variable heat load. The advantages of steam power plants over other cogeneration technologies are:

- technological schemes well developed, high reliability of equipment, long time in use;
- possibility to use any fuels, including moist wood fuels;
- wide range of equipment capacities;
- the most common technology in large cogeneration plants.

Disadvantages of cogeneration plants with steam power plants include:

- the ratio of electricity and heat production is relatively modest (approx. 0.5) even in high-capacity plants and at high steam parameters, and drops to approx. 0.1 when the power and steam parameters decrease;
- at low capacities, ~ 2 MW_{el} and below, the electrical efficiency and electrical-heat ratio (due to low fresh steam parameters) are low;
- the specific cost of a low-capacity cogeneration plant is relatively high.

Figure 8.24. OÜ Utilitas Tallinn Power Plant CHP plants in Tallinn, Väo (on the left Väo II, on the right Väo I) [77]

8.4.2. Cogeneration Units with an Organic Heat Carrier

Although cogeneration units with an organic heat carrier belong to the category of steam power units, this technology is usually treated differently from water team power units due to a number of features.

The Organic Rankine Cycle (ORC) is based on the evaporation and condensation of an organic heat carrier. CFCs, freons, isopentane, Genetron 245fa, and various silicone fluids are used in ORC devices as thermodynamic bodies (heat carriers).

The ORC cycle is similar to the normal Rankine cycle. Heat is converted into mechanical energy during the Rankine cycle, but the working body is not water, but high molecular organic compounds. Initially, ORC technological solutions were developed for the production of electricity on the basis of geothermal and solar energy, but today this technology is also being applied in cogeneration plants using biofuels.

When using biomass, the principle of operation of the ORC cycle system is as follows: solid biomass fuel (wood) is burned in the furnace of a boiler where water is used instead of thermal oil as a heat carrier, which is heated up to 300 °C (higher temperatures are not tolerated by oils). The heat of the thermal oil is then used in a steam generator (heat exchanger) to heat and evaporate the organic liquid (e.g. silicone oil) circulating in the ORC cycle. The silicone oil vapor is directed to a turbine where it expands and works and drives an electric generator. ORC cycle equipment is manufactured on a wide range of capacities from a few kilowatts to about 20 MW_{el}. The steam leaving the turbine is led to a heat exchanger, where it condenses and transfers its heat to the water circulating in the district heating network. The organic liquid is then pumped back to the steam generator, and the cycle is repeated (Figure 8.25).

In Estonia, cogeneration plants with ORC technology are located in Kuressaare (Figure 8.27, electric capacity P_{el} = 2.8 MW_{el}) and in Adven Eesti AS station in Rakvere (Pel = 1.0 MW_{el}). Both stations use modules from the Italian company Turboden ORC (Figure 8.26).

The advantages of ORC technology compared to other technologies include:

- thermal oil operates at low pressure and temperature conditions, which makes the boiler (especially the boiler metal) cheaper than steam boilers with higher parameters (above 500 °C);
- the organic working body used in the cycle does not cause corrosion and does not wear the turbine blades;
- maintenance costs are lower than for a conventional steam engine;
- the ORC module can be relatively easily added to an existing biofuel boiler;
- the device is well automated, works essentially unmanned, maintenance costs are lower than in the case of a system with a steam boiler;
- does not require chemical treatment of water;
- noise level is low;
- very wide load range (10 – 100%) and high efficiency even at low loads.

Disadvantages of ORC devices:

- relatively new technology and development continues (especially for micro-devices);
- thermal oil needs to be changed from time to time (expensive);
- silicone oil and other organic heat carriers are highly flammable and can be toxic, so leaks must not occur;
- although the cost of the ORC module is low, the cost of an ORC cogeneration unit for biofuels may be up to 4 times higher;
- relatively large investments, few equipment manufacturers and no competition.

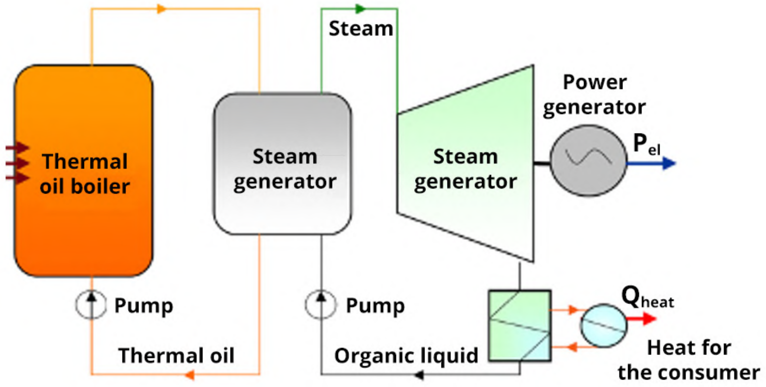


Figure 8.25. Schematic diagram of a cogeneration unit operating on the organic Rankine cycle

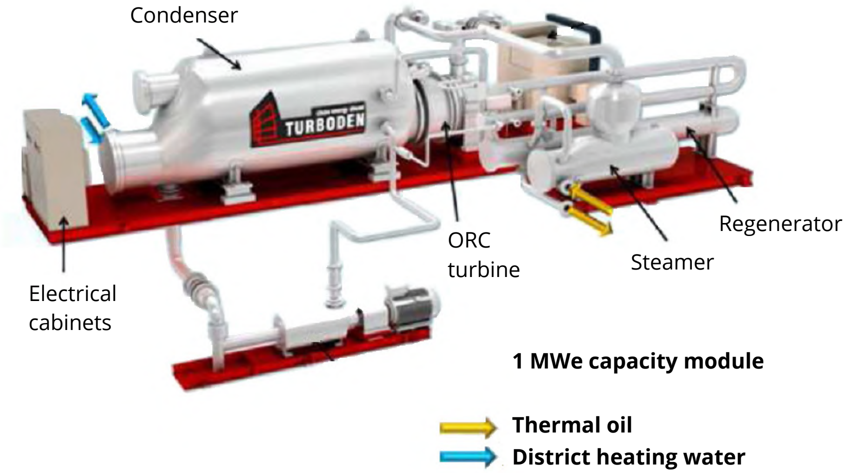


Figure 8.26. 1 MW$_{el}$ ORC device module (Turboden) [78]

Figure 8.27. AS Kuressaare Soojus Cogeneration plant based on ORC technology and using wood fuel [79]

8.4.3. Biomass Cogeneration Units with Gas Turbines and Internal Combustion Engines

As the name suggests, the main fuel for gas turbines is gas, mostly natural gas, but also other combustible gases, including gas from thermal gasification of biomass. Fuels combined with a gas-vapor cycle do not normally use fuels other than natural gas and are therefore not considered in more detail here.

As explained for biomass gasification (see Chapter 7.5), the gas from the gasification reactor needs to be cleaned of both particulates and tar before operating the gas turbine or internal combustion engine. Gas turbine cogeneration solutions have not yet been installed in Estonia, but one positive example is known from Güssing, Austria, where a fluidized bed and gas turbine cogeneration plant with an electrical capacity of 2 MW_{el} and a thermal capacity of 4.5 MW_{th} has been operating for a number of years, Figure 8.28. [80]

As gas purity requirements are somewhat less stringent in engines than in gas turbines, more common biomass cogeneration plants are usually equipped with internal combustion engines. The basic solution for biomass gasification and cogeneration unit with an internal combustion engine (gas engine) is given in Figure 8.29 and the diagrams of the cogeneration units of the two companies in the following two figures (Figure 8.30 and Figure 8.31).

The Spanner wood gas generator and internal combustion engine cogeneration units shown in Figure 8.31 have been produced for years in the power range of 30 – 68 kW_{el} and 70 – 123 kW_{th}. The cogeneration plant with this equipment closest to Estonia with three devices and the total production of electrical power 135 kW_{el} operates in Latvia, Valka, at a timber plant (see Figure 8.31, photo on the right). Tests are held in the Spanner company for the deployment of cogeneration equipment with a capacity of 100 kW_{el}. In Estonia, cogeneration units with a wood gas generator have been experimentally installed in Tartu and Võhma, but their deployment has not been successful due to technical reasons.

Disadvantages of biomass gasification and cogeneration systems with gas engines:

- the total efficiency of the gas-fired cogeneration unit is more than 85%;
- high electrical efficiency (30 – 45%);
- relatively low gas engine price,
- gasification technology has long been known and used.

Disadvantages of biomass gasification and cogeneration systems with gas engines:

- high noise level;
- the service life of gas engines depends directly on the quality of the gas;
- characteristic wear of cylinders, rings, connecting rods and frame bearings;
- dry biomass with uniformly piece size is as a general rule suitable for gasification;
- insufficient development of efficient wood gas (generator gas) purification technologies;
- high cost of gasification reactor and gas purification equipment (catalysts).

Figure 8.28. CHP plant in Güssing (Austria) with a fluidized bed gas generator and a gas turbine running on local wood industry residues. Electrical capacity 2 MW_{el} and thermal capacity 4.5 MW_{th} [80]

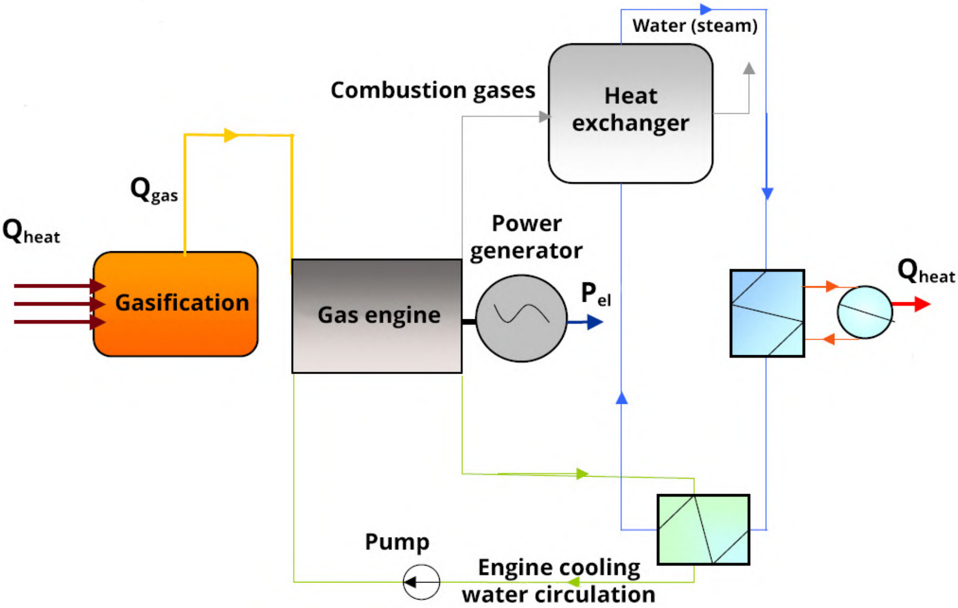


Figure 8.29. Schematic diagram of a biomass (incl. wood fuel) gasification and gas-fired cogeneration plant

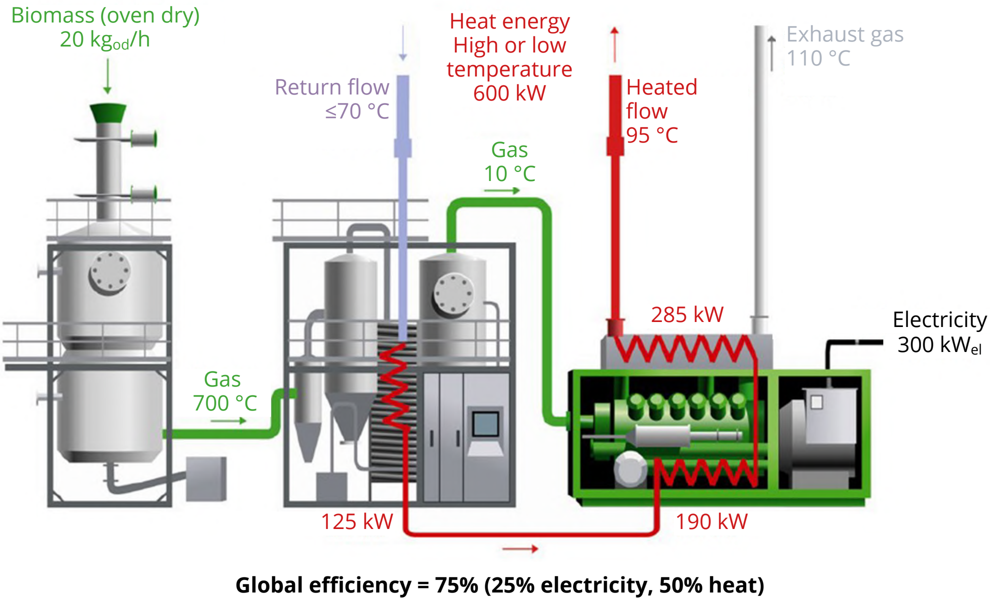


Figure 8.30. Xylowatt NOTAR Gasifier (Belgium), 300 kW$_{el}$ cogeneration plant with wood/gas generator and gas engine. Works with dry woodchips [81]

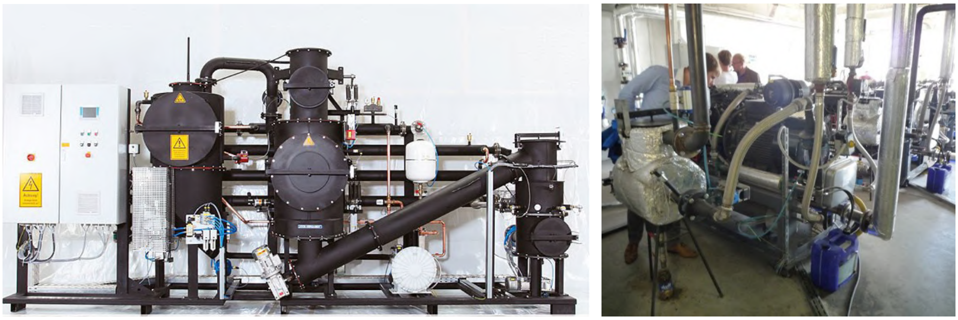


Figure 8.31. Wood gas generator cogeneration unit HKA45 (Spanner Re^2 GmbH, Germany) [50] . In the photo on the right Valka CHP plant engine compartment (Photo Ü. Kask)

8.4.4. Micro-Cogeneration Units Using Biomass

According to EU Energy Efficiency and Cogeneration Directive, [82] cogeneration units are divided into three power groups according to their electrical output:

- micro-cogeneration unit with an electrical power $P_{el} < 50$ kW;
- small cogeneration unit – 50 kW $< P_{el} <$1 MW;
- large cogeneration units – $P_{el} > 1$ MW.

The purpose of this classification is to apply different efficiency and primary energy-saving requirements to groups of appliances of different capacities (see chapter 11.1).

Micro-cogeneration units covered in several literature sources (e.g., in [83]) are less than 15 kW_{el}, which are significantly lower than the net power limit of the micro-devices shown in the Directive, [82] and therefore the requirements of the Directive do not apply to these devices.

A number of different technological solutions have been developed for micro-cogeneration systems, of which we briefly consider systems with an external combustion engine and a hot air turbine in this Handbook.

Micro-Cogeneration System with an External Combustion Engine

The Stirling engine used in cogeneration is the so-called external combustion engine (Figure 8.32 – Figure 8.34). Another type of external combustion engine is a cyclone engine. The Stirling engine differs from the internal combustion engine in that the cylinders are closed, and the combustion process takes place outside the cylinders. The pistons are actuated by a difference in gas pressures in the cylinder, which results from successive heating and cooling of the outer surface of the cylinder. The working body may even be air, but it would be more efficient to use hydrogen and helium. The motor usually starts the synchronous generator.

The electrical efficiency of Stirling cogeneration units ranges from 12 to 30%, the total efficiency from 80 to 90%, and the electrical to heat ratio from 0.2 to 0.5. [84] [85] The electrical efficiency of the Pellematic Condens_e cogeneration system with a 1.05 kWel electric power with Stirling engine powered with the heat obtained from the combustion of pellets shown in Figure 8.33 is 26% [86].

The technological solutions for Stirling engine cogeneration units are still under development, and there are no data on their operational reliability. The reliability is expected to be comparable to that of a diesel engine, with annual availability of 85 – 90% of the time.

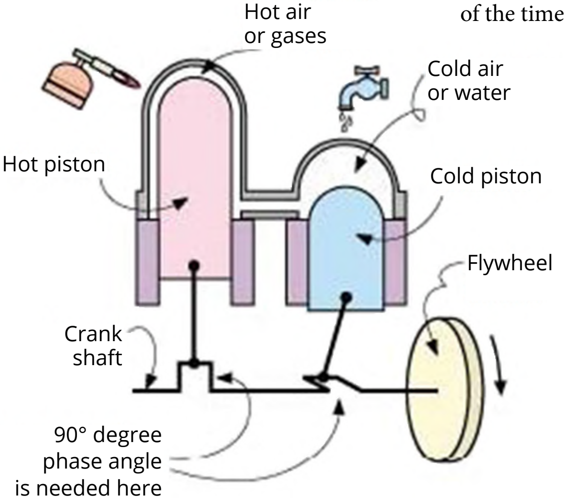


Figure 8.32. Schematic diagram of Stirling engine operation

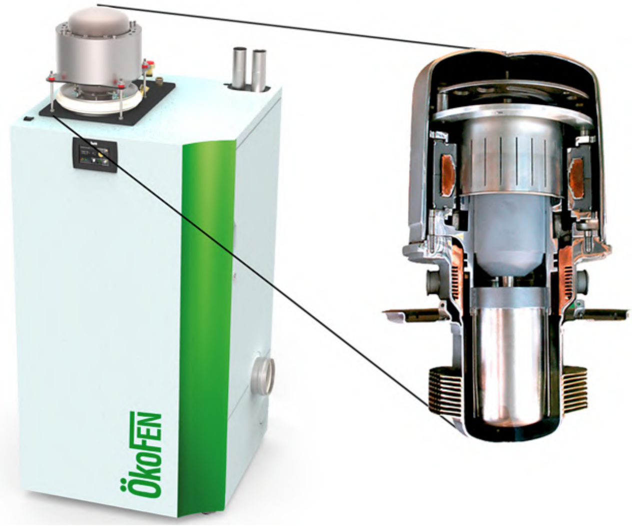


Figure 8.33. Pellematic Condens cogeneration system with an electric power of 1.05 kW_{el}, powered by heat from the combustion of pellets and operating with Stirling engine [86]

Figure 8.34. Cogeneration station with gasification factor, gas boiler and 35 kW power Stirling engine (Photos Ü. Kask)

According to the Danish Energy Agency, [87] the economic performance of cogeneration units with Stirling engines using biomass heat is modest. According to this source, the investment costs of a 40 kW_{el} and 120 kW_{th} biomass gasification according to this source are 3.8 million € and operating costs 32,000 €/MW_{el} (fixed component) and 21 €/MWh_{el} (variable component).

Hot air turbine cogeneration system

One possibility for cogeneration of heat and electricity is to operate together with a hot air boiler and with a hot air turbine, fired, for example, on wood chips (including wet). Such experimental cogeneration systems have been developed in Finland and Ireland. In Finland, for example, a cogeneration unit with a hot air turbine with a capacity of 100 kW_{el} and 300 kW_{th} was developed and installed. Its annual energy production was 800 MWh_{el} and 2500 MWh_{th} of heat (Figure 8.35).

The HLT-100 Compact hot air turbine cogeneration unit includes a hot air turbine, a wood-fired boiler, a compressor, and heat exchangers (Figure 8.36). The thermal power of the device is 465 kW_{th}, and the electrical power 80 – 105 kW_{el}. Due to the complexity and maintenance requirements, cogeneration units with both ORC cycle and steam turbines only cost more than 2 MW_{th} only at heat load. In many cases, such a high uniform heat load cannot be ensured throughout the year, and therefore a cogeneration unit with a hot air turbine is particularly suitable in the operating range of net capacity units without both ORC and conventional steam cycle units.

In the case of cogeneration technology with a hot air turbine, electricity is generated on the basis of the Brayton cycle process, with the heat source being wood-fired hot air boilers. The atmospheric air generated during the process is compressed in the compressor, heated to 680 °C in the boiler heat exchanger by means of hot flue gases from combustion, and directed to a turbine where the hot air expands in the turbine operating the generator. The still relatively hot air coming out of the turbine is used as combustion air in the boiler furnace, and part of the heat of this air can also be used to heat the water in the heating system. The flue gases from the boiler also heat the water entering the heating system (Figure 8.35).

The hot flue gas taken after the heat exchanger can be partially used to control the combustion process. The remaining flue gases are cooled, for example, in a district heating exchanger and purified in a multi-cyclone or electric filter (Figure 8.36) before directing to the chimney. The use of turbine exhaust air and flue gas heat in the heating system ensures high overall efficiency of 74 – 77% of the cogeneration plant.

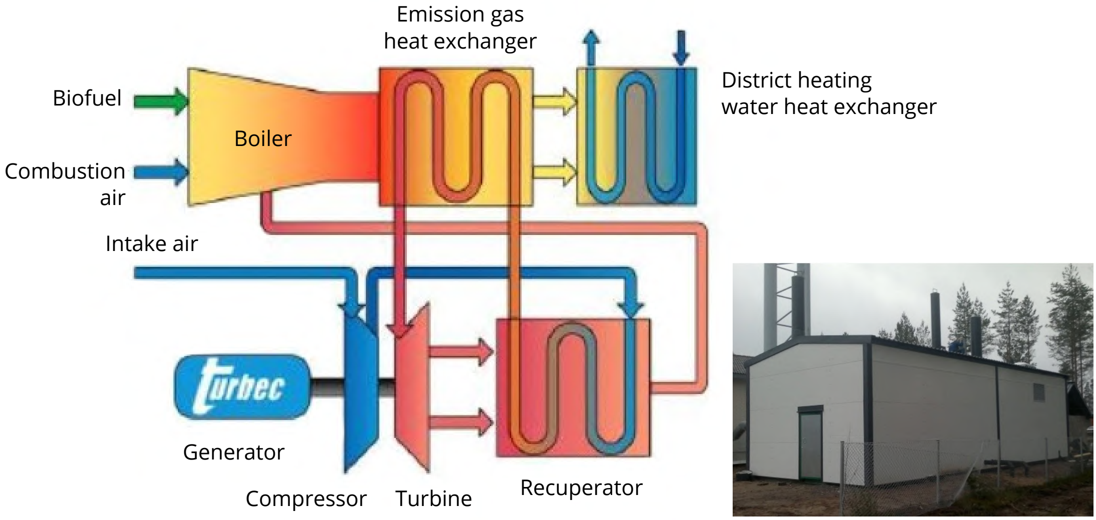


Figure 8.35. Scheme of wood chip cogeneration station with hot air turbine and exterior view of boilerhouse (Finland)

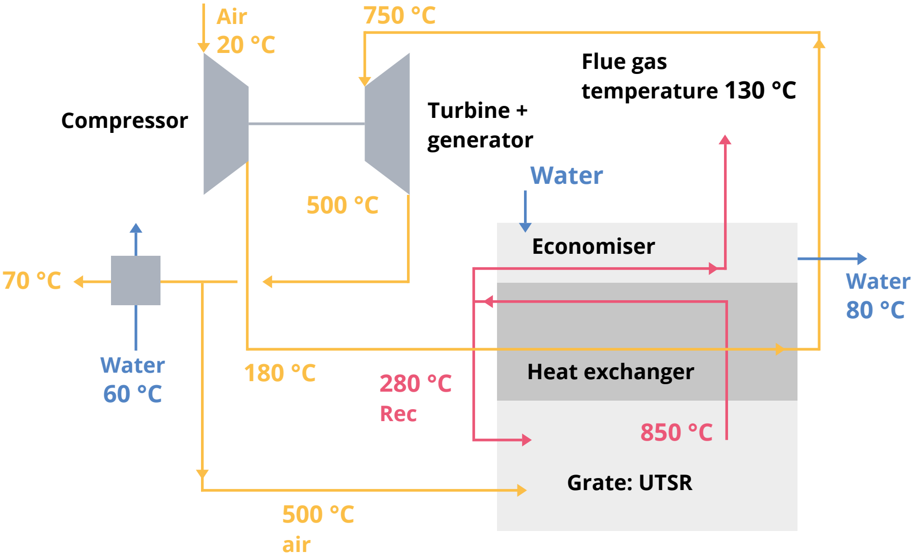


Figure 8.36. Hot air turbine cogeneration unit HLT-100 Compact (top) and schematic diagram (bottom), Schmid Energy Solutions. Electrical efficiency is 13%, and thermal efficiency is 63% [89]

9. Environmental Emissions from Heating Equipment

9.1. Impact of Heating Equipment on the Environment

Anthropogenic sources of pollution directly related to heating equipment are power plants, large boiler houses, and industrial enterprises, combustion of wood fuels and other fuels in block and local heating equipment: stoves, fireplaces, boilers, etc.

Boiler houses using fuel combustion technology, such as energy conversion sites and equipment using any technology, have a greater or lesser impact on the surrounding natural environment or the living environment of the residents of the area, if not otherwise, at least visually or through property prices.

The burning of wood fuels, like the burning of any other biofuel, is considered to be more environmentally friendly than the burning of fossil fuels. Nevertheless, the combustion of wood fuel also generates both solid and gaseous, in some cases liquid, emissions to the environment. The direct impacts of the wood fuel boiler house on the environment would be summarized as follows:

- gaseous and particulate emissions to air (including dust from storage sites);
- ash, whether wet or dry, to be disposed of;
- noise, vibration
- transport of fuel by heavy goods vehicles (may interfere with normal traffic);
- visual disturbance;
- possible decrease in real estate prices in the immediate vicinity of the boiler house (rather indirect disturbance).

The undesirable effects and visual effects of possible noise, vibration, and heavy goods vehicle traffic can be mitigated by the choice of the location of the boiler house, the architectural solution (Figure 9.1, A and B.) and with the right planning, however, in order to reduce particulate and gaseous emissions, much more attention needs to be paid to the improvement of combustion technology and gas purification technology, which must be able to meet one of the increasingly stringent environmental requirements.

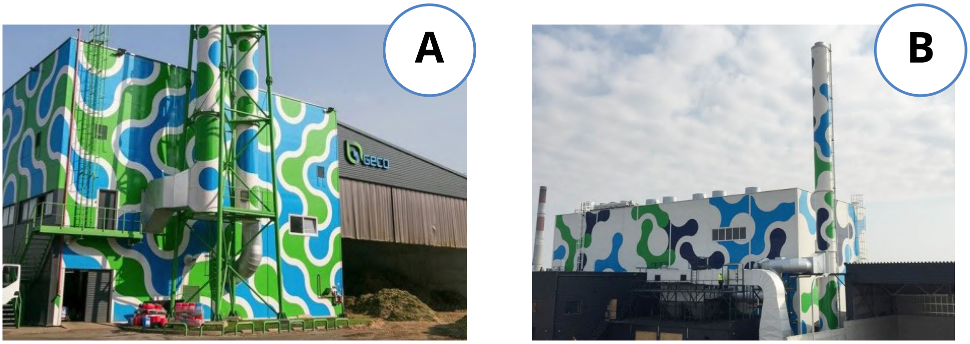


Figure 9.1. A) Architecturally outstanding woodchip boiler house in Kaunas (2012, GECO), B) Danpower Baltic wood fuel cogeneration plant in Kaunas (2017, capacity 20 MW_{th} and 5 MW_{el}) [90]

9.2. Particulate and Gaseous Emissions

As a result of burning wood fuel in the heating unit, ash remains as solid emissions, which in turn is divided into bottom ash and fly ash, which leaves the furnace with flue gases or gaseous emissions and, if not caught earlier, reaches the atmosphere through the chimney.

9.2.1. Particulate Emission

The mineral part of the fuel and the ash were discussed in more detail in subsection 3.5. It is important that both bottom ash and fly ash should be captured, collected, temporarily stored, and later disposed of within the boiler house. As described above, it would be more sensible to collect bottom ash and fly ash separately in larger boiler houses and cogeneration plants, because bottom ash, left-over from wood fuel combustion is suitable for composting or spreading directly on fields, while fly ash is not recommended for agricultural use due to its higher heavy metal content. It is usually landfilled.

In fact, wood ash is still a resource whose real value has not yet been widely recognized, and according to old habits, it is used as an alternative lime fertilizer in agriculture and is essentially valued only by its pH neutralizing capacity. In reality, wood ash also contains significant amounts of macro- and micronutrients, the best possible application of which would be for agricultural or forestry use, but alternative uses can also be found in road construction, as an improver/stabilizer of the soil contaminated with low pH, etc. The best Nordic practice for using wood ash is to recycle it as granular wood ash in forestry as a soil improver that supports biomass growth (the principle: what comes from the forest, should go back there), which is the basis for sustainable forest management and the growth of woody biomass. For example, in the Nordic agricultural sector, the use of wood ash is limited, because due to the peculiarities of soil composition and other factors, fly ash generated during combustion has relatively high concentrations of heavy metals, which are considerably higher than in Estonia. [91]

In addition to the quantities, the composition of the ash must be taken into account when storing or disposing, and whether the ash has been removed from the furnace using wet technology and equipment or whether dry ash removal has taken place. Some of the very fine fly ash can also pass through the traps, not to mention those sources of predominantly block boiler houses and local heating systems that do not have ash traps.

Nowadays, more attention has been paid to the emission of particulate matter (PM5 and PM10), i.e., solid particles formed during combustion and discharged from the boiler. The size of fine particles is inversely related to their potential to negatively affect our health. Particles smaller than 10 µm (PM10) usually pass through the nasal cavity and throat and reach the lungs. The particles larger than PM10, come mainly from the soil, pavements and dusty industrial plants and remain in the nasopharynx and trachea. Ultra-fine particles below 2.5 µm (PM2.5) come primarily from exhaust gases (transport), various combustion processes (boiler houses, local heating, industrial plants), and chemical reactions in the atmosphere. Such particles are fine enough to reach the alveoli of the lung. [92]

9.2.2. Gaseous Emission

The main gaseous pollutants from the combustion of wood fuels are: sulfur oxides (SO_x), which are produced primarily from the combustion of sulfur-containing fuels; nitrogen oxides (NO_x) are produced by combustion at high temperatures because air and fuels contain nitrogen (less in a fluidized bed boiler than in a dust boiler); carbon monoxide (CO) is formed during incomplete combustion; VOC (Volatile Organic Compounds) usually occur in the fuel and evaporation of the solvents; particulate matter (PM) can be both primary and secondary (primary are ultra-fine particles produced primarily by combustion); toxic metals such as lead, cadmium, and copper, mainly from the combustion of fuels, including in small households; polycyclic aromatic hydrocarbons or polyaromatic hydrocarbons – PAH) occur primarily during incomplete combustion. An important source is both industrial enterprises and locally heated residential and wooden house districts.[92]. In addition, incomplete combustion, especially when burning municipal waste (including plastics) with firewood in local heating furnaces, produces very toxic (including carcinogenic) dioxins and furans.

The CO_2 content in the flue gases depends on the composition of the fuel and the calorific value of the fuel. If wood fuel is burned in a condensing power plant with a net efficiency of 42% (fluidized bed technology), the specific CO_2 emissions would be 346 g/kWh_{fuel} and 824 g/kWh_{el}, but as explained above, CO_2 GHG emissions from wood combustion are not taken into account.

The concentration of carbon monoxide and unburnt hydrocarbon emissions in the flue gases depends practically only on the combustion conditions and the even distribution of the combustion air in the furnace (on the grate and in the post-combustion zone).

When planning the construction of new power plants and the reconstruction of existing ones, possible phenomena affecting the environment should be identified in particular, after which it is possible to recommend measures to prevent and mitigate the phenomena.

9.3. Emission Prevention Options

Contaminants (combustion waste) are always produced when any fuel is burned, but the amount of their emissions depends on the combustion technology, the combustion plant, their operational condition, and the fuel. Emissions from equipment with different technologies used on the same fuel may differ significantly. Emissions of soot particles and carbon monoxide from small old district heating (stoves) can affect the airway condition of nearby residents and pose a health risk. The efficiency of modern wood heaters with storage capability can be as high as 85% and their emission rate 90% less than older small appliances.

As emissions from a large number of small heaters (in low-density residential areas) cause high concentrations of pollutants in their vicinity, there are four main ways to avoid this: modernize all small heaters, equip small heaters also with emission traps, switch to district heating or fuel-free heat supply technologies (e.g., heat pumps). Previously, the switch to less-polluting fuel was not proposed, as the use of wood fuel was already expected. In Chapter 8, we also saw that in the case of district heating, combustion plants could be combined with fuel-free technologies to supply heat to consumers. Pollutants from the higher chimneys of district heating boiler houses spread over a larger area, and concentrations close to the ground are lower. It is also economically cheaper and socially more acceptable to place hundreds of small appliances in a district heating boiler house instead of installing traps, and this will also make the environment cleaner.

Here are some examples of the most important pollutants from wood fuel combustion (fly ash, volatile organic compounds (VOCs), sulfur dioxide, nitrogen oxides, and carbon dioxide). Their emissions have been reduced to energy demand of 25 MWh/yr, which more or less corresponds to the heat demand in an older private house or medium-sized apartment, in order to better compare heating systems (Table 9.1). The values provided in the table are quite old, but the proportions between the heating methods have remained the same.

Table 9.1. Mean values of pollutant emission measurements [93]

Heating method, heating device	Fuel, technology	Fly ash, kg/yr	VOC, kg/yr	SO_2, kg/yr	NO_X, kg/yr	CO_2, t/yr
District heating	90% wood chips, 10% fuel oil during peak hours, (80%)*	1	3	5	8	1
Local heating, wood fuel boilers	Existing, without storage tank, (50%)*	200	700	5	9	0
	New with storage tank, (80%)*	2	30	3	14	0
Local heating, pellet boilers	New device, wood pellets, (75%)*	2	6	4	6	0
Cogeneration	Biofuel, backpressure turbine (75 – 80%)*	1	3	4	6	0

* The value in brackets indicates the average annual efficiency of the use of the technology and equipment

9.4. Emission Limit Values for Pollutants

The three important directives to be followed in the construction and reconstruction of power plants are: Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants [94] and Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants[95]. The latter calls for more efficient efforts to achieve full compliance with EU air quality legislation and to define strategic goals and measures for the post-2020 period.

The latter Directive shall apply to combustion plants, including a combination of two or more new medium combustion plants, the total rated thermal input of which is equal to or greater than 1 MW and less than 50 MW. When calculating the total rated thermal input of a combination of combustion plants, individual combustion plants with a rated thermal input of less than 1 MW shall not be taken into account. In order to avoid legal loopholes, this Directive should also apply to a combination of new medium combustion plants with a total rated thermal input equal to or greater than 50 MW, without prejudice to Chapter III (Special provisions for combustion plants) of EU Directive 2010/75/EU. Directive 2010/75/EU of 24 November 2010 on industrial emissions (integrated pollution prevention and control). [95]

All emission limit values shall be calculated at a temperature of 273,15 K, a pressure of 101,3 kPa, and with a correction for the water content of the exhaust gases, taking 6% as the standardized O_2 content of the solid fuel.

All permits for installations containing combustion plants for which a permit was granted before 7 January 2013 or for which the operators have submitted a complete application for a permit before that date, provided that such plant is operational by 7 January 2014 at the latest, shall include conditions ensuring: that the emissions from those installations do not exceed the emission limit values set out in Part 1 of Annex V (Article 30 (2)).

If the total rated thermal output of the combustion plant (e.g., cogeneration plant) is 50 MW or more, the SO_2 emissions from the combustion of biomass (including wood fuels) shall not exceed 200 mg/Nm^3. The NO_x emission limit values vary according to the size of the combustion plant: for the rated thermal input between 50 and 100 MW, the limit value is 300 mg/Nm^3, for the rated thermal input between 100 and 300 MW, it is 250 mg/Nm^3, and for the rated thermal input greater than 300 MW, the limit value is 200 mg/Nm^3. Particulate (dust) emission limit values also depend on the power class of the biomass combustion plant: for the rated thermal input between 50 and 100 MW, the limit value is 30 mg/Nm^3, for the rated thermal input between 100 – 300 MW, it is 20 mg/Nm^3, and for the rated thermal input greater than 300 MW, the limit value is 20 mg/Nm^3. [96]

According to Article 30 (3) of the same Directive (installations authorized after 07.01.2013), the previous limit values are slightly stricter: In the rated thermal input between 50 and 300 MW, SO_2 emissions shall be below 200 mg/Nm^3, and in the rated thermal input greater than 300 MW, the emissions shall be below 150 mg/Nm^3. The NOx emission limit values for the rated thermal input between 50 and 100 MW are 250 mg/Nm^3, for the rated thermal input between 100 and 300 MW, they are 200 mg/Nm^3, and for the rated thermal input greater than 300 MW, the limit values are 150 mg/Nm^3. Particulate (dust) emission limit values for wood fuels at all rated outputs above 50 MW are 20 mg/Nm^3.

In accordance with Article 6 (2) of the Medium Combustion Plant Directive, from 1 January 2025 emissions of SO_2, NO_x and particulate matter (dust) from an existing medium combustion plant with a rated thermal input exceeding 5 MW shall not exceed the limit values set out in Tables 2 and 3 of Part 1 of Annex II. From 1 January 2030, emissions of SO_2, NO_x, and dust into the air from an existing medium combustion plant with a rated thermal input equal to or less than 5 MW shall not exceed the emission limit values set out in Tables 1 and 3 of Part 1 of Annex II. Here, it is recommended that each interested party read this directive individually [95].

For wood fuels, a dust emission limit value could be set: for existing medium combustion plant with a rated thermal input equal to or greater than 1 MW and less than or equal to 5 MW, this is 50 mg/Nm^3, and with the rated thermal input greater than 5 MW it is 30 mg/Nm^3. For all new plants with a rated thermal input of 1 – 50 MW, the limit value is 20 mg/Nm^3. [96] [97]

9.5. Ash Removal and Gas Purification Equipment

Purification of the flue gases from the boiler furnace and other combustion plants is necessary in order to reduce the content of particulate matter in the flue gas and to ensure their proper concentration limit. The ash content of the flue gases is determined during operational tests, and as we saw in the previous subsection, there are limit values set for their emissions.

Several different types of equipment and methods can be used to separate fly ash from flue gases: multicyclones, bag filters, electrostatic precipitators, and also scrubbers. A new direction in the purification of the flue gases of biofuel boilers from fly ash and increasing their energy efficiency is the cooling of the flue gases, which involves the condensation of the water vapor contained in it together with the capture of particulate matter.

All the above equipment has its advantages and disadvantages, and therefore their use in purification o flue gas of a particular boiler depends on several factors, including the size (capacity) of the boiler. In order to ensure the high efficiency of the purification device, the device must be correctly calculated and selected. In the cyclone and electrostatic precipitator calculations, the gas velocity (quantity) through the device is determined according to the size of the ash particles. What purity of the flue gas can be achieved with any type of device and what are the conditions for their use can be seen in Table 9.2.

Table 9.2. Some performance characteristics of gas purification equipment [14]

Device name	Ash content of the gas, mg/Nm^3	Operating temperature, °C
Multicyclone	150 – 500	<500
Bag filter	10 – 50	<150
Electrostatic precipitator	99.9%*	<300
A scrubber	50 – 100	<70 – 80

* The operation of the electric filter is characterized by purification efficiency.

Multicyclones

A cyclone is a device in which the separation of particulates from a gas stream takes place in a vertical tube by centrifugal forces. Multicyclone (Figure 9.2, A) consists of several parallel cyclones connected to a device with a common collector and a hopper. The multicyclone achieves smaller dimensions and lower gas duct resistance compared to a single large diameter cyclone. Fly ash contains relatively large particles, which make them well separable in cyclones by centrifugal forces. With a multicyclone it is possible to reduce the ash content of the flue gas to the level of ~150 mg/Nm^3. Multicyclones are relatively inexpensive, simple in construction, do not require special maintenance, are not sensitive to gas temperature, and are therefore used quite widely in boiler houses.

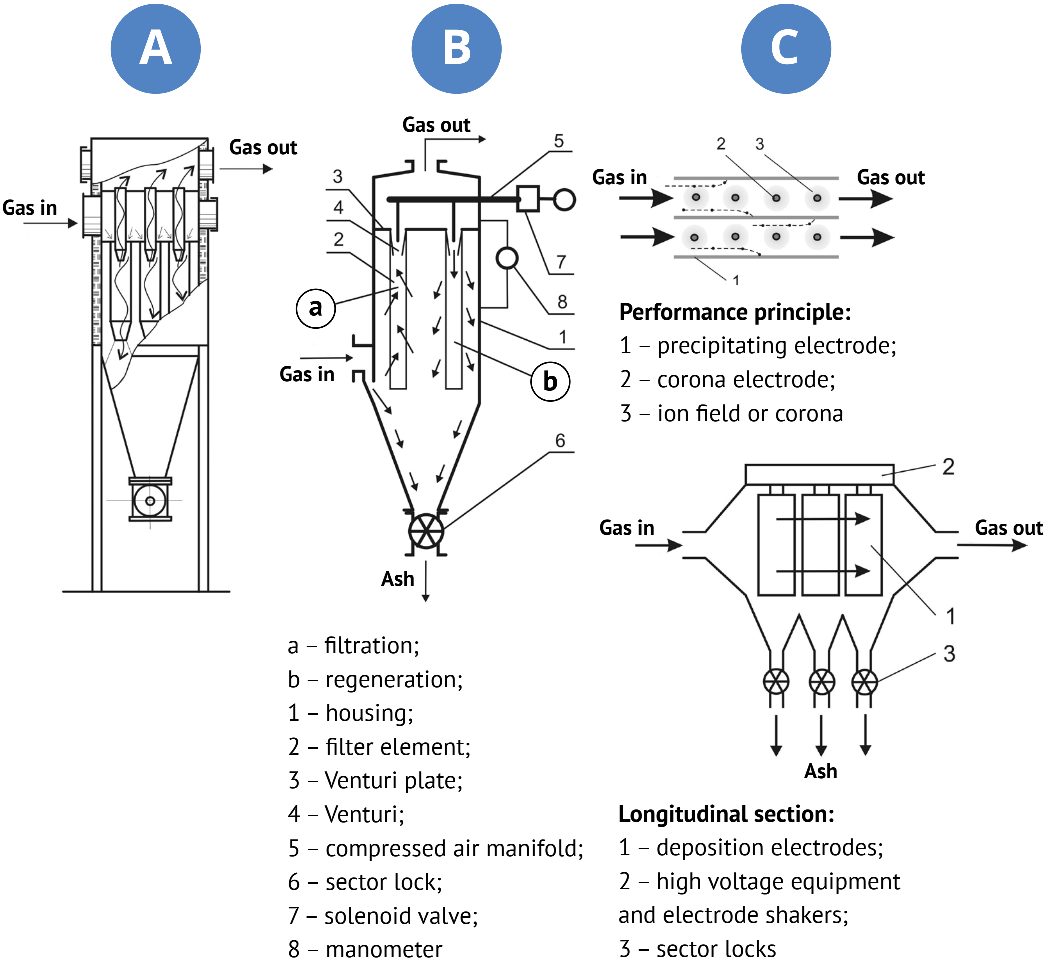
Bag filters

In the bag filter (Figure 9.2, B) the particulates are captured from the gas stream by means of a fine-mesh fabric or even a porous ceramic. Bag filters are much more efficient flue gas purification devices than multicyclones, ensuring an ash content in the flue gas at the level of 10 – 50 mg/Nm^3. As a rule, the operating temperature of bag filters does not exceed ~180 °C. The most commonly used filter material is polyester fabric. A cyclone or precipitation chamber is used in front of the filter to prevent sparks from entering the filter. The bag filter needs regular regeneration-cleaning to ensure filter efficiency and low resistance. The most common bag filter cleaning methods are: mechanical shaking, cleaning with reversible gas flow and pulse cleaning. Combined cleaning is also used; for example, reversing the gas flow is followed by mechanical shaking. Due to the risk of ignition, the bag filter must be protected against high temperatures and high oxygen content in the flue gases. Automatic protection is usually used to divert the gas past the filter. In biofuel devices, bag filters are used less frequently than multicyclones.

Electrostatic precipitators

In an electrostatic precipitator (Figure 9.2, C) the gas to be purified passes through an electric field and the solid particles are deposited on the electrodes. The electrodes of the electrostatic precipitator are given a rectified high voltage, whereas the coronating electrode is usually negative. The high voltage causes a corona discharge between the electrodes, and most of the gas between the electrodes is negatively ionized. Negative ions move to the deposition electrodes under the action of an electric field. The ions moving in the dusty gas towards the deposition electrode collide with the solid particles and are absorbed on the surface of the latter, as a result of which the dust particles with negative potential move to the deposition electrodes. The electrodes are cleaned of accumulated material by shaking them regularly.

An electrostatic precipitator is an efficient but relatively expensive gas purification device. The latter circumstance has so far limited their use in small wood heating plants, but in the conditions of stricter environmental requirements, they must be installed when burning wood fuels already at the capacity of 1 MW or greater (see Chapter 9.4).



a – filtration;
b – regeneration;
1 – housing;
2 – filter element;
3 – Venturi plate;
4 – Venturi;
5 – compressed air manifold;
6 – sector lock;
7 – solenoid valve;
8 – manometer

Performance principle:
1 – precipitating electrode;
2 – corona electrode;
3 – ion field or corona

Longitudinal section:
1 – deposition electrodes;
2 – high voltage equipment and electrode shakers;
3 – sector locks

Figure 9.2. Schemes of multicyclone (A), pulse jet bag filter (B) and electrostatic precipitator (C) [14]

Flue gas condensation

Condensing water vapor from flue gases achieves two goals: firstly, the content of ash particles in the flue gas is reduced to a level comparable to a bag filter, and secondly, energy efficiency is increased at the expense of the heat released during condensation.

The flue gas of a biofuel boiler contains water vapor for two reasons: the hydrogen in the fuel reacts with the atmospheric oxygen in the combustion process to produce water vapor, and the moisture in the fuel (moisture of wood chips is usually 35 – 55%) also becomes water vapor.

The water vapor content of the flue gas is of interest mainly because it is unused energy (waste heat) released during condensation (see also Chapter 6.5). Theoretically, the energy of condensation released is equal to the heat of evaporation of the water, plus the heat obtained from cooling. By cooling the flue gas below the dew point, water vapor begins to condense out of the flue gas. The lower the flue gas is cooled, the greater the amount of condensed water and the heat generated. Water returned from the heating system is used to cool the flue gas (Figure 9.3, [98].

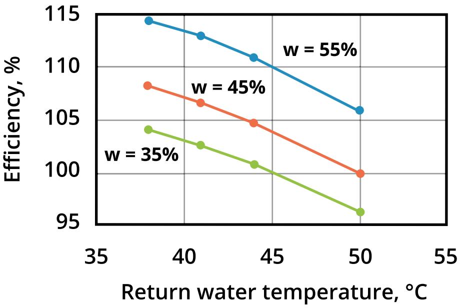


Figure 9.3. The effect of flue gas condensation on the efficiency of a woodchip boiler house

The flue gas cooler is the first assembly that the return water passes through in the boiler house. Flue gas condensation residue is a condensate consisting of water that contains small amounts of dust particles and organic matter from incomplete combustion of the fuel. The condensate also contains some heavy metals, chlorine, and sulfur. The pH of the condensate can vary widely depending on the system but is usually in the range of pH 6 – 7. Heavy metals, especially cadmium, are present in solids and are insoluble in water. Therefore, it is necessary to pre-treat the condensate before releasing it into nature. The treatment usually consists of filtering the solids and neutralizing the water to an environmentally sound level. An efficient drip trap is used after the flue gas cooler to prevent water droplets from passing into the flue and chimney. In small boiler houses where flue gas condensation is used, it is reasonable to use corrosion-resistant materials in the construction of the flue and chimney to reduce the risk of corrosion.

Flue gas condensing has been widely used in Estonia in recent years, because the wood fuel burned is mostly of suitable moisture and the additional amount of heat obtained allows to cover the needs of additional consumers without adding new capacities (boilers). It also meets the requirements of the Energy Efficiency Directive to maximize the use of waste heat and improve the efficiency of existing combustion plants.[82].

10. Planning the Implementation of Solid Biofuels in District and Local Heating

The use of biofuels in district and local heating has two important objectives:

- reduction of greenhouse gas emissions in heat supply;
- using cheaper fuel compared to local and fossil fuels and lowering the price of heat.

While the environmental and greenhouse gas emission reduction targets for biofuel use are generally met, achieving economic viability requires skilled economic planning of the entire project and consideration of the associated impacts due to the relatively high investment needs.

10.1. Necessary Input Data for Heat Supply System Design

Before planning a heat supply based on biofuels, the possibilities of obtaining fuel must be thoroughly considered. To ensure the security of supply, it is advisable to conclude initial contracts with fuel companies indicating the required fuel properties and quantities, delivery terms, and pricing principles. If there are no obstacles to the supply of biofuels, the necessary baseline data can be specified, and the design of a biofuel-based heat supply system can be started.

The analysis of district heating projects implemented so far has shown that the biggest mistakes in project preparation have been an overestimation of consumption volume and selection of too powerful boilers. In most cases, this leads to unreasonably high investments and relatively high heat prices; moreover, often boilers have to be operated at unsuitable low loads.

The following information must be obtained for heat consumers:

- estimated annual heat consumption;
- required connection capacity;
- the size of the heated surface;
- the technical condition of the building, the energy saving potential, and the indicative plan for the implementation of the savings measures.

Typically, heat is needed in buildings to compensate for heat loss to the outside environment, i.e., for heating and ventilation air heating. Domestic hot water can also be produced on the basis of district heating.

10.2. Load Duration Curve

In district and local heating, the heat load fluctuates over time both by year and by day. Therefore, the graph of the change in heat demand over time is somewhat different from year to year, and a special diagram of the change in sequenced loads is used to simplify the calculations – the so-called load duration curve, see Figure 10.1, which is the sequence of descending hourly loads throughout the year. The horizontal axis of the graph shows the hours of one year (8,760) and the vertical axis the capacity – so we get a graph showing the service life of one year. The size of the surface of the base of the curved line in the graph shows the amount of heat produced in this period in energy units. Depending on the climate of the location, the nature of the heat demand of consumers, and several other factors, the shape of the load curve can vary greatly.

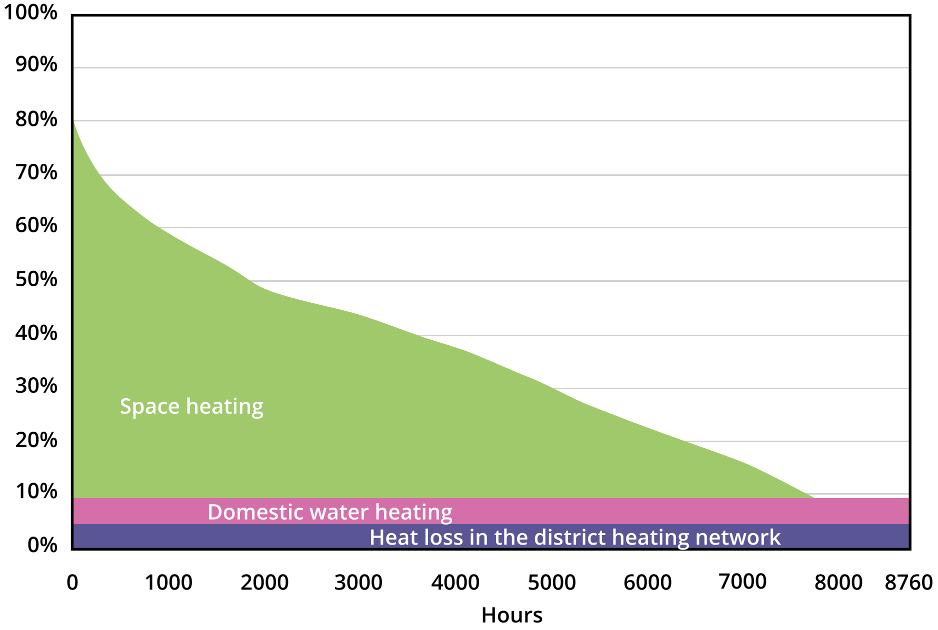


Figure 10.1. Load duration diagram of district heating system when the heat is needed for both space heating and domestic water heating

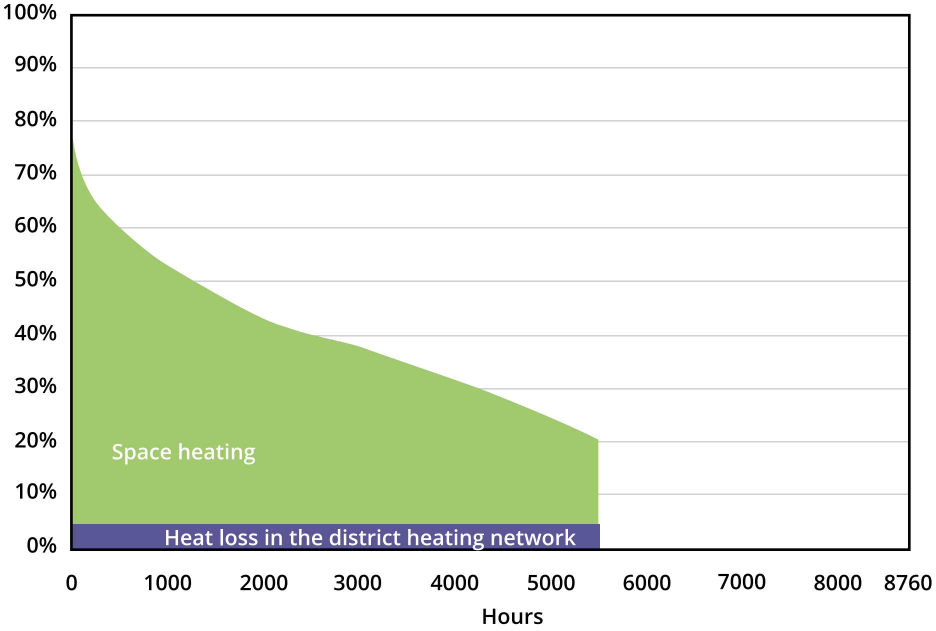


Figure 10.2. Load duration diagram of district heating system if domestic hot water is not produced on the basis of district heating and there is no summer heat load

10.3. Heat Load Analysis and Selection of Heat Sources

10.3.1. Characteristics of Heat Loads

As heat load duration graphs (see Figure 10.1 and Figure 10.2) show that the heat load of a district heating system fluctuates to a very large extent during the year, mainly due to large fluctuations in space heating load depending on climatic conditions. Load fluctuations need to be analyzed in order to make efficient choices of heat sources.

Load fluctuations are characterized by a capacity factor μ and/or utilization time of the equipment [99, 100] The capacity factor indicates the ratio of the annual average capacity demand to maximum capacity demand of the equipment, while utilization time (often simply called service time) shows the time in hours per year during which the equipment would be able to produce annual heat output at rated load.

$$\mu = \frac{\text{average capacity demand,MW}}{\text{maximum capacity demand, MW}} \qquad (10.1)$$

$$\tau_{ut} = \frac{\text{annual heat output,MWh/yr}}{\text{maximum capacity demand,MW}} \qquad (10.2)$$

$$\tau_{ut} = 8760 \cdot \mu\,, \qquad (10.3)$$

where μ – capacity factor;
τ_{ut} – utilization time, h/yr.

The capacity factor for the entire district heating system can be found through space heating load, domestic hot water production load and capacity factor due to losses in the district heating network:

$$\frac{1}{\mu} = \frac{f_{sh}}{\mu_{sh}} + \frac{f_{dhw}}{\mu_{dhw}} + \frac{f_{hl}}{\mu_{hl}}\,, \qquad (10.4)$$

where μ – capacity factor for the entire system;
μ_{sh} – capacity factor for space heating alone;
μ_{dhw} – capacity factor for domestic hot water alone;
μ_{hl} – capacity factor for distribution heat loss alone;
f_{sh} – annual proportion of heat supply for space heating;
f_{dhw} – annual proportion of heat supply for domestic hot water;
f_{hl} – annual proportion of heat supply for distribution heat loss.

The capacity factor of space heating load depends directly on the climatic conditions and the effective indoor temperature of the heated buildings[6]:

$$\mu_{sh} = \frac{G/365}{t_{i,e} - t_{o,min}}\,, \qquad (10.5)$$

where G – number of degree days per year;
$t_{i,e}$ – effective indoor temperature, °C;
$t_{o,min}$ – extreme (minimum) outdoor temperature, °C.

In the absence of more detailed effective indoor temperature data, its value in Estonia is taken to be 17 °C, i.e., from this temperature to the internal temperature of the building (21°C) the air is heated at the expense of the so-called free heat. For recently renovated dwellings and new ones, the equilibrium temperature can be several degrees lower – so the actual equilibrium temperature and the corresponding number of degree days must be used when planning the heat supply of new residential areas.

The estimated minimum outdoor air temperature in Estonia, depending on the loca-

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[6] Effective indoor temperature is defined by the indoor air temperature (°C) of the building, until which the room air is to be heated by the space heating system, considering that the heating of air temperature from the effective temperature to the necessary indoor air temperature takes place at the expense of the free heat (the heat emitting from people, electrical appliances, sunlight etc.)

tion, is between −19 °C (Kuressaare, Kärdla) and −25 °C (Tartu, Võru, Jõgeva), including −21 °C in Tallinn.

The values of the domestic hot water load capacity factor are determined on the basis of daily averages. As no such analyzes have been performed in Estonian district heating systems, the value 0.58 (Swedish average value between 0.54 and 0.62) corresponding to the Swedish experience [99] can be approximated as a basis.

When determining the capacity factor of heat losses in a district heating network, annual fluctuations between the temperature of the water in the network pipelines and the ambient temperature surrounding the pipelines are taken into account. The power factor of heat losses thus depends on the temperature schedule of the district heating system and the soil temperatures. According to the Swedish experience[99], 0.71 can be considered the average value of μ_{hl}.

Using the climatic data of Tallinn in the normal year[7], the relative heat loss of the district heating network 12%, the ratio of heat consumption components (heating and hot water) 85% and 15%, we get a calculated district heating system capacity factor of 0.35, i.e., the average annual load in such a district heating system is 35% of the maximum and the utilization time of the heat sources is 3,066 h.

10.3.2. Determining the Optimal Capacity of a Biofuel Boiler According to the Load Duration Curve

One of the bases for a practical choice of heat sources is the volume of investments and the cost of fuel used for the respective heat source. The level of investment is usually expressed as a specific investment per unit of capacity, i.e., either €/MW or €/kW.

$$I_{sp} = \frac{\text{investment, €}}{\text{unit capacity, MW}} , \qquad (10.6)$$

where I_{sp} – specific investment, €/MW.

It is important to note that the level of specific investment is strongly dependent on the capacity of the equipment. The lower the unit capacity of a device, the higher is usually its specific investment. Approximately, this dependence can be expressed by the following relationship [101]:

$$I_{sp,2} = I_{sp,1} \cdot \left(\frac{Q_2}{Q_1}\right)^n , \qquad (10.7)$$

where Q_1 – unit capacity of unit 1, MW;

Q_2 – unit capacity of unit 2, MW;

$I_{sp,1}$ – specific investment of device 1, €/MW.

$I_{sp,2}$ – specific investment of device 2, €/MW.

n – an exponent, the value of which may be between 0.5 and 0.8.

If we know the volume of investments of a 6 MW biofuel boiler house € million € (specific investment of 500,000 €/MW, respectively), then with the value of the indicative exponent n=0.6, the level of investments of a 3 MW boiler house of the same type can be estimated. According to these data, the estimated amount of specific investments would be 758,000 €/MW, and the total investment would be approx. 2.28 million €.

Although a biofuel boiler with associated equipment is relatively expensive, the fuel used (e.g., wood chips) is much cheaper than natural gas or light fuel oil (see Table 10.1).

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[7] The normal year in Estonia is the average year of the period 1975 - 2004

The economic viability of an expensive biomass boiler or boiler house using relatively cheap fuel can only be achieved at maximum load.

Depending on the level of specific investments in the heat source, the cost of the fuels used, and the operational parameters, the heat sources in the heat supply system are divided into base and peak load heat sources. Baseload heat sources should cover the major part of the annual heat demand and peak load heat sources using more expensive fuel will be used for a short period during the peak heat load period. The following table describes the technological solutions suitable for covering the base and peak loads and their characteristics (see Table 10.2).

Table 10.1. Typical values for specific investments in some heat sources and costs of fuels used

Heat source combustion system	**Approximate level of specific investments, €/MW**	**Fuel cost, €/MWh$_{fuel}$**
Wood chip boiler	300 000 – 800 000	15 – 20
Pellet boiler	100 000 – 130 000	40 – 45
Fuel oil boiler	50 000 – 100 000	60 – 110
Gas boiler		40 – 50

Table 10.2. Base and peak load heat sources and their typical properties

	Baseload heat sources	**Peak load heat sources**
Types of heat sources	Waste incineration plants Combined heat and power plants Biomass boilers Heat pumps Industrial waste heat	Gas boilers Fuel oil boilers Electric boilers or heaters
Properties	Peavad kasutama odavat kütust Kõrged püsikulud (kapitalikulud) Aeglane käivitamine Piiratud manööverdamisvõime	Low fixed costs (capital costs) May use expensive fuel Quick start Good maneuverability

In a typical Estonian district heating system (see Figure 10.3 and Figure 10.4), the period of near-maximum heat loads is relatively short, and more than 50% of the load occurs in normal year conditions for up to 1700 h, but only 6% of the annual heat consumption would need to be produced with the peak load heat source. If the capacity of the biofuel boiler is chosen to be half of the maximum load (50%) and to load it throughout the year, it could cover about 94% of the annual heat demand.

Based on previous experience, investments in the introduction of biofuels will be profitable if the utilization time of the equipment running on biofuel is higher than 4,000 – 4,500 h/yr and capacity factor by almost 0.5 and greater.

When choosing the capacity of a biofuel boiler, it is necessary to take into account the fact that its stable operating range is 30 – 100% of the nominal capacity according to the standard. However, most modern boilers can also operate at somewhat lower loads (approx. 20%) and can be overloaded by up to 20% in the short term. In order to cover the low heat load of the summer period with a biofuel boiler, the average summer heat load should not be lower than approx., 20% of the nominal capacity of the biofuel boiler.

The previous discussion and recommendations apply to district heating systems, where consumers are supplied with heat throughout the year, i.e., domestic hot water is produced on the basis of district heating. In Estonian conditions, a situation has often developed historically in smaller district heating systems, where the production of domestic hot water on the basis of district heating has been abandoned, and consumers use electric boilers for this purpose (see e.g., Figure 10.2). Given the fact that the climate has become much milder in recent years compared to the so-called normal year climate, the heating of buildings in such district heating systems usually takes place during about 7.5 months or even less.

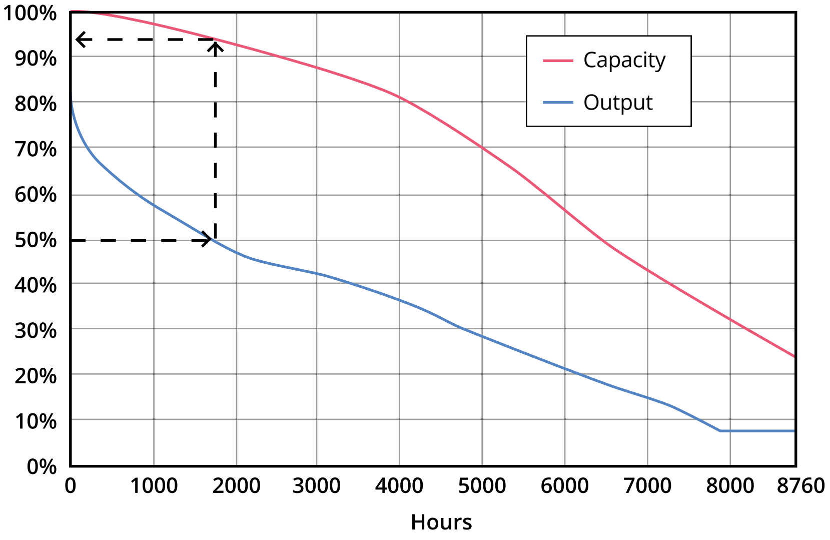

Figure 10.3. Duration chart with load and output coverage by a biofuel boiler in Estonian climatic conditions

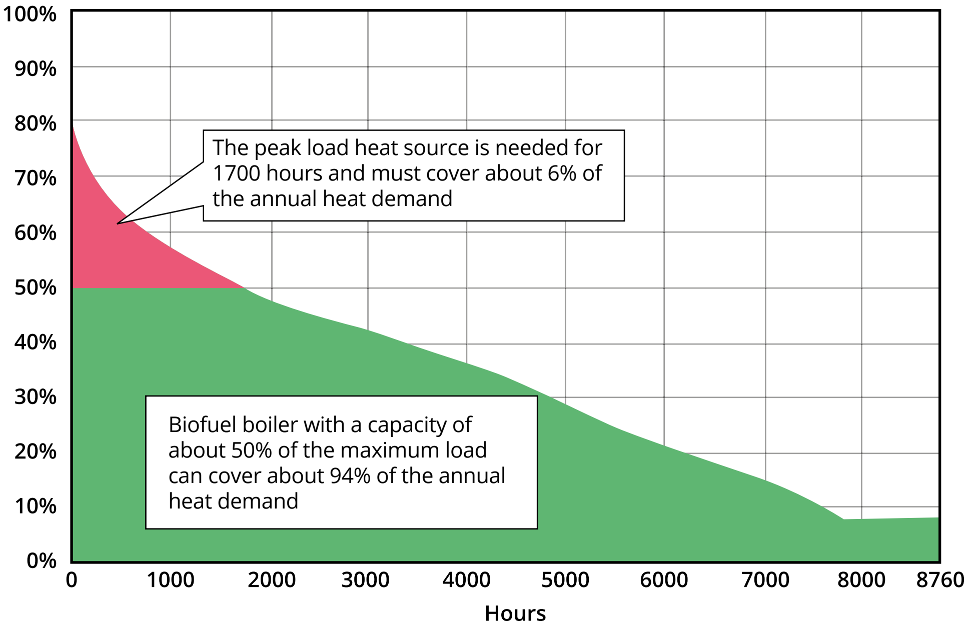

Figure 10.4. Covering loads in a typical district heating system with biofuel boiler

10.4. Boiler House Infrastructure

The infrastructure of a biofuel boiler house is considerably more diverse than that of a fossil fuel boiler house, and the planning must, therefore, take into account the requirements arising from the location, the need for the territory, access roads, environmental requirements, noise, and other factors.

A biofuel boiler house can include quite a few different devices, systems, and units:

- biofuel storage (long-term storage, short-term or daily storage);
- fuel feed and handling system;
- furnace for burning biomass;
- biofuel boiler (hot water, steam or thermal oil boiler);
- peak load boiler (gas or liquid fuel boiler);
- flue gas purification device (multicyclone, electrostatic precipitator);
- flue gas water vapor condensing unit;
- ash collection and handling system;
- chimney;
- control and monitoring system;
- power supply system;
- heat accumulator;
- CHP plant, e.g., Rankine steam cycle, ORC cycle plant or biofuel gasification reactor with internal combustion engine or gas turbine.

The need for the territory is usually determined by the technical solution of the fuel storage (see Ch 5.3) and the required storage capacity. The minimum storage volume is usually considered to be a couple of days' fuel stocks, but the volumes of fuel trucks and the needs of fuel suppliers must also be taken into account.

10.5. Assessing the Economic Viability of an Investment in Heat Supply

10.5.1. Calculation of Annual Fixed Costs

The calculation of capital costs as the main fixed costs is based on the initial cost of the equipment and the estimated useful life in years through which the annual depreciation of the equipment (depreciation provisions) is found. In addition, changes in the value of capital over time, which are characterized by a discount rate, must be taken into account. The annual cost of capital can be calculated using the following formula:

$$A = I_0 \cdot \frac{r \cdot (1+r)^n}{r \cdot (1+r)^n - 1} \;, \qquad (10.8)$$

where A – capital expenditure per year, €/yr;
I_0 – initial investment, €;
r – discount rate
n – the estimated service life of the device in years.

Although the annual cost of capital can be found using the following formula using computer technology, it is more convenient to use the PMT financial calculation function in spreadsheet programs (EXCEL, Open Office Spreadsheet, Numbers).[8]

When reviewing the maximum price of heat, the Estonian Competition Authority refers narrowly to the annual cost of capital, which is obtained by dividing the total volume of the investment by the estimated useful life in years. In doing so, the Competition Authority takes into account additional fixed costs, which are considered to be justified profitability. If the discount rate r in the annual cost of capital formula or in the financial function PMT is equal to the average cost of capital WACC applied to district heating companies, we get the value of the annual fixed cost, which the Estonian Competition Authority considers as the sum of capital cost and reasonable yield[9].

10.5.2. Payback Period Method

The profitability method is based on an estimate of the time over which the capital invested will be repaid in full through the income received. A distinction is made between simple and discounted payback periods.

The payback period method is appropriate when the return on an investment is the same for each year of a lifetime. The unadjusted payback period is calculated from the following simple relationship:

$$\tau = \frac{I_0}{a} \;, \qquad (10.9)$$

where I_0 – initial investment, €;

a – annual return on investment, €/yr.

The annual return on investment must be understood as the reduction in variable costs, including the reduction in fuel costs.

Although the payback period does not take into account changes in the value of capital over time and bank loan interest, the unadjusted payback period is suitable for an initial approximate assessment of the return on a project. The discounted payback period is longer than the unadjusted payback period because it also takes into account interest payments.

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[8] It is important to note that the function labels of spreadsheet programs depend on the software language version. The name of this function PMT comes from the English version of the software and is also used in the Estonian spreadsheet software.

[9] The Estonian Competition Authority is of the opinion that if the company's justified profitability or operating profit does not exceed the Weighted Average Cost of Capital (WACC), then the company will earn a reasonable profit. WACC is thus the revenue rate permitted by the Competition Authority, on the basis of which the justified profitability to be included in the price of district heating is calculated.

It is suitable to find the discounted payback period with the financial calculation function NPER of the spreadsheet programs, in which, in addition to the initial investment I_0 and the annual return on investment a, the discount rate r is also taken into account.

There are several important disadvantages to using the payback period method, including:

- It does not take into account income received after the return on investment until the end of the lifetime of the investment.
- The method cannot be applied when the values of the return on investment change from year to year, e.g., due to changes in fuel prices.

10.5.3. The Net Present Value (NPV) Method

In case of net present value (NPV) method[10] all values of income and expenses received over the lifetime of the investment are taken into account – cash flows:

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - I_0 \ , \qquad (10.10)$$

where NPV – net present value of the investment, €;

CF_i – cash flow in year i, €/year;

n – the design working life of the device, a;

r – discount rate

I_0 – initial investment, €.

In the formula (10.10), the annual cash flow is the difference between income and expenses, the values of which have been reduced to the year of the investment. The sum of the annual net cash flows and the initial investment determine the economic justification for the investment, i.e., and a positive NPV value indicates the income earned over the lifetime of the project. If the NPV is negative, the investment is unprofitable.

In most cases, the corresponding NPV function of the spreadsheet programs is used to calculate the net present value. The advantage of this method over the payback period method is that cash flows are taken into account throughout the life of the investment. However, it is relatively difficult to forecast cash flows over the lifetime of the investment, as both energy and fuel prices can change significantly.

10.5.4. Internal Rate of Return (IRR) Method

The internal rate of return method consists in finding a discount rate at which the present value of income would be zero, i.e., NPV=0 (see formula 10.10). An investment is considered economically justified if the calculated IRR value is higher than the actual discount rate (in the case of a bank loan, the loan interest).

To calculate the value of the internal rate of return, it is appropriate to use the corresponding spreadsheet function IRR, which is a numerical solution of the following equation with respect to IRR:

$$\sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i} - I_0 = 0 \ , \qquad (10.11)$$

where CF_i – cash flow in year i, €/year;

n – the design working life of the device, a;

IRR – internal rate of return;

I_0 – initial investment, €.

It is useful to know that the internal rate of return IRR, the net present value of return NPV and the discounted payback period NPER are related but describe the economic

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[10] NPV - abbreviation of the term Net Present Value.

return on investment from different perspectives. For example, if the IRR is equal to the effective discount rate r (bank loan interest), then the net present value is zero and the discounted payback period NPER is equal to the lifetime of the investment n.

If IRR> r, then NPV>0 and NPER<n, i.e., the investment project is profitable. However, if IRR<r, then NPV<0 and NPER>n, then the project is unprofitable.

10.6. Breakdown of Costs for Heat Production

The total costs of a heating company are divided into fixed costs, which are proportional to the set heat capacity (€/MW), and variable costs, which are proportional to the heat production (€/MWh), both in the economic analysis and in the calculation of the heating cost.

Fixed costs are, in particular, capital costs, to which may be added a certain component of operating costs, which also depends only on the installed capacity. Capacity-dependent operating costs may include, for example, maintenance costs for back-up equipment and personnel costs for key personnel.

The majority of variable costs are costs for fuel; in addition, variable costs include costs for electricity, pollution charges, costs for obtaining consumables, repair costs, etc.

10.6.1. Estimation of Fuel Costs

Fuel costs make up the bulk of variable costs, and it is therefore useful to know the factors that affect it: the price of fuel and the efficiency of the heat source.

The price of biofuel depends mostly on its quality but fluctuates to some extent both from year to year and from season to season, as well as depending on the market situation. Although the moisture content of the fuel is an important indicator of the quality of wood chips (see Chapter 3.1 and Chapter 4), the choice of this fuel must be based mainly on the combustion plant. Biofuel operated district heating systems predominantly use equipment designed to use moist (35 – 55%) wood chips.

In Estonia, wood chips are mostly measured in bulk m^3, and thus the energy of the fuel arriving at the boiler house can be easily determined by the amount of fuel expressed in bulk m^3 and the energy content of the fuel E_{ar}.

Knowing the price of fuel, the energy content of the fuel and the efficiency of the heat source (boiler), we can determine the variable cost component related to fuel costs in the heat production price from the following relationship:

$$Q_f = V_{bulk} \cdot E_{ar} \ , \qquad (10.12)$$

where Q_f – energy content of fuel, MWh;

V_{bulk} – bulk volume of the fuel, l m^3;

E_{ar} – energy content of the fuel as received, MWh/l m^3.

The energy content and price of fuel and heat production can be used to determine the fuel cost component in the heat production price.

$$h_f = \frac{Q_f \cdot h_f}{Q_b} \ , \qquad (10.13)$$

where Q_f – energy content of fuel, MWh$_f$;

h_f – fuel price, €/MWh$_f$;

Q_b – boiler house or boiler heat production, MWh.

Equations (11.12) and (11.13) can be used for boiler house or boiler operating data, but when planning a boiler house, we should take into account the boiler efficiency η when determining fuel consumption:

$$Q_f = \frac{Q_b}{\eta_b}, \tag{10.14}$$

where Q_f – fuel consumption by energy content, MWh_f;

Q_b – boiler house or boiler heat production, MWh;

η_b – boiler house or boiler efficiency.

In terms of efficiency of a biofuel boiler,we must take into account the fact that it depends on the boiler load. In most cases, boiler manufacturers only provide an efficiency value at rated thermal input. As a general rule, the efficiency of a biofuel boiler at low loads is lower, so the average annual efficiency of the boiler depends on its operating mode. If the boiler has to operate for a long time at abnormally low loads (less than 30%), this can significantly reduce the average annual efficiency of the device.

As most biofuel boiler manufacturers guarantee the normal operation of boilers in the range of 30 – 100%, this should be taken into account when planning a boiler house.

10.6.2. Dependence of Heat Price on the Ratio of Fixed and Variable Costs

The following figure (see Figure 10.5) characterizes the possible distribution of costs and the dependence of the production price on the annual production in a typical biofuel boiler house with a capacity of about 3 MW.

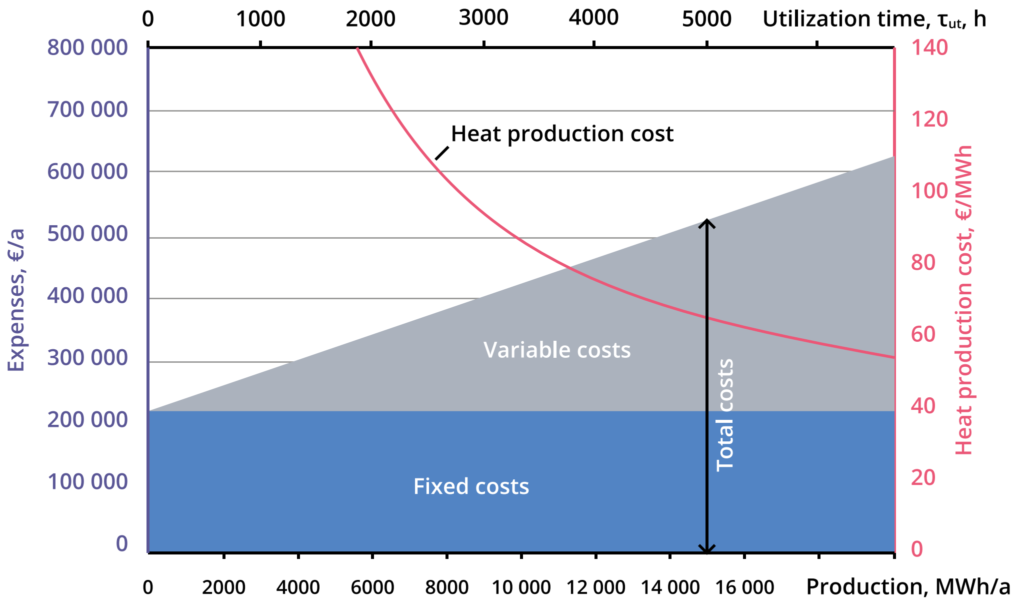

Figure 10.5. Fixed and variable costs in heat production and the dependence of the production cost of heat on the volume of production

One of the indicators of the district heating system, which deteriorates as the consumption volume decreases, is the relative heat loss of the district heating network. The absolute heat loss in the network depends only on the quality of the piping insulation and the temperature difference between the heat transfer carrier flowing in the pipes and the environment (soil) surrounding the pipes. The absolute heat loss does not depend on the amount of heat transferred through the pipeline.

If, for example, the relative heat loss of a district heating system was initially 14%, then after a 15% decrease in consumption, the relative heat loss increases to about 16%, or by two percent, and this, in turn, increases the price of heat.

The decrease in consumption volume also affects the change in the ratio of fixed and variable costs in the district heating system. As consumption decreases, variable costs in the district heating system decrease because less fuel is needed. At the same time, fixed costs do not change in absolute value, but the fixed cost component in the price of heat increases, and this is proved by e.g., Figure 10.5.

The decline in consumption volume particularly affects the district heating systems where heat sources (boilers) are underloaded. In the example of Figure 10.5, the capacity of the heat source (woodchip boiler) was 3 MW, which is considered to require the time of use of nominal capacity in order τ_{ut} over 4000 h (power factor $\mu \cong 0.46$ or higher), i.e., annual heat production of at least 12,000 MWh$_{th}$, to achieve economic viability. In the case of this heat production, the production price would be about 38.58 €/MWh$_{th}$, if the consumption decreased by 15% to 10,200 MWh$_{th}$ per year, the new production price would be 41.86 €/MWh$_{th}$, i.e., 3.28 €/MWh$_{th}$ higher. If the number of operating hours of the rated thermal input of the heat source remains even lower, the increase of the heat production price curve will become steeper, and the production price will increase faster as the load decreases.

In conclusion, it can be said that as the volume of consumption decreases, both production and transmission costs increase, and, unfortunately, the sales price of heat increases.

10.7. Combining Different Renewable Heat Sources in a District Heating System

In a district heating system, the main heat source running on biofuel can be combined with other renewable energy sources, such as solar collectors, heat pumps, etc. As the fixed costs of renewable energy sources are generally relatively high, such a combination must be analyzed in advance in order to be economically viable.

As shown in Figure 10.5, as the heat production of a biofuel boiler decreases, the production price of heat increases – thus, for example, the addition of solar collectors to a district heating system with a biofuel boiler will inevitably increase the production price of heat from a biofuel boiler. This effect can be significantly mitigated if [102] solar collectors can fully cover the heat consumption of the whole summer period (see Figure 10.6). In this case, either abnormally low load operation of a biofuel boiler in summer [57] or summer operation of a fossil fuel peak load boiler is avoided.

According to the Estonian District Heating Act [57] the consumer of district heating may additionally use heat from fuel-free renewable energy sources, including heat from solar collectors or heat produced by heat pumps specified by law, provided that renewable electricity is used to operate the heat pumps, so-called green electricity.

If only a part of consumers exercises the right granted to them by law to consume heat from renewable energy sources in addition to district heating,[11] a situation may arise in the district heating system where these consumers do not use district

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[11] In addition to heat from district heating network, the use use of heat from local renewable energy sources is considered as “parallel consumption”.

heating in the summer period and partly in the spring-autumn period, and the district heating becomes a heat source for them at essentially the peak load. Such so-called parallel consumption is in substantial conflict with the principles of the feasibility of a biofuel-based district heating system.

Problems related to parallel consumption in the district heating system can be alleviated by implementing a multi-component heat tariff system [102].

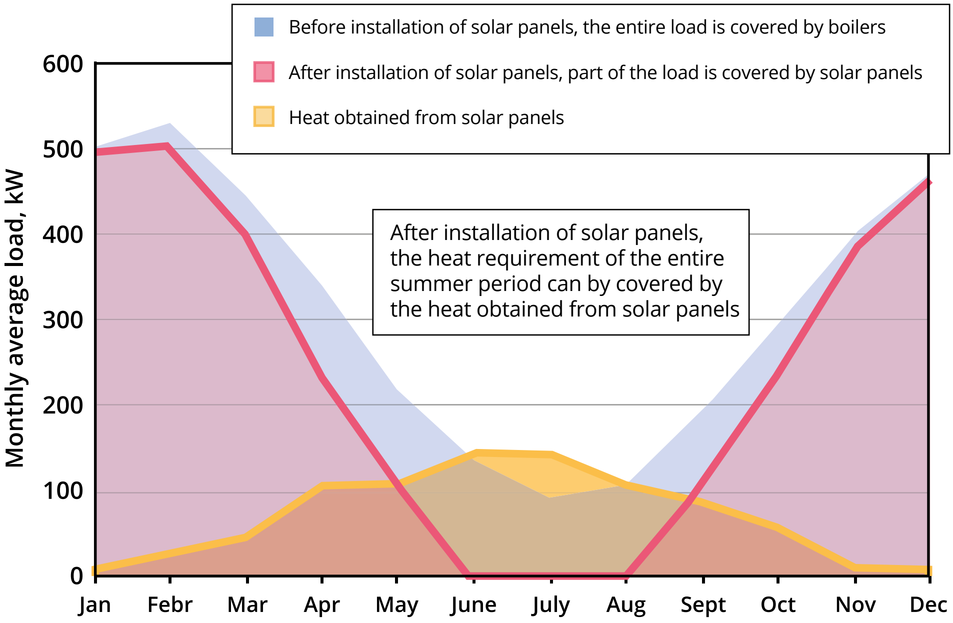

Figure 10.6. Heat production in a district heating system with a biofuel boiler before and after the installation of solar collectors

10.8. Quantities Characterizing the Operation of District Heating Systems

When analyzing the operation of a district heating system, parameters are used that characterize the entire district heating system, the boiler house and the heat source, heat transfer and losses in the district heating system, and the location of consumers. In most cases, the following characteristics of a district heating system are used:

- output capacity of heat sources (e.g., boilers), MW;
- total primary energy (fuels) consumption in energy units, MWh_{th};
- biofuel consumption in energy units and relatively total primary energy consumption, MWh_{th}, and %;
- heat output of the district heating system, MWh_{th};
- heat actually sold to consumers, MWh_{th};
- heat sold under normal year climatic conditions, MWh_{th};
- district heating network length (m), water volume (m^3) and average pipe diameter, mm;
- absolute heat loss in the district heating network, MWh_{th}/yr;
- relative heat loss in the district heating network, %;
- specific heat loss of the district heating network, W/m;
- combined annual consumption density per meter of pipeline route, kWh_{th}/(yr*m);
- the specific load characteristic K of the district heating network, which relates the annual consumption volume to the average diameter and length of the pipeline, kWh_{th}/(yr*mm*m);
- heat delivery capacity, which is the capacity of the installed heat sources per meter of network length, kW_{th}/m;
- heat production efficiency, %;
- efficiency of district heating system, %.

In addition to the parameters listed, the district heating system of the technical condition is characterized by of the water exchange rate per year m^3/m^3, from an economic point of view is more important special electricity consumption kWh_{el} per sold heat MWh_{th}.

The listed indicators allow to compare the analyzed district heating system with other district heating systems on the basis of both technical and economic indicators, to evaluate the system and, if necessary, to develop improvement measures.

As heated buildings are constantly being renovated, heat consumption decreases from year to year and this can significantly affect several parameters of the district heating system as well as the selling price of heat.

11. Economic Evaluation of Cogeneration Systems

When using biofuel, it is in principle possible to apply various combined heat and power technologies, the most important of which are:

- a Rankine steam cycle cogeneration unit with a biofuel steam boiler and a back-pressure turbine;
- a biofuel organic heat carrier (ORC) cogeneration unit under the Rankine cycle,
- a cogeneration unit with a biofuel thermal gasification unit and a gas engine or gas turbine.

The latest cogeneration solution has not been successfully implemented in Estonia so far, but in addition to the Rankine steam cycle cogeneration units with a backpressure turbine, several ORC cogeneration units are also operating in Estonia.

11.1. The Efficiency of Cogeneration in Heat Supply

The application of combined heat and power solutions as a heat source for district heating has begun to be applied to smaller and smaller district heating systems. The peculiarity of the cogeneration solution is that it is technologically a single process in which the heat and electricity ratio depends primarily on the technology, but the energy is realized in two relatively independent markets.

The advantage of cogeneration over separate production of heat and electricity is the potential to save primary energy, i.e., fuels, as well as reduce CO_2 emissions and other environmental impacts.

The total efficiency of a cogeneration unit is as follows [103] :

$$\eta_{CHP} = \frac{P_{el} + Q_{th}}{Q_f} = \eta_{el} + \eta_{th} , \qquad (11.1)$$

where P_{el} – electrical load, MW_{el};

Q_{th} – thermal load, MW_{th};

Q_f – energy from fuel, MW_k;

η_{el} – electrical efficiency of cogeneration;

η_{th} – thermal efficiency of cogeneration;

For each cogeneration technology and operating mode, the ratio between the electrical and thermal load of the process is C:

$$C = \frac{P_{el}}{Q_{th}} = \frac{\eta_{el}}{\eta_{th}} , \qquad (11.2)$$

where P_{el} – electrical load, MW_{el};

Q_{th} – thermal load, MW_{th};

η_{el} – electrical efficiency of cogeneration;

η_{th} – thermal efficiency of cogeneration;

In a steam power unit with a backpressure turbine, the ratio of electricity to heatC depends on the pressure of the fresh steam supplied by the turbine and the backpressure after the turbine. The pressure of fresh steam, in turn, depends on the capacity of the steam power unit – the higher the power of the unit, the more reasonable it is to use higher steam parameters.

The implementation of high steam parameters in a low-capacity steam generator and turbine would require the use of technological solutions that are economically and operationally viable only at high capacities. For this reason, the vapor pressure of a cogeneration unit with an electrical capacity of up to a few megawatts is usually 20 bar.

In the case of a 20 bar steam power plant used in a district heating system, the back pressure is typically 1.5 bar to achieve a sufficient temperature for the district heating water, which allows the electrical/thermal load ratio to be maintained at up to 0.2 (Figure 11.1).

The higher the fresh steam pressure, the higher the share of electricity in cogeneration and in large cogeneration plants with an electrical capacity of about 10 MW, the fresh steam pressure is about 40 bar, and the ratio of electrical to thermal load is about 0.25 (e.g., Tallinn power plant in Väos). Powerful cogeneration units with a fresh steam pressure of more than 100 bar can achieve a C value of 0.5, i.e., 1/3 of the emitted energy is electricity, and 2/3 is heat.

Since a cogeneration unit is a technological process with two outputs (electricity and heat), the process can be controlled according to either electricity or heat consumption.

As a general rule, all cogeneration units in Estonia are managed according to heat consumption, so the design of cogeneration units is also based on the heat load, more precisely the heat load duration schedule.

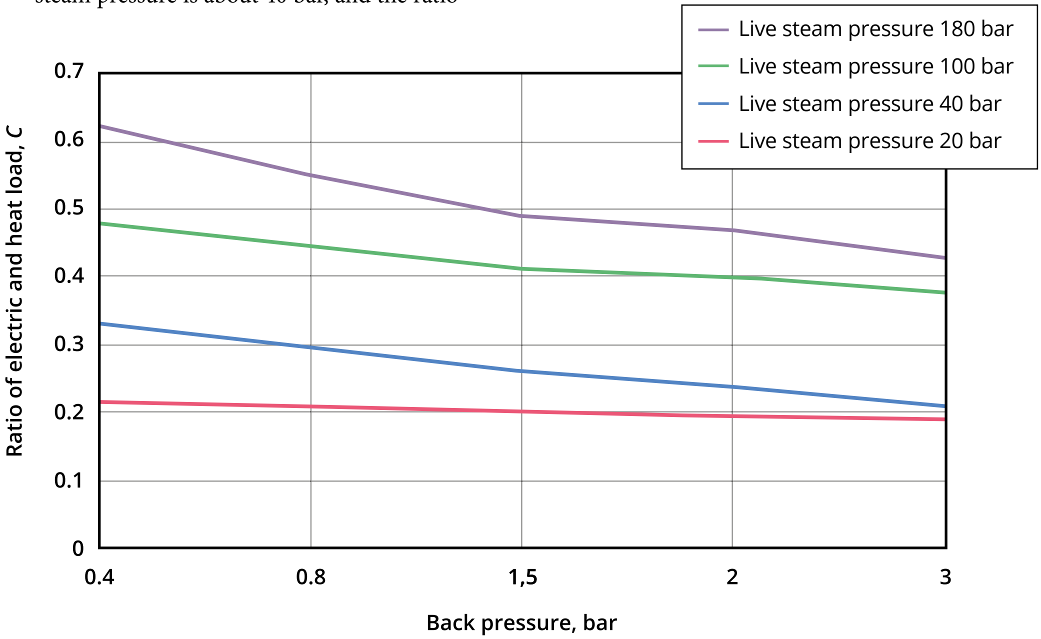

Figure 11.1. Ratio of electrical to thermal load C of a cogeneration unit with back-pressure turbine depending on live steam pressure and back pressure

11.2. Distribution of Energy Production Prices in Combined Heat and Power

The aim of cogeneration is to reduce the consumption of primary energy (fuels) compared to production in separate installations [82] [104]. Primary energy savings PES [12] is calculated by the formula:

$$PES = \left\{ \frac{1}{\frac{\eta_{th}^{CHP}}{\eta_{th}^{REF}} + \frac{\eta_{el}^{CHP}}{\eta_{el}^{REF}}} \right\} \cdot 100\% \,, \qquad (11.3)$$

where PES – primary energy savings,%;

η_{th}^{CHP} – thermal efficiency of cogeneration;

η_{el}^{REF} – electrical efficiency of cogeneration;

η_{th}^{CHP} – thermal efficiency reference value;

η_{el}^{REF} – electrical efficiency reference value

According to the instructions of the Estonian Competition Authority [105] the thermal and electrical efficiencies of cogeneration are found as averages over the previous 12 months. The guide [105] also provides efficiency reference values for individual production.

If the primary energy savings calculated by the formula (12.3) in cogeneration units with a capacity of more than 1 MW_{el} are at least 10%, then cogeneration is considered efficient. In small and micro appliances, cogeneration is already considered efficient when primary energy savings are actually achieved, i.e., the PES must be greater than zero percent (positive)[13].

The division of the costs of separate production of electricity and heat between electricity and heat is conditional, it is one technological process, the outputs of which (electricity and heat) are sold in separate markets. Thus, in principle, all costs can be covered either by the sale of electricity only or by the sale of heat only (point A and point D, respectively, Figure 11.2). In the area between B and C, both electricity and heat from cogeneration are competitive. Points B and C can be determined, for example, by the average production price of electricity and the production price of heat produced in the so-called alternative boiler house.

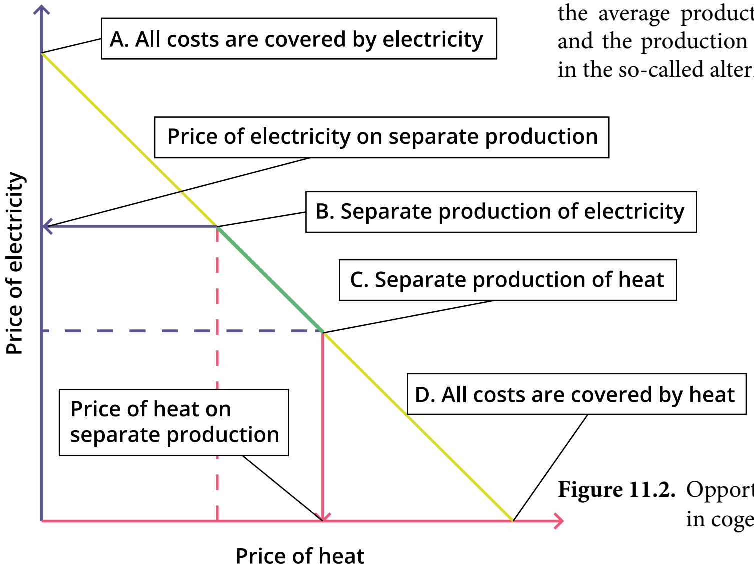

Figure 11.2. Opportunities for cost sharing in cogeneration

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[12] PES - abbreviation: Primary Energy Savings

[13] In the case of cogeneration based on fossil fuels, it is possible in certain cases in Estonia to receive support for electricity produced in the efficient cogeneration mode. In the case of cogeneration based on biofuels, support is paid for electricity transmitted to the grid, regardless of whether the production took place in an efficient cogeneration mode or not.

The following methods are often used to share the costs of a cogeneration unit [103, 105]:

- Alternative boiler house method – it is assumed that the heat sold to the district heating network is produced in a separate boiler house intended for heat production.
- physical (calorimetric) method – total costs are divided proportionally between electricity and heat production.

11.3. Cogeneration in a Heat Supply System With a Technological Heat Load

A typical example of a heat supply system with a technological heat load can be a sawmill with wood dryers, where the drying of wood would take place almost continuously (about 11 months a year); the residues generated in the sawmill (sawdust, splinters) can be successfully used as fuel, and the company also has a relatively even electricity consumption (see Figure 11.3).

Using a back-pressure turbine cogeneration unit as the energy source, the figure (Figure 11.3), it is possible to cover about 91% of the total heat consumption of the plant with a cogeneration unit with a capacity of 1 MW_{el} and 5 MW_{th} (the number of hours of heat capacity use is almost 8 000 h). All electricity production is consumed in the company, and the missing electricity is bought from the grid.

About 9% of the company's heat consumption is covered by a water heating boiler, which is also heated by sawmill residues.

The high load on the equipment ensures moderate fixed costs per unit of energy production. The price of electricity from the cogeneration unit and the electricity consumed by the company do not include electricity transmission charges and should generally ensure economic viability.

11.4. Cogeneration in a District Heating System

Unlike the main technological heat consumption system described above, the heat load in district heating is very strongly influenced by the outside air temperature, and the average summer load is often about 10% of the maximum instantaneous load. If a biofuel-based cogeneration unit is used as a heat source in such a system, then, e.g., Arto Nuorkivi [106] considers it economically feasible to limit the capacity of a biofuel cogeneration unit to 10 – 20% of the maximum load.

Such a recommendation does not take into account the fact that electricity produced on the basis of biofuel and transmitted to the grid is paid support to in Estonia, which in accordance with the Electricity Market Act [107] (§59) in the case of up to 125 MW of production equipment is 0.0537 €/kWh_{el}.

The support paid for renewable electricity enables the installation of a biofuel cogeneration unit with a capacity of more than 20% of the maximum load in the district heating system.

In the following example (see Figure 11.4), the capacity of a biofuel cogeneration unit is 33% of the maximum load, and a thorough economic analysis must be carried out when planning the CHP unit in order to assess the economic feasibility of its implementation.

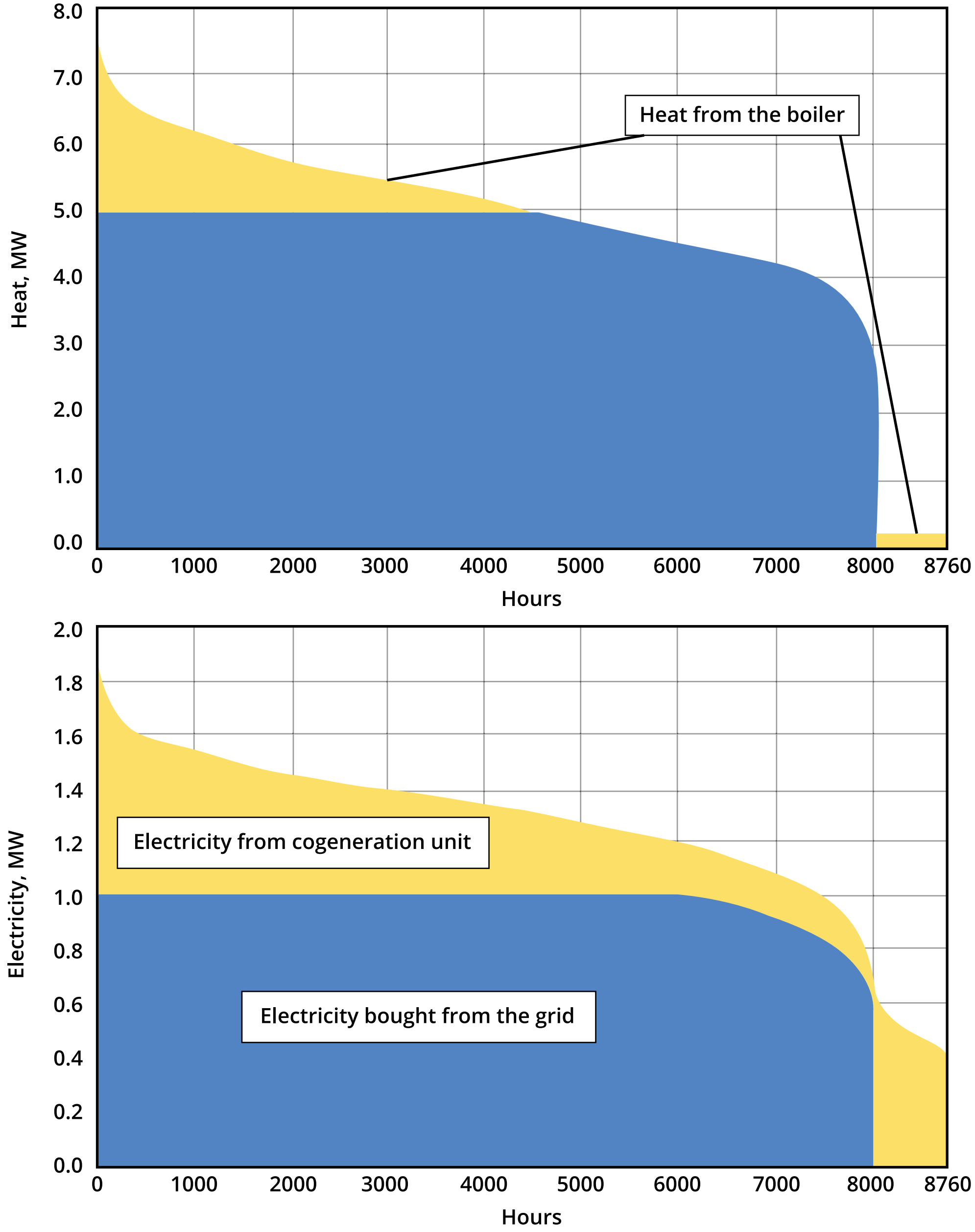
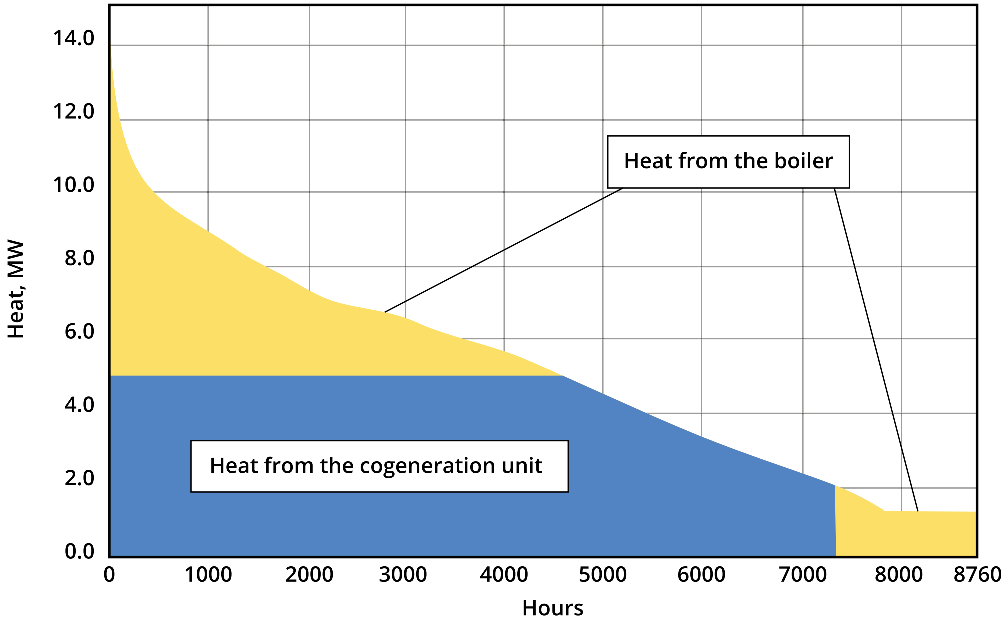


Figure 11.3. Coating of heat and electricity consumption of a sawmill with wood driers with a back-pressure turbine cogeneration unit*

* The cogeneration unit has a rated electrical input of 1 MW_{el} and a rated thermal input of 5 MW_{th}. The rated thermal capacity covers about 62% of the company's maximum heat load, and the number of operating hours of rated thermal input is almost 8000 h per year.
The electricity production of the cogeneration unit is fully utilized in the company and the missing electricity is purchased from the grid.



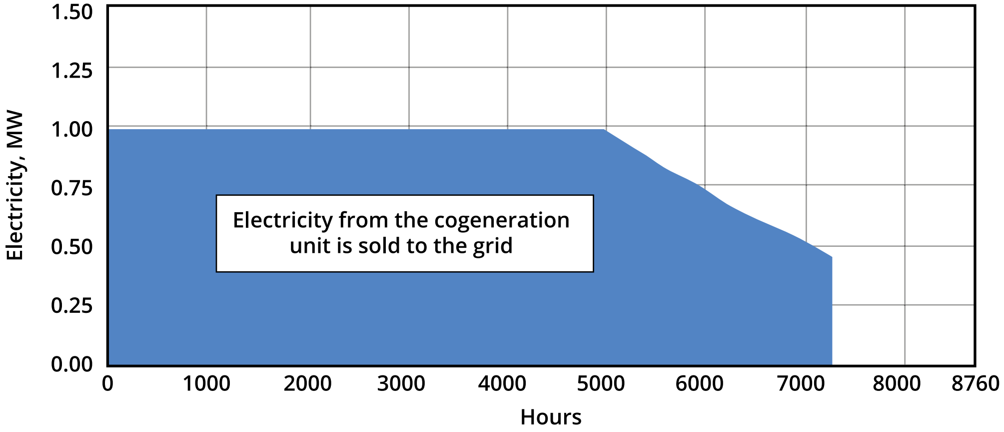


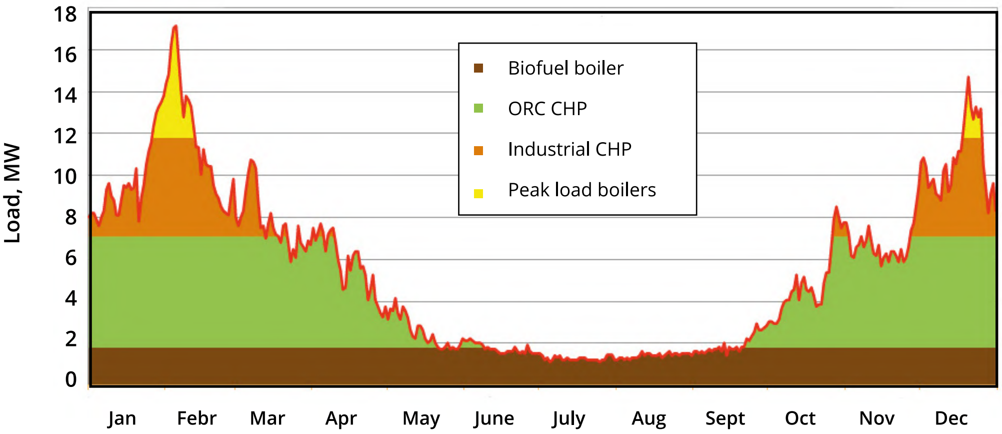
Figure 11.4. Implementation of a cogeneration unit in a district heating system*

* The electrical capacity of the cogeneration unit is 1 MW_{el} and the thermal capacity is 5 MW_{th}. Cogeneration covers about 33% of the company's maximum heat load. The number of operating hours of the heat capacity of the cogeneration unit is about 6200 h per year.
All electricity production is sold to the electricity grid.

Rankine cycle (ORC) can be economically viable even if it does not work during periods of low heat load (see Figure 11.5, [108, 109]). However, it should be noted that in addition to the support paid for renewable electricity, the project received investment support of 1.4 million € out of a total investment of 4 million €, which improves the profitability of the project.

As biofuel-based cogeneration can receive both investment support and renewable electricity support, a preliminary economic analysis must be carried out for each specific project.

In this example, in addition to the ORC unit, another biofuel operation heat source was used for the district heating system, the priority in the system allowed to implement it only after the biofuel boiler and boiler and the ORC unit could not cover the entire load, i.e., it was applied essentially for compering the peak load, and therefore, its implementation proved to be not economically feasible.



Joonis 11.5. Distribution of loads between different heat sources in one year in one Estonian district heating system

12. Literature

[1] Cost-effective and sustainable harvest methods (WP2). Natural Resources Institute Finland Luke. Interreg Baltic Sea Region program, project Baltic ForBio, 2020.

[2] Agriculture, forestry and fisheries - forestry section. European Statistical Office. European Commission.

[3] Solid Biomass Barometer. EurObserv'ER. 2019.

[4] The State of Renewable Energies in Europe. 2019 edition. EurObserv'ER.

[5] European Commission. Statistical Pocketbook 2019 - EU energy in figures. Drukarnia INTERAK SP ZOO, 2019.

[6] Parviainen, J., Västilä, S. State of Finland´s Forests 2011. Ministry of Agriculture and Forestry & Finnish Forest Research Institute.

[7] Tree species distribution in Germany. German Forestry Council.

[8] BALTI Group. Latvia's Forest During 20 Years of Independence. Forest Development Fund.

[9] Turs, A. A review on biomass: importance, chemistry, classification and conversion. Review Paper. *Biofuel Research Journal, 22,* 2019.

[10] *Solid Biofuels – Fuel Specification and Classes CEN/TS 14961:2005(E),* 2005.

[11] Lauri, P., Havlík, P., Kindermann, G., Forsell, N., Böttcher, H., Obersteiner, M. Woody biomass energy potential in 2050. *Energy Policy. Volume 66,* 03 2014.

[12] Fowler, P. Wood Combustion for Heating (Demirbas A. Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion, 30(2),* 2004.

[13] Tillman, D.A., Rossi, A.J., Kitto, W.D. Wood combustion - Principles, Processes and Economics. Washington, Bellevue: Academic Press, 1981.

[14] Vares, V., Kask, Ü., Muiste, P., Pihu, T., Soosaar, S. Manual for Biofuel Users, Tallinn: TUT Press, 2005.

[15] Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999-2003. *Technology Programme Report 6/2004,* Helsinki: 2004.

[16] Alakangas, E., Hursakainen, M., Lantikainen-Luutama, J., Korhonen, J. *Properties of indigenous fuels in Finland,* Jyväskylä: VTT Technology 272, 2016.

[17] Chidumayo, E.N. Above-ground woody biomass structure and productivity in a Zambezion Woodland. *Forest Ecology and Management, 36,* 1990.

[18] Ma, Z., Xiao, L., Zhu, S. Primary Productivity and Energy Flow of Hardwood Forests. – *Proceedings of XII World Forestry Congress,* Quebec City, Canada, 2003.

[19] Alakangas, E. Suomessa käytettävien poltoaineiden ominaisuuksia, Espoo: VTT, 2000. (in Finnish)

[20] *Eesti standard: Tahked biokütused. Kütuste spetsifikatsioon ja klassid. Osa 1: üldised nõuded (EN ISO 17225-1:2014).* Tallinn: 2014. (in Estonian)

[21] Francescato, V. Wood Fuels Handbook, Italy: AEIL, 2008.

[22] Paist, A., Plamus, K. Lokaalkatlamajad. Tallinn: TTÜ Kirjastus, 2013. (in Estonian)

[23] Olenius, H. Pilkkeen laadun vaikutus palamiseen ja päästöihin tulisijassa. Pilkeseminaari, 2.9.2005. (in Finnsih)

[24] Krajnc, N. Wood Fuels Handbook. Food and Agriculture Organization of the United Nations, Pristina: 2015.

[25] Röser, D., Erkkilä, A., Mola-Yudego, B. et al. Natural drying methods to promote fuel quality enhancement of small energywood stems. *In Working Papers of the Finnish Forest Research Institute 186,* 2010.

[26] Hillebrand, K., Nurmi, J. Puupolttoaineiden laadunhallinta. [Quality control of wood fuels]. Wood Energy Technology Programme Yearbook, Espoo: VTT Symposium 205, 2000. (in Finnish)

[27] Ots, A. Soojustehnika aluskursus, Tallinn: TTÜ Kirjastus, 2011.

[28] Kask, Ü., Muiste, P., Vares, V. Puitkütus. Tallinn: Erametsakeskus SA ja EBÜ, 2014. (in Estonian)

[29] *Wood chips for energy production.* Technology-Environment.Economy.
The Centre of Biomass Technology, 1993.

[30] *A guide to small-scale wood fuel (biomass) heating systems.* Wood Fuel South West Advice Service. Forestry Commision England, 2009.

[31] Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G. An overview of the chemical composition of biomass. *Fuel. Volume 89, Issue 5,* 05 2010.

[32] BISYPLAN web-based handbook, 2012,
http://www.bioenergyprof.eu/handbooks/bisyplan/html-files-en/handbook-intro.html

[33] Alakangas, E. Properties of Fuels Used in Finland, Espoo, Finland: VTT, 2000.

[34] Pesonen, J., Kuokkanen, T., Kaupiainen, E. et al. Chemical and physical properties of short rotation tree species. *European Journal of Wood and Wood Products, 72,* 2014.

[35] *Wood for Energy Production Technology - Environment – Economy.*
Coford: National Council for Forest Research & Development.
The Danish Center For Biomass Technology, 2005.

[36] Yin, C., Lasse, L.A., Rosendahl, A., Kær, S.K. Grate-firing of biomass for heat and power production. *Progress in Energy and Combustion Science, 34,* 2008.

[37] Ots, A. Tahkekütuse keevkihtpõletustehnika. Tallinn: TTÜ Kirjastus, 2016. (in Estonian)

[38] Irak, A., Veide, H. Aurukatlad. Tallinn: Eesti Riiklik Kirjastus, 1952. (in Estonian)

[39] Jääskeläinen, J., Alakangas, E. Bioenergy Utilisation and Potentials in the Baltic and other CEE Countries. Altener Programme. VTT Energy, Jyväskylä, 1999.

[40] Moving Grate Principle. Core Biomass Ltd.
http://corebiomass.co.uk/moving_grate_principle

[41] Wood chip boiler HACK VR 250 to 500 kW. ETA.
https://www.eta.co.at/en/products/product-overview/wood-chips/eta-hack-vr-333-500-kw/.

[42] Kortela, J., Jämsä-Jounela, S.-L. Modelling and model predictive cintrol of the BioPower combined heat and power (CHP) plant. International Journal of Electrical Power & Energy Systems 65, 2015.

[43] Flake type chain grate. Jinma Boiler Equipment Co.
http://www.jinmaboiler.com/product_02.html.

[44] Travelling Grate Boiler. Supertherm Engineering Private Limited.
https://www.indiamart.com/proddetail/travelling-grate-boiler-12955157655.htm.

[45] Boiler in thermal power plant. Coal Handling Plants.
https://www.coalhandlingplants.com/boiler-in-thermal-power-plant.

[46] Cyclone combustor. National Energy Technology Laboratory. https://www.netl.doe.gov/.

[47] Fluidized Bed Combustion FBC Boiler. Boilers Info.

https://boilersinfo.com/fluidized-bed-combustion-fbc-boiler.

[48] Thermal conversion of biomass into secondary products – the case of gasification and pyrolyses. *The 12th European conference on Biomass and Waste,* Amsterdam, 2002.

[49] Biomass Gasification. Rauha Energy. http://ruahaenergy.com/wp-content/uploads/2016/06/energy-biomass.jpg.

[50] Medium-scale wood gasifier from Spanner Re. Spanner Re Gmbh. https://www.holz-kraft.com/en/products/hka-35-45-49.html.

[51] Compact pellet boilers. Atmos Energy Corporation. https://www.atmos.eu/en/compact-pellet-boilers.

[52] Ariterm OY. Biopolttimet. https://www.ariterm.fi/lammitysratkaisut/jarjestelmakomponentit/biopolttimet/hakejet/.

[53] Vento Bio Roto. Moderator Sp. https://moderator.com.pl/en/products.

[54] Easyfire 1. Artechpro. https://atechpro.nl/producten/easyfire-i.

[55] *Audit Procedures for Solid-Fuel-Fired Heating Plants.* MOTIVA, Ekono Energy, VTT Energy, Helsinki, 1997.

[56] Majandus- ja taristuministri määrus nr 36 30.04.2015: Nõuded energiamärgise andmisele ja energiamärgisele. RT I, 06.05.2015. 2. (in Estonian)

[57] Kaugkütteseadus. RT I, 03.03.2017, 12. (in Estonian)

[58] Kask, Ü. Kaugküte, mugav, tõhus ja soodne. Tallinn: EJKÜ, 2013. (in Estonian)

[59] District Heating. Veolia. https://vesr.sk/en/district-heating.

[60] Generations of district heating systems. https://en.wikipedia.org/wiki/District_heating#/media/File:Generations_of_district_heating_systems_EN.svg.

[61] Salaženkov, M. Energia kokkuhoid soojusvarustussüsteemides. https://invest-monitoring.ru/et/komplektuyuschie/centralizovannye-sistemy-teplosnabzheniya-centralnoe.html. (in Estonian)

[62] Moland District Heating. Energos Contract AS. https://energoscontract.com/portfolio_page/moland-district-heating.

[63] Illison, M. *Soojuspumpade konkurentsivõime uurimine kaugküttesüsteemis Eesti tingimustes. Magistritöö.* Tallinn: TTÜ, Elektroenergeetika ja mehhatroonika instituut., 2019. (in Estonian)

[64] Silkeborg gets the world largest solar thermal plant. SDH. https://www.solar-district-heating.eu/silkeborg-gets-the-world-largest-solar-thermal-plant.

[65] Tian, Z., Zhang, S., Deng, J., et al. Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends. *Energy Conversion and Management. Volume 189,* 1 June 2019.

[66] Understand and apply domestic central heating system installation and maintenance techniques - Level 2 Diploma In plumbling Foundation. BPEC. https://bpec.org.uk/wp-content/uploads/2018/10/Section-8-%E2%80%93-Y6022888.pdf/.

[67] Bioenergy Plants. Rapla Metall OÜ. https://www.raplametall.ee/bioenergy-plants/biofuel-container-boiler-houses/container-boiler-houses.

[68] Gasification boiler firestar 18-40. Herz Energietechnik GmbH. https://www.herz-energie.at/en/products/boiler-for-log-wood/herz-firestar-gasification-boiler-18-40.

[69] Pros And Cons Of Wood Pellet Boilers. Greenmatch. https://www.greenmatch.co.uk/blog/2015/02/pros-and-cons-of-wood-pellet-boiler.

[70] Woodchip boilers. ESPE Group. http://www.espegroup.com/en/biomass/biomass-boilers/woodchip-boilers/.

[71] Hannula, I., Hakkarainen, E. *Integrated Bioenergy Hybrids. Flexible renewable energy solution.* IEA Bioenergy, 2017.

[72] Solar Integration – Solamander Hydronic Energy Hub. Devex Systems. https://www.devexsystems.com.au

[73] Bulder ahju lühitutvustus. Avena Projekt OÜ. http://www.avena-projekt.ee. (in Estonian)

[74] Õhksoojuspump - soodne lahendus küttekulude kokkuhoiuks. Kütteseade OÜ. (in Estonian) https://kytteseade.ee/blog/ohksoojuspump-ja-kuttekulud.

[75] Wolfram, J. *Decentralised Power Generation in the Liberalised EU Energy Markets: Results from the DECENT Research Project,* Springer, 2003.

[76] *Combined Heat and Power - an effekctive and clean solution for energy production.* Helsinki: Finnish District Heating Association, Ministry of Trade and Industry and Tekes, 2004.

[77] OÜ Utilitas Tallinna Elektrijaam. Utilitas Energy Group. https://www.utilitas.ee/en/company/ou-utilitas-tallinna-elektrijaam/.

[78] Combined Cycles. Turboden S.p.a. https://www.turboden.com/solutions/.

[79] Kuressaare soojuse ja elektri koostootmisjaam. AS Kuressaare Soojus. http://www.kuressaaresoojus.ee

[80] Gussing Power Plant. Gussing Renewable Energy International. https://gussingrenewable.com

[81] The NOTAR Gasification Solution. XYLOWATT S.A. https://www.xylowatt.com.

[82] Euroopa Parlamendi ja Nõukogu Direktiiv 2012/27/EL. Euroopa Liidu Teataja, 2012. (in Estonian)

[83] Simader, G.R., Krawinkler, R., Trnka, G. *Micro CHP systems: state-of-the-art. Deliverable 8 (D8) of Green Lodges Project (EIE/04/252/S07.38608),* Austrian Energy Agency, 2006.

[84] Islas, J., Manzini, F., Mateo, O., Vargas, V. Solid Biomass to Heat and Power. *The Role of Bioenergy in the Emerging Bioeconomy,* Academic Press, 2019, pp. 145-177.

[85] Small-scale Combined Heat and Power. Climate Tecnology Centre & Network. https://www.ctc-n.org/technologies/small-scale-combined-heat-and-power, 2020.

[86] Pellematic Condens_e. ÖkoFEN Forschungs- und Entwicklungs Ges.m.b.H. https://www.oekofen.com/en-gb/pellematic-condens_e/.

[87] Technology Data. Generation of Electricity and District Heating, Copenhagen: Danish Energy Agency, 2019, p. 414.

[88] Ekogen CHP. Ekogen Oy. http://www.ekogen.fi

[89] Hot-air turbine HLT-100. Schmid Energy Solutions. https://www.schmid-energy.ch/en/hot-air-turbine.

[90] Study on a sustainable district heating system in Kaunas. Lithuanian Energy Institute. https://www.balticenergyareas.eu/regional-pilot-projects/kaunas-county

[91] Pitk, P., Raave, H., Ots, K. *Puidutuha väärindamise võimalused ja perspektiiv granuleeritud kompleksväetisena põllumajanduses ja metsanduses aruanne. KIK-i projekt nr 10053,* Tartu: EMÜ, 2016. (in Estonian)

[92] Orru, H. *Välisõhu kvaliteedi mõju inimeste tervisele – peentest osakestest tuleneva mõju hindamine kogu Eesti lõikes.* Tartu: Tartu Ülikool, 2011. (in Estonian)

[93] *Keskkonnasõbralikud piirkondlikud energiasüsteemid.* Tallinn: FEMOPET Eesti, Eesti Energeetika Instituut, Tallinn , 1998. (in Estonian)

[94] EUROOPA PARLAMENDI JA NÕUKOGU DIREKTIIV 2001/80/EÜ, 23. oktoober 2001. Teatavate suurtest põletusseadmetest õhku eralduvate saasteainete piiramise kohta. (in Estonian)

[95] EUROOPA PARLAMENDI JA NÕUKOGU DIREKTIIV (EL) 2015/2193, 25. november 2015. Keskmise võimsusega põletusseadmetest õhku eralduvate teatavate saasteainete heite piiramise kohta. (in Estonian)

[96] Keskkonnaministri 05.11.2017 määrus nr 44: *Väljaspool tööstusheite seaduse reguleerimisala olevatest põletusseadmetest väljutatavate saasteainete heite piirväärtused, saasteainete heite seirenõuded ja heite piirväärtuste järgimise kriteeriumid.* Tallinn: Riigiteataja, 2017. (in Estonian)

[97] Keskkonnaministri 28. juuni 2013. a määruse nr 48: *Suurte põletusseadmete saasteainete heite piirväärtused, nende kohaldamine mitme kütuse põletusseadme korral ja väävliärastuse astme nõuded muutmine.* Tallinn: Riigiteataja, 10.09.2018. (in Estonian)

[98] Aagard Jensen, J.-O., Jakobsen, L. *DH production based on bio fuels.* News from DBDH, 02.2005.

[99] Frederiksen, S., Werner, S. District Heating and Cooling, Lund: Studentlitteratur AB, 2013.

[100] Narbel, P.A., Hansen, J.P., Lien, J.R. Energy Technologies and Economics, London: Springer, 2014.

[101] Hohle H.E. Bioenergi: Miljø, Teknikk og Marked, Brandbu: Energigården, 2001.

[102] Soojuse paralleeltarbimise mõju kaugküttesüsteemile. TTÜ, Tallinn: 2016. (in Estonian)

[103] Kruus, R., Vares, V. Perspektiivsetest elektri ja soojuse koostootmise tehnoloogiatest Eestis, Tallinn: OPET Eesti, 2002. (in Estonian)

[104] Tõhusa koostootmise nõuded. Majandus- ja kommunikatsiooniministri määrus RTL 2007, 41, 696, Tallinn, 2007. (in Estonian)

[105] Koostootmisjaama kulude jagamise põhimõtted soojuse ja elektri koostootmisel. Konkurentsiamet, Tallinn: 2013. (in Estonian)

[106] Nuorkivi, A. Institutional Handbook for Combined Heat and Power with District Heating, BASREC, 2002.

[107] Elektrituruseadu., Riigi teataja, 2019. (in Estonian)

[108] Tiit, P. Adven Eesti koostootmisjaama roll Rakvere kaugküttes. *Rakvere Targa maja Teabekonverents,* Rakvere: 2014. (in Estonian)

[109] Kimme, J. Rakvere koostootmisjaama töötsükli analüüs ja optimeerimine, Tallinn: TTÜ, 2014. (in Estonian)

[110] Levald, H. Tehnoökoloogia. Tallinn: Euroülikool, 2009. (in Estonian)

[111] Wood Fuels Basic Information Pack. Jyväskylä: 2000.

[112] Kõiv, T.A., Rant, A. Hoonete küte. Tallinn: TTÜ Kirjastus, 2013. (in Estonian)

[113] Guidelines for Calculating Energy Generation in Combined Heat and Power Plants. Suomen Kaukolämpö ry, 1999.

[114] The Expanding Bio-energy Market in the Nordic Countries – Possibilities and Consequences. Copenhage:, 2007.

[115] Kask, Ü. *Puitkütus ja selle osakaal Eesti energiabilansis. TTÜ Magistritöö.* Tallinn: 2001. (in Estonian)

13. Annexes

13.1. Units and Their Conversion

Table 13.1. Heat unit conversion factors

Ühik	kJ	kcal	kWh	toe*
1 kJ	1	0.239	0.278×10^{-3}	23.88×10^{-9}
1 kcal	4.1868	1	1.163×10^{-3}	0.1×10^{-6}
1 kWh	3600	860	1	86×10^{-6}
1 toe*	41.87×10^{6}	10×10^{6}	11.63×10^{3}	1

* tons of oil equivalent

Table 13.2. Frequently used multiple units

k	= kilo	$= 10^{3}$	= 1,000
M	= mega	$= 10^{6}$	= 1,000,000
G	= giga	$= 10^{9}$	= 1,000,000,000
T	= tera	$= 10^{12}$	= 1,000,000,000,000
P	= peta	$= 10^{15}$	= 1,000,000,000,000,000
E	= exa	$= 10^{18}$	= 1,000,000,000,000,000,000

13.2. Standards for the Quality of Solid Biofuels, Fuel Sampling and Preparation, and the Classification and Classes of Different Biofuels

- EN 15234-1: 2011, Solid biofuels. Fuel quality assurance. Part 1: General requirements
- EN 15234-4:2012, Solid biofuels. Fuel quality assurance. Part 4: Wood chips for non-industrial use
- EN 14778:2011 / EN ISO 18135, Solid biofuels. Sampling
- EN 14780:2011 / EN ISO 14780, Solid biofuels. Sample preparation
- EN ISO 17225-1:2014, Solid biofuels. Fuel specifications and classes. Part 1: General requirements
- EN ISO 17225-2:2014, Solid biofuels. Fuel specifications and classes. Part 2: Graded wood pellets
- EN ISO 17225-3:2014, Solid biofuels. Fuel specifications and classes. Part 3: Graded wood briquettes
- EN ISO 17225-3:2014, Solid biofuels. Fuel specifications and classes. Part 4: Graded wood chips
- EN ISO 17225-5:2014, Solid biofuels. Fuel specifications and classes. Part 5: Graded firewood
- EN ISO 17225-6:2014, Solid biofuels. Fuel specifications and classes. Part 6: Graded non-woody pellets
- EN ISO 17225-7:2014, Solid biofuels. Fuel specifications and classes. Part 7: Graded non-woody briquettes
- ISO/TS 17225-8:2016, Solid biofuels. Fuel specifications and classes. Part 8: Graded thermally treated and densified biomass fuels

This book talks about wood fuels, introducing its main properties, quality classes and standards, storage and preparation for combustion, main combustion technologies and equipment and their impact on the environment. One of the topics is different heat supply methods, with an emphasis on cogeneration and hybrid heat supply. In last chapters of the book, an overview of planning, designing and calculation of economic profitability of heating systems is given.

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