9. CHP and Power Plants

In 1986 the Danish Government made an energy policy agreement on the construction of decentralised CHP plants with a total power output of 450 MW, fired with domestic fuels such as straw, wood, waste, biogas, and natural gas, to be completed by the year 1995. In 1990 the government made another agreement on the increased use of natural gas and biofuels to be accomplished primarily by means of the construction of new CHP plants and retrofitting the existing coal and oil-fired district heating plants to natural gas and biomass-based CHP generation.

CHP Generation Principle

At a traditional steam-based, coal-fired CHP plant with condensation operation, 40-45% of the energy input is converted to electrical power, while the remaining part is not utilised. It disappears with the cooling water into the sea and with the hot flue gas from the boiler up through the chimney into thin air.

A back pressure CHP plant generates electrical power in the same way as a power plant, but instead of discharging the condensation heat from the steam together with the cooling water into the sea, the steam is cooled by means of the recycling water from a district heating distribution system and thus used for the generation of heat. The advantage of combined heat and power production is that up to 85-90% of the energy in the fuel input can be utilised. Of this approx. 20-30 % of the energy input will be converted to electrical power, while 55-70 % of the energy input will be converted to heat. Thus by combining heat and electrical power generation, the total utilisation of energy increases, but as a whole the electrical power output will be reduced.

Another advantage of a back pressure CHP plant instead of a power plant is that there is no need for seawater for cooling. The plant can therefore be located near large towns (decentralised) with sufficient demand and a distribution system to cope with demands. The operation of a CHP plant depends on the heat demand of the district heating system. In case of a small heat demand, the power generation will also be small, because the district heating water cannot cool the steam cycle to that extent at the CHP plant. For the purpose of equalising the variations in the cooling of the district heating water, the CHP plants are often equipped with storage tanks for the storage of “heat” during periods with little district heating demand.

It is the system steam data on pressure and temperature that determine the electrical power utilisation of the system. With equal steam data for a coal-fired power plant and a biomass-fired power plant, the electrical power efficiency will also be the same. However, the risk of slagging and corrosion during firing with biofuels has deterred boiler engineers and manufacturers from applying steam data to biomass-fired heating plants at the same level as coal-fired heating plants. The most recent advances in the field of heating system technologies and design have constituted a break-through, and a couple of new heating plants demonstrate that high steam data can also be achieved by biofuels. This is set out in more detail under the description of the heating plants at Masnedø, Ensted, and Avedøre.

A number of industrial enterprises require steam for their manufacturing processes. Several large enterprises have realised the advantage of establishing steam production plants, so that in addition to the process steam, electrical power can also be generated. Especially in forest product industries, this opportunity is quite evident, since wood waste can then be utilised as a fuel on the spot. The energy can naturally only be utilised once, so when energy is drawn off in the form of process steam, the electrical power output and perhaps also the generation of heat are reduced. The process steam is normally extracted from a special type of steam turbine termed an extraction turbine. Depending on the steam requirement, steam can be withdrawn at various high-pressure stages of the turbine, thereby applying various methods for the adjustment of the steam pressure.

Heating plants owned by electrical power companies are under the obligation to supply electrical power to the supply mains. Decentralised CHP plants owned by district heating companies and industrial enterprises are not likewise committed. Heating plants owned by electrical power companies must therefore be constructed so as to include greater operational reliability which results in larger capital investment.

Plants Owned by Electrical Power Corporations

Måbjergværket, Holstebro

In Måbjerg near Holstebro, Vestkraft A.m.b.a. has constructed a CHP plant,

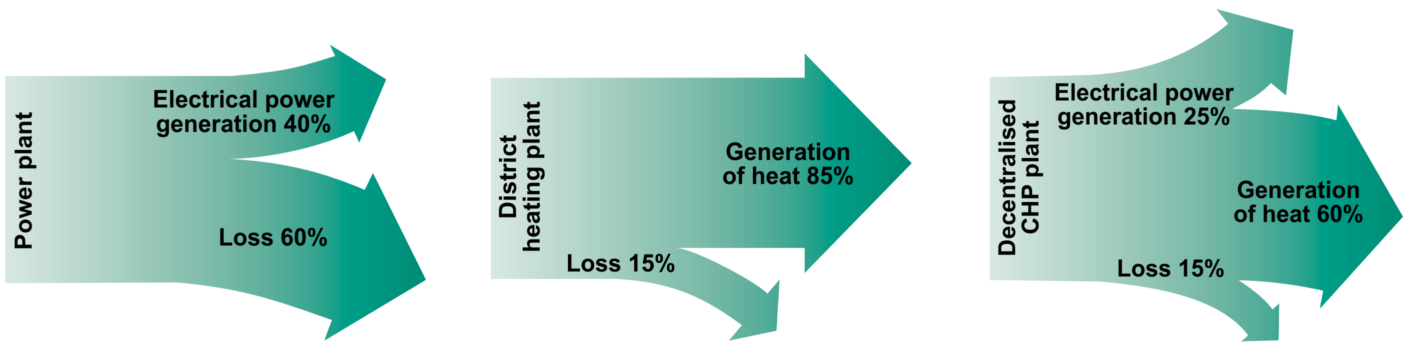


Figure 24: By separate electrical power generation and generation of heat at a power plant and at a district heating plant, total losses are much larger than by combined heat and power production at a CHP plant.

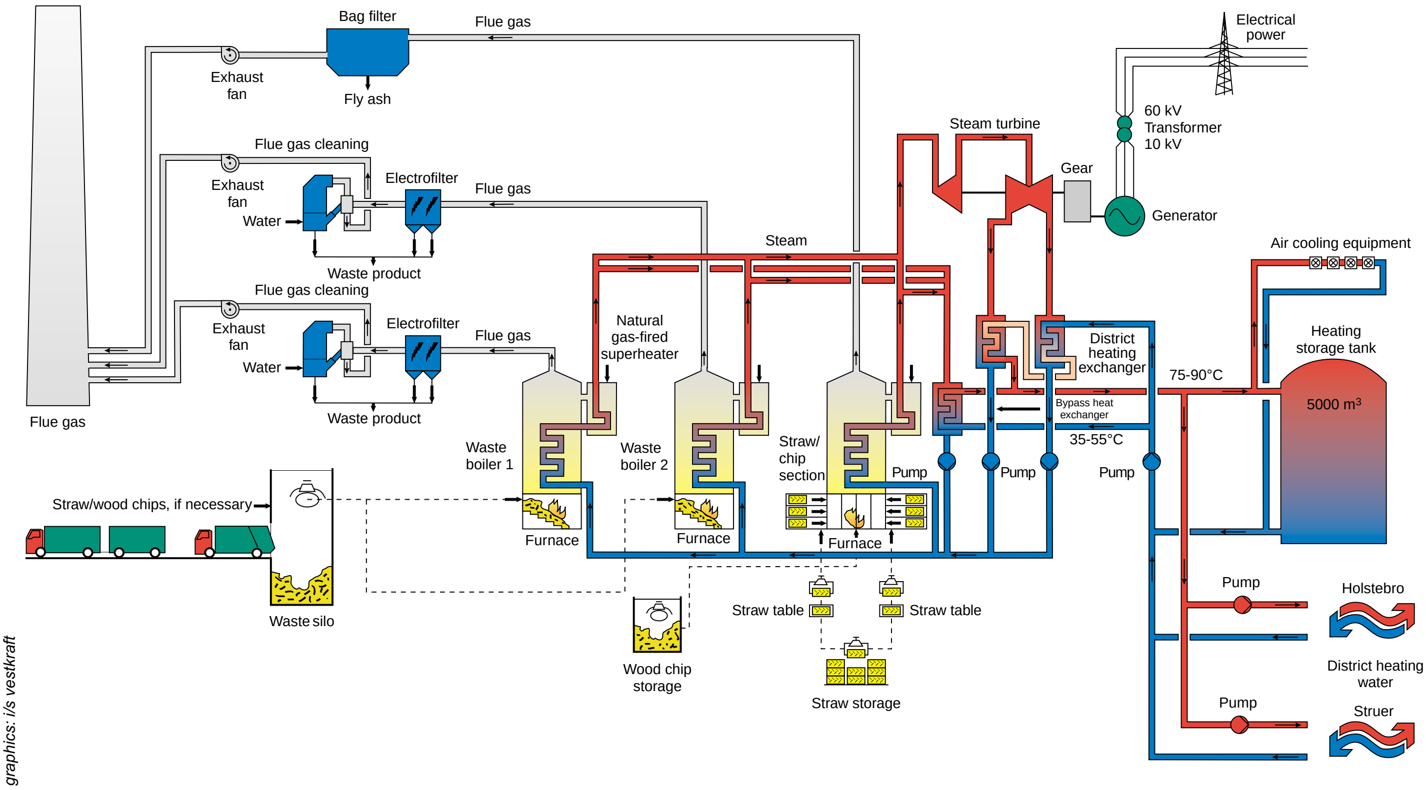


Figure 25: Schematic diagram of Måbjergværket.

fired with waste, straw, wood chips, and natural gas.

The plant is noteworthy because it demonstrates the combined application of renewable and fossil fuels in a way in which one of the positive properties of natural gas (low content of impurities) is utilised so as to increase the aggregate energy output. Furthermore, the increase in the energy output is achieved without wasteful use of gas, which as known is a limited resource.

The system is divided into three boiler lines, two for waste and one for straw and wood chips.

The boilers were delivered by Ansaldo Vølund A/S, and all three boilers are equipped with a separate natural gas-fired superheater so as to increase the steam temperature from 410 °C to 520 °C at a pressure of 65 bar. By superheating the steam, a more energy efficient process is achieved in the form of increased electrical power efficiency with reduced risks of corrosion of the superheater tubes.

Straw is fired in the form of whole big bales into six "cigar burners", installed three and three opposite one another. The wood chips are fed by means of a pneumatic feeding system on to an oscillating grate, where unburned straw and wood chips burn out.

The flue gas from the straw and chip-fired boiler is cleaned in a bag filter to a dust content of max. 40 mg/m^{3}n. In the case of the waste-fired boilers, the flue gas purifying is supplemented with lime reactors for the purpose of reducing hydrogen chloride, hydrogen fluoride and sulphur oxide emissions. The three boilers have separate flues in the 117 metre high chimney. The straw and chip-fired boiler can operate 100% on either wood chips or straw or combined wood chips and straw.

The waste-fired boilers (traditional grate-fired Vølund waste-fired boilers) have an input capacity of 9 tonnes of waste per hour (calorific value 10.5 GJ per ton), and the capacity of the straw and chip-fired boiler is 12 tonnes per hour with the average calorific value being 14 GJ per tonne.

The electrical power output is 30 MW$_e$ and 67 MJ/s heat. The system is equipped with district heating storage tank the size of approx. 5,000 m^3. Heating is supplied to the district heating systems in Holstebro and Struer.

Vejen CHP Plant

The CHP plant in Vejen is a special combined fuel system, because the steam producing boiler, delivered by Ansaldo Vølund A/S, can be fired with either waste, straw, wood chips, or pulverised coal.

The output of the system is 3.1 MW$_e$ and 9 MJ/s heat at a steam production of 15.7 tonnes per hour at 50 bar and 425 °C. The turbine is an AEG Kanis manufacture.

Wood chips and waste are fed on to a Vølund Miljø waste grate (sectional step grate). Straw can be fired as whole big bales in a single "cigar burner". The plant's annual consumption of wood was originally estimated at approx. 1,200 tonnes per year. The idea was to use wood as a supplementary fuel in periods with too low calorific value of the waste. However, the annual consumption of wood chips is estimated to be reduced significantly, since the waste input has been of a sufficiently high calorific value and at the same time, sufficient quantities of waste are available.

As a consequence, it is the intention in the future only to use wood during the starting up and closing down of the system. Environmental considerations prohibit the use of waste during those periods, because the temperature in the combustion chamber is too low for complete combustion to take place.

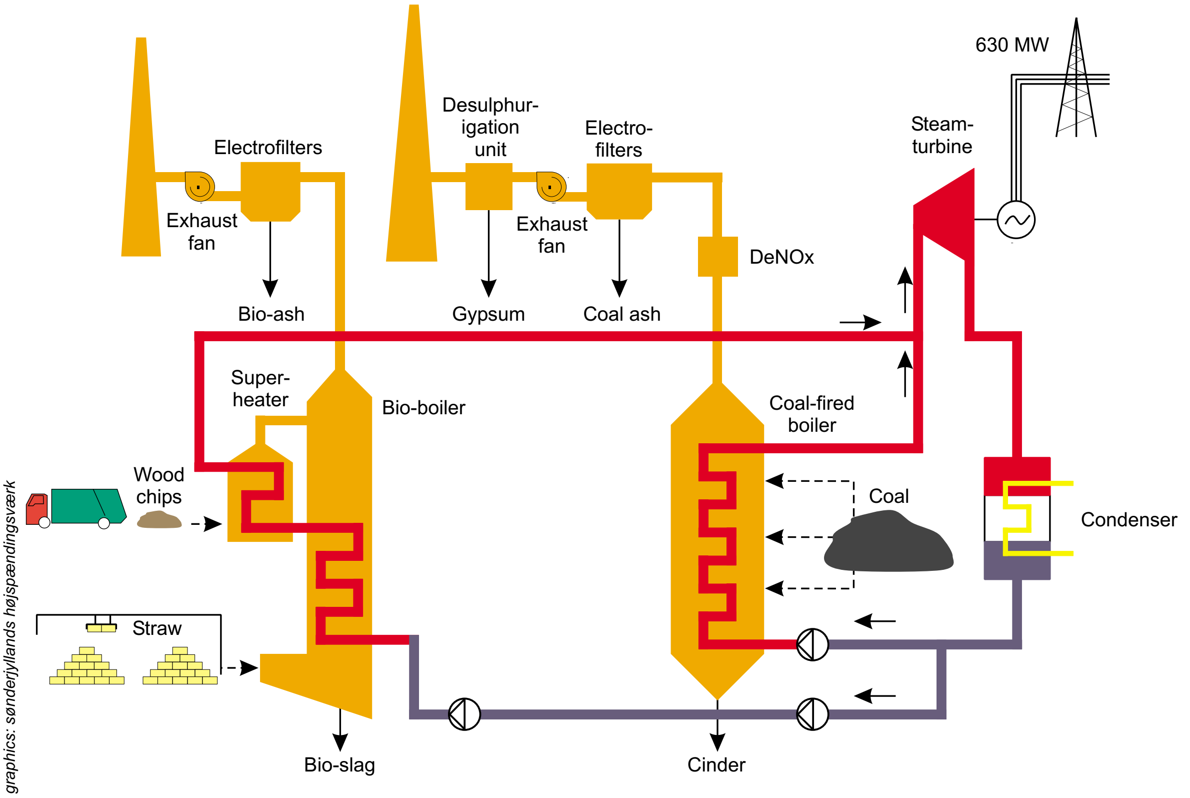


Figure 26: Schematic diagram of Enstedværket's bio-boiler of 40 MW_e and coal-boiler of 630 MW_e. The bio-boiler replaces the consumption of 80,000 tonnes of coal per year, thus reducing CO_2 emissions to the atmosphere by 192,000 tonnes per year.

Masnedøværket (CHP Plant)
Masnedø CHP plant that is owned by I/S Sjællandske Kraftværker (electrical power corporation), was put into operation in 1995. It is a biomass-fired back pressure system for electrical power and district heating supply to Vordingborg. The boiler is designed for straw with 20% of the energy supplied by supplementary firing with wood chips. The annual consumption of fuel amounts to 40,000 tonnes of straw and 5-10,000 tonnes of wood chips.

The steam data of the plant are 92 bar and a steam temperature of 522 °C. The electrical power efficiency is 9.5 MW, while the heat output that can be supplied to the district heating system is 20.8 MJ/s. The input is 33.2 MW.

The boiler, constructed by Burmeister & Wain Energy A/S, is a shell boiler with natural circulation. It is a retrofit system, where the steam data have been boldly set close to standard coal-fired plants of the same size, despite the fact that the primary fuel here is straw. Experiences acquired from operating the system in practice suggest that the system concept is successful.

The boiler has two feeding systems, one consisting of a straw shredder followed by a screw feeder. The chip feeding system consists of transport and screw feeders in the bottom of the silo to the straw-fired unit. The wood chips are mixed with the straw and fired together on to a water-cooled oscillating grate.

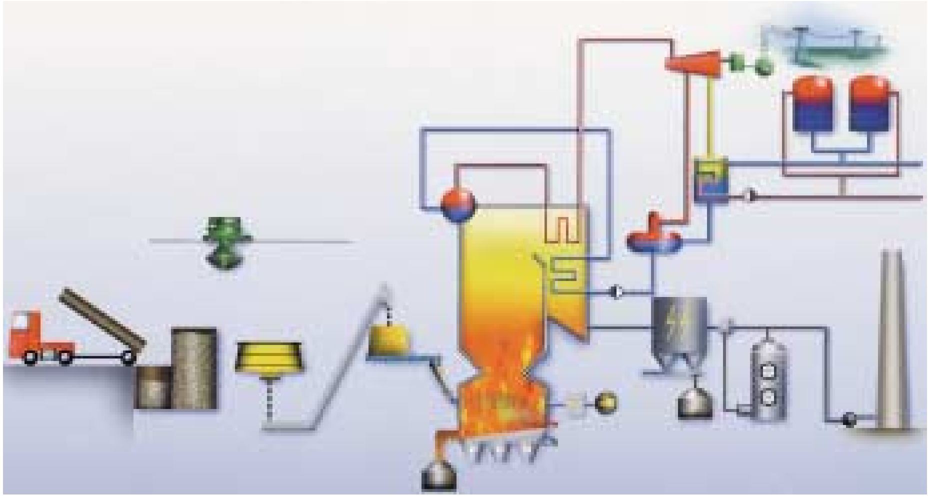
Enstedværket
Denmark's largest electrical power plant boiler exclusively fired with biofuel was put into operation in 1998 at Enstedværket near Aabenraa.

The system that has been delivered by FSL Miljø A/S and Burmeister & Wain Energi A/S, is located in the old building of the earlier coal-fired Unit 2. The system consists of two boilers, a straw-fired boiler that produces steam at 470 °C, and a chip-fired boiler that superheats the steam from the straw boiler further to 542 °C. The superheated steam is passed to the high-pressure system (200 bar) of Enstedværket's coal-fired Unit 3. With an annual consumption of 120,000 tonnes of straw and 30,000 tonnes of wood chips, equal to an input of 95.2 MJ/s, the thermal efficiency of the biomass boiler is 88 MW of which a proportion of 39.7 MW electrical power is generated (approx. 6.6% of the total electrical power generation of Unit 3). The biomass boiler is thus considerably larger than the largest of the decentralised biomass-fired CHP systems. The gross electrical power efficiency is approx. 41%. Annual efficiency is expected to be a little lower due to the incorporation with Unit 3 and varying load conditions. It is the intention that the biomass boiler will operate 6,000 hours per year at full load. With a storage capacity of only 1,008 bales, equal to the daily consumption, deliveries of 914 big bales will be required on average a day, equal to 4 truckloads per hour for 9.5 hours a day.

The straw boiler is equipped with four straw lines. However, only three system lines can operate 100% (at full load). Each of the straw lines consists of a fireproof tunnel, chain conveyors, straw shredder, fire damper, screw stoker, and a feed tunnel. Like the straw shredder at Masnedøværket, the straw shredder is designed as two coupled, conical, vertical screws towards which the straw bale is pressed. From the straw shredder, the shredded straw is dosed via the fire damper into the screw stoker, which presses the straw as a plug through the feed tunnel on to the grate.

The chip boiler is equipped with two spreader stokers that throw the wood chips on to a grate. The feeding of wood chips is performed by a screw feeder from an intermediate silo.

The flue gas is purified in electrofilters. In order to be able to apply the bottom ash from the biomass boiler as fertiliser, the fly ash from the filters that con-



graphics: ansaldo vølund a/s

Figure 27: Schematic diagram of the biomass-based CHP plant in Assens.

tain the majority of the heavy metals of the ash, is kept apart from the bottom ash.

Østkraft A.m.b.a., Rønne
At Østkraft, Unit 6 was put into operation in 1995. At loads varying from 0-65%, the boiler is coal-fired on grate with supplementary firing with wood chips. At boiler loads above approx. 65% of the boiler nominal output, the boiler is fired with oil. The boiler and the pre-combustor for wood-firing have been delivered by Ansaldo Vølund A/S.

Coal-firing takes place by means of four spreaders on to a travelling grate, while the wood chips are fired by means of four pneumatic feeders situated above the coal spreaders.

The system electrical power output (gross) is 16 MW_e and the heat output is 35 MJ/s. The boiler operates at a pressure of 80 bar, and the steam temperature is 525 °C. The boiler is capable of being fired with a combination of coal and wood chips in the ratio 80% coal and 20% wood chips in terms of energy contribution. The combustion takes place both while the fuel is suspended in the combustion chamber and on the grate, where the larger fuel pieces are thrown furthest backwards on the slat grate that travels from the back-end plate to the slag/ash pit at the front wall under the fuel feeders.

The system is equipped with an electro static precipitator.

Avedøre 2.
Avedøre 2 that is owned by I/S Sjællandske Kraftværker (electrical power corporation) and expected to be put into operation in 2001, is presently in the middle of the construction phase, but since the design is a large, specialised, and highly efficient CHP plant with biomass playing an important role, it deserves a brief description here.

The design is a steam-power plant with turbine and boiler system and desulphurization and $deNO_x$ system. A separate biomass boiler and a gas turbine, coupled in parallel, are added. The boiler system is a so-called KAD system (power plant with advanced steam data), i.e. a high pressure and a high temperature of the steam from the boiler to the steam turbine providing high electrical power efficiencies. The gas turbine will be coupled to the steam system, so that the flue gas from the gas turbine can be used to preheat the feed water to the steam boiler. At the same time the gas turbine generates electrical power and gives off heat. This special coupling creates a synergy effect that results in the high degree of utilisation of the fuels.

The biomass is burnt in a separate boiler system that produces steam. The steam passes to the KAD system, where the steam is used for the generation of electrical power in the steam turbine. In this way the biomass utilisation efficiency is much better than in a separate biomass-fired CHP plant. The design represents a major step forward in that it offers the possibility of utilising three different fuels, ensuring both a more flexible energy production and more reliable supplies. The combination of three different power plant technologies also makes Avedøre 2 the world's most energy efficient and flexible plant so far.

Steam:	300 bar/582 °C (KAD steam boiler and biomass boiler)
Outputs:	365 MW_e net in back pressure operation, 480 MJ/s heat
Fuels:	Natural gas, biomass (straw and wood chips) and fuel oil (the total input of straw and wood chips is 100 MJ/s)

The system biomass capacity will amount to 150,000 tonnes per year. If the high steam temperature cannot be achieved without too high risk of corrosion, the wood chip proportion can be increased, or it could be arranged for part of the superheating to take place in a natural gas-fired superheater. The design estimates an electrical power efficiency of the biomass unit of 43%.

Systems at District Heating Plants

Assens Fjernvarme
In January 1999 a new wood-fired CHP plant, constructed by Ansaldo Vølund A/S, will be installed at the district heating plant Assens Fjernvarme. Two pneumatic feeders throw fuel on to a water-cooled oscillating grate. The fuel is primarily wood chips, but depending on the market conditions, wood waste and residual products will be utilised as fuels.

The plant's steam data are 77 bar and 525 °C steam temperature. The electrical power efficiency is 4.7 MW with a heat output of 10.3 MJ/s for the district heating system. An installed flue gas condenser can increase the generation of heat to 13.8 MJ/s. The input is 17.3 MW. The fuel is pure wood fuels with a moisture content in the range of 5 to 55%. The system is designed with an indoor storage capacity of up to 5,800 m^3, equal to approx. 10 days' consumption. Furthermore there is an outdoor fuel storage equal to approx. 50 days' consumption.

After the electro static precipitator the combined wet scrubber/condenser unit is installed. Here the flue gas temperature is reduced to approx. 70 °C, and the efficiency is considerably increased.

Hjordkær CHP Plant
The CHP plant at Hjordkær is the smallest steam turbine system installed at a

district heating plant in Denmark. One of the ideas behind the plant is to demonstrate whether steam turbines this size are remunerative, which is also the reason why the Danish Energy Agency has subsidised the construction of it. It was constructed in 1997, in order to obtain guarantee data on the use of forest chips with a moisture content of up to 50%. In addition to that, the fuel spectrum is a wide range of combustible materials, including a number of residual products from industries.

The system steam data are 30 bar and 396 °C steam temperature. The electrical power efficiency is 0.6 MW with a heat output of 2.7 MJ/s for the district heating system. The input is 3.8 MW. The relatively low steam data were not selected due to it being a biofuel system, but due to the fact that for systems that size, it is rather expensive to produce boilers with higher steam data.

The boiler design is a pre-combustor coupled as a vaporiser, containing a step grate, refractory reflection surfaces, and a superheater divided into two sections, a fire tube section as a convective vaporiser and an economiser in steel plate casing, standing apart.

The grate that is hydraulically operated, consists of a bottom frame of steel, which to some extent is water-cooled. The grate itself consists of elements in special cast iron.

Industrial Systems

Junckers Industrier A/S

At Junckers Industrier in Køge two large wood-fired boiler systems have been installed, called Unit 7 and Unit 8, respectively. They were put into operation in 1987 and 1998 respectively.

Junckers' Boiler Unit 7

At the beginning of 1987 a new power station was put into operation at Junckers Industrier in Køge, fired with wood waste from the production. The system was delivered turn-key by B&W Energi A/S.

Until 1998 the system was the largest Danish system fired with wood only. The boiler produces 55 tonnes of steam per hour at 93 bar and 525 °C. The steam operates an AEG Kanis back pressure turbine with a steam extraction of 14 bar and a back pressure of 4 bar. The max. electrical power efficiency is 9.4 MW.

The fuel is wood waste from the production and consists of shavings, sawdust, bark, and wood chips. The boiler can also be fired with fuel oil at max. 75% load. Sawdust, wood chips, and bark are fired via three pneumatic spreader stokers on a water-cooled grate

Data	Unit	Junckers K-7[1]	Junckers K-8[1]	Novopan [1]	Enstedv. EV3[2]	Masnedø Unit 12[2]	Vejen [2]	Måbjerg [2) 6)]	Østkraft [2]	Hjordkær [3) 5)]	Assens [3]
Power output (gross)	MW	9.4	16.5	4.2	39.7	9.5	3.1	30	16	0.6	4.7
Heat output	MJ/s	process steam	process steam	process steam + dist. heat.		20.8	9.0	67	35	2.7	10.3 [8]
Steam pressure	bar	93	93	71	200	92	50	65	80	30	77
Steam temperature	°C	525	525	450	542 [4]	522	425	520	525	396	525
Max. steam production	Tonnes/h	55	64	35	120	43	16	125	140	4,4	19
Storage tank	m^3	process steam	process steam	process steam		5,000	1,500	5,000	6,700	1,000	2 x 2,500
Flue gas temperature	°C		140			110		95	165	160/120	110/70
Flue gas purifying	-	ESP[9]	ESP[9]	ESP[9]	ESP[9]	ESP[9]	bag filter	straw: bag filter waste: ESP[9]	ESP[9]	multi-cyclone bag filter	ESP[7) 9)]
Fuels		chips bark sawdust sander dust	chips bark sawdust sander dust	chips bark sawdust sander dust	straw chips (0-20%)	straw chips	waste straw chips	waste straw N-gas chips	coal chips oil	chips bio-waste	various bio-fuels chips
Turbine	Make	AEG Kanis	Siemens		ex. unit 3	ABB	Blohm + Voss	W.H. Allen	ABB	Kaluga/ Siemens	Blohm + Voss
Electrical eff. (gross)	%					28	21	27	35	16	27
Overall efficiency	%					91	83	88	88	86	87[8]

Table 19: Operating data on ten biomass-fired plants and systems.

Notes:
1) Industrial systems.
2) Owned by power corporations.
3) District heating plants.
4) Steam temperature increased from 470 °C to 542 °C in separate wood chip-fired superheater.
5) Special flue gas boiler with superheater and pre-combustor for wood chips and industrial residual products.
6) 2 waste lines and 1 line for straw and wood chips. All 3 lines are equipped with separate natural gas-fired superheater (410 °C to 520 °C).
7) The system is also equipped with flue gas condenser.
8) Without flue gas condensation in operation. 13.8 MJ/s with flue gas condensation.
9) ESP - electro static precipitator.

with inclined oscillating steps. The spreaders are fed from the fuel silos via screw conveyors.

The system is guaranteed an overall efficiency of 89.4% (before deductions for own consumption) at 100% load.

The flue gas is purified to a guaranteed max. solid matter content of 100 mg/m^3 at 12% CO_2 in a Research Cottrell electrofilter. The flue gas temperature before the filter is approx. 130 °C.

Junckers' Boiler Unit 8

Boiler Unit 8, delivered by Ansaldo Vølund A/S, is coupled in parallel to the company's existing Boiler Unit 7. The input of Boiler Unit 8 is 50 MW equal to 64 tonnes of steam per hour. The steam data are 93 bar at 525 °C. Flue gas temperature at full load is 140 °C. Boiler efficiency is 90%.

Boiler Unit 8 and Boiler Unit 7 together are designed for burning the total amount of secondary waste products from the production. The fuels are wood chips, sawdust, sander dust, and shavings. In addition to that also smaller amounts of granulated material, medium-density fibreboard chips, bottom logs etc. In emergency situations, the system can be fired with fuel oil (up to 80% load). Wood chips and sawdust etc. are fired on to a water-cooled oscillating grate by means of three spreaders. Sander dust and shavings are fed through separate Low NO_x dust burners higher up in the boiler room. The storage tank and return pipes are located outside with the Eckrohr boiler. The three boiler superheater sections are equipped with water inlets for steam temperature control. In order to keep the boiler heating surfaces purify, the boiler is equipped with steam soot blowers that are activated 3-4 times a day. In order to comply with the environmental requirements, the boiler is designed for approx. 15% flue gas recirculation.

The SIEMENS turbine is designed for the full steam amount with a max. electrical power output of 16.5 MW_e. The turbine has an uncontrolled steam extraction at 13 bar and a controlled extraction at 3 bar. Both provide process steam for the factory's manufacturing process. The turbine is also equipped with a sea water-cooled condenser unit capable of receiving max. 40 tonnes of steam per hour. In an operating situation with the max. electrical power output, the electrical power efficiency is approx. 33% simultaneously with extracting 24 tonnes of steam per hour at a pressure of 3 bar, while an amount of 40 tonnes of steam per hour is cooled off in the condenser.

Novopan Træindustri A/S

In 1980 Novopan Træindustri A/S constructed a CHP plant for firing with wood waste from the chip board production. The system consists of two boilers, of which a Vølund Eckrohr boiler produces 35 tonnes of steam per hour at a pressure of 62 bar and a steam temperature of 450 °C.

The boiler is equipped with two superheaters, economiser and air preheater.

The fuel consists of sander dust, bark, wet wood waste, and residues from chipboards, clippings, and milling waste that are fed via an air sluice on to an inclined Lambion grate. A total of approx. 150 tonnes of wood waste is consumed per day.

The energy input contained in the fuel distributed on utilised energy and loss is as follows:

Electrical power (4.2 MW):	19%
Heat for drying process:	64%
District heating:	5%
Loss:	12%

The flue gas is purified for particles in a Rothemühle electro static precipitator.