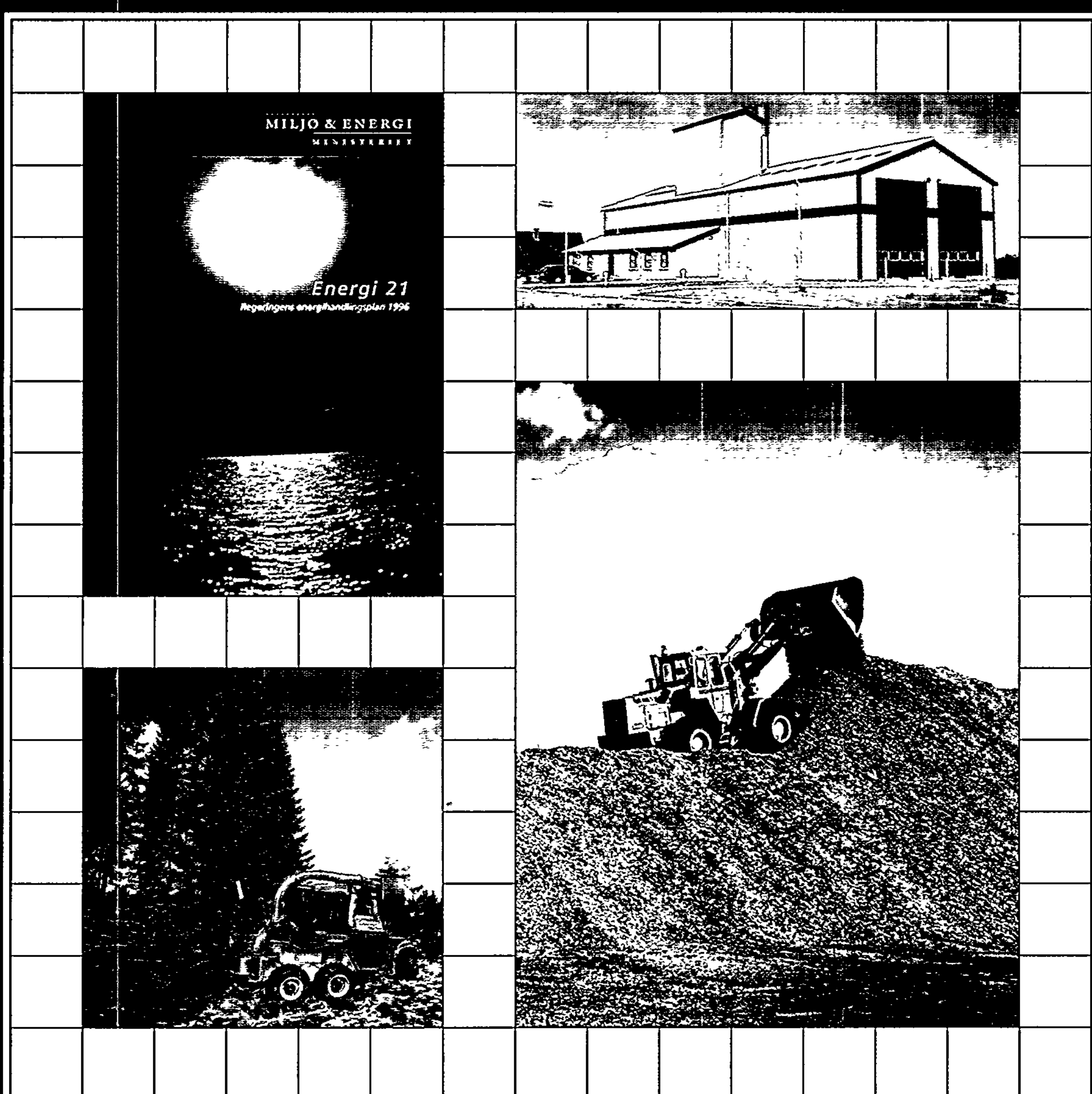
Wood for Energy Production

Technology - Environment - Economy



The Centre for Biomass Technology

1999

Second Edition

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Chipper in operation, BioPress/Torben Skøtt
Front-end loader on a wood chip pile at Måbjergværket, BioPress/Torben Skøtt

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Energistyrelsen
MILJØ- OG ENERGIMINISTERIET

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DISCLAIMER

Foreword

The emission of CO_2 and other greenhouse gases is one of the greatest environmental problems of our time. At the United Nations Climate Change Conference in 1997 in Japan, it was agreed that total world-wide emissions should be reduced by 5.2% by the year 2012. The European Union has undertaken the major reduction of 8% compared to the 1990 level.

Today only 6% of the European Union's consumption of energy is covered by renewable energy, but the EU Commission Renewable Energy White Paper, published in December 1997, prescribes a doubling of the proportion of renewable energy by the end of the year 2010.

Biomass is the sector that must be developed most and fastest. It is estimated that in 2010 it should amount to 74% of the European Union's total consumption of renewable energy.

Danish experiences acquired in the field of biomass are already now significant. We have achieved much in the field of both the individual and the collective energy supply. Denmark's strongholds are in the field of collective heating supply and decentralised CHP (combined heat and power) generation based on biomass, and cost-effective fuel production, in particular.

This publication illustrates how Denmark has succeeded in utilising its wood resources in an environmentally desirable and CO_2-neutral energy production. It provides an introduction to the most recent Danish developments in the field of wood for energy production, both with regard to technology, environment, and economy.

At present more than 10% of Denmark is covered with forests, and the intention is a doubling of the area within the next century. The forest trees are used for timber and for manufacturing in the wood industry. The forest also provides thinning wood and other wood waste that can all be used for energy production.

The long-term perspective of the Government's plan for a sustainable energy development in Denmark, Energy 21 (Energi 21), is to develop an energy system where the proportion of renewable energy continuously increases. This preconditions a continuous and gradual fitting in of renewable energy concurrent with the technological and financial possibilities.

The enlargement will primarily take place by means of an increased application of bioenergy and wind power. Therefore, biomass will contribute considerably to Denmark's and the European Union's energy production in the next decades.

At the same time, biomass is an area of great potential for the Danish energy industry - also on the export market.

Svend Auken
Minister for the Environment and Energy

1. Danish Energy Policy

Danish energy policy is in a constant process of change. The Government's Energy Action Plan of 1996, Energi 21, is the fourth in a series of plans that all have or have had as their aim to optimise the Danish energy sector to the present national and international conditions in the field of energy.

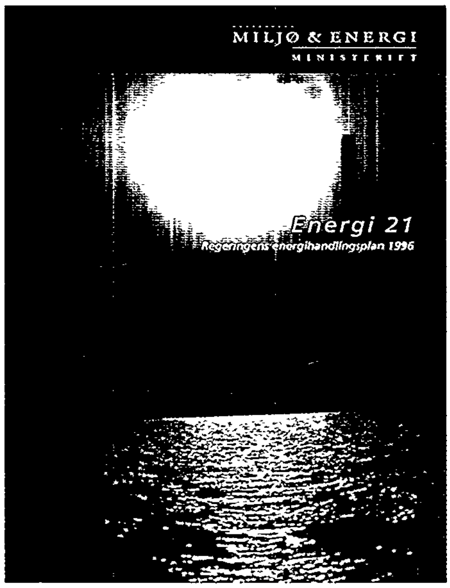
The Four Energy Plans

The aim of the first energy plan, Danish Energy Policy 1976 (Dansk Energipolitik 1976), was to safeguard Denmark against supply crises like the energy crisis in 1973/74.

The second energy plan, Energy Plan 81 (Energiplan 81), gave added weight to socio-economic and environmental considerations, thus continuing the efforts of reducing the dependence on the import of fuels.

The third energy plan in the series is the action plan Energy 2000 (Energi 2000) /ref. 1/ of 1990. This plan is an ambitious attempt to increase the use of environmentally desirable fuels. At the same time, the aim of a sustainable development of the energy sector is introduced. In Energy 2000, the environmentally desirable fuels are defined as natural gas, solar energy, wind, and biomass (straw, wood, liquid manure, and household waste). The use of biomass is based on the facts that it is CO_2 neutral, that it saves foreign currency, that it creates Danish jobs, that it utilises waste products from agriculture, forestry, households, trade and industry. The ambitious aim of Energy 2000 is that Denmark compared to the year 1988 shall achieve the following aims by the end of 2005:

- Reduce the energy consumption by 15%.
- Increase the consumption of natural gas by 170%.
- Increase the consumption of renewable energy by 100%.
- Reduce the consumption of coal by 45%.
- Reduce the consumption of oil by 40%.
- Reduce the CO_2 emission by at least 20%.
- Reduce the SO_2 emission by 60%.
- Reduce the NO_x emission by 50%.



Energy 21(Energi 21) shall contribute to a sustainable development of the Danish society. The energy sector shall continue to be a financially, vigorously, and technologically efficient sector that forms part of a dynamic development of society.

The aims are achieved by means of a wide range of activities: Energy savings, tax on CO_2 emission, conversion to the use of environmentally desirable fuels by means of CHP generation, subsidised construction and operation of district heating systems, subsidised establishing of biofuel boilers in rural districts etc.

The fourth and last energy plan is Energy 21 (Energi 21) /ref. 2/ that was introduced in 1996. The intention of this plan is that the administration of our resources shall have a central role. Our consumption of depletable, fossil energy sources, and emissions resulting from the consumption and energy production shall be further reduced. A significant aspect of Energy 21 is thus that the existing aim of Energy 2000, i.e., that Denmark should reduce its CO_2 emission by 20% in 2005 compared to the 1988 level, is supplemented with a long-term aim. The CO_2 emission should be halved in 2030 compared to 1998. In addition, international climate change negotiators will advocate that the industrialised countries by 2030 halve their emissions of CO_2 compared to the 1990 level. At the UN Climate Change Conference in Kyoto in 1997, the EU reduction was fixed at 8% in 2012 compared to the 1990 level.

Denmark's CO_2 aim shall be achieved by both improving the energy intensity by 50% up to the year 2030 and by renewable energy contributing by 35% of the gross energy consumption in 2030.

Energy 21 assumes that renewable energy covers 12-14% of the country's total energy consumption in 2005. By far the most significant renewable energy source is and will continue to be biomass. Biomass contributed with 61 PJ in 1996, which should increase to 85 PJ in 2005 and 145 PJ in 2030. The increase up to 2005 will primarily be achieved by the centralised power plants' increased use of straw and wood chips (see the section on the Biomass Agreement). An increased use of biomass and landfill gas also contributes to achieving the aim of 85 PJ. In connection with Energy 21, the Danish island Samsø has been declared a renewable energy island, and the island shall thus function as display window for Danish renewable energy technology.

Thus the initiatives in the field of biomass are directed at the following partial aims of Energy 21:

- Increased use of straw and wood chips at centralised power plants.
- Increased CHP generation based on straw, wood chips, biogas, and landfill gas.
- Conversion to the greatest possible extent of block heating units above 250 kW in rural districts from fossil fuels to biofuels.
- Permission to establish biofuel systems and biogas production from collective systems, industrial systems, and landfill sites etc. in areas previously reserved for natural gas.

Figure 2 shows the distribution of the individual renewable energy sources.

EU Influence

EU Commission Renewable Energy White Paper 1997/ref. 3/ fixes an increase in the EU use of renewable energy from 6% to 12% up to the year 2010. It is estimated that the biomass sector will be the fastest growing sector in the field of renewable energy technologies. The use of agricultural land is closely connected with the EU agricultural policy. The most recent EU draft proposal for future agricultural policies suggests that the legal obligation to fallow land shall be abolished, and that there shall be one rate for subsidies no matter the choice of crop. This will affect the farmers' managements also with regard to growing energy crops on land, voluntarily left fallow. Energy 21 mentions explicitly that the aim of 45 PJ energy crops in 2030 can be achieved by other biomass use subject to EU modifying its agricultural policy and subsidy schemes so as to encourage this.

The Heat Supply Act

For the purpose of implementing the activities suggested in Energy 2000 /ref. 1/, the Heat Supply Act June 3,1990 was passed by the Danish parliament "Folketinget". This Act gave the Minister of Energy wide powers to control the choice of fuel in block heating units, district heating plants, and decentralised CHP plants. This was accomplished by the so-called "Letters of Specific and General Preconditions" /ref. 5/ that are circulated to municipalities and owners of plants in three staggered phases. The "Letters of Specific and General Preconditions" describe in details the conversion to environmentally desirable fuels to selected municipalities and owners of plants. In addition, "Letters of General Preconditions" that describe the prospects of voluntary conversion from coal and oil to more environmentally desirable fuels are circulated to all Danish municipalities.

The conversion was immediately implemented. Phase 1 took place from 1990-1994 and included the conversion of a number of coal and natural gas-fired district heating plants that should be converted to natural gas-fired, decentralised CHP. Phase 2 took place from 1994-1996 and included the remaining coal and natural gas-fired district heating plants that are converted to natural gas-fired, decentralised CHP. In addition, small district heating plants outside the large district heating systems should be converted to biofuels. Phase 3 began in 1996 and is not finished yet. The aim was that small, gas-fired district heating plants should be converted to natural gas-fired CHP plants and the remaining district heating plants to biofuels. See also the section on the Biomass Agreement on the adjustment of the progress of the phase.

The CO_2 Acts

The Heat Supply Act was followed by three new acts offering the prospective of subsidising the process of conversion to environmentally more desirable fuels. The purpose was that the Minister of Energy could then counteract consumers being charged higher heating prices as a result of the conversion.

The three acts are Acts Nos. 2, 3, and 4, 1992 and the titles are:

- "State-Subsidised Promotion of Decentralised Combined Heat and Power and Utilisation of Biomass Fuels Act". Under this act, it is possible to receive subsidies of up to 50% of the construction costs. In practice, subsidies have been in the range of 20-30% of the construction costs.
- "State-Subsidised Electrical Power Generation Act". A subsidy of DKK 0.10 /kWh is granted for electrical power generation based on natural gas, and a subsidy of DKK 0.17/kWh for electrical power generation based on straw and wood chips. On January 1, 1997, an executive order was put into force requiring e.g. a biomass plant overall efficiency of 80% in order for the plant to receive the max. subsidy. In addition, the CO_2 tax of DKK 0.10/kWh is refunded in the case of renewable energy. Thus private producers of renewable energy receive a total subsidy of DKK 0.27/kWh.
- "State-Subsidised Completion of District Heating Nets". Under this act, up to 50% of the construction costs could be subsidised. The scheme expired at the end of 1997.

The present subsidies of DKK 0.10/kWh and DKK 0.17/kWh respectively in connection with the electrical power reform will be financed via the consumption price in a transitional period. In the future, the electrical power generation subsidies and the DKK 0.10/kWh from the CO_2 tax will be replaced by "green" renewable certificates with the minimum price being DKK 0.10/kWh. The organisation and function of the "green" market will be clarified during 1999.

Development of Renewable Energy Scheme

A 3-year bioenergy development programme for 1995-97 (BUP-95) /ref. 6/ has had the aim to encourage the technological development in the field of biomass-based systems. The programme recommends the following activities:

- The development of CHP technologies based on straw and wood chips as fuels. The technologies are steam, gasification, and the Stirling engine.
- District heating systems should focus on fuel flexibility and an environmentally desirable handling of fuels.
- Environmentally desirable and user-friendly boiler systems should be developed for private dwellings.

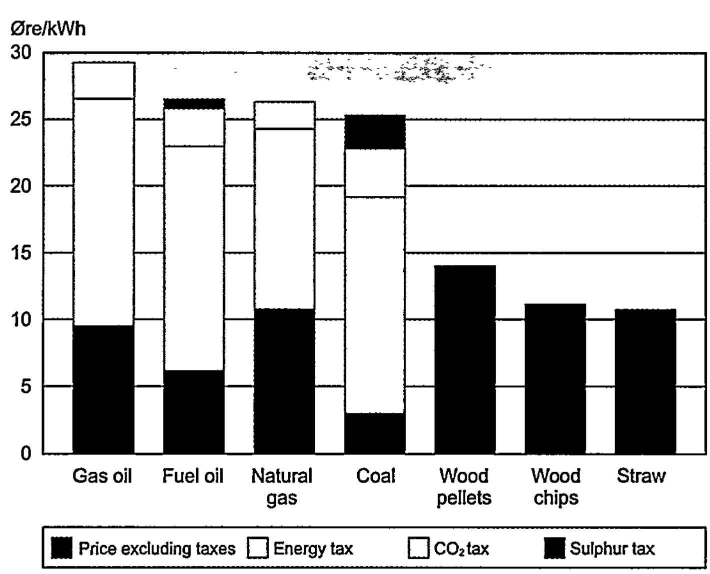


Figure 1: Fuel prices at the beginning of 1999 for district heating purposes including taxes but excluding VAT /ref. 4/.

- Energy crops should be investigated with a view to the growing, handling, and use of them.

The Danish Energy Agency's scheme, the "Development Scheme for Renewable Energy", subsidises projects for the promotion of biomass in the energy supply and uses e.g. the Bioenergy Development Programme (BUP)-95 as the basis of their decisions when considering applications for subsidies.

The Plant Pool

The Government subsidises the promotion of decentralised CHP generation and the utilisation of biofuels. The scheme includes subsidies for the conversion of district heating plants to CHP plants based on biofuels and for the promotion of an increased use of biofuels in areas without collective heating supply. Under this scheme, subsidies amounting to DKK 25 million can be granted per year.

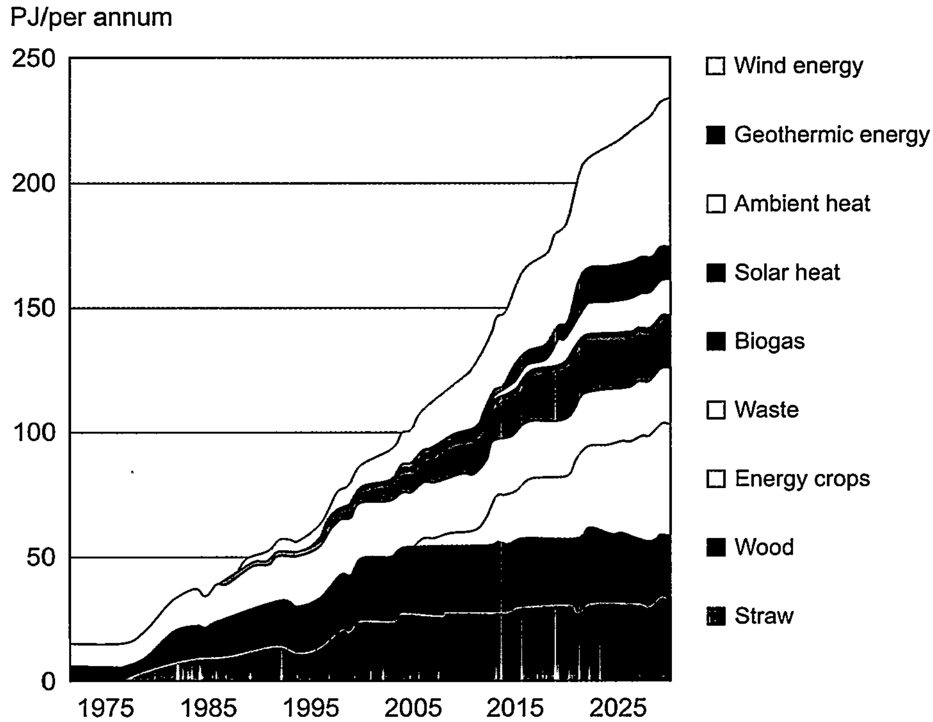


Figure 2: Energy 21(Energi 21) proposal for the use of renewable energy sources up to the year 2030 /ref. 2/.

The Biomass Agreement

In order to ensure the achievement of the aims of Energy 2000, the Government, the Conservative Party, the Liberal Party, and the Socialist People's Party entered into an agreement on June 14, 1993, on an increased use of biomass in the energy supply with a special view to use at centralised power plants. The main points of the agreement are as follows:

- A gradual increase in the use of biomass at power plants shall take place so that the consumption by the year 2000 amounts to 1.2 million tonnes of straw and 0.2 million tonnes of wood chips per year equal to 19.5 PJ.
- Eleven towns in natural gas districts that have not converted to natural gas-fired CHP generation within Phase 1 or Phase 2 may choose between biofuels and natural gas as fuels. It is possible to wait until 2000 in order to e.g. await the development and commercialisation of technologies in the field of biomass.
- Phase 2 towns outside natural gas areas can postpone the conversion until 1998 if they choose biomass-based CHP.
- Six towns in Phase 3 may postpone the conversion to biomass-based CHP until 2000.
- Approx. 60 small towns in Phase 3 should be converted to biomass-based district heating by the end of 1998.

The agreement has resulted in Sønderjyllands Højspændingsværk (electricity utility) having constructed a biomass-based power plant in Aabenraa with a consumption of 120,000 tonnes of straw and 30,000 tonnes of wood chips per year. Sjællandske Kraftværker (electricity utility group) has constructed a straw and wood chip-fired CHP plant in Masnedø with an annual consumption of 40,000 tonnes of straw and 5-10,000 tonnes of wood chips, and is presently also constructing plants in Maribo-Sakskøbing and in Avedøre near Copenhagen.

On July 1, 1997 the political parties to the Biomass Agreement drafted a supplementary agreement with the intention of improving the prospects of integrating biomass in the energy supply. In principle, the supplementary agreement means that:

- The centralised power plants are allowed a freer hand when choosing among straw, wood chips, and willow chips, since the consumption should include 1.0 million tonnes of straw and 0.2 million tonnes of wood chips but with the remaining part being optional, but so as to make out a total of 19.5 PJ.
- Biomass-based CHP generation will be permitted in natural gas areas.
- The municipalities shall give priority to CHP generation based on biogas, landfill gas, and other gasified biomass.
- Seven towns in Phase 3 may continue the present district heating supply until a conversion to biomass-based CHP generation is technically and financially appropriate.

Political Harmony

It is characteristic that since the middle of the 1980s, changing governments, parliamentary majorities, and ministers of energy have persisted in the importance of an active energy policy thereby adding weight to the resource-based and environmentally responsible policy. Denmark has a leading position in several fields of renewable energy, and Energy 21 will maintain this leading position.

2. Wood as Energy Resource

2.1 Amount of Consumption and Resources

Wood is an important energy source all over the world. In Denmark energy wood is available in the form of forest chips, fuelwood, wood waste, wood pellets, and also it is produced to a very limited extent from willow crops in short rotation forestry. The major part of wood harvested on the forest area of approx. 460,000 ha ends up as energy wood directly or after having been applied for other purposes first. In the light of the Government's aim to increase the forest area by doubling it during a rotation, Denmark's total wood fuel resources will increase over the years.

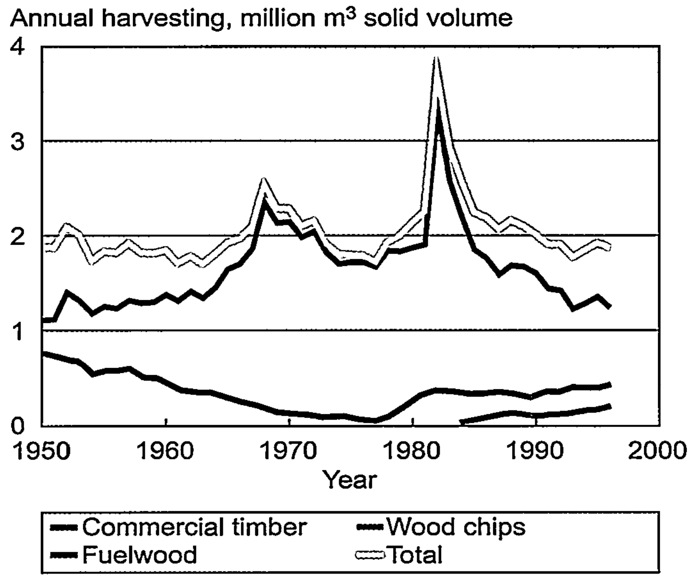


Figure 3: Wood Harvest 1950-1996 distributed on commercial timber, fuelwood, and wood chips. The wind breakages in 1967 and 1981, in particular, resulted in increased harvesting /ref. 8/.

Consumption of Energy Wood

According to the Danish Energy Agency's survey of the energy production in 1997, wood covers approx. 21,000 TJ which is equal to 28% of the total production of renewable energy and equal to approx. 500,000 tonnes of oil. Table 1 illustrates the distribution among the individual wood fuels.

Since 1950, Statistics Denmark has made detailed statistics classifying the wood harvest in Danish forests, and it amounts to approx. 2 million m^3 s. vol (solid volume) with fluctuations around the wind breakage disasters in 1967 and 1981. In 1996, an amount of approx. 620,000 m^3 s. vol, equal to approx. 108,000 tonnes of oil, was used for direct energy production, which is approx. 33% of the total harvest.

Fuel	Consumed 1997 (TJ)	Proportion (%)
Forest chips	2,703	13
Fuelwood	9,603	46
Wood waste	5,879	28
Wood pellets	2,828	13
Totalling	21,013	100

Table 1: Consumption of wood fuels. By way of comparison, it may be mentioned that the energy content of 1000 tonnes of oil is 42 TJ /ref. 7/.

Wood chips result from first and second thinnings in spruce stands, from harvesting overmature and partly dying pine plantations, from harvesting in climate- and insect damaged stands, from the harvesting of nurse trees (species that are planted at the same time of the primary tree species in order to protect them against e.g. frost and weeds), and from tops by clear-cutting (timber harvesting of the whole stand at the end of the rotation) in spruce stands. Wood chips have become a still more important fuel over the two most recent decades, and the production amounts to approx. 200,000 m^3 s. vol per year.

Fuelwood is obtained primarily in hardwood stands by thinning and by clear-cutting in the form of tops, branches and butt ends. Earlier, fuelwood was the most important product of the forest, but around the turn of the century, wood as a source of energy was substituted by coal and later by oil. The oil crisis in the 1970s and the increase in taxes imposed on oil and coal in the middle of the 1980s resulted in an increased interest in wood for the purpose of energy production.

According to statistics, forestry produces 420,000 m^3 s. vol of fuel, but the consumption of fuelwood from gardens, parks, hedges/fringes etc. is not registered. The total consumption is estimated at approx. 700,000 m^3 s. vol per year /ref. 9/.

Wood waste consisting of bark, sawdust, shavings, demolition wood etc. is used primarily in the industry's own boiler furnaces. Approx. 640,000 m^3 s. vol is used per year of which part of it is used for the production of wood pellets and wood briquettes, a rather new production in Denmark. In addition to that, a huge amount of wood waste is imported for the purpose of this production. The consumption of wood pellets and wood briquettes amounts to approx. 200,000 tonnes and approx. 20,000 tonnes respectively per year.

Energy willow is grown in short rotations (3-4 years) on farmland, but the production is not yet so widespread in Denmark, where willow covers an area of only approx. 500 ha. The amount of fuel produced from willow is therefore not so important compared to other wood fuels.

Future Resources

The Danish Forest and Landscape Research Institute has calculated the amount of available wood fuel resources (fuelwood and wood chips) from Danish forests above 0.5 ha /ref. 10/. The resources have been calculated on the basis of information provided by the forest inventory in 1990 of tree species, age-class determination, and wood production of the individual forests. The calculations have been made in the form of annual averages from 1990-1999, 2000-2009, and 2010-2019 based on hypotheses that are deemed to be realistic under the prevail-

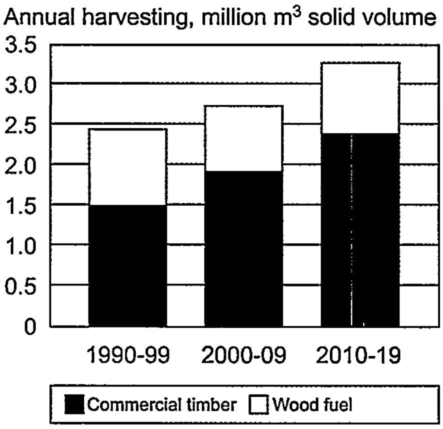


Figure 4: Forecast from 1994 of the potential annual harvesting of commercial timber and wood fuel in the periods 1990-99, 2000-09, and 2010-19. Harvesting is expected to rise in a good two decades /ref. 10/.

ing outlets for cellulose wood and other competing products for wood fuel.

Total annual harvesting is expected to increase in the next two decades to approx. 3.2 million m^3 s. vol due to, among other things, afforestation (Figure 4). Note that the total harvesting (Figure 3) according to Statistics Denmark is approx. 500,000 m^3 s. vol lower per year compared to the forecast for 1990-99. This apparent divergence is due to the fact that forestry does not have sufficient outlets for wood for energy. The annual commercial timber harvest is expected to increase in both periods after the year 2000, while the harvesting of fuelwood and wood chips is predicted to decrease from approx. 950,000 m^3 s. vol to approx. 800,000 m^3 s. vol, and then again increase to approx. 900,000 m^3 s. vol in the last period (Figure 4). The change in harvesting is due to an unequal age-class distribution of the spruce area, the finishing of mountain- and contorta pine wood stands, and an increase in the harvesting of wood fuel in hardwood stands /ref. 11/.

While the total potential annual harvesting can be forecast with great certainty, the distribution among fuel and other products will be subject to a range of outward circumstances. If the development of the most recent years continues, the fuel proportion will increase.

Based on the figures of the survey, the forests are capable of currently supplying the present chip-fired heating and CHP plants with wood chips and in addition supply the necessary amount of wood, i.e., 200,000 tonnes of wood chips per year, which is equal to approx. 250,000 m^3 s. vol, which the power plants according to the Biomass Agreement shall use as from the year 2004.

2.2 Afforestation and Wood for Energy

Afforestation includes the planting of new forests on agricultural land. The future supply of energy wood should be ensured partly through afforestation. Here, the energy wood production can be increased by increasing the number of plants compared to the number of plants in normal stands, and by using nurse trees.

The Energy Political Aim

It says in the preamble to the Danish Forestry Act that in addition to protect and preserve the Danish forests and improve the stability of forestry, ownership structure, and productivity, the aim is to"... contribute to increasing the forest area" /ref.12/. It is the aim of the Government to double the forest area over the next rotation (80-100 years). This aim is also in relation to the energy policy of political interest, and it should be seen in connection with the Biomass Agreement of 1993 and the Government's action plan, Energy 21, of which it appears that the use of biomass in the energy sector should be increased, including wood chips /ref. 2/. In the Danish strategy for sustainable forestry, it is clearly stated that this doubling of the forest area should be achieved by "... aiming at a regular planting intervals" /ref. 13/. This means that approx. 5,000 ha should be planted per year in order to achieve the aim, of this 2,000-2,500 ha by private forest owners. Since 1989, only approx. 50% of the plants has been planted.

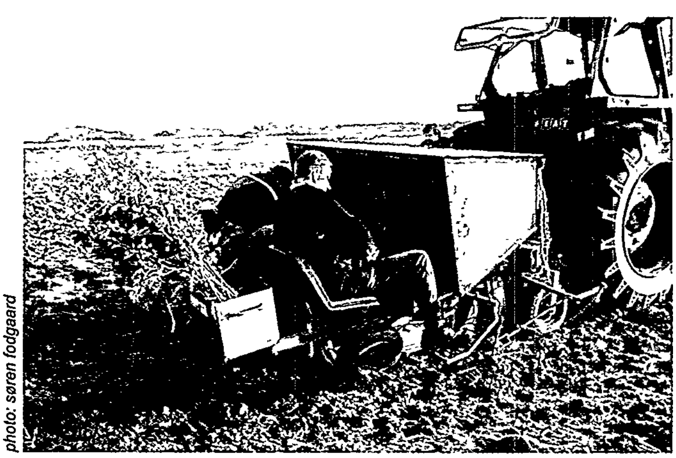
In the Danish Energy Agency's survey of 1996 on the wood chip amounts from Danish forests up to the year 2025, which is based on /ref. 10/, an increase of the forest area of 5,000 ha per year has been included. Energy wood production in the form of wood chips from afforestation is estimated at 4 PJ per year out of a total energy contribution of almost 10 PJ per year from wood chips. Thus afforestation is expected to contribute considerably to the total consumption of energy wood in future /ref. 14/.

Energy Wood from Future Afforestation

The energy wood production by future afforestation can be increased in proportion to the energy wood production in the existing forests by, e.g., increasing the number of plants in proportion to normal practice, and by using nurse trees. An increase in yield should not be at the expense of the all-round forestry where the production of quality wood, preservation of nature, protection of the cultural heritage, and recreation are given high priority.

A high stocking percentage results in a faster plant cover of the area and thus a larger production. Calculations show that the prospective spruce wood chip production can be increased by 30-50 % by increasing the number of plants from approx. 4,500 to 6,500 plants per ha. As the cost of planting increases with the larger number of plants, and the increased yield of wood chips does not cover the cost of more plants, the method of large numbers of plants will only be of interest if in addi-

photo: søren fodgaard



Afforestation on agricultural land. With the present planting program of 2,000-2,500 ha per year, it is necessary to increase the afforestation or increase the energy wood production from the existing forest areas in order to comply with the aim of the Danish Energy Agency.

tion to the increased yield of wood chips, the added benefit of improved wood quality, improved stand stability and reduced cost of weed control etc. can also be achieved.

Traditionally, nurse trees are planted at the same time of the primary tree species, which are normally more sensitive species, in order to protect against frost, weeds etc. As nurse trees are trees that are fast growing in their youth, the wood production increases resulting in larger quantities of wood chips produced from the thinnings in immature stands that are performed by harvesting the nurse trees row by row. Relevant nurse tree species are e.g. hybrid larch, alder, poplar, Scotch pine and birch. By using hybrid larch as nurse trees in a spruce stand, the yield of wood chips can be increased by approx. 35% with a number of plants of 6,400 per ha distributed on 4,200 spruce and 2,200 hybrid larch compared to an unmixed Norway spruce plantation (Figure 5) /ref. 15/.

Normally, wood chips are only harvested in softwood stands, but by producing wood chips from hardwood, such as beech, the yield of wood chips can be greatly increased when using nurse trees. By planting hybrid larch also, the yield of wood chips could be tripled in proportion to a pure beech stand.

The calculations of the yield of wood chips are based on existing research data on spruce, but new requirements for the forests in respect of increased diversity and flexible stands may mean that more mixed stands will be established in the future.

The effect of increased stand density is investigated by research.

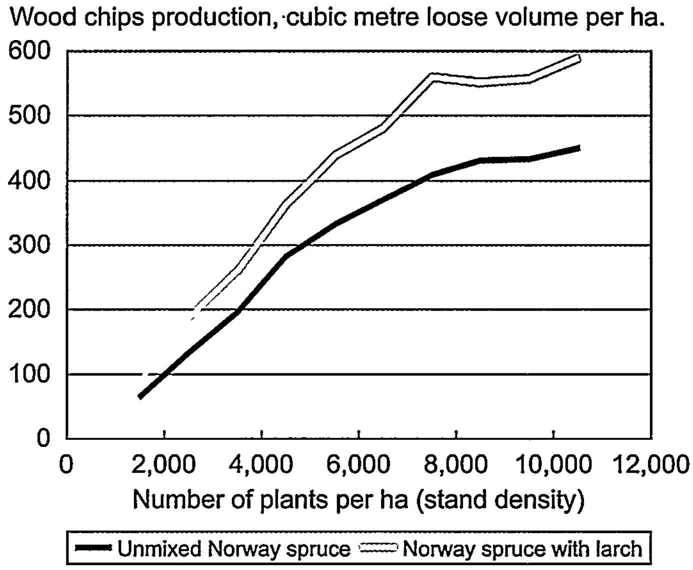


Figure 5: Production of wood chips in m³ l. vol per ha for an unmixed Norway spruce stand and a stand consisting of Norway spruce with larch as nurse trees with variations in the number of plants in the Eastern part of Denmark. The wood chip production increases considerably by using nurse trees. /ref. 15/.

Demo - Field Experiments

In co-operation with The National Forest and Nature Agency, the Danish Forest and Landscape Research Institute established in 1998-99 demo - field experiments on three afforestation areas in Denmark. The purpose of the experiments is, among other things, to investigate the energy wood production in mixed stands on various soil types. The experiments are aiming at demonstrating the additional expenditure involved in increasing the number of plants, prospective gains in the form of reduced need for weed control and replanting (replanting after dead plants), and in the long term an improvement of the wood quality.

The demo - field experiments include nine different planting models using the following mixture of species:

- Mixed softwoods (Sitka spruce/Norway spruce, and Douglas fir with or without larch as nurse trees).
- Pure hardwood stands and mixed hardwood stands (beech, oak, and oak with alder).
- Mixed hardwood- and softwood stands (beech with Douglas fir and beech with larch).

A standard number of plants is chosen, which is doubled either with the primary tree species (beech, Norway spruce/Sitka spruce, oak, Douglas fir) or by using nurse tree species (alder, larch).

The experiments are currently inspected and measurements are taken, and the actual energy wood yield figures will be available in connection with thinning in immature stands in approx. 15-20 years. The results form the basis of the planning of future afforestation.

Legislation and Subsidies

In connection with afforestation, the planting plans must be approved by the Directorate for Agricultural Development, and the afforestation must be shown to be in conformity with the counties' designations in their regional land use plans of plus and minus land for afforestation, i.e., the areas where afforestation is wanted or not.

photo: the danish land development service/bert wiklund

The Danish forest area will be doubled over the next 80-100 years. Many of the new forests will be hardwood forests with oak and beech being the primary species.

The public authorities try to encourage private forest owners to carry out afforestation via various subsidy schemes, but so far they have only succeeded partly. The major part of the afforestation takes place on the National Forest and Nature Agency's own areas or on privately owned properties without subsidies. At the turn of the year 1996-97, a new subsidy scheme under the Danish Forestry Act came into force which has intensified the interest in afforestation, e.g., due to income compensation and increased possibilities of being subsidised. This has resulted in applications exceeding the means available within the schemes.

The framework of afforestation and the possibilities of being granted subsidies are laid down in a range of acts and executive orders. A precondition for being granted subsidies is, that the area is designated as a forest reserve in order to secure the existence of the forest in future. In addition to that, there are certain requirements for the structural design and the size of the forest. The subsidy schemes include among other things subsidies for preparatory investigations like locality mapping (investigations of soil) and land plotting, planting, and care of stands, establishing of hedges and income compensation for a period of 20 years /ref. 16/. Further information can be obtained by contacting the State Forest Service.

2.3 Energy Plantation (Short Rotation Coppice)

Willow has been used as a cultivar for centuries for the purpose of tools, barrel hoops, basketry, and wattles. For the purpose of the production of wood chips for energy, willow has only been cultivated for a few years in Denmark, and at present willow wood chips are only used to a limited extent at heating plants in Denmark.

Energy Plantations in Denmark

The term energy plantations applies to hardwood plantations (generally willow) that are growing fast in their juvenile phase and capable of multiplication by cuttings and stump shooting. Through intensive cultivation, these properties are utilised for the production of biomass that can be used for energy production.

photo: biopress/torben skøtt

The area has been carefully cleaned before planting the willow cuttings. The planting takes place by a two-furrow planting machine, and a tractor marking arm ensures quite parallel rows. The dual wheels of the tractor distribute the ground pressure so that the soil is not unnecessarily compressed.

According to the Energy Action Plan of 1996 (Energi 21), it is the intention that the contribution of energy crops or other biomass, excluding straw, to the energy supply shall be increased from 0 in the year 2005 to approx. 45 PJ in the year 2030. If not supplemented with other biomass, this is equal to the yield of approx. 500,000 ha willow. However, the growing of energy crops will to a high extent depend on the EU agricultural policy and subsidy schemes. In order to estimate the potential of the energy crops, a demo and development programme has been implemented in order to analyse future use of energy crops.

In Denmark, willow is only grown on 500 ha agricultural land /ref. 15/, while it is estimated that willow is grown on approx. 17,000 ha land in Sweden. Willow is an agricultural crop, which means that it is possible to stop growing willow and change to another crop if so desired.

Willow Growing

Willow can be grown on various soil types. Soil types ensuring a good supply of water are suitable. Light soil types without irrigation will result in unstable yield. Willow roots may block drain systems. The area should be suitable for mechanical equipment including being capable of bearing machines during the winter months when harvesting takes place /ref. 17/.

When establishing energy plantations in Denmark, cloned withy cuttings have so far proven to have the best production potential. When planting, which takes place in spring, traditionally approx. 15,000-20,000 cuttings taken from one year old shoots are planted per ha. The cuttings are inserted in the ground by machine, and the 20 cm long cuttings are forced straight into the ground so that only a few cm stand up. By way of comparison, it may be mentioned that a new method has proven that the cost of planting can be reduced by 50% by horizontally spreading the material, cut in lengths of approx. 20 cm, and hence grooving it down into the ground /ref. 18/. The first winter after planting, the shoots can be cut off at a height of 5-8 cm in order to encourage more sprouting. Cutting down is considered advantageous in thin stands and where there are only 1-2 shoots per cutting /ref. 19/.

The worst enemy during the initial phase is weeds, particularly grasses, and the area should therefore be thoroughly cleaned before planting e.g. by subsoil ploughing. Weed control is easiest and best performed by means of herbicides combined with mechanical weeding. At the time of harvesting, which is done at a few years interval, everything is removed except leaves and roots, and that makes the application of fertiliser necessary in order to maintain the level of production.

Table 2 illustrates the application of fertiliser to a willow cultivation over the individual years.

	N	P	K
Planting year	-	0-30	80-130
1st prod. year	45-60	-	-
2nd prod. year	100-150	-	-
3rd prod. year	90-120	-	-
1st year after harv.	60-80	0-30	80-160
2nd year after harv.	90-110	-	-
3rd year after harv.	60-80	-	-

Table 2: Recommended application of fertiliser to energy willow before and after first harvesting (kg per ha). - means no fertiliser applied. The amount of fertiliser varies with the soil characteristic /ref. 19/.

The application of nutrients to energy willow with waste water, sewage sludge or liquid manure is an alternative to the application of fertiliser. The dense, deep striking willow root system is suitable for capturing the plant nutrients and heavy metal content of the sludge. Thus compared to wood chips, the fuel will contain relatively large quantities of nitrogen and cadmium. Under ideal combustion conditions, the major part of the nitrogen will be released in the form of N_2, and the heavy metals will remain in the ash. This is an important precondition for stating that using sludge for energy willow will be environmentally beneficial /ref. 20/.

Harvesting and Storage

The first harvesting on the area takes place 3-4 years after planting when the willow shoots are approx. 6 metres high. It is done in winter, and the following spring the plants start growing from the stumps, and after another 3-4 years, harvesting can take place again. It is expected that the willows can grow for at least 20 years without any reduction in the plant yield, and that means that harvesting can take place 4-5 times before new planting will be necessary.

Research has shown that long-time storage of willow chips is difficult to handle. This is due to the fact that the moisture content is approx. 55 - 58% of the total weight of green willow, and that young willow shoots contain a large proportion of bark and nutrients. In piles of willow chips, a fast temperature development typically takes place resulting in a considerable loss of dry matter. This development depends on the size of the chips. The larger the chips are, the lesser is the decomposition. Long-term storage is best if the willow has not been chipped but is stored in the form of whole shoots, which is expensive. A different method that has proven successful during experiments is airtight sealing of willow chips. Without oxygen, no decomposition takes place /ref. 21/. The difficult long-time storage means that willow wood chips are normally hauled directly to the heating plant.

Fuel Characteristics

Willow chips do not differ very much from other types of wood chips, but may contain more bark and more water. The lower calorific value of bone dry willow does not differ from that of other wood species, but is approx. 18 GJ per tonne of bone dry material. But compared to most other wood species, willow wood is relatively light. This means that one m^3 l. vol (loose volume) of willow chips contains less dry matter (approx. 120 kg/m^3 l. vol) than e.g. one m^3 l. vol of beech chips (approx. 225 kg/m^3 l. vol) This is of importance to the amounts by volume a heating plant must be capable of handling in order to achieve the same generation of heat. The high moisture content makes the wood chips particularly suitable at plants equipped with a flue gas condensation unit. If so, the evaporation heat is recovered.

photo: biopress/torben skøtt

By harvesting of whole shoots which takes place by specially designed machines during the winter, everything, except leaves and roots, is removed. The willow shoots are harvested close to the soil surface.

The Production of Willow Chips

In plantations, the entire cost of production should be paid by a low value product, i.e. willow chips. This makes the production of energy willow chips vulnerable compared to the production of straw or forest chips. By the production of straw for energy, the cereal production carries all the costs including combine harvesting, and the straw will only have to pay for the collection, transport and storage. Similarly, the production of sawmill timber pays for tree growth, while the wood chips pay for chipping, storage, and transport to heating plant. Willow growing is therefore financially risky and depends to a high extent on the harvesting yield.

Therefore, the calculation of the production level for willow plantations in Denmark has received much attention. Occasionally, high yield figures of 10-12 tonnes of dry matter per ha per year or more are recorded, but they have often been achieved in individual, small and very intensively cultivated willow stands and are thus not a realistic estimate for yields in commercial stands. Yield measurements, carried out in Danish cultivated willow stands from 1989 to 1994, show that the average yield is approx. 7.5 tonnes of dry matter per ha per year, which is not as much as previously estimated. The results of the yield measurements have not been able to unambiguously explain the influence of the stand factors on the production level, but this average yield has been achieved in willow stands with fertiliser being intensively applied and with half of the stands being irrigated. Measurements of the yield have been carried out on clones, that were common at the beginning of the 1990s /ref. 22/. Danish measurements on new clones form part of an EU project. Preliminary results indicate that the additional yield of the new clones is modest in comparison with the old clones.

Willow Growing in the Future

For the time being, there is good reason to follow the development of willow growing in Sweden, who has taken the lead. More and more information is obtained about cloning developments, harvesting yields, cost of harvesting, and soil types preferred by willow. It may be possible for agriculture to take up a niche production of willow on soils suitable for the growing of willow, but less suitable for cereals. Finally, willow may conquer a niche where it can contribute to solving some environmental problems in the form of waste water and soil purification.

2.4 Physical Characterisation of Wood Fuels

In Denmark, wood from forestry and from wood industry is used in the form of firewood, wood chips, bark, shavings, briquettes, pellets, and demolition wood for firing in, e.g., wood stoves, wood pellet-fired boilers, district heating plants, and CHP plants. The technologies used at these plants stipulate various requirements in respect of the physical properties of the wood i.e. size, size distribution, moisture content, ash content, and pollutants (stones, soil, and sand).

A physical characterisation of wood fuels is important when choosing fuels for various boiler systems and technologies. In addition, information on the physical properties of the wood fuels can be used when drafting contracts for future deliveries, specifying the fuel in relation to certain types of boiler systems, and the drafting of quality descriptions of the wood fuel. Knowledge of these properties in relation to various types of wood fuels thus contributes to a promotion of an environmentally and economically optimal application of the fuel /ref. 23/.

Fuelwood

Fuelwood is split, round or chopped wood from delimbed stems, cut-off root ends, and tops and branches of hardwood or softwood. Ready-to-use firewood is normally split to 15-35 cm. Chunks of 6-8 cm thickness are most suitable for the majority of wood stoves. Firewood consists of wood and bark.

The moisture content in green spruce is approx. 55-60% of the total weight and correspondingly approx. 45% for beech /ref. 24/. After drying during the summer season, the moisture content is reduced to approx. 15% of the total weight - depending on weather, stacking and covering - which is the recommended moisture content for use in wood stoves /ref. 25/. The ash content is often below 2% of the dry matter.

		Fraction unit (%)	
Name	Screen tray	Fine	Coar.
Overlarge	45 mm round holes	< 5	< 15
Overthick	8 mm slats	< 25	< 40
Accept	7 mm round holes	> 40	> 23
Pin chips	3 mm round holes	< 20	< 15
Fines		< 10	< 7
Hereof:			
Slivers 100-200*	100-200 mm length	< 2	< 12
Slivers > 200*	> 200 mm length	< 0,5	< 6

Table 3: Requirements for the size classification of fine and coarse fuel chips according to the old Standard No. 1 which is currently being revised /ref. 26/.

** Diameter > 10 mm.*

Wood Chips

Wood chips are comminuted wood in lengths of 5-50 mm in the fibre direction, longer twigs (slivers), and a fine fraction (fines). Whole-tree chips are chipped from whole trees including branches in the first thinning of spruce stands or in connection with converting old mountain pine and contorta pine plantations. Wood chips are also produced from top ends and other residues in clear-cuttings. Sawmill wood chips are a by-product of the sawing of logs. Furthermore willow wood chips are produced from short rotation coppice grown on agricultural land.

The required type of wood chips depends on the type of heating system. A new system for the quality description of wood chips based on size classification is currently underway because the old standard from 1987 no longer covers the kind of wood chips produced and used today. The old standard divided wood chips into fine and coarse wood chips (Table 3).

The wood chips delivered nowadays to the heating plants are coarser than coarse wood chips. The new quality description is therefore based on three types of wood chips: fine, coarse, and extra coarse. Note that the names refer to the size distribution only and not to the quality.

Parallel with the preparation of a new Danish quality description, a European standardisation work on solid biofuels is being implemented. The purpose of this work is to standardise measuring methods and quality descriptions.

Size distribution analyses indicate the weight distribution among the wood chip classes. In the old standard, these size categories were based on an oscillating classifier that is also used for cellulose and classifier chip board chips. The new quality description is based on a new rotating classifier unit that gives a better size distribution of the wood chips.

The new rotating classifier is equipped with a hopper, a shaking table, and a rotary screen. The shaking table makes it possible to separate slivers. The rotating drum is equipped with five screens with 3, 8, 16, 45, and 63 mm round holes. On the basis of the classifier, a draft standard has been prepared designating three wood chip qualities: Fine, coarse, and extra coarse (Table 4).

According to the old standard, slivers were defined as particles longer than 10 cm and at the same time thicker than 1 cm. These particles can be very troublesome in screw conveyors. In the new quality description, the term overlong covers all particles longer than 10 cm, irrespective of diameter. These particles are problematic during feed stock handling. The proportion of particles above

10 cm length is of great importance to the wood chip bridging propensity.

The moisture content in whole-tree chips depends on the production method. The moisture content of wood chips produced from green trees is approx. 50-60% of total weight, but after summer drying of the trees for 3-6 months, the moisture content is reduced to approx. 35-45% of the total weight. Chip-fired boilers with stoker for detached houses etc. can manage wood chips with a moisture content between 20 and 50% of the total weight, while district heating plants normally accept wood chips with a moisture content of 30-55%. District heating plants with flue gas condensation normally want wood chips with a high moisture content in order to utilise the condensation heat.

Wood chips may be polluted with stones, soil, and sand which increase the ash content. The ash content in whole trees depends on the wood species and the quantity of needles, branches, and stemwood. The natural ash content in needles may exceed 5% of the dry matter weight, in branches and bark approx. 3%, and in stemwood approx. 0.6% /ref. 27/. Wood fuel for small boilers and district heating plants has an ash content of 1-2% of the dry matter weight.

Bark

Bark for energy production is produced by peeling of bark at softwood sawmills and by the cutting of slabs at hardwood sawmills. Strictly speaking, comminuted bark cannot be regarded as wood chips, but size analyses of bark - based on wood chip standard - show that bark has a very heterogeneous size distribution with a large proportion of fines /ref. 28/. Bark is very moist, approx. 55-60 % of the total weight, and single firing with bark normally takes place in special boilers because of problems with the high moisture content. Bark is the outermost layer of the tree, where pollutants are often found in the form of soil, sand, and to a certain extent lead from cartriges.

Sawdust and Shavings

Sawdust and shavings that are produced by planing, milling etc. are a by-product or residue from wood industries. Sawdust and shavings are between 1 and 5 mm in diameter and length. The moisture content in sawdust varies with the material that has been sawed, originating from wood industries that manufacture rafters and windows etc., and may have a moisture content of 6-10% of the dry matter weight, but 45-65% of the total weight if the wood was green, recently harvested.

Shavings are very dry with a moisture content between 5 and 15% of the total weight. Therefore, they are normally used for the production of wood pellets and wood briquettes. They contain few pollutants, since it is normally stemwood that is used, and the ash content is therefore less than 0.5% of dry weight.

Wood Briquettes and Wood Pellets

Wood briquettes are square or cylindrical fuels in lengths of 10-30 cm and a diameter/width of 6-12 cm. Wood pellets are cylindrical in lengths of 5-40 mm and a diameter of 8-12 mm.

		Fraction unit (%)		
Name	Screen tray	Fine	Coarse	Extra coarse
Overlong 20*	> 200 mm length	< 0,5	< 1.5	< 1.5
Overlong 10	100-200 mm length	< 3	< 6	< 6
Overlarge	> 63 mm	0	< 3	**
Extra large	> 45 and < 63 mm	< 2	< 15	**
Large	> 16 and < 45 mm	< 60	no req.	**
Medium	> 8 and < 16 mm	no req.	no req.	< 25
Small	> 3 and < 8 mm	< 35	< 25	< 8
Fines	< 3 mm	< 10	< 8	< 4

* *Overlong: If the diameter exceeds 1 cm, the length of the pieces should not exceed 50 cm or max. 5 x 5 x 25 cm.*
** *The three classes together should comprise at least 60%.*

Table 4: Draft standard designating the new chip qualities based on the rotating classifier. The draft standard is published in spring 1999 and is open to comments. The contents of the table has therefore not been approved at the time of writing.

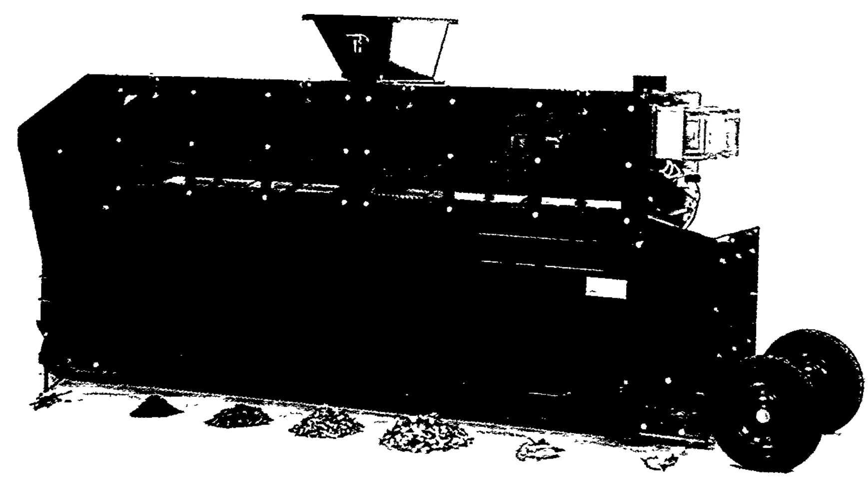


photo: finn jensen

The prototype of a new rotating classifier. Wood chips are filled into the hopper from the top, lengthwise orientated on a shaking table, and passed to the funnel tube (on the left), where the chips fall into the rotating drum. The round holes in the drum increase in size from left to right. The content of the drawers is weighed. From left: Overlong, fines, small, medium, large, extra large and overlarge.

Briquettes and pellets consist of dry, comminuted wood, primarily consisting of shavings and sawdust compressed at high pressure. The size distribution is very uniform which makes the fuel easy to handle. Pellets from the same consignment will be of the same diameter. Moreover the moisture content is low, approx. 8-10 % of the total weight /ref. 29/. Slagging problems are very limited when burning briquettes and pellets, and the amount of ash is low, approx. 0.5-1% of the dry matter weight /ref. 30/.

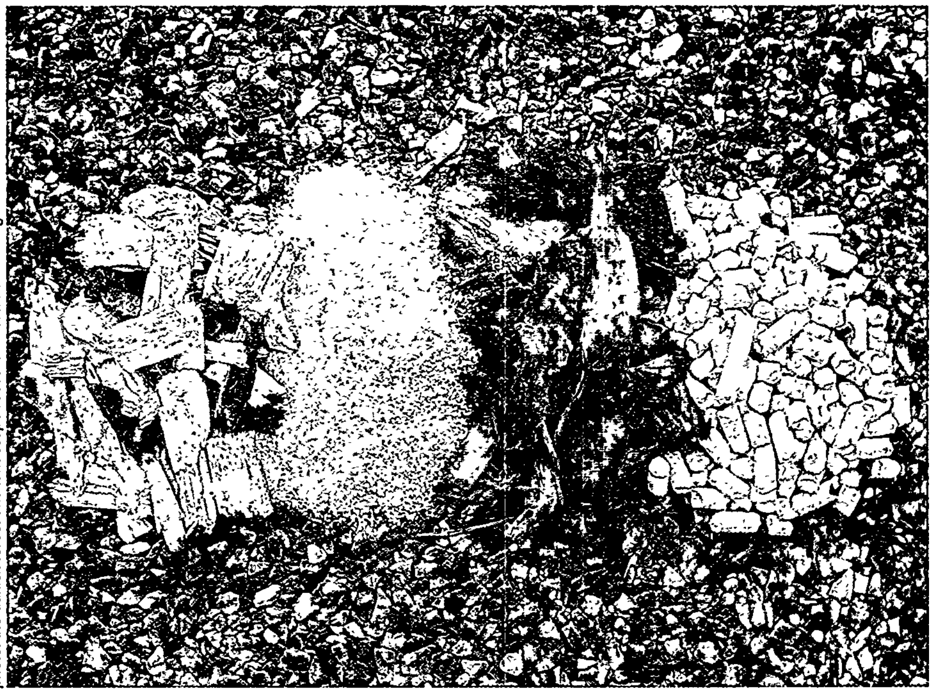


photo: the danish forest and landscape research institute/flemming rune

Forest chips, sawdust, and fresh bark from spruce, and wood pellets.

Wood Waste

Wood waste is wood that has been used for other purposes e.g. constructions, residues from new buildings or reconstructed buildings before being used as fuelwood. Other types of recycling wood include disposable pallets and wood containers. The wood that is comminuted before burning varies very much in size. Demolition wood is often relatively dry with a moisture content of approx. 10-20% of the total weight. The burning of demolition wood and other industrial wood waste may be problematic, since the wood may be polluted with residues from paint, glue, wood preservatives, metal, rubber, and plastic material depending on the previous use. If the wood waste contains glue (more than 1% of the dry matter weight), paint etc., a waste tax should be paid, and the wood waste cannot be burnt in conventional boilers /ref. 31/.

3. Production of Wood Fuels

The utilisation of forest chips for fuel is of great importance to forestry, since the production and sale of forest chips enable the necessary stand care and also the conversion of stands from one species to another. For heating and CHP plants, wood is an easy fuel to handle.

Production of Forest Chips

The production of forest chips typically takes place in connection with three different tasks:

- Thinning in immature softwood stands.
- Conversion of stands.
- Clearing of logging residues.

Quantitatively, the proportion of the first-mentioned task is absolutely predominant, but the proportion of logging residues is growing. The conversion of mountain pine and contorta pine to other more productive species is slowly being completed.

Thinning in Immature Softwood Stands

Thinning in immature stands is made in order to encourage the growth and thus increase the total yield of useful material from the trees that remain in the stand. Additional benefits of thinning are improved health of the stands and higher recreational value for the visiting public.

In establishing a softwood stand, a stock of 3,500-5,000 trees is planted per ha. First thinning is normally performed when the trees are approx. 8 m high. 25-50% of the trees are removed, thereby reducing the number of stems to 2,000-2,500 trees per ha. When the trees in the stand are approx. 10 m high, a second thinning is performed, often a selective thinning, thereby reducing the number of stems to approx. 1,000-1,500 trees per ha.

The trees from first thinning are so small that it is difficult to sell them as commercial timber, and chipping is therefore a widely used practice. In periods when the price of pulp is low, trees from second thinning are also chipped.

It appears from a survey made by the Danish Forest and Landscape Research Institute on behalf of the Danish Energy Agency /ref. 10/ that in addition to the amount of 553,000 m^3 solid mass of wood for energy production that was consumed already in 1994, the production can be further increased by an amount in the range of 400,000 and 720,000 m^3 solid mass.

The sale of forest chips is a prerequisite of carrying out early thinnings at a low price or without any costs for the owner of the forest. Without the market outlets, thinnings would most often be postponed until the trees have attained a size where a balance can be achieved between the cost of thinning and the income from the sale of the product. Thinning in due time is a prerequisite of the production of high quality commercial timber. In other words, it is not possible to maintain a production of high quality commercial timber without at the same time producing (and selling) wood fuel.

Conversion of Stands

Today the conversion of pine wood stands (mountain pine and contorta pine) primarily takes place in order to make space for new, more productive stands, typically of spruce, Scotch pine or broad-leaved trees (primarily oak). In addition, clear-cutting of certain older pine stands is done with the purpose of restoring heath or dune landscapes.

The sale of forest chips is an absolute prerequisite of carrying through the conversion in a financially justifiable way. Without market outlets for wood chips, the owner of the forest will have to pay for both the forest clearing and restocking of the area, and thus the price is higher than the estimated income of the new stand in the future. The sale of forest chips from a conversion can normally more or less pay for the clearing of the area so that the owner only has to pay for the restocking of the area with forest trees.

Clearing of Forest Residues

After clear-cutting of stands, large amounts of forest residues are left in the area, primarily tops from trees that have been harvested, but also branches and logs that have been cut off due to rot.

Normally it is necessary to clear the cultivation area for residues so as to facilitate restocking. Often residues are gathered and arranged in long rows. The rows can be used as skidrows along which vehicles can move later on in the life of the stand, but it takes at least 5-10 years for the rows to rot away so as to enable vehicles to pass along them.

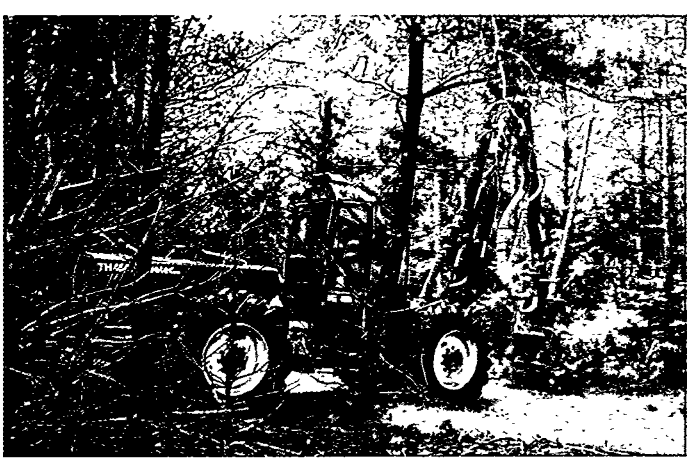
Research has proven that tops from clear-cuttings can be profitably chipped and used for fuel. Thus chipping contributes to the benefit of the harvesting, and often makes the clearing of the area unnecessary, since chipping removes a large proportion of the residues /ref. 32/.

The annual clear-cutting in Denmark amounts to approx. 2,500 ha of old spruce. With an estimated yield of the tops of approx. 40 m^3 l. vol per ha, approx. 100,000 m^3 l. vol of wood chips can be produced per year by the chipping of residues left after old spruce.

Harvesting of Forest Chips

The production of forest chips can be divided into several stages /ref. 33/:

photo: the danish land development service/dorte thomsen



The feller-buncher, which is a narrow off-road machine with a crane mounted saw felling head, fells the thinning trees and arranges them in rows, so that the chipper can subsequently chip them after drying for a couple of months.

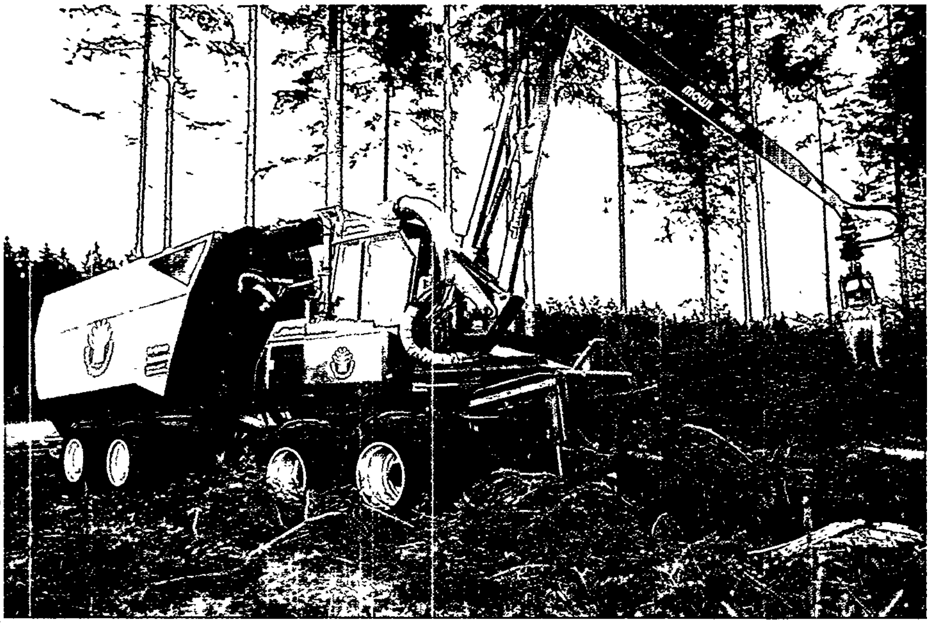


photo: søren fodgaard

Chipper in operation in a clear-cutting area in an old Norway spruce plantation at Gludsted Plantage. Residues consisting of tops are chipped. This ensures, among other things, a better passage when restocking the area with new forest trees.

- Felling for chipping.
- Chipping.
- Off-road hauling.
- Storage in the forest.
- Road transport.

Felling for Chipping

Felling for chipping is made in a way that ensures that the wood chips produced are as dry as possible. The moisture content of the trees is lowest from January-March, and the felling of trees for chipping should therefore take place in the first three months of the year. This may also limit the risk of stump infection by the decay fungus *Heterobasidion annosum* which can subsequently spread from the roots of the stumps to the remaining trees in the stand. The trees that have been felled are left in the area for the summer. This is done in order to achieve drying of the trees to a certain extent and in order to enable needles and small branches to detach before chipping. The moisture content in wood chips is thus reduced from 50-55% to approx. 35-45%, and the majority of the nutrients in the trees - actually contained in the needles and small branches - remains in the area.

By felling of the trees in the early part of the year for the purpose of chipping after the summer season, there is a certain risk of insect infestation in relation to softwood. In risk areas, the trees should be inspected frequently. If the insect infestation is too serious, the chipper can at relatively short notice be ordered to remove the trees that have been attacked. So far, no serious insect infestation of felled trees has been noticed in Denmark, because they are normally placed in the shade of the residual stand, resulting in poor living conditions for the insects.

Felling is performed by chain saw or by a feller-buncher. The feller-buncher is a special machine equipped with a crane mounted saw felling head. During thinning, the feller-buncher requires a track in order to travel in the stand. The establishing of skid rows normally takes place by manual chain saw felling. The material is dried over the summer and chipped one season before selective thinning takes place.

During the establishing of skid rows and during felling, it must be remembered that the chipper has limited movability on soft areas, when passing ditches or operating on steep slopes. Also chippers have large turning radii and require much space for entering skid rows. The feller-buncher dumps the trees in rows, butt ends in the same direction, enabling the chipper to easily take them by the crane and feed them into the chipper, while the machine simultaneously travels slowly forward.

During clear-cutting of old spruce stands, the felling is normally performed with chain saw or by means of harvesting machinery. During harvesting by a one grip harvester, the tops can be placed in the same direction in rows, after the processing of commercial timber, thereby making the chipping operation easier. Harvesting should also be planned, so that the greatest possible amount of tops are placed in the rows /ref. 32/. It is of great importance not to drive over the tops during the haulage of the commercial timber products, since it would result in an increased amount of broken material and an increase in the sand content.

Chipping

A chipper consists of a self-propelled basic machine with cabin, chipper and crane equipment mounted at the front part of the machine. At the rear end of the basic machine, a high-tipping container is mounted. There are both specialised machines designed for the purpose of chipping only and also large agricultural tractors equipped with a chipper and high-tipping trailer.

The chipper has an infeed opening with hydraulic rollers that push the logs into the chipper. The chippers have undergone a rapid development over the recent 20 years. Thus their productivity has been increased from approx. 80 m^3 l. vol of wood chips per day in 1980 to approx. 300-400 m^3 l. vol per day in 1998.

Chippers can be classified in three different categories: Disc chippers, drum chippers, and screw chippers. They differ only in their way of chipping. All chippers are equipped with a fan to blow the chips out of the chipper housing through the chute into the container. The screw chipper is not used in Denmark anymore.

The disc chipper consists of a heavy, rotating disc with rectangular holes in which chipper knives are mounted radially (Figure 6). Normally a disc chipper for fuel chips has 2-4 knives.

When rotating, the disc with the chipper knives pass the anvil, which is a fixed steel block, at short distance. The size of the wood chips can be controlled by varying the anvil and knife position from 12 to 35 mm.

The disc chipper is the most common type of chipper in Denmark. It produces a uniform quality wood chips and consumes less energy than a similar size drum chipper. The machine is suitable for chipping whole trees and logs, but less suitable for logging residues.

The drum chipper consists of a rotating drum, in the curving of which 2-4 longitudinal holes are situated equipped with knives (Figure 7). The drum chipper knives also pass a fixed anvil. The size of the wood chips can be controlled in the same way as described under the disc chipper, i.e., from 10 to 50 mm in fibre length.

There are only few drum chippers in Denmark. These machines are suitable for comminuting whole trees, logs, and residues. A drum chipper cuts over the whole knife width and is therefore less sensitive to sand and other pollutants than the disc chipper.

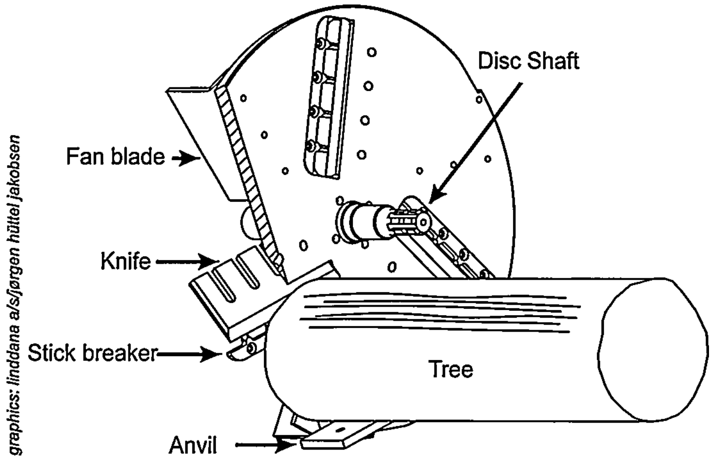


Figure 6: The disc chipper principle ensures that the wood chips are produced to a rather uniform size, since the entrance angle in relation to the fibre direction of the tree is the same irrespective of the thickness of the tree.

Off-Road Hauling

As the chipper is a very expensive machine, the work should to a high extent be arranged so as to comply with the requirements of the machine. It is usual to have a tractor with high-tipping trailer or a specialised forwarder following the chipper, thereby enabling it to continue chipping while the forwarder carries the wood chips to the roadside.

Storage in the Forest

The storage of wood chips forms an important part of the distribution of the fuel from forest to heating plant. It is necessary to store wood chips for several reasons:

- The consumption of wood chips varies heavily with the time of the year.
- There are periods when harvesting of wood chips is not possible.
- During the summer more wood chips are produced than consumed.

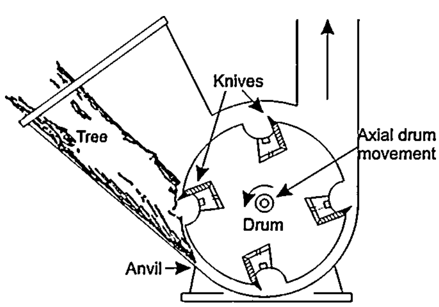


Figure 7: The drum chipper circular movements cause the knife entrance angle in relation to the tree fibre direction to change with the tree diameter. It therefore produces wood chips of a more non-uniform size than a disc chipper /ref. 34/.

Wood chips should preferably be produced as the need for it arises at the heating plant. However, storage cannot be avoided, as the forests have to meet larger demands for wood chips in cold periods and be capable of delivering wood chips even if stand conditions make working there impossible. Normally it is specified in the contract of supply, how large quantities of wood chips, the forest has undertaken to store during the heating season (normally 10-20% of the heating plant's annual consumption).

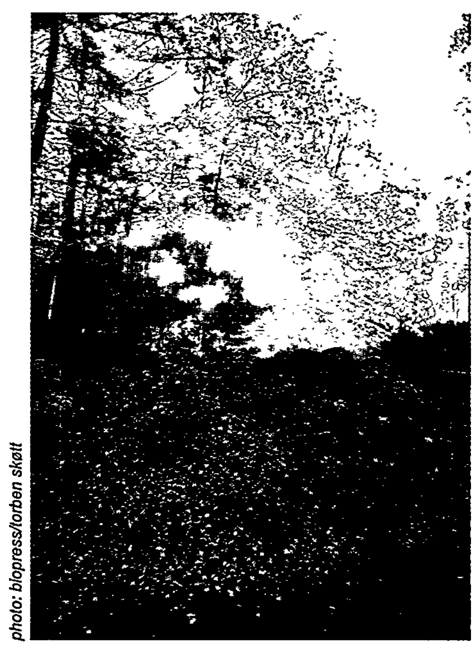
The storage site should be carefully selected /ref. 35/. The wood chip pile should first and foremost be placed close to an all-weather road that is capable of carrying trucks throughout the year. The road should be dry, since the pile would otherwise be splattered when vehicles pass. The pile should be located higher than the road, as water would otherwise percolate from the road into the wood chip pile. The ground under the pile should be level and free of stumps, large stones or residues. Wood chip piles should be made as large as possible, since it minimises the loss at the bottom of the pile. However, wood chip piles must not be higher than 7-8 metres, due to the risk of spontaneous combustion in piles.

Chips for storing should be as dry as possible and of the best possible quality. If the wood chips are to be stored for more than two weeks, the pile should be covered with tarpaulins. A certain drying takes place in the central part of a wood chip pile that has been covered with tarpaulins. The evaporated water condenses in the outer wood chip layers, which thereby become equally wetter.

If wood chips are stored with a view to reducing the moisture content, it should be stored under roof. Experiments have shown that storage under roof for 4-6 months may result in a reduction of the moisture content from approx. 45% to 25-30 % /ref. 36/. In the case of outdoor storage without tarpaulins, the wood chip moisture content will increase, whereas the overall moisture content of chips stored under tarpaulins remains constant.

Road Transport

Road transport of forest chips is normally performed by means of container trucks which with a container on the tractor and one on the trailer can transport approx. 80 m^3 l. vol at a time. If delivered at the



The pile of wood chips releases vapour due to the natural decomposition by fungi and bacteria. The decomposition breaks down the wood into carbon dioxide, water, and heat.

time of chipping, at least two containers, preferably more, should be placed in the forest. The containers are filled as the chips are produced, and the truck carries the wood chips to the heating plant or storage site concurrently. During loading from storage, it is normal to use a wheel loader for filling the containers. With an output of 30-50 m^3 l. vol per hour, a chipper can fill up two containers in 2-3 hours /ref. 37/.

photo: biopress/torben skøtt

Container being loaded with wood chips by means of a tractor equipped with a high-tipping trailer. The truck picks up the container subsequently in order to transport the wood chips to the heating plant.

Production of Wood Pellets

Wood pellets are normally produced from dry industrial wood waste, as e.g. shavings, sawdust and sander dust. Pulverised material is forced through a die under high pressure. The hole size of the die determines the diameter of the pellets and is generally between 8 and 12 mm. It is not necessary to use any agent for binding the particles together into pellets, but if an agent is added, this information must be included at sale and delivery. The pellets are cooled after pelletizing. Then they are screened in order to separate fines etc. from acceptable pellets, and finally they are stored either in bulk or in bags. Pellets are delivered by tipping trailer or by fodder wagon using a fan to load the pellets into a silo at the consumer's place.

If pellets are burnt as purify fuelwood, it should comply with the executive order concerning bio-waste /ref. 31/. This executive order sets out that wood pellets should not contain more than max.1% glue and no paint or any other products for surface treatment. If the pellets contain these substances, a waste tax (1999: DKK 350/tonne) shall be paid, and the pellets should not be burnt on plants that have not been approved for waste incineration.

Production Based on Wood Waste

Large amounts of wood waste are used for energy production (see Chapter 2.1). Wood waste may be recycled wood, e.g. demolition wood, which has been used for applications before being burnt, or it may be residues from the forest product industries in the form of by-products etc. The wood that often varies a lot in size is comminuted before burning. Wood waste falls under the provisions of the executive order on biomass waste mentioned above.

4. Purchase and Sale of Wood for Energy Production

In Denmark, there are many different wood fuels, e.g., firewood, wood chips, wood pellets, and wood briquettes, bark, sawdust and shavings. In the following chapter, the most common methods for the purchase and sale of these fuels will be described.

Firewood

Standard firewood is paid by the volume. There are many different volume indications for wood, but they all refer to principally different units:

- One cubic metre stacked volume including air equals the content of a cube (with six equal sides) of 1 × 1 × 1 m, exterior measure.
- One cubic metre solid volume equals the amount of solid wood containing exactly 1 m^3, e.g., a solid block of wood with length, height, and width being 1 m.

In Denmark firewood is sold primarily by the stacked cubic metre (a m^3 of sawn, split and stacked wood, a m^3 stacked volume of whole-tree wood, or a loose volume cubic metre) /ref. 38/.

A m^3 stacked volume of sawn, split, and stacked wood contains the most wood of the three units, but the volume of wood depends on the density of the stack and the size of the pieces. The larger the pieces are, the more wood is in the m^3 stacked volume.

A m^3 stacked volume of whole-tree is wood that is stacked in the forest after harvesting and shortening. It is often cut into two-meter pieces, but softwood also in lengths of one and three meters. It is typically wood that is delivered for the purpose of do-it-yourself cutting/splitting. There may be a lot of air in such a stack. If the pieces are long or crooked and perhaps stacked by crane, the wood content is small. A stack consisting of short pieces of large diameters contains more wood than if it consists of long, thin pieces.

Species	Kg dry matter per m^3	Compared to beech in %
Hornbeam	640	110
Beech/oak	580	100
Ash	570	98
Sycamore	540	93
Birch	510	88
Mount. pine	480	83
Spruce	390	67
Poplar	380	65

Table 5: The most common Danish wood species average content of dry wood per cubic metre solid mass /ref. 39/.

A loose volume cubic metre consists of wood that is not stacked, but just loaded into a cube of 1 × 1 × 1 m. This gives space for a lot of air, because the pieces are placed just anyhow. It is estimated that a loose volume cubic metre of firewood contains a solid mass amounting to between half and two thirds of a m^3 of sawn, split, and stacked wood.

When fixing the value of a stacked m^3 of firewood, regard should be taken to the degree of processing of the firewood, the tree species, and the solid mass or solid mass percentage.

The degree of processing describes whether the firewood is cut in appropriate lengths and split. All Danish tree species have more or less the same calorific value per kg dry matter, but with large variations in dry weight per volume unit (Table 5).

Solid mass or solid mass percentage indicates the amount of solid mass of wood in a m^3 stacked volume of firewood. If the solid mass factor for example is 0.65, then the solid mass percentage is 65, and both designate that one stacked m^3 of firewood contains 0.65 cu-

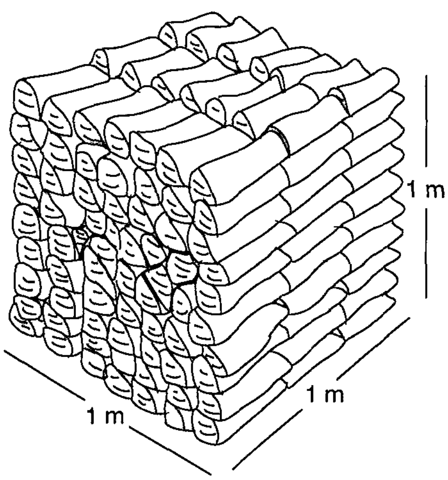


Figure 8: One cubic metre stacked volume of sawn, split, and stacked wood. The calorific value of a stacked m^3 of beech with a moisture content of 20% is 7.6-8.6 GJ.

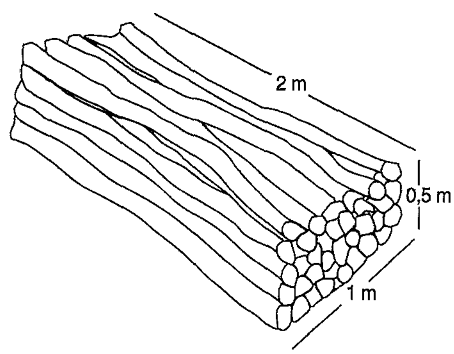


Figure 9: One cubic metre stacked volume of whole-tree wood. A m^3 stacked volume of beech consisting of 1-meter pieces contains 65% solid mass, while one m^3 stacked volume of 3-meter pieces contains 55% solid mass. The calorific value of one stacked m^3 of beech in 2-meter pieces with a moisture content of 20% is approx. 6.5 GJ.

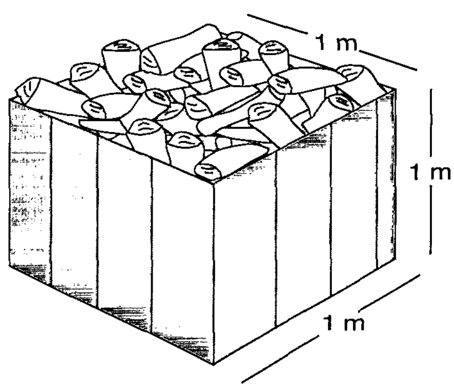


Figure 10: A loose volume cubic metre. For beech and spruce with a moisture content of 20% of the total weight, the solid mass content is 45%. The calorific value of a loose volume cubic metre of beech in 40 cm pieces with a moisture content of 20% is approx. 4.8 GJ.

bic metre of solid wood or 65% wood. The remaining part is air.

The solid mass varies a lot and the care with which the firewood has been stacked plays an important role. The tree species and lenghts of the firewood pieces also affect the solid mass, as illustrated by Table 6.

The wood content for the same solid mass figure is the same in a stacked m^3 of firewood irrespective of the moisture content. Thus, when purchasing and selling firewood, the moisture content is normally not taken into consideration. However, it is a prerequisite of firing with firewood in a wood stove that the firewood is dry. This means that the moisture content in percentage of the total weight should be below 20%.

Wood Chips

The sale of wood chips for firing requires a measurement of the wood chips for the purpose of fixing the price. However the price must depend on the quality and calorific value of the wood chips.

Quality

The quality of the wood chips depends on the size distribution, moisture content, and on impurities (soil, stone etc.). We often associate the quality of wood chips with its handling and burning properties. Thus a poor wood chip quality is often tantamount to difficult handling, i.e. disadvantageous properties of the chips as to angle of friction, angle of slide, and its propensity to bridging. The wood chip quality may also have an important influence on the combustion efficiency and on the content of harmful substances in smoke/flue gas and ash.

In 1987, the Danish Forestry Society published a standard for the determination of the quality of fuel chips as regards the size distribution of wood chips chipped in average lengths from 5 to 50 mm /ref. 26/. Time and technological advances in the field of firing technology have surpassed the standard, and it is now being revised (see Chapter 2.4).

Calorific Value

The number of heat units obtained either per weight or volume unit by the complete combustion of a unit mass of a fuel

photo: biopress/torben skøtt

Processing of fuelwood, ingeniously stacked in old-fashioned, round stacks improving drying.

is termed the calorific value. There are different calorific values: gross calorific value, net calorific value, and actual calorific value. The most commonly used calorific value in Denmark and the one that forms the basis of the sale and purchase of wood chips is the net calorific value.

Gross calorific value or, as it is also termed, the calorimetric value, is defined as the heat units developed by the complete combustion of a well-defined amount of wood fuel at constant pressure and with condensation of the original moisture content of the wood and the water vapour that is formed during combustion (approx. 0.5 kg water per kg dry matter). Unit: Often MJ per kg or GJ per tonne.

Net calorific value is defined as the units of heat produced by the complete combustion of a well-defined amount of wood fuel with the moisture content in the wood and the vapour that is formed during combustion (approx. 0.5 kg water per kg dry matter) being in a gaseous state. This means that the recovery of heat by condensing the vapour in the flue gas is not included. Unit: Often MJ per kg or GJ per tonne.

The amount of water always contained in wood fuel in practice, will be evaporated during the first stage of combustion. The energy for that is produced by the combustion of the wood. This means that the amount of energy that can actually be utilised is reduced. The influence of the moisture content on the calorific value can be calculated by the following formula:

$$H_{n,v} = H_n \left(\frac{100 - F}{100}\right) - \frac{2.442 \times F}{100}$$

where:

- $H_{n,v}$ is the net calorific value of wet wood (GJ per tonne total weight)

- H_n is the net calorific value of dry wood (GJ per tonne total weight)
- F is the moisture content in percentage of total weight
- 2.442 is the latent heat of evaporation of water at 25°C (GJ per tonne)

The following conditions should be taken into account where calorific values are stated /ref. 15/:

- Whether the calorific value in question is the: (1) gross calorific value, (2) net calorific value of kiln-dry wood, or (3) the net calorific value of wet wood.
- Pay attention to the fact that the term actual calorific value sometimes is used instead of net calorific value for wet wood.
- In the case of net calorific value, i.e., the calorific value with deduction of the condensed evaporation heat for the water vapour produced, the moisture content should be specified. Attention should be paid to whether the moisture content is stated on the basis of (1) total weight (F) or (2) dry matter (u). In foreign and some Danish literature, the symbols "F" and "u" are not necessarily used, but may be indicated by "w" instead of "F".
- In addition attention should be paid to whether the net calorific value at the given moisture content has been stated: (1) per dry matter weight, (2) per total weight, (3) per m^3 stacked volume or (4) per m^3 solid volume.

Forest Chip Payment

For most Danish chip-fired heating and CHP plants by far, the payment of forest chips is based on the energy content of the wood chips determined as the net calorific value per tonne total weight. In a few cases, there may be consignments that are paid per m^3 l. vol of wood chips. The net calorific value is calculated according to the above-mentioned formulae and can be converted to:

For forest chips of Scandinavian origin consisting of primarily pine, spruce and birch wood

$H_{n,v} = 19.2 - 0.2164 \times F$
(GJ per tonne total weight)

where F is the moisture content of the wood chips in percentage of the total weight of the wood chips.

Firewood length m	Solid mass in beech fuelwood	Solid mass in spruce fuelw.
0.40	0.70	0.80
1.00	0.65	0.75
2.00	0.60	0.70
3.00	0.55	0.65

Table 6: Figures for the solid mass contained in one m^3 stacked volume of beech and spruce firewood, respectively, stacked in different lengths /ref. 39/.

For mixed wood chips of various origin consisting primarily of hardwood of unknown mixture

$H_{n,v} = 19.0 - 0.2144 \times F$
(GJ per tonne total weight)

where F is the moisture content of the wood chips in percentage of the total weight of the wood chips.

The calculation of the value of a truckload of wood chips requires knowledge of the weight of the load and the moisture content. The weight of the load is determined by a weighbridge as the gross weight of the loaded vehicle minus the weight of the vehicle itself. The difference shows the total weight of the load, i.e. the content of dry matter + water of the load.

In practice, the moisture content of the load is determined by taking representative samples totalling 5-10 litres with a bucket at 3-5 places in the pile after unloading. Then the samples are mixed thoroughly, and one sample of approx. 3 litres is taken for the determination of the average moisture content in the load. The moisture content is normally expressed in percentages of the total weight in the following way:

- The sample is weighed after sampling.
- The sample is dried in a drying cabinet at 105 °C to constant weight. In practice, the drying of three litres of wood chips distributed in a tray in a ventilated drying cabinet to constant weight takes 16 hours.

	Dry matter calorific value in GJ/tonne
Pure wood	19.5
Forest chips	19.2
Bark	18.0
Wood pellets	19.0

Table 7: Net calorific value of different forms of biomass /ref. 40/.

$$\text{Water content} = \frac{\text{fresh weight - kiln-dry weight}}{\text{fresh weight}} \times 100\%$$

- The difference in weight between the fresh sample and the dried sample expressed in percentage shows the moisture content in percentage (F) of the total weight.

Calorific Value of Load
The calorific value of the load in GJ per tonne total weight is determined by using one of the two above-mentioned formulae for the net calorific value ($H_{n,v}$). Then the weight of the load in tonne total is multiplied with the number of GJ per tonne and with the price agreed per GJ (e.g. in 1998 DKK 35 per GJ). Figure 11 illustrates the net calorific value (total weight-basis) in GJ per tonne as a function of the moisture content in percentage of the total weight.

Calculation example for softwood forest chips:

- Moisture content in wood chips: 55% of total weight
- Weight of load: 15 tonnes
- Energy price (1998): DKK 35.00/GJ
- Wood chip calorific value $H_{n,v}$: 19.2 GJ/tonne - (0.2164 × 55) = 7.30 GJ/tonne
- Wood chip energy content: 15 tonnes × 7.30 GJ/tonne = 109.50 GJ
- Wood chip price: DKK 35.00/GJ × 109.50 GJ = DKK 3,832.50

The Danish method that has been used since 1980 is simple and easy to use in practice, and there have only been minor problems in practical use. The method can be simplified if it has to do with a large number of truckloads from the same supplier. If so, the number of wood chip samples for the determination of the moisture content in the loads can be reduced. Deviations from the official sampling method can be agreed by the parties upon entering into the contract. It can also be agreed who is to take the samples.

Wood Pellets and Wood Briquettes

Of those two categories of fuel, the amount of wood pellets is the largest by far. Pellets are used in district heating plants and have the advantageous property that they can be used in boilers designed for coal-firing without any difficulties. In addition to being used at district heating plants, wood pellets are very popular as a fuel in single-family houses where they typically replace oil and electrical power for heating purposes. Wood pellets and wood briquettes are sold per kg total weight. The moisture content is so small (5-10% of the total weight) and uniform that it is almost superfluous to decide the moisture content in the individual supply. So far, Denmark has no standard or norm for the determination of the quality of the pellets, but the law stipulates limits beyond which impurities should not be found in wood pellets /ref. 31/.

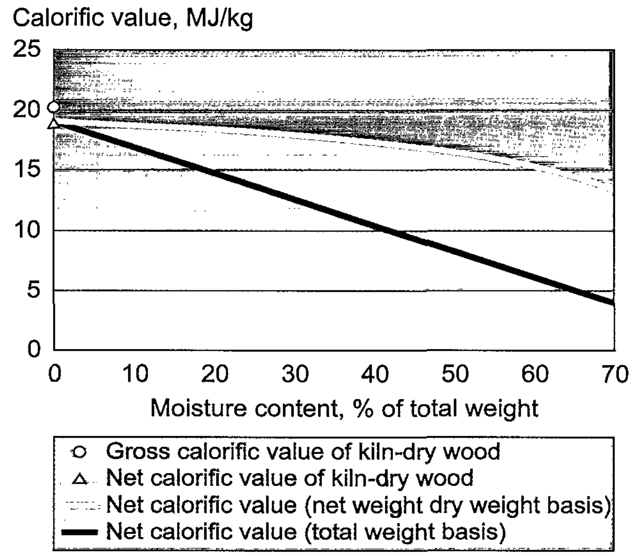


Figure 11: Gross and net calorific values of wood without bark as a function of the moisture content in percentage of total weight /ref. 15/.

Bark

Danish bark is used to a great extent for firing purposes at district heating plants, and the payment is calculated in the same way as for fuel chips. This means that the weight of the load and its moisture content is determined, and the payment is per GJ. Since bark is often of poorer quality than wood chips, the price per GJ is often lower than for wood chips.

Sawdust and Shavings

Sawdust and shavings can be paid in the same way as bark and wood chips, i.e. by payment according to energy content, determined by the total weight of the fuel and its moisture content. However, with dry fuel with a moisture content below 10-15 % of the total weight, it will often only be necessary to weigh the truckload and then agree on a price per tonne total irrespective of minor variation in the almost dry material.

5. Environmental Issues During the Production and Handling of Wood Fuels

5.1 Chipping and Sustainable Forestry

It is clearly advantageous to the environment to use wood fuels, but at the same time chipping involves an increased use of the forest ecosystem compared to conventional timber harvesting, since a greater part of the biomass is thereby removed. This use may perhaps affect the stability and growth of forests in a long term, thereby creating the need for fertilisation.

An increased utilisation of the forest ecosystem by chipping of thinning trees and logging residues may have consequences connected with the following two aspects, in particular:

- Chipping increases the removal of plant nutrients from the area, since a major proportion of the nutrient-rich parts (needles, branches, and bark) are removed.
- A great proportion of organic material is removed, which may reduce the humus content of the soil and thereby its capability to support wood production.

In order to avoid these effects, it is necessary to balance the utilisation with the yielding capacity of the soil or, e.g. to return the wood chip ash to the forest in order to compensate for the loss of nutrients.

Plant Nutrients

Historicaly, the exhaustion of the forests is well-known. In certain German forest areas, a considerable soil depletion can still be demonstrated due to the utilisation of limbwood, branches, and leaves for fuel and animal feed in the past century.

The major part of the nutrients is bound in the active parts of the tree (needles and bark) that make out a rather small proportion of the biomass. An exception is calcium of which the wood also contains a considerable amount. Figure 12 illustrates an example of the distribution of biomass and of the most important nutrients. Thus the removal of nutrients by chipping depends to a high extent on the parts of biomass that are removed. The max. removal occurs by whole-tree harvesting of green chips (chips with needles and branches). This increases (for the example illustrated in Figure 12) the yield - 8% needles and 13% branches (including a great proportion of bark) - but by this increase in yield, 68% of the nitrogen amount of the trees, 72% of the phosphorus amount, 58% of the potassium amount, and 50% of the calcium amount are removed.

The absolutely predominant part of the Danish harvesting of wood chips is obtained by thinnings in immature stands. In practice, the thinning trees are felled during the winter (in order to reduce the danger of stump infection by fungus *H. annosum*) and hence dry at the place of felling for four to six months. By this method, the following is achieved:

- Evaporation of approx. 50% of the moisture content of the trees.
- Shedding of needles and a number of thin branches before the trees are fed into the chipper.

Danish practice therefore reduces the amount of plant nutrients removed compared to the chipping of green trees. This has been calculated in the example illustrated by Table 8 in relation to the most commonly used practice of chipping of the first two thinnings. The removal of the largest amount of nutrients occurs in connection with stems and bark by conventional thinning and particularly by clear-cutting. Whole-tree chipping following predrying of the two thinnings increases the removal by approx. 4% and 26% respectively depending on nutrient, while whole-tree chipping of green wood will increase it 2-3 times from 12% to 48% (Table 8).

The removal of nutrients during the entire rotation should be viewed in relation to the capability of the area to supplement these nutrients by the weathering of soil minerals or in the form of fallout. On very nutrient-poor soil, conventional logging of stems removes more nutrients than is applied, thereby exhausting the soil little by little resulting in a state of nutrient deficiency. However, on the basis of the present knowledge, it is not possible to point out these areas. Stands close to the coast will be less exposed, since these areas are currently supplied with nutrients in sea salt being carried over the country by storms.

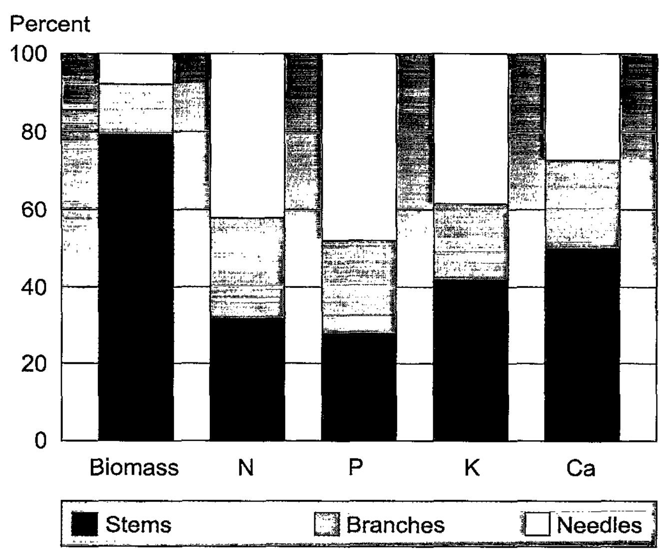


Figure 12: The distribution of biomass on needles, branches, and stems, and the relative content of plant nutrients of the same parts of wood for spruce /ref. 41/.

A range of experiments has been laid out in the Scandinavian countries with the purpose of clarifying the consequences of increased removal of biofuels from the forests. The experiments have not yet proven any effect on the growth after whole-tree utilisation of the first thinnings. This may be due to the fact that the experiments have existed for a too short period of time (10-15 years) in relation to the normal stand life (up to 100 years). A few experiments in Sweden have proven a reduction in growth, though, but this could be referred to an increased nitrogen deficiency after whole-tree utilisation. This will most probably not be experienced in Denmark, where the nitrogen deposition from the atmosphere is capable of covering the nitrogen requirement of the trees.

The ash from the combustion of wood chips contains more or less the amount of nutrients being removed from the stand by chipping (with the exception, though, of nitrogen). It is therefore obvious to solve the nutrient problem by returning the wood chip ash to the forest.

The amount of ash that is produced by the combustion of wood is often expressed in percentage of the dry weight of the wood (0% water). Here, pure wood ash should be distinguished from crude ash. By pure wood ash is understood the pure ash without a content of sand, unburned wood, or other substances. By crude ash is understood the pure ash plus the inevitable content of other substances.

On average, the pure ash content is estimated at 2.5% by the combustion of whole-tree chips. The amount of crude ash varies a lot, but the crude ash content is estimated at 5% by the combustion of whole-tree chips /ref. 27/. Table 9 illustrates the estimated average amounts of plant nutrients in kg per tonne of dry crude ash.

Wood ash contains small amounts of heavy metals, e.g. cadmium 0-0.08 g/kg dry ash and lead 0.02-0.6 g/kg dry ash. The content of such matter may be problematic in connection with the recycling of the ash for forest and field applications. So far, the application of wood chip ash in forests has been controlled by the Executive Order on Waste Products for Soil Application /ref. 31/, but at the time of writing (the beginning of 1999), the Ministry of Environment and Energy is preparing an "Executive Order on Ash from Gasification and the Combustion of Biomass and Biowaste for Soil Applications". This executive order is expected to offer better opportunities for a reasonable and environmentally desirable application of the biomass ash (see Chapter 8).

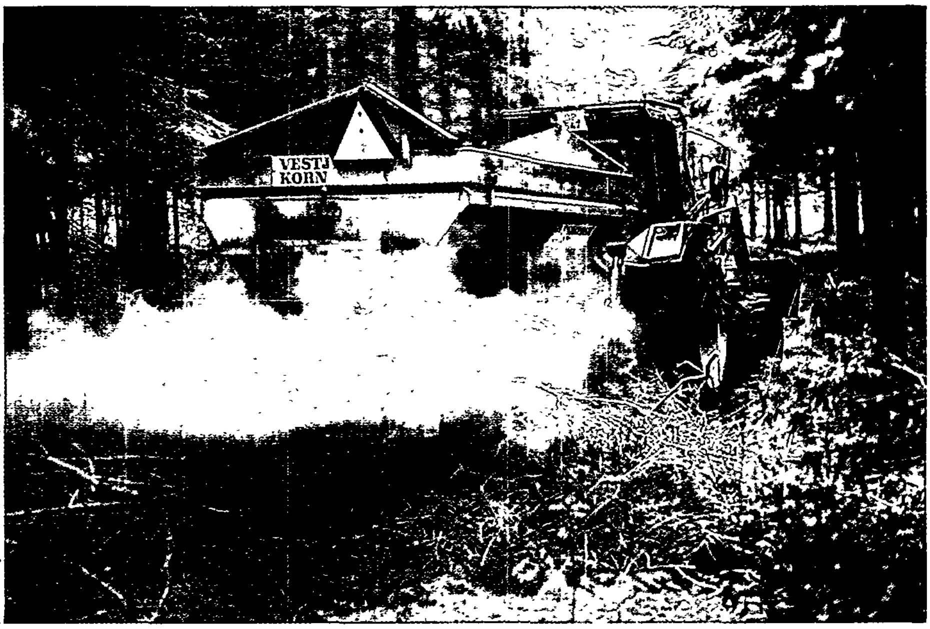


photo: thy statsskovdistrikt/per kynde.

An amount of approx. 2 tonnes of dry ash is spread per ha (which equals approx. 3 tonnes of wet ash) after second or third thinning when the trees are 30-40 years old. The nutrients that have been removed from the stand with the chips are returned by the ash.

Humus Content

By whole-tree chips produced from whole, predried trees, more wood is removed from the stand than by means of well-known, conventional harvesting of delimbed roundwood. This means that fewer branches and tops are left on the forest floor for natural decomposition. Dead, organic matter contains the flora and fauna involved in decomposition. Whether or not chipping thus contributes to reducing the biodiversity in the forests is a highly debated issue which at present is uninvestigated.

Another issue that is debated for the time being is the embedment of carbon in the soil content of stable humus matter (humus formation). Any stand of trees produces a continuous stream of dead, biological material ending on the forest floor. It may be leaves, needles, branches, twigs, dead trees etc. By conventional harvesting of delimbed roundwood, branches and tops are left on the forest floor, but by whole-tree chipping, a larger proportion of the total biomass production of the stand is removed. However, by normal Danish chipping primarily taking place in connection with the two first thinnings in the stands, only a small extra proportion of wood is removed from the stand compared to roundwood logging.

Removal of nutrients (kg/ha)	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Magnesium (Mg)	Calcium (Ca)
1. Stems	170	54	205	23	234
2. Chipping with predrying	214	58	213	26	259
3. Chipping of green trees	252	61	230	30	294
Increased removal of nut. (% of 1) by					
2. Chipping with predrying	26	7	4	13	11
3. Green trees	48	13	12	30	26

Table 8: Total removal of nutrients (kg/ha) over a rotation of 70 years by different chipping strategies for the two first thinnings in spruce stands at Gludsted Plantage /ref. 42/.

The major part of the dead, organic matter is mineralised, i.e. it is decomposed into plant nutrients, carbon dioxide, and water, while a minor proportion, of varying and unknown size, enters into the soil content of permanent humus matter. The proportion and importance of this entering is being currently debated and investigated, but at present, there are no measurements so as to shed light on whether or not chipping reduces the soil content of permanent humus matter, and whether it is of any importance to the growth and health of the trees.

Sustainable Utilisation

Harvesting of whole trees during the first and second thinnings normally results in a modest drain on nutrients, but if the trees are drying in the stands for six months before chipping, there should most probably be nothing to be concerned about. Clear-cut purifying by chipping of logging residues often substitutes a normal purifying by burning of the logging waste. If the logging residues dry for at least a summer before chipping, there should be no immediate risk of nutrient loss by chipping. In both cases, attention should be paid to the need for supplementary fertiliser.

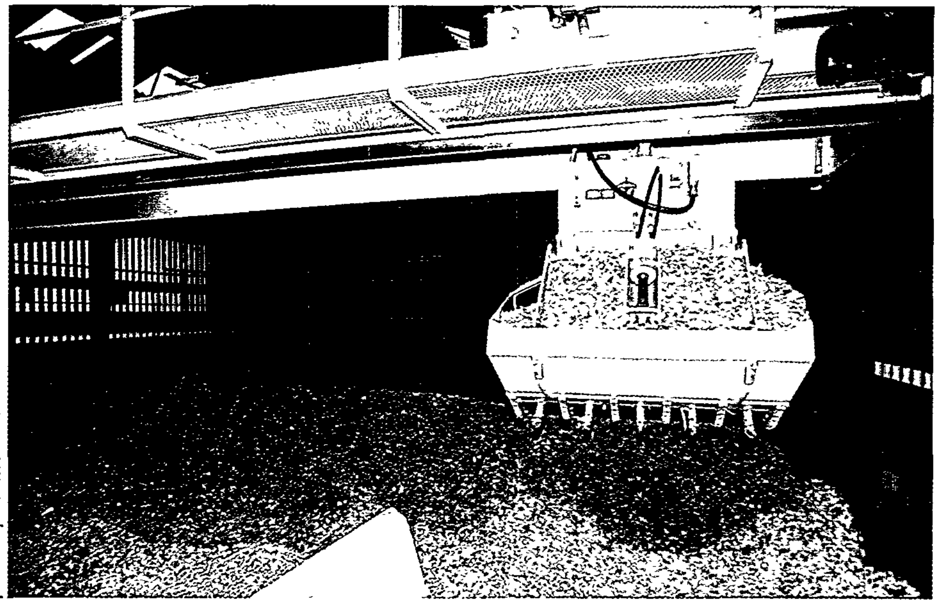


photo: biopress/torben skøtt

Wood chip storage with crane for the feeding of the wood chip boiler furnace at Harboøre. The crane can be automatically controlled and monitored from a screened control room.

5.2 Working Environment During the Handling of Chips and Pellets

The handling of biofuels, as e.g. wood chips, may cause working environment problems especially in relation to dust and micro organisms, such as fungi and bacteria. With regard to wood chips, especially the propagation of fungi and bacteria in stored wood chips may be problematic, while dust is considered the greatest risk factor involved in the handling of wood pellets.

Health Problems

Health problems in connection with the handling of biofuels typically occur when small particles are breathed in with the air passing through the throat to the lungs. Dust, fungal spores, and bacteria, are generally the size of 1-5 μm i.e. 1-5 thousandth mm. They are easily whirled up and may be suspended in the air for a long time. Besides the direct irritation of the mucous membranes and lung tissue, many fungal spores and bacteria cause allergy.

The typical symptoms are respiratory trouble, colds, fever, shivers, cough, headache, muscle pain, pain in the joints, stomach trouble, loss of weight, and general malaise and tiredness. Disease caused by breathing in bacteria and fungal spores may be either acute or chronic.

Acute Disease

The acute disease is often termed ODTS or "organic dust toxic syndrome". This disease typically occurs when exposed to a high concentration of spores and/or dust in the air, often amounting to 9-10 million particles per litre of air or more. By way of comparison, it may be mentioned that air normally contains 10-30,000 spores per litre /ref. 43/. The ODTS is characterised by symptoms like those of influenza, such as fever, shivers, muscle pain, pain in the joints, perhaps accompanied by cough and slight difficulty in breathing. The symptoms often occur 4-8 hours after exposure and they seldom last longer than 1-3 days. The disease does not require treatment and does not cause permanent injury, but repeated exposures should be avoided. The reasons are both the unpleasant symptoms and sickness absence suffered by the victim, and also the risk of developing a chronic disease /ref. 44, 45/.

Phosphorus (P)	13 kg
Potassium (K)	48 kg
Calcium (Ca)	137 kg
Magnesium (Mg)	17 kg
Iron (Fe)	12 kg
Sodium (Na)	20 kg
Manganese (Mn)	13 kg

Table 9: The content of plant nutrients in kg per tonne of dry crude ash /ref. 27/.

Chronic Disease

The chronic bronchial problems are normally named after the connection in which they originally occurred, i.e. thresher lung. The international name of the chronic disease is "allergic alveolitis" (AA), i.e. an allergic reaction in the lung tissue. This does normally not occur before having been exposed to air with an average content of fungal spores or bacteria, generally at least 2-3 million micro-organisms per litre of air for a prolonged period of time. Among the most important symptoms of AA are respiratory trouble, cough, fever, and loss of weight, perhaps accompanied by a combination of the other symptoms. As with ODTS, the symptoms do not occur until

6-8 hours after exposure. The disease often develops insidiously, and it gradually becomes a chronic disease that is aggravated if the person is again exposed to fungal spores and bacteria /ref. 46, 44/.

The chronic disease is very rare and probably requires a predisposition in the victim. When occurring, however, the consequences are rather serious. This is due to both the permanent injuries of the lungs and that AA often causes a higher sensitivity to micro-organisms in the air /ref. 46/. The symptoms and illness may then occur at lower spore concentrations than those originally causing the disease. Persons with allergic alveolitis may thus be forced to find a new job that does not involve the risk of being exposed to spores. Allergic alveolitis must be reported to The National Board of Industrial Injuries.

Hazardous Working Processes

If wood chips are used shortly after chipping, problems with micro-organisms will seldom occur. The storage of wood chips in the forest or at heating plants will normally be in the form of uncovered chip piles, in the forest also covered with tarpaulins or plastic. It is wood chips from such storages that may cause working environment problems due to bacteria and fungal spores.

Wood pellets consist of shavings and sawdust in compressed form. Dust problems are assumed to be associated with the handling of wood pellets, but the issue has not been further investigated. Anyhow, a range of working situations involving the risk of problems in connection with dust and micro-organisms can be pointed out in relation to both wood chips and wood pellets.

- During the moving of chip storages in forests and at heating plants, a tractor or tractor loader may often be used. As the wood chips are lifted, spores and bacteria are whirled up in the air. Without an enclosed cabin, the driver will be exposed to micro-organisms in the air. The same applies to the unloading of wood chips.
- When wood chips arrive at the heating plant, samples are taken for the determination of the moisture content. Sampling is done by a shovel by which the chips are taken out from the loaded or unloaded pile. The person taking out the samples is exposed to micro-organisms in the air.
- The indoor wood chip storage is no doubt the place with most dust and most micro-organisms in the air. The feeding of wood chips into the heating system is normally performed by means of an automatic crane, and the process can be monitored from outside. Staying in the wood chip storage takes place only in connection with repair work or the solution of other problems. Persons who are staying in the wood chip storage are therefore highly exposed to the risk of breathing in large amounts of particles if not protected.
- In small wood chip heating systems, the feeding system of the furnace is often manual, and wood chips are moved from the intermediate storage by tractor or manually. Persons who perform this work frequently run a certain risk of being exposed to pathogenic amounts of dust and micro-organisms. Locating wood chip storages in connection with dwellings should definitely be avoided.
- If wood chips are stored in silos, ensilage processes may occur, thereby using up the oxygen of the air so that nitrous gases are formed.
- For wood pellets, dust problems may be expected during unloading, moving, and during the loading of the wood pellets into the heating system.

Countermeasures

If wood chips have been stored (for a long time) under conditions encouraging the growth of fungi and bacteria, the persons handling the chips should be protected. This applies to both storage in the forest and at the consumer's place. The same applies if wood pellets cause dust problems.

The first step is to find the places and work situations involving elements of risk. The scope of the problem may perhaps be assessed by means of a spore trapping test. Wood chips undergoing a heavy attack by mould fungi often discharge a "mouldy" odour. The next step is to distinguish between the long-time effect of moderate to high spore levels and the effect of a large amount of spores for a short period of time.

Where the constant presence of suspended dust and harmful micro-organisms in the air may be expected, working processes should be automated so as to be performed or controlled from screened areas. The indoor storage with a crane feeding the heating system is probably the most important place to isolate from employees at the heating plant. To accomplish this task, monitoring takes place from enclosed areas in which the air pressure is kept slightly above the atmospheric standard. Alternatively, the air from the wood chip storage may bee drawn into the boiler furnace, thereby creating a slight negative pressure.

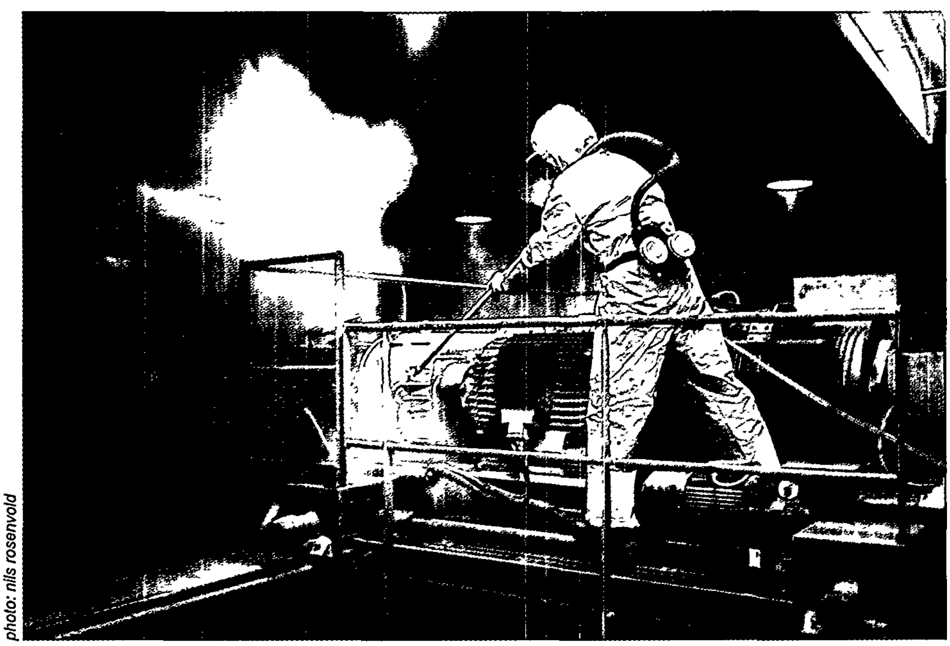


photo: nils rosenvold

Worker at Måbjergværket wearing P3 filter respirator for toxic particles during the purifying of machinery.

Shielding is not possible in practice during sampling for the determination of moisture content or during unloading. In these instances, the persons involved should be equipped with a personal respiratory protection equipment. Truck drivers who frequently transport wood chips should be informed about the problem.

In relation to chip-fired plants, it is of great importance to inform about the problem of dust and micro-organisms. Already during installation, the subject should be in focus in order for the boiler and the storage to be located appropriately in an extension, and so that the manual handling will be reduced. The ventilation system should be designed so as to drive spores out of areas, frequented by the operators during day-to-day work. A course instructing in how to use individual protection equipment would be useful.

Crane repair work in indoor storage is an example of a task during the performance of which the person is staying for a short period of time in an area with high dust and spore concentrations. Persons involved should be equipped with a P3 filter respirator for toxic particles. This equipment is typically portable, i.e. with filter and fan attached to a belt. Persons who often work in polluted environments, or who are hypersensitive, should be equipped with a breathing apparatus with fresh air supply. These consist of a unit with a compressor at a fixed place in the building and an air supply hose that can be connected at different places. During working in silos with wood chips, a breathing apparatus and a life line should be used /ref. 47/.

As individual protection equipment typically is unpleasant to wear, it should only be used during short-time exposures. Protection equipment is no solution to a constant level of pollutants, such as dust and spores. In that respect, measures should be taken in the form of changes in working conditions and ventilation.

6. Theory of Wood Firing

Efficient and complete combustion is a prerequisite of utilising wood as an environmentally desirable fuel. In addition to a high rate of energy utilisation, the combustion process should therefore ensure the complete destruction of the wood and avoid the formation of environmentally undesirable compounds.

In order for combustion to continue, there are certain basic conditions to be complied with /ref. 48/.

- An adequate mixture of fuel and oxygen (air) in a controlled ratio should be ensured.
- The fire already started in the boiler furnace should transfer some of its heat to the infeed in order to ensure a continuous combustion process.

It is important to understand that gases burn like flames, that solid particles glow, and that during the combustion of wood, approx. 80% of the energy is released in the form of gas and the remaining part from the charcoal.

During mixing of the fuel and air, it is important to achieve good contact between the oxygen of the air and the combustible constituents of the wood. The better the contact is, the faster and more complete is the combustion. If the fuel is in the form of gas, such as natural gas, the mixing is optimal, since we have two gaseous substances that can be mixed to exactly the desired ratio. The combustion may then occur rapidly, and thus the control is fast too, since we can introduce more or less fuel. In order to achieve approximately the same situation with wood, it may be necessary to pulverise the wood to very small particle size (like that of flour). These fine particles will follow the movements of the air. A good mixture can thus be achieved with a combustion resembling a gas or oil flame. The production of wood powder is very expensive, though, and therefore wood powder is only used to a limited extent in Denmark. In practice, fuel is therefore marketed in sizes varying from wood chips to logs.

Firing technology for wood and other solid fuels is thus difficult and more complicated than for example the firing technology in a natural gas or oil-fired heating system.

Stages of Combustion

In order for combustion to occur, the fuel must pass through three stages, which are shown in Figure 13.

- Drying
- Gasification and combustion
- Charcoal burnout

When wood is heated, water begins evaporating from the surface of the wood. Hence two things occur: Gasification occurs at the wood surface - pyrolysis (the heating of a fuel without the introduction of gasification medium, i.e. oxygen and water, is termed pyrolysis) - and the temperature deeper inside the wood will increase resulting in evaporation of moisture from the interior of the wood. As the water evaporates and is passed away, the area that is pyrolysed spreads into the wood.

The gas thus produced is ignited above the fuel and transfers heat to the ongoing evaporation and pyrolysis. The combustion process is continuous. The gasified wood becomes glowing charcoal, transformed by oxygen, until only ash is left.

Fuel Size

The larger the fuel particle is, the longer is the combustion process. Imagine a handful of sawdust quickly burning if it is thrown into a hot fire. There is a good contact between fuel and air, since the small particles quickly dry, give off gases and burn, resulting in a high combustion intensity.

If instead you throw a log into a hot fire, it will take a long time before it is burnt out. It can be compared to a roast that is put in the oven. Although it has roasted for an hour in the oven, it is still raw in the middle. The size of the fuel, therefore, is of great importance to the speed of combustion.

Moisture Content

The moisture content in fuel reduces the energy content expressed by the calorific value, $H_{n,v}$ (see Chapter 4), since part of the energy will be used for evaporation of the water. Dry wood has a high calorific value, and the heat from the combustion should be drawn away from the combustion chamber in order to prevent overheating and consequent damage to material. Wet wood has a low calorific value per kg total weight, and the combustion chamber should be insulated so as to

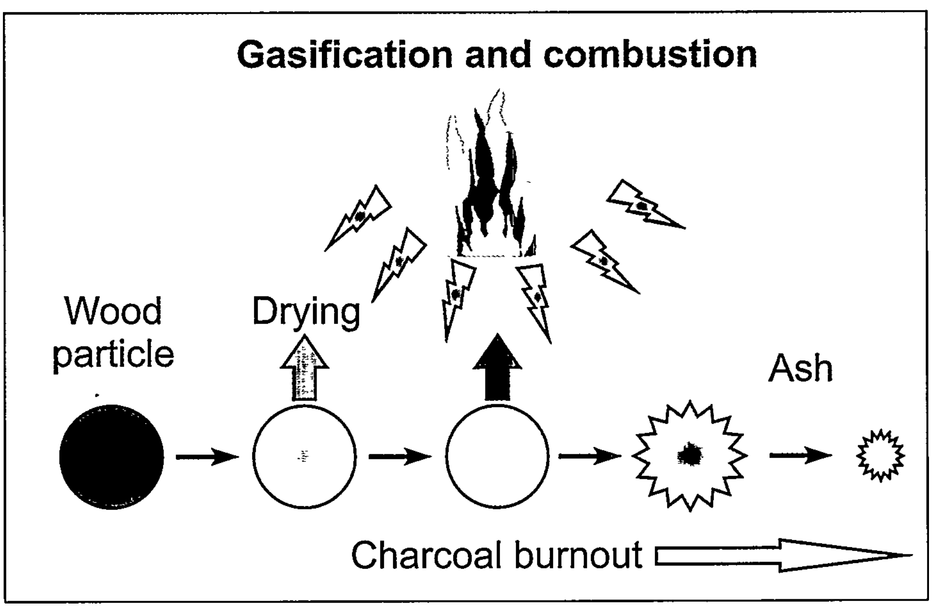


Figure 13. A wood particle combustion route. The green wood particle undergoes drying and gasification, thereby producing flames. The particle burns out and ends as an ash particle /ref. 49/.

avoid reduction in boiler efficiency and enable a continuous combustion process. This is typically accomplished by using refractory linings round the walls of the chamber so as to conserve the heat which is generated. The boiler chamber will therefore normally be designed for burning wood within a certain moisture interval.

A moisture content in wood above 55-60% of the total weight will make it very difficult to maintain the combustion process.

Ash Content

The fuel contains various impurities in the form of incombustible component parts - ash. Ash itself is undesirable, since it requires purifying of the flue gas for particles with a subsequent ash and slag disposal as the result. The ash contained in wood comes primarily from soil and sand absorbed in the bark. A minor proportion also comes from salts absorbed during the period of growth of the tree.

The ash also contains heavy metals, causing an undesirable environmental effect, but the content of heavy metals is normally lower than in other solid fuels.

A special characteristic of ash is its heat conservation property. For wood stoves, the ash layer at the bottom of the stove forms a heating surface, transferring heat to the final burnout of the char. For heating systems using a grate, the ash content is important in order to protect the grate against heat from the flames.

Wood also contains salts that are of importance to the combustion process. It is primarily potassium (K) and partly sodium (Na), based salts resulting in sticky ash which may cause deposits in the boiler unit. The Na and K content in wood is normally so low that it will not cause problems with traditional heating technologies.

	% of DM
Potassium (K)	0.1
Sodium (Na)	0.015
Phosphurus (P)	0.02
Calcium (Ca)	0.2
Magnesium (Mg)	0.04

Table 11: Typical mineral fractions in wood chips expressed in percentage of the dry matter (DM) of the wood. Compared to straw, the K content in wood chips is approx. 10 times lower /ref. 50, 51/.

		Wood chips	Straw (wheat)	Variation according to spec.		
				Beech	Pine	Spruce
Carbon	C % of DM	50	47.4	49.3	51	50.9
Hydrogen	H % of DM	6.2	6	5.8	6.1	5.8
Oxygen	O % of DM	43	40	43.9	42.3	41.3
Nitrogen	N % of DM	0.3	0.6	0.22	0.1	0.39
Sulphur	S % of DM	0.05	0.12	0.04	0.02	0.06
Chlorine	Cl % of DM	0.02	0.4	0.01	0.01	0.03
Ash	a % of DM	1	4.8	0.7	0.5	1.5
Volatiles	% of DM	81	81	83.8	81.8	80
Actual calorific value	MJ/kg DM	19.4	17.9	18.7	19.4	19.7
Typical content	%	35-45	10-15			
Actual calorific value	MJ/kg	9.7-11.7	14.8-15.8			

Table 10: Fuel data for wood chips and a comparison with straw. Note that the elements of dry matter (DM) in the wood vary both with species and the conditions of growth. As an example, Table 10 illustrates the variation between beech, pine wood, and spruce. For wood chips the bark fraction contains approx. 6% ash and the wood fraction only approx. 0.25% ash /ref. 50, 51/.

Volatiles

Wood and other types of biomass contain approx. 80% volatiles (in percentage of dry matter). This means that the component part of wood will give up 80% of its weight in the form of gases, while the remaining part will be turned into charcoal. This is one reason why a sack of charcoal seems light compared to the visual volume. The charcoal has more or less kept the original volume of the green wood, but has lost 80% of its weight.

The high content of volatiles means that the combustion air should generally be introduced above the fuel bed (secondary air), where the gases are burnt, and not under the fuel bed (primary air).

Excess Air

A given fuel requires a given amount of air (oxygen) in order to be converted stoichiometrically, i.e. the amount of excess air λ (lambda) should be equal to 1. The fuel is converted stoichiometrically when the exact amount of oxygen that is required for the conversion of all of the fuel under ideal conditions is present. If more oxygen is introduced than an amount corresponding to λ is equal to 1, oxygen will be present in the flue gas. At, e.g. λ is equal to 2, twice as much air is introduced as necessary for the combustion of the fuel.

In practice, combustion will always take place at an excess air figure higher than 1, since it is not possible to achieve complete combustion at a stoichiometric amount of air. In Table 12, the typical excess air figures are shown together with the corresponding, resulting oxygen percentage in the flue gas.

As shown in Table 12, the excess air figure depends to a high extent on the heating technology and to some extent on the fuel.

Environment

The fuel has an influence on the combustion efficiency. At complete combus-

	Excess air ratio λ	O_2, dry (%)
Fireplace open	>3	>14
Wood stove	2.1-2.3	11-12
District heating forest chips	1.4-1.6	6-8
District heating wood pellets	1.2-1.3	4-5
CHP wood powder	1.1-1.2	2-3

Table 12: Typical excess air figures, λ, and the resulting oxygen content in the flue gas /ref. 23/.

tion, carbon dioxide (CO_2) and water (H_2O) are formed. An incorrect mixture of fuel, type of heating system, and introduction of air may result in an unsatisfactory utilisation of the fuel and a consequent undesirable environmental effect.

An efficient combustion requires sufficient:

- High temperature
- Excess oxygen
- Combustion time
- Mixture

This ensures a low emission of carbon monoxide (CO), hydrocarbons, polyaromatic hydrocarbons (PAH), and a small amount of unburned carbon in the slag. Unfortunately, these conditions (high temperature, a high amount of excess air, long combustion time) are also directly related to the formation of NO_x. The technology applied should therefore be a so-called "low-NO_x" technology, i.e., a technology applying methods resulting in a reduced NO_x emission.

In addition to CO_2 and H_2O, the flue gas will contain air (O_2 , N_2 and Ar) and a high or low amount of undesirable reaction products, such as CO, hydrocarbons, PAH, NO_x etc.

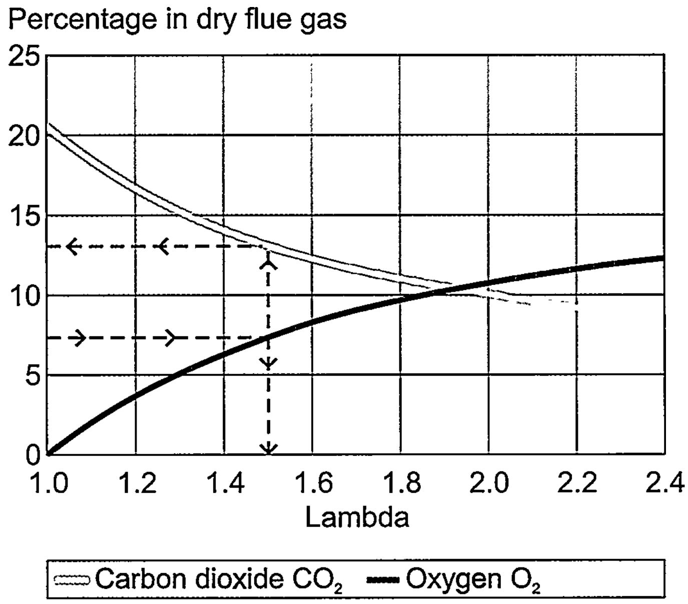


Figure 14: Ideal combustion of wood takes place at an excess air figure λ between 1.4 and 1.6. The oxygen percentage in the flue gas will thus be 7.5%. The curve illustrates that the carbon dioxide percentage is approx. 13% and the excess air 1.5.

7. Small Boilers

The present number of small boilers for solid fuel in Denmark is approx. 80,000 of which approx. 70,000 are fired with firewood, wood chips, or wood pellets. In addition to that, there are approx. 300,000 wood stoves. Since the introduction of the state-subsidised scheme for approved boilers for solid fuels in 1995, more than 8,000 subsidised systems have been installed. In addition to that, 3,000-4,000 systems have been installed without subsidies. Approx. 30% of the new installations are manually fired boilers for fuelwood with storage tank. The efficiency of many of the old boilers is insufficient and emissions too high. Thus it would be advantageous to replace them by new approved boilers.

Destinctions should be made between manually fired boilers for fuelwood and automatically fired boilers for wood chips and wood pellets. Manually fired boilers should be installed with storage tank so as to accumulate the heat energy from one infeed of fuel (a full magazine). Automatic boilers are equipped with a silo containing wood pellets or wood chips. A screw feeder feeds the fuel simultaneously with the output demand of the dwelling.

Great advances have been made over the recent 10 years for both boiler types in respect of higher efficiency and reduced emission from the chimney (dust and carbon monoxide (CO)). Improvements have been achieved particularly in respect of the design of combustion chamber, combustion air supply, and the automatics controlling the process of combustion. In the field of manually fired boilers, an increase in the efficiency has been achieved from below 50% to 75-90%. For the automatically fired boilers, an increase in the efficiency from 60% to 85-92% has been achieved.

Nominal output

The boiler nominal output (at full load) can be calculated on the basis of the known annual consumption of oil or the floor space and age of the dwelling (and insulation).

Manually Fired Boilers

The principal rule is that manually fired boilers for fuelwood only have an acceptable combustion at the boiler rated output (at full load). At individual plants with oxygen control, the load can, however, be reduced to approx. 50% of the nominal output without thereby influencing neither the efficiency nor emissions to any appreciable extent. By oxygen control, a lambda probe measures the oxygen content in the flue gas, and the automatic boiler control varies the combustion air inlet. The same system is used in cars. In order for the boiler not to need feeding at intervals of 2-4 hours a day, during the coldest periods of the year, the fuelwood boiler nominal output is selected so as to be up to 2-3 times the output demand of the dwelling. This means that the boiler efficiency figures shown in Figure 15 and 16 should be multiplied by 2 or 3 in the case of manually fired boilers.

Boilers designed for fuelwood should always be equipped with storage tank. This ensures both the greatest comfort for the user and the least financial and environmental strain. In case of no storage tank, an increased corrosion of the boiler is often seen due to variations in water and flue gas temperatures, and in addition to that, the manufacturer

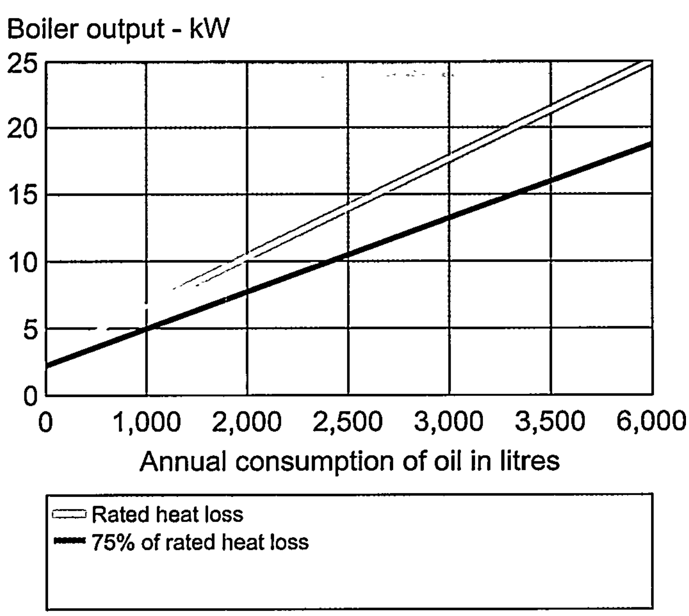


Figure 15: Boiler nominal output based on an annual consumption of oil in a relatively new, well-insulated dwelling. Output for hot water and loss (2 kW) included. If an oil-fired furnace is also installed, it will be sufficient to, install a boiler for 75% of the output demand in the case of automatic boilers. Thereby a more stable operation is achieved during the summer /ref.52/.

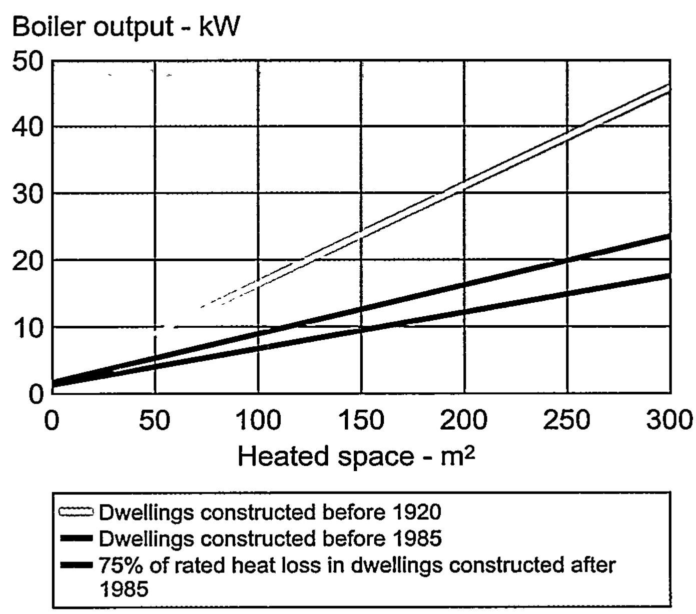


Figure 16: Boiler nominal output based on the age of the dwelling and floor space to be heated. If a relatively old dwelling is re-insulated, an estimated reduction in the boiler nominal output should be made. As shown in Figure 15, an oil-fired furnace may be installed /ref. 52/.

warranty may also lapse. The size of the storage tank can be determined on the basis of Figure 18.

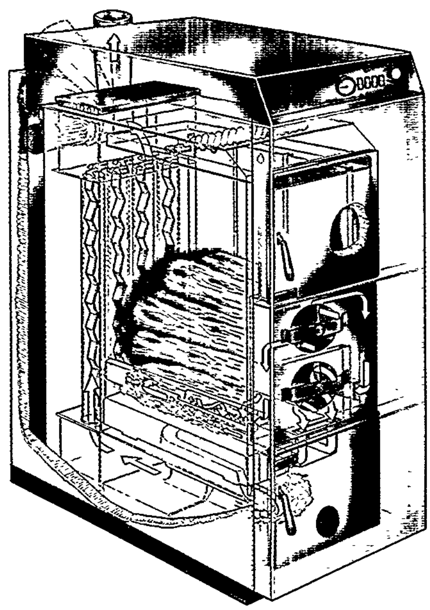
Automatically Fired Boilers

Despite an often simple construction, most of the automatically fired boilers can achieve an efficiency of 80-90% and a CO emission of approx. 100 ppm (100 ppm = 0.01 volume %) . For some boilers, the figures are 92% and 20 ppm, respectively. An important condition for achieving these good results is that the boiler efficiency during day-to-day operation is close to full load.

For automatic boilers, it is of great importance that the boiler nominal output (at full load) does not exceed the max. output demand in winter periods. In the transition periods (3-5 months) spring and autumn, the output demand of the dwelling will typically be approx. 20-40% of the boiler nominal output, which means a deteriorated operating result. During the summer period, the output demand of the dwelling will often be in the range of 1-3 kW, since only the hot water supply will be maintained. This equals 5 -10% of the boiler nominal output. This operating method reduces the efficiency - typically 20-30% lower than that of the nominal output - and an increased negative effect on the environment. The alternative to the deteriorated summer operating is to combine the installation with a storage tank, oil-fired furnace, electrical power heated hot water supply or solar heat.

Type Testing of Small Biofuel Boilers

So far, there has been no tradition in Denmark for systematic type testing of heating systems for solid fuels - apart from boilers for straw that have been type tested at Research Centre Bygholm, Horsens, in connection with previous subsidy schemes. The market for small heating systems has been uncontrolled, i.e. so far there have been no statutory requirements in respect of type testing of energy, environmental, or safety properties. The only statutory requirements are safety requirements laid down in the Directory of Labour Inspection Publication No. 42 /ref. 53/, dealing with safety systems for fired hot-water systems, and in Brandteknisk vejledning nr. 32 /ref. 54/, dealing with fire protection of equipment and boiler room.



graphics: hs boilers - term a/s

Figure 17: "X-ray" of manually fired boiler. The magazine is almost half full of fuelwood, and the combustion is in the form of downdraft combustion, i.e., the burning gases pass down through a lined chamber, where the combustion is completed. The combustion air is introduced through inlets in the gate and is preheated. The flue gases move backwards and pass the tubes (the convection unit). The tubes are equipped with spirals so as to increase the amount of heat being given off to the boiler water. An exhaust fan at the back of the boiler ensures a correct negative pressure in the combustion chamber.

With the introduction of the subsidy schemes for small biofuel boilers in 1995, type testing immediately became of great interest to the manufacturers. This is due to the Danish Energy Agency requiring as a precondition for granting subsidies a type approval of the boiler in order for it to comply with a wide range of requirements in respect of low emissions and high energy utilisation. The type testing was carried out at the Test Laboratory for Small Biofuel Boilers in accordance with test directions setting out in detail the guidelines for testing, and the requirements to be met in order to achieve a type approval. The directions are drafted on the basis of recommendations for a joint European standard for solid fuel systems. However, the requirements in respect of efficiency and emissions have been made more rigorous and grouped according to firing technology (manual or automatic) and fuel type (straw or wood). The requirements are established in a joint collaboration between the manufacturers of biofuel boilers, the Test Laboratory for Small Biofuel Boilers, the Danish Energy Agency, and the Danish Environmental Protection Agency /ref. 55/.

The type testing can be carried out on the basis of various fuels, e.g.: Fuelwood, straw, wood pellets, wood chips, cereals, or sawdust/shavings. The type approval only applies to the fuel that was used during the testing. The scheme applies to automatic boilers up to 250 kW

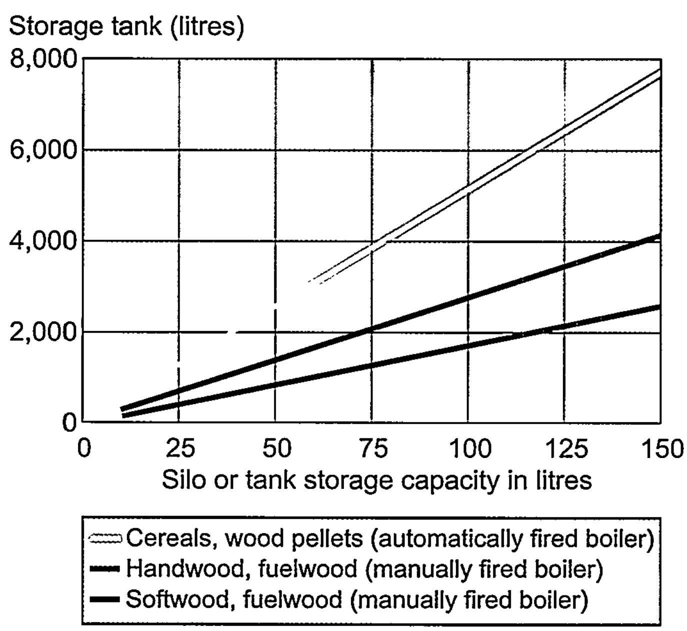


Figure 18: When knowing the boiler magazine size (i.e. the unit of the boiler that is filled with fuelwood), the necessary size of the storage tank can be determined /ref. 52/.

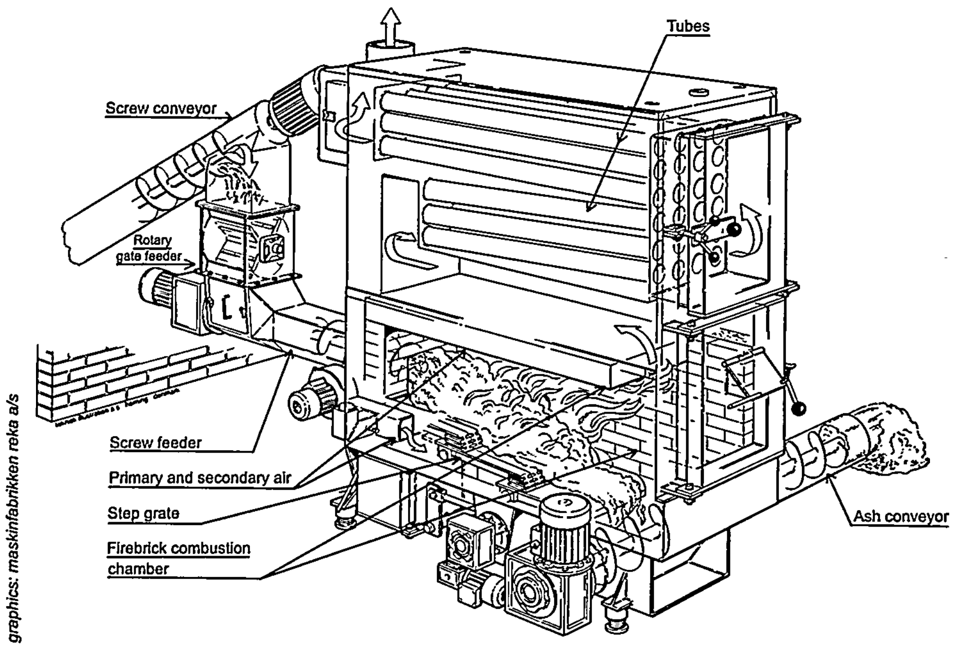


Figure 19: Automatic chip-fired system. The chips are loaded onto a conveyor and screw feeder from the silo, then pass onto the grate, where the combustion takes place. The movements of the grate push the ash towards the ash chute and further out with the ash conveyor. The flue gases are cooled by passing through the tubes that are surrounded by boiler water.

and for manually fired (batch-fired) boilers up to 400 kW. By raising the level to 400 kW, a reasonable combustion time is achieved for big bales for boiler systems for farms. A list of type-approved systems is published approx. 5 times per year /ref. 56/.

The values for CO emission, dust emission, and efficiency are determined during the type testing as the mean value over 2 x 6 hours at nominal output. The nominal output should be stated by the manufacturer and is an expression of the boiler optimal output with the efficiency being high and emissions low.

In addition to testing at nominal output, type testing also includes testing at low load, which is max. 30% of the nominal output. The requirements in respect of dust emissions and CO-emission are listed in Table 13, while the efficiency should at least be such as listed in Figure 20.

Other important requirements are:

- Securing against backfire/burn-back in magazine (e.g. mechanical damper or by sprinkling with water).
- Max. allowable surface temperatures.
- Leakage tightness so as to prevent flue gas penetrating into the room.
- Documentation, e.g. technical information, operating and installation manual etc.

The subsidy scheme applies to biofuel boilers that are installed in areas without district heating supply. The subsidy percentage is calculated on the basis of the testing result, and the amount of money is calculated in proportion to the consumer's expenses for boiler plant and installations. The subsidy scheme is administered by the Danish Energy Agency.

Experiences and Future Developmental Requirements

Since the introduction and implementation of systematic type testing in 1995, a wide range of experiences has been acquired from small heating systems. It was obvious at the beginning that many manufacturers were marketing heating systems, whose output exceeded by far the heat demand of ordinary dwellings. This resulted in an obvious disparity between the actual demand of the consumers and the supply of heat by the heating systems with an output of less than 20 kW. The situation has changed since then, and the greater number of manufacturers by far now offer systems with outputs in the range of 10-20 kW, or are developing new systems. The small systems are often designed for wood pellets or perhaps for cereals.

There is still a need for improvements of boiler efficiencies. Several concepts are being developed at present, e.g.:

- Improvements of the boiler convection unit so as to reduce the flue gas temperature from the present 250-300 °C to 150-200 °C.
- Improvements of the lining (for wet fuels) and the design of air nozzles so as to keep constant the excess air and CO, contained in the flue gas thus at the same time contributing to reduce dust emissions. Note that dust emis-

Fuel	Feeding	CO emission at 10% O_2, 30% load	CO emission at 10% O_2 nominal output	Dust emission at 10% O_2 (mg/nm³)
Fuelwood, pellets, shavings/powder, chips, cereals	Manual	0.50 %	0.50 %	300
Fuelwood, pellets, shavings/powder, chips, cereals	Automatic	0.15 %	0.10 %	300
Straw	Manual	0.80 %	0.80 %	600
Straw	Automatic	0.40 %	0.30 %	600

Table 13: Max. allowable CO emission and dust emission at nominal output and low load during type testing.

sions do not always depend on the combustion. Variations in fuel quality may result in variations in emissions.

- Improvements of the boiler control equipment so as to ensure an environmentally desirable and energy efficient optimal operation at the same time as being highly user-friendly requiring only minimal weekly attendance. Note that several boilers have advanced controls with several output options, and sometimes also oxygen control which to a high extent can handle the variations in consumption in a typical central heating installation. The Danish Energy Agency is funding a research and development project aiming at developing an inexpensive, universal oxygen control unit that can be adapted to the majority of small boilers on the market.
- Improvements of the low-load properties so as to maintain an acceptable operation during the summer period.

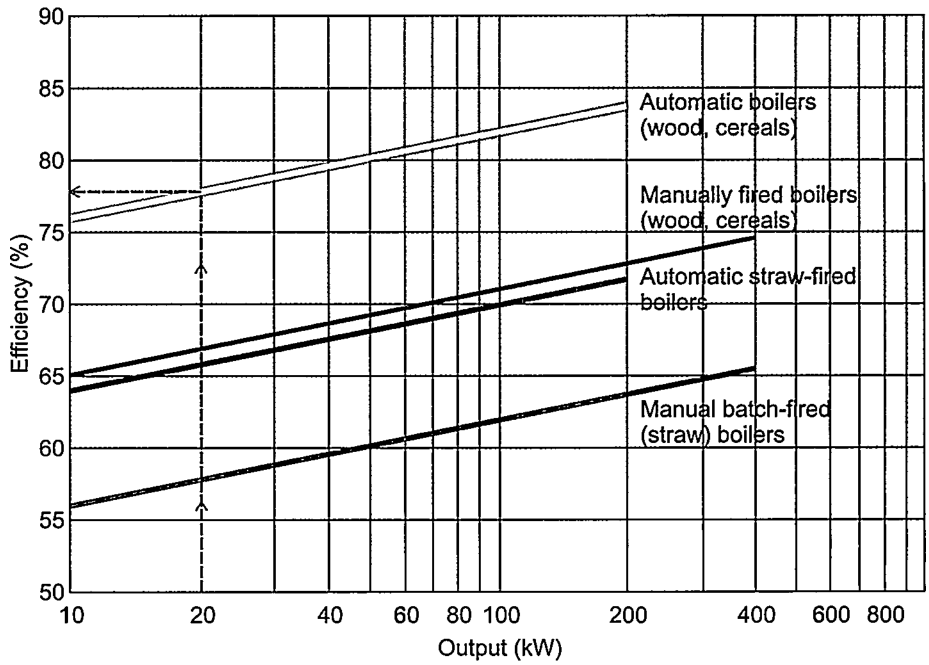


Figure 20: Minimum efficiencies depending on the type of system. An automatic 20 kW system for wood should have an efficiency of at least 77.5% in order to be type approved.

8. District Heating Plants

The term district heating plants refers to plants with own generation of heat, but without power generation. The heat is distributed to a district heating system to which all consumers living within the system have the opportunity of being connected.

The use of forest chips at district heating plants has increased significantly since the first systems came into operation at the beginning of the 1980s. While there were only three wood chip-fired district heating plants in 1984, the number has increased to approx. 50 plants today. The consumption of wood chips in the same period has increased to approx. 725,000 m^3 l. vol per year which is equal to an amount of energy of approx. 1,800 TJ. At the end of the publication, there is a list of wood chip-fired district heating plants in Denmark.

Seen in an international perspective, the use of wood chips at district heating plants has increased tremendously during a relative short period of time. Only in few other countries, such as Sweden, Finland, and Austria, has the use of wood chips at district heating plants increased more than in Denmark.

Wood chip-fired district heating plants are established either in order to replace oil- or coal-fired district heating plants, connected to old district heating systems, or as new plants and systems (the so-called "urbanisation" projects). Wood chip-fired boilers at Danish district heating plants are designed for the generation of heat in the range of 1 MW and 10 MW; the average being 3.5 MW.

Subsidies are granted under the State-Subsidised Promotion of Decentralised Combined Heat and Power and Utilisation of Biomass Fuels Act /ref. 57/. It is obvious that this is financially beneficial to these projects, and it is assumed that the subsidy scheme is of great importance to the continuos enlargement of the district heating supply based on biomass. "Urbanisation" projects are started from scratch. The heating plant, the district heating system and the consumer service installations thus all have to be established. These plants require a considerable total investment and have typically been implemented in small communities, wherefore wood chip-fired boilers used here are smaller than the average of 3.5 MW mentioned above.

About 7 to 9 manufacturers in Denmark are making turn-key wood chip-fired district heating systems. In addition a large number of manufacturers are supplying small systems for farms and institutions or parts of systems (see List of Manufacturers).

The biomass technology has recently received increased interest by trade compagnies and industries. This is due to the fact that the compagnies no longer can deduct energy and environmental taxes on indoor heating. Trade and industry are also offered the opportunity of being granted subsidies from the Danish Energy Agency for investments in installations which may reduce emissions of e.g. CO_2 /ref. 58, 59/.

Choice of System Size

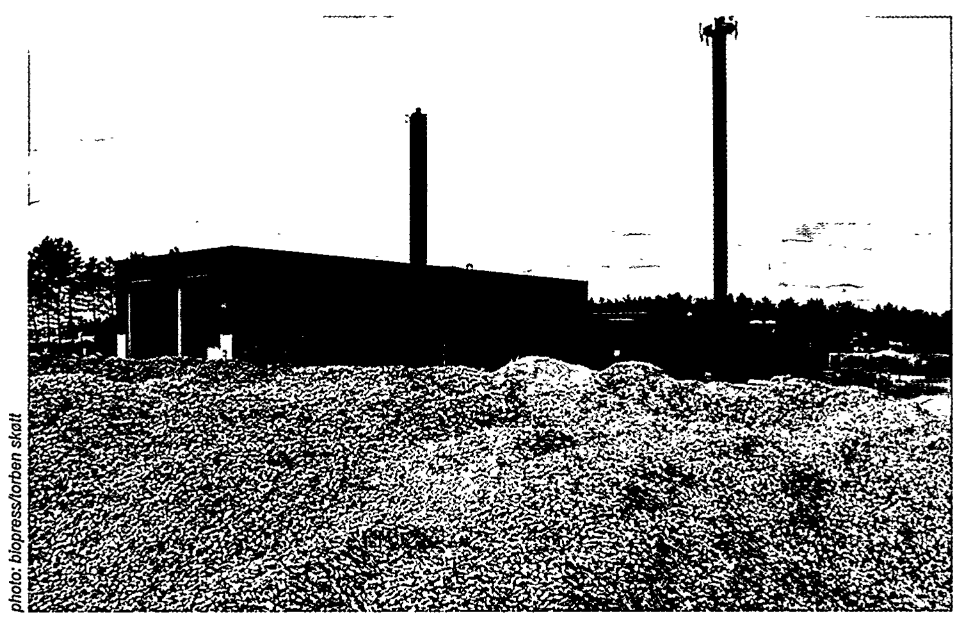
When deciding the size of a new chip-fired system at a district heating plant, it is necessary to know the annual heating demand of the district heating system. It is also necessary to know the changes in the heating demand of the district heating system per day and per year.

/Ref. 60/ describes how to decide the boiler size in relation to the heating demand of the district heating system. The method is the same for straw and wood chip plants, so the example in /ref. 60/ can be transferred directly to wood chip-fired heating plants.

It is important for new district heating plants, in particular, to pay attention to the distribution loss. In Danish District Heating Association's statistics from 1995/96, information is given on distribution losses for 19 wood chip-fired heating plants. The average distribution loss in that period was 26% with the highest distribution loss being 36% and the lowest being 19%. There were approx. 3,300 degree days in 1995/96. When correcting to a normal year, the average distribution loss of the 19 plants is approx. 28%.

Plant Technology

The typical wood chip plant is constructed around a solid fuel boiler with step grate or travelling grate. The boiler has refractory linings round the walls of the chamber in order to ensure the combustion temperature despite the relatively wet fuel. The plant designs are highly automated so that e.g. the feeding system of wood chips from the storage onto the grate is carried out by means of a computer controlled crane that simultaneously keeps track of the storage.



When a district heating plant has its own outdoor storage as in Ebeltoft, it seems as if the forest has entered the town. There are advantages in relation to management and economy, but it requires adequate distance to neighbours.

All the systems have the same main components:

- Wood chip storage
- Crane or other chip handling
- Feeding system
- Combustion chamber and boiler
- Flue gas purifying
- Flue gas condensation
- Chimney
- Handling of ash

The following describes the main principles of the technique that is typically used at wood chip-fired district heating plants.

Wood Chip Storage

The size of the fuel storage depends on various factors, e.g. the contract made with the fuel supplier. However, a storage of wood chips that equals the consumption of minimum 5 days and nights at max. heat production should always be available for the purposes of operation during week-ends and for security of supply during extreme weather conditions.

Most plants settle for an indoor storage and leave the handling of larger storages to the suppliers of wood chips. However, a few plants also have an outdoor storage of their own and may therefore receive a discount from the supplier of wood chips. Due to the risk of spontaneous fire, the wood chips are piled to a height of max. 7-8 metres, and this also applies to indoor storages. Wood chip storages are discussed in Chapter 3.

During work in the wood chip storage, there may be a risk of breathing in allergy-causing dust and micro-organisms, such as fungi and bacteria. It must be strongly recommended never to work alone in wood chip silos. Working environment issues are also discussed in Chapter 5.2.

Handling of Fuel

The majority of operating problems experienced is no doubt caused by the plant system for transport of wood chips from storage to the feeding system. The entire transport system from storage to boiler should be viewed as a chain in which the reliability of operation of the individual links is equally important. The entire district heating plant stops in case of a "missing link" in the transport chain, e.g. a defective crane wire.

Wheel Loader

At plants with outdoor storage, it is normal to use a wheel loader with a large shovel for the transport of wood chips to the indoor wood chip storage.

Crane Transport

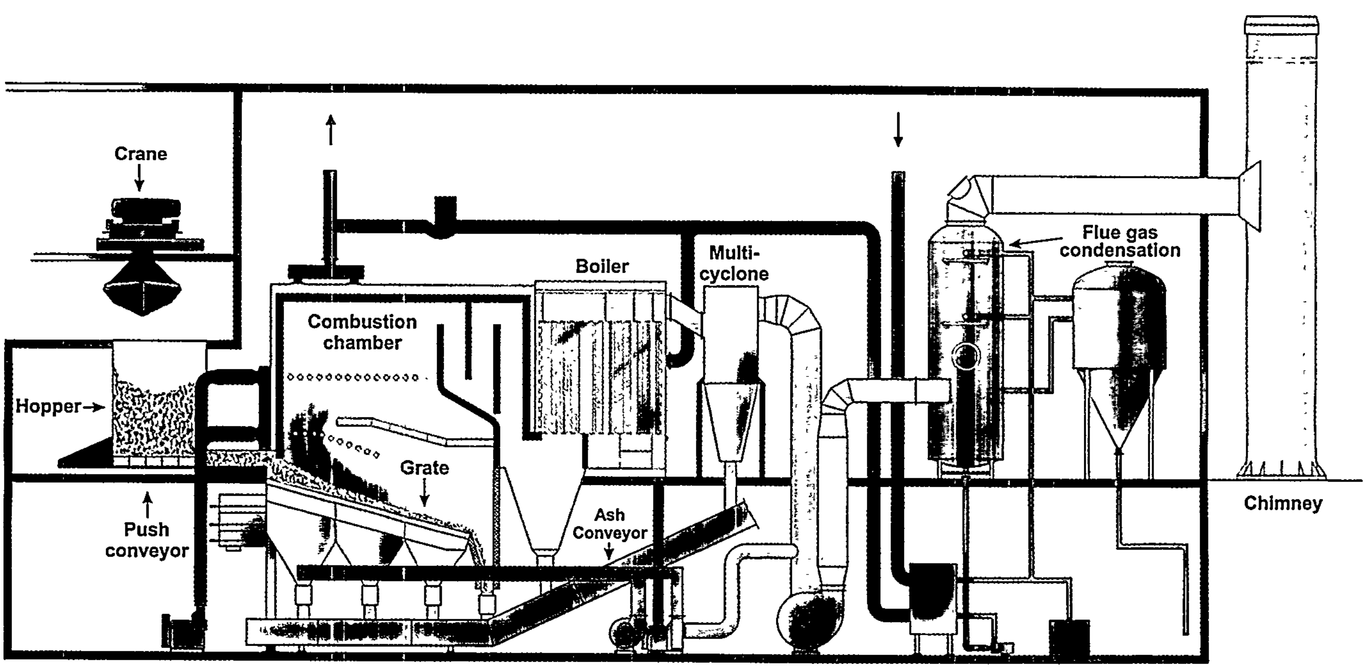
Between the indoor wood chip storage and boiler feeding system, a crane is often used for the transport of wood chips. The crane is flexible, has a high capacity, and is also the transport equipment that best tolerates a poor wood chip quality. However, it is important for the crane shovel to be toothed. If not toothed, it is difficult to fill and it easily turns over on top of the pile. For relatively large plants, the crane is also relatively inexpensive, while it is a too expensive solution for very small systems.

Hydraulic Push Conveyor

The hydraulic push conveyor is used for unloading rectangular silos with level floors. It is normally not as technically reliable as the crane solution. The hydraulic push conveyor is relatively inexpensive and is therefore particularly suitable for small systems (0.1-1 MW boiler nominal output).

Tower Silos

Tower silos with rotating screw conveyor should not be used for wood chips. The silo is time-consuming to fill due to the great tower height, and the mechanical parts in the silo bottom are not very accessible for the purposes of maintenance and repair work. Technical problems nor-



graphics: volund systems a/s

Figure 21: In Thyborøn the district heating is supplied by a 4 MW chip-fired boiler. The system flue gas condenser produces an additional 0.8 MW heat at 50% moisture contained in the wood chips.

photo: dk-teknik/henrik houmann jakobsen

Mist eliminator in brilliant blue and insulating jackets with glittering surfaces situated on the flue gas condenser. The boiler room at Græsted Varmeværk being demonstrated to a foreign visitor look like a "sittingroom".

mally arise when the silo is full of wood chips. Before starting any repair work, it must be emptied - manually or preferably with crane grab. For storage of wood pellets, the equipment used in animal feed industry is normally suitable.

Screw Conveyors
Conveyors are inexpensive, but vulnerable to foreign matter and slivers. In general, screw conveyors with bolted-on top are recommended instead of conveyors enclosed in tubes. The recommendation is easily understood after just one experience of manually emptying of a tube conveyor blocked by slivers or foreign matter. Similarly, it may be considered erroneous projecting if screw conveyors are embedded in concrete floors or otherwise located so that repair work and replacement of parts are impossible. Like other mechanical conveyors, screw conveyors should be considered a part prone to wearing and must be easily accessible for maintenance work.

Correctly dimensioned, screw conveyors are an acceptable solution at small plants (0.1-1 MW boiler nominal output). But unless hardened steel is used, normal wear and tear will result in a relatively short life of the screw conveyor. Screw conveyors are seldom used as transport equipment at large district heating plants.

Belt Conveyors
Belt conveyors are rather insensitive to foreign matter. At this point, they are better than screw conveyors, but unless equipped with barriers, the belt conveyor cannot manage as high inclinations as the screw conveyor. High price and dust emissions (which may necessitate covering) are the major drawbacks of the belt conveyor.

Pneumatic Conveyors
In general, wood chips are not suitable for transport in pneumatic systems. If wood chips are available in a particularly uniform size, however, transport by pneumatic conveyors may be a possibility, but the energy consumption of pneumatic conveyors is great.

Feeding Systems

There are several types of feeding systems for wood chip-fired boilers. The choice of feeding system depends on the size of the plant and whether the use of other solid fuels than wood chips is desired.

Hydraulic Feeding System
Many plants use this quite reliable feeding system. Wood chips fall from a hopper into a horizontal, square box, from where hydraulic feeding devices force wood chips on to the grate. The construction of the system is of decisive importance to its reliability. If correctly designed as most often seen today, it is among the best feeding systems for wood chips.

Stoking
Small systems (0.1-1 MW boiler nominal output) often have screw stokers feeding the boiler. At some plants, the screw stoker is positioned across the longitudinal direction of the grate. This gives a good distribution of the fuel over the width of the grate.

Grate with Feed Hopper
Some wood chip plants have a simple hopper that feeds the wood chips on to the grate. The system is known from coal-fired boilers with travelling grate and requires that the height of the wood chips in the hopper will be high enough so as to function as an airtight plug between the feeding system and the boiler. The problem of the blocking of the hopper can be remedied by an appropriate design of the hopper, and as a last resort by mechanical stirring/scraping systems.

Spreader Stoker
Wood chips are thrown into the combustion chamber by a rotating drum in a spreader stoker. Only a few plants use the system.

Pneumatic Stoker
Wood chips are blown into the combustion chamber and fall on to the grate. Spreaders and pneumatic stokers are often used in connection with combustion of wood chips with a high moisture content.

Combustion Chamber and Boiler

Wood chips are introduced for combustion on the grate in the combustion chamber that is often situated immediately below the boiler. The most common type of grate in wood chip-fired systems in district heating plants is the step grate/inclined grate and the chain grate/travelling grate. For both grate types, the primary air that is needed for the combustion is supplied from underneath the grate and passed up through the grate.

The step grate has the advantage that wood chips are turned upside down when tumbling down the "steps", which increases the air mixing and burnout. The travelling grate is known from coal-fired systems. There the wood chips lie without moving in a uniform layer, whose thickness is controlled by a sliding gate. During combustion the grate and the chips move towards the ash chute.

Air for combustion is introduced by two air fans in the form of primary and secondary air (see Chapter 6). For the combustion of moist wood chips, the combustion chamber has refractory linings round the walls. This insulation ensures a high combustion temperature and suspended arches radiating heat to the wood chips. The amount and the design of the lining are factors of great importance to the combustion quality during the combustion of wet fuels. When firing with dry fuels, e.g. wood pellets, the lining is of no benefit to the combustion quality. Rather the opposite, since the combustion temperature will be too high, thereby risking soot in the flue gas and grate slagging. Therefore, the type of fuel and its water content should be determined before choosing installation.

Combustion Quality

Chapter 6 sets out in detail the requirements for a good combustion quality. These requirements can be "boiled down to" "the 3 T's" (Temperature, Turbulence and Time). The temperature should be sufficiently high to enable efficient drying, gasification, and combustion. Air and combustible gases should be mixed adequately (turbulence), and finally there should be space and time for the gases to burn out before they are cooled too much by the boiler water.

Boiler

The flue gases pass from the combustion chamber to the part of the boiler, where the heat is given off to the circulating boiler water. Most often, the boiler is situated above the grate. The flue gas flows inside the tubes that are water cooled on the outside surface.

In small systems, the combustion unit and the boiler may be completely separated, since wood chips are burnt in a separate pre-combustor, from where the flue gases are passed into the boiler.

In the boiler unit or as a section after this unit, an economiser may be installed that cools the flue gas down to a temperature of approx. 100 °C. The increased cooling improves the efficiency. The boiler room should be large enough for repair work and for ordinary maintenance work, including boiler purifying, to be carried out in a proper way. The building round the boiler should be designed so as to give room for purifying of the boiler tubes and replacements of tubes. With respect to the boiler life, it is important that the temperature of the return water to the boiler is sufficiently high. It is recommended to keep a return water temperature of at least 75-80 °C in order to reduce the corrosion of the boiler tubes in particular. The life of tubes varies a lot at the various wood chip-fired plants. In addition to the operating temperature, the boiler life depends on the operational patterns, fuel, combustion quality, and choice of material.

Flue Gas Purifying - Fly Ash

The fly ash is the part of the ash that remains in the flue gases on its way through the boiler. Flue gas purifying is first and foremost a question of reducing the amount of fly ash emitted through the chimney. The emission of other pollutants is discussed later on in this chapter.

The fly ash is transported from the flue gas purifying unit to the remaining part of the ash system by screws. The separation of fly ash from the flue gas may be accomplished either by means of multicyclone, bag filter, or other flue gas purifying equipment.

The fly ash from the combustion of wood consists primarily of relatively large particles that can be trapped by means of a multicyclone. Most plants are equipped with multicyclones. A well-dimensioned system can purify to a level of approx. 200 mg/m^{3}n /ref. 61/ (1 m^{3}n is a normal cubic metre, i.e., a cubic metre of gas converted to standard conditions 0 °C and 1 bar). Multicyclones that are inexpensive to buy and maintain, are used for precleaning before the flue gas condensation unit.

Bag filters can purify to a level of 10-50 mg/m^{3}n. Normally, bag filters are only capable of withstanding flue gas temperatures of up to approx. 180 °C. In order to avoid embers and sparks in the bag filters, the flue gas must pass cyclones or a filter chamber situated before the bag filters. Bag filters are automatically deactivated if the max. temperature or the max. value for the oxygen content in the flue gas are exceeded.

Like the bag filter, the electrostatic precipitator (ESP) cleans efficiently, but it is more expensive to install in relatively small wood chip-fired systems. However, operating costs are lower, however, than those of the bag filters. Bag filters, ESPs etc. are not extensively used today at wood chip-fired district heating plants.

Flue Gas Condensation

Flue gas condensation units are now in general use in both new and existing systems. It is a technique that both purifies the smoke/flue gas for particles to a level

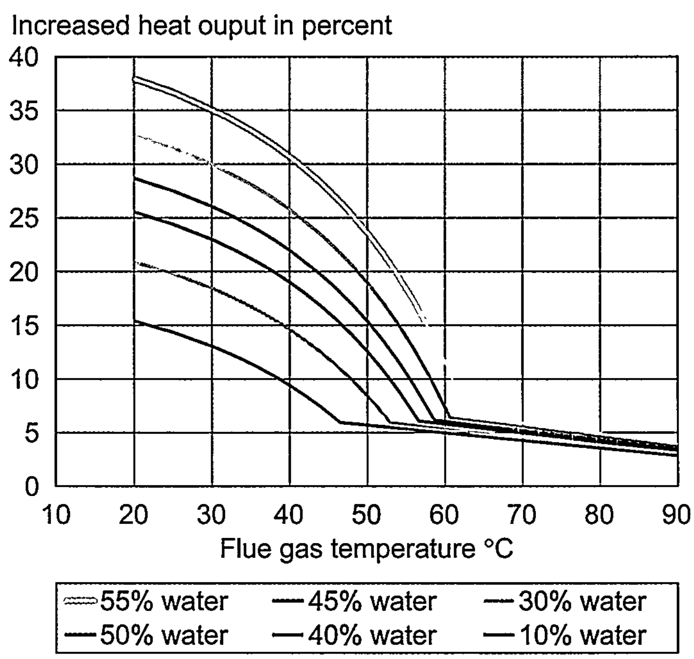


Figure 22: Flue gas condensation increases the generation of heat and the efficiency of the plant. The graph illustrates how the additional heat output depends on the flue gas temperature and on the wood chip moisture content.

almost similar to that of bag filters at the same time of increasing the energy efficiency. Most of the Danish wood chip-fired district heating plants have either been delivered with flue gas condensation or have had the equipment installed with the boiler system.

Like most other fuels, wood contains hydrogen. Together with oxygen from the air, the hydrogen is converted to water vapour by combustion, and the water vapour forms part of the flue gas together with other products of combustion. Furthermore, wood chips used at district heating plants typically have a moisture content of 40-55% of the total weight. By the combustion, this water is also converted to water vapour in the flue gas.

The flue gas water vapour content is interesting because it represents unutilised energy that can be released by condensation. The theoretical amount of energy that can be released by the condensation of water vapour is equal to the heat of evaporation for water plus the thermal energy from the cooling.

When flue gas is cooled to a temperature below the dew point temperature, the water vapour will start condensing. The more the flue gas is cooled down, the larger is the amount of water that is condensed, and the amount of heat that is released is increased. The lowering in temperature from the normal flue gas temperature of the system to dew point temperature automatically increases the heat output. The effect increases, however, when the condensation starts, and the heat of evaporation is released. Figure 22 illustrates in percentages the increased generation of heat that can be achieved by lowering the flue gas temperature. The normal operating situation that forms the basis of the calculations is a flue gas temperature of 130 °C with CO_2 being 12%. The various lines in the figure illustrate various values for the wood chip moisture content in percentage of the total weight.

The curves show the theoretical improvement of the efficiency that can be calculated on the basis of the moisture content and the flue gas temperature. Experiences acquired from condensation units in operation indicate that an increase in efficiencies can also be achieved in practice /ref. 62/. Thus, the annual efficiencies for almost all plants are above 100% (based on the net calorific value of the fuel which does not include the condensation heat).

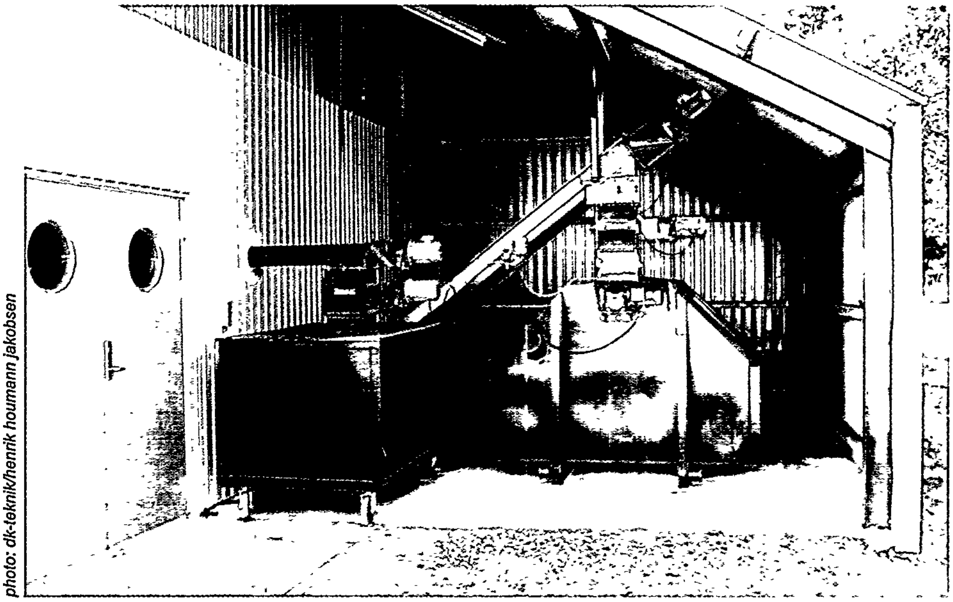


photo: dk-teknik/henrik houmann jakobsen

Fly ash from the cyclone is stored in the ash container to the left, while bottom ash from the heating plant is deposited in the large container.

The return water from the district heating system is used for cooling the flue gas. The water should be as cold as possible. The flue gas cooling unit is therefore the first unit the water passes when it returns from the district heating system.

Condensate

Condensate consists of water with a small content of dust particles and organic compounds from incomplete combustion. There is also a minor content of mineral and heavy metal compounds, and of chlorine and sulphur from the wood.

The pH value of the condensate varies a lot from system to system, and it also varies with the operational pattern. A typical value lies between pH 6-7, but there have been measured pH values from 2.7 to above 8. The dust particles contained in the condensate affects the pH value heavily. High pH values are connected with large particle contents - i.e. the fly ash seems to be alkaline/basic, and the majority of it by far is dissolved in the condensate. Indissoluble particles only contribute 10%.

The condensate should be treated before being discharged. The minerals and heavy metals contained in wood, such as cadmium that has been absorbed during the growth in the forest, concentrate in the condensate and may reach a level exceeding the limit values for discharge. Investigations have shown that the large amount of cadmium contained in the condensate is found in the condensate particles and not in dissolved form in the water. The particles can be removed from the condensate liquid by filtering, so that the cadmium content is reduced to below the limit values for discharge /ref. 63/. This is the reason why filtration equipment for the separation of condensate particles is being installed in an increasing number of plants right now. After treatment and neutralisation, the condensate is generally discharged into the municipal sewage system.

When the flue gas leaves the flue gas condenser, it should pass through an efficient mist eliminator for the collection of entrapped droplets, thereby avoiding mist being carried further into the tube, exhaust fan, and chimney.

The first prerequisite of success with flue gas condensation is a return flow temperature in the district heating system that is so low that the vapour in the flue gas can be condensed. In addition, the fuel should have a high moisture content. Wetter fuel increases the overall efficiency of the plant! This applies only as long as the moisture content is not so high as to result in incomplete combustion. Forest chips with a moisture content in the range of 40 and 50% are ideal for systems with flue gas condenser.

The installation of flue gas condensers may often make the installation of other equipment for flue gas purifying unnecessary. If the installation of a bag filter can be avoided, the money thereby saved can often pay the investment in the flue gas condensation unit. Consequently, the energy saved is almost free.

Chimney

Before chimney and flue gas condenser an exhaust fan is installed, which creates negative pressure throughout the flue gas passes of the heating system. A control device ensures that the exhaust fan in interaction with the combustion air fans keeps a preset negative pressure in the combustion chamber. The exhaust fan then forces the flue gas into the flue gas condenser and the chimney. Individual chimney heights should be determined on the basis of the environmental requirements. Further information about chimney heights can be found in /ref. 64/. For small plants with flue gas condenser, the chimney should be designed so as to avoid corrosion damage, i.e., glass fibre or rust-proof materials should be used.

Soot emission from chimneys of systems with flue gas condensation causes problems at some heating plants. The smoke is saturated with water vapour. It also contains dissolved salts and perhaps impurities from the flue gas condensate, which may be deposited in the chimney. Soot emission occurs when the deposits in the chimney loosen and are passed along with the flue gas flow. Efficient mist eliminators, low velocities in the chimney, and perhaps the installation of a wash-down system in the chimney can be recommended so as to eliminate the problem /ref. 65/.

Handling of Ash

Wood chips contain 0.5-2.0% of the dry weight in the form of incombustible minerals which are turned into ash in the combustion process. The ash is handled automatically at all district heating plants. The manual work in connection with the ash system is limited to ordinary inspections and intervention in case of operations stoppage. The composition of wood ash means that slagging is not a widespread phenomenon at wood chip-fired heating plants.

The ash drops from the grate onto an ash conveyor or other ash collection system. The sludge from the flue gas condensate contains a large amount of heavy metal and is collected separately for later disposal.

The ash system may be arranged as a wet or dry ash system. A wet ash system is a dual function system, since it is efficient as a trap hindering false air entering the boiler at the same time as extinguishing glowing ash. A drawback of the system is the heavy weight ash in the ash container and the corrosion resulting from the wet ash. The emptying of the containers varies with the consumption of wood chips, i.e., from approx. every second week to once every three months.

Category	Description	Max. Cd content (mg Cd/kg DM)	Max. amount of application (tonnes DM/ha/year)
H1	Straw ash, mixed	5	0.56
H2	Straw ash, mixed	2.5	1.12
H3	Straw ash, bottom ash	0.5	5.6
F1	Wood chip ash, mixed	15	0.19
F2	Wood chip ash, mixed	8	0.35
F3	Wood chip ash, bottom ash	0.5	5.6
H+F	Mixed straw/wood chip ash	5 (as H1)	0.56

Table 14: Limit values for cadmium and the max. allowable amount of application according to the "Executive Order on Ash from Gasification and the Combustion of Biomass and Biomass Residual Products for Agricultural Applications", submitted to the Ministry. DM stands for dry matter.

Disposal

Ash contains the unburned constituents of fuel, including a range of nutrients, such as potassium, magnesium and phosphorus, and it can therefore be used as fertiliser in the forests if the content of other substances that are problematic to the environment is not too high. When the biomass agreement is fully implemented in the year 2005, the annual amount of biomass ash produced will be in the range of 80 to 100,000 tonnes. With the amount of ash being that huge, it is important to find a reasonable and environmentally acceptable use of it, thereby utilising the nutrients of the ash in the best possible way.

Using the ash in agriculture requires permission from the county. Applications submitted to the county are being considered at the time of writing (at the beginning of 1999), thereby also having regard to the Department of the Environment Executive Order No. 823 September 16, 1996 on Residual Products for Agricultural Applications /ref. 66/. However, this executive order is primarily directed towards industrial residual products, sewage sludge, compost etc., and is not particularly suitable for the administration of the application of ash. The low cadmium limit values make it difficult for biomass heating plants to comply with the executive order, and the use of the ash has therefore to a high extent been based on exemptions granted by The Danish Environmental Protection Agency and permissions from the county. In the event of no exemption being granted, the ash should be dumped at a controlled disposal site. However, in the long term perspective basing waste disposals on exemptions is an unwise solution, and therefore an independent executive order for ash has recently been submitted to the Ministry of Environment and Energy. The coming executive order "Executive Order on Ash from Gasification and the

Heavy metals	Limit value (mg per kg dry matter)
Mercury	0.8
Lead	120 (private gardening 60)
Nickel	30
Chromium	100

Table 15: Limit values for the remaining heavy metals according to the " Executive Order on Ash from Gasification and the Combustion of Biomass and Biomass Residual Products for Agricultural Applications", submitted to the Ministry.

	Cut-off levels (mg per kg dry matter)
Sum of Acenaphthene, Phenanthrene, Fluorene, Fluoranthene, Pyrene, Benzofluoranthenes (b+j+k), Benzo-a-pyrene, Benzo-g-h-i-perylene, Indole-1-2-3-cd-pyrene	6 (From July 1, 2000, the value is 3)

Table 16: In addition to heavy metals, the ash may also contain the so-called polyaromatic hydrocarbons (PAH), which typically occur in connection with incomplete combustion. The concentration cut-off levels for PAH as designated in the Executive Order on Ash from Gasification and the Combustion of Biomass and Biomass Residual Products for Agricultural Applications", which is at the reading stage, are listed here.

Combustion of Biomass and Biomass Residual Products for Agricultural Applications" is based on the view that it seems to be reasonable to return straw and wood chip ash to the areas from where the straw and wood chips come. With straw or wood chips remaining in the field or in the forest, heavy metals would remain in the soil. When burning the straw or wood chips the heavy metals in the ash will of course concentrate, but if the ash is returned in reasonable amounts, the heavy metal impact will not be different from the situation where the straw and wood chips remain in the field/forest. The limit values in the new executive order are therefore modified according to the existing executive order, while the max. allowable application amount secures that the application of heavy metals to the areas will not exceed the amount that is normally removed with the biofuel during the harvesting of it.

Pure straw ash should only be applied to agricultural land, while pure wood chip ash should only be applied to forest areas. Mixtures of wood chip and straw ash can be applied to both forests and agricultural land. Ash applied to agricultural land can be dosed as an average over 5 years, while ash applied to forest areas can be dosed as an average over 10 years. The max. allowable application to forest areas is 7.5 tonnes of dry matter per ha per rotation (100 years).

As there is a certain connection between the combustion quality and the PAH contained in the ash, an analysis of unburned carbon in the ash must be made in connection with each of the heavy metal analyses according to the suggested executive order. If the residual carbon in the ash is below 5%, PAH analyses must be made every second year, but if the result of an analysis of unburned carbon exceeds 5%, thus indicating incomplete combustion, then a PAH analysis must be made immediately.

When the new executive order has come into force, it is expected to offer better outlets for a reasonable and environmentally acceptable use of the biomass ash.

	Unit	Typical value	Typical variation
SO_x as SO_2	g/GJ	15	5 - 30
NO_x as NO_2	g/GJ	90	40 -140
Dust, multicyclone	mg/m³n	300	200 - 400
Dust, flue gas condensation	mg/m³n	50	20 - 90
CO_2 (see text)		0	0

Table 17: Typical emission values in connection with wood chip firing. The figures vary very much in practice, even beyond the typical variations listed /ref. 67/.

Size of system Input in MW	Recommended limit value for dust mg/m³n at 10% O_2	
	Systems with dust filters	Systems with condensing or technology without dust filters
> 0,12 < 1	100	300
> 1 < 50	40	100

Table 18: Recommended limit values for dust from wood-fired systems /ref. 61/.

Environmental Conditions

This section describes the impact on the air environment in connection with firing with fuel chips at district heating plants. Table 17 illustrates typical emission values for chip-firing.

Dust

After intensifying the emission standards in 1990 for air pollution, most of the municipalities decided to require lower emission levels for dust from small wood chip-fired heating systems than earlier. Emission standards for dust from heating systems are described in the Danish Environmental Protection Agency's guide, Limitation of Industrial Air Pollution /ref. 64/. The guide designates emission levels for a range of heating systems, but not for wood, though.

When dealing with applications for wood-fired systems, the approving authorities have most often used the limit values for "other dust pollutants" in which the limit value for dust is fixed in proportion to the size of the mass flow before purifying. In some instances regard has also been had to the recommended limit values for straw-fired systems larger than 1 MW input, designating not only dust but also the recommended limit value for a carbon monoxide content not to exceed a volume percentage of 0.05 at 10% O_2. In 1996 the Danish Environmental Protection Agency had a report prepared, Dust Emission Standards for Wood-fired systems smaller than 50 MW /ref. 61/, designating the recommended limit values for wood-fired systems, in particular.

When fixing the limit values for dust, the report suggests that regard should be had to both the size of the system and the technology applied to firing and dust purification.

Carbon Monoxide (CO)

A high CO content is a certain indication of incomplete combustion and should be as low as possible, because:

- CO is a combustible gas. A high CO content results in poor efficiency.
- Odour nuisance and a high CO value go together.
- PAH, dioxin and a high CO value go together.
- Exposure to high concentrations of CO is hazardous.

According to The Danish Environmental Protection Agency's guide /ref. 64/, the CO content in the flue gas may not exceed 0.05% for straw-fired heating plants. The same requirements apply to the environmental approval of many wood chip-fired heating plants. During normal operating the wood chip-fired heating plants can comply with this, but in connection with starting up, very wet fuel and other unusual operating situations, problems may arise.

Carbon Dioxide (CO_2)

The emission of CO_2 to the atmosphere is problematic, since CO_2 is considered a major cause of the greenhouse effect. During the combustion of wood chips and other wood fuels, not more CO_2 is developed than bound during the growth of the tree. Furthermore, during combustion the same amount of CO_2 is developed as during the decomposition that is the final alternative to the use of the wood for energy purposes. Wood chips are thus considered CO_2-neutral.

Sulphur Dioxide (SO_2)

Sulphur from the combustion of wood chips comes from sulphur compounds that have been absorbed by the tree during its growth. Therefore, the combustion of wood chips does not change the total amount of sulphur present in the environment, but it entails that the emission of sulphur with the smoke contributes to the pollution of the air. However, pure wood from the forestry contains only a very limited amount of sulphur. During combustion approx. 75 % of the sulphur in the wood will be captured in the bottom and fly ash, so that only the remaining 25 % will end as SO_2 in the flue gas /ref. 68/.

Many analyses of the sulphur content in fuel chips show values that are below the laboratory equipment limits of detection. The average of a range of analyses shows a sulphur content of approx. 0.05% (percentage by weight in proportion to the dry matter content in the fuel) /ref. 67/.

Firing with wood chips at heating plants causes much less SO_2 emission than the fuel oil or coal the wood chips often replace. If the alternative is natural gas, and if it is sulphur-free at production, there will be no SO_2 advantage by using wood chips as a fuel.

Nitrogenoxides (NO_x)

During the combustion of wood chips, approx. the same amounts of NO_x are produced as during the combustion of other fuels. NO_x is the sum of NO and NO_2.

The formation of nitrogenoxides occurs on the basis of the nitrogen contained in the air and the fuel. Both nitrogen contained in the fuel and the design of the system combustion chamber play an important role in the production of NO_x. Of important parameters for low NO_x formation can be mentioned:

- Low nitrogen content of the fuel.
- Staged combustion at low excess air during the first stage /ref. 69/.
- Low flame temperature.
- Recirculation of flue gases.

Other Pollutants

In addition to particles, SO_2, NO_x and CO, flue gases may contain other pollutants, such as polyaromatic hydrocarbons (PAH), dioxins, hydrogen chloride (HCl), etc.

PAH is a joint designation for a range of chemical compounds consisting of carbon and hydrogen. It occurs by incomplete combustion. Some of them are noxious (some even cancer-causing) and should therefore be avoided. Since 1985 several investigations have been carried out all showing that there is a close connection between the formation of PAH and CO. Low CO content and low PAH content go together /ref. 70/.

Like sulphurdioxide, hydrogen chloride (HCl) contributes to the acidification, but condenses faster (to hydrochloric acid) and can therefore locally contribute to damage to materials in particular, but also to plants. The emission of HCl depends on both the condition of the wood chips (wood chips from nearshore forests contain salt from sea fog) and on combustion conditions and flue gas purifying, including condensation, which removes a considerable part of the HCl contained in the flue gas.

Noise

The heating plant must comply with the conditions of the environmental authorities regarding the limitation of noise - cf. the Danish Environmental Protection Agency Guide No. 5/1984 /ref. 71/. The noise level load should be measured according to the Danish Environmental Protection Agency Guide No. 6/1984 /ref. 72/ No. 5 respectively /1993 /ref. 73/.

If the heating plant is located in a residential neighbourhood, the noise limits here will normally be:

- 45 dB(A) during days (weekdays from 07:00 - 18:00, Saturdays from 07:00 - 14:00)
- 40 dB(A) during evenings (weekdays from 18:00 - 22:00, Saturdays from 14:00 - 22:00, Sundays and non-working days from 07:00 - 22:00)
- 35 dB(A) during nights (all days from 22:00 - 07:00)

The noise limits vary with the various types of area and may not be exceeded at any point in the neighbourhoods. If the heating plant is located in an industrial area, where the noise limit is 60 dB(A) during all periods of the day and year, the noise limits in an adjacent residential neighbourhood may be decisive. The noise comes primarily from fans and air inlets or exhaust systems (including the chimney), but also from other machines (compressors, cranes, belt conveyors, screw conveyors, and hydraulic systems) and from all the traffic on the plant site. For most areas, the noise limit is lowest during the night, and it will therefore normally be this limit that will form the basis of the dimensioning. However, the delivery of fuel may often give rise to problems, although it takes place during the day if the driveway of the plant is inexpediently located.

It is important already at the stage of planning to take into account the noise emissions, since subsequent antinoise measures are often very expensive, and also operational restrictions (such as how to avoid all traffic during evening and night periods) may be problematic. Today it is possible to forecast the noise in the surrounding neighbourhood, so that the suppliers should warrant not to exceed the noise limits.

Fire Protection

When firing with forest wood chips, the risk of fire is lesser than by firing with dry fuels. However, certain safety regulations must be complied with.

The fuel system should be equipped with an airtight dividing wall, thereby preventing fire from spreading backwards from the combustion chamber to the storage. At most plants, the feeding systems are designed with an airtight "plug" of wood chips and a sprinkler system located just before the combustion chamber.

Attention should be paid to the risk of flue gas explosions. Unburned gases in an incorrect mixture with atmospheric air may cause extremely violent explosions if gases, e.g. due to a positive pressure in the combustion chamber leaking into the boiler room or the feeding system. Flue gas explosions may also occur in the combustion chamber if, e.g. the fuel due to suspension of operations has been smouldering with too little atmospheric air, and air is suddenly introduced.

In the wood chip storage one should beware of the risk of spontaneous combustion. Here storage height, wood chip storage time, moisture content, and the access to air will be a decisive parameter. During firing with wood pellets and dry wood waste, there is a risk of dust explosion in the storage and the feeding system. Here fire extinguishing equipment should be built in just before the boiler. The risk of fire in the fuel storage also applies to pellets.

Control, Adjustment, and Supervision

Control, adjustment, and supervision (Styring, Regulering og Overvågning) is called the SRO system. The system is designed on the basis of two computers:

- A PLC (Programmable Logic Control) with system data recording controls the plant's various flows according to pre-set operating values.
- An ordinary computer displays the flow of data from the PLC to the operators' monitor. The preselected operating values in the PLC can be changed via the computer.

The system is divided into three main functions covering the following:

- The control ensures that the system performs according to a preselected sequential order.
- The adjustment unit ensures that the preselected values for pressure, temperature etc. are complied with.
- The supervision unit sets off alarms in case of malfunctions.

The SRO system enables automatic operation of the plant, thereby making the permanent pressence of operators unnecessary. In case of operation failures, the remote supervisory and monitoring unit calls in the operators via the public telephone network. In emergency situations, an oil-fired furnace is automatically started, taking over the supply of heat.

Plant Manpower

The manpower necessary for the operation of the plant naturally depends on the degree of automation, the scope of own wood chip handling, the age of the heating plant etc. Individual small heating plants are designed so as to remove the need for permanent on-site attendance even during the day. By being on call via telephone and daily inspections, the plant manager can occupy another job at the same time.

When estimating the manpower required, the calculation can be based on systems from approx. 1.5 MW to 5 MW requiring approx. 1-2 man-years for the operation. Systems above 5 MW will require approx. 2-3 man-years for the operation. The construction of the system is of decisive importance to the amount of maintenance work.

In-Plant Safety

In-plant safety includes fire safety and personnel safety. Before commencing production, the plant must be approved by the local fire authorities.

In-plant personnel safety must be approved by the Danish Working Environment Service. It includes safety measures against scalding, burn, poisoning with flue gas or dust, and injuries caused by cranes or other machinery.

Organisational Structures

Wood chip-fired heating plants can be established as:

- An A.m.b.a. - i.e. a co-operative society with limited liability.
- An ApS - i.e. a private limited liability company.
- An A/S - i.e. a limited liability company.
- A public corporation.

The wood chip-fired district heating plants in Denmark are typically organised as local user-owned co-operative societies with limited liability (A.m.b.a), where all users connected to the district heating system are attached to the company. The owners are only liable to the extent of their contribution, and they are all placed on an equal footing. In addition the organisational structure is already known by many people. Almost all wood chip-fired heating plants in Denmark are organised in the form of an A.m.b.a.. The organisational structure of the user-owned companies are democratic so that all users have the possibility of participating in decision making via the annual owners' meeting of the heating plant.

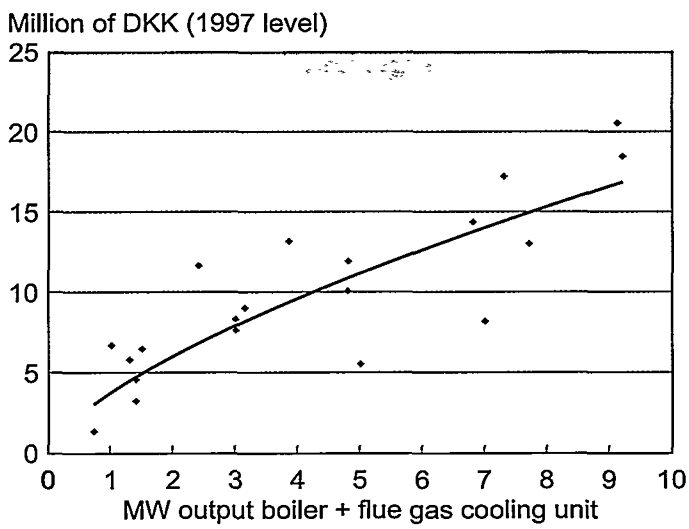


Figure 23: Initial capital investment regarding chip-fired district heating plants at 1997 prices in Denmark. The dots show the individual initial capital investments, while the line shows an approximate price formula /ref. 28/.

photo: biopress/torben skøtt

Trustrup-Lyngby Varmeværk at Djursland is a "urbanisation" project established in 1997.

A few plants are owned and operated by the municipality.

It is also possible to choose a private limited liability company (ApS) or a limited liability company (A/S), where the participants are liable to the extent of their invested share capital.

Investment and Operation

The following example illustrates the plant operating efficiency of a given 2 MW wood chip-fired heating plant established right from the beginning as a so-called "urbanisation" project. By "urbanisation" project is meant a town where both a new heating plant and a complete district heating system for the supply of heat to the consumers are established. The wood chip price is fixed at DKK 36/GJ, and the oil price at DKK 95/GJ. All figures in the example are exclusive of value added tax (VAT).

Capital investment

In the report Initial Capital Investment and Efficiencies of Wood chip-fired Heating Plants /ref. 28/, information has been collected in respect of initial capital investment regarding site, land development, buildings, installation of machines, and projecting. All prices are in terms of 1994 prices so that they are comparable with one another. The curve in Figure 23 shows projected 1997 prices for the individual heating plants in proportion to the total nominal output of the wood chip boiler and flue gas condenser.

It is important for a new project to get "a head start". Therefore, at least 80% of the previously oil-fired furnaces and all public large-scale consumers should participate in the project right from the beginning. Public large-scale consumers are local government offices, schools, sports centres, etc. Contrary to earlier practice, energy and environmental taxes in connection with indoor heating will not be refunded to industrial enterprises and liberal professions, which will therefore also be a target group.

The data of the example are:

260 small consumers	4,550 MWh/year
10 large consumers	3,300 MWh/year
Distribution loss	30%
Generation of heat	11,200 MWh
Heat from wood chips	93%
Heat from oil	7%
Max. output demand	3 MW
Chip boiler rated output	2 MW
Annual efficiency (wood chips)	100%
Annual efficiency (oil)	80%

For a densely built-up town, the distribution loss is 30% in a year with approx. 3,112 "ELO" degree days" (ELO stands for EnergiLedelsesOrdningen (Energy Control Scheme)). If the area is not so densely built-up or smaller towns are connected via a transmission line, the distribution loss will increase to above 35%.

It is possibly to apply to the Danish Energy Agency for subsidies to be granted for "urbanisation" projects according to the CO_2 statute /ref. 57/.

The initial capital investment is as follows:

	Million of DKK
The heating plant	6.8
Street piping/advisory service	10.0
Consumer service pipes	4.0
Consumer house installations	4.0
Unpredictable expenses	1.0
Total initial capital investment	25.8
Danish Energy Agency subsidised	4.4
Loan requirement	21.4

The initial capital investment can be mortgaged in full by means of index-linked loan. An index-linked loan is a type of loan that is repaid by annual payments that increase concurrently with inflation. It is a cheaper type of loan than the conventional loans, repayable by equal semi-annual instalments or annuity loans, as long as inflation is below 7% per annum. The structure of index-linked loans is set out in more detail in the following references /ref. 74, 75/. The real rate of return on index-linked loans, which was introduced with the government's economic intervention in the spring of 1998, is expected to be of decisive importance to whether or not this type of loan will continue being attractive to the financing of new heating plants.

Operating Costs and Income

The heating plant's income derives from the sale of heat and is distributed on fixed contributions and consumer charge for the heat. The standard charge for the sale of heat to consumers may, e.g., be:

Variable charge	DKK 350/MWh
Fixed annual charge	DKK 1,000/con
Capacity charge, private	30 DKK/m^2
Capacity charge, industry	30 DKK/m^2

Add to that value added tax (25%). For a private consumer in a single family house of 120-130 m^2 with an average consumption of 17.5 MWh (equal to approx. 2,500 litres of oil), the heating expenses will amount to DKK 13,800. This expenditure is more or less equal to the operating costs of oil firing: Oil, chimney sweeping, and maintenance.

This rate will yield the following income and expenses:

Income:	Thousand of DKK
Sale of heat, 7,850 MWh	2,748
Fixed annual charge	270
Capacity charge, private cons.	1,014
Capacity charge, industry	350
Total income	4,382

Expenses:	Thousand of DKK
Wood chips, DKK 36/GJ	1,350
Oil, 87,000 litres	295
Maintenance, heating plant	130
Maintenance, distribution system	200
Electrical power consumption	85
Water and chemicals etc.	30
Other costs	70
Personnel and administration	500
Depreciation (20 years)	1,070
Depreciation (indexation)	21
Interest and contribution	570
Total expenses	4,321
Net result	61

With regard to accounting principles, a straight line method of depreciation which charges an equal sum each year, more adequately reflects the decrease in value during the life of the heating plant than does the other practice where the depreciation is booked as being equal to the instalments on the loan. By the last-mentioned method, the expenses will increase as the instalments increase over the period of repayment. The indexation of instalments is the expense for the annual appreciation of instalments with the index of net prices. The remaining debt is also revalued according to the index of net prices. This item is booked in an exchange equalisation fund under the equity capital /ref. 75/.

Approval by the Authorities

As early as possible during the first stage of the project, it should be investigated whether either the local environmental or building restrictions or preservation regulations will constitute a hindrance to a new or retrofit heating plant. In order to be able to establish a district heating plant, the following approvals should be obtained from the authorities:

- Planning permission.
- Approval of draft project according to the Heat Supply Act.
- Environmental approval.
- Perhaps local planning.

Matters concerning the approval by the authorities are described in more detail in /ref. 76/.

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,

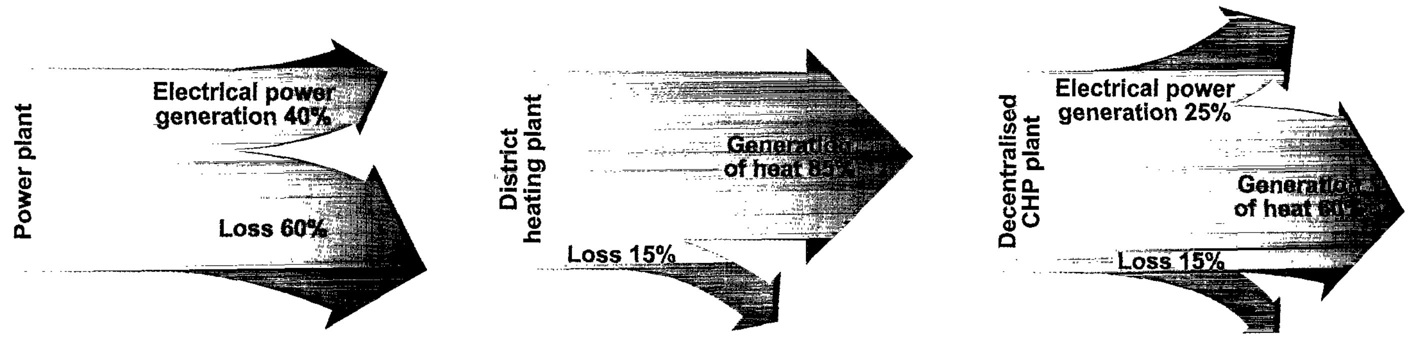
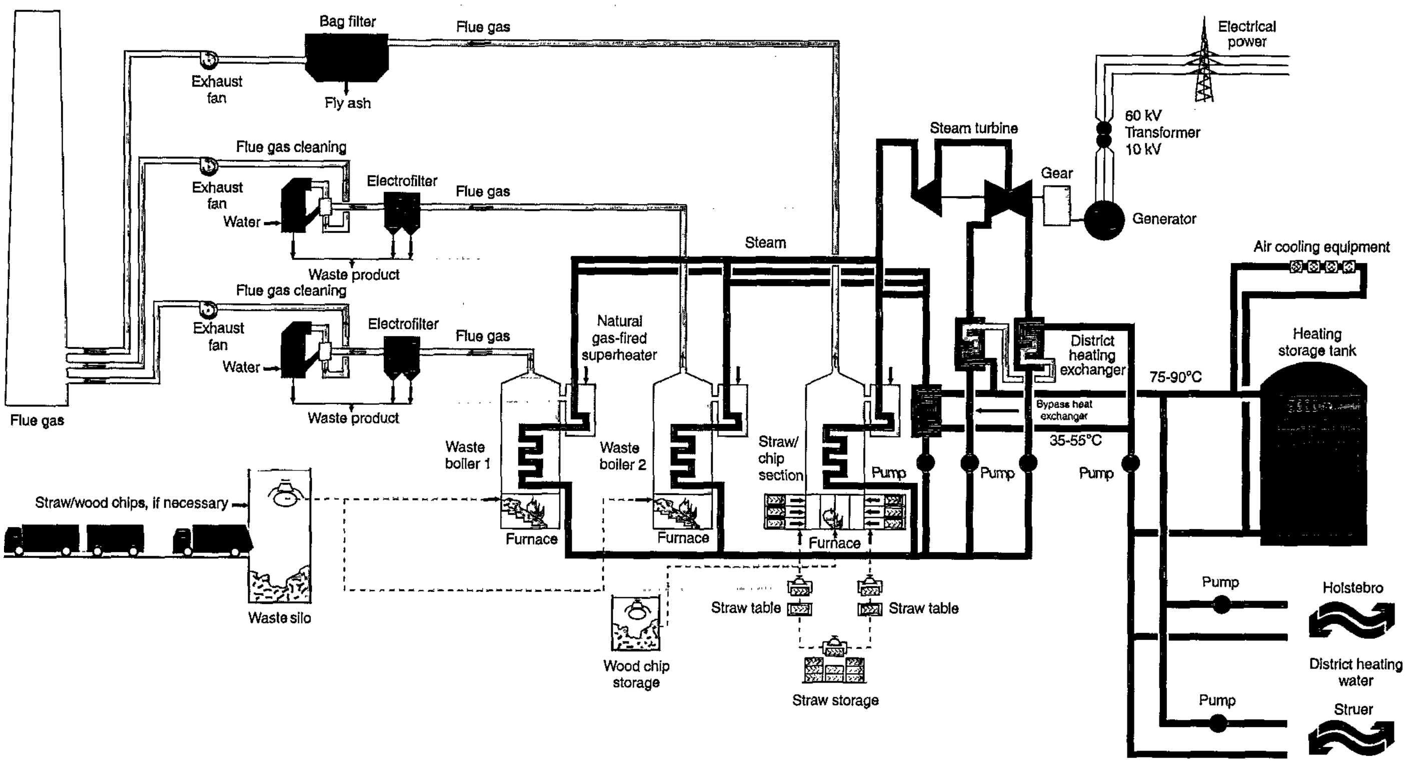


Figure 24: By separate electrical power generation and generation of heat at a power plant and at a district heating plant, total losses are much larger than by combined heat and power production at a CHP plant.



graphics: i/s vestkraft

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.

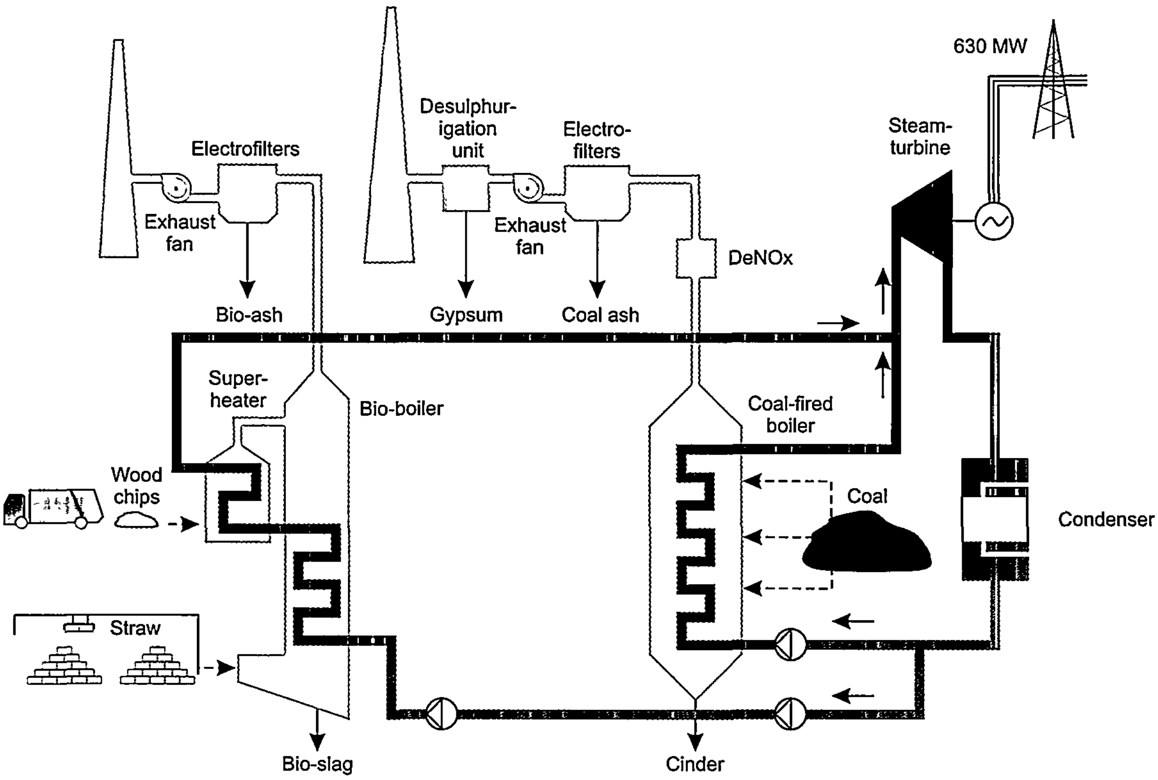


Figure 26: Schematic diagram of Enstedværket's bio-boiler of 40 MW_e and coal-boiler of 630 MW_e. The bio-boiler replaces the consumption of 80,000 tonnes of coal per year, thus reducing CO_2 emissions to the atmosphere by 192,000 tonnes per year.

graphics: sønderjyllands højspændingsværk

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

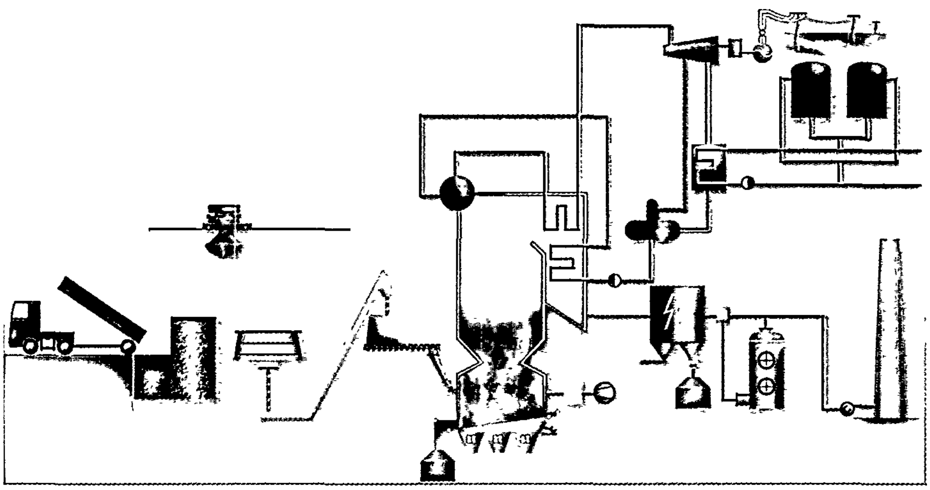
Denmark's largest electrical power plant boiler exclusively fired with biofuel was put into operation in 1998 at Enstedværket near Aabenraa.

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 volund 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.

10. Gasification and Other CHP Technologies

Small scale CHP generation is of immediate interest to district heating plants, large institutions, and industries, and the technology has market potentialities both in Denmark and abroad. The major driving force behind the development of gasification systems is the prospect of higher electrical power efficiencies than, e.g. by means of steam turbine systems the same size. This chapter deals with Danish development projects in the field of pilot and demo systems, supported by the Danish Energy Agency's Development Scheme for Renewable Energy among others. The projects work in the field of CHP generation by different systems such as updraft gasification, several forms of downdraft gasification, Stirling engine and steam engine.

CHP with Thermal Gasification

Small scale CHP plants using natural gas as a fuel are easily designed just by letting a combustion engine operate a generator for the generation of electrical power and utilise the engine waste heat for district heating. However, it is not that easy when the fuel is wood. Not even in the form of powder can wood be used directly as a fuel in a combustion engine or perhaps a turbine. First the wood must be converted to gas. This can be accomplished in a gasification process in a gas generator that is also termed a gasifier. The secret of gasification is the conversion of wood into gas at the least possible loss of energy and in a way that the combustible gas thus produced - product gas - is as purify as possible. The gas engine is damaged if the gas contains tar and particles, and the process must not result in polluted water. Thus there are many requirements to comply with at the same time.

During World War II, dried beech blocks the size of tobacco tins were used for the operation of cars. Today this fuel can only be obtained in very limited quantities at reasonable prices. Commercial fuel chips are available today, but they are normally wet when coming directly from the forest. In addition fuel chips are not so much cheaper than gas and oil that investing in the large-scale technology needed for a CHP-based gasification work is economically feasible.

In order to produce combustible gas, the wood should first be heated. It is most common to heat it by burning a small proportion of the wood. The heating dries the fuel, and not until then will the temperature be increased. At a temperature of approx. 200 °C, the so-called pyrolysis begins where the volatile constituents of the wood are given off. They consist of a mixture of gases and tars. When the pyrolysis is completed, the wood has been converted to volatile constituents and a solid carbon residual (the char).

The char can be converted into gas by adding a fluidising agent which may typically be air, carbon dioxide, or water vapour. If using CO_2 or H_2O, this process requires heat and will only occur at a reasonably acceptable speed at temperatures above approx. 800 °C. The combustible constituents in the product gas are primarily carbon monoxide, hydrogen, and a little methane. Together they constitute approx. 40% of the volume of the gas when using air for the gasification, while the residual part consists of incombustible gases such as nitrogen and carbon dioxide. The major part of the tars from the pyrolysis can be converted to gas, if heated to 900-1,200 °C by passing through a hot char gasification zone. Many different types of gas generators have been developed over the approx. 100 years the technology has been known. Normally, gas generators are classified according to how fuel and air are fed in relation to one another. In the following, development projects will be used, which apply updraft gasifiers and downdraft gasifiers. There are also other gasification principles, e.g. fluidized bed gasification, which has its stronghold in large systems. Atmospheric fluidized bed gasification of wood in large systems may be considered fully developed abroad. Also forced draught fluidized bed gasification is used for expensive demo systems abroad. The international development is monitored, but it has not yet been planned to have that type of system constructed for wood in Denmark.

Updraft Gasifiers (Counter Current Flow Gasification)

In updraft gasifiers (gas generators) the combustion air is drawn in underneath the grate in the bottom and passes the fuel from beneath and upward (Figure 28). Fuel is fed from the top of the gasifier undergoing the various processes as it moves to the bottom of the gasifier against the air and gas flow. In traditional types of gasifiers, all substances that are produced during the heating of the fuel, including tar and acetic acid, will leave the gas generator without having been decomposed first. Up to 20-40% of the energy may in that case be bound in this tar. The gas cannot be

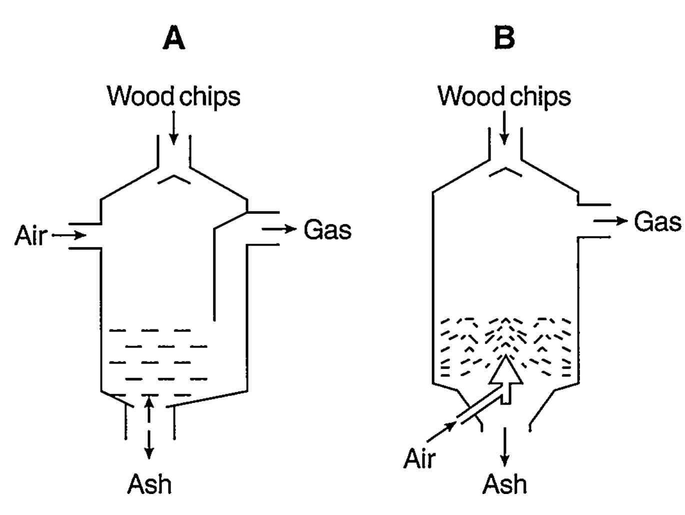
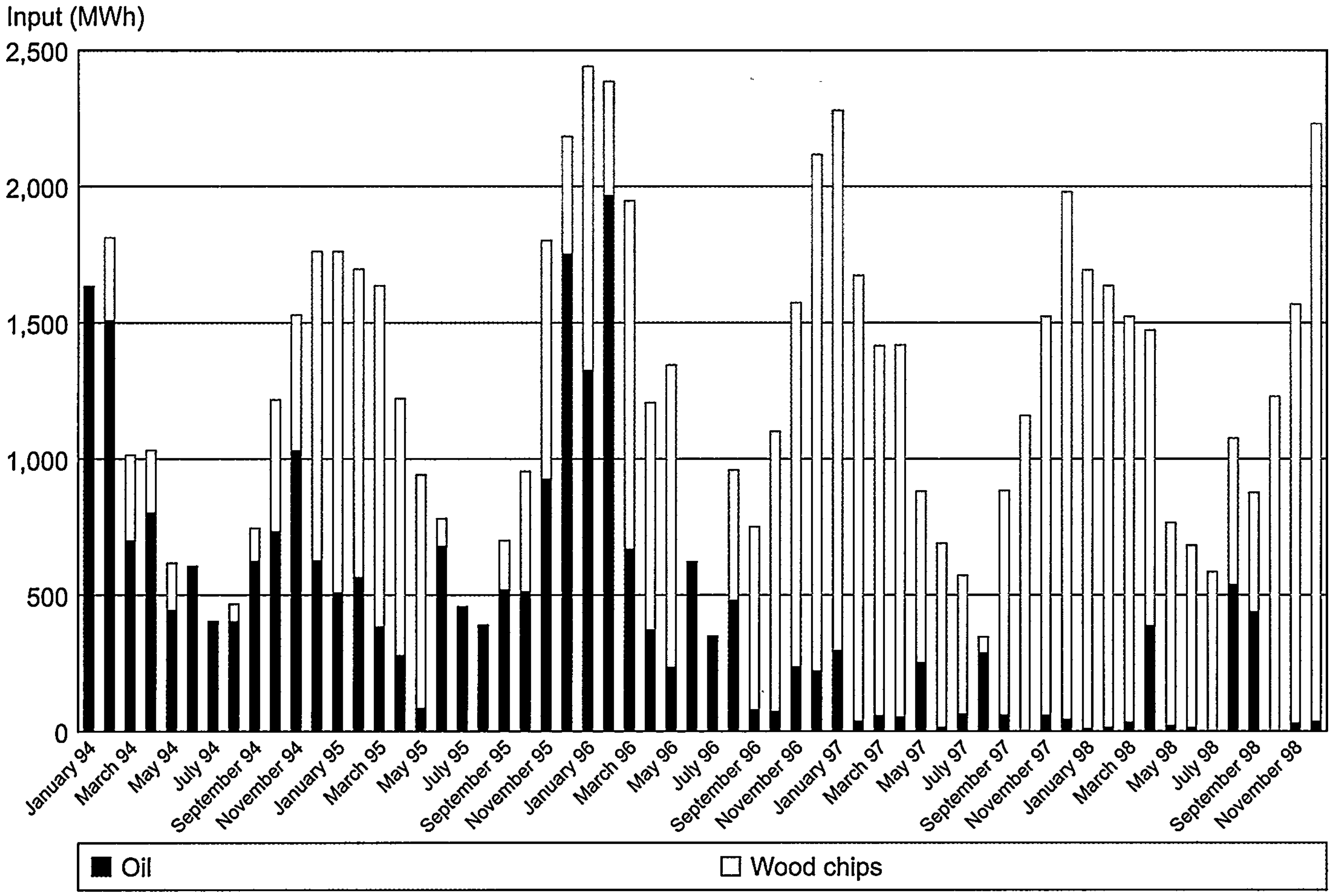


Figure 28: Schematic diagram of the gas generator principles, A - downdraft gasifier, B - updraft gasifier /ref. 77/.



graphics: volund r&d center

Figure 29: When Harboøre Varmeværk was put into operation, a large amount of oil was consumed for the supply of heat and only a small amount of wood chips, but now the situation has been reversed. The figure showing the fuel consumption of oil and wood chips per month illustrates that the reversal took place during 1996. The most recent couple of years the gasification system has covered more than 90% of the town's heat demand, and the oil boiler now plays a minor part.

used for driving engines without an intensive purification, so therefore the application of updraft gasifiers in connection with wood makes heavy demands on the gas purifying system. For the same reason, updraft gasifiers in the 1940s were primarily used for fuels with a low tar content such as anthracite and coke. /ref. 77/. The great advantage of the updraft gasifier is its ability to gasify both very wet fuels (up to a moisture content of approx. 50%) and fuels with a low slag melting point such as straw.

Downdraft Gasification (Co-Current Flow Gasification)

Downdraft gasifiers fed with wood were the predominant principle used for operation of cars during World War II. The fuel is fed from the top of the gasifier, undergoing the various processes as it moves downward to the bottom of the gasifier. The air is injected either in the middle section of the gasifier or from the top above the fuel storage (Open Core principle) and passes downwards in the same direction as both the fuel and the gases so developed (Figure 28). For tar forming fuel such as wood, this principle is particularly usable, because tar, organic acids, and other pyrolysis products pass down through the combustion zone and decompose to light, combustible gaseous compounds.

In its traditional design the downdraft gasifier principle has the drawback that it is not suitable for fuels with a low ash melting point. Straw will therefore not be suitable, while wood can be used with a good result. Another drawback is that it requires relatively dry fuels with a max. moisture content of 25-30%. When the fuel is delivered directly from the forest, it should be dried before it can be fed into a downdraft gasifier. A modified design of the downdraft gasifier according to a two-stage principle is another option under development at the Technical University of Denmark, and with this design it has been possible to improve the weak points of the downdraft gasifier.

Systems in Process of Development

Updraft Gasification (Counter Current Flow Gasification) System at Harboøre

Ansaldo Vølund A/S has constructed the system and operates a full scale gasification system at Harboøre. The system is designed for conventional forest chips that can be fired without prior drying. The system input is 4 MW and consists of an updraft gasifier, gas purifying, and a gas burner installed on a boiler, where the gas is burnt for the generation of heat. The heat is supplied to Harboøre Varmeværk. The plant has been in operation since 1993 only producing heat and the plant holds the world record in respect of unmanned hours of operation with forest chips as a fuel. At the same time ongoing development has constantly increased the system reliability, which currently tends to even surpass the reliability of conventional chip-fired plants.

The aim of the system is to produce both electrical power and heat. This requires thorough gas and water purifying, because wet wood chips produce a gas that contains relatively large amounts of tarry condensate. Every effort has been made to purify the gas to a level that makes it fit for the purpose of gas engines. This aim has most probably been achieved by now, so in 1999 two gas engines are being installed with output (guarantee data) of 1.3 MW_e. The electrical power efficiency calculated from fuel to electrical power is estimated at approx. 32%, based on the operating data for the gasification system and the data provided by the supplier of the engine. The future operating results shall prove whether the updraft gasification technology for CHP generation is now ready to be commercialised.

Two-Stage Downdraft Gasification Systems

Since the middle of the 1980's, the Technical University of Denmark in Lyngby has carried out research work in the field of the gasification of biomass. At the beginning, the activities were concentrated on the gasification of straw, and new processes were developed. The two-stage process has been named so because pyrolysis and char gasification processes are kept separate from one another. A system was constructed for 50 kW input, and for the first time the researchers succeeded in demonstrating the operation of an engine by using straw. Since then the researchers have focused on wood.

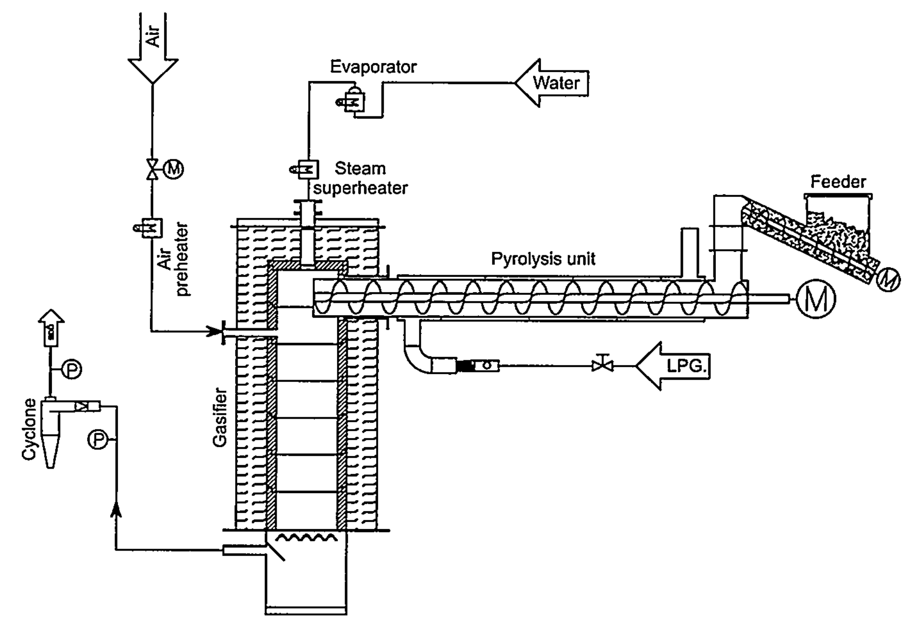
At present a system set-up of 100 kW input with a test engine connected to it has been installed at the Technical University of Denmark. Together with Maskinfabrikken REKA A/S, a complete system with 400 kW input capacity and a 100 kW gas engine has been constructed at a farm in Blære. The system in Blære has been operated for more than 100 hours generating CHP from the gas engine. The Technical University of Denmark has described in detail both the theoretical aspects and demonstrated the gasification process applied in practice, so the process should now be considered perfected. The practical tests have shown that the system is capable of producing perhaps the cleanest gas ever produced by a gasification system. It is also characterised by a high hydrogen content. The two-stage system can manage higher moisture contents in the fuels than other downdraft gasifiers, and due to the efficient gasification process, the condensate from the gas purifying plant is so purify that it most probably can be discharged without any further treatment. As the process uses exhaust heat from a connected engine as energy source for the pyrolysis, this gasifier has a high energy efficiency.

Downdraft Gasification (Co-Current Flow Gasification) in Høgild

The district heating system in the village Høgild has a downdraft gasification system as basic supply system. The system was built by Herning Kommunale Værker. When the gas from the gasifier has been purified by passing a wet scrubber and a fine filter, it is used as a fuel in a gas engine coupled to an electric generator. As with the original downdraft gasifiers, the air is injected in the middle section of the system. The fuel is dried blocks of industrial wood, while it has not yet been possible to use forest chips with a good result. The gasifier was originally bought in France in 1993, but toward the end of 1997, it had to be totally replaced. Only the gas engine and fine filter from the French system was kept. As a replacement a new Danish construction of a downdraft gasifier from Hollensen Ingeniør- and Kedelfirma ApS (engineering and boiler enterprise) was installed. The retrofit system was put into operation in January 1998 and has already been operating for more than 1,500 hours generating electrical power /ref. 78/. Thus it is the system in Denmark so far (November 1998) with most hours of generating electrical power. The input is approx. 500 kW, while the electrical power output is approx. 120 kW. The electrical power efficiency is 19-22% according to information provided.

Open Core Downdraft Gasification (Co-Current Flow Gasification)

The development project that started as a pilot project with dk-TEKNIK ENERGY & ENVIRONMENT being the project manager, was based on the fuel charac-



graphics: dtu, institut for energiteknik

Figure 30: The Technical University of Denmark's 100 kW two-stage gasifier consists of a feeding system, a preheated pyrolysis unit, a gasification reactor, and air- and steam inlet. Wood chips are transported from the feeder to the pyrolysis tube. In the test system the pyrolysis tube is heated by the gas from a LPG-gas burner flowing in a vessel outside the pyrolysis tube; (in "real" systems exhaust gas is used). The pyrolysis products and char are fed from the top of the gasifier where air and pyrolysis gas mix. The gas so produced passes though the char and out though the gasifier reactor, whereby a cyclone separates the largest particles.

teristics of forest chips and the Open Core principle of gasification that had shown successful results abroad based on wood chips.

The concept behind the system is designed for ordinary wet forest chips that are dried in a rotary drum drier heated by residual heat from the gas engine before it reaches the gasifier. In 1995 the construction and testing of a pilot system with a gas generator and gas purifying at Zealand was implemented. The system input is 210 kW, and it is capable of operating a gas engine with an approx. 50 kW electric generator. In the developed Open Core gas generator, the air for the process is injected at several stages, so that a partial combustion of the pyrolysis gas takes place, similar to that of the Danish Technical University two-stage gasification system set-up, before it passes through the char bed.

So far the test system has had approx. 350 manned hours of operation in connection with testing. In November 1998 a gas engine was coupled to it in order to also acquire practical operating experiences with the engine. At the first actual start-up of the engine, it was operated non-stop for 24 hours before it was decided to stop the testing. This was followed up by operating testing over five days in December 1998, when 100 hours' non-stop successful test operating of the system was completed. Of the 100 hours, 86 hours were used for operating the engine.

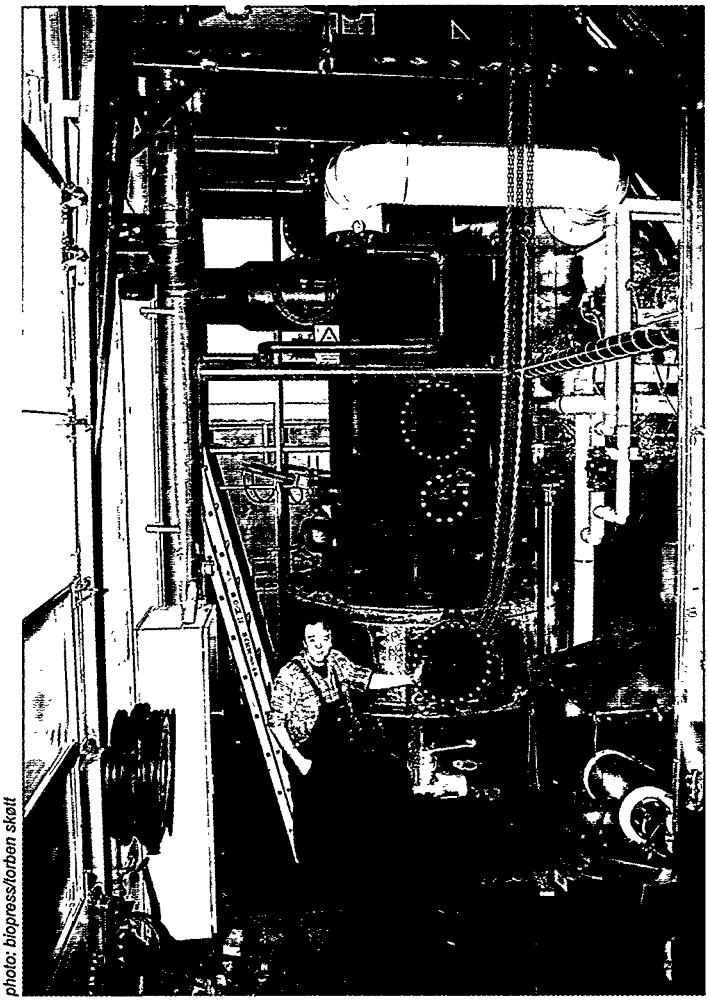


photo: biopress/torben skøtt

The gasification system in Høgild is now a retrofit system which fully meets the Danish standard. Preben Jensen from Herning Kommunale Værker in front of the new gasifier.

New Gasification Projects

At the end of 1998, several new gasification projects were implemented.

Thomas Koch Energy A/S is developing a downdraft (co-current) two-stage Open Core gasifier based on De La Cotte's principle. The gasifier will generate electrical power in the range of 50-1,000 kW_e and use wood chips as a fuel. The gasifier consists of an internally heated pyrolysis unit that is situated above a combustion chamber and en char gasifier. In the pyrolysis unit the wood chips are separated into tarry gas and char. The tarry gas is burnt in the combustion chamber, and the char is gasified by means of the heat from the burning of the gas. Gas passes via a cyclone, a cooler, and a filter to an engine, where electrical power and heat are generated. The system rated output is 60 kW_e, and it is financed by the Danish Energy Agency and Thomas Koch Energy A/S and is expected to be put into operation in August 1999.

Danish Fluid Bed Technology ApS (DFBT) and the Technical University of Denmark, Institute for Energy Technology, carry on a project supported by the Danish Energy Board for testing and further developing an innovative circulating fluidized bed (CFB) gasifier. Initially, the intention behind the gasifier is to use it as a so-called coupled gasifier, i.e. for co-firing with straw at power plants. The gasifier can operate at relatively low temperatures, thereby avoiding both problematic ash melting and crude gas cooling. It is expected that the concept will be suitable for other types of biomass, including pulverised dry wood. The construction height will be considerably lower than in normal CFB-gasifiers which will hopefully contribute to making the gasifier competitive in sizes down to an input of 1-2 MW. Thus combustible gas can be produced for e.g. small boilers, indirectly fired gas turbines, and (larger) Stirling engines. At present a test system is being constructed for inputs in the range of 50-75 kW at the Danish Technical University, and the first operating experiences based on straw will be available in the spring of 1999.

KN Consult ApS has been granted an amount of money by the Ministry of Environment and Energy for dimensioning, constructing and testing a 150 kW test gasifier for the gasification of straw according to the principle of updraft gasification. The test gasifier is a pilot project of the actual project "Updraft gasification of straw" that deals with dimensioning and putting into operation a 500 kW test system for the gasification of straw. The work will be carried out in co-operation with KN Consult Polska Sp. z o.o. in Poland, and the results of the 150 kW system will be available during 1999.

CHP with Combustion

The hot flue gases from the conventional combustion of biomass in boiler systems can also be utilised for small scale CHP generation. Two projects under development concerning a Stirling engine and a steam engine respectively will prove it in practice.

Stirling Engine

In the Stirling engine there is no combustible gaseous fuel mixture in the engine cylinders, but only a gas as the working fluid which is heated and cooled by turns. The heat for the Stirling engine working fluid comes from the combustion process as known from conventional grate fired systems. The transfer of the heat from the combustion process to the engine working fluid takes place by means of a heat exchanger.

At the Technical University of Denmark, a project is underway on the development of three engines with electrical power outputs of 9, 35, and 150 kW respectively. The 9 kW_e engine is designed for gaseous fuels, e.g. natural gas and biogas and will not be described in more detail. The 35 kW_e engine is supported by the Danish Energy Agency, and the project is carried through in co-operation with the enterprises Danstoker a•s, I.B. Bruun, and Klee & Weilbach. Maskinfabrikken REKA A/S, has developed the combustion unit for the first system in co-operation with Planenergi A/S. Ansaldo Vølund R&D is developing the combustion unit for the next system.

The design of a 150 kW engine was carried out with support from ELKRAFT A.m.b.a., but in 1998, the work was suspended, the reason being that the decision whether or not to manufacture a prototype is awaiting the experiences acquired from operating the 35 kW_e engines.

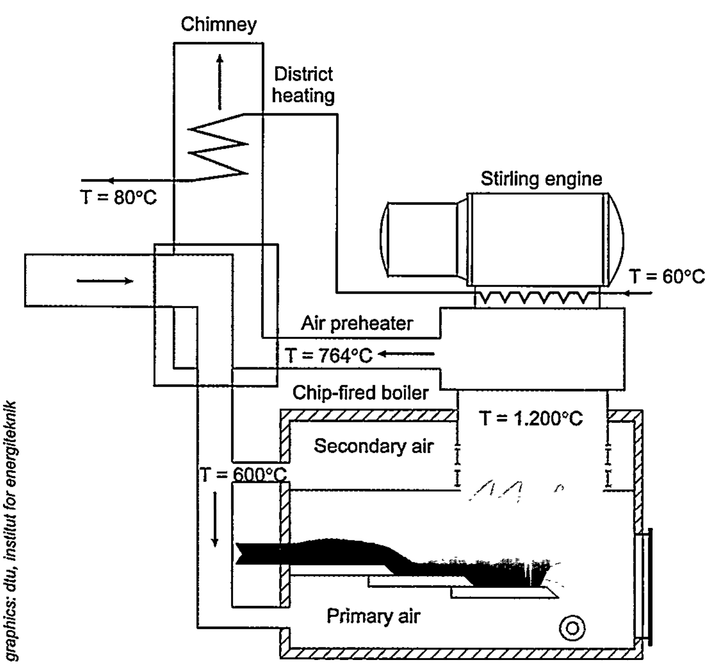
The Danish Technical University's Stirling engine is designed for the purpose of utilising biomass only. The heating surface design is based on the experiences acquired from the kind of biomass systems that are working at high temperatures. It is characteristic for the Danish Technical University's engine that it is hermetical in the same way as a hermetical refrigerator compressor. The electric cable is the only external connection, and even the cable entry point has been sealed. Inside the pressurised engine casing are both the engine mechanical parts, which have greased bearings, and the electric generator itself. The difficulties in connection with leakage of working fluid (gas or oil) in the working spaces, troubling other Stirling engine producers, have been avoided.

A high temperature at the heating surfaces is decisive for a high engine efficiency. In practice this means 650-700 °C, so when the flue gas leaves the heating surface, it still contains much energy. When leaving the engine, the hot flue gas can be utilised for preheating the combustion air, and not until then is the remaining part of the flue gas heat used in a boiler. The hot combustion air exhausted by the engine increases the entire temperature level in the combustion system and makes heavy demands of the combustion chamber design and the choice of material. The risks of slagging and deposits on the engine heating surfaces have been taken into account when designing the combustion system for the engine. The heating surfaces have also been designed with the particle content in the flue gas in mind. Large dimensions and large spaces between the heating surface tubes have been used in order to avoid depositions clogging it.

A complete demo plant with 35 kW_e engine for firing with forest chips has been developed and put into operation. The system is set up at a farm in Salling, and so far it has operated for approx. 700 hours (September 1998) for CHP generation. It is perhaps the first Stirling engine in the world that has demonstrated unmanned automatic operation for a long period of time with forest chips as a fuel. The electrical power efficiency is 18-19% when operating on forest chips with a moisture content of 49%. Overall fuel utilisation efficiency is more than 90%. It has only been necessary to purify the engine heating surfaces once after approx. 500 hours' operation /ref. 79/. With this construction the problems of dust and slagging that can otherwise close the heating surfaces by depositing, have been avoided, nor is there any sign of corrosion. The positive experiences acquired from this heating surface design are among the most important partial aims of the project. The testing has also proven that the system is capable of using wood chips and bark with a moisture content of up to 60%. It is most probably the powerful preheating of the air that contributes to the system capability of coping with the above-mentioned fuel moisture contents.

If including the initial engine testing on natural gas, the system has operated for more than 1,000 hours. This is an impressive performance that can be considered a major breakthrough for the Stirling engine, and the Danish Technical University's engine thus seems a really promising system for small scale CHP generation.

A new 35 kW_e engine subsidised by the Danish Energy Agency is being developed. Based on experiences acquired from the first 35 kW_e engine, the engine design has been modified. The new engine is much simpler to construct and assemble than the first prototype. At the same time it is expected that the new en-



graphics: dtu, institut for energiteknik

Figure 31: The heating system of the first Stirling engine is based on a conventional boiler, which has been modified so that the ash particles do not deposit on the engine heating surfaces. The electric generator is built into the engine, so that all its moving parts are under pressure and leakage avoided.

gine has improved efficiencies. The engine is equipped with a high temperature gas burner and an updraft gasifier for wood chips, developed by Ansaldo Vølund R & D. The system is expected to be ready for testing during the second half of 1999.

Steam Engine

Steam engines represent a familiar technique invented before the combustion engine. It is in fact considered the starter of the Western industrialisation, because it efficiently - by the standards of that time - could supply mechanical energy to the machines of industry. Today there is still a potential of the steam engine in small scale CHP.

With a view to producing a modern steam engine, a prototype is in the process of development by Milton Andersen A/S and dk-TEKNIK ENERGY & ENVIRONMENT. The aim is to avoid the technical drawbacks and low efficiencies which previously were connected with steam engines. The project is supported by the Danish Energy Agency and EU.

The main problems associated with the old types of engines were that lubricating oil leakages at the cylinders spoiled the steam quality, and that the old-fashioned slide-valve gear resulted in low efficiencies.

A two cylinder prototype has been constructed with a steam pressure of 24 bar and a steam temperature of 380 °C with oil-free piston rings of graphite and computer supervised servo-hydraulically controlled valves. The prototype is rated for an output of 500 kW_e. The initial testing of the prototype has been carried through, and it is now being connected to a steam supply at an industrial enterprise with a view to load testing and perhaps long-time testing of the engine.

11. Table of References

The table of references contains titles of literature referred to in this brochure. Further references, table of books, prices etc. can be requested through the Centre for Biomass Technology.

1. Energiministeriet 1990: Energi 2000. Handlingsplan for en bæredygtig udvikling. - Energiministeriet.
2. Miljø- & Energiministeriet 1996: Energi 21. Regeringens energihandlingsplan 1996. - Miljø- & Energiministeriet. 77 p.
3. Kommissionen for de europæiske fællesskaber 1997: Energi for fremtiden: Vedvarende energikilder. Hvidbog vedrørende en strategi og handlingsplan på fællesskabsplan. - Kommissionen for de europæiske fællesskaber.
4. Danske Fjernvarmeværkers Forening 1999: Brændselsstatistik nr. 114 pr. 1. januar 1999. - Danske Fjernvarmeværkers Forening, Kolding. 5 p. + bilag.
5. Energiministerens skrivelse af 13. september 1990 om generelle og specifikke forudsætninger for brændselsvalg og samproduktion i fjernvarmeværker.
6. Energistyrelsen 1995: Bioenergi udviklingsprogram. - Energistyrelsen.
7. Energistyrelsen 1998: Energistatistik 1997. - Energistyrelsen, Miljø- & Energiministeriet. 24 p.
8. Danmarks Statistik (mange årgange): Landbrugsstatistik, Hugsten i skove og plantager. - Danmarks Statistik.
9. Houmøller, S. 1995: Kedler, brændeovne, pejse, forbrug af brænde og forbrugsvaner - en del af informationskampagnen "Fyr bare løs". - dk-TEKNIK, Søborg. 21 p. + bilag.
10. Lind, C. H. 1994: Træbrændselsressourcer fra danske skove over 1/2 ha - Opgørelse og prognose. - Skovbrugsserien nr. 10. Forskningscentret for Skov & Landskab, Landbrugsministeriet. 103 p. + appendiks A-P.
11. Lind, C. H. & K. Suadicani 1995: Træressourcer i de danske skove over 1/2 ha. - Videnblade Skovbrug nr. 10.4-1. Forskningscentret for Skov & Landskab, Hørsholm. 2 p.
12. Miljø- og Energiministeriet 1989: Skovlov. Lov nr. 383 af 7.6.1989. Ændret ved lov nr. 392 af 22.5.1996. - Miljø- og Energiministeriet.
13. Miljøministeriet 1994: Strategi for bæredygtig skovdrift. Betænkning nr. 1267. - Miljøministeriet, Skov- og Naturstyrelsen. 217 p.
14. Energistyrelsen 1996: Danmarks vedvarende energiressourcer. - Energistyrelsen, Miljø- og Energiministeriet. 53 p.
15. Gamborg, C. 1996: Skovrejsning og energiskov - produktion, miljø og økonomi. Skovbrugsserien nr. 17-1996, Forskningscentret for Skov & Landskab, Hørsholm 1996. 228 p., ill.
16. Skov- og Naturstyrelsen 1998: Skovrejsning. Vejledning. - Miljø- og Energiministeriet. Skov- og Naturstyrelsen. 31 p.
17. Heding, N. & Matthesen, P. 1994: Energipil. - Videnblade Skovbrug nr. 3.1-1. Forskningscentret for Skov & Landskab, Lyngby. 2 p.
18. Sunde, K. 1998: Pileplantning - Ny tilplantningsteknik. - Forskningscentret for Skov & Landskab, Hørsholm. 25 p. + bilag.
19. Landskontoret for Planteavl 1996: Dyrkningsvejledning - pil 1996. - Landskontoret for Planteavl, Århus. 2 p.
20. Nielsen, K. H. 1996: Virkning af slamgødskning på det omgivende miljø og på biomassekvantitet og -kvalitet i energiskove af pil. - Forskningsserien nr. 16-1996, Forskningscentret for Skov & Landskab, Hørsholm. 111 p. + bilag.
21. Kofman, P. D. & Spinelli, R. 1997: Storage and Handling of Willow from Short Rotation Coppice. 118 p., ill.
22. Morsing, M. & K. H. Nielsen 1995: Tørstofproduktionen i danske pilekulturer 1989-94. - Skovbrugsserien nr. 13-1995, Forskningscentret for Skov & Landskab, Hørsholm 1995. 36 p. + bilag.
23. Gamborg, C. & Stenholm, M. 1998: Fysisk karakterisering af træbrændsler. - Skovbrugsserien nr. 24-1998, Forskningscentret for Skov & Landskab, Hørsholm. 133 p.
24. Heding, N. 1995. Granbrænde. - Videnblade Skovbrug nr. 7.4-2. Forskningscentret for Skov & Landskab, Hørsholm. 2 p.
25. Heding, N. 1994: Fornuftig brændefyring. - Videnblade Skovbrug nr. 7.9-1. Forskningscentret for Skov & Landskab, Hørsholm. 2 p.
26. Danske Skoves Handelsudvalg 1987: Norm nr. 1 for bestemmelse af kvaliteten på brændselsflis med hensyn til størrelsesfordelingen. - Danske Skoves Handelsudvalg, Dansk Skovforening, Frederiksberg. 2 p.
27. Heding, N. 1996. Om træaske. - Videnblade Skovbrug nr. 4.9-4. Forskningscentret for Skov & Landskab, Hørsholm. 2 p.
28. Videncenter for Halm- og Flisfyring 1994: Anlægs- og driftsdata for flisfyrede varmeværker 1993. - Videncenter for Halm- og Flisfyring. 40 p.

29. Ringman, M. 1996: Trädbränslesortiment. Definitioner och egenskaper. - Rapport nr. 250, Institutionen för virkeslära, Sveriges Lantbruksuniversitet (SLU), Uppsala. 125 p.

30. Vinterbäck, J. 1996: Pelleteldning i villa - ett konkurrenskraftigt alternativ. FaktaSkog nr. 17-1996, Sveriges Lantbruksuniversitet, Alnarp. 4 p.

31. Bekendtgørelse nr. 638 af 3. juli 1997 om biomasseaffald.

32. Kofman, P. D. 1989: Integreret skovning af brændselsflis og industritræ. Skovteknisk Institut 1-1989. 37 p., ill.

33. Hansen, E. B. 1995: Forsyningskæder for træ. - Skovbrugsserien nr. 14-1995, Forskningscentret for Skov & Landskab, Hørsholm, 1995. 87 p., ill.

34. Kofman, P. D. 1992: Fyring med flis i varme- og kraftvarmeværker. - Skovbrugsserien nr. 1-1992, Forskningscentret for Skov- & Landskab, Hørsholm, 1992. 90 p., ill.

35. Kofman, P. D. 1989: Lagring af flis i skoven. Skoven (6/7):236-237.

36. Nielsen, K. H. 1989: Storage of Chips under Roof. Research report nr. 6, Danish Institute of Forest Technology, 36 p.

37. Kofman, P.D. 1993: Flishugning. *Dokumentation af nuværende* systemer. Maskinrapport nr. 12, Skov- og Naturstyrelsen. 39 p.

38. Videncenter for Halm- og Flisfyring 1993: Opmåling af brænde. - Videnblad nr. 68. Videncenter for Halm- og Flisfyring. 2 p.

39. Heding, N. 1992: Brænde. - Videnblade Skovbrug nr. 7.4-1, Forskningscentret for Skov & Landskab, Hørsholm, 2 p.

40. Videncenter for Halm- og Flisfyring 1996: Brændværdier. - Videnblad nr. 107. Videncenter for Halm- og Flisfyring. 2 p.

41. Heding, N. & Løyche, M. 1984: Om rødgrannåles mængde og næringsindhold. - Dansk Skovforenings Tidsskrift 69: 302-306.

42. Beier, C., Gundersen, P. & Møller, I. S. 1995: Fjernelse af næringsstoffer med flisning. - Videnblade Skovbrug 6.3-9, Forskningscentret for Skov & Landskab, Hørsholm. 2 p.

43. Malmberg, P. & Rask-Andersen, A. 1988: Natural and adaptive immune reactions to inhaled microorganisms in the lungs of farmers. Scandinavian Journal of Work, Environment and Health, 14 (1):68-71.

44. Lacey, J. & Crook, B. 1988: Fungal and actinomycete spores as pollutants of the workplace and occupational allergens. Annals of occupational Hygiene, 32 (4):515-533.

45. Rask-Andersen, A. & Malmberg, P. 1990: Organic Dust Toxic Syndrome in Swedish Farmers: Symptoms, Clinical Findings, and Exposure in 98 Cases. American Journal of Industrial Medicine, 17, p. 116-117.

46. Butcher, B.T. & Doll, N.J. 1985: Respiratory Responses to Inhaled Small Organic Molecules and Related Agents Encountered in the Workplace. Clinical Reviews in Allergy, 3:351-361.

47. Lund-Larsen, J. 1996: Regler om arbejdsmiljø. Landbrug og maskinstationer. Specialarbejder-forbundet i Danmark, København. 99 p.

48. Falster, H. 1989: Fyringsteknologi, andre brændsler. In: Bech, N. & Dahlin, J. (ed.) 1989. Forbrænding i teori og praksis. Polyteknisk Forlag.

49. Falster, H. 1996: Brændsler, forbrændingsteknologi og rensning. Kompendium til kursus i Teknik og grønne afgifter, dk-TEKNIK.

50. dk-TEKNIK, Elkraft, Elsam, Risø 1996: Biomasses brændsels- og fyringskarakteristika. - dk-TEKNIK, Elkraft, Elsam, Risø.

51. Videncenter for Halm- og Flisfyring 1996: Træflis - kemisk sammensætning. - Videnblad nr. 106. Videncenter for Halm- og Flisfyring. 2 p.

52. Dansk Teknologisk Institut 1997: Installationsvejledning - træfyring/oliefyring. 1. udgave. Dansk Teknologisk Institut, Århus. 51 p.

53. Arbejdstilsynet 1980: Forskrifter for fyrede varmtvandsanlæg. 2.udgave, Arbejdstilsynets publikation nr. 42.

54. Dansk Brandteknisk Institut 1998: Biobrændselsfyrede centralvarmekedler. 1. udgave, Dansk Brandteknisk Instituts publikation nr. 32.

55. Dansk Teknologisk Institut 1998: Prøvningsforskrift i forbindelse med prøvning og godkendelse af mindre biobrændselskedler. 3. udgave. - Dansk Teknologisk Institut.

56. Informationssekretariatet for Vedvarende Energi: Typegodkendte og tilskudsberettigede biobrændselsanlæg. Informationssekretariatet ændrede per 1.1.1999 navn til EnergiOplysningen.

57. Lov nr. 3 af 3. januar 1992 om statstilskud til fremme af decentral kraftvarme og udnyttelse af biobrændsler som ændret ved lov nr. 143 af 3. marts 1992.

58. Miljø- og energiministeriets bekendtgørelse nr. 864 af 17. november 1995 om statstilskud til energibesparelser m.v. i erhvervsvirksomheder.

59. Lovbekendtgørelse nr. 742 af 9 august 1996 om statstilskud til energibesparelser m.v. i erhvervsvirksomheder som ændret ved lov nr. 188 af 12. marts 1997 og lov nr. 480 af 1. juli 1998.

60. Videncenter for Halm- og Flisfyring 1998: Halm til energiformål. - Videncenter for Halm- og Flisfyring. 2. udgave. 55 p.

61. dk-Teknik, Energi og Miljø 1996: Støvemissionsvilkår for træfyrede anlæg mindre end 50 MW. - dk-Teknik Energi & Miljø. 41 p.

62. Jakobsen, H. H. 1995: Fyring med våd skovflis. dk-TEKNIK ENERGI & MILJØ. 83 p. + bilag.

63. Evald, A. 1998: Cadmium i aske fra halm og træ. - Fjernvarmen 37(9):26-28.

64. Miljøstyrelsen 1990: Begrænsning af luftforurening fra virksomheder. Vejledning nr. 6. - Miljøstyrelsen.

65. Videncenter for Halm- og Flisfyring 1998: Forholdsregler mod sodmedrivning i våde skorstene. - Videnblad nr. 124. Videncenter for Halm- og Flisfyring, 1 p.

66. Bekendtgørelse nr. 823 af 16. september 1996 om anvendelse af affaldsprodukter til jordbrugsformål. Ændret ved BEK nr. 567 af 3. juli 1997.

67. Videncenter for Halm- og Flisfyring 1998: Svovlindhold i halm, træflis og træpiller. - Videnblad nr. 126. Videncenter for Halm- og Flisfyring, 1998. 2 p.

68. Houmøller, S. 1996: Svovlbinding i aske fra biobrændsler - forundersøgelse. - dk-Teknik, Energi & Miljø. 11 p. + bilag.

69. Nussbaumer, T. 1997: Primary and secondary measures for NO_x reduction in biomass combustion. In: Development in Thermochemical Biomass Conversion. Blackie Academic, Chapman & Hall, London. p. 1447-1462.

70. Videncenter for Halm- og Flisfyring 1991: Derfor er en lav kulilte emission vigtig. Videnblad nr. 33. - Videncenter for Halm- og Flisfyring. 2 p.

71. Miljøstyrelsens vejledning nr. 5 1984.

72. Miljøstyrelsens vejledning nr. 6 1984.

73. Miljøstyrelsens vejledning nr. 5 1993.

74. Energistyrelsen 1988: Forsyningskatlog 1988. - Udgivet af Styregruppen for Forsyningskataloget, Energistyrelsen.

75. Videncenter for Halm- og Flisfyring 1997: Afskrivninger, henlæggelser, indexregulering. - Videnblad nr. 117. Videncenter for Halm- og Flisfyring. 2 p.

76. Energistyrelsen 1992: Fra planlægning til drift. Omstilling af fjernvarmeværker til kraftvarmeproduktion eller udnyttelse af biobrændsler. - Energistyrelsen. 77 p.

77. Norup, P.A.F. 1942: Gasgenerator - Elektricitet. - Selskabet til udgivelse af kulturskrifter.

78. Mouritsen, J. 1998: Forgasningsanlægget i Høgild. Præsenteret på efterårsmøde i "Opfølgningsprogrammet decentral kraftvarme på biobrændsler". - Energistyrelsen nov. 1998.

79. Carlsen, H. 1998: Status for stirlingmotor til flis. Præsenteret på efterårsmøde i "Opfølgningsprogrammet decentral kraftvarme på biobrændsler." - Energistyrelsen nov. 1998.

12. Further Information

The following list includes centres for technology, institutions, trade associations, and authorities that can give information and guidelines on the application of wood as a source of energy.

Centres for Biomass Technology are found at the following addresses:

Danish Technological Institute
Teknologiparken
Kongsvang Allé 29
DK-8000 Århus C
Tel: +45 8943 8556 Fax: +45 8943 8543
E-mail: biomass@dti.dk

dk-TEKNIK ENERGY & ENVIRONMENT
Gladsaxe Møllevej 15
DK-2860 Søborg
Tel: +45 3955 5999 Fax: +45 3969 6002
E-mail: viden@dk-TEKNIK.dk

Danish Institute of Agricultural Sciences
Research Centre Bygholm
Dept. of Agricultural Engineering
Schüttesvej 17
DK-8700 Horsens
Tel: +45 7560 2211 Fax: +45 7562 4880
E-mail: villy.nielsen@agrsci.dk

Danish Forest and Landscape Research Institute
Hørsholm Kongevej 11
DK-2970 Hørsholm
Tel: +45 4576 3200 Fax: +45 4576 3233
E-mail: nih@fsl.dk

Danish Energy Agency
Amaliegade 44
DK-1256 Copenhagen K
Tel: +45 3392 6700 Fax: +45 3311 4743
E-mail: ens@ens.dk

Danish Environmental Protection Agency
Strandgade 29
DK-1401 Copenhagen K
Tel: +45 3266 0100 Fax: +45 3266 0479
E-mail: mst@mst.dk

National Forest and Nature Agency
Haraldsgade 53
DK-2100 Copenhagen Ø
Tel: +45 3947 2000 Fax: +45 3927 9899
E-mail: sns@sns.dk

Danish Institute of Agricultural and Fisheries Economics
Gl. Køge Landevej 1-3
DK-2500 Valby
Tel: +45 3644 2080 Fax: +45 3644 1110
E-mail: diafe@sjfi.dk

Technical University of Denmark
Institut for Energiteknik
Bygning 404
DK-2800 Lyngby
Tel: +45 4593 2711 Fax: +45 4588 2421

National Energy Information Centre
Teknikerbyen 45
DK-2830 Virum
Tel: +45 7021 8010 Fax: +45 7021 8011
E-mail: energioplysningen@ens.dk

Associated Energy and Environment Offices
Preislers Plads 1
DK-8800 Viborg
Tel: +45 8725 2170 Fax: +45 8725 2165
E-mail: sek@sek.dk

Danish Directorate for Development
Strukturdirektoratet
Toldbogade 29
DK-1253 Copenhagen K
Tel: +45 3363 7300 Fax: +45 3363 7333
E-mail: ub@strukdir.dk

The Danish Forestry Society
Amalievej 20
DK-1875 Frederiksberg C
Tel: +45 3324 4266 Fax: +45 3324 0242
E-mail: info@skovenes-hus.dk

Danish Land Development Service
Klostermarken 12
DK-8800 Viborg
Tel: +45 8667 6111 Fax: +45 8667 5101
E-mail: sl-drift@hedeselskabet.dk

Danish Forestry Extension
Amalievej 20
DK-1875 Frederiksberg C
Tel: +45 3324 4266 Fax: +45 3324 1844
E-mail: skovdyrk@image.dk

ELKRAFT Power Company Ltd.
Lautruphøj 5
DK-2750 Ballerup
Tel: +45 4466 0022 Fax: +45 4465 6104
E-mail: elkraft@elkraft.dk

Electricity Utility Group ELSAM
Overgade 45
DK-7000 Fredericia
Tel: +45 7622 2000 Fax: +45 7622 2009
E-mail: info@elsam.dk

Danish District Heating Association
Galgebjergvej 44
DK-6000 Kolding
Tel: +45 7630 8000 Fax: +45 7552 8962
E-mail: dff@dff.dk

Association of Danish Manufacturers of Biomass Boilers
c/o Håndværksrådet
Amaliegade 31
DK-1256 Copenhagen K
Tel: +45 3393 2000 Fax: +45 3332 0174
E-mail: hvr@hvr.dk

The Association of Danish Manufacturers of Stoves
c/o Håndværksrådet
Amaliegade 31
DK-1256 Copenhagen K
Tel: +45 3393 2000 Fax: +45 3332 0174
E-mail: aagaard@hvr.dk

Dansk Skoventreprenør Forening
Illerbyvej 6
DK-8643 Ans
Tel: +45 8687 0982 Fax: +45 8687 0982
E-mail: dsf@po.ia.dk

Test Laboratory for Small Biofuel Boilers
Danish Technological Institute
Teknologiparken
Kongsvang Allé 29
DK-8000 Århus C
Tel: +45 8943 8556 Fax: +45 8943 8543

Dansk BioEnergi (magazine)
Forlaget BioPress
Vestre Skovvej 8
DK-8240 Risskov
Tel: +45 8617 3407 Fax: +45 8617 8507
E-mail: biopress@post4.tele.dk

13. List of Manufacturers - Chipping

Manufacturers, suppliers, and repairers of chippers and high-level tipping trailers for chipping.

Chippers

Agro Maskinimport A/S
Tranevej 4
DK-4100 Ringsted
Tel: +45 5761 2100

Doppstadt Danmark ApS
Hjulmagervej 9C
DK-7100 Vejle
Tel: +45 7585 9687

Hedetræ A/S
Herningvej 144
DK-6950 Ringkøbing
Tel: +45 9734 3111

Interforst K/S
Blåkildevej 8
DK-5610 Assens
Tel: +45 6479 1075

Linddana A/S
Ølholm Bygade 70
DK-7160 Tørring
Tel: +45 7580 5200

Maskinfabrikken LOMA
Lyngvejen 14
DK-4350 Uggerløse
Tel: +45 5918 8520

NHS Maskinfabrik A/S
Bergsøesvej 6
DK-8600 Silkeborg
Tel: +45 8681 0922

Nordisk Vermeer A/S
Paltholmvej 100
P.O. Box 138
DK-3520 Farum
Tel: +45 4295 1188

SC - Svend Carlsen A/S
Lunden 10
DK-5320 Agedrup
Tel: +45 6610 9200

Silvatec Skovmaskiner ApS
Fabriksvej 6
DK-9640 Farsø
Tel: +45 9863 2411

Sønderup Maskinhandel
Hjedsbæksvej 464
DK-9541 Suldrup
Tel: +45 9865 3255

Tim Environment Products A/S
Fabriksvej 13
DK-6980 Tim
Tel: +45 9674 7500

Chippers and High-level Trailers

H. A. Agro Service ApS
Hvidegaardsparken 69
DK-2800 Lyngby
Tel: +45 4588 4422

Spragelse Maskinfabrik
Vejlemosevej 14
DK-4160 Herlufmagle
Tel: +45 5764 2105

High-level Trailers

H-T Vogne
Thorsgade 4
DK-9620 Ålestrup
Tel: +45 9864 8899

Tim Maskinfabrik A/S
Fabriksvej 13
DK-6980 Tim
Tel: +45 9733 3144

14. List of Manufacturers - Wood-Firing

(T) = Supplier of wood-fired boilers with type approval (end 1998).
(DS) = Supplier of boilers with type approval according to Danish Standard (mid 1998).

Large Boiler Systems

Manufacturers, suppliers, and repairers of large, automatic feeding systems and boiler systems for wood chips and wood pellets. Some of the companies also supply systems for other biofuels.

Ansaldo Vølund A/S
Falkevej 2
DK-6705 Esbjerg Ø
Tel: +45 7614 3400

Danstoker a•s
Industrivej Nord 13, P.O. Box 160
DK-7400 Herning
Tel: +45 9712 6444

Euro Therm A/S
Søren Nymarksvej 25A
DK-8270 Højbjerg
Tel: +45 8629 9299

FLS miljø a/s
Teknikerbyen 25
DK-2830 Virum
Tel: +45 4585 7100

Hollensen Ingeniør- og Kedelfirma ApS
Drejervej 22
DK-7451 Sunds
Tel: +45 9714 2022

I.F. Energy Systems A/S
Avedøre Holme 88
DK-2650 Hvidovre
Tel: +45 3678 6633

Passat Energi A/S
Vestergade 36
DK-8830 Tjele
Tel: +45 8665 2100

Tjæreborg Industri A/S
Kærvej 19
DK-6731 Tjæreborg
Tel: +45 7517 5244

TP 2000 Stokerfyr
Gilbjergvej 9, P.O. Box 23
DK-6623 Vorbasse
Tel: +45 7533 3069

Weiss A/S
Plastvænget 13
DK-9560 Hadsund
Tel: +45 9652 0444

Small Boiler Systems

Manufacturers, suppliers, and repairers of boiler systems below 1 MW for wood chips, wood pellets, and fuelwood. Some of the companies also supply boiler systems for other biofuels.

Americoal Trading A/S
Langgade 33A
DK-8700 Horsens
Tel: +45 7565 4833

Argusfyr Energiteknik A.S.
Vibeholmsvej 16
DK-2605 Brøndby
Tel: +45 4343 2016

Bioenergirådgivning
Hobro Landevej 142
DK-8830 Tjele
Tel: +45 9854 4432

Brændstrup Smede- og Maskinværksted (T)
Røddingvej 7
DK-6630 Rødding
Tel: +45 7482 1334

Buskegård Skovmateriel
Buskevej 8
DK-3751 Østermarie
Tel: +45 5647 0434

Casus
Herstedøster Kirkestræde 1
DK-2620 Albertslund
Tel: +45 4342 0790

Dan Trim A/S (T)
Islandsvej 2
DK-7480 Vildbjerg
Tel: +45 9713 3400

EB Kedler (T)
Slotsherrensvej 112
DK-2720 Vanløse
Tel: +45 3871 3555

E. H. Stoker (T)
Hedevej 4
Barde
DK-6920 Videbæk
Tel: +45 9717 5427

E.L. Projekt (T)
Viborgvej 442
DK-8900 Randers
Tel: +45 8645 0134

Fladså Smedie ApS (T)
Hovedvejen 57
DK-4733 Tappernøje
Tel: +45 5596 6070

Himmestrup Smede- og Maskinværksted (T)
Himmestrupvej 33
DK-8850 Bjerringbro
Tel: +45 8668 6332

Hollensen Ingeniør- og Kedelfirma ApS
Drejervej 22
DK-7451 Sunds
Tel: +45 9714 2022

HS Kedler-Tarm A/S (T)
Smedevej 2
DK-6880 Tarm
Tel: +45 9737 1511

Interforst K/S
Blåkildevej 8
DK-5610 Assens
Tel: +45 6479 1075

Jens Andersens Maskinfabrik ApS (T)
Klintebjergvej 13
DK-5450 Otterup
Tel: +45 6482 1078

Justsen Energiteknik A/S
Grimhøjvej 11
DK-8220 Brabrand
Tel: +45 8626 0500

Jørna Stoker I/S (T)
Engvej 19
DK-7950 Erslev
Tel: +45 9774 6164

Karby Smede- og Maskinværksted I/S (T)
Næssundvej 440
DK-7960 Karby
Tel: +45 9776 1072

Kokholm Energi- & Miljøteknik A/S
Ådumvej 12
DK-6880 Tarm
Tel: +45 9737 2100

KV Varmeservice A/S
Engvangsvej 9
DK-8464 Galten
Tel: +45 8694 6665

LIN-KA Maskinfabrik A/S (T)
Nylandsvej 38
DK-6940 Lem
Tel: +45 9734 1655

Manna Stoker (T)
Jens Thisevej 5
DK-9700 Brønderslev
Tel: +45 9888 7266

Maskinfabrikken Cormall A/S (T)
Tornholm 3
DK-6400 Sønderborg
Tel: +45 7448 6111

Maskinfabrikken Faust ApS (T)
Vester Fjordvej 2
DK-9280 Storvorde
Tel: +45 9831 1055

Maskinfabrikken REKA A/S (T)
Vestvej 7
DK-9600 Aars
Tel: +45 9862 4011

MS-Stoker (T)
Rebslagervej 22
DK-7950 Erslev
Tel: +45 9774 1760

Multiservice ApS (T)
Borgervej 41
DK-9900 Frederikshavn
Tel: +45 9847 3211

Nr. Nissum Maskinværksted
Ringvej 20
DK-7620 Lemvig
Tel: +45 9789 1032

Overdahl Kedler ApS (T)
Hjallerupvej 21
DK-9320 Hjallerup
Tel: +45 9828 1606

Passat Energi A/S (T)
Vestergade 36
DK-8830 Tjele
Tel: +45 8665 2100

Pilevang A/S (T)
Havrebjergvej 57
DK-4100 Ringsted
Tel: +45 5761 1956

Primdahl & Haugesen I/S (T)
Holstebrovej 88
DK-7600 Struer
Tel: +45 8645 0082

Sydthy Maskincenter ApS (T)
Nørregade 15
DK-7760 Hurup Thy
Tel: +45 9795 1044

Twin Heat (T)
T. T. Smede- og Maskinværksted I/S
Nørrevangen 7
DK-9631 Gedsted
Tel: +45 9864 5222

Varmehuset A/S
Frichsvej 40A
DK-8600 Silkeborg
Tel: +45 8682 6355

Vølund Varmeteknik (T)
Brogårdsvej 7
DK-6920 Videbæk
Tel: +45 9717 2033

Fireplaces and Wood Stoves
Manufacturers, suppliers and repairers of fireplaces and wood stoves.

ABC Pejse Industri A/S (T)(DS)
Nydamsvej 53-55
DK-8362 Hørning
Tel: +45 8692 1833

Bandholm Maskinfabrik A/S (DS)
Birketvej 13
DK-4941 Bandholm
Tel: +45 5388 8018

Bioenergi (T)
Gammel Møllevej 39
DK-9640 Farsø
Tel: +45 9863 6580

Euro-flame A/S (DS)
Ahornsvinget 9
DK-7500 Holstebro
Tel: +45 9740 6616

Heta A/S (T)(DS)
Jupitervej 22
DK-7620 Lemvig
Tel: +45 9782 3666

Jydepejsen A/S (T)(DS)
Ahornsvinget 3-7
DK-7500 Holstebro
Tel: +45 9741 0099

Krog Iversen & Co. A/S (DS)
Glasvænget 3-9
DK-5492 Vissenbjerg
Tel: +45 6447 3131

Lotus Heating Systems A/S (T)
Stæremosen 22
DK-3250 Gilleleje
Tel: +45 4830 1071

Morsø Jernstøberi A/S (DS)
Furvej 6
DK-7900 Nykøbing Mors
Tel: +45 9669 1900

Rais A/S (DS)
Industrivej 20
DK-9900 Frederikshavn
Tel: +45 9847 9033

Wiking A/S
Nydamsvej 53-55
DK-8362 Hørning
Tel: +45 8692 1833

Westfire A/S
Borgmester Niels Jensensvej 21
DK-6800 Varde
Tel: +45 7522 5352

15. Survey of Chip and Wood Pellet-Fired Plants

The list includes plants that supply heat and power for collective district heating systems primarily using wood chips and wood pellets as a fuel. Several of the plants also use bark and wood waste from trade and industry, biogas, and straw. Information about boiler equipment, consumption of fuel etc. concerning many of the plants is set out in detail in /ref. 15.1/.

Wood Chip-Fired District Heating Plants

Plant	Address	Postal Code/Town	Telephone
Allingåbro Varmeværk	Granbakkevej 1	DK-8961 Allingaabro	+45 8648 0122
Assens Fjernvarme	Fabriksvej 5	DK-9550 Mariager	+45 9858 3866
Blåhøj Energiselskab	Sdr. Omme Vej 38	DK-7330 Brande	+45 7534 5521
Byrum Varmeværk	Gydensvej	DK-9940 Byrum	+45 3096 0817
Bækmarksbro Varmeværk	Bækmarksbrovej 4	DK-7660 Bækmarksbro	+45 9788 1072
Farsø Fjernvarmeværk	Johan Skjoldborgsvej 12	DK-9640 Farsø	+45 9863 1419
Filskov Energiselskab	Hjortlundvej 13B	DK-7200 Grindsted	+45 7534 8348
Fjerritslev Fjernvarme	Industrivej 27	DK-9690 Fjerritslev	+45 9821 1309
Galten Varmeværk	Skolebakken 29	DK-8464 Galten	+45 8694 3320
Gilleleje Flisværk	Fiskerengen 2	DK-3250 Gilleleje	+45 4830 0761
Glesborg Lokalvarmeværk	Haandværkervej 3	DK-8585 Glesborg	+45 8739 0404
Græsted Fjernvarme	Mesterbuen 8	DK-3230 Græsted	+45 4839 4580
Gørding Varmeværk	Nørregade 55	DK-6690 Gørding	+45 7517 8036
Harboøre Varmeværk	Industrivej 1	DK-7673 Harboøre	+45 9783 5200
Hemmet Varmeværk	Bandsbølvej (Lyngbyvej 1)	DK-6893 Hemmet	+45 9737 5413
Hinnerup Fjernvarme	Fanøvej 15	DK-8382 Hinnerup	+45 8698 5340
Hodsager Energiselskab	Hestbjergvej 1A	DK-7490 Aulum	+45 9747 6499
Hovedgaard Fjernvarmeværk	Frydsvej 18	DK-8732 Hovedgaard	+45 7566 1296
Hurup Fjernvarmeværk	Nygade 22	DK-7760 Hurup	+45 9795 1522
Kibæk Varmeværk	Energivej 6	DK-6933 Kibæk	+45 9719 1436
Kjellerup Fjernvarmeværk	Tværgade 4	DK-8620 Kjellerup	+45 8688 1390
Løkken Varmeværk	Den skæve linie 7	DK-9480 Løkken	+45 9899 1220
Nørre Nebel Fjernvarme	Præstbølvej 9	DK-6830 Nørre Nebel	+45 7528 8040
Rosmus Skole	Bispemosevej 5	DK-8444 Balle	+45 8739 0404
Sdr. Felding Varmeværk	Bjergvej 33	DK-7280 Sdr. Felding	+45 9719 8272
Skave Varmecentral	Ravnshøjvej 1	DK-7500 Holstebro	+45 9746 8602
Skovsgård Varmeværk	Poststrædet 28	DK-9460 Brovst	+45 9823 1222
Skørping Varmeværk	Møldrupvej 2	DK-9520 Skørping	+45 9839 1437
Snertinge, Serslev, Føllenslev Energiselskab	Kirkemosevej 13	DK-4591 Føllenslev	+45 5926 7091
Stenvad Varmeværk	Stenvad Bygade 57	DK-8586 Ørum	+45 8739 0404
Stubbekøbing Fjernvarmeselskab	Asylvej 8A	DK-4850 Stubbekøbing	+45 5444 1544
Studsgård Biogasanlæg	Enghavevej 10	DK-7400 Herning	+45 9926 8211
Svebølle-Viskinge Fjernvarmeselskab	Frederiksberg 1D	DK-4470 Svebølle	+45 5929 4604
Søndbjerg Fjernvarme	Ballevej 19	DK-7790 Thyholm	+45 9787 5762
Thorsminde Varmeværk	Havnevej 11	DK-6990 Ulfborg	+45 9749 7313
Thyborøn Fjernvarme	Ærøvej 83	DK-7680 Thyborøn	+45 9783 2600

Trustrup-Lyngby Varmeværk	Tværvej 11	DK-8570 Trustrup	+45 8633 4399
Uldum Varmeværk	Industrisvinget 9	DK-7171 Uldum	+45 7567 8609
Ulfborg Fjernvarme	Sportsvej 2	DK-6990 Ulfborg	+45 9749 2458
Vemb Varmeværk	Vestergade 17	DK-7570 Vemb	+45 9748 1699
Vesløs Fjernvarmeværk	Møllebakvej 4	DK-7742 Vesløs	+45 9799 3033
Vestervig Fjernvarmeværk	Vestergade 14	DK-7770 Vestervig	+45 9794 1288
Vivild Holding A/S	C. M. Rasmussens Vej 5	DK-8961 Allingaabro	+45 8786 7199
Ørum Lokalvarmeværk	Industrivej 7	DK-8586 Ørum	+45 8739 0404
Østerild Fjernvarme	Hedevej 1	DK-7700 Thisted	+45 9799 7177
Aabybro Varmeværk	Industrivej 40	DK-9440 Aabybro	+45 9824 2330
Aalestrup Varmeværk	Elmegaardsvej 6	DK-9620 Aalestrup	+45 9864 1355

Wood Pellet-Fired District Heating Plants

Ansager Varmeværk	Østre Allé 2	DK-6823 Ansager	+45 7529 7701
Balling Fjernvarmeværk	Anlægsvej 1	DK-7860 Spøttrup	+45 9756 4505
Bedsted Fjernvarme	Balsbyvej 3	DK-7755 Bedsted	+45 9794 5046
Bøvlingbjerg Varmeværk	Marievej 3A	DK-7650 Bøvlingbjerg	+45 9788 5544
Dybvad Varmeværk	Jernbanegade 8A	DK-9352 Dybvad	+45 9886 4208
Ebeltoft Fjernvarmeværk	Hans Winthersvej 9-11	DK-8400 Ebeltoft	+45 8634 2655
Frederiksværk Kommunale Varmeværk	Havnevej 8	DK-3300 Frederiksværk	+45 4777 1022
Gjern Varmeværk	Bjerrehaven 7	DK-8883 Gjern	+45 8687 5293
Haunstrup Fjernvarmeværk	Fjelstervangvej 15	DK-7400 Herning	+45 9926 8211
Højslev Nr. Søby Fjernvarmeværk	Rolighedsvej 6	DK-7840 Højslev	+45 9753 5604
Lemvig Varmeværk	Industrivej 10	DK-7620 Lemvig	+45 9781 0233
Løgstør Fjernvarmeværk	Blekingevej 8	DK-9670 Løgstør	+45 9867 1258
Maribo Varmeværk	C. E. Christiansens Vej 40	DK-4930 Maribo	+45 5388 1226
Mørke Fjernvarmeselskab	Parkvej 10	DK-8544 Mørke	+45 8637 7230
Ry Varmeværk	Brunshøjvej 7	DK-8680 Ry	+45 8689 1365
Rødding Varmecentral	Bakkevej 22	DK-6630 Rødding	+45 7484 1670
Skive Fjernvarme	Thorsvej 11	DK-7800 Skive	+45 9752 0966
Skjern Fjernvarmecentral	Kongevej 41	DK-6900 Skjern	+45 9735 1444
Spøttrup Fjernvarme	Kærgaardsvej 2	DK-7861 Balling	+45 9756 1351
Sønder Omme Varmeværk	Farvergade 18	DK-7620 Sønder Omme	+45 7534 1246
Tarm Varmeværk	Skolegade 23	DK-6880 Tarm	+45 9737 1087
Ulsted Varmeværk	Stadionvej 11	DK-9370 Hals	+45 9825 4330

Wood Chip-Fired CHP Plants

Assens Fjernvarme	Stejlebjergvej 4	DK-5610 Assens	+45 6471 1024
Enstedværket	Flensborgvej 185	DK-6200 Aabenraa	+45 7431 4141
Hjordkær Kraftvarmeværk	Grønhøj 13	DK-6230 Rødekro	+45 7466 6747
Høgild Fjernvarmeværk	Skomagerbakken 15	DK-7400 Herning	+45 9926 8211
Masnedø Kraftvarmeværk	Brovejen 10	DK-4760 Vordingborg	+45 5537 0777
Måbjergværket	Energivej 2	DK-7500 Holstebro	+45 9740 6080
Vejen Kraftvarme	Koldingvej 30B	DK-6600 Vejen	+45 7536 7600
Østkraft, Rønne	Skansen 2	DK-3700 Rønne	+45 5695 1130

16. Units, Conversion Factors, and Calorific Values

Conversion factors concerning units of energy

1 kilojoule [kJ] = 1000 J
1 megajoule [MJ] = 1000 kJ
1 gigajoule [GJ] = 1000 MJ
1 terajoule [TJ] = 1000 GJ
1 petajoule [PJ] = 1000 TJ

1 kWh (kilowatt-hour) = 3.6 MJ = 860 kcal (kilogram calories)
1 MWh (megawatt-hour) = 3.6 GJ
1 GWh (gigawatt-hour) = 3.6 TJ
1 TWh (terawatt-hour) = 3.6 PJ

Conversion factors concerning units of power

1 kilowatt [kW] = 1000 W
1 megawatt [MW] = 1000 kW
1 gigawatt [GW] = 1000 MW
1 megajoule per second [MJ/s] = 1 MW
1 horsepower [HP] = 632 kcal/h = 0.735 kW

Conversion factors concerning quantities of wood chips, energy, and calorific value

Cubic content/weight:
1 cubic metre of solid wood chipped takes up approx. 2.8 cubic metres
1 cubic metre of wood chips contains approx. 0.35 cubic metre of solid wood
1 cubic metre of wood chips weighs approx. 250 kg*
1 cubic metre of solid wood chipped weighs approx. 700 kg*
1 tonne of wood chips fills approx. 4.0 cubic metre*
1 tonne of wood chips contains approx. 1.4 cubic metre solid wood *

Calorific value:
Calorific value in 1 cubic metre of wood chips = 2.6 GJ*
Calorific value in 1 cubic metre of solid content wood chips = 7.3 GJ*
Calorific value in 1 tonne of wood chips = 10.4 GJ*
1 megatonne (Mt.) (1 million tonnes of oil equivalent, crude oil) = 41.868 PJ
1 tonne of fuel oil = 42.7 GJ
1000 litres of fuel oil = 36.0 GJ
1 litre of fuel oil = 36.0 MJ = 10 kWh

** The calculations are based on wood chips of Norway spruce. The starting point is Norway spruce with a specific gravity (solid matter content) of 400 kg per cubic metre of solid wood and wood chips with a moisture content of approx. 40% which is equal to the moisture content in storage-dry wood chips.*