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Bioenergy for electricity and heat

- experiences from biomass-fired CHP plants in Denmark

VATTENFALL

DONG energy

Contents

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Foreword

In recent years, great efforts have been made to reduce CO_2 emissions and other greenhouse gasses with a view to limiting global warming. One of the measures is the use of CO_2 neutral biofuels such as wood and straw in the energy sector.

In 1993, the Danish parliament “Folketinget” instructed the Danish power plant companies to use 1.4 million tonnes of biomass for the production of electricity and heat and consequently replace a considerable quantity of coal. This goal is finally within reach.

Technically, it has been a huge challenge to use biomass for the production of electricity. This is particularly true of straw, which is both difficult to handle and has a high content of elements which are harmful to boiler plants. Through substantial development efforts with contributions from suppliers, power plants, universities, research centres and technological service institutions, it has been possible to develop reliable technologies which have been established and tested at the plants. In the process, a large number of research and development projects have been carried out with public support from eg gas and electricity transmission grid owners, the Danish Energy Agency and the EU.

With this publication, the power plant companies DONG Energy and Vattenfall wish to present the experience they have gained from 15 years of targeted efforts in connection with the establishment of biomass-fired CHP plants. Efforts which prove that with a successful cooperation between companies, authorities and public energy research programmes, it is possible to achieve significant results within the development of environmentally friendly energy technology.

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Anders Eldrup, DONG Energy　　*Bjarne Korshøj, Vattenfall*

Thirty years of Danish Energy Policy

– *with focus on security of supply, environment and climate*

30 years ago, the first energy plan, Danish Energy Policy 1976 (Dansk Energipolitik 1976), was introduced in Denmark and in the following decades, Denmark became known as a country with a very active energy policy with focus on efficient energy use, energy savings and renewable energy.

Before the energy crisis of 1973, approx. 90 per cent of the energy consumption was covered by imported oil, but today Denmark is more than self-sufficient in energy. The main reason is a considerable production of oil and natural gas from the North Sea, but the renewable energy resources also contribute significantly. In 2005, renewable energy contributed 126PJ, the production of natural gas 393PJ, while the oil production reached 796PJ. This should be compared with the energy consumption for the entire country at 830PJ - a self-sufficiency ratio of more than 150 per cent.

30 years ago, the energy policy mainly focused on security of supply. Later on, the environment became important and during the past few years, the climate commitments have had the highest priority. Today, the focus has returned to security of supply. We can see an end to the oil and gas adventure and the EU is becoming increasingly dependent on imported energy from especially the Middle East and Russia. Overall, the EU countries were only able to cover half of their own energy consumption in 2000 and if nothing is done, 70 per cent of the energy consumption must be imported in 2030.

Photo: Torben Skøtt/BioPress

After the energy crisis of 1973, coal became the preferred fuel at the power plants in Denmark. Later on, natural gas gained a foothold and today considerable quantities of biofuels are used at the power plants. This is a picture of the now closed CHP plant at the port of Aarhus, where straw-firing trials were carried out in the early 1990s.

The First Energy Plan

The energy crisis of 1973 came as rather a shock to the entire Western world. We came to realise how dependent we were on oil from the Middle East, and Denmark's first energy plan was consequently primarily based on security of supply. Instead of oil, Denmark had to increase its focus on natural gas, nuclear power, coal and renewable energy.

The result was a change in the electricity production to coal and increased use of natural gas and renewable energy. At the same time, the growth in the energy consumption was slowed down by means of energy-saving campaigns and financial management. The introduction of nuclear power was, however, temporarily postponed and later abandoned.

Already in 1979, Denmark experienced the second energy crisis as a result of the revolution in Iran. In this connection, the government entered into an agreement with Dansk Undergrunds Consortium on the purchase of 55 billion cubic metres of natural gas and later that year, the first Department of Energy was set up in Denmark.

Oil and Gas from the North Sea

In the next energy plan from 1981, the focus was still on limiting the import of fossil fuels, but socio-economic and environmental considerations were also given a high priority. The plan gave impetus to the development of the oil and gas fields in the North Sea, and the nationwide natural gas net was established. After Energy plan 81 (Energiplan 81), the first subsidy schemes for the utilisation of straw and wood chips were implemented and through increasing taxes on fossil fuels, biomass was made competitive as fuel. The first biomass-fired district heating plants were built, the number of farm-scale boilers within agriculture increased considerably and the consumption of fuelwood in private households gained momentum.

After years of discussions, the Danish parliament in 1985 decided to put a definitive end to the possible plans of nuclear power in Danish energy policy. In the same year, an international conference on the greenhouse effect, climate changes and ecosystems led to the political acknowledgement that the emission of carbon dioxide might become the future overriding problem for the energy sector.

In June 1986, the majority of the parties in the Danish parliament entered into an energy policy agreement which, among other things, involved the expansion of the electricity capacity by 1,000MW. The expansion was to be divided between new, large power plants and a number of small, local plants fired with natural gas, straw, wood chips, waste and biogas. As part of the agreement, it was also decided to initiate a pilot and demonstration programme for local CHP plants with a total capacity of 80-100MW.

The Brundtland Commission

In the spring of 1987, the so-called Brundtland Commission published the report "Our Common Future". The report focused on supporting sustainable development and, as a subobjective, it was mentioned that the energy consumption per capita in the industrialised countries was to be reduced by 50 per cent over 40 years to allow a growth in the developing countries of approx. 30 per cent.

In 1990, the Brundtland report gave rise to "Energy 2000 – An Action Plan for Sustainable Development" (Energi 2000). Now, the environment was given top priority. By 2005, the energy consumption was to be reduced by 15 per cent, the consumption of coal and oil was to be reduced by 45 and 40 per cent, respectively, and at the same time , natural gas and renewable energy were to take over a considerable part of the energy supply.

However, Energi 2000 did not include the transport sector. It subsequently had its own action plan with the objective of stabilising the energy consumption until 2005 and afterwards reducing it by 25 per cent before 2030. This later turned out to be a very difficult task. The energy consumption for transportation has increased considerably and there are no signs that it will be reduced by 25 per cent before 2030.

Photo: Mærsk Olie og Gas AS

The oil and gas production from the North Sea has made Denmark more than self-sufficient in energy. Here the platform for the DAN field is being hoisted into position.

The Heat Supply Act

To kick-start the activities suggested in Energi 2000, the Danish parliament passed the so-called Heat Supply Act in 1990, which gave the Minister for Energy extensive powers to regulate the choice of fuel at district heating plants and local CHP plants. On the basis of this Act, a large number of coal and natural gas-fired district heating plants have been converted to natural gas-fired local CHP plants. In addition, many

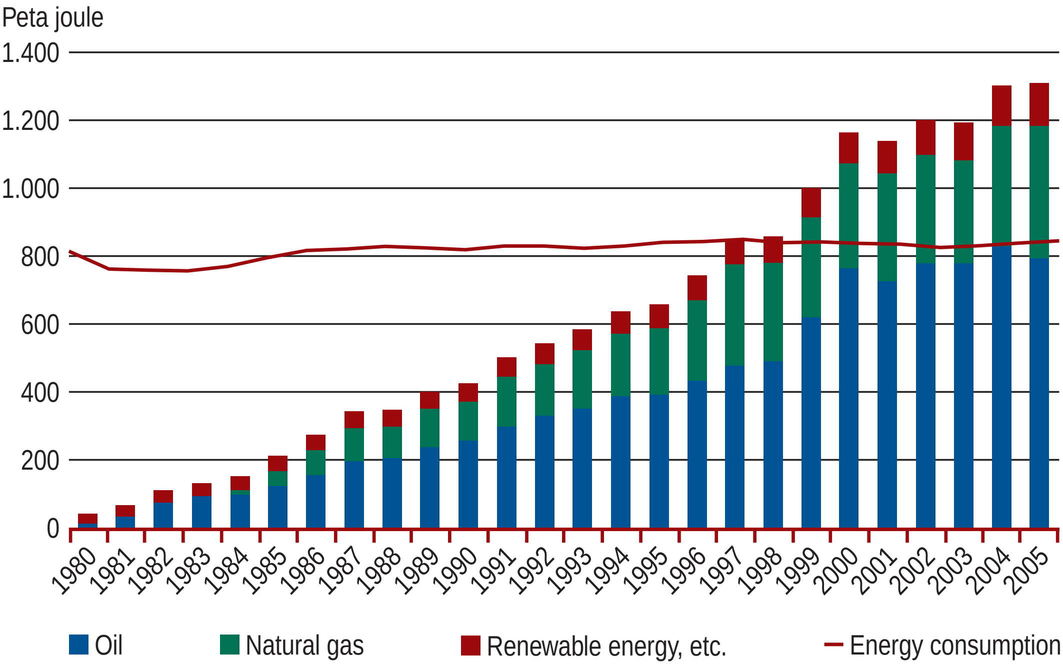


Figure 1.1. The energy production in Denmark from 1980 to 2006 compared with the adjusted energy consumption, i.e. the consumption adjusted for trade in electricity across borders and climate fluctuations compared with a normal year. In 1997, we became self-sufficient in energy for the first time in recent history and in 2005, we produced more than 150 per cent surplus energy. Source: The Danish Energy Agency.

Photo: Torben Skøtt/BioPress

The biomass plan of 1993 instructs the power plants to use 1.4 million tonnes of biomass a year, including at least one million tonnes of straw.

smaller district heating plants, outside the large district heating network, have been converted to biofuels.

Energi 21

The fourth of Denmark's six energy plans is Energi 21, which was introduced in 1996. The plan, among other things, contains a long-term objective stating that CO_2 emissions must be reduced by 50 per cent in 2030 compared with 1998. The objective is to be reached through energy savings, better exploitation of the energy resources and the contribution of 35 per cent of the gross energy consumption from renewable energy by 2030. The consumption of coal is to be almost completely phased out, while the consumption of oil and gas is expected to remain practically unchanged.

The Department of Energy Abolished

After the general election in November 2001, the Liberal Party and the Conservative Party formed a government and in this connection the Department of Energy was abolished and placed under the Ministry of Economy and Business Affairs. At the same time, the former energy policy pursued was drastically changed. Instead of fixed objectives and a tight control of the energy supply, it became increasingly up to the market to decide which energy sources to rely on.

This approach is again used in Energy Strategy 2025 (Energistrategi 2025), which was published in June 2005. Once again, it was established that it is primarily the market which is to determine the priority of the individual energy sources or in other words: the higher the prices of fossil energy, the greater the emphasis on energy savings and renewable energy.

However, in January 2007, the government introduced a completely new energy policy with the energy plan "A Visionary Danish Energy Policy" (En visionær dansk energipolitik). This plan contained specific objectives for making Denmark independent of fossil fuels such as coal, oil and natural gas. This will, for example, be achieved by:

- doubling the use of renewable energy from 15 per cent in 2005 to 30 per cent in 2025
- increasing the energy saving efforts amounting to annual savings equal to 1.25 per cent of the current energy consumption
- ensuring that 10 per cent of the fuel consumption of the transport sector is covered by biofuels in 2020
- doubling the investments in energy research to DKK 1 billion a year.

With this plan, the government expects the consumption of fossil fuels to be reduced by 15 per cent by 2025 and Denmark's total energy consumption in 2025 not to have increased since the mid-1970s, – in spite of economic growth and progress.

The Biomass Plan

To meet the targets laid down in Energi 2000, the majority of the parties in the Danish parliament entered into an agreement on 14 June 1993 on an increased use of biomass in the energy supply. A very important part of the agreement concerns the central power plants, which are placed under an obligation to apply 1.4 million tonnes of biomass a year, including at least one million tonnes of straw. Initially, the target was to have been reached by 2000, but the

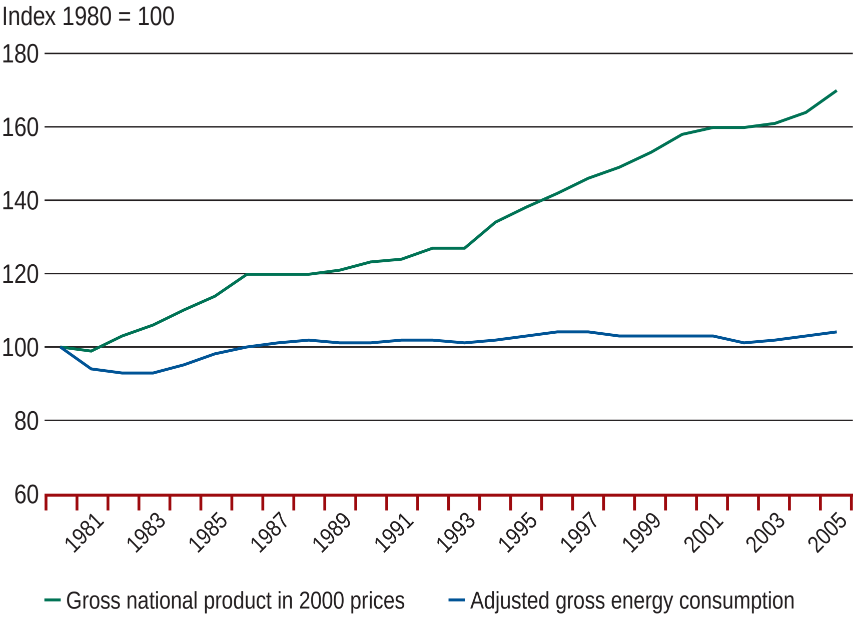


Figure 1.2. The development in Denmark's energy consumption and gross national product during the period from 1980 to 2006. As the figure shows, the gross national product has successfully been raised without an equivalent increase in the energy consumption. Source: The Danish Energy Agency.

agreement has been revised several times and the final elements are not expected to fall into place until 2009. This will happen when Fynsværket opens a new power plant unit capable of using 170,000 tonnes of straw a year.

The main reason for the postponements is that the electricity market is liberalised today, which was not the case in 1993 when the agreement was entered. Back then, the power plants could simply pass the bill on to the consumers, but this is not possible today with a free market for the purchase and sale of electricity. Instead, the state has chosen to provide subsidies to the biomass-fired plants, so that the power plants can continue to supply electricity at competitive prices. This agreement is acceptable to the state, the power plants and the consumers, but it has taken a long time to negotiate the various schemes into place.

The Kyoto Protocol

A few decades ago, the energy policy was considered primarily a national concern, but today it is very much international issues that create the framework for our arrangements in Denmark. The development in the global energy markets, the liberalisation of the energy sector and above all our climate obligations according to the Kyoto Protocol have increasingly influenced the Danish energy sector.

The objective of the Kyoto Protocol is that the industrialised countries on average during the period 2008-2012, are to reduce their emission of greenhouse gases by at least five per cent compared with the level in 1990.

The industrialised countries have different obligations. Overall, the EU has to reduce its emissions by eight per cent, but the individual member states have not assumed the same level of obligation. Thus Denmark and Germany aim to reduce their emissions by 21 per cent, while other countries such as Portugal, Spain and Greece are allowed to increase their emission of greenhouse gasses. The background to this is that Denmark and Germany in 1990 had significantly higher emissions of greenhouse gases per capita than the other EU countries and consequently we also have the best chances of reducing the emissions, for example by replacing coal with more environmentally friendly fuels.

CO_2 emission allowances

The most effective means of reducing the emission of greenhouse gasses is the so-called quota scheme, which today includes all EU member states. In Denmark, a considerable part of the energy sector and the energy heavy industry is covered by the scheme, which means that the companies every year have to obtain a quota covering the current CO_2 emission. If the CO_2 accounts do not balance, the balance must be restored either by reducing the company's CO_2 emission internally or by buying more quotas. Large emissions may be expensive, especially after 2008, where the penalty for discharging too much CO_2 is raised from EUR 40/ton to EUR 100/ton.

In the period from November 2005 to November 2006, the price of CO_2 emission allowances has fluctuated from DKK 75 to 225/ton. The higher the price, the more profitable it is to invest in energy saving measures and replace coal and oil with for example biofuels.

The Danish government has set an annual quota of 33.5 million tonnes of CO_2 in the period 2005-2007 for sectors that are included in the quota scheme. This equals a reduction of approx. 15 per cent compared with the expected emission in the period..

During the period from 2008 to 2012, the number of free quotas will be reduced by 25 per cent compared with 2005-2007. All other things being equal, this will make the quota price go up, thus making it more attractive to invest in energy savings and renewable energy. What is going to happen after 2012 is more uncertain, but there are indications that the quota system is here to stay and that the price of CO_2 emission allowances will increase in future years.

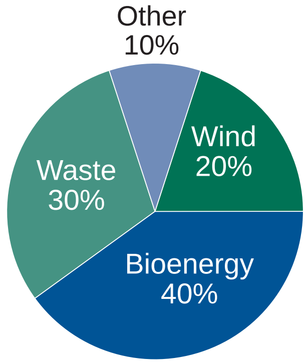


Figure 1.3. The distribution of renewable energy on the individual energy sources in 2005. The largest contribution comes from bioenergy followed by waste and wind. In total, renewable energy accounted for more than 15 per cent of the gross energy consumption in 2005. Source: The Danish Energy Agency.

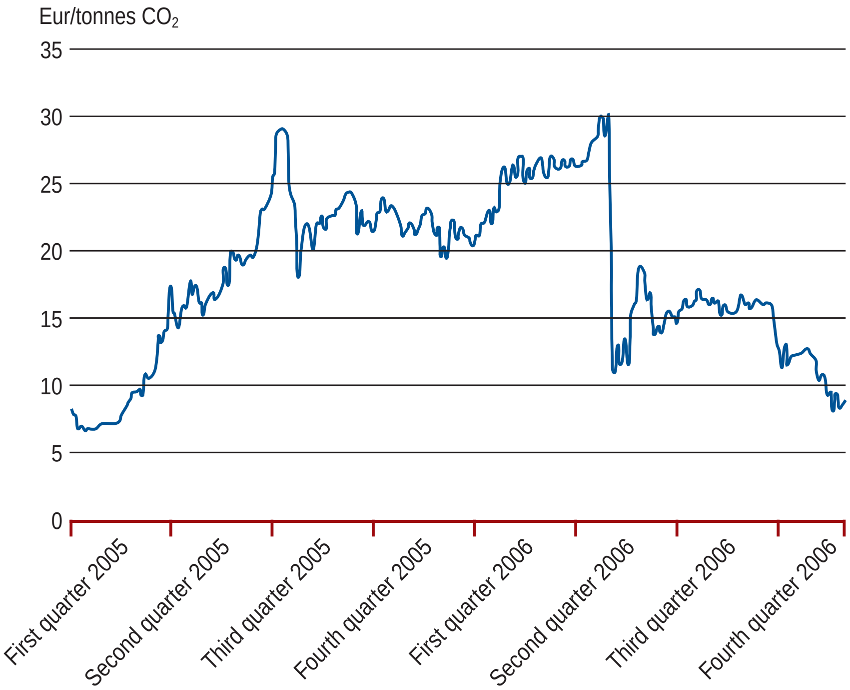


Figure 1.4. The price development of CO_2 emission allowances in 2005 and 2006. The higher the quota price, the more profitable it is to invest in energy saving measures and replace fossil fuels with renewable energy. Source: Nordpool.

Today, it is primarily residual products from farming and forestry which are used for energy purposes. Here the Danish Land Development Service is chipping thinning wood.

Photo: Torben Skøtt/BioPress

Biomass Resources

– with focus on straw and wood

Biomass is a general term for all plant and animal material. By means of photosynthesis, the plants convert the carbon dioxide, water and nutritive salts into organic matter in the form of carbohydrates. In this way, the energy of the sun is stored in the plants, which can subsequently be used by humans and animals.

Traditionally, biomass has been used for energy purposes for thousands of years and it is still one of the most frequently used energy sources in the world. A conservative estimate suggests that biomass covers approx. 12 per cent of the world's energy consumption. The developing countries cover approx. one third of their energy consumption by biomass and in the poorest countries, bioenergy represents up to 90 per cent of the energy supply.

Biomass is a CO_2 neutral energy source, as the plants collect an amount of CO_2 during the photosynthesis equal to the amount they emit when they are later used for energy purposes. The energy consumption used for collection and transport of the biomass will normally not be CO_2 neutral, but will only represent a few percentages of the energy content of the biomass.

Photo: Torben Skøtt/BioPress

The definition of when wood is biomass or waste varies from country to country.

When Is It Biomass?

The definition of what legally constitutes biomass may vary from country to country. In Denmark, the rules have been laid down in the so-called Biomass Executive Order of 1997. The order describes precisely which forms of biomass can be used for the production of energy without having to pay waste taxes for the state. This applies to straw, wood, wood waste with less than one per cent glue, pips or seeds from fruit, seed coats, grain, cotton, roof thatch, etc. The list seems extensive – even ice-cream sticks are included – but compared with several of our neighbouring countries, it is rather restrictive. To mention an example, crushed wooden pallets, windows and doors are defined as waste in Denmark, whereas these are defined as biomass in Sweden, Holland, and Germany.

World Resources

As biomass, in principle, includes all plant and animal material, the resources are enormous, but there is of course a limit to how much it is practically possible to use for energy purposes. A substantial proportion of the plants is used for food, animal feed and textiles. In addition, there is the issue of sustainable farming and the extent to which it is responsible to use nature areas for the production of biomass.

In theory, it will be possible to cover the entire world's energy consumption by biomass but in practice, this would hardly be possible. Already today, many people question whether it is responsible to use large areas for the production of energy crops, and there is considerable uncertainty about the possible sustainable production of biomass for energy purposes globally.

An OECD report from 2004 included a number of studies of the potential exploitation of bioenergy in 2025 and 2050, respectively. The figures vary between 72 and 145 exajoule for 2025, while the estimates for 2050 vary from 181 exajoule to 450 exajoule (see table 2.1). This should be compared with the global energy consumption in 2001 of 400 exajoule, 50 exajoule of which was produced by means of biomass.

Today, it is primarily residual products from farming and forestry which are used for energy purposes, but the borderlines are constantly changing, and it is expected that farmland will increasingly be used for the production of energy. It is primarily a matter of crops for the production of liquid biofuels, but the production of crops for biogas is also going well and for example in Sweden and England, willow growers supply wood chips for the power plants.

The growing of energy crops does not necessarily have to supplant the production of food. Through careful planning, it would often be possible to achieve higher production and more fertile farmland by combining the production of energy crops and traditional agricultural crops. The possibilities are endless, but it is important to choose crops with a limited need for fertilisers and pesticides.

Most countries have surplus areas where energy crops can be grown, but there are exceptions. In Asia, most countries have a larger consumption of biomass than they are capable of producing themselves, which means that it is necessary to import biomass to cover the need. The largest potentials can be found in the former Soviet Union, South America and North America, but Africa and Europe also have considerable resources. In many developing countries, the residual products from farming and forestry could cover the basic energy need of the local population and in industrial countries, it will often be possible to produce considerable quantities of biomass on the fields which have been lying fallow for the past few decades.

International Trade

Today, considerable quantities of biomass/waste are transported across the borders, primarily because the countries have their own rules specifying how biomass may be used in the energy supply. Overall, the trade in biomass has become quite diversified and volatile and for a number of years, the European organisation CEN has been working on preparing common standards for biofuel to facilitate the trade between the individual countries.

Survey	**2025**	**2050**
Shell (1996)	85EJ	200 – 220EJ
IPCC (1996)	72EJ	280EJ
Greenpeace (1993)	114EJ	181EJ
Johansson et al. (1993)	145EJ	206EJ
Dessus et al. (1992)	135EJ	–
Lashof and Tirpak (1991)	130EJ	215EJ
Fischer and Schrattenholzer	–	350 – 450EJ

Table 2.1. Surveys of the potential for using biomass for the production of energy in 2025 and 2050, respectively. In 2001, the world's total energy consumption amounted to 400 exajoule (EJ), 50EJ of which was produced by means of biomass. Source: Biomass and Agriculture – sustainability, markets and policies, OECD 2004.

So far, the international trade in biomass has almost exclusively involved wood supplied as pellets, wood chips, fuelwood or whole logs. However, nothing prevents other forms of biomass from being traded in a similar way, although this would probably require them to be processed into pellets to facilitate handling and reduce transport costs. For example, straw in the form of straw pellets could become an international commodity, with among others the Ukraine as a large-scale supplier.

The major manufacturers and buyers of biomass agree that the international trade in biofuel will develop considerably in the years to come. This is particularly true of wood pellets but, in principle, it would be possible to process most forms of biomass into pellets for sale internationally.

Photo: Torben Skøtt/BioPress

Today, wood for energy purposes is an international commodity. Wood pellets from Latvia being discharged in the port of Grenaa.

Biomass	Potential	Import (+) Export (-)	Consumption	Utilisation
Straw	55PJ	–	18PJ	33%
Wood	40PJ	14PJ	48PJ	120%
Biodegradable waste	30PJ	–	29PJ	97%
Biogas	40PJ	–	4PJ	10%
Biodiesel	–	- 3PJ	0PJ	–
Fish oil	1PJ	–	1PJ	100%
Total	**165PJ**	**11PJ**	**100PJ**	**–**

Table 2.2. Danish resources and consumption of biomass for energy purposes in 2005. Note the considerable import of wood today, primarily in the form of wood pellets. Source: The Danish Energy Agency.

Danish Resources

The Danish resources of biomass for the production of energy are estimated to approx. 165PJ a year, approx. half of which are used today (see table 2.2). In addition, there is considerable import of wood, primarily in the form of wood pellets, which means that the total consumption amounts to just under 100PJ. There is some uncertainty about the available quantities of biomass, especially wood, and it must be assumed that the prices will increase if all resources are fully used. The unused resources consist primarily of straw and especially animal manure, etc. for the production of biogas, where only about ten per cent is used today.

A number of residual products are available within the animal feed and food industry which, so far, have been considered uninteresting because there used to be plenty of straw and wood available. These products include grain residue, seed residue, husks from peas, soy, cocoa, sunflowers and coffee as well as waste from sugar beet, potatoes and tobacco. Several of these products are only available in limited quantities and as wet raw materials, but nevertheless they amount to approx. 300,000 tonnes a year, which means that several of them may become interesting in the long term.

As table 2.2 shows, there is considerable potential for using the large quantities of animal manure for the production of energy. Animal manure is particularly suitable for the production of biogas, but several biogas plants have started to separate the degassed manure into a solid and a liquid fraction. So far, both fractions have been used as manure, but today it is possible to use the solid fraction as fuel without having to pay taxes to the state.

In the long run, sea alga, in the form of for example sea lettuce, may also be used for the production of energy. According to the National Environmental Research Institute, it will be possible to harvest between 80,000 and 100,000 tonnes of sea lettuce in the Danish waters annually. This will provide valuable raw material for the production of, for example, bioethanol and result in reduced deoxygenation. The stench from many inlets and closed waters will also disappear.

Researchers at the National Environmental Research Institute are also working on developing systems which will make it possible to harvest sea lettuce in closed reservoirs. Technically, it is not particularly easy, but the perspectives are enormous, as it will be possible to harvest up to 500 tonnes of biomass per hectare or approx. 50 times the quantity that can be harvested in the traditional agricultural sector.

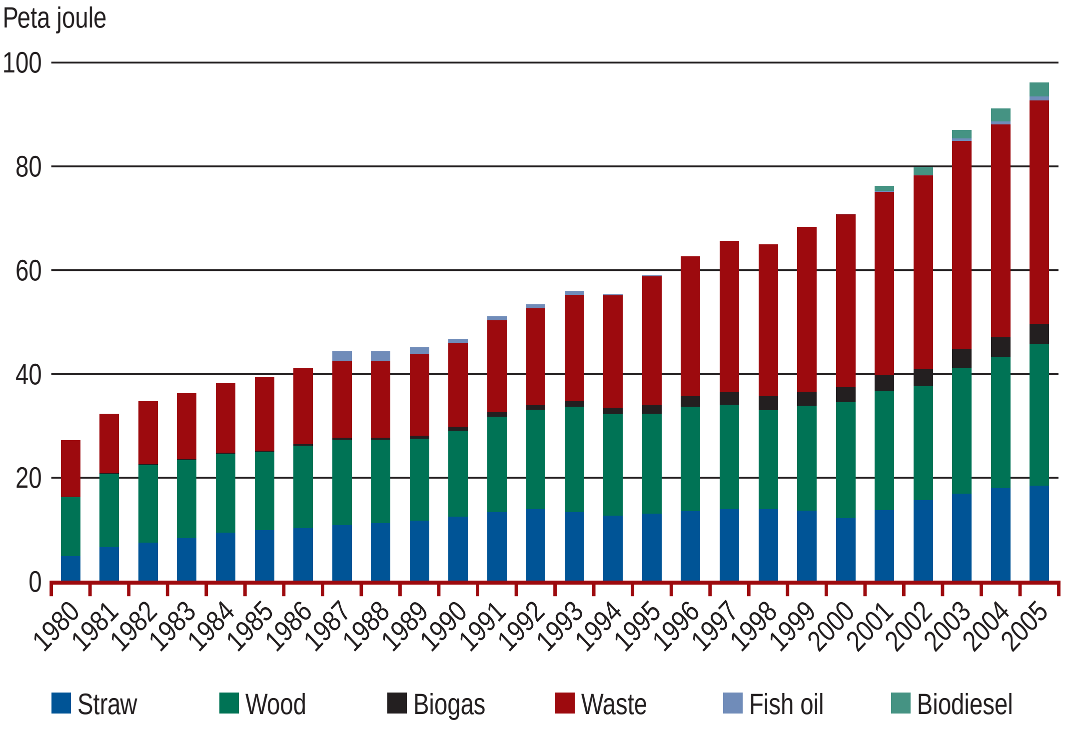


Figure 2.1. The energy production from biomass and waste in Denmark from 1980 to 2006. Source: The Danish Energy Agency.


Photo: Torben Skøtt/BioPress

Straw is primarily sold locally, which means that the prices will vary significantly in the various parts of the country. It is primarily a question of supply and demand and the quality of the straw that the farmer is able to deliver.

Straw for Energy Purposes

Straw is a residual product from the growing of grain and the annual production is consequently influenced by the weather and the current prices of grain. In addition, the current agriculture politics also play a part, including the size of areas which have lain fallow as well as environmentally friendly agriculture. Straw from rape and other seed-producing crops may also be used for energy purposes, but the quality is significantly inferior to straw from grain, which means that in practice it is only used to a limited extent.

In Denmark, approx. 25 per cent of the total straw production is used for energy purposes. Approx. one third forms part of the agricultural production as animal feed and bedding, while the rest is ploughed in. This means that there is still a considerable surplus of straw which can be used for the production of energy.

It is mainly the power plants which use straw as fuel. According to the latest energy statistics, more than 18 peta joule of straw was used as fuel in 2005. More than half of this was used by the power plants, while the rest was equally divided between the district heating plants and farms.

Straw Market

Straw is not an international commodity in the same way as wood chips and wood pellets. Straw is primarily sold locally, which means that there will often be a significant price differential between the various parts of the country. It is primarily a question of supply and demand and the quality of the straw that the farmer is able to deliver.

As straw has a relatively low calorific value based on volume and weight, the price of straw is sensitive to the distance to the power plant, which results in regional price differentials for straw.

Compared with fossil fuels, the price level has been very stable for the past 10-15 years, with an average price of approx. DKK 30/gigajoule. In the past few years, there has even been a tendency towards slightly declining prices despite the increasing demand. Previously, the prices were mainly determined in agreements lasting several years, but lately the tendency has been towards one-year agreements. Today, a small proportion of the straw is also sold on the spot market.

Danish straw suppliers have often criticised the power plants for abusing their dominance in the market to push down the prices to an unreasonably low level. This made the Danish Competition Authority carry out a detailed study in 2005, where information about prices and terms were obtained from the power producers Elsam and Energi E2 which, at that time, were responsible for purchase of straw for the power plants in West and East Denmark, respectively. The result of the survey was an agreement between the straw suppliers and the power plants, which describe in detail how the straw supply contracts must be formulated. Most of the straw has to be purchased through public tenders and all tenders must be treated equally. The tenders must not be negotiated between the power companies and the individual straw suppliers and the tenders must be opened in the presence of an independent controlling official.

Energy Wood

According to the latest survey of the energy production in Denmark, approx. 48 peta joule was used in 2005 on the basis of wood, 14 peta joule of which was imported. This corresponds to more than 40 per cent of the total contribution from renewable energy or significantly more than wind power, which represents 20 per cent of the renewable energy production.

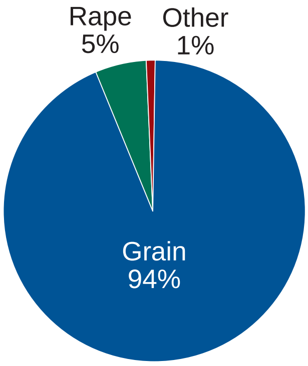


Figure 2.2. Straw is primarily a residual product from the growing of grain. Straw from rape and other seed-producing crops can also be used for energy purposes, but the quality is significantly inferior from the quality of grain. Source: Statistics Denmark.

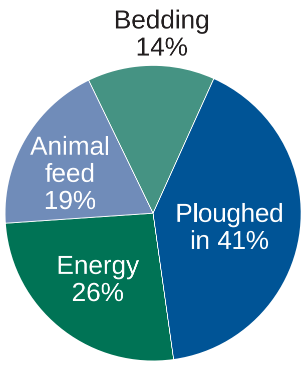


Figure 2.3. In Denmark, approx. 25 per cent of the total straw production is used for energy purposes. Source: Statistics Denmark.

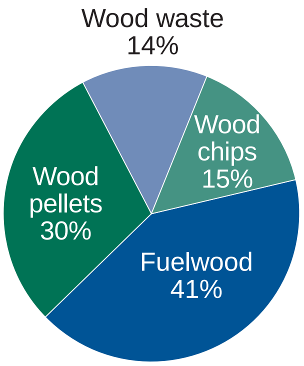


Figure 2.4. Approx. 41 per cent of the production of energy from wood comes from fuelwood. Wood pellets represent approx. 30 per cent, while the rest is evenly distributed between wood chips and wood waste. Source: The Danish Energy Agency.

Approx. 41 per cent of the production of energy from wood comes from fuelwood. Wood pellets represent approx. 30 per cent, while the rest is almost evenly distributed between wood chips and wood waste. Fuelwood is almost exclusively used by private households, wood chips and wood waste are mainly used for large boiler plants at district heating plants and power plants, while wood pellets are used by private households as well as district heating plants and power plants.

The latest survey of the Danish forest area shows that just under 490,000 hectares are covered by forest today. Most of the wood removed from the forests ends up as energy wood - either directly or indirectly as residual products from the wood industry or the sawmills.

The Danish production of wood chips has quadrupled over the past 15 years and generally the resources are used in full. The annual production of fuelwood and energy wood in the form of logs has also increased and according to Statistics Denmark, the total production of energy wood reached 1.26 million cubic metres in 2005.

The majority of the Danish wood chip production comes from thinning of young tree plantations, where the small trees can be chipped whole. The trees which have to be removed are harvested in the winter and are typically allowed to dry during the summer before they are chipped. This reduces the moisture content and the needles fall off, which means that fewer nutrients are removed from the forest floor.

A small quantity of the wood chips comes from diseased trees. In addition, wood chips are chipped from the so-called nurse trees, and the tops of commercial timber are also normally used for the production of wood chips. The use of forest chips for energy purposes is very important to forestry, as the income from the sale of wood chips improves the opportunities to maintain the stands and change from one tree species to another.

Today, there are various subsidy schemes aimed at establishing a larger forest area in Denmark. The objective is to double the forest areas within the next tree generation, i.e. during the coming 80-100 years. This will, of course, provide new opportunities to increase the production of energy wood.

Energy Crops

As the consumption of biomass increases, it becomes more and more interesting for the farmers to grow crops intended for the production of energy. This is a development which has really gained momentum in for example Germany and Sweden, but in Denmark the areas set aside for energy crops are very limited. So far, these areas have primarily been used for rape, which is subsequently processed into biodiesel and exported to countries with less strict tax rules than the Danish.

Several traditional agricultural crops can be used for energy products. They include rape for the production of biodiesel as well as sugar beet, grain and maize for the production of bioethanol.

According to the latest survey of the production of energy in Denmark, more than 48 peta joule was produced on the basis of wood in 2005. This corresponds to more than 40 per cent of the total contribution from renewable energy. Approx. 41 per cent of the production of energy from wood comes from fuelwood.

Photo: Torben Skøtt/BioPress

Grain and maize are also used as feed for biogas plants during periods when there is a shortage of organic waste with high gas potential for the plants.

The problem with the traditional agricultural crops is that considerable quantities of pesticides and fossil fuels are often used. As a result, the traditional crops are problematic from an energy-economic and environmental point of view, and this is one of the reasons why Denmark, so far, has not wanted to promote the production of liquid biofuels as long as the raw materials are traditional agricultural crops such as grain and rape.

However, a number of perennial energy crops are available which, in addition to high production of dry matter, involve low consumption of both pesticides and fertilisers. They include willow, poplar and elephant grass, which can be used as fuel in the power plants, as well as perennial grass, which can be used for the production of biogas. Besides, several of the crops are very efficient at absorbing nutrients and they are thus very suitable in particularly sensitive agricultural areas, where the farmers can obtain subsidies to develop a more environmentally friendly agricultural form.

Biomass Prices

The prices of biomass are to a very high degree cost-determined, but the issue of quality, supply and demand also influences the price levels.

The quality of certain forms of biomass is so inferior that companies are offered money to receive it. The large common biogas facilities thus earn a respectable income from receiving organic waste with low gas potential, while they have to pay for the more attractive waste with high gas potential.

Traditional agricultural crops such as rape and grain are generally at the expensive end of the scale, but here the price is not determined by the demand for energy purposes, but rather the general demand for agricultural crops. The increasing demand for crops for liquid biofuels will, however, also force up the prices of rape, grain and maize.

In Denmark, the price of solid biofuels such as straw and wood chips for the district heating sector has been practically constant for the past

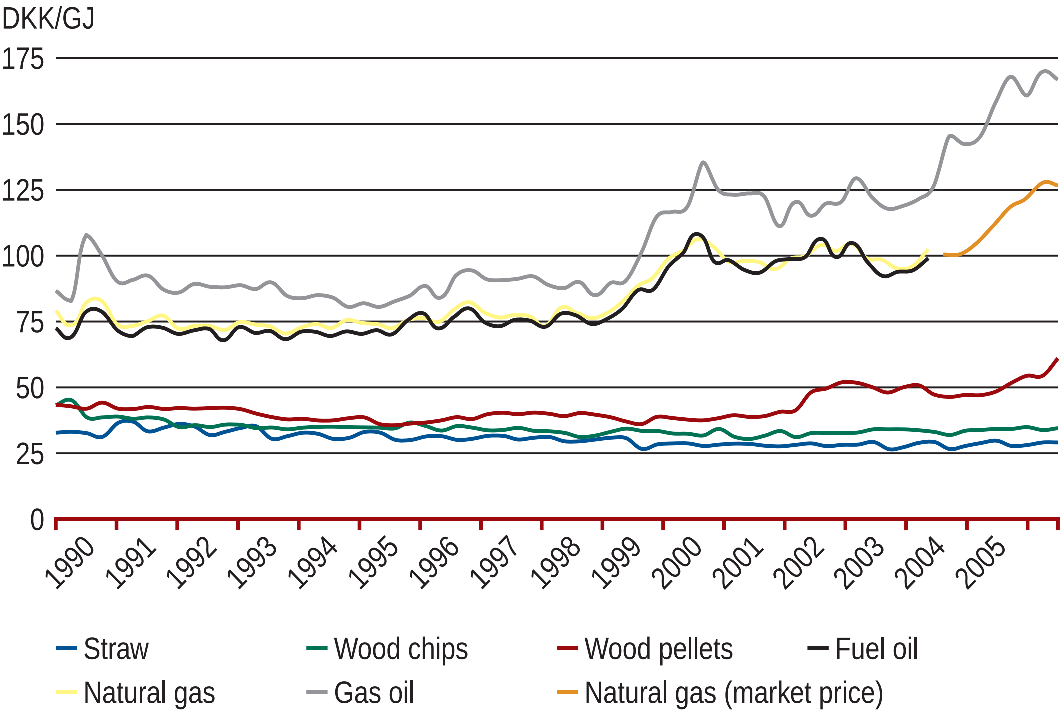
Photo: Torben Skøtt/BioPress

Willow is one of the most environmentally friendly energy crops available and suitable as fuel in power plants and district heating plants.

Photo: Torben Skøtt/BioPress

The prices of sawdust and shavings from the furniture industry have increased from a level of approx. DKK 50/ton in the 1990s to approx. DKK 500/ton in 2002. This has resulted in substantial price increases for wood pellets.

Figure 2.5. The price development of various energy sources in the period from 1990 to 2006, including taxes. The significant price differential is primarily due to oil and gas being subject to taxes, whereas straw, wood chips and wood pellets are exempt from taxes. Source: Danish District Heating Association (Dansk Fjernvarme).



15-20 years (see figure 2.5). Wood chips have typically been sold for approx. DKK 35/gigajoule, while the price of straw has normally been less than DKK 30/gigajoule. Straw has never been an international commodity in line with wood chips, which means that the local straw prices have often varied considerably.

From 1990 to 2002, the price of wood pellets for district heating plants varied between DKK 35 and DKK 40/gigajoule, but lately the price has been close to DKK 50/gigajoule. The market is far more volatile than the straw and wood chips market and periodically, it has been very difficult for the suppliers to keep up with the demand.

A major reason for the rising prices is the increase of the prices of sawdust and shavings from the furniture industry from a level of approx. DKK 50/ton in the 1990s to approx. DKK 500/ton in 2002. In the past few years, Denmark has imported considerable quantities of wood pellets, which has to a certain extent helped stabilise the prices, while the prices of raw materials from the furniture industry have dropped by approx. DKK 200/ton. The price of wood pellets is, however, far less predictable than the price of straw and wood chips.

It is noteworthy that the prices of biofuels have been independent of the price development of fossil energy. Since 1990, the prices of straw and wood chips have declined slightly, while the prices of fossil fuels have increased. In the autumn of 2006, the prices of wood chips seem to be increasing. It is unknown whether this tendency will continue in the coming years, but the increasing prices of CO_2 emission allowances and fossil energy will undoubtedly lead to higher prices of biofuels in future.

Handling of Biofuels

– from field and forest to combustion at the power plant

Photo: Lars Nikolaisen

In many ways, the handling of biofuels is more complicated and time-consuming than the handling of fossil fuels such as oil, coal and natural gas. Biofuels are very bulky, which means that transport costs may be high, especially for handling of straw bales. In addition, it is important to ensure a reasonable working environment as there may be considerable nuisance in the form of dust and mould fungi.

In the 1990s, straw and energy wood were almost exclusively handled as straw bales and wood chips, but today a large quantity of straw and wood is processed into fuel pellets to facilitate transport and handling at the power plant. At Avedøreværket (power plant) south of Copenhagen, approx. 300,000 tonnes of wood pellets are used annually and in 2003, Amagerværket was rebuilt to introduce trial firing with straw pellets in unit 2 of the power plant. At both plants, the pellets are ground into dust and blown into the boiler in the same way as coal, which makes it relatively simple to convert a coal-fired plant to fuel pellets.

Baling of Straw

The handling of straw has gradually developed into an independent discipline in the agricultural industry with special machinery in which primarily large farms and machine pools invest.

When the grain fields are harvested, the straw is left in long rows. The farmer will normally be interested in having the straw removed as soon as possible to be able to start preparing the soil for the following year's crop, but the power plant may want the straw left in the field during one or two showers before it is gathered. Experience has shown that straw which has been exposed to a little rain has a reduced content of chlorine and potassium, thereby reducing the risk of operational problems at the power plant.

In practice, it may, however, be difficult to have the straw gathered at the perfect time. Many farmers are dependent on available capacity at the local machine pool and, above all, the straw must be dry before it is gathered - otherwise it will be rejected at the power plant or the district heating plant.

In the agricultural industry, several kinds of bales are used, from small straw bales of approx. 12kg up to big bales of approx. 500kg. The power plants only accept the big bales and the most of the heating plants also only receive the big bales.

The baler for big bales was developed more than 25 years ago at the Hesston factory in the USA and big bales are thus commonly known as Hesston bales. The width of the big bales is approx.

Big bales are the only kind of straw bales that the power plants can handle. The picture shows a completely new baler from Krone, which is able to press bales weighing approx. 600kg.

Photo: Lars Nikolaisen

The straw bales are fastened with straps. In many places, the carriers are also required to use nets to avoid that the straw fly off the truck.

Photo: Torben Skøtt/BioPress

At large plants like this in Studstrup, the overhead travelling crane is used for lifting the straw bales from the storage to the conveyor belt.

120cm, the height is 130cm and the bale length is 230-270cm. The weight of a bale is approx. 500kg, but the weight has increased slightly over the years and the latest balers are able to make bales weighing up to approx. 600kg.

Transport of Straw

In many ways, big bales are an excellent solution for gathering the straw from the field, but it is less effective for the transport to the power plant. A truck has room for only 24 bales, equal to 12 tonnes of straw, which is less than half the weight that the truck is allowed to carry. The result of the poor utilisation of the capacity is not only high transport costs, but also results in extra costs for handling the straw bales and poor utilisation of the storage facilities.

The optimal weight would be approx. one tonne per bale, but that will require the development of a completely new type of baler and considerable investments in new balers, front-end loaders and cranes. This will probably not happen for a long time, but there is no doubt that the tendency is towards heavier bales. The Danish Institute of Agricultural Sciences has calculated that the Danish power plants would be able to save approx. DKK 40 million annually if they started using straw bales of one tonne, which makes it an area with considerable saving potential.

Farmers who live close to the power plant will often choose to transport their own straw to the plant using a tractor, but unless the distance is very short, it is more profitable to use a truck. At the plants where a crane is used for unloading the straw, the bales must be placed in a certain position on the truck body, which may make the use of trucks necessary.

Handling of Straw at the Plant

At the small power plants, the straw is unloaded with a fork-lift truck, but at the larger plants, the unloading is carried out with a so-called overhead travelling crane, which can empty a truckload in two stages. First, the 12 top bales are lifted of the truck and then the 12 bottom bales are unloaded. Afterwards, the truck body is cleaned of any remaining straw before the truck again leaves the plant.

The system with the overhead travelling crane is very efficient and ensures fast handling of the straw bales to avoid queuing in the cold winter months. The crane is not only capable of unloading the bales from the truck. It also registers the weight of the straw and its moisture content. In this way, the plant is sure of a correct settlement with the farmer and able to reject straw with too high moisture content.

At the small plants, the moisture content is registered with a spear which is manually stuck into each straw bale. If the moisture content is above a certain limit, the straw is returned to the farmer.

Generally, the storage capacity of the power plants is only large enough for a few days' consumption at full load, so during the winter months, the plants normally receive new supplies on all weekdays. The transport from the storage to the boiler is fully automated, which allows the small plants to run unmanned during nights and weekends.

Unloading of straw bales at Studstrupværket. The overhead travelling crane is capable of lifting 12 bales at a time, which means that a truck and trailer or a tractor-driven platform truck can be emptied in two stages.

Photo: Torben Skøtt/BioPress

Photo: Torben Skøtt/BioPress

Chipper from the Danish Land Development Service loading wood chips into a forwarder. This ensures maximum utilisation of the expensive chipper.

Production of Forest Chips

The majority of the Danish wood chip production comes from the thinning of young tree plantations, but wood chips are also produced from top ends and other residues in the so-called clear-cuttings, i.e. when a forest area is completely cleared. Finally, wood chips are produced from trees which have been infected by rot, discoloration and fungus attacks or which cannot be used as commercial timber due to other reasons.

The felling of the trees should take place in the period from January to March, when the moisture content is relatively low. Afterwards, the trees that have been felled should be left in the forest during the summer to reduce the moisture content even further and to enable needles and small branches to detach. This is where the majority of the nutrients are contained, so it is important that they remain in the area to ensure a healthy and vigorous forest floor.

Felling of trees is performed manually by chain saw or a so-called feller-buncher. It is a special machine, which grabs the logs, cuts them close to the roots and dumps them in long rows, so that it is easy for the chipper to catch hold on the trees. The feller-buncher requires space to travel in the stand, so it is usually necessary to fell a row of trees by chain saw before the machine is able to work.

Chippers

A chipper is built around a basic machine with engine and cabin. The chipper is mounted at the front part of the machine, which also has a crane capable of pushing the trees into the chipper. At the rear end of the machine, a tipping container is mounted allowing the wood chips to be poured into truck containers or special vehicles used for transporting the wood chips out of the forest.

The large chippers are specialised machines designed for the purpose of chipping only, while the smaller machines are often built around a large agricultural tractor with tipping trailer. The chipper part consists of an infeed opening with two hydraulic rollers that push the logs into the chipper. It comes in various shapes but in Denmark a rotating disc with 2-4 knives chipping the wood into small pieces is primarily used.

The chippers have undergone rapid development over the past 25 years. Previously, it could take half a day to fill a truck with wood chips - today, the same task is carried out in approx. one hour. However, the large chippers weight quite a lot and this means that they have limited movability on very soft areas and they also have large turning radii and require much space for entering skid rows.

Modern chippers are expensive so it is usual to have a tractor with tipping trailer or a specialised

Photo: Torben Skøtt/BioPress

Smaller chipper which have been built around a large agricultural tractor with tipping trailer. The chipper part consists of an infeed opening with two hydraulic rollers that push the logs into the chipper.

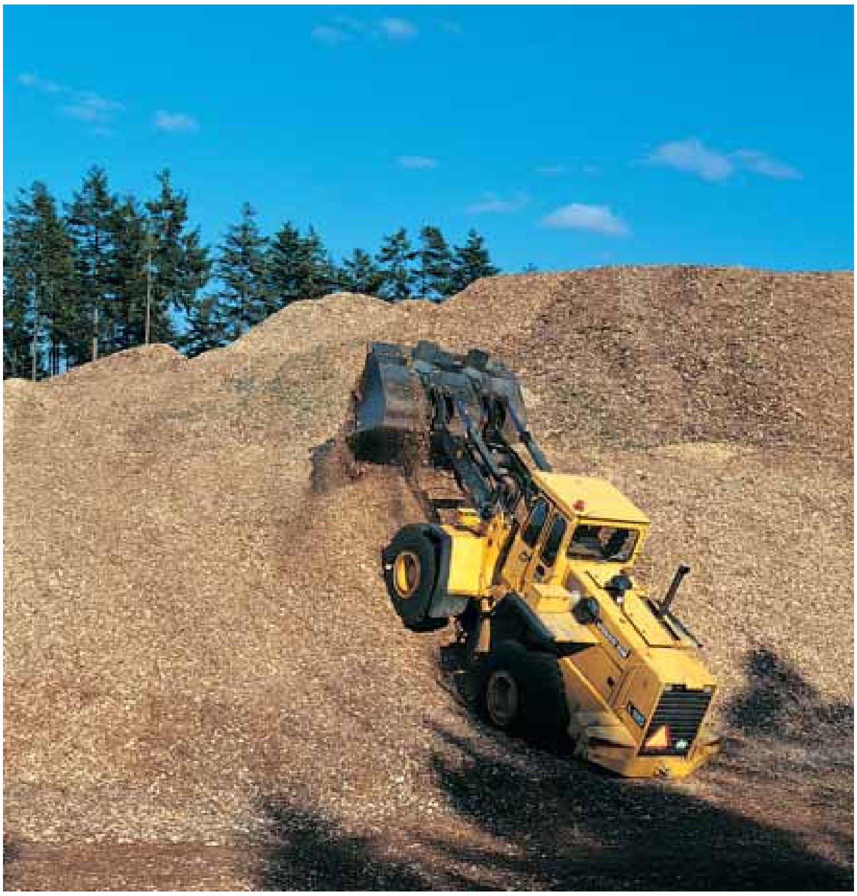


Photo: Torben Skøtt/BioPress

Establishing of outdoor wood chips storage at a plantation south of Herning.

forwarder following the chipper through the forest. This provides optimal utilisation of the chipper, as it no longer has to transport the chips to the nearest road, where the trucks are able to pick them up.

Storing of Wood Chips

Wood chips should preferable be produced as the need arises at the power plant. However, this is not always possible in practice. There will almost always be periods during the year when the harvesting of wood chips is not possible, while during the summer, more wood chips are produced than the power plants are able to consume. A certain storage capacity is therefore necessary, typically located in the forest or close to the power plant.

Chips for storage should be of the best possible quality. In most cases, wood chip piles are placed outdoor, but if the moisture content needs to be reduced, it is necessary to place the wood chips under roof. Experiments have shown that storage under roof for four to six months may result in a reduction of the moisture content from approx. 45 per cent to just under 30 per cent. In the case of outdoor storage without tarpaulins, the wood chip moisture content will usually increase, whereas the overall moisture content of chips stored under tarpaulins remains constant.

Photo: Torben Skøtt/BioPress

There are different types of wood chips. The length may vary between 5 and 50 millimetres and wood chips may contain small twigs.

Transport of Wood Chips

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. 80m^3 at a time. If the wood chips are delivered immediately after chipping in the forest, a number of containers is normally placed at the outskirts of the forest and filled as the chips are produced. Modern chippers can produce 30-50m^3 per hour, which means that a chipper can fill two containers in 2-3 hours.

Different Types of Wood Chips

In general terms, wood chips are wood that has been comminuted. The length may vary between 5 and 50 millimetres and in addition, wood chips may contain longer twigs, the so-called slivers as well as a finer fraction which can almost be referred to as fines. The main part of the Danish wood chip production comes from the forests, but the sawmills also produce wood chips. In addition, willow chips are produced on the basis of whole shoots from the plantations of the farmers.

The type of wood chips most suitable for energy purposes depends on the boiler plant. Most district heating plants have boiler plants where the wood chips are pushed into a so-called travelling grate. Here it is an advantage to use coarse wood chips. If the wood chips are too small and there are too many fines, it may be difficult to blow air through the chip layers and the result is poor combustion.

The power plants, however, tend to prefer wood chips with very varied particle size, as this is more suitable for boilers where the fuel is thrown onto the grate. Here, fines and small pieces of fuelwood burn in the air above the grate, while the large pieces burn out on the grate in the same way as in a district heating boiler.

To make it easier for the district heating plants and power plants to obtain the right type of wood chips, the Danish Forest and Landscape Research Institute (today called Danish Centre for Forest, Landscape and Planning, University of Copenhagen) has prepared a specification of when wood chips are categorised as fine, coarse or extra coarse (see table 3.1).

Just as there may be different requirements in relation to the size of the wood chips, there may also be different requirements in relation to the types of wood preferred by the individual plants. In case of a hardwood such as beech, the calorific value on the basis of volume is considerable higher than for wood chips produced from spruce or willow (table 3.2). Financially, this is not important to the plants, as the wood chips are priced according to the energy content, but if the

Name	Size	Fine fraction	Coarse fraction	Extra coarse fraction
Overlong 20	> 200mm length	< 0.5%	< 1.5%	< 1.5%
Overlong 10	100 – 200mm length	< 3%	< 6%	< 6%
Overlarge	> 63mm	0%	< 3%	**
Extra large	> 45 and < 63mm	< 2%	< 15%	**
Large	> 16 and < 45mm	< 60%	–	**
Medium	> 8 and < 16mm	–	–	< 25%
Small	> 3 and < 8mm	< 35%	< 25%	< 8%
Fines	< 3mm	< 10%	< 8%	< 4%

Table 3.1. Overview of the current requirements for fine, coarse and extra coarse wood chips.

combustion plant is undersized, using wood chips with a low calorific value may be a problem.

Wood chips may contain various pollutants such as stones, soil and sand, which result in a larger ash content when the wood chips are burned. The ash content also depends on the kind of wood as well as the quantity of needles, branches and stemwood. The natural ash content in needles may be more than five per cent, in branches and bark approx. three per cent and in stemwood only approx. 0.6 per cent. Many boiler plants can be adjusted according to the different kinds of wood chips, so many power plants are particularly keen to obtain wood chip supplies with limited variations between the individual loads.

Fuel Pellets

Fuel pellets are particularly suitable if the biomass has to be transported over long distances, as the energy density is larger than in for example straw bales and wood chips. This provides better opportunities to use the enormous biomass resources available in the world, and it may be more convenient to transport pellets than for example straw bales.

In 2001, the energy company Energi E2 (today called DONG Energy) chose to use 450,000 tonnes of biopellets in existing power plants instead of building new plans capable of using the biomass directly. Soon afterwards, the establishment of a factory in Køge was initiated with a capacity to produce 150,000 tonnes of straw pellets and 180,000 tonnes of wood pellets a year.

Tree species	Calorific value
Willow	2.0GJ/m^3
Spruce	2.6GJ/m^3
Pine	3.0GJ/m^3
Beech	3.6GJ/m^3

Table 3.2. Typical calorific values for different types of wood chips with a moisture content of 50 per cent.

Photo: Torben Skøtt/BioPress

Køge Biopillefabrik, which produces both wood pellets and straw pellets. The pellets are sailed to Avedøreværket and Amagerværket respectively for use as fuel.

Photo: Torben Skøtt/BioPress

One of the three feeding lines at Køge Biopillefabrik. Here the strings that hold the bales together are removed and the straw is shredded before being ground into fines in three large hammer mills.

Photo: Torben Skøtt/BioPress

Unloading of straw at the pellet factory in Køge.

Photo: Torben Skøtt/BioPress

Discharging of straw pellets for Amagerværket.

The factory, which was ready in 2003, provides straw pellets for the power plants Amagerværket and Avedøreværket with some of the 300,000 tonnes of pellets that are used annually - the rest is purchased on the free market.

Pellets for Existing Power Plants

At first glance, it may seem expensive and difficult to use fuel pellets in large power plants. First of all, the wood chips and the straw need to be disintegrated by means of hammer mills and the wood fines need to be dried before they can be pelleted. After that, the pellets are transported to Avedøreværket and Amagerværket, where they are crushed. The pellets cannot be used directly as fuel in the power plants - they need to be disintegrated first, so that they can be fired as dust in the same way as coal dust.

The advantage of fuel pellets is that they can be used at existing plants, thereby avoiding the need to build new power plants capable of taking the biomass directly from farming and forestry. In addition, the volume of the pellets is significantly smaller than the volume of wood chips and straw bales, which reduces the transport costs. This is particularly important in connection with the import of biomass and at Amagerværket, it has incidentally been a requirement that biomass must be transported by sea. The authorities simply would not permit the truck transport through the already congested road network in Copenhagen.

The production of fuel pellets also requires energy but, on the other hand, the pellets can be used at very large power plants with high electricity efficiency. Although the high electricity efficiency results in slightly lower heat production, this is of minor importance, as most power plants produce more heat than required for district heating.

Approx. 4 per cent of the energy content of the straw is used for the production of straw pellets, while the corresponding figure for wood pellets is approx. two per cent.

Furthermore, the fuel pellet solution has the advantage of being very flexible. The pellets can be transported from anywhere in the world to any power plant, so the owners of the power plants are not dependent on local suppliers of biomass.

Running-in of Plant

The running-in of the new factory has, however, caused some problems. When the factory was built, practically nobody had any experience with plants for the production of straw pellets, while experience with production of fuel pellets was very limited and based on wet wood chips from various types of wood.

The problems with the production of the wood pellets have mainly involved the drying process, which must ensure that the moisture content is reduced from approx. 45 to 10 per cent. The first step in the drying process takes place in a drying installation driven by steam from the nearby power plant at Junckers Industrier.

In connection with the drying installation, a so-called steam converter has been installed which makes it possible to reuse 85 per cent of the steam and send the impurities released during the drying process to a sewage treatment plant.

In theory, this sounds relatively simple, but in practice, it has not been an easy task to feed wet wood chip into a vessel with a pressure of four bar and afterwards remove it again in a controlled manner. However, it now works and the knowledge gained in Køge will no doubt benefit many other plants.

Straw Pellets

The straw used for the pellet production in Køge is exclusively supplied by farmers from Zealand, Møn and Lolland-Falster. The prices for crossing the Great Belt Bridge are still too high to make it profitable to transport straw from Funen, where the straw prices are generally slightly lower than in Zealand.

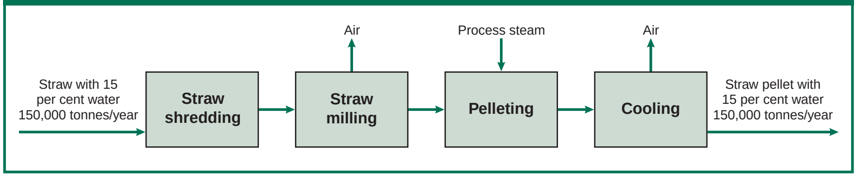
At the pellet factory, the straw is unloaded by means of a specially constructed overhead travelling crane, which can empty a truck in two stages. First, the straw bales are lifted into a storage area from where they are later transported into the factory. Here the strings that hold the bales together are removed and the straw is shredded before being ground into fines in a hammer mill. The pelleting is carried out in a pelleting press, where a small amount of steam and water is added. Finally, the pellets are cooled before being transported on a 800 metre long conveyor belt to a pellet storage at the port of Køge.

Wood Pellets

When the trees are felled in the Danish forests, part of the tree is used for the production of for example flooring at Junckers Industrier. Today, the surplus wood from this production is used at the pellet factory but, in addition, quite a lot of wood coming directly from the forests is used. This is wood which for some reason cannot be used as commercial timber.

The large quantities of wood chips that are used for pellet production are stored outdoor, until they are taken to a hammer mill which grinds the wood chips into fines. Next, the fines are dried by means of steam from the power plant at Junckers Industrier before being pressed into pellets. Afterwards, the pellets are cooled and transported to a storage on the port.

Straw pellet production process



Wood pellet production process

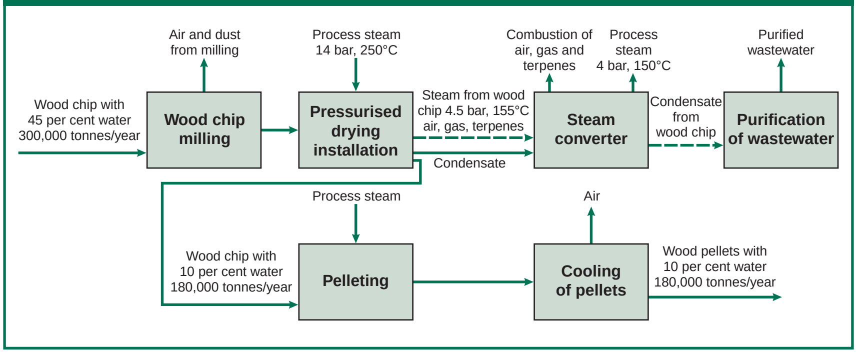


Photo: Torben Skøtt/BioPress

Pelleting press open for inspection.

Building of straw storage at Halm80 in Nyborg. During the peak season, the company employs 80 people to harvest, bale and handle straw.

Photo: Torben Skøtt/BioPress

Biomass as Fuel

– a challenge to the power plants

Biomass such as wood and straw are CO_2 neutral fuels, which may help reduce the greenhouse effect. The reason is that the amount of CO_2 released during combustion of biomass corresponds to the amount of CO_2 absorbed from the atmosphere at the growth of the biomass. By partly replacing the use of fossil fuels such as coal, oil and gas with biomass, the CO_2 emission from the production of electricity and heat is reduced significantly. Furthermore, biofuels have a lower content of sulphur and heavy metals than coal, which contributes to a better environment.

On the other hand, biofuels have a number of properties that involve huge challenges when they are used for the production of electricity:

- Biofuels are much more bulky than coal and oil, so the power plants have to handle much larger quantities of fuel.
- Biofuels are difficult to handle, which has made it necessary to develop new handling systems. For example, it may be tricky to remove the strings round a straw bale automatically or to deal with the cold of the winter spreading to the biomass storage and the associated conveyor system.
- Biofuels contain potassium and chlorine, which may cause problems in terms of slagging, corrosion, emissions and the utilisation of residual products.
- Biofuels may cause working environment problems in the form of for example dust and fungal spores, which may cause bronchial diseases.

Photo: Torben Skøtt/BioPress

Chipping in Klosterhede Plantage north of Holstebro.

A Little Chemistry

Biomass mainly consists of carbohydrate compounds (cellulose and hemicellulose) and lignin. These compounds primarily consist of carbon, hydrogen and oxygen, which are converted into CO_2 and water during combustion.

Biomass has a higher content of oxygen than coal and thus a lower calorific value. In addition, wood chips have a high moisture content, which reduces the calorific value even further. Typical

Fuel	Water content	Calorific value
Coal	10%	25MJ/kg
Wood pellets	8%	17.5MJ/kg
Straw	14%	15MJ/kg
Wood chips	45%	9.5MJ/kg

Table 4.1. Typical values for the water and energy content of coal, straw, wood pellets and wood chips. Note that wood pellets are the fuel that resembles coal the most with regard to water content and calorific value.

values for the water and energy content of the various fuels are shown in table 4.1.

Furthermore, biomass contains a small quantity of nitrogen (N), sulphur (S) and chlorine (Cl), which during combustion are partly converted into gaseous emissions in the form of NO_x, SO_2 and HCl. To this should be added the ash producing elements such as silicon (Si), calcium (Ca) and potassium (K). During combustion, these substances produce oxides, sulphates and chlorides, which are separated from the combustion plant as bottom ash and fly ash.

In figure 4.1, the content of sulphur, nitrogen, chorine, potassium and silicon in straw and wood chips is compared with coal. To allow the comparison of fuels with different calorific values, the content of the various substances in the figure is related to the calorific value. It is obvious that the sulphur content is considerable higher in coal than in straw and wood chips and that the chlorine and potassium content in straw is much higher than in coal and wood chips.

During combustion of straw, potassium and chlorine are deposited on the tubes of the boiler as a salt coating (potassium chloride), which is highly corrosive in plants with high steam temperatures. The content of potassium and chlorine in wood chips is at the same level as in coal, but nonetheless the corrosion risk in connection with combustion of wood chips is much higher than for coal. The reason is that coal - as shown in the figure - has a very high content of silicon which can react with potassium chloride, thereby avoiding the chlorine-containing deposits.

Different Types of Straw

The composition of straw is influenced by type, fertiliser and rain conditions. Wheat, barley and rye straw is almost identical in composition, except for the fact that wheat has a higher content of silicon than barley and rye. Rape straw differs from grain straw by its very low content of silicon and higher content of calcium.

The chlorine content in straw comes mainly from the use of fertiliser. Growing experiments using chlorine free and normal fertiliser containing chlorine have shown a considerable decline in the chlorine content of the straw in the areas where the chlorine free fertiliser was used. By contrast, the supply of potassium with fertiliser does not directly affect the potassium content in the straw, which is due to the fact that the farm land normally contains a large surplus of potassium.

Photo: Torben Skøtt/BioPress

Construction of wood chip storage at Herningværket (power plant), which uses approx. 250,000 tonnes of wood chips a year.

Potassium and chlorine are washed out of the straw when it rains. This applies to both standing straw immediately before harvesting and straw lying in the field after harvesting. Drought in the period before and after harvesting consequently results in a heating season with a high content of potassium and chlorine in the straw and thus operational problems at the straw-fired CHP plants.

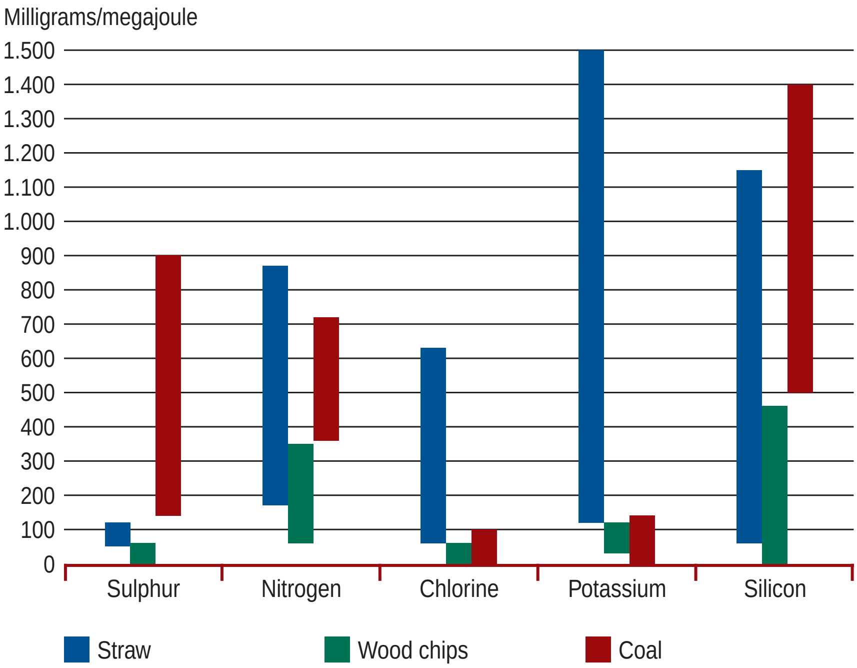


Figure 4.1. The content of sulphur, nitrogen, chlorine, potassium and silicon in biofuels and coal. Note that the content of the various substances is related to the calorific value.

Power Plant Technologies

– combustion of straw and wood in steam turbine plants

When the interest in biomass-based electricity and heat production began to emerge in Denmark in the late 1980s, it became clear that international experience was limited and only included the use of wood as fuel. Straw-based CHP production was an unknown phenomenon, but from straw-fired district heating plants it was well-known that straw is a complex fuel.

To be able to realise the objective of using large quantities of biomass for CHP production, the Danish power plants and suppliers therefore had to initiate an ambitious development and demonstration programme, which was primarily aimed at straw power plant technology.

The initiatives have included combustion as well as gasification technologies. However, it is only technical solutions based on combustion which, so far, have contributed significantly to biomass-based electricity production in Denmark and the gasification technology therefore is not included in this section. Within biomass combustion, the following four technology paths have been followed:

– grate-firing of straw and wood
– co-firing of straw in coal-fired power plant boiler
– biodust-firing (co-firing of wood pellets, gas and oil)
– circulating fluidized bed (CFB) combustion of straw and coal.

An overview of the establishment of the various plants is shown in table 5.1 and figure 5.1. At all plants, electricity is produced by means of a steam turbine. The energy from the combustion process in the combustion chamber is transferred in the boiler to a water/steam cycle, where steam is produced by means of high pressure and high temperature. The energy of the steam is converted into electrical energy via the steam turbine. Afterwards, the steam is condensed and led back to the water/steam cycle. In addition, district heating can be produced for the consumers via a district heating network.

Grate-firing of Straw and Wood

As table 5.1 shows, grate-firing is the most common technology for CHP production in Denmark.

Plant	Technology	Biomass consumption/ year	Steam temper-ature	Steam pressure	Commis-sioned
Haslev Kraftvarmeværk	Grate-firing of straw	26,000 tonnes	455°C	67 bar	1989
Rudkøbing Kraftvarmeværk	Grate-firing of straw	14,000 tonnes	450°C	60 bar	1990
Slagelse Kraftvarmeværk	Grate-firing of straw	30,000 tonnes	450°C	67 bar	1990
Maribo-Sakskøbing Kraftvarmeværk	Grate-firing of straw	45,000 tonnes	540°C	93 bar	2000
Fynsværket	Grate-firing of straw	150,000 tonnes	540°C	110 bar	2009
Køge Kraftvarmeværk unit 7	Grate-firing of wood	80,000 tonnes	525°C	93 bar	1987
Køge Kraftvarmeværk unit 8	Grate-firing of wood	120,000 tonnes	525°C	93 bar	1999
Herningværket	Grate-firing of wood	250,000 tonnes	525°C	115 bar	2002
Assens Kraftvarmeværk	Grate-firing of wood	45,000 tonnes	525°C	77 bar	1999
Randers	Grate-firing of coal and dry biomass	74,000 tonnes	525°C	111 bar	2002*
Måbjerg bio-boiler	Grate-firing of wood and straw	65,000 tonnes	520°C	67 bar	1993
Masnedø Kraftvarmeværk	Grate-firing of wood and straw	45,000 tonnes	522°C	92 bar	1996
Ensted bio-boiler	Grate-firing of wood and straw	150,000 tonnes	510°C	210 bar	1998
Avedøre 2 bioboiler	Grate-firing of straw	150,000 tonnes	545°C	310 bar	2001
Studstrupværket unit 4	Co-firing, straw to coal	100,000 tonnes	540°C	270 bar	2002*
Studstrupværket unit 3	Co-firing, straw to coal	30,000 tonnes	540°C	270 bar	2005*
Avedøre 2 main boiler	Biodust-firing in power plant boiler	300,000 tonnes	542°C	310 bar	2001
Amagerværket	Biodust-firing	130,000 tonnes	480°C	120 bar	2003
Grenaa	CFB combustion of straw and coal	40,000 tonnes	505°C	92 bar	1992

*Table 5.1. Overview of biomass-fired CHP plants in Denmark. * Converted to biomass.*

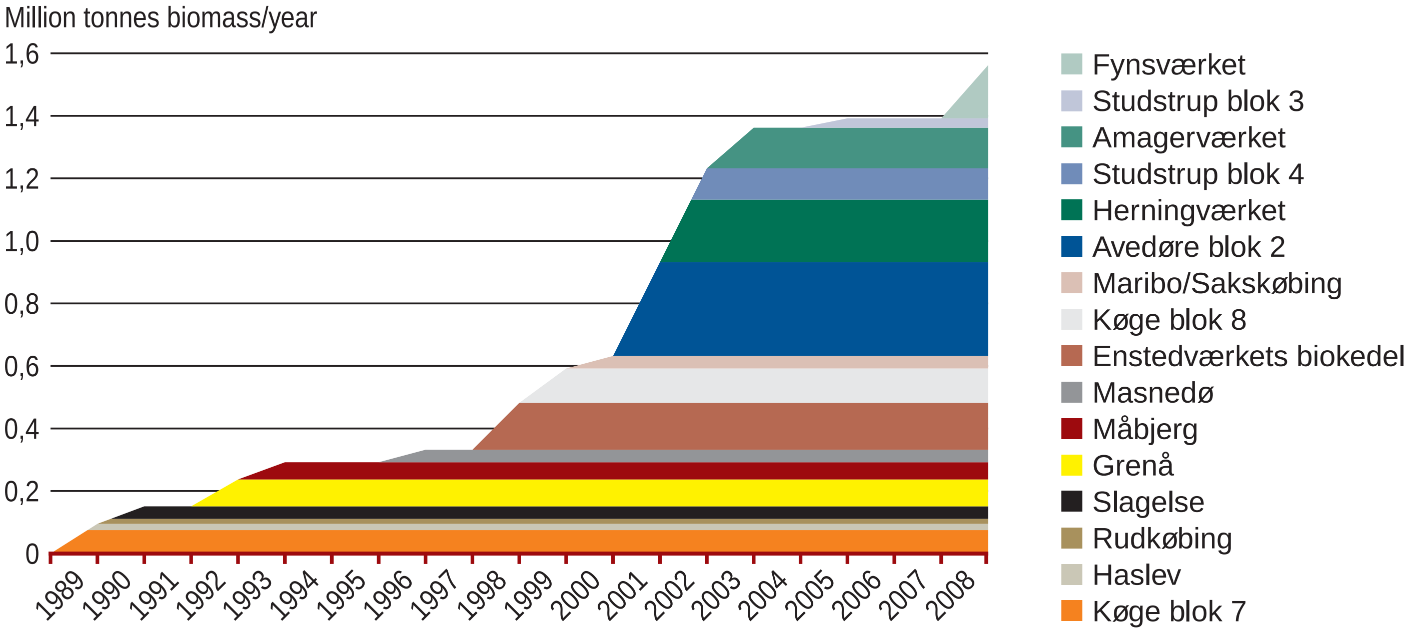


Figure 5.1. The development of the consumption of biomass in the CHP plants owned by the power plants in the period 1989-2002.

As the name indicates, the biofuel is fed to a grate at the bottom of the combustion chamber, which is where the biomass combustion takes place. A cross section of a typical modern grate-firing straw boiler is shown in figure 5.2.

From the straw storage, the straw bales are transferred to typically 2-4 feeding lines. In most plants, the straw bales are fed into a shredder, where the straw is loosened and fed onto the grate by means of screw conveyors. When the straw is pressed through the feeding channel, a straw plug is formed, which protects against burn-back combustion in the transport system and ingress of false air in the combustion chamber.

The straw is fed into a grate at the bottom of the combustion chamber. Almost all plants have a sloping, water-cooled grate that vibrates regularly, thereby causing the fuel to move across the grate. The ash which is left after the combustion at the vibrating grate (bottom ash) is collected at the end of the grate in a container filled with water. A small part of the ash (the fly ash) is led through the boiler plant with the flue gas.

At the plants in Haslev and Måbjerg, the bales are directly feed into the boiler according to the so-called "cigar burning principle". This means that there is no shredding of the straw, as the bales simply burn from one end. Some of the straw will of course fall on the grate where it burns.

The design of superheaters with reliable operation and high steam data has been one of the largest challenges at the grate-fired straw plants. Straw ash has a low melting point and there is a high risk of deposits on the superheater tubes, which may result in a need to stop the boiler and clean the tubes. In more recent plants, a superheater section has been installed at the top of the combustion chamber, where the distance between the superheater tubes is sufficiently wide to allow the build-up of a thick deposit of straw ash. In combination with soot blowers for the cleaning of the other heating surfaces, the

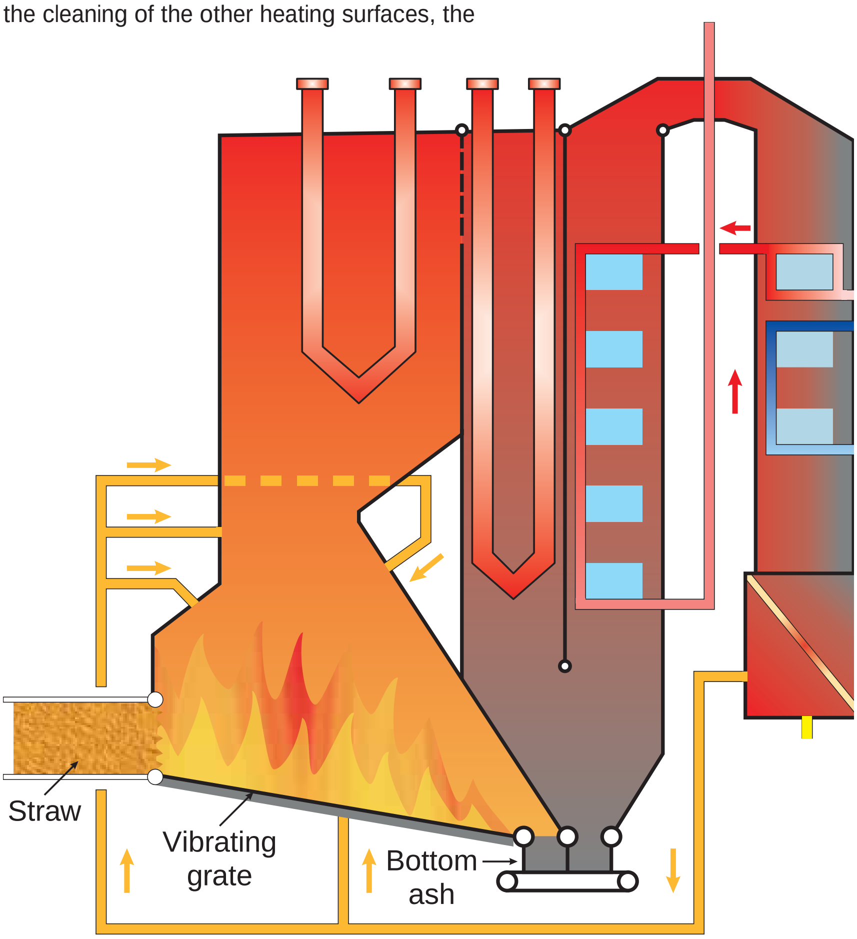


Figure 5.2. Cross section of a modern grate-fired straw boiler.

Figure 5.3. Development of temperature and pressure in the biomass-fired plants.

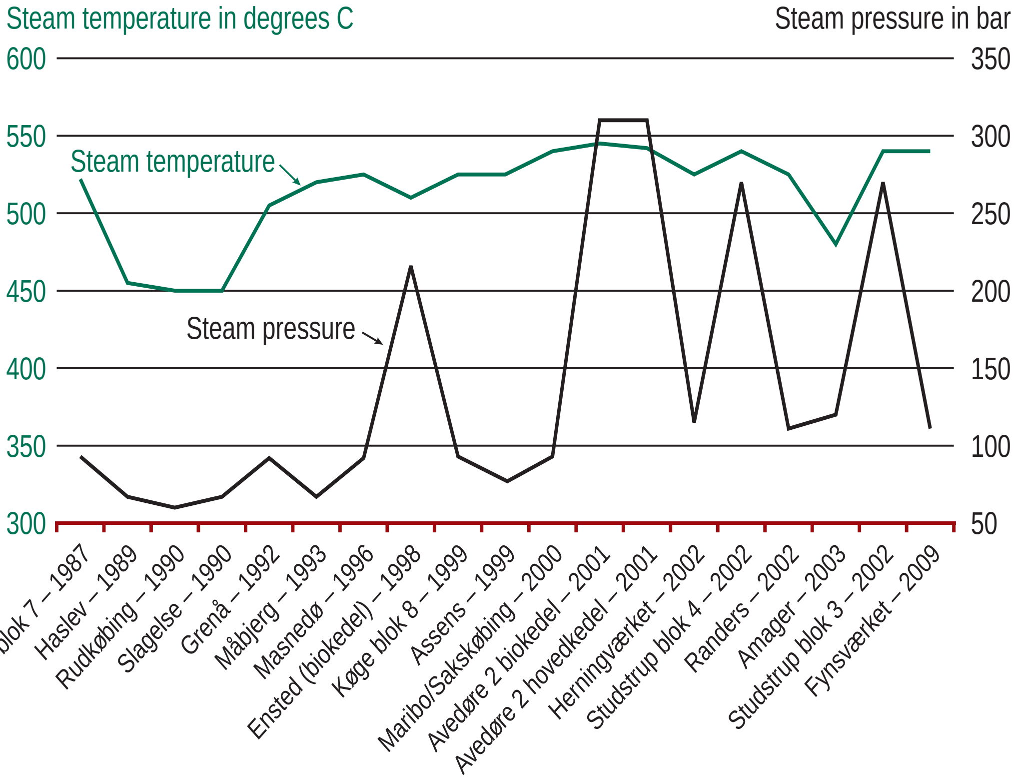


Photo: Forskningscentret CHEC

Deposits on superheater tubes at a straw-fired power plant.

Photo: Torben Skøtt/BioPress

In most plants, the straw bales are fed into a shredder, where the straw is loosened before it is fed onto the vibrating grate in the boiler.

performance of straw-fired plants has thus been improved.

The latest superheater design has also made it possible to increase the steam temperature and thus the electrical efficiency. Figure 5.3 shows the development in temperature and pressure at the grate-fired plants. It has been possible to raise the temperature from 450° C in the first plants to 540° C in later plants. Modern coal-fired power plants have steam temperatures of 580-600° C, but it is not possible to reach such temperatures with biomass combustion on grates. The reason is that the chlorine-contained deposits formed on the superheaters are highly corrosive.

There has been extensive research into deposit formation and corrosion in connection with the grate-firing of straw. Among other things, it has been analysed how potassium chloride from straw evaporates during combustion and is deposited on the superheater tubes.

Similarly, the corrosion mechanisms have been carefully studied. The superheater tubes contain iron, chromium and nickel and studies show that at high temperatures, the chlorides selectively remove chromium from the iron, thus weakening the mechanical strength of the tubes. A chromium content of 12-18 per cent has proved to provide the best protection of the superheater tubes.

In addition, tests have been carried out involving the addition of various additives to the combustion to reduce the corrosion attacks. In connection with wood-firing, it is possible to remove chloride in the deposits, but in connection with straw-firing, the ash quantities are so large that the consumption of additives is too high to make it financially viable.

Before the flue gas is released into the atmosphere through the stack, it has to be cleaned of fly ash. Much of the straw fly ash contains many fine particles which it may be difficult to separate in an electrostatic precipitator. Most straw-fired CHP plants consequently use bag filters for flue gas cleaning.

Photo: Torben Skøtt/BioPress

Combustion of straw on vibrating grate. Today, grate-firing is the most widespread technology for combustion of biomass in power plant boilers.

Photo: Torben Skøtt/BioPress

Two of the four feeding lines at Studstrupværket leading the straw from the storage to the shredders.

At woodchip-fired CHP plants, the boiler plant is built according to the same principles as those shown in figure 5.2, but fed by means of spreaderstokers that throw the wood chips onto the grate. Wood has a considerably lower content of ash and straw and wood ash has a higher melting point than straw ash. In connection with wood-firing, deposits in the boiler are less of a problem than in connection with straw-firing. In woodchip-fired plants, the maximum steam temperature is likewise limited to 540° C due to chlorine-contained deposits.

Co-firing of Straw at Coal-fired Power Plant Boiler

Co-firing involves the combustion of straw together with coal in a pulverized coal-fired power plant boiler. This solution does not require the building of a new boiler and turbine plant, so the investment costs are much lower than for grate-fired plants. Emissions into the atmosphere are also limited, as the coal-fired power plants are already equipped with effective flue gas cleaning installations for the reduction of SO_2, HCl and NO_x. Co-firing was developed in the early 1990s and tested full-scale at Studstrupværket's unit 1 in 1996-97. It was proven that co-firing is a reliable combustion technical solution but at that time, there were no ideas for using the fly ash. However, after a few years, it became possible to sell the ash for the production of cement and thus the way was paved for the establishment of the first commercial plant at Studstrupværket's unit 4. This was put into operation in 2002. Later, it also became possible to use the fly ash for the production of concrete. To make the ash useable, the proportion of straw is limited to 20 per cent of the weight, equal to 13 per cent of the fired energy.

The straw handling plant at Studstrupværket is shown in figure 5.4. Via a conveyor, the straw bales are led from the storage to a string remover, where the strings that hold the bale together are removed. Subsequently, the straw is loosened in a straw shredder and sucked through a stone trap, where stones and other foreign bodies are separated. In the final stage, the straw is processed in a hammer mill to a maximum length of 50 mm and blown with air to the burners of the boiler.

The straw is combusted together with coal in combined coal/straw burners. Four out of the 24

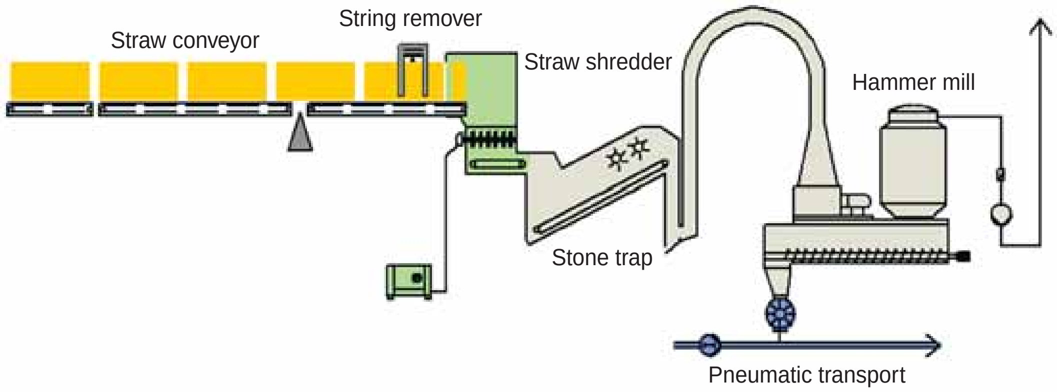
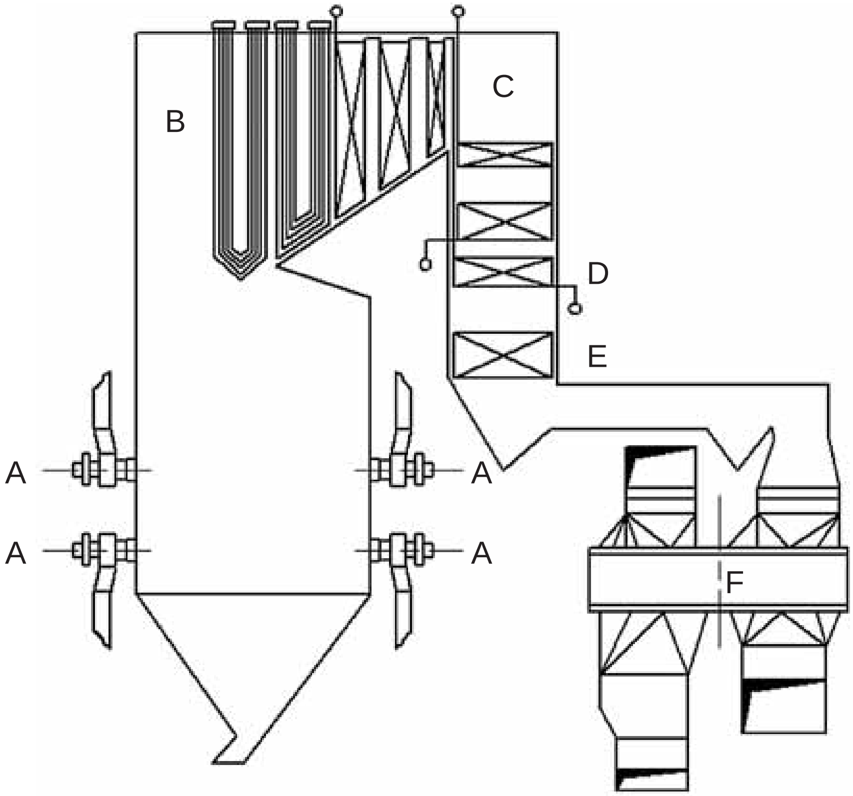


Figure 5.4 The straw handling plant at Studstrupværket.



A: Burner
B: Secondary superheater
C: Re-superheater
D: Primary superheater
E: Economizer
F: Air preheater

Figure 5.5. Position of the burners at Studstrupværket.

burners of the boiler are converted to coal/straw by allowing straw to be sent into the centre tubes of the burner. The position of the burner in the boiler is shown in figure 5.5 and an outline of a converted burner is shown in figure 5.6. The combined coal/straw burner provides very efficient combustion and the content of residue carbon in the ash is generally lower at straw co-firing than at combustion of coal on its own.

During the development of the co-firing technology, the risk of increased corrosion in the boiler

Test reactor for the study of catalyst deactivation.

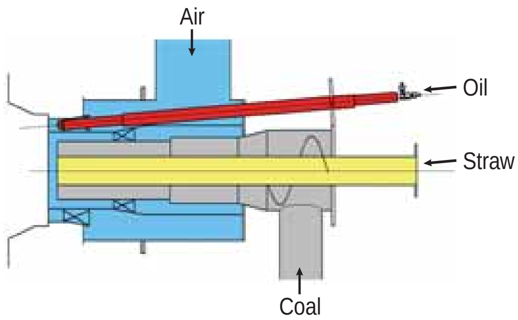


Figure 5.6. Outline of a coal burner which has been converted to coal and straw-firing.

was extensively studied, as this is familiar in the grate-fired plants. However, the coal ash proved to have a very beneficial effect on the corrosive elements in the straw. In a reaction between the potassium chloride from the straw and the coal ash, potassium is bound to the ash and chloride is released as HCl in the flue gas. As long as the amount of straw is not too large, no chlorine-containing deposits are formed in the boiler and the risk of corrosion is thus limited.

The reaction between potassium chloride and coal ash also has a positive effect on the SCR catalysts inserted to reduce the emission of NO_x. The catalysts are poisoned by potassium compounds and quickly deactivated in flue gas from grate-fired straw plants. During co-firing, potassium is bound in the coal ash and thus becomes less harmful. This has been shown in a test at Studstrupværket, where flue gas from straw co-firing was sent through a reactor with nine catalyst elements for 15,000 hours.

Biodust-firing in Power Plant Boiler

In Avedøre 2's main boiler, gas, oil and wood pellets are used as fuel. This is a modern power plant boiler designed for a steam temperature of 580°C for high-pressure steam and 600°C for mid-pressure steam. There are four levels of burners placed in the corners of the boiler and the three bottom rows are designed for wood pellet-firing. The plant is equipped with flue gas cleaning in the form of a SCR plant for NO_x reduction, electrostatic precipitators and a wet desulphurisation plant.

The wood pellets are transported on conveyor belts from the storage of the plant to silos in the boiler building. From the silos, the wood pellets are led to traditional coal mills where the pellets are pulverised and the wood powder is led to the 12 powder burners. 135 tonnes of wood pellets can be fired per hour. As wood powder is explosive, new explosion suppression equipment has been installed in the transport system.

When wood pellets and oil are co-fired, deposits are formed on the boiler tubes consisting of potassium from the biomass and sulphur and vanadium from the oil. Such deposits are corrosive and to limit the risk of corrosion, the steam temperature is reduced. The ash from co-firing of wood pellets and oil also causes increased deactivation of SCR catalysts.

Tests have been carried out involving the addition of coal ash to the boiler and the results show that coal ash can reduce the risk of both corrosion and deactivation of the catalyst. Coal ash also helps minimise the problems of air preheater blocking, reduces the formation of sulphuric acid, makes the ash product more suitable for utilisation and reduces the dust emission from the plant. Consequently, equipment for permanent injection of coal ash into the combustion chamber has been installed.

Circulating Fluidized Bed Combustion of Straw and Coal

At Grenaa Kraftvarmeværk, straw is combusted with coal in a circulating fluidized bed boiler. In fluidized bed boilers, the combustion takes place in a fluidized bed of sand particles. In a circulating fluidized bed, some of the particles are led via the flue gas out of the combustion chamber, separated in a cyclone and re-circulated.

During fluidized bed combustion, the combustion temperature is lower than at co-firing and grate-firing and the formation of NO_x is thus reduced. In addition, it is possible to remove sulphur from the flue gas by adding limestone to the bed.

Fluidized bed boilers are flexible as regards choice of fuel, but sensitive to ash with a low melting point such as straw ash. The reason is that melted ash makes the sand particles in the bed stick together, which means that the particles can no longer remain fluidized. Consequently, the straw proportion can be maximum 50 per cent. In Grenaa, smaller quantities of other biofuels are used in addition to coal and straw.

Like the grate-fired straw combustion plants, the fluidized bed plant in Grenaa has involved many challenges in relation to the formation of deposits and corrosion. In addition, there have been difficulties with mechanical wear in the boiler tubes, but various replacements and rebuilding have solved the main problems.

The fluidized bed combustion of coal and straw produces a residual product which is a mixture of coal ash, straw ash, lime stone and desulphurisation products. It has not yet been possible to find a use for this product, which therefore has to be landfilled. The inability to utilise the residual product is one of the main reasons why the fluidized bed principle is only used at the plant in Grenaa.

In connection with biomass-firing, the ash is removed as bottom ash from the boiler and as fly ash separated from the flue gas. Both types of ash contain fertilising substances, primarily potassium, which the biomass has absorbed from the soil.

Photo: Torben Skøtt/BioPress

Emissions and Residual Products

– flue gas and ash from biofuels

In all kinds of energy production, it is important to use the residual products in the best possible way in order to reduce the environmental impact. The ash from traditional coal-firing is used for the production of cement and concrete, while gypsum from desulphurisation is used for the production of plasterboard. When biomass is combusted, the utilisation options for the ash depend on the firing technology used.

Photo: Torben Skøtt/BioPress

Spreading of bottom ash from straw-fired CHP plant. The bottom ash amounts to approx. 80 per cent of the total amount of straw ash from the plant.

In connection with grate-firing of biomass, the ash is removed as bottom ash from the grate and as fly ash separated from the flue gas. Both types of ash contain fertilising substances, primarily potassium, which the biomass has absorbed from the soil. The return of the ash to farming and forestry may ensure that some of the fertilising substances remain in the cycle and make it possible to reduce the import of inorganic fertilisers slightly.

Executive Order

The spreading of ash within farming and forestry is in Denmark regulated by the "Executive Order" (Executive Order on Ash from Gasification and Combustion of Biomass and Biomass Residual Products for Agricultural Applications). The Executive Order specifies the rules for the quantity of ash which may be spread per hectare and the requirements which the ash has to comply with. Today, the bottom ash from the straw-fired plants is spread on farm land, which means that the majority of the straw ash is utilised.

The fly ash amounts to approx. 20 per cent of the total amount of straw ash, but it contains large quantities of valuable fertiliser in the form of potassium chloride and potassium sulphate. During the combustion, the potassium salts are released into the flue gas and they are thus concentrated in the fly ash. However, this also applies to the heavy metal cadmium, which means that the fly ash does not comply with the cadmium content requirements of the Executive Order. Consequently, straw fly ash must not be spread on farm land and has to be landfilled for many years.

Lately, however, a new process has been successfully developed, for extracting liquid potassium fertiliser with virtually no heavy metal content from the fly ash. The fertiliser can be delivered to either a fertiliser manufacturer or directly to the farmer. This kind of production plant has been established at Kommunekemi (a treatment plant for hazardous waste) and a similar small-scale plant exists at Enstedværket.

In principle, the ash from the combustion of wood chips can be used within forestry, but the spreading of wood ash is very rare in Denmark. The reason is either that the limit values for heavy metals in the Executive Order cannot be complied with or that the allowed spreading volume per hectare is too low to make the spreading financially viable. However, research is being carried out to establish whether pre-treatment of wood ash can make it more suitable for spreading.

In connection with co-firing of straw, straw ash only represents a small fraction of the ash volume - the majority is still coal ash. Consequently, the effort has been concentrated on ensuring that the traditional utilisation of the ash for the production of concrete and cement can continue even though the straw adds large quantities of potassium. In a cooperation with the industrial buyers of fly ash, it has been successfully demonstrated that fly ash from co-firing can be used in the same way as the familiar coal ash as long as the proportion of straw is not too large and/or coal with a low alkaline content is used.

Emissions

The emissions from biomass combustion depend on the composition of the biomass, the firing technology and the flue gas cleaning system which is used.

Photo: Per Kynde/Thy Statskovdistrikt

Test where wood chip ash is spread in the forest.

When biomass is grate-fired, flue gas cleaning typically includes a bag filter, which removes the ash particles, and the emission of dust is consequently very low. The content of S, Cl and N in the biomass is partly converted into SO_2, HCl and NO_x, which are emitted with the flue gas.

In connection with straw-firing, most of the S and Cl content is bound to the ash as potassium sulphate and potassium chloride and only a small fraction of the N content is converted into NO_x – the rest is converted into N_2, which is already the main component of air. The emission of dioxins from grate-fired CHP plants is very low and well below the requirements for waste combustion plants. Wood contains less S and Cl than straw and the emission of SO_2 and HCl is thus lower.

In connection with co-firing of straw, the coal-fired power plant is equipped with a desulphurisation plant and usually also a SCR plant for catalytic NO_x reduction using ammonium. The emissions of HCl, SO_2 and NO_x are therefore lower than when straw is grate-fired. Due to the efficient combustion process in connection with coal dust-firing, the emission of CO is also considerably lower. Similar conditions apply at co-firing of oil and wood pellets as in the case of Avedøreværket's unit 2.

Emission	10% O_2, dry
CO	200mg/Nm^3
SO_2	100mg/Nm^3
HCl	50mg/Nm^3
NO_x	200mg/Nm^3
Dust	10mg/Nm^3

Table 6.1. Typical annual average values of emissions from grate-fired straw plants.

Emission	10% O_2, dry
CO	75mg/Nm^3
SO_2	5mg/Nm^3
NO_x	150mg/Nm^3
Dust	10mg/Nm^3

Table 6.2. Typical annual average values of emissions from grate-fired wood chip plants.

Cleaning at Måbjergværket near Holstebro. Employee wearing protective equipment with mask, P3 filter respirator during the cleaning.

Photo: Niels Rosenvold

Working Environment

– with focus on dust and mould fungi

Employees working with biofuels must of course pay attention to the safety problems which may arise when handling heavy logs and straw bales, but a number of health aspects also need to be taken into consideration.

They involve dust and microorganisms in the form of fungal spores from mould and bacteria. Dust may be a problem when handling all forms of biofuels, but the health problems are largest when handling fuel pellets and straw. When handling wood chips, fungal spores represent the largest risk.

Photo: Torben Skøtt/BioPress

When wood chips are discharged, as here at the port of Grenaa, the air may be filled with dust and fungal spores.

Dust may contain different kinds of solid particles, but regardless of the content of the dust, sufficient quantities may affect the health. Symptoms include irritation of the mucous membranes in eyes, air passages and skin. Long-term exposure may cause pulmonary diseases and, in the worst case, cancer. In Denmark, approx. 650,000 persons work in industries where high concentrations of dust occur at regular intervals.

If the wood chips are used immediately after production, problems are rare. The fungal spores mainly have the opportunity to multiply extensively in wood chip stores. It is therefore primarily when the wood chips are handled later that working environment problems occur.

Mould Fungi

Fungal spores from mould are found everywhere and they are essential in nature's life cycle. The spores of the fungi float freely in the air and when they land on a suitable habitat, they establish themselves and soon form a whole colony. In private homes, the mould fungi are found in connection with old food and in wet rooms that are not properly ventilated.

Biofuels consist of organic material and are consequently a suitable growth medium for mould fungi – in particular in connection with moisture as in a pile of wood chips. Here the fungi grow very fast and soon the entire pile is infected with mould fungi. Other microorganisms also exist in connection with wood chips, including several bacteria, but the main risk consists in the contact with mould fungi.

Disease

If a person is exposed to a high concentration of fungal spores for a long period of time, this may result in serious health problems. The typical symptoms are running eyes, respiratory trouble, cough, colds, headache and stomach trouble.

Disease caused by breathing in fungal spores and bacteria may be either acute or chronic. The acute disease normally occurs when exposed to a very high concentration of spores – typically 500 times higher than the normal level in the air. The symptoms resemble influenza, perhaps followed by cough and slight shortness of breath. The first symptoms occur 4-8 hours after exposure of the fungal spores, but the disease seldom lasts more than 1-3 days. It does not require medical treatment and does not cause permanent damage, but in the case of repeated exposure, the disease may become chronic.

There is a risk of developing allergy if a person is exposed to fungal spores for a long period. Then even small quantities of spores may result in for example asthma, runny nose, running eyes, cough and general malaise.

The chronic bronchial problems are normally named after the connection in which they originally occurred. This is for example true of the disease thresher lung, which is characterised by shortness of breath, cough, fever and loss of weight. The disease often develops insidiously, but is fortunately rare and probably requires some predisposition in the patient.

The quantity of fungal spores and bacteria needed for someone to become ill varies from person to person. Consequently, there are no limit values for the quantities to which a person may be exposed during a working day. The Working Environment Act merely states that exposure of harmful organisms must be limited as much as possible.

Workplace Assessment

Today, the Working Environment Act requires all companies with employees to prepare a workplace assessment of the working environment of the entire company. This workplace assessment must among other things describe where there is a risk of inhalation of dust and microorganisms and also contain instructions on avoiding exposure to polluted air.

Photo: Lars Nikolaisen

Straw has a relatively low water content, so it does not involve a great risk of mould fungi. On the other hand, moving the straw to and from the storage produces a lot of dust.

The workplace must of course be organised to protect the working environment as much as possible. For example, wood chip storages must be entirely separate from the other parts of the plant to ensure that air containing fungal spores does not spread unnecessarily. Front-end loaders, fork-lift trucks and other machinery must be equipped with ventilating equipment and filters to ensure a sensible indoor climate in the cab. Personal protective equipment such as breathing apparatus and one-piece suits must be used in areas where there is a particular risk of exposure to fungal spores and dust. There are different types of breathing apparatus for the various tasks and it is important to follow the instructions carefully in relation to use, cleaning and maintenance.

Daily cleaning and systematic maintenance of the plants are important to minimise the risk. Furthermore, it is important that the employees are thoroughly informed about the correct way of handling the biofuels.

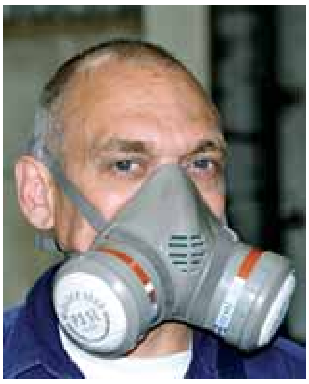


Photo: Simon Skov

When wood chips are handled for short periods, a half-mask with A2 and P3 filters is suitable.

Research Centres

– increased focus on research into bioenergy

As part of the Danish pilot and demonstration programme for biomass-based power plants, competent Danish research centres within bioenergy have been established since the mid-1990s and, in total, very considerable amounts have been invested in the realisation of research projects within the area.

Initially, the efforts were primarily financed by the power plants' R&D programmes and by government support schemes, but since the late 1990s, the so-called PSO funding, which is now administered by Energinet.dk, has played an important part. International cooperation via the EU's research programmes has also been very important.

The research work has included virtually all aspects of the use of biomass for CHP production. The entire chain - from field and forest to emissions and residual products from the power plants - has been examined.

The purpose of the research is to establish the basic knowledge that is necessary to obtain a qualified technical development and to contribute to a solution of specific technical challenges at suppliers and power plants. Much of the research has been aimed at straw as fuel, as this is an important Danish resource and an area where the international experience is very limited. The utilisation of wood chips and other biofuels has, however, also been examined thoroughly.

In the years to come, there will undoubtedly still be focus on research into bioenergy, but it is expected that the emphasis will be on the development of biofuel substances and not so much

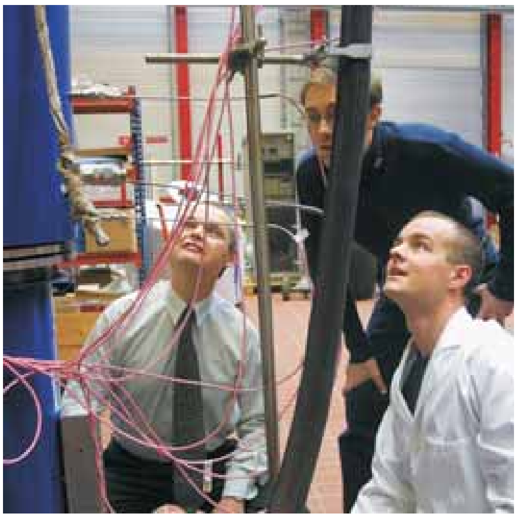


Photo: CHEC/Danmarks Tekniske Universitet

At the CHEC Research Centre at the Technical University of Denmark, a number of test plants have been built which can simulate the conditions in boiler plants and plants for cleaning of flue gas.

Photo: CHEC/Danmarks Tekniske Universitet

At the CHEC Research Centre at the Technical University of Denmark more than 40 researches and students of ten different nationalities are working determinedly to improve the exploitation of biomass for energy purposes.

on CHP plants. In the latest EU framework programme, energy research is given a huge boost and when the energy research funds from the PSO scheme were distributed in 2007, bioenergy and waste received almost half of the total framework of DKK 130 million.

Research into the development of biofuel substances has received a lot of attention, including especially the so-called second generation technology for the production of bioethanol. In many cases, it will be possible to use the residual fractions from the production of ethanol as fuel at the power plants. It will likewise be possible to use the surplus production of steam from the power plants as process energy for the production of ethanol.

Two Main Areas

The research work within biomass-based power production can be divided into two main areas. One area concerns production and handling of biomass as well as biomass properties as fuel at a power plant. In this connection, the following topics have been researched:

- mapping of available resources of straw, wood and other biomass
- physical/chemical characterisation of biofuels
- sampling and analysis
- the chemical composition of biofuel in relation to soil conditions, amount of rain, fertilisation, species, sort, etc.
- optimisation of machinery and logistics for the production and delivery of biofuels
- acceptance testing and development of moisture measurement methods
- working environment in connection with the handling of biofuels
- European standardisation
- growing of energy crops.

The other main area comprises the four different technologies used at biomass-fired CHP plants. They are grate-firing of straw and wood, co-firing of straw at coal-fired power plant, dust-firing of wood powder and circulating fluidized bed combustion of coal and straw. Within each technology, combustion processes, regulation, corrosion, formation of deposits, flue gas cleaning, emission and residual products have been researched. Examples of research areas are:

- feeding of biofuels
- combustion optimisation
- CFD modelling of biomass boiler (CFD is short for computational fluid dynamics)
- problems with alkali, chlorine and sulphur in connection with the combustion of biomass
- mechanisms for deposit formation and corrosion
- studies of boiler materials
- use of additives to limit deposit formation and corrosion
- studies of deactivation of SCR catalysts to reduce NO_x
- development of alkali resistant catalysts
- flue gas cleaning of SO_2 and HCl
- methods for recirculation of ash from grate-firing in fields and forests.

In addition, considerable research has been carried out within thermal gasification, biogas and bioethanol. The description of these is, however, outside the framework of this publication.

Research Programmes

The energy research within bioenergy has been supported by a number of public research programmes in both Denmark and the EU. In addition, several of the projects have received significant co-funding from the players and in some cases research programmes in countries outside the EU have supported the projects.

Today, there are five different programmes in Denmark which support energy research as well as a Nordic energy research programme and the EU's framework programme, which also supports energy research.

For new applicants it can often be difficult to know which research programmes are best suited to a particular project. Methods are continuously being developed to make it easier for the applicants to understand the area, including the establishment of a common Internet portal at the address www.energiforskning.dk, and today the sets of rules applying to the programmes are virtually identical. In addition, there is close cooperation between several of the research programmes and applications are frequently exchanged between the individual programmes. Applicants therefore should not despair if they have submitted an application to for example a PSO programme and it subsequently turns out that it falls under the EUDP scheme, which is administered by the Danish Energy Agency.

To a large extent, the choice of energy research programme depends on whether the project in

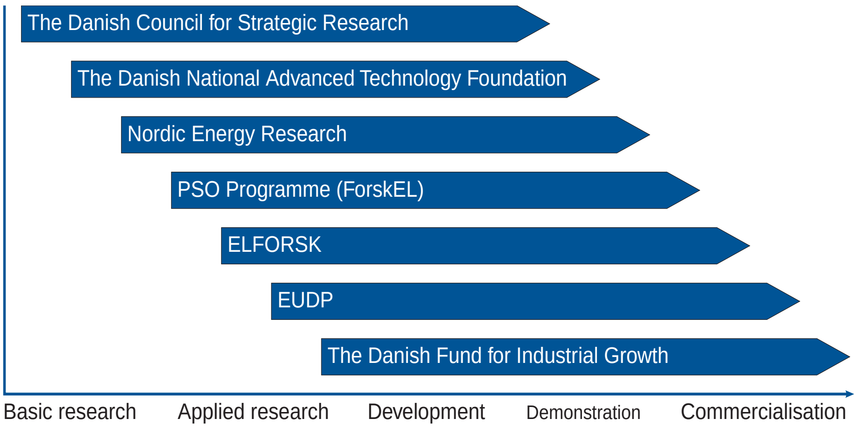


Figure 8.1. To a large extent, the choice of energy research programme depends on whether the project in question involves basic research or a technology which is almost fully developed. From 2007, the EUDP (Energy Technology Development and Demonstration Programme) replaces the Energy Research Programme governed by the Danish Energy Agency.

Photo: Lasse Rosendahl, Aalborg Universitet.

Researchers and engineers from the Institute of Energy Technology at Aalborg University preparing measuring equipment for tests of a power plant boiler.

Photo: CHEC/Danmarks Tekniske Universitet

Employees from the CHEC group at the Technical University of Denmark measuring the deposits on a biomass-fired power plant boiler.

question involves basic research or a technology which is almost fully developed. If basic research is involved, it will be sensible to approach The Danish Council for Strategic Research. If, on the other hand, the technology is close to being tested in practice, it is better to choose one of the other programmes. Finally, it is possible to apply to the Danish Fund for Industrial Growth for support if the project in question is almost ready for a big export adventure.

In 2007, part of the research funding is directed towards consortiums where private companies work with universities and other research institutions on large projects. In general, the consortiums have obtained a more flexible framework but must, in return, contribute a significant level of co-funding.

The Danish Council for Strategic Research

The Danish Council for Strategic Research under the Danish Agency for Science, Technology and Innovation supports research within a number of politically prioritised areas to strengthen the interaction between public and private research. The Council will also seek out new research trends and provide professional advice to the Science Minister.

The Danish Council for Strategic Research consists of a board and a number of programme committees, including an energy and environment committee, which can make grants towards bioenergy research. In 2006, the committee had more than DDK 100 million at its disposal.

For further information, see the website www.fist.dk.

The Danish National Advanced Technology Foundation

The Danish National Advanced Technology Foundation has been set up to stimulate research and innovation efforts within areas where Denmark has special qualifications and potentials.

In 2006, the Danish National Advanced Technology Foundation initiated new research cooperation costing almost DKK 400 million. Including the funds that the parties invest in the projects, the Danish National Advanced Technology Foundation has invested more than DKK 800 million in new Danish technology. Some of the money has been spent on projects involving biofuel substances, including the development of the so-called second generation technology for the production of bioethanol and biodiesel.

For further information, see the website www.hoejteknologifonden.dk.

Nordic Energy Research

Nordic Energy Research is an institution under the Nordic Council of Ministers, which is to contribute to achieving the political objectives within the Nordic energy cooperation. Nordic Energy Research supports selected projects within the following five main areas:

– reduction of greenhouse gases
– hydrogen technology
– energy efficiency
– renewable energy
– integration of the energy markets

For further information, see the website www.nordicenergy.net.

PSO Programme

PSO (Public Service Obligation) is administered by Energinet.dk. As the body with system responsibility for the electricity and natural gas network, the company is under an obligation to spend money on research and development. The activities are financed via the tariffs which Energinet.dk charges for the transport of electricity and natural gas. In addition, research into environmentally friendly electricity production technologies is financed via a special PSO charge of DKK 0.4/kWh paid by all electricity customers through their electricity bill.

Energinet.dk administers three research programmes: ForskNG, ForskIN and the FoskEL programme. The latter provides subsidies for environmentally friendly electricity production technologies and this is where the bioenergy research funds come from. In the period 2005-2008, the annual framework allocation amounts to DKK 130 million.

For further information, see the website www.energinet.dk.

ELFORSK

Dansk Energi | Net administers the energy research programme ELFORSK (research and development in efficient energy use). The programme has a capital of DKK 25 million a year, which comes from the PSO contributions paid by the electricity consumers.

For further information, see the website www.elforsk.dk.

EUDP

From 2007, the Energy Technology Development and Demonstration Programme (EUDP) replaces the Energy Research Programme governed by the Danish Energy Agency. The programme focuses on the establishment of pilot plants and the realisation of demonstration projects, but is also able to support actual research activities. In 2007, the EUDP programme has a capital of more than DKK 186 million, but the amount will increase continuously until 2010, when the programme will have DKK 394 million at its disposal. The programme has its secretariat at the Danish Energy Agency and is an independent committee appointed by the Minister for Transport and Energy.

For further information, see the website www.ens.dk.

The Danish Fund for Industrial Growth

The Danish Fund for Industrial Growth does not provide grants for research, but invests in Danish companies that develop new technology. The Fund is part of the Danish trade and industry development system and its purpose is to create financing possibilities for promising projects in small and mid-sized companies.

The Danish Fund for Industrial Growth has a capital base of more than DKK 2 billion and is thus one of the largest venture investors in Denmark. The Fund finances on commercial terms when other hesitates and works actively to strengthen the company network.

For further information, see the website www.vf.dk.

Photo: Torben Skøtt/BioPress

Tests with wet oxidation of straw at RISØ National Laboratory. The wet oxidation is the first step in a process where the straw is converted into bioethanol, animal feed and fuel or the power plants.

The EU's Seventh Framework Programme

In June 2006, the Council of the European Union decided to allocate approx. DKK 400 billion to research and development in the seventh framework programme which runs from 2007 to 2013. This is a considerable lift compared with previous programmes and at the same time, energy received its own budget with a framework allocation of approx. DKK 17 billion, which will be distributed between the areas:

- hydrogen and fuel cells
- renewable energy for electricity production
- renewable energy for fuel
- renewable energy for heating/cooling
- CO_2 free electricity production (storage of CO_2)
- clean coal technologies
- energy efficiency and energy savings
- energy policy awareness.

In addition to a larger research budget, the seventh framework programme invites a strengthening of company participation in European research.

Players

A large number of players have contributed to Danish research and development within biomass combustion. The list below includes a variety of important Danish research and development environments within biomass combustion.

Universities and Research Centres

Technical University of Denmark (DTU):

- CHEC Research Centre
  telephone +45 45 25 28 00
  www.kt.dtu.dk
- Department of Manufacturing and Engineering and Management (IPL)
  telephone +45 45 25 47 08
  www.ipl.dtu.dk
- Department of Mechanical Engineering (MEK)
  telephone +45 45 25 19 60
  www.mek.dtu.dk

Aalborg University (AAU):

- Institute of Energy Technology
  telephone +45 96 35 92 40
  www.iet.aau.dk
- Esbjerg Tekniske Institut
  telephone +45 79 12 76 66
  www.aaue.dk

RISØ National Laboratory
telephone +45 46 77 46 77
http://risoe-staged.risoe.dk

Faculty of Agricultural Sciences
University of Aarhus
telephone +45 89 99 19 00
www.agrsci.dk/ny_navigation/om_djf

National Research Centre for the Working Environment
telephone +45 39 16 52 00
www.arbejdsmiljoforskning.dk

Forest & Landscape
telephone +45 35 28 15 00
www.sl.kvl.dk

Technological Service Institutions

Danish Technological Institute
telephone +45 72 20 20 00
www.teknologisk.dk

FORCE Technology
telephone +45 43 26 70 00
http://force.dk/da

Danish Agricultrual Advisory Service
telephone +45 87 40 50 00
www.lr.dk

Power Plants and Suppliers

DONG Energy Generation
telephone +45 76 22 20 00
www.dongenergy.com

Vattenfall
telephone +45 88 27 50 00
www.vattenfall.dk

Babcock & Wilcox Vølund
telephone +45 76 14 34 00
www.volund.dk

Burmeister & Wain Energy
telephone +45 39 45 20 00
www.bwe.dk

Bioener
telephone +45 36 18 12 00
www.bioener.dk/index.html

Thomas Koch Energi
telephone +45 46 18 90 00
www.tke.dk

Aalborg Energie Technik
telephone +45 96 32 86 00
www.aet-biomass.com/aet/dk

Alternative Utilisation of Biomass

- simultaneous production of biofuels, electricity and heat

Photo: Torben Skøtt/BioPress

From the opening of the IBUS plant at Fynsværket in autumn 2005. The pilot plant was later moved to Skærbækværket near Fredericia.

By traditional use of biomass in the energy section, the biomass is converted into electricity and heat. This produces a residual product in the form of ash, which can be fully or partly utilised. In the future, the biotechnological development will make it possible to integrate biomass-based production of electricity and heat with the production of liquid biofuels for the transport sector in the form of bioethanol, with animal feed as a valuable by-product. In this way, the utilisation of biomass becomes more valuable and a contribution is made to reducing the CO_2 emission of the transport sector.

Production of bioethanol on the basis of grain, maize or sugar cane is well-known technology. A large number of these first generation plants have been established in for example the USA and Brazil and they deliver large quantities of bioethanol to replace petrol. Bioethanol is produced by fermentation of sugars and it is relatively simple to extract sugars for the process from grain, maize and sugar cane.

Straw and other surplus products from the agricultural industry also contain sugars but in the form of cellulose and hemicellulose which are difficult to degrade. First, the straw needs to go through a pre-treatment under pressure at temperatures close to 200° C. Then, enzymes have to be added to degrade the biomass. So far, there have been no reliable technologies available for this pre-treatment and the cost of enzymes has been far too high. In recent years, both areas have experienced important progress and Danish companies play an essential role in the development of this second generation technology.

Enzyme Development

Novozymes and the Danisco-owned company Genencor are world leaders within the development and production of industrial enzymes and both contribute to the development of enzymes which can convert cellulose and hemicellulose into sugar.

In January 2001, Novozymes and National Renewable Energy Laboratory (NREL), supported by the American Ministry of Energy, entered into a three-year research agreement, which was followed by a one year extension in April 2004. The purpose of the agreement was to obtain a significant cost reduction in connection with the conversion into sugar of biomass containing cellulose such as maize leaves and stems.

Novozymes has used its comprehensive range of patent technologies to find new enzymes and increase the output, thus successfully reducing the total enzyme costs by a factor of 30. This means that a financially competitive production of bioethanol made from maize leaves and stems is within reach.

Photo: Volvo

Today, it is possible to fill the tank with bioethanol at a large number of petrol stations in Europe.

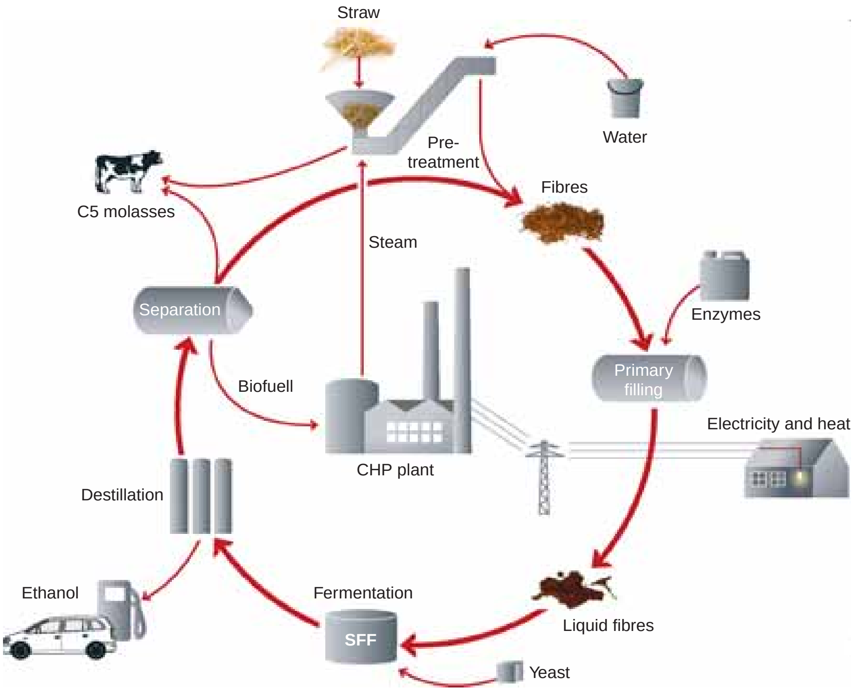


Figure 9.1. The principle of the IBUS process.

At the same time, Genencor has entered into a similar research agreement with NREL and has gained similarly good results.

IBUS Process

IBUS (Integrated Biomass Utilisation System) is a concept whereby straw and similar residual products are converted into bioethanol, solid biofuels and animal feed in a process which is integrated with a power plant. The IBUS concept is characterised by a high content of dry matter in the process, simple process with no ancillary materials apart from water and enzymes and low energy consumption, as the surplus heat from the power plant can be used for the production of ethanol.

IBUS is also the name of an EU project which was carried out in the period 2002-2006 with DONG Energy as project coordinator and with the participation of three Danish partners (Sicco, the Danish Royal Veterinary and Agricultural University and RISØ National Laboratory) as well as an English partner (TMO Biotech). A demonstration plant has been established for the project with the purpose of testing and optimising the most important process steps and discovering the synergy between ethanol production and a CHP plant. The plant is located at Skærbækværket near Fredericia.

The principle in the IBUS process is shown in figure 9.1. The straw is shredded and pre-treated in a continuous hydrothermal process at 180- 200° C. In this way, the cellulose is made available for enzymatic decomposition and the chloride salts in the straw are washed out. Enzymes are added to the fibres in a specially developed reactor, which is capable of handling fibres with a high content of dry matter. The cellulose is converted into sugars, which are subsequently fermented into ethanol and concentrated by distillation. The remaining biomass is separated into a solid fuel fraction, which can be used at the power plant, and a fraction (C5 molasses) which can be used as animal feed.

In the period 2007-2010, the intention is to build a complete IBUS demonstration plant with a straw capacity of four tonnes/hour. This is the last step before a commercial full-scale IBUS plant can be established.

MaxiFuel

The Danish development company BIOGASOL has developed another Danish concept for the production of bioethanol where the by-products, in addition to solid biofuel, include gaseous fuels in the form of methane and hydrogen. The principle in the process is shown in figure 9.2.

First of all, a thermal pre-treatment of the straw is carried out while oxygen is added. Enzymatic decomposition and fermentation are carried out in two stages where the first stage converts glucose from cellulose into bioethanol and the second converts xylose from hemicellulose. In the final steps of the process, process water containing biomass residue is led to a reactor, where methane and hydrogen are produced.

A pilot plant named MaxiFuel was inaugurated in September 2006 at the Technical University of Denmark. In the MaxiFuel plant, all steps of the process can be tested and optimised with a view to subsequently upgrading of the process.

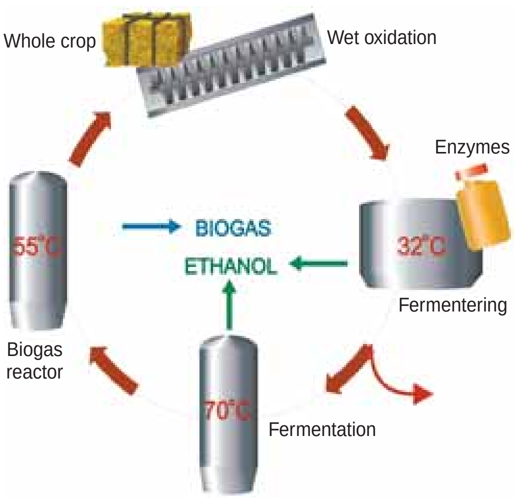


Figure 9.2. The principle of the MaxiFuel process.

Part 2

Description of Biomass-fired CHP Plants

Køge Kraftvarmeværk

– bioenergy for the industry


Photo: Torben Skøtt/BioPress

Køge Kraftvarmeværk consists of two power plant units, which supply electricity and steam to Junckers Industrier and Køge Biopillefabrik.

Køge Kraftvarmeværk is a wood-fired CHP plant, which produces process steam for Junckers Industrier and Køge Biopillefabrik. The CHP plant was originally established by Junckers Industrier, but in 2001 it was taken over by Energi E2, which subsequently established a factory for the production of biopellets at the plant. In June 2006, the CHP plant was transferred to the new large energy company DONG Energy.

The plant consists of two power plant units, unit 7 and unit 8, which began operation in 1987 and 1999, respectively. The two boiler plants have their own steam turbine and electricity generator. As both boilers supply steam for industrial purposes, the electricity production is of course dependent on how much steam the companies need.

Both plants are fired with various woodfuels such as wood chips, sawdust, shavings and dust from, among others, Junckers Industrier. The wood chips are stored in an outdoor storage, while sawdust, shavings and dust are stored in


Photo: Torben Skøtt/BioPress

Outdoor wood chip storage in Køge.

silos. A common transport system transports the various fuels to the two power plant units.

Unit 7

With an electrical power efficiency of 9.4MW, unit 7 was the largest wood-fired power plant unit in Denmark until 1998. The boiler is a traditional drum boiler with a water-cooled vibrating grate, two superheaters in the second pass and one superheater in the combustion chamber.

The combustion plant includes three spreader-stokers, two combined dust and oil burners and a separate dust burner. Wood chips and shavings are fired through the three stokers, while sander dust is added via dust burners. In addition to woodfuels, the boiler can be fired with fuel oil up to 75 per cent load.

Unit 8

In many ways, unit 8 is similar to unit 7, but it has slightly larger capacity. It is also a drum boiler with spreaderstokers and dust burners for the feeding of fuel. Steam pressure and temperatures are identical in the two boiler plants, but while unit 7 delivers 55 tonnes of steam per hour, unit 8 can deliver 64 tonnes of steam per hour. To keep the heating surfaces of the boiler clean, unit 8 is equipped with steam soot blowers, which are activated 3-4 times a day.

Data for Køge Kraftvarmeværk	
Commercial operation (units 7/8)	1987/1999
Supplier (units 7/8)	Burmeister & Wain Energi/Vølund
Fuels	Wood chips, sawdust, shavings and dust
Consumption of woodfuels (units 7/8)	16/19 tonnes/time
Fired out (units 7/8)	46/56MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	93 bar
Steam volume (units 7/8)	15/18kg/second
Steam temperature	525°C
Electricity efficiency (units 7/8)	20/29 per cent
Boiler efficiency (units 7/8)	90/91 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency (units 7/8)	10/16MW
Steam output for industry (units 7/8)	75/62 tonnes/time

Flue Gas and Ash

The flue gas from the two boilers is cleaned of fly ash in separate electrostatic precipitators. Flue gas and bottom ash are stored.

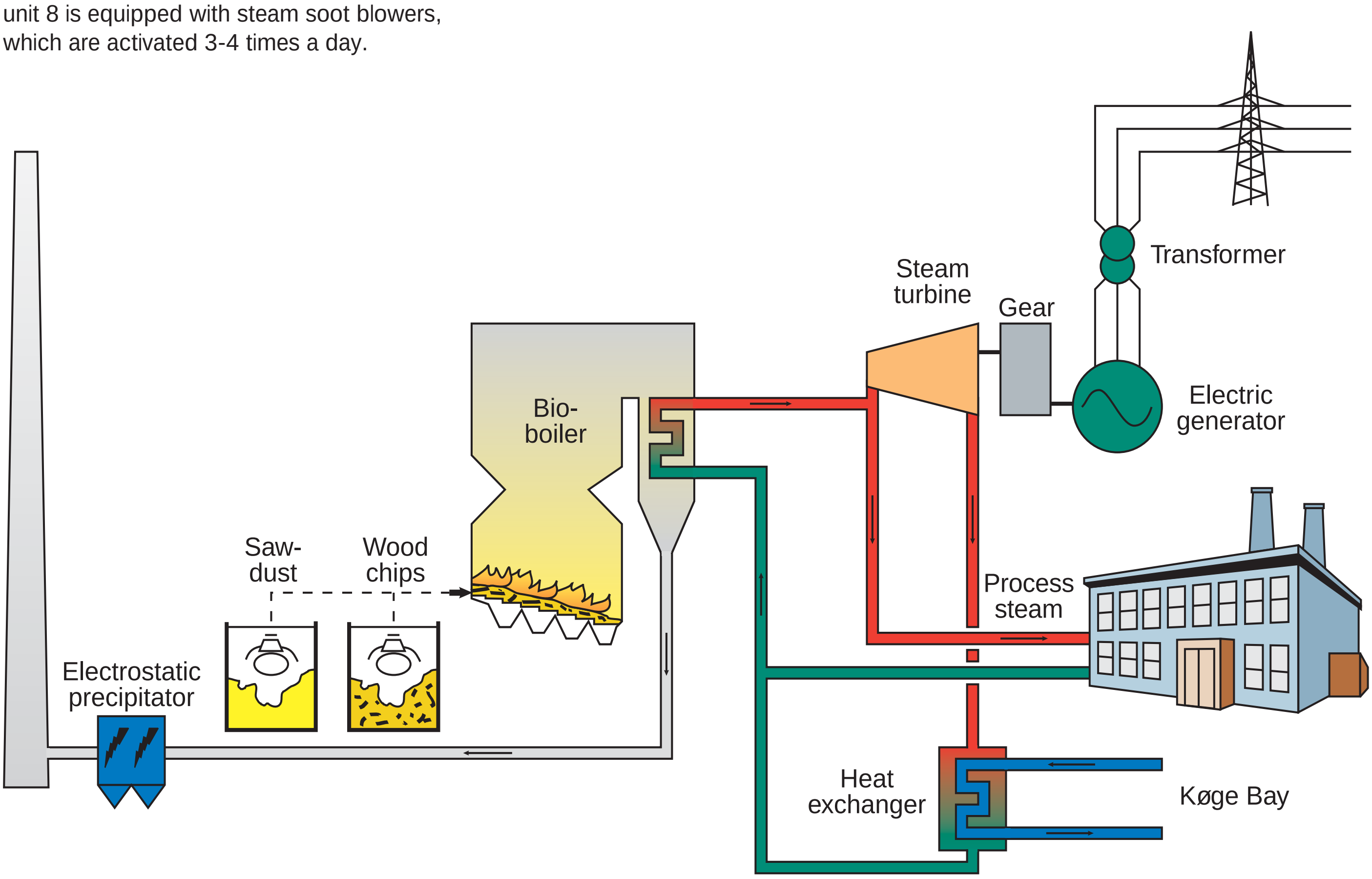


Figure 10.1. Simplified diagram of Køge Kraftvarmeværk.

Haslev Kraftvarmeværk

– the world's first straw-fired CHP plant

Haslev Kraftvarmeværk supplies electricity to the East Danish high-voltage system and district heating to approx. 2,000 houses in Haslev.

Photo: Mogens Carrebye

The CHP plant in Haslev was put into operation in 1989 as the world's first straw-fired CHP plant. The plant delivers electricity for the East Danish high-voltage system and district heating for approx. 2,000 houses in Haslev.

In 1999, the plant was rebuilt. The system used for the transport of straw was replaced, new burners were installed and the plant got a new control system. The rebuilding helped increase the efficiency and make the plant more robust. Haslev Kraftvarmeværk is a fully automated plant, which is approved for 24 hours of unmanned operation when all control and monitoring can be carried out from a central control room at Kundbyværket (power plant) near Frederikssund.

The plant uses approx. 26,000 tonnes of straw a year, which is supplied by the farmers in South Zealand. The capacity of the straw storage is up to 700 big bales, which equals 2-3 days' full production, and during the winter months, the plant receives straw bales every day.

Boiler Plant

The boiler plant is delivered by Vølund and consists of a drum boiler with natural circulation in the evaporation system.

Four straw burners have been installed to continuously feed the bales directly into the boiler in accordance with the so-called “cigar burning principle”. The straw thus is not shredded, as the bales burn from one end to the other. Some of the straw will of course fall on the grate, where it burns.

Approx. 90 per cent of the preheated combustion air is blown directly towards the end of the straw bales, while approx. three per cent is added through the grate at the bottom of the boiler. The remaining air is introduced immediately above the straw bales as secondary air.

The ash particles melt at relatively low temperatures and can therefore tend to form solid and viscid slag, which is difficult to remove during normal operation. The slag obstructs the heat transfer from the flue gas to the steam in the tubes and, in severe cases, may shut off the flue gas so that the boiler cannot operate at full load. To minimise the slagging problems, it has been decided to limit the superheater temperature to a maximum of 455°C but, on the other hand, this reduces the electricity efficiency.

The boiler is equipped with two soot blowers placed between the three superheaters at the top of the boiler. In addition, so-called ball cleaning equipment has been installed to keep the superheaters clean. Metal balls with diameters of 4-6 mm are poured into the tubes to knock off the deposits. The balls end in the ash removal tray, where they are separated for reuse.

Flue Gas and Ash

The plant is equipped with a bag filter for cleaning of the flue gas. The filter arrangement consists of 792 bags with a length of 2.3 metres. The bags are changed each year to keep the particle emission below the limit value of 40mg/Nm^3 flue gas. Most of the bottom ash and fly ash is returned to the farmers as fertiliser, but if the fly ash contains too much cadmium, it is stored.

Data for Haslev Kraftvarmeværk	
Commercial operation	1989
Supplier of boiler plants	Vølund
Fuels	Straw
Consumption of straw	26,000 tonnes/year
Fired output	20MW
Boiler type	Drum boiler
Firing concept	Cigar burner and solid grate
Steam pressure	67 bar
Steam volume	7.37kg/second
Steam temperature	455°C
Electricity efficiency	19 per cent
Boiler efficiency	88 per cent
Flue gas cleaning	Bag filter
Electrical power efficiency	5MW
District heating output	13MJ/second

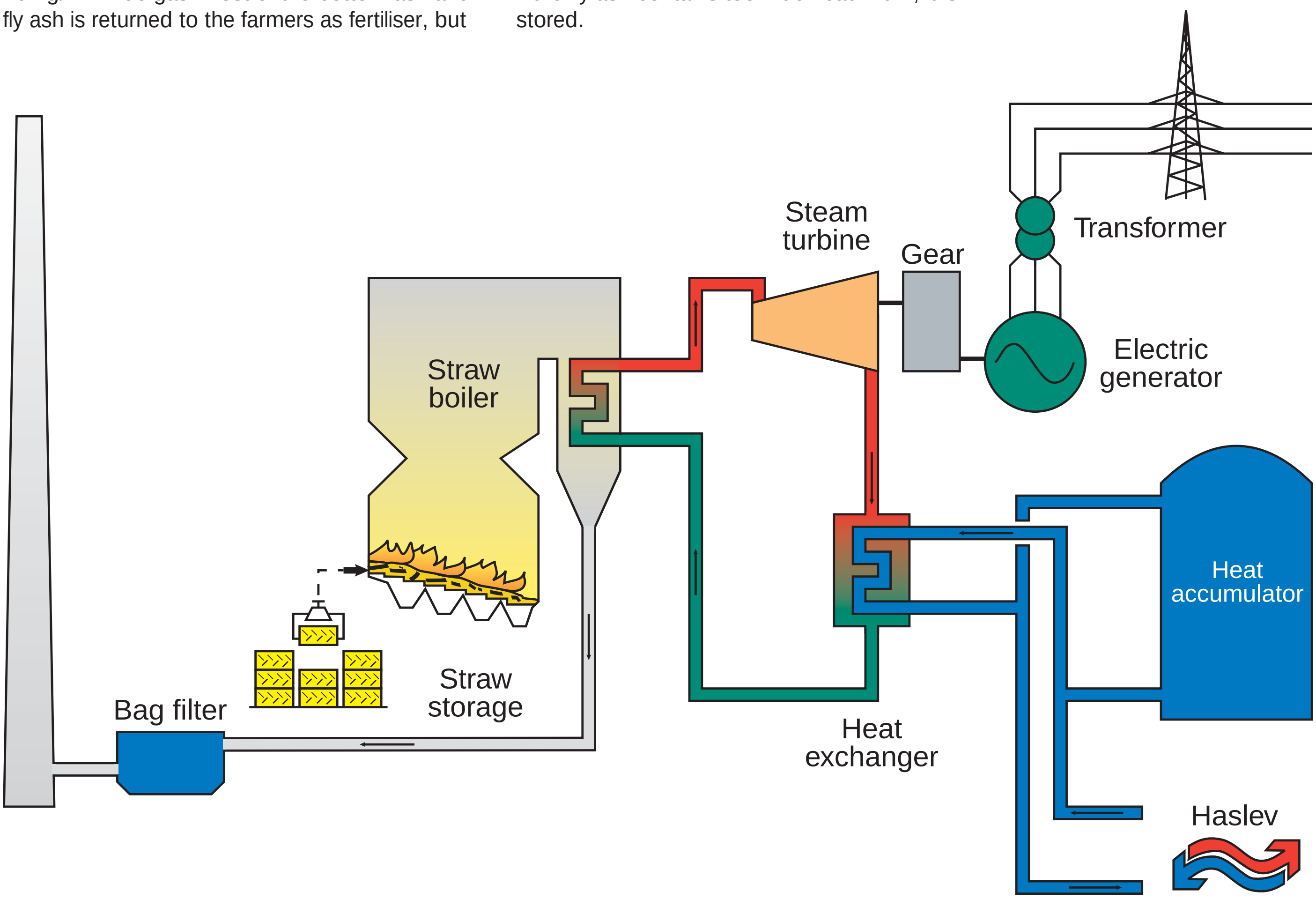


Figure 11.1. Simplified diagram of the straw-fired CHP plant in Haslev.

Rudkøbing Kraftvarmeværk

– the first straw-fired plant in West Denmark

Photo: Torben Skøtt/BioPress

The plant in Rudkøbing is the smallest straw-fired CHP plant in Denmark.

The CHP plant in Rudkøbing was put into operation in 1990 as the first straw-fired CHP plant in West Denmark. The plant, which supplies district heating to approx. 1,900 consumers, has an electrical power efficiency of only 2.55MW and it is thus one of the smallest biofuel-fired CHP plants. The annual straw consumption is 14,000 tonnes. The capacity of the straw storage is 700 big bales, which equals five days' consumption at full load. The storage is operated manually as the straw bales are stacked using a fork-lift truck.

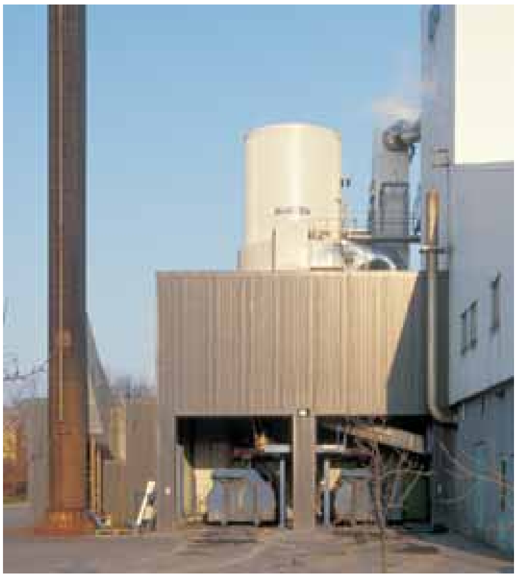


Photo: Torben Skøtt/BioPress

Slag and bottom ash from the boiler is collected in containers and returned to the farmers for use as fertiliser.

In connection with the plant, a storage tank of 2,500m^3 has been established. This is capable of covering the district heating consumption for 5-10 hours during the winter. In addition, the plant is equipped with a bypass valve, which makes it possible to increase the heat production periodically by directing the steam away from the turbine.

Boiler Plant

The boiler is a grate-fired drum boiler with natural circulation in the evaporation system. After the boiler, the steam is superheated by means of two superheaters and one radiation superheater, and the temperature is regulated with cooling water before the steam reaches the turbine.

The ash particles melt at relatively low temperatures and may therefore tend to form solid and viscid slag, which is difficult to remove during normal operation. The slag reduces the heat transfer from the flue gas to the steam in the tubes and, in severe cases, may shut off the flue gas so that the boiler cannot operate at full load. To minimise the problems, it has - as in Haslev - been decided to limit the superheater temperature to a maximum of 450°C.

From the straw storage, the bales are transported to a shredder where the straw is divided into fine particles. From here, the straw is fed into a water-cooled feeding tunnel by means of a screw stoker, which presses the straw through the feeding tunnel like a plug and onto the vibrating grate in the boiler.

The cooling of the vibrating grate has been changed from steam cooling to cooling with feed water. In this way, the grate has become cooler, which reduces the tendency of the ash to produce slag.

Flue Gas and Ash

The original electrostatic precipitator has been replaced by a bag filter. In connection with start-up of the boiler, the filter is pre-heated with oil so that it is ready to use right away. Fly ash from the filter has so far been stored, but today plants are available for converting the ash into fertiliser. Bottom ash from the boiler is returned to the farmers for use as fertiliser.

Data for Rudkøbing Kraftvarmeværk	
Commercial operation	1990
Supplier of boiler plants	Burmeister & Wain Energi
Fuels	Straw
Consumption of straw	14,000 tonnes/year
Fired output	11.2MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	60 bar
Steam volume	3.6kg/second
Steam temperature	450°C
Electricity efficiency	22 per cent
Boiler efficiency	89 per cent
Flue gas cleaning	Bag filter
Electrical power efficiency	2.55MW
District heating output	7.5MJ/second

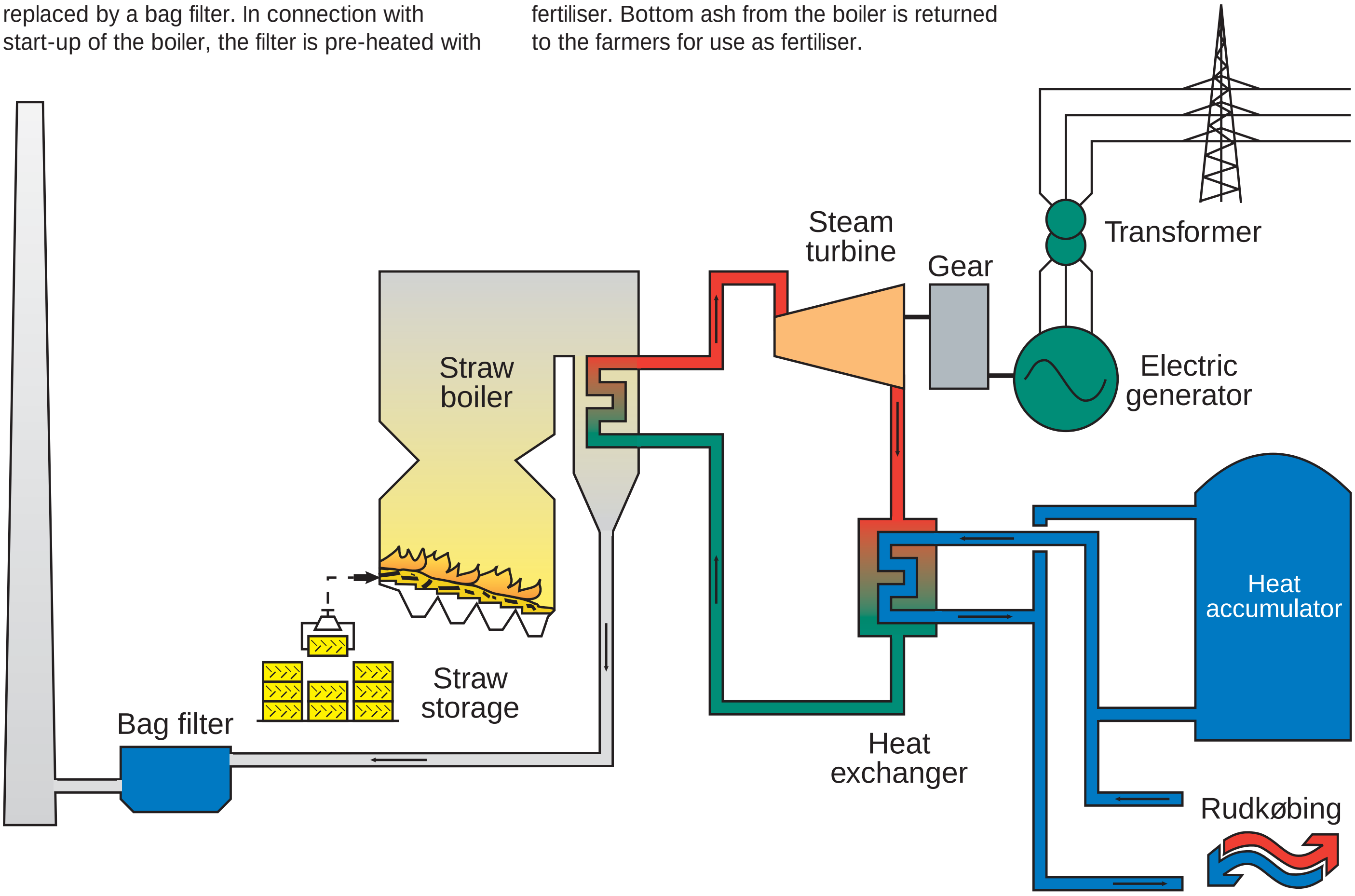


Figure 12.1. Simplified diagram of the straw-fired CHP plant in Rudkøbing.

Slagelse Kraftvarmeværk

– interplay between straw-firing and waste combustion

Photo: Torben Skøtt/BioPress

The CHP plant in Slagelse is connected to the nearby waste combustion plant.

Slagelse Kraftvarmeværk (CHP plant) was put into operation in 1990 and is thus one of the first biomass-fired plants. At that time, there was limited experience of straw-firing in steam boilers and as a result the superheater temperature is limited to 450°C, which produces a relatively low electricity efficiency of 25 per cent.

Photo: Torben Skøtt/BioPress

The water content in the straw bales is checked before unloading. If they are too damp, they will be rejected. The bales are unloaded with a fork-lift truck.

The CHP plant in Slagelse differs from the other biomass-fired plants in receiving steam and hot water from a nearby waste combustion plant. The plant has an electrical power efficiency of 12MW, which equals the consumption of approx. 9,000 households. In addition, the plant supplies district heating for approx. 6,000 houses or approx. 85 per cent of the heating requirement in Slagelse.

The boiler plant is delivered by Aalborg Boilers. It consists of a drum boiler with natural circulation in the steam evaporator and five flue gas passes with two vertical superheaters.

Five soot blowers have been installed in the combustion chamber along with two soot blowers below the bottom superheater and so-called ball cleaning equipment to keep the superheaters clean. Metal balls with diameters of 4-6 mm are poured into the tubes to knock off the deposits. The balls end in the ash removal tray, where they are separated for reuse.

Fuel Handling

Two automatic cranes handle the transport of the big bales from the storage to three parallel feeding lines. The strings that hold the bales together are cut and also fired in the boiler. When the strings have been removed, the straw is fed into the straw shredders, which each consists of three rotating cylinders positioned above each other. The loose straw drops down on a rotary valve and from there to the screw stokers, which push the straw through a feeding tunnel onto the grate.

The grate consists of two parts, a horizontal main grate and a vertical combustion grate. The main grate is a push grate, which means that the straw is pushed forward in the combustion chamber during combustion. In this way, the risk of the straw spreading, which is very common on a vibrating grate, is minimised.

The main grate is divided into 3 x 3 sections, in which primary air is added. After the main grate, the straw drops down on the combustion grate, which is divided into three sections crosswise but only one section lengthwise. The distribution of air between the individual sections can be varied. The retention time of the straw on the grate is estimated at approx. 30 minutes.

At full production, 16-18 bales are fired per hour and the annual consumption of fuel is approx. 30,000 tonnes of straw. The capacity of the straw storage is up to 1,200 big bales, which equals approx. three days' consumption at full load.

Data for Slagelse Kraftvarmeværk	
Commercial operation	1990
Supplier of boiler plants	Aalborg Boilers
Fuels	Straw
Consumption of straw	30,000 tonnes/year
Fired output	31MW
Boiler type	Drum boiler
Firing concept	Push grate
Steam pressure	67 bar
Steam volume	16kg/second
Steam temperature	450°C
Electricity efficiency	25 per cent
Boiler efficiency	89 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency	11.4MW
District heating output	28MJ/second

Flue Gas and Ash

For flue gas cleaning, a three step electro filter is used. Most of the fly ash from the filter is stored. Bottom ash from the boiler is returned to the farmers for use as fertiliser.

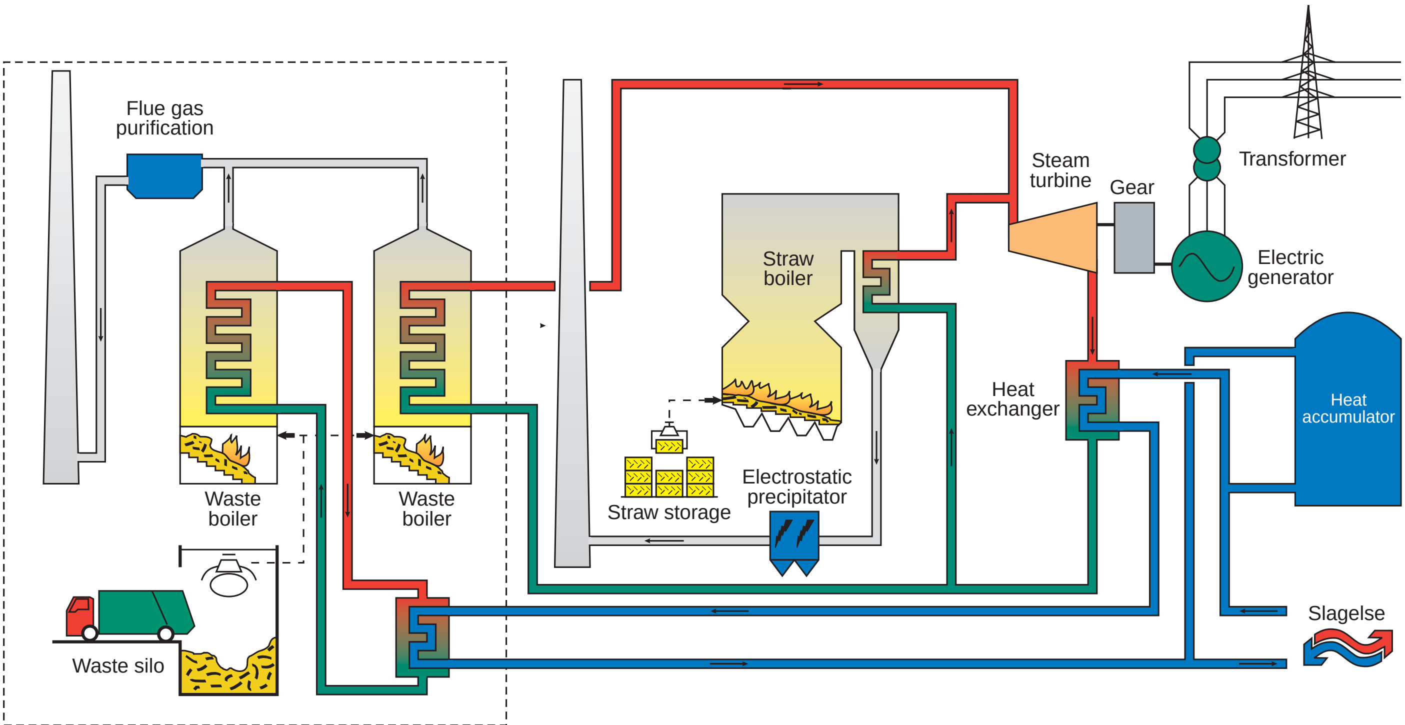


Figure 13.1. Simplified diagram of the CHP plant in Slagelse and the connection to the waste combustion plant.

Grenaa Kraftvarmeværk

– only plant with fluidized bed boiler

Photo: Torben Skøtt/BioPress

Grenaa Kraftvarmeværk is located in an industrial area and supplies steam to several companies.

Grenaa Kraftvarmeværk (CHP plant) is located north-east of Grenaa town centre in an industrial area dominated by a number of energy-intensive companies. The plant, which was opened in 1992, supplies steam to several of these companies and, in addition, Grenaa is supplied with district heating as well as electricity for the high-voltage system.

Photo: Torben Skøtt/BioPress

The operations manager at Grenaa Kraftvarmeværk (CHP plant) stands by the straw shredder, which is open for inspection.

Grenaa Kraftvarmeværk uses a combination of coal and straw, but other forms of biofuels such as energy grain, sunflower seed shells, olive stones and grain residue have also been used from time to time. The plant is capable of operating as a 100 per cent coal-fired plant or with a combination of coal and straw containing up to 60 per cent straw.

Fluidized Bed Boiler

So far the only biomass-fired plant in Denmark, the plant in Grenaa is equipped with a so-called circulating fluidized bed boiler, which is especially suitable for handling different types of fuels.

The principle involves a particulate material inside the boiler, such as sand or coal ash, which has the same properties as liquid when the combustion air is blown through it. This has several advantages. It is easy to maintain a constant temperature, the fuel is quickly spread inside the boiler and it is possible to add lime in order to "desulphurise" the coals inside the combustion chamber. Finally, the combustion can take place at relatively low temperatures which reduces the release of nitric oxide.

Straw Handling

With an annual supply of approx. 55,000 tonnes of straw, it has been necessary to develop a system to ensure fast unloading of the many tonnes of straw transported to the plant every day. A crane capable of lifting 12 big bales at a time has therefore been installed, which means that each truck can be emptied in two stages. At the same time as the crane lifts the bales, microwaves are sent through the straw to register the water content. Information about weight, water content and supplier is subsequently recorded in a database and used when settling with the farmer.

From the storage, the bales are conveyed by a crane onto four feeding lines where they continue to four straw shredders. The loose straw is then conveyed via rotary valves to two firing systems, which blow the straw into the boiler.

Data for Grenaa Kraftvarmeværk	
Commercial operation	1992
Supplier of boiler plants	Aalborg Boilers & Ahlstrøm
Fuels	Straw and coal
Consumption of biomass	40,000 tonnes/year
Fired output	88MW
Boiler type	Drum boiler
Firing concept	Fluidized bed
Steam pressure	92 bar
Steam volume	28.9kg/second
Steam temperature	505°C
Electricity efficiency	22 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency	19.6MW
District heating output	40MJ/second

Flue Gas and Ash

The flue gas from the boiler is cleaned of particles in an electrostatic precipitator. Normally, the ash from the biomass-fired plants is used as fertiliser, but as the ash in Grenaa comes from both coal and biomass, it is necessary to store all residual products from the plant.

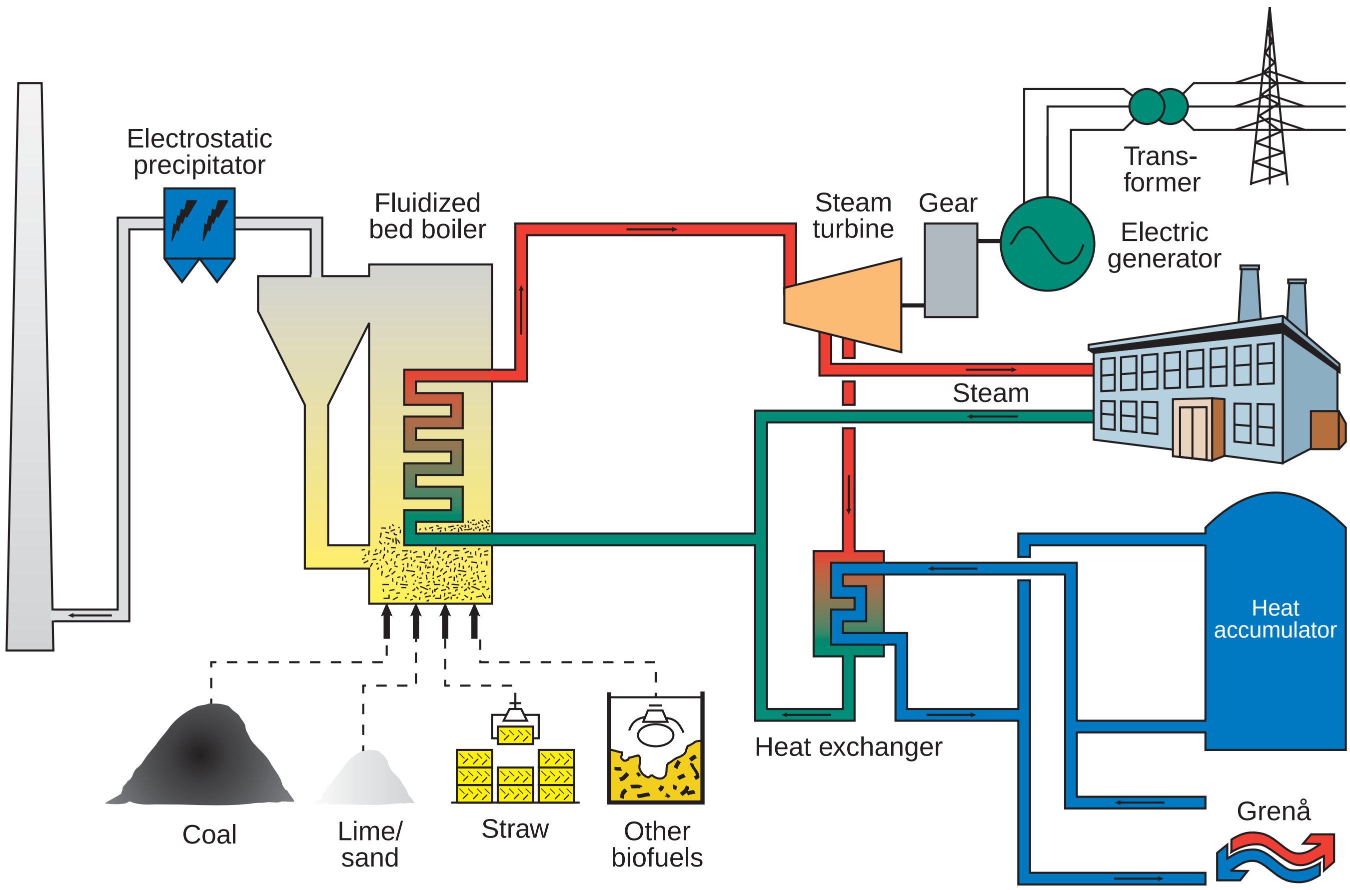


Figure 14.1. Simplified diagram of the straw and coal-fired CHP plant in Grenaa.

Måbjergværket

– the first multi-fired CHP plant

Photo: Torben Skøtt/BioPress

Måbjergværket near Holstebro covers the majority of the district heating requirements in Holstebro and Struer.

Måbjergværket near Holstebro supplies electricity to the high-voltage system and covers most of heating requirements in the municipalities of Holstebro and Struer. The plant, which was put into operation in 1993, is the first plant in the country to be built as a multi-fired CHP plant, where waste, wood chips, straw and gas can be used. There are two boilers for waste and one boiler for biofuels. Initially, each boiler was equipped with natural gas-fired superheaters but today, the superheater for the bio-boiler has been replaced by two biomass-fired superheaters.

Photo: Torben Skøtt/BioPress

Mobile chipper filling the storage at Måbjergværket.

In connection with the plant, a waste storage of 5,500m^3 has been established as well as a straw storage for 800 big bales, a silo for wood chips measuring 700m^3 and an outdoor storage for wood chips. In addition, the plant is equipped with a district heating accumulator of 5,000m^3, which equals three hours of heat consumption at full load.

Boiler Plant

The bio-boiler, which has been delivered by Vølund, is a vertical drum boiler with natural circulation where the walls, bottom and ceiling of the boiler constitute the steam evaporator.

The firing system for straw consists of a feeding tunnel, from which the straw bales are pushed directly into the boiler in accordance with the so-called cigar burner principle. The straw bales are thus not shredded before they are burned in the boiler via six cigar burners, installed in groups of three opposite each another. Air nozzles for injection of combustion air are placed close to all burners and, in addition, four of the six burners have in-built water-cooled grates.

The wood chips are fired using spreaderstokers in the lower part of the boiler. The part of the biomass which does not burn by direct feeding will burn on the grate, which is divided into nine zones where the inlet of air can be regulated individually. The design of the combustion chamber is different from other biomass boilers in not having the characteristic narrowing which helps increase the turbulence.

In 2005, two biomass-fired superheaters were built into the boiler for biofuel as a replacement of the natural gas-fired superheater. The system is designed to allow the build-up of a thick layer of slag on the superheater tubes. The new superheaters increase the steam temperature to approx. 522°C or the same temperature level which was used before the conversion.

The bio-boiler was originally designed to operate at full load on either straw or wood chips but in practice, it turned out not to be possible to fire more than 70 per cent straw, equal to approx. nine tonnes an hour.

Data for Måbjergværket's bio-boiler	
Commercial operation	1993
Supplier of boiler plants	Vølund
Fuels	Straw, wood chips and biopellets
Consumption of straw	30,000 tonnes/year
Consumption of wood chips	35,000 tonnes/year
Fired output (biomass)	39MW
Boiler type	Drum boiler
Firing concept	Vibrating grate and cigar burners
Steam pressure	67 bar
Steam volume	14kg/second
Steam temperature	520°C
Boiler efficiency	90 – 92 per cent
Flue gas cleaning	Bag filter
Electrical power efficiency	28MW[1]

Notes:
1. The efficiency applies to both the bio-boiler and the two waste boilers. The bio-boiler delivers approx. 27 per cent of the total output.

Flue Gas and Ash

The flue gas from the bio-boiler is cleaned in a bag filter, while the flue gas from the waste boilers is cleaned in electrostatic precipitators. The three boilers have separate flue gas tubes in the 120 metre high stack. The bottom ash from the bio-boiler is returned to farming and forestry, whereas the fly ash is stored.

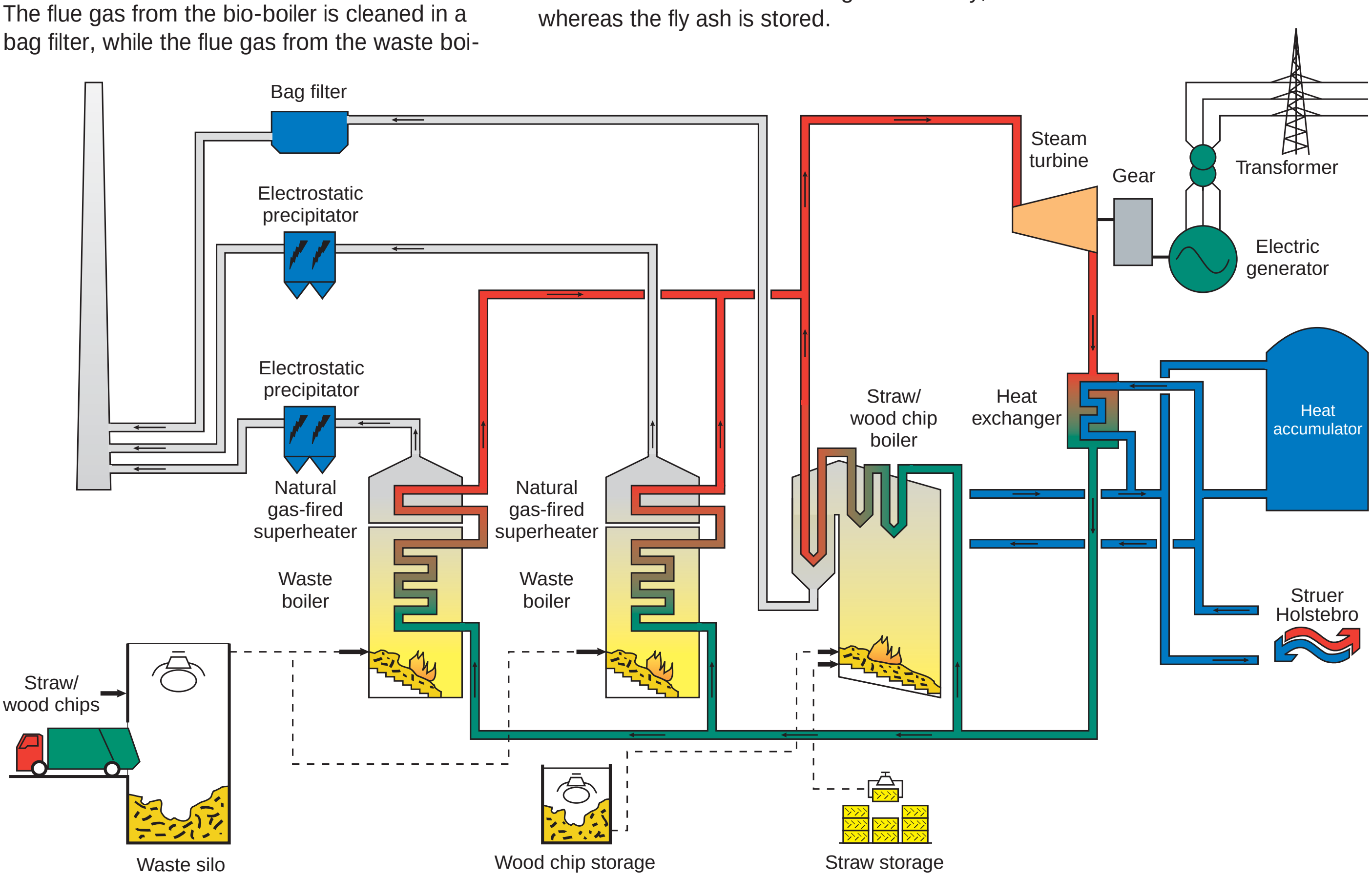


Figure 15.1. Simplified diagram of Måbjergværket, including the connection between the bio-boiler and the waste-fired boilers.

Masnedø Kraftvarmeværk

– first retrofit plant for biofuels

Photo: Torben Skøtt/BioPress

Masnedø Kraftvarmeværk (CHP plant) is a so-called retrofit plant, where steam pressures as well as temperatures are considerably higher than in the straw plants which were built around 1990.

The CHP plant near Masnedø was put into operation in 1996 and supplies electricity to the East Danish high-voltage system as well as heat to approx. 7,000 households in Vordingborg.

The Masnedø plant is a fully automated plant, where all control and monitoring can be carried out from a central control room at Kyndbyværket near Frederikssund. The plant is approved for 24 hours of unmanned operation but within normal working hours, the plant has nine employees.

Photo: Torben Skøtt/BioPress

The Masnedø plant uses 40,000 tonnes of straw a year. The capacity of the straw storage is 2,000 big bales, equal to approx. three days' production at full load.

In 2002, the production of the plant was increased by approx. 12 per cent when studies showed that there was unexploited capacity in the boiler plant, at the same time as the district heating consumption in Vordingborg was increasing.

Masnedø Kraftvarmeværk is intended for straw, but has been designed so that 25 per cent of the straw can be replaced by wood chips. The annual consumption of fuel is 40,000 tonnes of straw and 5-10,000 tonnes of wood chips. The capacity of the straw storage is 2,000 big bales, equal to approx. three days' production at full load.

Boiler Plant

The boiler at the Masnedø plant is a drum boiler with natural circulation. The plant is a so-called retrofit plant, where steam pressures and temperatures are considerably higher than in the straw plants built around 1990.

Experience from Masnedø shows that this is a good concept. The superheaters have been constructed to allow for considerable amounts of slag before they are blocked, and the boiler is equipped with 12 soot blowers to ensure good heat transfer. In addition, the top of the boiler and the superheaters have been constructed in such a way that it is relatively simple to replace the individual parts.

In the summer of 2000, a new flue gas cooler was installed when the old one turned out to be completely corroded. The new cooler is 30 per cent larger than the old one, which means that it has been possible to raise the water temperature to 90°C and thus minimise the risk of corrosion.

Straw Handling

The straw is conveyed to the firing system by a crane and two feeding lines. The bales are shredded by two vertical screws, after which the straw is fed into the combustion chamber as an airtight plug by means of two sets of screw stokers. In each of the two systems, it is possible to fire wood chips in combination with the straw.

The plant for wood chips consists of two push bottoms in the storage, from which the wood chips are transported to a so-called day silo. From the silo, the wood chips are transported to the firing system where they are mixed with straw and fired on a vibrating grate in the boiler.

Flue Gas and Ash

For the reduction of dust emission, the plant was originally equipped with electrostatic precipitators which in 2005 were replaced by a bag filter. Since May 2000, fly ash and bottom ash have been mixed at Masnedø. The ash is returned to the straw suppliers for use as fertiliser, as they have been granted an exemption allowing up to 25 per cent wood ash in the total amount of slag and ash.

Data for Masnedø Kraftvarmeværk	
Commercial operation	1996
Supplier of boiler plants	Burmeister & Wain Energi A/S
Fuels	Straw and wood chips
Consumption of straw	40,000 tonnes/year
Consumption of wood chips	5 – 10,000 tonnes/year
Fired output	36.4MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	92 bar
Steam volume	12.9kg/second
Steam temperature	522°C
Electricity efficiency	25 per cent
Boiler efficiency	88 per cent
Flue gas cleaning	Bag filter
Electrical power efficiency	9MW

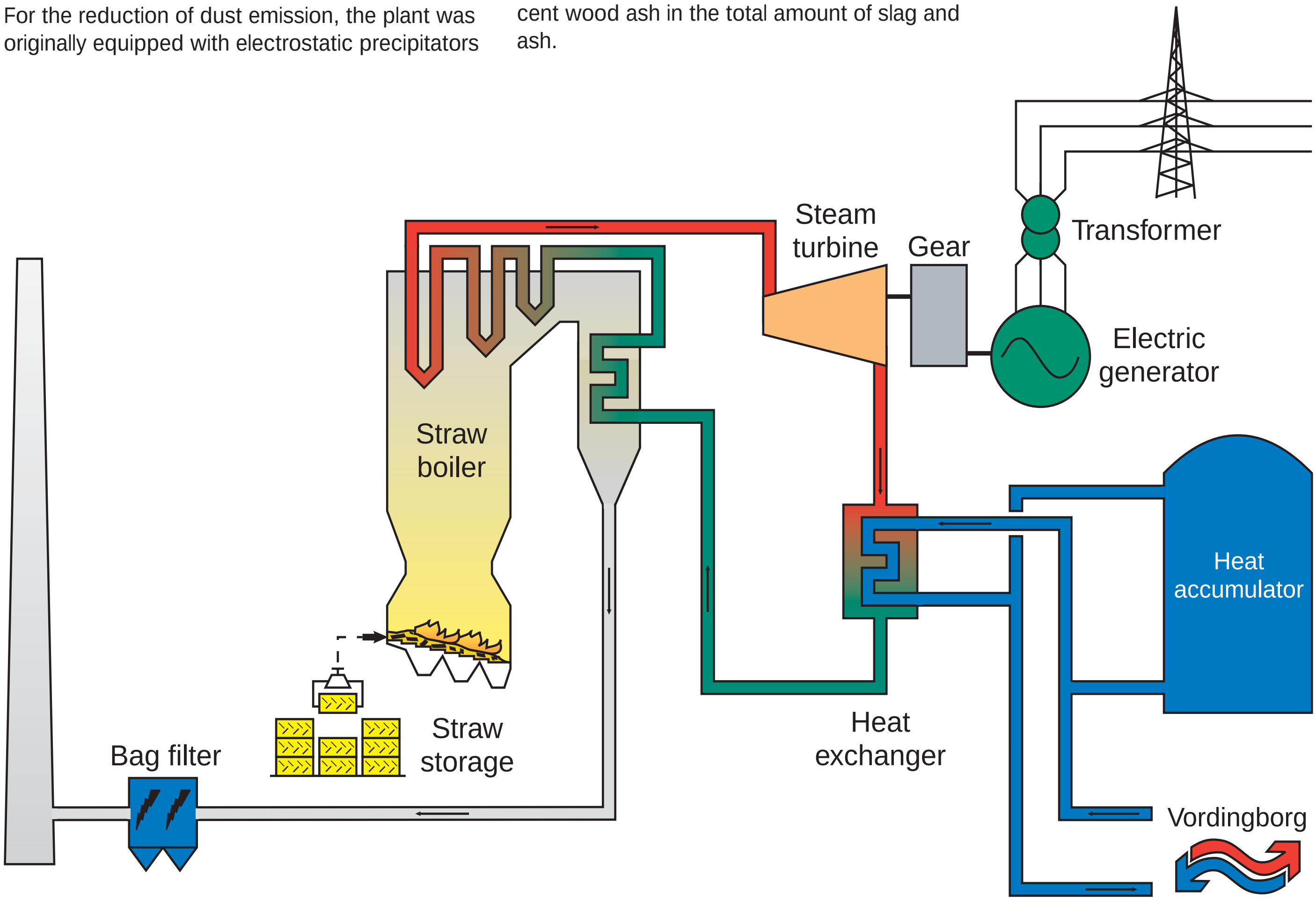


Figure 16.1. Simplified diagram of Masnedø Kraftvarmeværk (CHP plant).

Enstedværket

– *efficient straw boiler with woodchip-fired superheater*

Photo: Torben Skøtt/BioPress

The bio-boiler at Enstedværket is installed in an old building, which used to house a coal-fired power plant unit.

Photo: Torben Skøtt/BioPress

The capacity of the straw storage is 1,000 big bales, which equals the daily consumption.

Enstedværket's bio-boiler was the first biomass-fired plant in Denmark which was built according to the principles developed for actual power plant units. Previously, bio-boilers were normally produced as drum boilers with relatively low steam pressure and temperatures, but at Enstedværket it was for the first time possible to use steam at a pressure of more than 200 bar and a temperature of 540°C. In this way, the electricity efficiency was successfully raised to 41 per cent.

The bio-boiler at Enstedværket is located in an old building, which used to house a coal-fired power plant unit. The plant is divided into two stages: a straw boiler producing steam at 470°C and a woodchip-fired superheater, which raises the temperature to a maximum of 542°C.

The reason for this construction was the assumption that the corrosion of the superheater tubes of the boiler would be significantly lower when firing with wood chips than with straw, which contains considerable quantities of alkali and chlorine. However, just two years after the start of the boiler operation, it was obvious that the wood chip superheater was badly attacked by corrosion. Today, the majority of the wood chip superheater has got a new coating and the steam temperature has been lowered from 540°C to 510°C.

The steam production from the bio-boiler is combined with the steam from Enstedværket's unit 3, which is coal-fired, and it is then passed to a common turbine. The bio-boiler is primarily used for a basic load of approx. 6,000 operating hours a year or more in joint operation with unit 3. In periods where this unit is not in operation, the bio-boiler is often used exclusively to provide steam for the production of district heating.

The flue gas from the bio-boiler is cleaned in electrostatic precipitators and bag filters. Fly ash and bottom ash are kept separate so that the bottom ash can be used as fertiliser.

The straw storage has a capacity of approx. 1,000 big bales, equal to approx. the daily consumption. On average, the plant uses more than 900 big bales a day or 38 truckloads each containing 24 bales. In addition, the plant receives approx. six truckloads of wood chips.

Straw Boiler

The straw boiler is equipped with four feeding lines, but the plant is capable of operating at full load using only three feeding lines. Each of the feeding systems consists of a fireproof tunnel, conveyors, straw shredder, fire damper, screw stoker and a feeding tunnel. Like the straw shredder at Masnedøværket, this straw shredder is designed as two vertical screws towards which the straw bale is pressed, which loosen the straw. From the shredder, the shredded straw is fed via the fire damper into the screw stoker, which presses the straw as a plug through the feeding tunnel and on to the vibrating grate in the boiler.

The feeding tunnel for straw is water-cooled and the temperature is kept as close to 60°C as possible, but not above this temperature. In this way, the risk of corrosion is reduced, as is the tendency to formation of deposits. In the feeding tunnel, the straw is compressed into a light plug with the purpose of preventing ingress of false air in the boiler. At the same time, it also protects against heat radiation.

Wood chips can also be fired in the straw boiler and can replace up to 20 per cent straw. The adding of wood chips is carried out using four screws that feed the wood chips to the straw shedder tunnels.

Wood Chip Boiler

The wood chip boiler is equipped with two spreaderstokers for feeding and distribution of the wood chips on the vibrating grate. They are both operated by means of air, which means that the largest pieces land at the back of the grate near the back wall, while the smaller pieces land further down the grate. In this way, the large pieces remain on the grate for a long time, while the small pieces remain on the grate for a shorter time.

Data for Enstedværket's bio-boiler	
Commercial operation	1998
Supplier of boiler plants	Burmeister & Wain Energi
Fuels	Straw and wood chips
Straw consumption	120,000 tonnes/year
Wood chip consumption	30,000 tonnes/year
Fired output for straw boiler	80MJ/s
Fired output for wood chip superheater	15MJ/s
Boiler type	Boiler with forced circulation
Firing concept	Vibrating grate
Steam pressure	210 bar
Steam volume	34kg/second
Current steam temperature	510°C
Maximum steam temperature	542°C
Electricity efficiency	41 per cent
Boiler efficiency	92 per cent
Flue gas cleaning	Electrostatic precipitator and bag filter

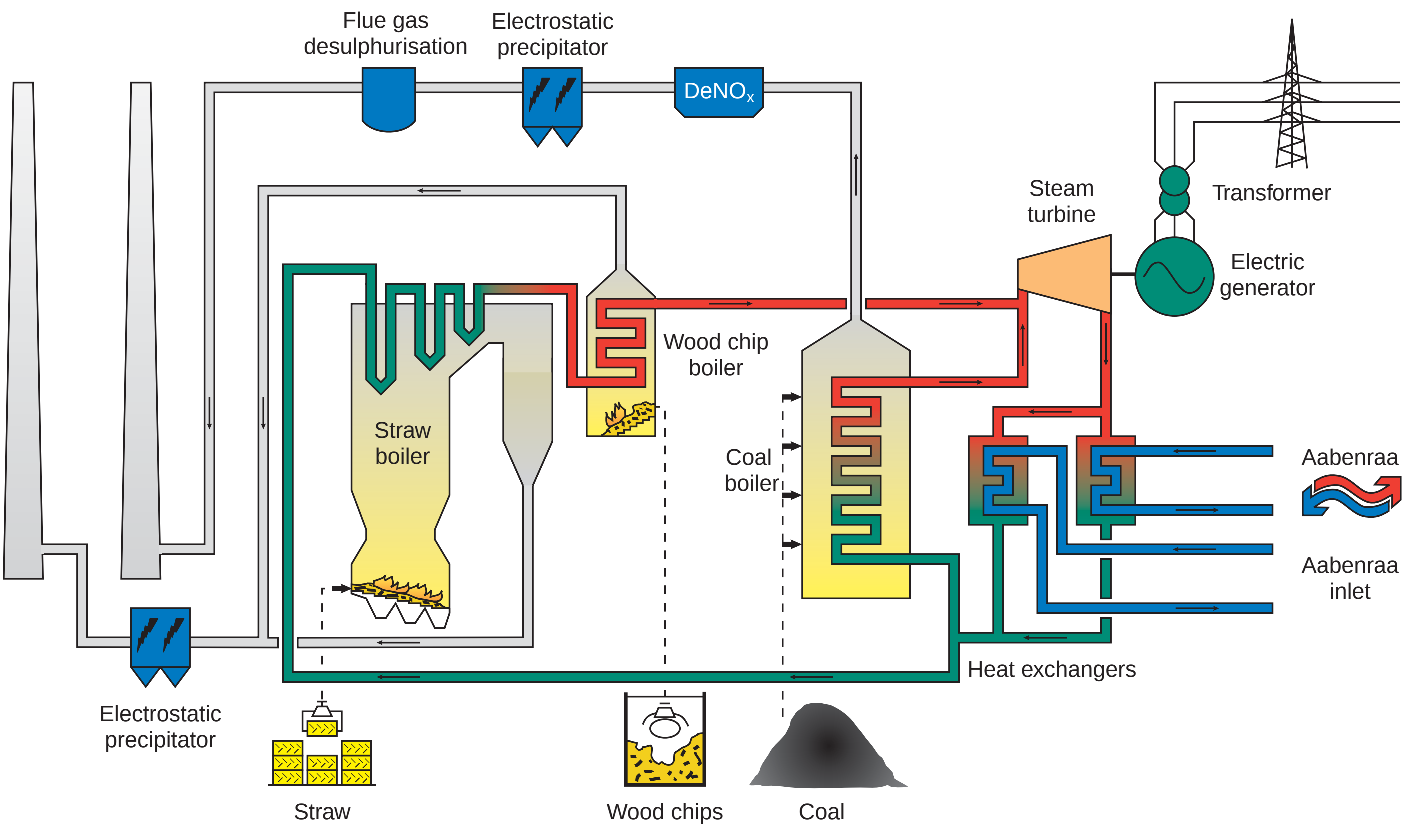


Figure 17.1. Simplified diagram of Enstedværket (power plant), including the connection between the bio-boiler and the coal-fired boiler.

Assens Kraftvarmeværk

– one of the smallest steam turbine plants for biofuels

Photo: Torben Skøtt/BioPress

Assens Kraftvarmeværk in Funen is one of the smallest steam turbine plants in the country that is entirely biomass-fired.

In 1999, Assens Kraftvarmeværk was constructed by Assens Fjernvarme Amba. It is one of the smallest steam turbine plants in the country that is entirely biomass-fired. The plant supplies district heating to 2,500 customers in Assens in Funen, including almost all industries in the area. Approx. 98 per cent of the heat consumption in the town is covered by district heating, which contributes to a good exploitation of the installed effect.

The CHP plant is equipped with two heat storage tanks of 2,500m^3 each. This makes it possible to close down production during periods with low heat consumption and easier for the operations manager to adjust the production for the current electricity prices. The power is paid for according to the so-called three-part tariff, which means that it is important to produce as much electricity as possible in peak load periods.

Boiler Plant

The plant has an electrical power efficiency of 5MW at the maximum load allowed by the supplier. The boiler can deliver 10.3MJ heat per second to the district heating system, but when the flue gas condenser is attached, the heat output may be increased by 15.1MJ/second. According to the original data from the supplier, the total efficiency should be 108 per cent, but it has only been possible to reach 94 per cent.

Originally, the intention was to run the plant up to 110 per cent load, but it turned out to cause problems if the energy content in the fuel varies. Under normal conditions, the plant is consequently kept at the nominal output.

Fuel Handling

The fuel is mainly wood chips, but it is possible to use a wide range of pure woodfuels with a

Photo: Torben Skøtt/BioPress

Assens Kraftvarmeværk imports considerable quantities of logs, which are chipped using a mobile chipper outside the plant.

moisture content in the range of 5 to 55 per cent. Most of the fuel consists of wood chips, but wood pellets are also used as are sawdust and other residual products from the wood industry.

The plant has an indoor storage capacity of 5,800m^3 fuel, equal to approx. 10 day's consumption. Furthermore, there is considerable outdoor storage capacity for whole logs, wood chips and fines. Over the years, a substantial part of the fuel consumption has been covered by the import of wood chips and whole logs from for example Germany, Poland and Estonia. The logs are stored outdoor and subsequently chipped at the plant using a mobile chipper.

By means of automatic cranes, the fuels are transported from the storage to a special mixing system where, among other things, it is possible to make a mixture consisting of 70 per cent wood chips and 30 per cent fines. Via conveyor belts, the mixture is fed into a dosing silo and it continues to two spreaderstokers which throw the fuel into the combustion chamber. The light elements will burn out while they float towards the grate in the combustion chamber, while the larger pieces burn out on the grate.

Flue Gas and Ash

The flue gas is cleaned of fly ash in an electrostatic precipitator and then led through the flue gas condenser if more heat is required. In periods with low heat consumption, the flue gas is led directly from the electrostatic precipitator up through the stack. Slag and ash are stored, as the cadmium content is too high for use as fertiliser.

Data for Assens Kraftvarmeværk	
Commercial operation	1999
Supplier of boiler plants	Ansaldo Vølund A/S
Fuels	Forest chips, wood pellets and sawdust
Consumption of woodfuels	45,000 tonnes/year
Fired output	22MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	77 bar
Steam volume	5.8kg/second
Steam temperature	525°C
Electricity efficiency	24 per cent
Boiler efficiency	94 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency	5MW
District heating output	15MJ/second (including condensing)

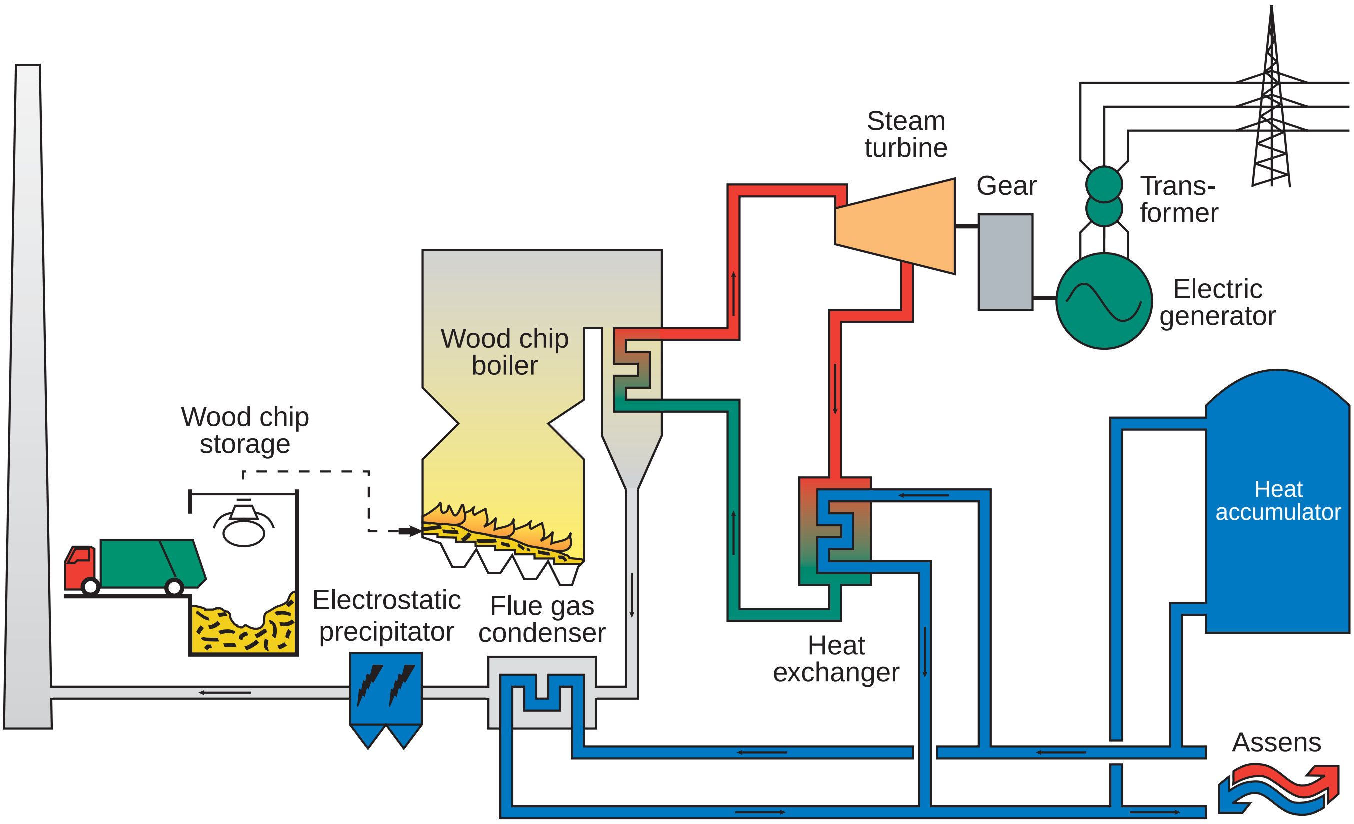


Figure 18.1. Simplified diagram of Assens Kraftvarmeværk.

Maribo-Sakskøbing Kraftvarmeværk

– the most recently built straw plant in Denmark

Photo: Torben Skøtt/BioPress

The CHP plant in Maribo Sakskøbing covers approx. 90 per cent of the district heating consumption in the two towns.

The plant in Maribo Sakskøbing is the most recently built local straw-fired CHP plant in Denmark. It was opened in 1999 and covers approx. 90 per cent of the district heating requirements in Maribo and Sakskøbing.

The plant is a further development of the straw-fired plant in Masnedø. The two plants have similar fired output but by lowering the district heating temperature, increasing the steam temperature and modifying the turbine, a number of remarkable improvements have been made. The electricity production has thus been increased by 10 per cent, the power consumption has been lowered by 15 per cent and the investments have been reduced by approx. 10 per cent compared with Masnedø.

The CHP plant is approved for 24 hours of unmanned operation and can - like a number of other local plants in Zealand - be monitored from Kyndbyværket near Frederikssund. The plant has seven employees, who operate the plant within normal working hours.

Photo: Torben Skøtt/BioPress

There are two fire gates between the straw storage and the boiler building in order to minimise the risk of fire.

The plant has an annual consumption of approx. 40,000 tonnes of straw, which is supplied by farmers from Lolland Falster. The capacity of the straw storage is 900 tonnes, which equals approx. four days' consumption at full production.

Boiler Plant

The boiler is of the same type as the boiler at Masnedø, but due to a higher steam temperature, the electricity efficiency has reached 29 per cent compared with 25 per cent at Masnedø. Initially, the plant produced 12kg steam per second but after the expansion of the district heating system in Maribo in recent years, the plant has been upgraded to supply 13.8kg steam per second. The production is variable from 35 to 100 per cent of full load, but does not normally drop below 70 per cent of full load.

To maintain the heat transfer between the flue gas and the heating surfaces of the boiler, a number of soot blowers are installed, which use superheated steam at a temperature of 350°C. The pressure from the individual soot blowers varies between 6 and 13 bar, depending on the location. Soot blowing is performed automatically when required, which in practice is approx. three times a day. In 2006, the system was extended with water soot blowers in the combustion chamber.

There is normally no more than 25 per cent moisture in the straw bales which the plant receives, but if the moisture is equally spread in the bale, it is possible to burn bales with up to 35 per cent moisture. However, this only happens in periods when the plant is manned, as the moist straw may cause problems during firing.

Straw Handling

The boiler is supplied with fuel from two feeding lines. Two fire gates have also been built between the straw storage and the boiler building, but to minimise the risk of fire, only one gate is used at a time.

The straw bales are shredded by two vertical screws, after which the straw is fed into the combustion chamber as an airtight plug by means of two sets of screw stokers.

The moisture content of the fuel is not measured in connection with the firing. When it is decided to use straw with a high water content, the amount of primary air is increased and the amount of secondary air proportionally reduced. This is done manually.

Flue Gas and Ash

The flue gas is cleaned in a filter system consisting of 2 x 200 bags. The bags are 10 metres long and 140mm in diameter. The bags are designed to last for just over two years.

Part of the fly ash is mixed with the bottom ash and returned to the farmers for spreading on the fields. The remaining fly ash is stored.

Data for Maribo Sakskøbing Kraftvarmeværk	
Commercial operation	2000
Supplier of boiler plants	FLS Miljø A/S
Fuels	Straw
Consumption of straw	45,000 tonnes/year
Fired output	37MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	102 bar
Steam volume	13.8kg/second
Steam temperature	540°C
Electricity efficiency	29 per cent
Boiler efficiency	88 per cent
Flue gas cleaning	Bag filter
Electrical power efficiency	10.6MW
District heating output	22.5MJ/second

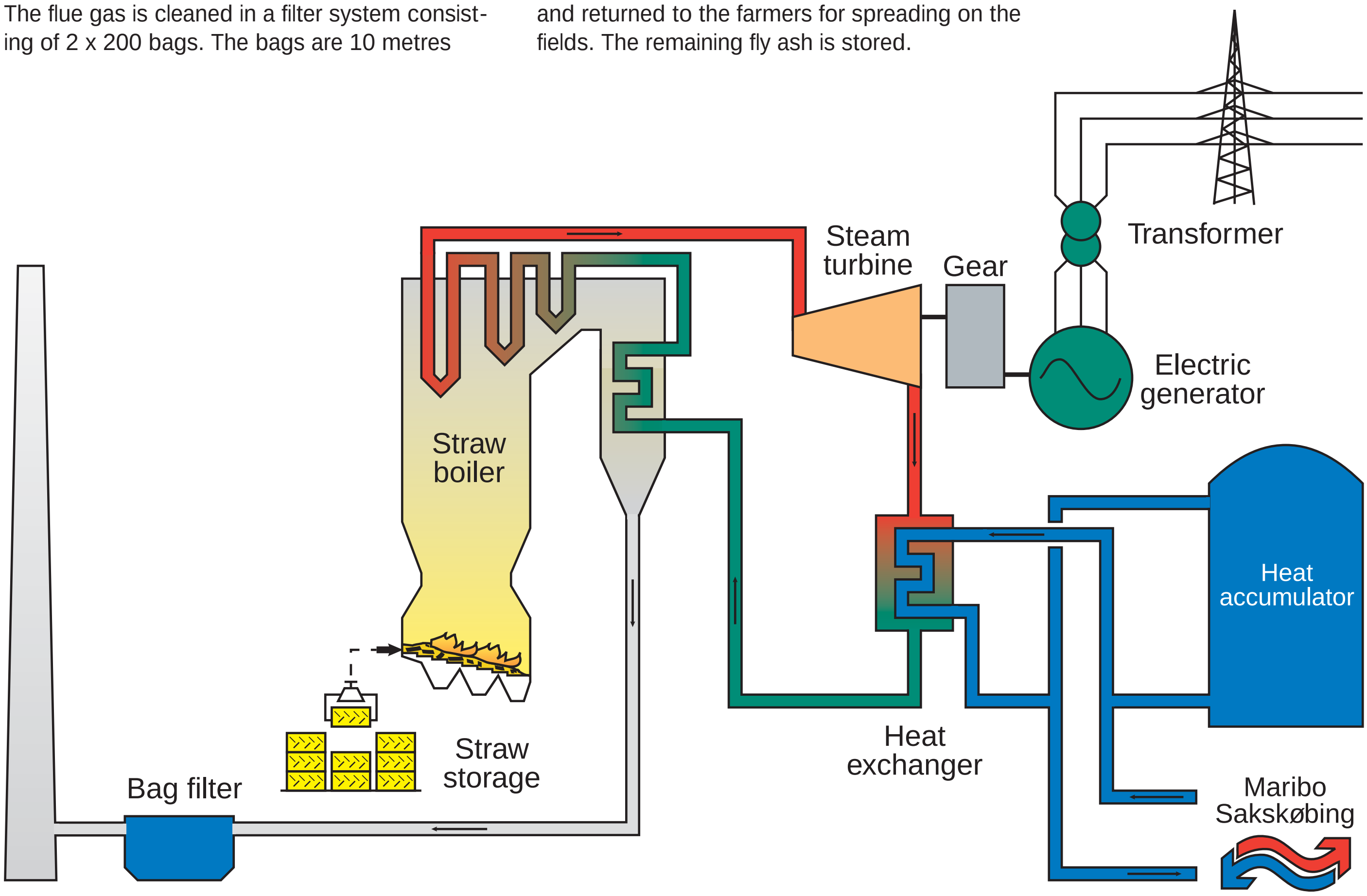


Figure 19.1. Simplified diagram of Maribo Sakskøbing Kraftvarmeværk.

Avedøreværket

– one of the world's most efficient power plants

Photo: Torben Skøtt/BioPress

Avedøreværket south of Copenhagen consists of two power plant units. The newest unit has an input of 150,000 tonnes of straw and 300,000 tonnes of wood pellets per annum.

Avedøreværket is located on Avedøre Holme south of Copenhagen and consists of two power plant units, Avedøre 1 from 1990 and Avedøre 2 from 2001. Avedøre 1 primarily uses coal, whereas Avedøre 2 is capable of firing with various types of fuels, including natural gas, oil, straw and wood pellets.

Photo: Energi E2

The main boiler at Avedøre 2, where up to 300,000 tonnes of wood pellets can be fired a year.

Avedøre 2 is one of the world's most efficient power plant units. The plant is capable of exploiting up to 94 per cent of the energy in the fuels, and the electricity efficiency is no less than 49 per cent. It is a relatively complicated plant, but basically it consists of a main boiler which can be fired with oil, natural gas or wood pellets as well as a straw boiler with an input of 150,000 tonnes of straw per annum. The plant also contains two gas turbines which, among other things, are used for heating feed water.

Main Boiler

The main boiler is a so-called tower boiler, i.e. a boiler with one flue gas pass. There are four high pressure superheaters and three intermediate pressure superheaters. To maintain the temperature of the superheated stream and thus the efficiency, a system for recirculation of the flue gas has been installed.

Originally, the main boiler was only intended for oil and natural gas but in 2002, the plant was rebuilt, making it possible to fire up to 300,000 tonnes of wood pellets a year. The wood pellets are pulverised in traditional coal mills and blown into the combustion chamber through 12 of the 16 burners with which the boiler is equipped.

The wood pellets are partly from DONG Energy's own pellet factory in Køge and partly bought on market terms. At the coal storage at Avedøreværket, a short-term storage for 13,000 tonnes of wood pellets and two long-term storages for a total of 36,000 tonnes of wood pellets have been built.

Straw Boiler and Straw Storage

The straw boiler is a so-called Benson boiler with hanging superheaters in the combustion chamber. Originally, the boiler was equipped with two gas burners, but they were dismantled in the spring of 2004. The boiler is equipped with a vibrating grate, which is divided into three air zones for each of the four feeding lines.

The capacity of the straw storage is almost 3,000 big bales and the storage has been designed to receive 10-12 trucks an hour. From the storage, the straw bales are transported in four lines to the boiler. A new type of straw shredder is used here which shreds the loosened straw bale layers between two cylinders. The shredded straw is transported into the boiler by means of screw stokers.

Flue Gas and Ash

The bottom ash from the straw boiler is returned to the farmers, while the fly ash is sent to Kommunekemi in Nyborg where it is processed into fertiliser. The main boiler is equipped with $deNO_x$ plant, electrostatic precipitator and desulphurisation plant for cleaning of the flue gas.

Data for Avedøreværket (Avedøre 2)	
Commercial operation	2001
Supplier of boiler plants	FLS miljø, BWE, Vølund
Fuels	Oil, natural gas, wood pellets and straw
Consumption of wood pellets	300,000 tonnes/year
Consumption of straw	150,000 tonnes/year
Fired output	800MW
Boiler type	Benson
Firing concept	Biodust-firing/vibrating grate
Steam pressure (main boiler/straw boiler)	305/310 bar
Steam pressure (main boiler/straw boiler)	296/40kg/second
Steam temperature (main boiler/straw boiler)	582/545°C
Electricity efficiency	49 per cent
Boiler efficiency	94 per cent
Flue gas cleaning (main boiler/straw boiler)	$DeNO_x$-plant, electrostatic precipitator and desulphurisation plant/bag filter
Electrical power efficiency	390/275MW

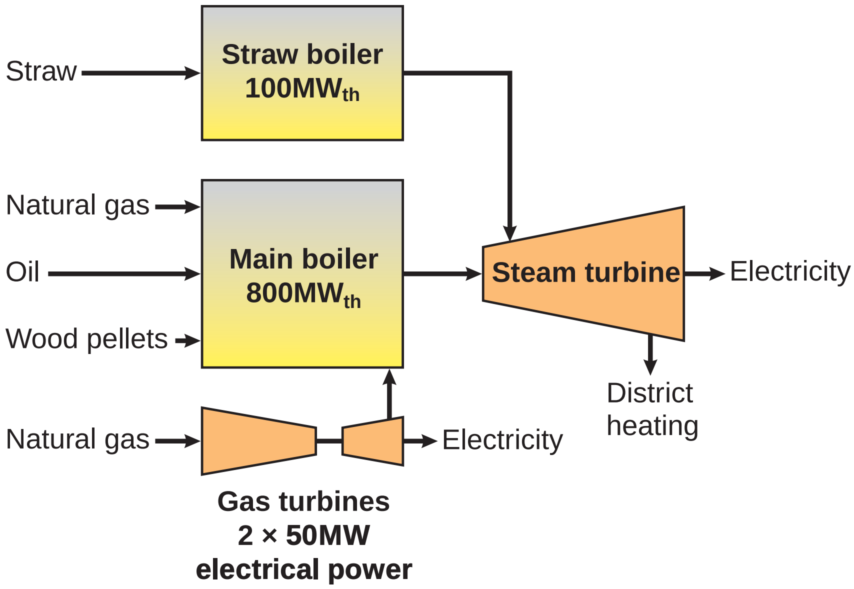


Figure 20.1. Simplified diagram of Avedøreværket.

Randers Kraftvarmeværk

– from coal to biomass

Photo: Torben Skøtt/BioPress

With a relatively modest investment, Randers Kraftvarmeværk has been converted into firing with various types of biomass.

Randers Kraftvarmeværk, with the official name Energi Randers Produktion A/S, is owned by the local energy company in Randers Kommune (municipality). The plant, which was put into operation in 1982, was originally coal-fired but was later converted to firing with a high percentage of biomass.

The boiler plant consists of two drum boilers with natural circulation. This provides high operational reliability and good opportunities to adjust the production to the actual district heating consumption. The steam system comprises an economizer, a vaporiser which makes up the walls in the combustion chamber, a boiler drum and three superheaters.

Photo: Torben Skøtt/BioPress

A peep into one of the two storage areas with a total capacity of 25,000m^3 biomass.

A steam converter has been installed as backup for the turbine plant, allowing the district heating to be supplied to take place outside the turbine. In November 1991, Randers Kommunale Værker installed a heat accumulator at the plant, making it easier to separate the electricity production from the heat production.

Conversion to Biomass

The boilers were originally equipped with spreaderstokers for coal-firing but in 1994, the system was expanded with gas burners to allow the combustion of biogas from the municipal landfill site in the town. In 2002, the plant was equipped with pneumatic firing of biomass in three positions above the spreaderstokers and in 2004, the system was further expanded to allow the addition of up to 75 per cent biomass. In practice, it has, however, only been possible to reach 50 per cent biomass, but another rebuilding planned for 2008 will make it possible to fire up to 100 per cent biomass on the grate.

The conversion of the plant for firing with biomass cost almost DKK 30 million. Among other things, the money was spent on a system capable of handling the various types of biomass, two silos and two storage areas with a total capacity of 25,000m^3 biomass.

Initially, olive stones from Spain were used. Later on, meat and bone meal were used, but this resulted in problems with the use of the residual products from the plant. Today, a wide range of different types of biomass is used, such as cocoa husks, shea nuts, wood pellets, olive stones and remains of pelleted feed and coffee beans. The requirements from the suppliers are that it must be dry biomass as mentioned in the Biomass Executive Order. Wood chips have never been used due to the high moisture content and straw is also avoided in order to minimise the risk of corrosion. In 2006, the fuel consisted of 62 per cent coal and 38 per cent biomass (calculated on the basis of energy).

Residual Products

The plant is equipped with an electrostatic precipitator for flue gas cleaning as well as a desulphurisation plant, which removes 97 per cent of the sulphur content of the flue gas. The fly ash is sent to Sweden, where it is used for the production of cement, while the residual products from the desulphurisation plant are used for the production of plasterboards. Slag from the two drum boilers is collected by a local carrier who, among other things, uses it as road fill.

Data for Randersværket	
Commercial operation	1982/1994/2002
Supplier of boiler plants	Aalborg Værft/Aalborg Energie Technik
Fuels	Coal and dry biomass
Consumption of biomass	74,000 tonnes/year
Firing output	180MW
Boiler type	Drum boiler
Firing concept	Spreaderstoker and travelling grate
Steam pressure	111 bar
Steam volume	32kg/second
Steam temperature	525°C
Electricity efficiency	25 per cent
Boiler efficiency	89 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency	52MW
District heating output	112MJ/second

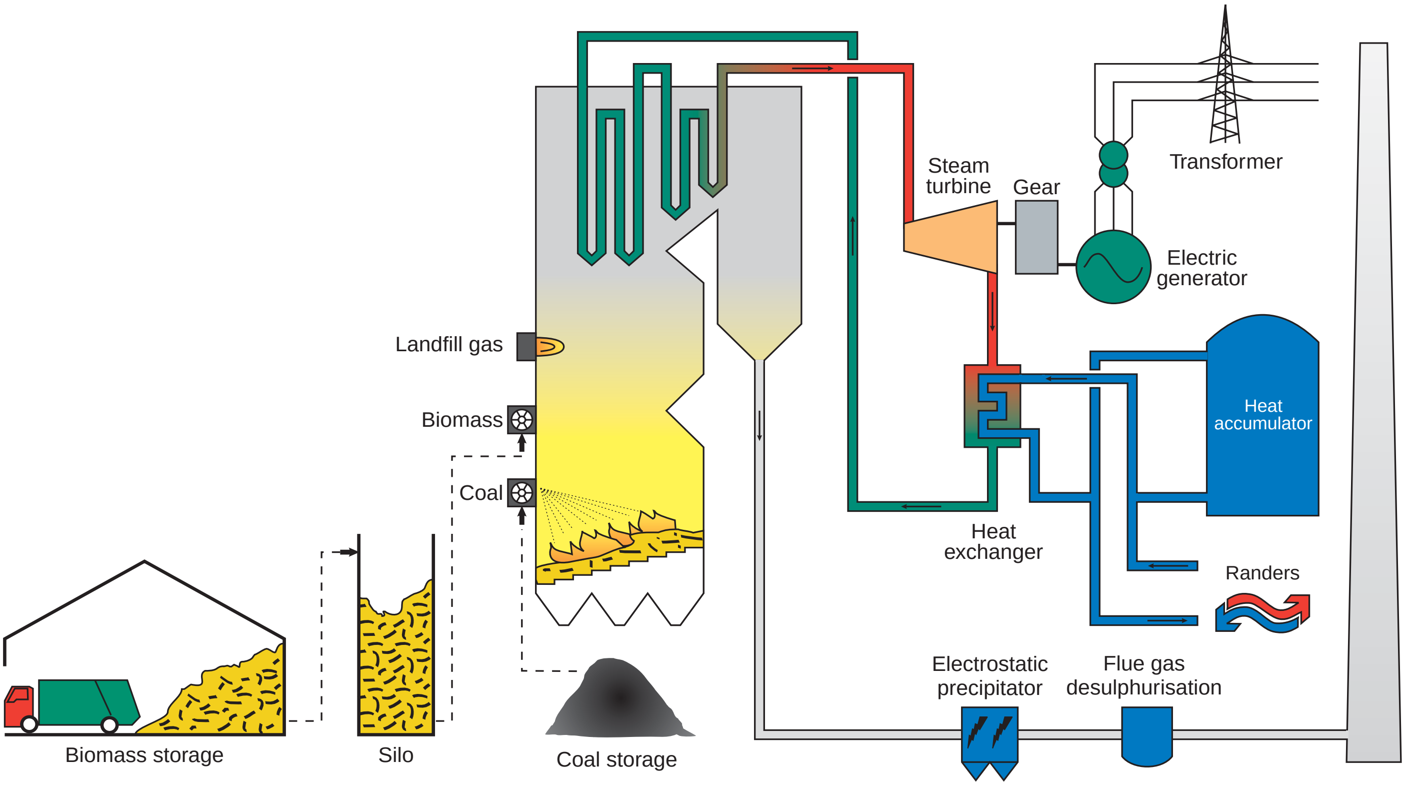


Figure 21.1. Simplified diagram of Randers Kraftvarmeværk

Herningværket

– *largest woodchip-fired plant in Denmark*


Photo: Torben Skøtt/BioPress

Herningværket with wood chip storage in the fore-ground.

Herningværket from 1984 was originally built as a coal and oil-firing plant. In 2000, the plant was converted to natural gas, but just two years later, it was converted to firing with a combination of natural gas and wood chips.

At the conversion, the lowest part of the boiler was replaced and a vibrating grate was installed for the combustion of wood chips. In addition, equipment for the handling of the wood chips was installed, storage facilities were established and finally a large chipper was installed so that the plant is capable of receiving whole logs as fuel.


Photo: Torben Skøtt/BioPress

The wood chips are regularly tested to determine the moisture content.

The decision to replace the coal with natural gas and wood chips was, among other things, based on the tightened environmental requirements for the power plants. In Herning, it was a choice between installing a desulphurisation plant or finding a more environmentally friendly fuel. As it was also necessary to increase the capacity for biofuels in order to comply with the requirements in the Biomass Plan, wood chips were a natural choice.

Boiler Plant

Burmeister & Wain Energy was in charge of the conversion in cooperation with FLS Miljø and Raumaster, who installed the system for transporting and handling of wood chips.

The boiler is a so-called hanging drum boiler with natural circulation, where the walls, bottom and ceiling of the boiler are built from panel sections which form the evaporation system. At the conversion to wood chip-firing, a vibrating grate was installed and the lowest section now has the characteristic "duct" which is found on most biomass-fired boilers. The boiler is equipped with three superheaters placed as two radiation superheaters at the top of the combustion chamber and a convection superheater in the second pass of the boiler. First of all, the steam flows to the convection superheater, which raises the temperature to 453°C, and from here on to the two radiation superheaters, which provide a further increase of temperature to 525°C.


Photo: Torben Skøtt/BioPress

Establishment of wood chip storage at Herningværket.

Fuel Handling

After the conversion, Herningværket is capable of using 250,000 tonnes of wood chips a year, which makes it the CHP plant with the largest consumption of wood chips in Denmark.

For the handling of the large quantities of wood chips, silos have been installed along with various transport systems and an indoor storage of 13,000m^3, equal to approx. 75 hours' operation. In addition, a system for taking wood chip samples has been installed as well as a metal separator for the removal of impurities and a stationary chipper capable of handling whole logs.

The firing system for wood chips consists of two silos of 75m^3 each connected to a screw based transport system that feeds six spreaderstokers. The stokers ensure that the fuel is thrown onto the vibrating grate. The light elements are dried, degassed and combusted in the boiler room above the grate, while the large particles burn on the grate.

The water-cooled vibrating grate covers an area of 90m^2. The grate has more than 43,000 small holes, which are used for distribution of the primary air. Every fourth minute, the grate vibrates for approx. 4-5 seconds, which moves the fuel 200-300mm forward.

Data for Herningværket	
Commercial operation (coal/gas/wood chips)	1984/2000/2003
Supplier of boiler plants	Burmeister & Wain Energi
Fuels	Wood chips and natural gas
Consumption of wood chips	250,000 tonnes/year
Fired output	288MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	115 bar
Steam volume	118kg/second
Steam temperature	525°C
Electricity efficiency	30 per cent
Flue gas cleaning	Electrostatic precipitator
Electrical power efficiency	89MW
District heating output	174MJ/second

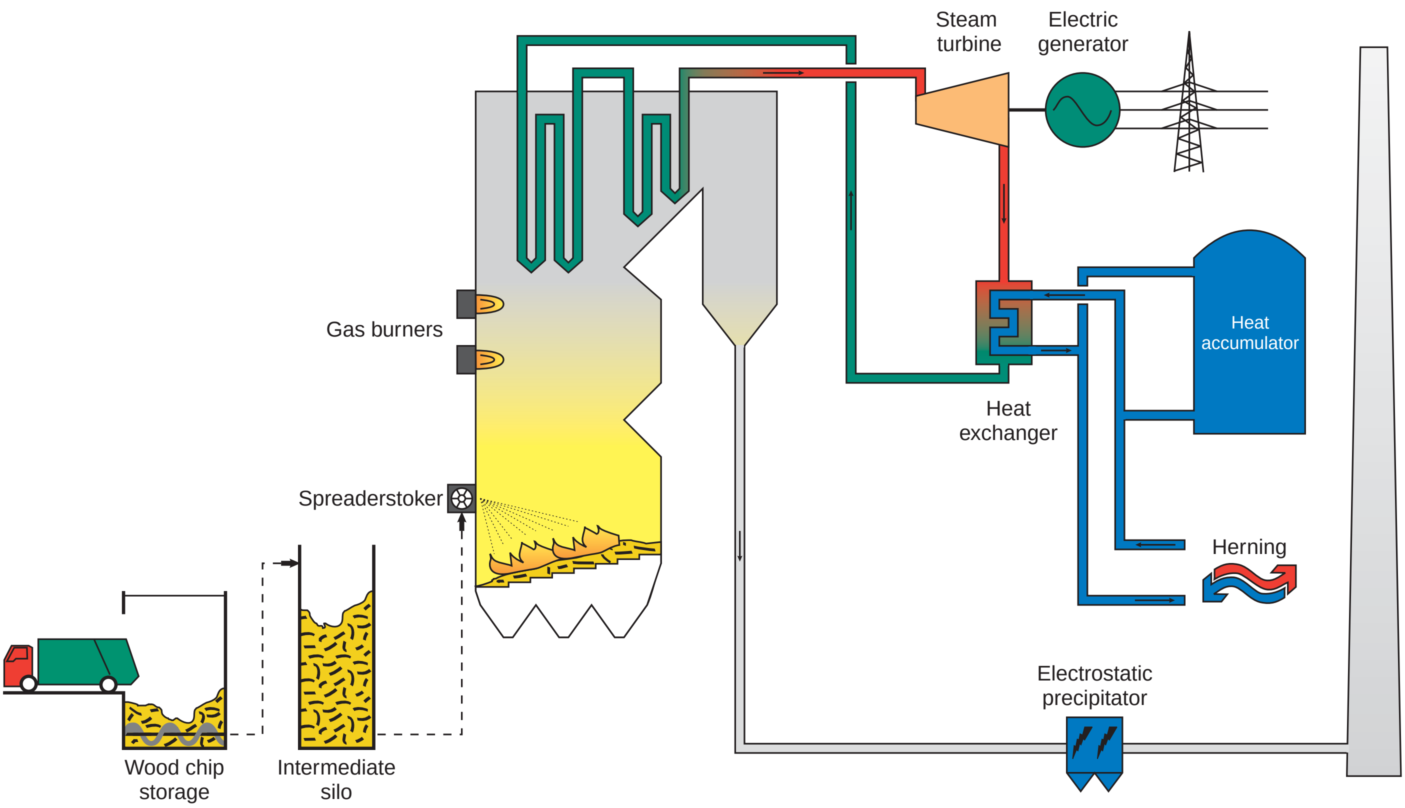


Figure 22.1. Simplified diagram of Herningværket, where 250,000 tonnes of wood chips are used per annum.

Amagerværket

– from coal to straw pellets

Photo: Torben Skøtt/BioPress

Amagerværket with surfer in the foreground.

Photo: Torben Skøtt/BioPress

Discharging of straw pellets from the pellet factory in Køge.

Amagerværket consists of no less than three power plant units, which were originally designed to fire coal as the primary fuel. Units 1 and 2 date from the early 1970s, while the larger unit 3 is from 1989. In connection with the plant, a heat accumulator has been established, containing 24,000m^3 of district heating water.

Unit 3 is equipped with desulphurisation plant as well as $deNO_x$ plant, whereas the environmental installations at the two older power plant units remain unchanged. At one point, units 1 and 2 were required to be equipped with modern environmental installations no later than 1 January 2005 if the boilers were to continue to be coal-fired.

In 2003, it was decided to carry out a minor conversion of unit 2 from coal to straw pellets and in 2006, a total renovation of unit 1 was initiated. All installations will be replaced, so that the plant in 2008 will be ready as a new special combined fuel system capable of firing coal, straw pellets and wood pellets.

Unit 2

By using dry fuel such as straw pellets, it has been possible to retain the existing coal-fired boiler at unit 2. The original coal mills have been renovated and are now used to pulverise the pellets. The straw dust is then divided between the 12 burners with which the boiler is equipped.

As is well known, the combustion of straw may cause corrosion problems in the superheater tubes of the boiler. To minimise the risk and thus prolong the working life of the boiler, it has been decided to reduce the steam temperature to 480°C. This means that the fired output of the boiler is reduced to approx. 70 per cent compared with coal-firing.

After the conversion of unit 2 to straw pellets, it is now possible to burn 130,000 tonnes of pellets annually, equal to approx. 2,100 hours at full load. The pellets are produced at Køge Biopillefabrik and transported to the plant by ship, as the road network between Køge and Amagerværket is heavily loaded.

Unit 1

The rebuilding of unit 1 is part of the so-called Copenhagen plan, which is intended to ensure adequate heat supply in Copenhagen for the next 20 years. In this connection, unit 1 will get a new boiler which can be fired with coal and biomass as well as a new turbine, a new environmental installation and a new stack. The plan also involves the establishment of a four kilometre long steam tunnel for transporting the steam from the Amagerværket to the Copenhagen district heating network in the inner city.

It will be possible to fire the new boiler plant 100 per cent with either coal or wood, 90 per cent with pure straw or a combination. Compared with coal-firing, it is especially straw that is challenging. This applies to corrosion conditions, deposits in the boiler and the type of environmental installation with which the plant has to be equipped.

The flue gas from the new boiler plant is led through a desulphurisation plant and a deNO$_x$ plant that removes approx. 90 per cent of the nitric oxide content of the flue gas. As straw ash contains potassium which poisons the catalyst, the deNO$_x$ plant is placed after the ash separator and the desulphurisation installation to minimise the content of potassium in the flue gas.

The newly renovated unit 1 will have a capacity of 80MW electricity and 250MJ/s district heating. In 2008, when the conversion is complete, the three power plant units will in total cover approx. 13 per cent of the power consumption in Zealand, equal to the heating requirement of 115,000 detached houses.

Data for Amagerværkets unit 1	
Commercial operation	1971/2009
Supplier of boiler plants	Burmeister og Wain Energy
Fuels	Coal, oil, wood pellets and straw pellets
Consumption of fuel	150,000 tonnes/year
Fired output	350MW
Boiler type	Benson
Firing concept	Dust-firing
Steam pressure	185 bar
Steam volume	139kg/second
Steam temperature	562°C
Electricity efficiency	23 per cent
Boiler efficiency	95 per cent
Flue gas cleaning	Desulphurisation plant and deNO$_x$ plant
Electrical power efficiency	80MW
District heating output	250MJ/second

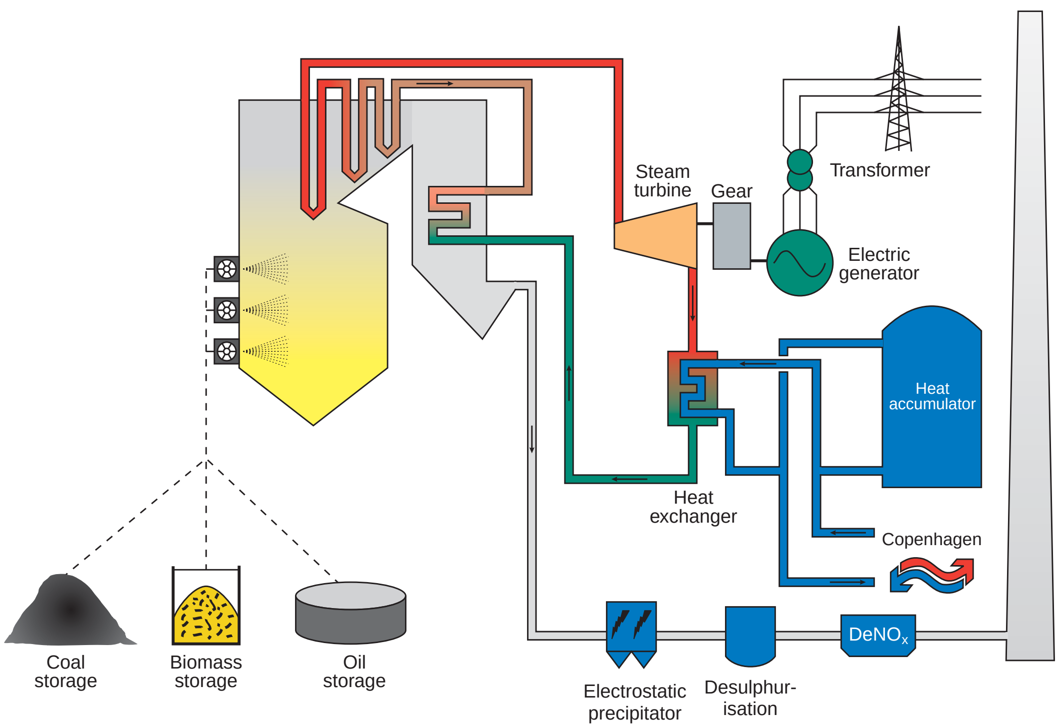


Figure 23.1. Simplified diagram of Amagerværket's unit 1.

Studstrupværket

– co-firing of coal and straw

Photo: Torben Skøtt/BioPress

Studstrupværket where today a mixture of coal and straw is fired in units 3 and 4. Units 1 and 2 are no longer operational.

Studstrupværket north of Aarhus was put into operation in 1968. There have been a total of four units at the power plant, but today only units 3 and 4 are operational.

In 1995, Studstrupværket's unit 1 was converted from coal-firing to a combined coal and straw-fired plant as part of a two-year demonstration programme. The purpose was to examine the influence of straw on boiler performance, combustion chemistry, formation of deposits, emissions and corrosion.

After two years' operation, it was possible to conclude that the technology was viable - at least up to a maximum straw input of 20 per cent. The straw did not significantly influence the performance of the boiler and both boiler corrosion and deposit formation could be maintained at an acceptable level.

On this basis, it was decided to convert the large unit 4 to co-firing of coal and straw. In practice, this was done by converting four of the existing 24 coal dust burners to straw-firing. The plant was put into operation in 2002 and has been in commercial operation since then.

In 2005, it was decided to convert unit 3 in the same way, so that today both power plant units at Strudstrup are capable of firing with a combination of straw and coal.

Conversion to Straw-firing

Studstrupværket's units 3 and 4 both date from 1985. The boilers in question are two so-called Benson boilers equipped with 24 burners at two levels.

The conversion of the two units to co-firing, among other things, included the modification of four burners in the top burner panel at the back wall of the boiler. The modification, among other things, included moving the oil lance to make room for firing ground straw in the centre tube. The converted burners can each burn up to five tonnes of straw an hour.

Straw Handling

Today, Studstrupværket is equipped with a straw storage with a capacity of approx. 1,150 straw bales. Trucks are unloaded with semi-automatic cranes and two trucks can be unloaded at a time.

The plant is equipped with four feeding lines for processing the straw before it is fired into the two boilers. First, the strings that hold the bales together are removed. Afterwards, the straw is shredded and stones and other impurities are removed. Then the straw is ground in a hammer mill. The straw is transported to the burners on the boiler via a pneumatic transport system equipped with rotary blowers.

Flue Gas and Ash

An electrostatic precipitator cleans the flue gas from its content of particles. In addition, the plant is equipped with desulphurisation plant and subsequent bag filters. The fly ash is used for the production of cement and concrete.

Data for Studstrupværket	
Commercial operation of straw firing	2002 (unit 4) and 2005 (unit 3)
Supplier of boiler plants	Babcock
Fuels	Straw and coal
Consumption of straw	130.000 tonnes/year
Boiler type	Benson
Firing concept	Co-firing
Steam pressure	250 bar
Steam volume	287kg/second
Steam temperature	540°C
Electricity efficiency	42 per cent
Flue gas cleaning	Eelectrostatic precipitator, $deNO_x$ plant and desulphurisation
Electrical power efficiency	2 × 350MW
District heating output	2 × 455MJ/second

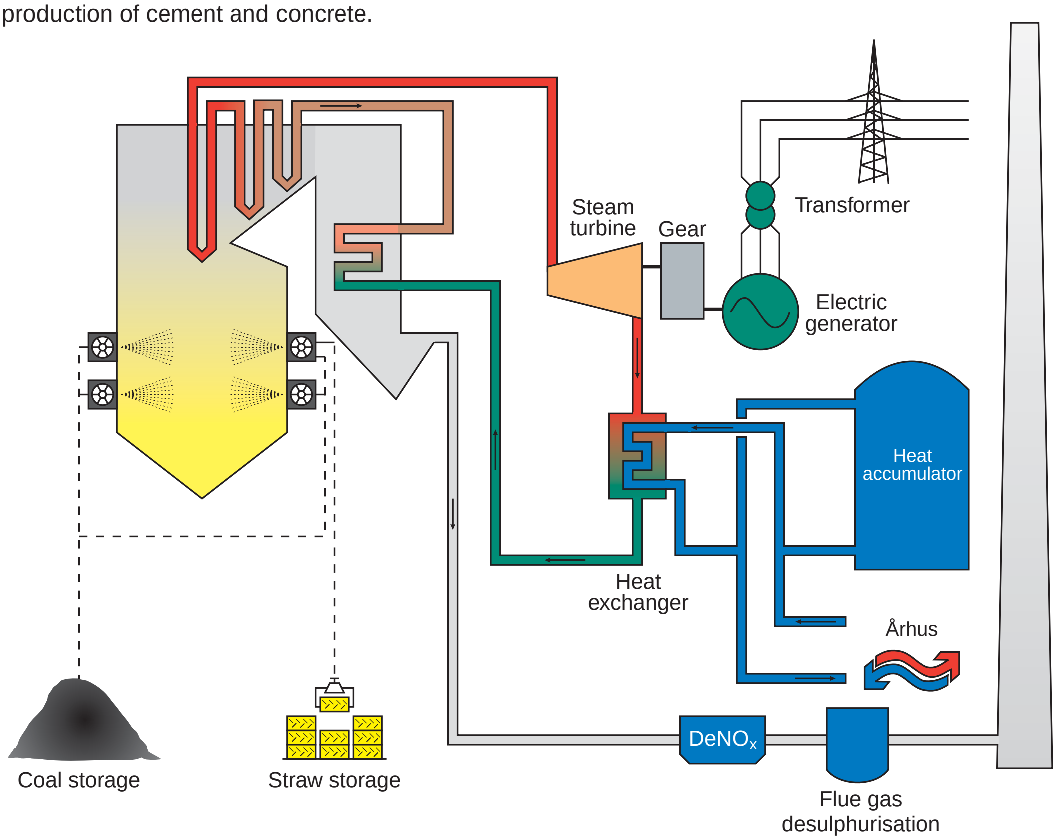


Figure 24.1. Simplified diagram of Studstrupværket.

Fynsværket

– *new straw plant ready in 2009*

Fynsværket as it looks today. The new straw-fired power plant unit will be located at the bottom left corner of the picture.

Photo: Elsam

On Friday 2 March 2007, the first sod was turned for a large straw-fired CHP plant at Fynsværket, which means that the last brick finally fell into place in the large Biomass Plan puzzle from 1993. The original plan was for the power plants to buy 1.4 million tonnes of biomass before the end of 2000, but for various reasons this target will not be met until the new power plant unit in Odense is put into operation in the spring of 2009.

Vattenfall is responsible for the building of the new plant at a cost of DKK 750 million. The plant is established as an independent unit capable of operating independently of the other plants at Fynsværket, which use coal and waste. The new boiler will be capable of burning several different types of biomass, but initially only straw will be used. The plant will be capable of consuming 170,000 tonnes of straw annually, resulting in a CO_2 reduction of approx. 200,000 tonnes a year compared with a coal-fired power plant unit.

The CHP plant will have an electrical power efficiency of 38MW and the annual production will be more than 190 million kWh, equal to the power consumption of approx. 43,000 households. The heat production will cover the requirements of approx. 20,000 households or approx. 15 per cent of the district heating consumption in Odense.

Technical Installations

The straw is transported to the plant in trucks which each has a capacity of 24 big bales with a total weight of approx. 13 tonnes. The plant will be open for straw reception Monday to Friday from 7 a.m. to 5 p.m. and Saturday from 7 a.m. to 2 p.m.

In the straw storage, the straw bales are unloaded with a crane that lifts 12 bales at a time. The crane drops the straw bales on a conveyor, which transports them to the boiler or places them in the straw storage for later use. The storage has a capacity of 2,300 straw bales, which equals the consumption from 2 p.m. on Saturday until Monday morning. This corresponds to the period when the plant does not receive any straw.

The straw is transported to the boiler using a conveyor. The straw is shredded just before the boiler and afterwards fed into the vibrating grate of the boiler by means of a screw conveyor.

In the boiler, steam is produced at a pressure of 110 bar and a temperature of 540°C. The flue gas is cleaned of fly ash in a bag filter. In addition, a flue gas condensing plant is installed which, in addition to producing 10 MJ/s district heating, also cleans the flue gas of hydrochloric acid and sulphur dioxide.

The boiler plant is delivered by Bioener, which has existed as a company since 2001, when it was spun off from FLS-miljø. Bioener's business area is the building of straw-fired boiler plants and several of the employees have experience from the earlier straw-fired plant, including Masnedø, Enstedværket and Maribo-Sakskøbing. The turbine plant is delivered by Skoda in the Czech Republic.

Data for Fynsværket	
Commercial operation	2009
Supplier of boiler plants	Bioener
Fuels	Straw
Consumption of straw	150,000 tonnes/year
Fired output	118MW
Boiler type	Drum boiler
Firing concept	Vibrating grate
Steam pressure	110 bar
Steam volume	46kg/second
Steam temperature	540°C
Electricity efficiency	33 per cent
Boiler efficiency	93 per cent
Flue gas cleaning	Bag filter as well as HCl and SO_2 cleaning
Electrical power efficiency	35MW
District heating output	75MJ/second excluding flue gas condensing 86MJ/second including flue gas condensing

Schedule

As already mentioned, the building of the plant has started and the construction of the boiler plant is expected to start at the end of 2007. One year later, the first test will be initiated and the turbine is expected to be put into operation on 1 March 2009. According to the contract, the plant will be completed on 1 June 2009.

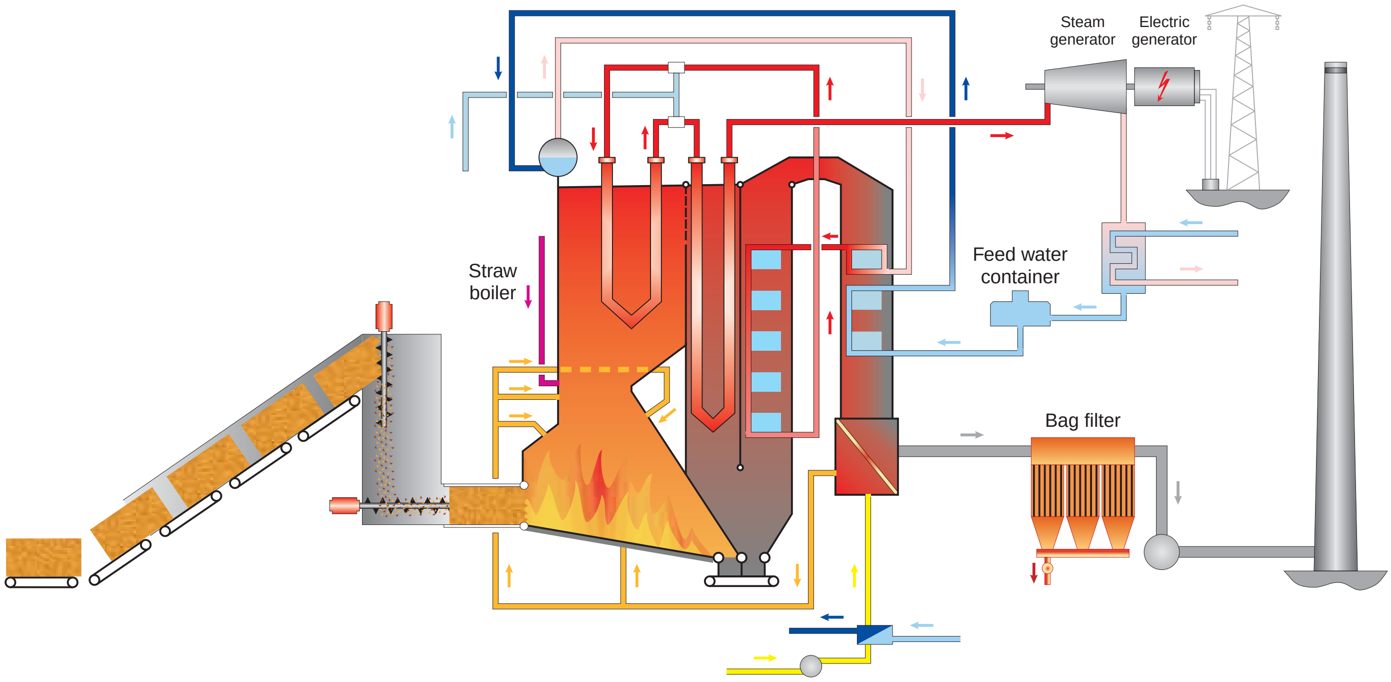


Figure 25.1. Simplified diagram of Fynsværket.

Published by:

DONG Energy
Kraftvaerksvej 53
DK-7000 Fredericia
Denmark
Telephone +45 79 23 33 33
www.dongenergy.dk

Vattenfall
Stoeberigade 14
DK-2450 Copenhagen SV
Denmark
Telephone +45 88 27 50 00
www.vattenfall.dk