Biomass CHP technologies

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Eija Alakangas
Martti Flyktman

VTT Energy
P. O. Box 1603, FIN-4010 JYVÄSKYLÄ, FINLAND
Phone +358 14 672 611, Telefax +358 14 672 596

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Eija Alakangas & Martti Flyktman

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Abstract

The future COGEN project, funded by the SAVE II Programme of DG Energy of the European Commission, National Governments and the cogeneration industry, will provide the first in-depth long-term market analysis for cogeneration for 28 countries of the EU, the EEA, the central European accession countries and other important neighbours.

This report is part of the future COGEN project and it is concentration on the technology solutions of biomass CHP and experience of biomass CHP in Finland.

Biomass CHP technologies are presented in different scale; under 1 $\mathrm{MW_e}$, from 1 to 10 $\mathrm{MW_e}$ and in large scale from to 10 to the 240 $\mathrm{MW_e}$. Technology solutions include solid, liquid and gaseous biomass fuels. In biomass CHP the prevailing technology is steam boiler with steam turbine. The Rankine cycle continues to be the prime power plant technology, when biomass CHP plants are built. Although new technologies are being developed, practically all industrial plants employ the Rankine cycle. A Rankine power plant has three main sections: fuel handling, boiler plant, and steam and power section. Biomass is burned in grate or fluidised bed boiler but also separate gasifiers are used in connection with conventional CHP boilers. Biogas and liquid biofuel CHP plants usually have engines for electricity production. In small-scale CHP a process based on Stirling engines is under development. Technologies are presented also by some case projects. Also costs of Finnish biomass CHP plants in different scale is presented.

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PREFACE

The future GOCEN project, funded by the SAVE II Programme of DG Energy of the European Commission, National Governments and the cogeneration industry, will provide the first in-depth long-term market analysis for cogeneration for 28 countries of the EU, the EEA, the central European accession countries and other important neighbours.

The future GOCEN project will be carried out by a consortium comprising COGEN Europe (Belgium), ESD (UK), VTT (Finland), Sigma Elektroteknisk (Norway), ETSU (UK) and KAPE (Poland). A “Data Network” of local partners, many of them COGEN Europe national members, provide a focus for information gathering and consensus building in each of the 30 countries covered. A "Consultative Group", drawn from key cogeneration stakeholders in each country, will test and verify the project's data, projections and conclusions.

This report is part of the TECS project and it is concentration on the technology solutions of biomass CHP based on Finnish experiences. This report will be also available from the Internet: http://tecs.energyprojects.net or www.vtt.fi/ene.

Jyväskylä, 7th March 2001

Eija Alakangas, VTT Energy

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App.1. Costs of biomass CHP plants in Finland in 1999

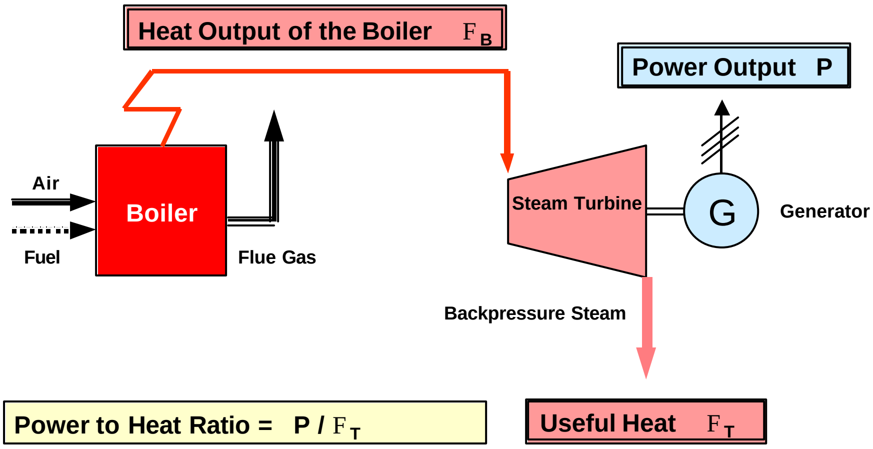
DEFINITIONS (10,11)

Combined Heat and Power (CHP) Combined Heat and Power (CHP) or cogeneration is defined by as an energy conversion process where electricity and useful heat are produced simultaneously in one process. CHP is generated by several types of CHP plants, such as conventional backpressure power plants, extraction condensing power plants, gas turbine heat recovery boiler plants, combined cycle power plants and reciprocating engine power plants.

District Heating (DH) District heating is a system in which heat is produced centrally in precise location(s), from where heat is distributed to the consumers, located in different buildings, in the form of hot water or steam circulating in a distribution piping network. Often, heat is also used not only to heat buildings but also to provide domestic hot water and for industrial purposes, such as process heat.

Heating-degree day Heating-degree day is used for analysing heat demand requirements in different geographical zones. It is a difference between the calculatory inside temperature and daily average outside temperature. Heating degree-days vary between 1 000-2 000 in Greece and Portugal, 3 000-4 000 in Denmark and 4 000-6 000 in Finland. Procedures for calculation of heating degree-days may vary a bit from country to country.

Power to heat ratio Power to heat ratio is relation of gross generated electricity to useful heat (0.30-0.95). The power to heat ratio of any particular power plant is not constant. It varies as a function of backpressure and load level of the power plant. Gross electricity generation is measured at the output terminals of the generator sets in power plant and it includes power supplies taken by: power plant auxiliaries and generator transformers.



1 INTRODUCTION

The greater use of cogeneration promises to contribute significantly to meeting national targets for the reduction of CO_2 emissions. In its pre-Kyoto Communication, the Commission identified CHP as the single largest potential contributor to CO_2 emission reductions. In the EU’s cogeneration strategy a target has been proposed for cogeneration’s share of total power generation in the EU to be doubled by 2010 to nearly one fifth of all electricity. Cogeneration will also be crucial to improve the environment in central Europe.

CHP plants make the maximum use of fuel energy by producing both electricity and heat with minimum losses (Fig. 1). The plants achieve a total efficiency of 80 to 90 %. In conventional condensing power plants the efficiencies remain in electricity production at around 40%.

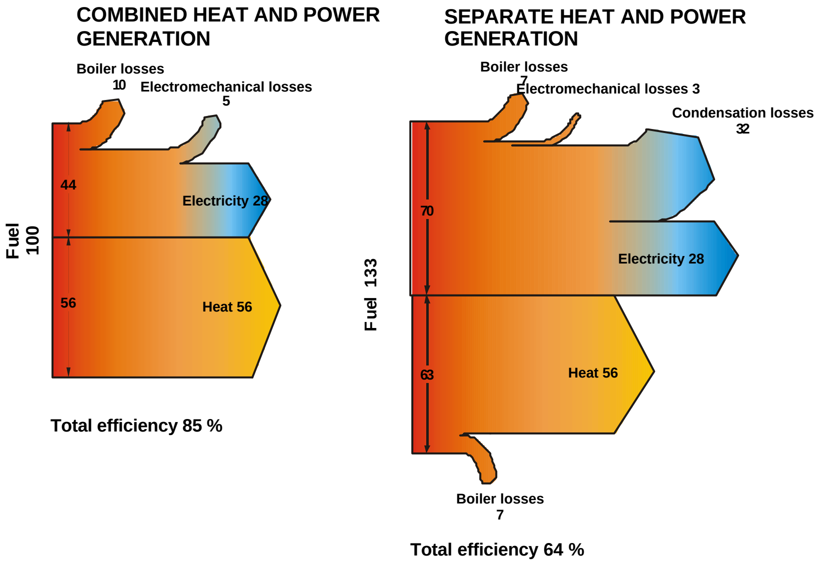


Figure 1. Primary energy consumption in CHP generation with corresponding generation in separate processes.

This report summaries the technical solutions for biomass CHP and experience in Finland. CHP is applied widely in Finland for the heating of communities and for heat and power from the utilisation of residues from industrial processes. The amount of energy Finland saves annually through CHP (compared to condensing power) corresponds to 11 % of all primary energy used in the country. Total CHP capacity of electricity generation (simultaneously available capacity) in the beginning of year 2000 was in industry 1 570 MW_e and district heating sector 3 320 MW_e according the Finnish Energy Statistics /7/.

Approximately 32 % of the electricity used in Finland in 1999 (77.8 TWh) were gained from CHP. Industrial CHP plants and district heating CHP plants respectively accounted for 47 % and 53 % of the cogeneration. Industry sector consumes 56 % of all electricity in Finland in 1999, and almost 30 % of this electricity is generated by CHP. As much as 75 % of district heating was produced by CHP in 1999. District heating covers 48 % of total Finnish space heating demand /5/.

Finland has long traditions using biomass CHP technologies. The first industrial cogeneration plants in Finland were built at the turn of the 1920s and 30s, and the first district heating plants in the 1950s. The aim was to increase the economy and reliability of power supply, and local energy sources were often used as a starting point /5/.

Industrial back-pressure power production is mainly based on spent liquors (wood-based liquid fuel) originating from pulp production. Black liquor is suitable for combustion because of the organic wood residues. The production of pulp for the production of paper started in Finland as early as in the 1880s. However, the residues and spent liquid were not utilised at that. The heat needed for the production of pulp and paper was generated mainly with wood and coal. Fuel prices went up sharply in the 1920s, which helped to promote the idea that spent liquors from pulp industry could be utilised in heat and power production /5/.

District heating was started in the largest cities of Finland in the 1950s and 60s, and in smaller towns after the oil crisis of the 1970s. There are over 200 heat distribution utilities in Finland, and most of them produce at least part of the heat themselves. Most district heating utilities are owned by municipalities and operate within the owners' area. District heating systems cover practically all density-populated areas of Finland where the sale of district heating is profitable /5/.

Many large cities own CHP power plants, which produce both power and heat. Most of their output is still sold within the area of the owner cities. Medium-sized and small towns purchase district heat from CHP plants or industrial CHP plants owned by other companies, or produce it themselves in heat-only boilers. The customers are today allowed to purchase electricity from any company operating in the deregulated electricity market /5/.

2 BIOMASS CONVERSION TECHNOLOGIES

2.1 FUEL PROCUREMENT

Logging residue - foliage of trees and tree tops, waste blocks and undergrowth trees - constitute a usable and significant source of raw material for the production on wood fuels. The amount and composition of logging residue generated at the felling stage, however, varies greatly by felling site. At the first thinning of birch stands, the logging residue that is left in the forest contains, for the most part, unmerchantable tree tops and branches, and accrual remains low. On the other hand, in the final felling of spruce stands the accrual of logging residue is significantly higher and consists largely of branches and needles and of a significant number of waste blocks, should the felling site contain trunks with butt decay.

Wood chips from the logging residue generated at the final felling of spruce stands has the best potential among forest chips for producing thermal energy at a competitive price. The production technology of fuel wood which has been developed for harvesting the logging residue of final felling is also the one most widely used, and the experience thus gained can be applied when operations are expanded to new areas.

Logging residue can be harvested either immediately after felling, fresh with needles, or dry, after the summer season, whereby a significant portion of the needles and a small amount of bark and thin branches are left in the cutting area. When dried logging residue is harvested, the recovery rate is reduced and the profitability of harvesting is lowered. Different methods are used or under development in Finland (Fig. 2). In these methods harvesting of forest residues is integrated in the procurement of the timber. Methods are based on where the chipping is taken place and they are:

- piling of residues and chipping at stand
- piling of residues and chipping at roadside
- piling of residues and chipping at terminal
- compacting of residues into bundles and chipping at plant
- piling of residues at stand and transportation of residues as loose material and chipping at plant

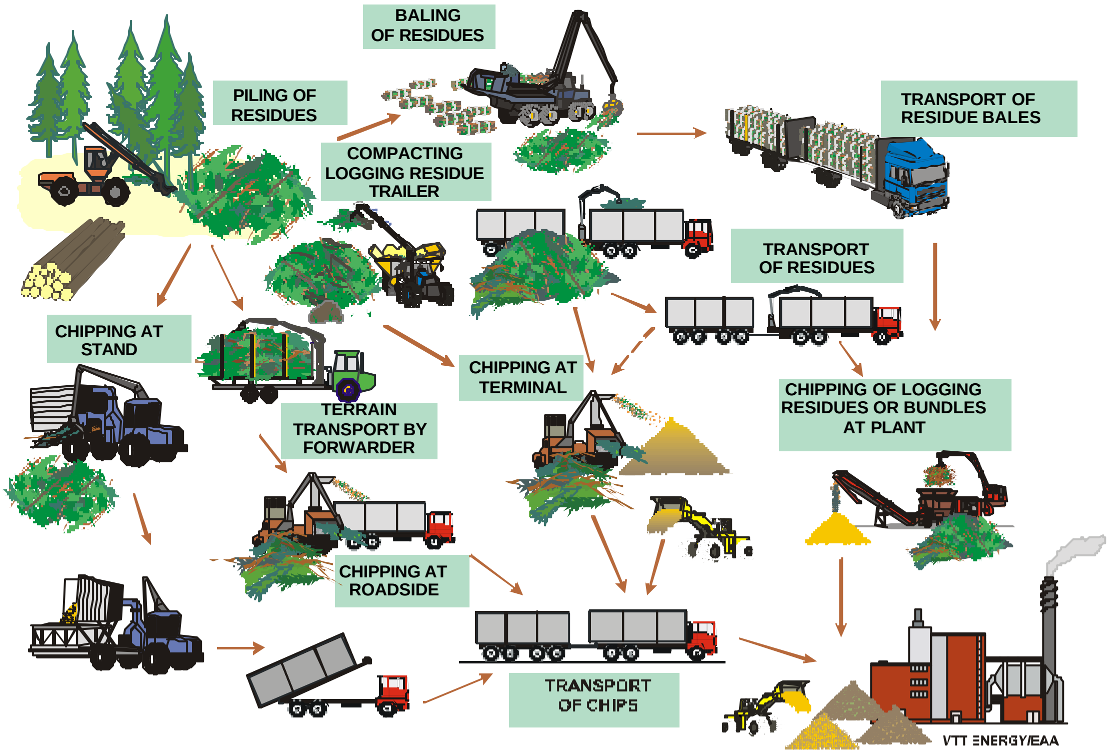


Figure 2. Production methods for logging residue chips in Finland. VTT Energy.

The use of forest chips started to increase again during the last decade. In 1999, the total number of the heating and power plants was 156 and total use of forest chips were 4085 TJ. At heating plants, the increase in the use of forest chips has been slow, however, and the level of the 1980s (3 112 TJ) has not been reached yet. Instead, growth is now rapid in the combined heat and power production. Many power plants have made or are making changes in their fuel receiving, handling and boiler plants in order to be able to use forest chips. In 1999, altogether 40% (4082 TJ) of all forest chips were used in CHP production, and the share is likely to exceed 50% as soon as 2000. In Finland electricity production by wood fuels is supported by the State through a partial tax refund (8 FIM/MWh, 1.35 €/MWh, table 8)/12/.

In the future the increase in the use of forest chips seems to concentrate on CHP production. The total number of the plants using forest chips is estimated to grow by 100—150 plants by 2010, and 25—35 of them will be over 20 MW_{th} in size. As much as 90% of the additional use of forest chips will probably be led to the over 20 MW_{th} plants and 70% to the over 100 MW_{th} plants /12/.

The other important wood fuel source in Finland is industrial wood residues such as bark, sawdust, cutter shaving, which are used mainly in forest industry, but also in municipal heating plants and CHP plants. Use of industrial wood residues have been about 67 000 TJ/a /12,5/.

The primary aim of Finnish and EU waste policy is to prevent the formation of wastes. In waste management the first priority is to recycle the material and the second priority is to recover the energy contained in waste. The national waste plan introduces targets for waste management in Finland until 2005. By 2005, 70% of waste should be recovered as material or energy /18/.

Finnish waste management is still today highly dependent on landfilling. This will change due to the landfill directive, which sets limits for biodegradable waste going to landfills. In Finland, the waste-to-energy concepts are based on cofiring of recovered fuels (processed from source separated waste, the quality is controlled) in existing CHP plants. The share of recovered fuels (REF) is about 1 % of the primary energy use and the potential of REF is 3 - 5%. The energy use of REF will grow within the next few years, the technologies/conditions being defined by the EU legislation on waste incineration /18/.

Waste management in Finland is based on source-separation of waste in order to produce raw materials for material recycling and for the production of recovered fuels (Fig. 3). Safe use of recovered fuels requires materials with a low content of noxious constituents and impurities, efficient source-separation and an appropriate production process. These requirements also support the recycling of materials /18/.

The dry source-separated fraction from households and companies is processed to fuel in a REF plant. The process usually comprises preliminary crushing, where bigger items are also removed, magnetic separators, screening, secondary crushing and normally, second magnetic separator and an eddy current for non-magnetic metals. The fuel can be baled or transported as such to a near CHP plant for energy use. The process depends on waste material, for commercial waste only preliminary crushing and magnetic separation may be enough /18/.

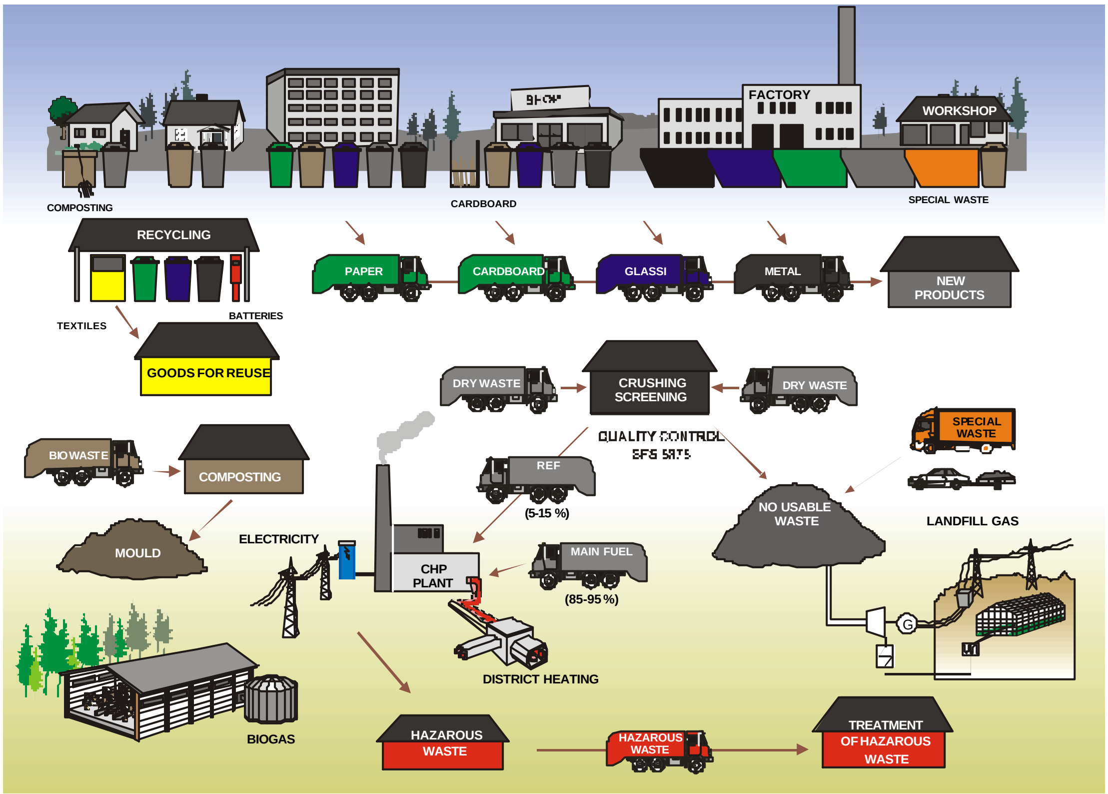


Figure 3. Separation of wastes and production of recovered fuels in Finland. VTT Energy.

2.2 COMBUSTION TECHNOLOGIES

2.2.1 General

The *Rankine cycle continues* to be the prime power plant technology, when biomass power plants are built. Although new technologies are being developed, practically all industrial plants employ the Rankine cycle. A Rankine power plant has three main sections: fuel handling, boiler plant, and steam and power section.

2.2.2 Grate combustion

Grate combustion systems in various forms have a long history of use solid fuels. Grates are still used in many small and medium sized boilers for hot water and steam production. They have been able to compete with more modern technologies and more convenient fuels due to continuous improvements and the use of modern control systems (fig 4). However, grates are less flexible than fluidised beds with regard to fuel quality and less suited to variable fuel mixtures and variable fuel quality. The common feature of all grate system is that the solid, non-volatile portion of the fuel is mixed with the air and burned on the grate itself. The grate is usually arranged to move so that the fuel travels towards the ash discharge during combustion. Fuel may be fed on top of the grate or fire-bed or from underneath the grate. Fuel may also be fed into the combustion volume above the fire-bed where the volatile matter is burned, with mostly char falling onto the grate itself.

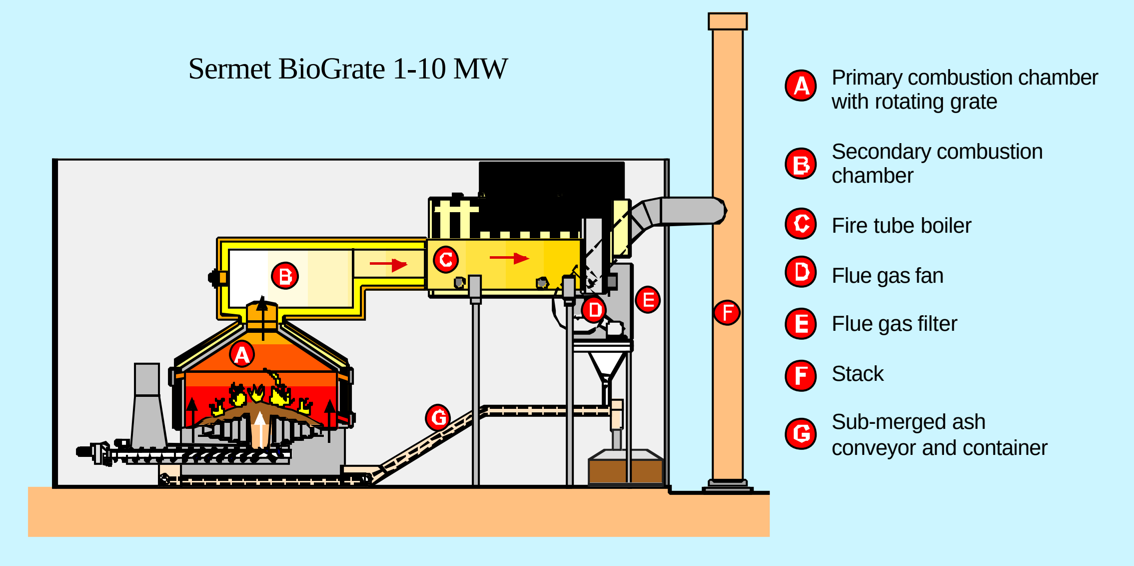


Figure 4. Underfeed rotating grate for wet biomass fuels. Sermet Oy.

2.2.3 Fluidised bed combustion

Competitive and environmentally compatible energy use of biomass requires combustion technology able to cope with the special requirements of biomass. Fluidised bed technology can be applied to a very wide range of fuels, from very moist fuels like bark and sludges up to high-grade fossil fuels. Fluidised bed boilers achieve fuel efficiency rates of over 90 per cent even with difficult, low-grade fuels.

In fluidised bed combustion (FBC) the large capacity of inert bed material helps stabilise combustion process, an important benefit when biomass with its typically large variations in fuel properties is burned. The low operating temperature of FBC boilers, coupled with stage combustion, effectively reduces formation of thermal nitrogen oxides NO_x. If lower NO_x levels are required injection of ammonia or urea can be used.

Sulphur emissions control is not required when biomass is combusted. However sulphur emissions can be controlled by simply adding a suitable sorbent to the bed of FBC boiler. This technology has been used successfully in coal fired circulating fluidised bed (CFB) power boilers.

Separation of suspended solid particles from the flue gases is the costliest emission control operation required by FBC boilers. The standard solution is to fit the plant with an electrostatic precipitator (ESP). When recycled fuels are used, halogen, heavy metal, dioxin and furan emissions may need to be controlled by means of combustion temperature, bed composition, dust removal or flue gas scrubbing.

The fluidized bed boilers can be divided into two types

- bubbling bed type (BFB) (Fig 5)
- circulating type (CFB) (Fig 6)

Typical feature of fluidised bed is a sand bed where the amount of fuel is only 1 – 2 % of the mass. The temperature of the bed is 800 – 950 °C. The height of the bed in the bubbling mode is around 1 m when fluidized. When circulated there is no clear bed. The particle size of the sand is 0,1 – 0,2 mm for the circulating and 0,5 – 1 mm for bubbling beds.

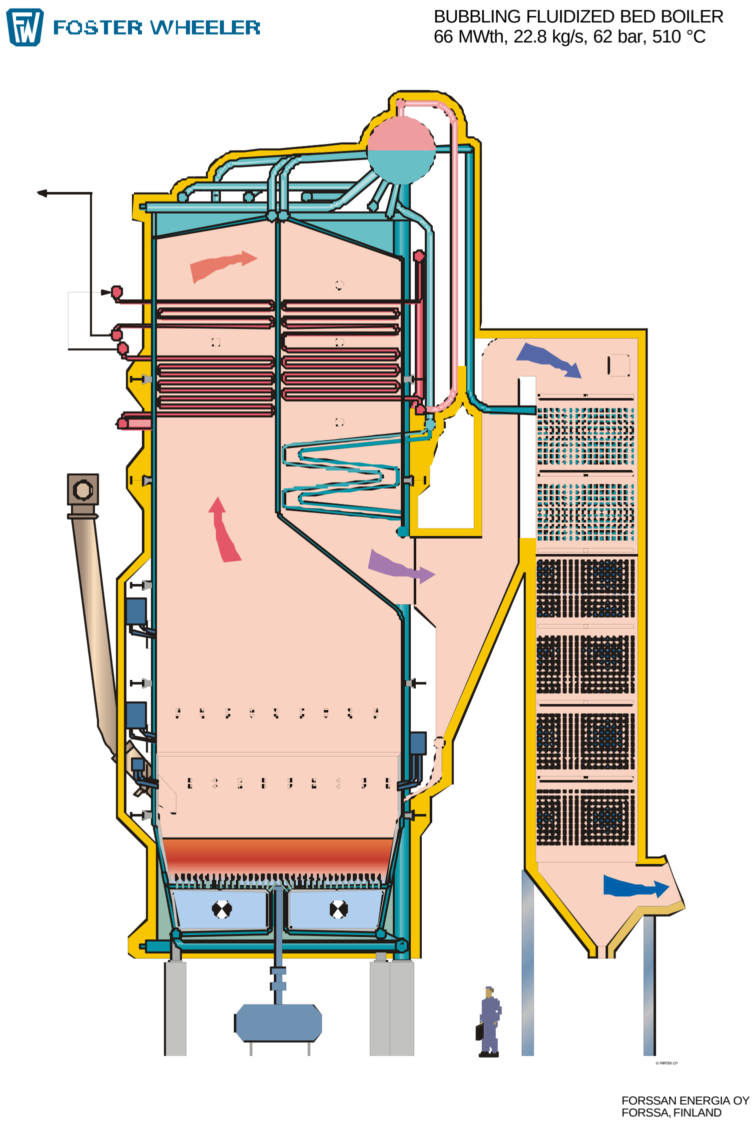


Figure 5. Bubbling fluidised bed boiler for biomass fuels. Foster Wheeler Energia Oy.

The choice between bubbling fluidised bed (BFB) and CFB technology has been largely linked to the choice of fuels. As the simpler and cheaper technology, BFB has been favoured for plants exclusively fuelled with biomass or similar low-grade fuels containing highly volatile substances. The new enhanced CFB designs can be a competitive choice even in smaller biomass-fired plants. CFB boiler has been the choice when sulphur-containing fuels are used. For reactive fuels like wood, wood wastes or peat both types are applicable. For less reactive fuels such as coal circulating type is preferred.

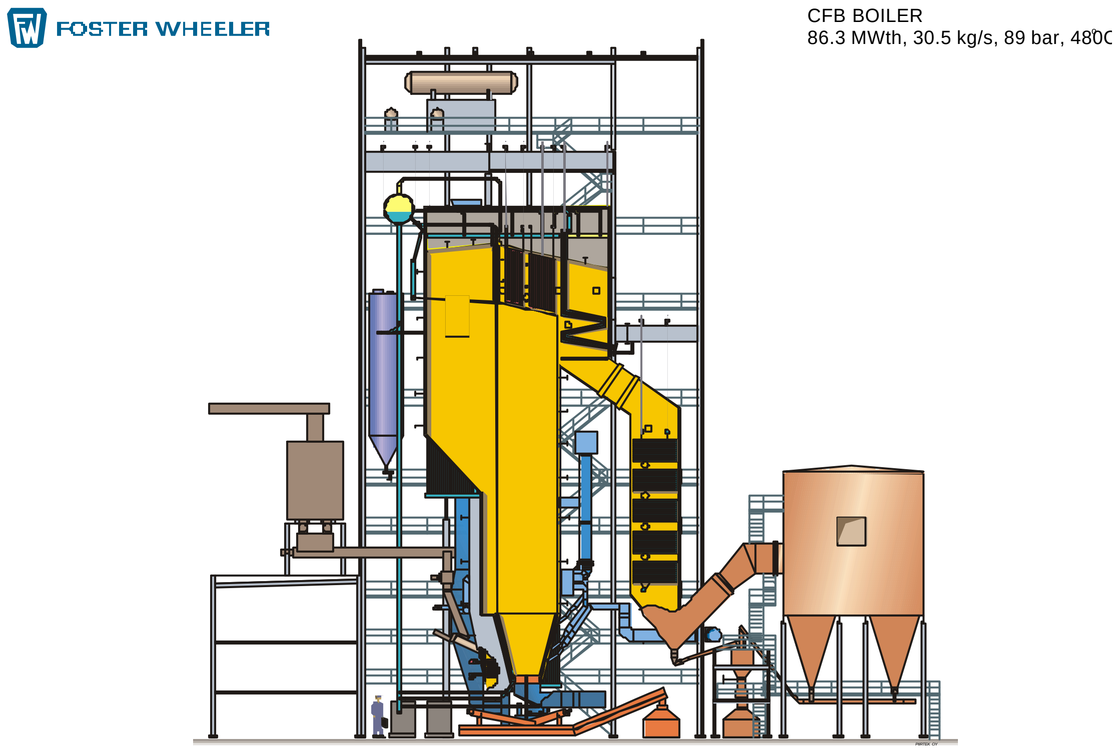


Figure 6. Circulating fluidised bed boiler. Foster Wheeler Energia Oy.

Fluidized bed combustion is ideal for low calorific value fuels. The advantages of the fluidized bed technology are as follows:

a) Stable combustion in spite of wide variations in the particle size, moisture content, ash content and heating value of the fuel

b) Possibility of using low volatile fuels with high ash content

c) Possibility of firing different fuels simultaneously with one combustion equipment (the bed)

d) Rapidity of load changes

e) Possibility of efficient control of SO_2 and NO_x emissions without expensive equipment

2.3 SMALL SCALE PROCESS ALTERNATIVES FOR ELECTRICITY PRODUCTION

In the size class of less than 3 MW_e studied in this chapter, the main alternatives for electricity production are /15/:

- Gasifier or direct combustor combined with a small steam turbine or steam engine: this alternative has a rather low power to heat ratio (due to inefficient small steam cycle) and the specific investments are high. On the other hand, this process concept is the only alternative that can be considered to be fully commercially available.
- Direct wood-fired gas turbines: these systems have been developed both in USA and in Europe, but so far none of the developments has been successful. The main reasons for this are: a) alkali metals released in combustion cause rapid corrosion in turbine blades, b) pretreatment of wood into dry powder is expensive, and feeding of pulverised wood into pressurised combustors is also problematic.
- Stirling engines seem to approach commercialisation and their best market may be in the smallest size range (<500 kW_e). The recent development in Denmark seems to be promising, but probably a few years are still required until the technical and economic performance of Stirling engines can be reliably estimated. Small-scale gasifiers may also have some advantages compared to direct combustion-based systems in Stirling applications (more easy to avoid erosion and corrosion and to control combustion conditions).
- Production of pyrolysis oil on a larger scale and distribution of produced oil to small-scale engine power plants: the technical feasibility of pyrolysis oil combustion in diesel engines has so far not been demonstrated, but there are several R&D projects going on and it is possible that this technology will become commercially available within a few years.
- Fixed-bed gasifiers coupled to diesel or gas engines are the focus of many R&D projects in Europe at the moment. There are several industrial development projects, e.g., in Switzerland, Germany, Denmark, UK and in the Netherlands, with which the fixed-bed gasification technologies (Finnish version; Novel gasifier combined with catalytic cleaning) will compete in the future. Most of the competing technologies are based on slightly modified classical downdraft gasifiers. In Denmark and UK, there are also teams utilising updraft fixed-bed gasifiers and having tried to develop catalytic gas cleaning systems. However, so far these developments have not led to commercial breakthrough (Fig.7).

2.3.1 Gasification

Gasification is a form of pyrolysis. Gasification is carried out with more air, and at high temperatures in order to optimise the gas production. In order to produce combustible gas, the biomass first should be heated. It is most common to heat it by burning a small proportion of biomass. The heating dries the fuel, and not until then the temperature will be increased. At the temperature of approximately 200 ^{o}C, the so-called pyrolysis begins where the volatile constituents of the fuel are given off. They build up a mixture of gases and tars. When pyrolysis is completed, the fuel has been converted to volatile constituents and a solid carbon residual /16/

The char can be converted into gas by adding a fluidising agent that may typically be air, carbon dioxide, or water vapour. If using CO_2 or H_2O, this process requires heat and will only occur at a reasonable acceptable speed at temperatures above approximately 800 ^oC. The combustible constituents in the product gas are primarily carbon monoxide, hydrogen and methane. Together they constitute approx. 40 % of the volume of gas when using air for the gasification, while the residual part consists of incombustible gases such as nitrogen and carbon dioxide. The major part of the tars from the pyrolysis can be converted to gas, if heated to 900 – 1200 ^oC by passing through a hot char gasification zone /16/

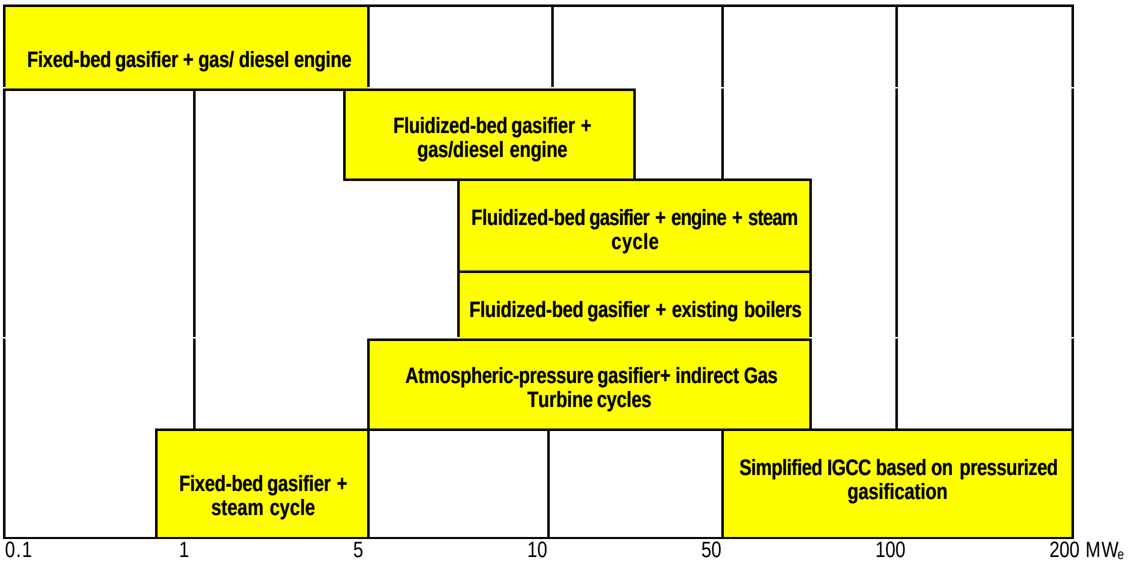


Figure 7. Gasification technologies for solid fuels suitable for use in power plants of different size classes. Source: VTT Energy.

The gas is more versatile than the original solid biomass (usually wood or charcoal): it can be burnt to produce process heat and steam, or used in internal combustion engines or gas turbines to produce electricity /16/.

Many different types of gas generators have been developed over the 100 years the technology has been known. Normally, gas generators are classified according to how fuel and air are fed in relation to one another, updraft gasifiers and downdraft gasifiers. There are also other gasification principles, e.g. fluidized bed gasification /16/.

Commercial gasifiers are available in a range of size and types, and can be run on a variety of fuels, including wood, charcoal, coconut shells and rice husks. Power output is determined by the economic supply of biomass, which is limited to a maximum of 80 MW_e in most cases (Fig 7) /16/.

The energy density of fresh biomass is low, less one tenth that of coal, making it uneconomic to transport biomass over long distances (usually less than 100 km). This is the main reason, why biomass fired power plants are typically small in comparison to coal-fired plants. The specific investment costs are significantly higher for a small plant than for a larger plant. As a result, technologies for utilising biomass in existing power plants are of great interest. Gasification makes it possible to utilise biomass in a medium–sized or large coal fired boilers /16/.

Gasification of biomass and cocombustion of the product gas in existing coal-fired boilers offers a number of environmental advantages (Fig 20):

- recycling of CO_2
- reduction of SO_2 and NO_x emissions
- and efficient utilisation of biomass and recycled fuels

Investment and operation costs are low and existing power plant capacity is utilised. Only minor modifications are required in the boiler.

Atmospheric CFB gasification technology of dried biomass is commercial technology. The product gas can be easily burned under ambient conditions. However, biomass must be dried in a special dryer, which represents a considerable capital cost. Gasification of wet biomass represents no technological problems. However, gasification in stand-alone boilers without support fuel produces gas of very low heat value that is difficult to burn. A solution is to lead the hot gas directly into a coal- or oil-fired large-scale boiler, enabling cocombustion of the lean gas in the gas burner. A fuel feeding system has been developed for adjusting the moisture content of the fuel mixture and so the heat value of the gas. This eliminates the need of an expensive fuel dryer.

The *updraft gasifier* (fig.8), has a refractory lined shaft furnace. The fuel is fed into the reactor shaft from the top by a feeder device. There is a hydraulically rotated mechanical grate at the bottom of the reactor. Gasification air is fed through the grate into the reactor shaft. The upwards streaming air reacts with the fuel, and consequently, the fuel is gasified completely. Dry ash is removed by an ash discharge system installed at the bottom of the gasifier. Ash sintering is prevented by water vapor supplied with the gasification air. The updraft gasifier can be connected to a hot water or steam boiler to produce heat and/or power. The power plant consists of fuel storage, conveying and handling section which suppliers fuel to the gasifier (Fig.8). The fuel is fed to the gasifier by a feeding system, which has to be designed to feed a large variety of fuels. Air of controlled moisture content is used as gasification agent. The gasifier produces low calorific value gas, which is directly burnt in a gas boiler generating hot water or steam. The burner of the boiler is designed to burn low calorific value gas with low emissions. Hot water is used in most cases for district heating. Steam is utilised in a back pressure steam turbine cogenerating power and district heat. The power plant consists of conventional plant equipment. This technology is suitable for size class from 100 to 3 000 kW_e. In Finland and in Sweden nine updraft gasifiers (Bioneer gasifiers) are in commercial operation since 1986 for heat production (1 – 15 MW_{th}).

In Finland also a gasification plant generating gas for gas engines is developed. The plant is built as a CHP plant, where the gas engines produce electricity and also district heat. The product gas existing the gasifier passes through a catalyst, whereby tar components are destroyed. The catalyst can be calcium or nickel based. Experience has shown that tar destruction in the temperature range of 850 – 1000 °C will be almost complete when applying a suitable catalyst. After the gas cooling the product gas will be cleaned of particulate mater in a fabric filter after cooling of the gas to approx. 200 °C. Downstream of the filter the fuel gas is further cooled close to ambient temperature. A typical performance of CHP based on updraft gasifier is presented in table 1.

Table 1.Process performance of updraft gasifier CHP and gas engine plant./9/.

Plant type		Gasifier Steam cycle power plant	Gasifier Steam cycle power plant	Gasifier with gas engine
Electricity	MW	2.0	5.0	2.0
Biomass fuel input	t/h	2.9	6.8	0.76
Heat generation	MJ/s	6.3	14.6	4.5
Power to heat ratio		0.32	0.34	0.44
Electrical efficiency (LHV)	%	20.9	22.3	28
Total efficiency (LHV)	%	86.7	87.5	90

LHV= lower heating value

In *downdraft gasifier* the fuel is fed from the top of the gasifier, undergoing the various processes as it moves downward to the bottom of the gasifier. The air is injected either in the middle section of the gasifier or from the top above the fuel storage and passes downwards in the same direction as both the fuel and the gases so developed. For tar forming fuel such as wood, this principle is particularly usable, because tar, organic acids and other pyrolysis products pass down through the combustion zone and decompose to light, combustible gaseous compounds. In its traditional design the downdraft gasifier has the drawback that it is not suitable for fuels with a low ash melting point. Another drawback is that it requires relatively dry fuels with maximum moisture content of 25 – 30 %. There is one new type of 2 MW downdraft gasification CHP plant under construction, which will be connected into 0.5 MW_e engine.

The plant consists of the following major units; wood receiving and storage, drying, gasification, particulate removal, and diesel engine generator system. The reactor is a *fixed bed gasifier*. A new type of fixed bed gasifier – Novel (1 – 15 MW) is developed by Condens Oy and VTT Energy. By catalytic gas cleaning gasifier is suitable for electricity production (1 – 3 MW_e). The Novel gasifier is suitable for moist wood fuels (moisture content 0- 60 %) like sawdust, bark, forest residues etc.

Wood is fed from the top of the reactor. The product gas flow through the hot part of the bed, and heavy tars produced in pyrolysis crack to form more combustible gas components. Fuel gas is led through a cyclone to the air preheater, where gasification air is heated to 300 °C. The gas is eventually cooled to approximately 40 °C, and part of water vapour in gas will condense. Finally the gas is filtered through a fabric filter to remove the remaining solid particulates. Approximately 15 % of the energy fed into the diesel engine is supplied with diesel oil, remaining provided by fuel gas. The engine is not equipped with a turbocharger. The efficiency of the engine is about 33 %. The generator efficiency is about 92 % in the size class 100 kW_e.

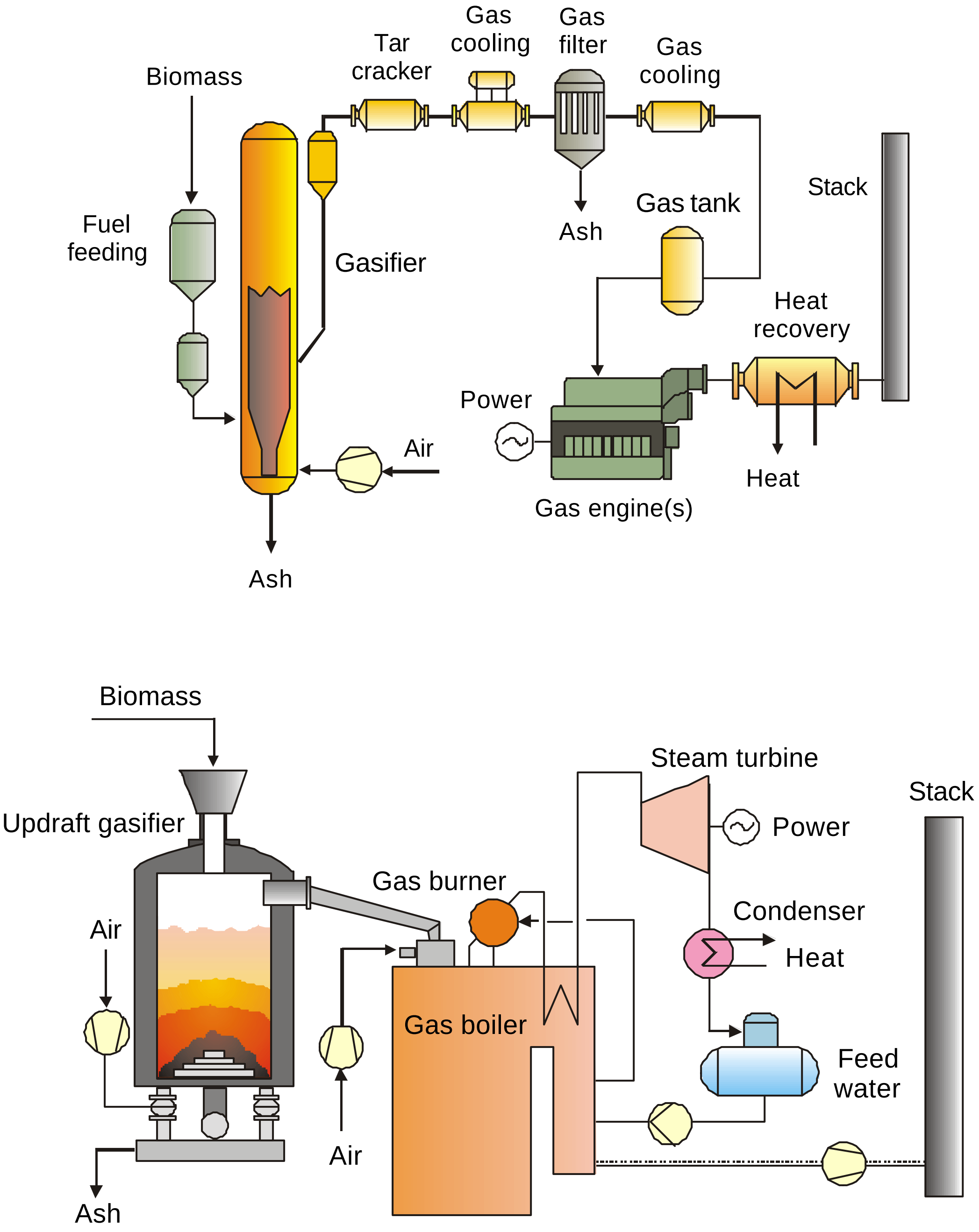


Figure 8. Gasifier biopower systems based on steam turbine or gas engine. /9,14/.

Integrated gasification combined cycles (IGCC) have been developed and demonstrated for power generation using fossil fuel. The main features are the possibility of cleaning the gas produced from impurities, such as particulates, sulphur, etc. under the pressure before the gas enters the combustor of the gas turbine, and also the relatively high electrical efficiency. Higher efficiencies also mean relatively lower emissions /16/.

Biomass gasification is the latest generation of biomass energy conversion processes, and is being used at a scale of up to 50 MW_e to improve the efficiency, and to reduce the investment costs of biomass electricity generation through the use of gas turbine technology. High efficiencies (up to about 50%) are achievable using combined-cycle gas turbine systems, where waste heat from the gas turbine is recovered to produce steam for use in a steam turbine. Economic studies show that biomass gasification plants can be as economical as conventional coal-fired plants. However gas cleanup to an acceptable standard remains the major challenge yet to be overcome /16/.

The first gasification combined-cycle power plant in the world is a 6 MW facility at Värnamo (fig. 9), Sweden, which is fuelled by wood residues. The proposed 75 MW alfalfa gasification combined-cycle power plant in Minnesota, USA, when completed, will be the first dedicated crop-fuel plant of its size in the world. Other installations have been built and tested but several have proven to be unacceptable /16/.

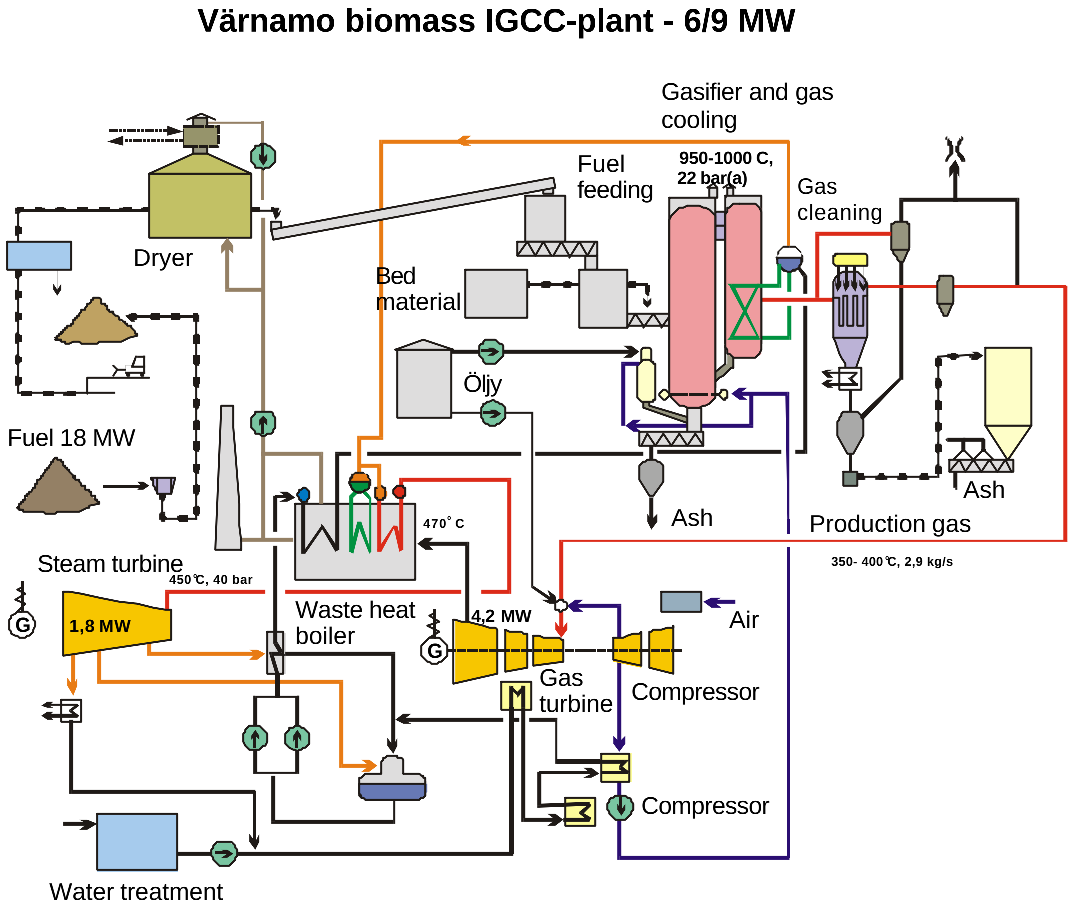


Figure 9. Process diagram of the Värnamo ICCG plant in Sweden.

2.3.2 Fast pyrolysis

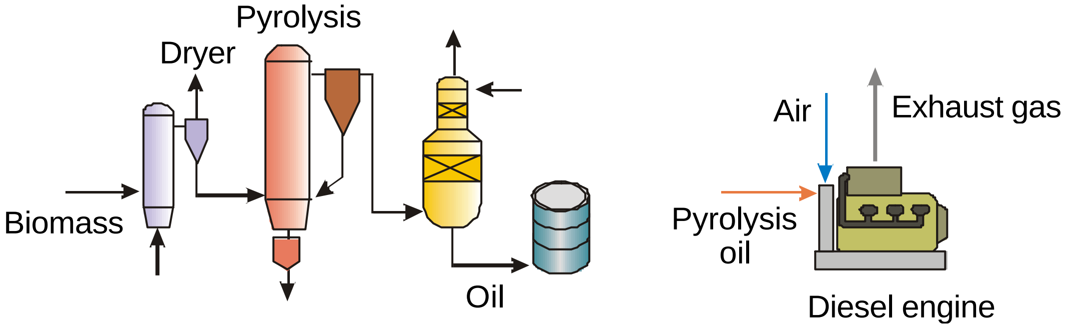


Figure 10. Fast pyrolysis and diesel engine. VTT Energy.

Pyrolysis is the basic thermochemical process for converting solid biomass to a more useful liquid fuel. Biomass is heated in the absence of oxygen, or partially combusted in a limited oxygen supply, to produce a hydrocarbon rich gas mixture, an oil-like liquid and a carbon rich solid residue. The pyrolytic or "bio-oil" produced can be easily transported and refined into a series of products similar to refining crude oil /16/.

Biomass pyrolysis technology offers a novel method of converting solid biomass to a liquid product that can easily be transported, stored and utilised for electricity production by diesel engines and gas turbines (fig 10).

Pyrolysis oil is produced from biomass in pyrolysis oil production unit. After that pyrolysis oil can be transported to diesel power plant and utilised in electricity production. A modern diesel power plant has an efficiency of 40 – 44% with a high power to heat ratio.

Pyrolysis oil can be produced by high energy efficiency, typically 65 – 90 % from wet wood chips.

In Finland, the research into pyrolysis oil production and utilisation was initiated in 1993 with a clear vision for the market opportunities. A consortium of VTT, Vapo Oy, Fortum and Wärtsilä stated in the beginning that the properties, stability and technical limitations for the boilers and diesel power plant are of crucial nature. The challenge of today is to understand and improve the properties of pyrolysis oils in order to reach a 12-month storage time without any changes in homogeneity of pyrolysis oils. Reliable operation of diesel power plants has to be demonstrated. As soon as these problems have been solved, biomass pyrolysis technologies will offer new attractive bioenergy market opportunities where a huge potential can be reached in converting existing petroleum-fired boilers, 0.1 – 10 MW to bio-oils and followed by combined heat and power production with high-efficiency diesel power plants in 0.1 – 10 MW scale /16/.

Pyrolysis technology is clearly the most attractive method for producing liquid biofuels, compared to bioalcohols and biodiesel. With the present price structure, pyrolysis oil can be competitive with light fuel oil in Finland, with light and heavy oil in Sweden and in CHP production in Denmark /16/.

Bio fuel oil (pyrolysis oil) is produced by fast (flash) pyrolysis. The oil may be employed as a heating fuel in boilers, or in combustion engines in power generation. All of the applications are in different stages of development /16/

Fast pyrolysis makes it possible to de-couple solid handling stage in product utilisation. Intermittent operation in power production is also possible with liquid fuels for example in diesel engines. In some cases this may be a distinct advantage /16/.

Fast pyrolysis is only proven in pilot-plant operation. Fast pyrolysis is still some years away from commercial operation and estimation of a potential commercial capacity includes large uncertainties /13/.

The biggest problem a user faces with biofuel oil is that the product is not well defined. Different biomasses yield oils with different characteristics. To be able to compete in an open market, a fixed quality for the fuel product has to be specified /16/.

However, improvements in product quality are also needed. Viscosity, stability, and solids content are properties, which need modifications before a successful introduction of bio fuel oil into markets may take place /16/.

2.3.3 Stirling engine and ORC

Stirling engine is a promising alternative in small-scale electricity production. Potential advantages related to Stirling engines are their high efficiency also in small scale, and their relative insensitivity towards impurities in flue gas, if special designed Stirling engines are used /16/.

A market has been defined in Austria and Denmark for these engines. Heating stations (more than 2500 in Austria) using biomass could cover their own internal power consumption in co-generation with a Stirling engine. Typical electric output for Stirling engine is 30 – 60 kW_e /16/

In the Stirling engine there is no combustible gaseous fuel mixture in the engine, but only a gas as the working fluid that is heated and cooled by turns. Figure 11 /13/. The heat for the Stirling engine working fluid comes from combustion process. The transfer of the heat from combustion process to the engine working fluid takes place by means of a heat exchanger /16/.

The advantage of the Stirling engine, when combustion biomass is concerned that the combustion is not inside the cylinders like in an internal combustion engine. The Stirling engine is based on a closed cycle, where working gas is compressed in cold cylinder volume and expanded in a hot cylinder volume. The heat input from the combustion fuel is transferred from the outside to the working gas through a hot heat exchanger at a high temperature. The heat, which is not made into work at the shaft, is rejected the cooling water in a cold heat exchanger at 300–350 K /16/.

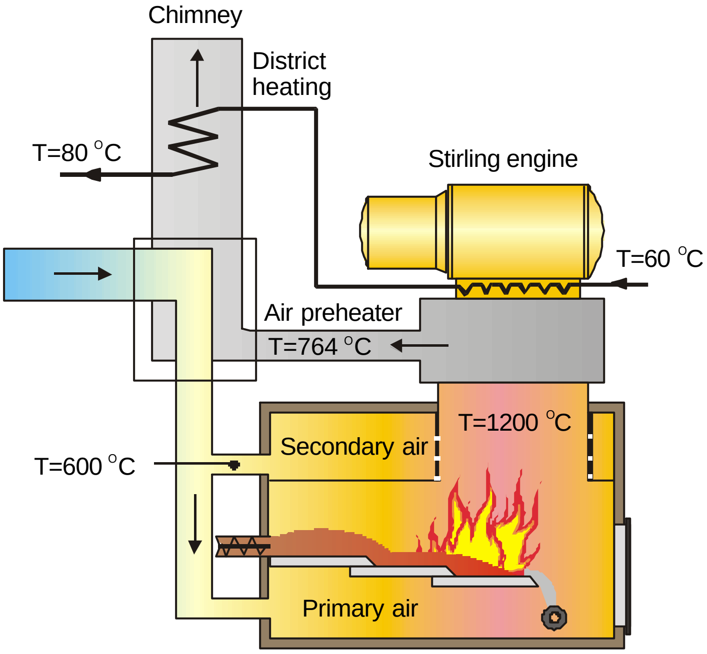


Figure 11. A process diagram of Stirling engine CHP plant.

The results from the tests show that the efficiency calculated as shaft power compared to the heat transferred into the hot heat exchanger without losses in the burner is approximately 35 % at full load. The efficiency of the electricity production is 19 % when water content of wood chips is 40 %. When the Stirling process is utilised in CHP total efficiency is about 87 %. Typically power output is less than 50 kW_e /16/.

In the ORC (Organic Rankine Cycle) a heat source vaporizes organic fluid in a vaporizer, and the vaporized fluid expands in the turbine of a high speed turbo alternator. The expanded vapour is then condensed in a condenser and pumped back to the pressurized vaporizer. The condenser is cooled by a suitable coolant, e.g. in cogeneration by the returning heating water. In Finland technology development is concentrated on high speed technology with high efficiency (power to heat ratio 0.35). The typical output of the plant is 350 – 3 500 kW_e. ORC process is suitable for the electricity production from solid, liquid or gaseous fuels, as well as from waste heat (Fig. 12). There is so far no commercial ORC plant build by biomass.

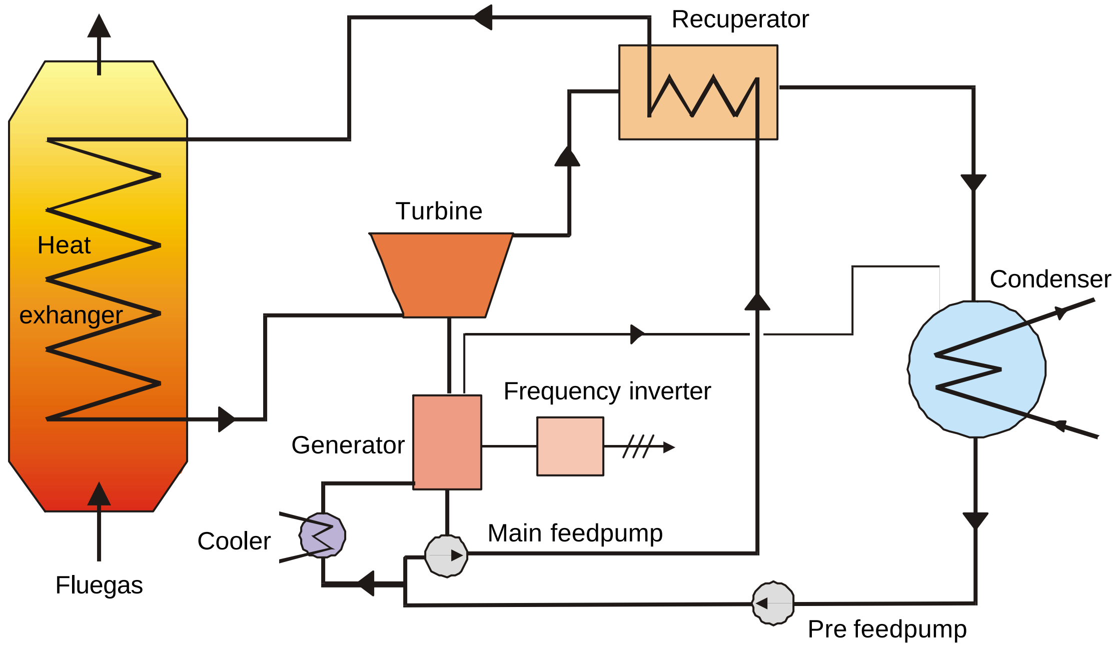


Figure 12. ORC process. Source: Elomatic Papertech Oy.

2.3.4 Anaerobic digestion and engine

The biogas production or anaerobic digestion processes have been developed since the middle of this century, in the beginning as low technology systems for handling agricultural manure types to generate energy, as the second world war and the fifties meant the demand for local produced energy. Anaerobic digestion systems not only became interesting for farm scale biogas plants but also as a result of increasing environmental pollution problems and awareness of these pollution problems, which created environmental problems at lakes, rivers and the total fresh water environment in all countries. This gave the right frame for making investment in waste water treatment plants including anaerobic treatment facilities for removing a bigger fraction of the organic waste, and making energy production. Today the most widespread biogas production in all the EU-15 country is the anaerobic digestion wastewater treatment plants. In Nordic countries mainly in Denmark and Sweden co-digestion of organic wastes and animal manure types, have been developed and there are 20 large-scale co-digestion installations in Denmark (fig. 13). Anaerobic digestion of especially wet biomass and waste is a commercially proven technology. In Europe alone, it is estimated that at least 1700 plants (including small- scale units) are currently in operation. These plants have limited power generating capacity (< 200 kW_e). The reason is that most emphasis placed on processing waste streams, while electric power is considered as a useful by-product, lowering processing tariffs by the sales of power delivered to the grid. Processing of wet biomass in anaerobic digestion system avoids expensive drying for thermal conversion processes /4/.

Anaerobic digestion is the decomposition of wet and green biomass through bacterial action in the absence of oxygen to produces a mixed gas output of methane and carbon dioxide known as biogas. The anaerobic digestion of municipal solid waste buried in landfill sites produces a gas known as *landfill gas* which occurs naturally as the bacterial decomposition of the organic matter continues over time. The methane gas produced in landfill sites eventually escapes into the atmosphere. However, the landfill gas can be extracted from existent landfill sites by inserting perforated pipes into the landfill. In this way, the gas will travel through the pipes under natural pressure to be used as an energy source, rather than simply escaping into the atmosphere to contribute to greenhouse gas emissions /4/.

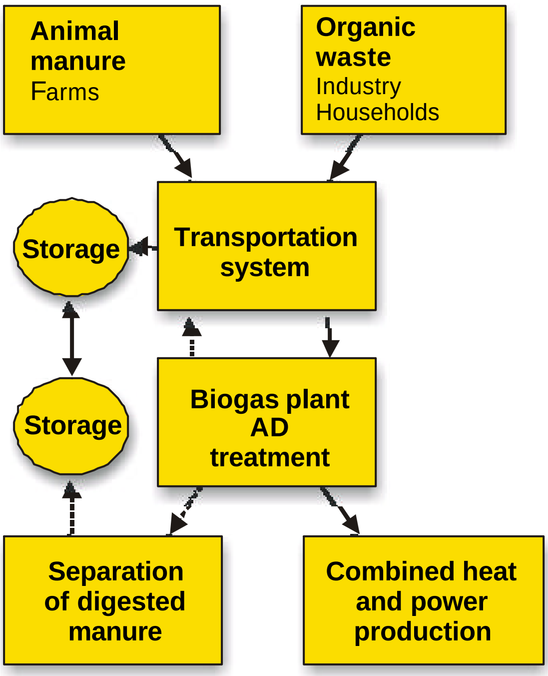


Figure 13. The centralised biogas plant concept /4/.

Biogas is a mixture of gases, mainly methane and carbon dioxide. An average biogas (containing 60 % of methane CH_4) is characteristised by the following parameters: minimal calorific value of about 21 500 kJ/m^3, a flame velocity of about 25 cm/s, a stoechiometric air-fuel ratio of 5,71 and an octane rating of 130. The minimum temperature at which methane shall autoignite lies around 600 ^{o}C. Buffer volume is necessary in most cases, between the moment of biogas production and combustion.

Biogas is most commonly produced using animal manure. Today nearly 600 agricultural biogas plants are in operation in Germany, but farm scale biogas plants are increasing in numbers in Austria, Switzerland and Denmark as well. Animal manure is mixed with water, which is stirred and warmed inside an airtight container, known as a digester. Digesters range in size from around 1m^3 for a small household unit to as large as 2000 m^3 for a large commercial installation. Biogas can also be used in internal combustion engines involving as well as the Otto (spark ignition), the Diesel (compressed ignition) or the Sabathe (mixed) cycles. These engines can be used for mechanical power, or for electrical power generation. When using biogas, cogeneration has proven energy efficiency. The waste heat (up to 70 %) generated by the engine is recovered as hot water.

3 CASE STUDIES

3.1 CAPACITY LESS THAN 100 kW_e

3.1.1 Biogas and engine (Walford College Farm in UK)

The introduction of an anaerobic digestion system, incorporating a combined heat and power unit, has provided Walford College Farm with clean, odour-free and simple-to-operate method of manure treatment. The 260-hectare mixed farm includes a herd of 130 dairy cows plus young dairy stock, 160 pigs and beef cattle. In a year the farm´s livestock produces about 3 000 tonnes of organic manure. In October 1994 an anaerobic digestion system incorporating and Enviropower CHP facility was commissioned as part of a three-year demonstration project. Slurry is fed from a pig and dairy units though channels to a reception pit. A chopper pump then transports the slurry into a 335 m^3 digester sited above ground. Digestion takes 16-20 days, producing 450 m^3/day of biogas, which fuels the CHP unit in heat is recovered from the engine´s coolants and exhaust system. A stand-by boiler is used to heat the digester in the event of failure of the CHP unit, or during excessive and sustained cold weather /3/.

After digestion, the treated slurry is passed over a sieve separator, the fibre is removed and passed to a composting shed and the remaining liquor is fed to a 950 000 litre storage tank. It is planned to use the farm´s existing irrigation main to transfer the liquor onto the grass fields /3/.

The CHP unit is rated at 35 kW_e and 57 kW_{th} output. Actual out averages 18.22 kW_e for 19.5 hours/day. About 30 kW_{th} is harnessed to maintain the digester at the require temperature of 35 –37 ^oC. The system also produces 15 m^3 /day of liquor and three tonnes/day of separated fibre. The electricity generated is worth EUR 27 200/year, and hot water, valued at EUR 4 185/year, is produced. Capital costs were 212 800 EUR /3/.

3.2 CAPACITY MORE THAN 100 kW_e, BUT LESS THAN 1000 kW_e

3.2.1 Grate combustion and steam engine plant (IPO Wood-Iisalmen Sahat in Finland)

Effective and low emission firing of residuals from sawmills and other wood processing plants can be achieved with advanced combustion technology only. In Finland a new type of grate combustion method – underfeed rotating grate - for wet wood fuels have been developed (fig. 4).

Advantages of underfeed rotating grate are /2/:

- simple and reliable operation
- high moisture levels for fuels up to 65 %
- fuels can be wood chips, bark, sawdust or processed wastes
- capacity range is 1 – 10 MW

Iisalmen Sahat Oy (IPO Wood) is a private sawmill, established in 1922. The total production of the sawmill is about 8 000 m^3 sawn wood a year. In Kiuruvesi an underfeed rotating grate fired boiler producers steam for steam engine (Fig 14). After the engine the steam is led to a heat exchanger to produce district heat. Condensed water is pumped back to the steam boiler. Kiuruvesi generates about 42 GWh heat. More than 90% of the heat is sold to Savon Voima Oy, which is responsible for district heat service for Kiuruvesi Town. The design power of the new CHP plant is about 5 GWh. The total investment costs in the CHP plant of Kiuruvesi Timber Oy amounted to 2.7 MEUR in 1999. About a half of the investment focused on power production equipment. Sermet Oy was responsible for the delivery of the whole system and the construction work took about half a year. Investment costs were reduced both by simplifying technology and by modular constructions. Different components are assembled to as big units as possible at Sermet´s engineering works. The second Sermet BioPower plant started operation in 2000 in Karstula (10/1 MW) and plant is using wood residues (cutter shavings, bark and sawdust, 70 GWh/a) from the loghouse company Honkarakenne Oy. The plant produced 3 MW process steam and 3 MW heat for Honkarakenne and 3 MW district heat for Karstula town /2/.

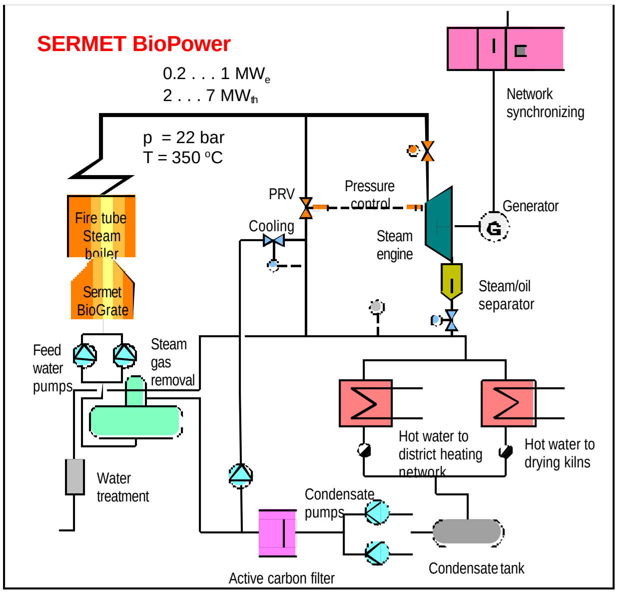


Figure 14. CHP production in small scale. Sermet Oy.

The technical data is summarised in Table 2.

Table 2. Technical data of Kiuruvesi power plant (IPO Wood) /2/.

Power generation	0,9 MW_e
Heat for district heating	6 MW_{th}
Fuel input	8,1 MW_{fuel}
Fuels	bark, sawdust with mixing ratio usually 60% sawdust and 40% bark Forest chips Moisture content 50-65%
Net electrical efficiency (LHV)	11 %
Total net efficiency (LHV)	85 %
Steam pressure	25 bar, 10 t/h
Steam temperature	350 °C

LHV=lower heating value

3.3 CAPACITY MORE 1 MW_e BUT LESS THAN 10 MW_e

3.3.1 Kuhmo power plant in Finland

The first Pyroflow Compact (circulating fluidized bed) started operation in Kuhmo, Finland, in 1992 for combined heat and power generation. The Kuhmo plant is of the second generation circulating fluidised bed combustion. The combustion chamber, the solids separator and the convection surfaces are of one compact construction, instead of having a separate cyclone solids separator as previously. The integrated structure results in a smaller plant size. This new Pyroflow Compact boiler need no sand separation cyclones. The traditional un-cooled cyclone following combustion chamber has been replaced with a cooled solids separator. Consequently, a boiler start-up and shut-down time than previously is obtained as a result of a thinner refractory lining in the cooled solids separator design.

The electric output of the plant is about 5 MW, district heat for Kuhmo city and process heat for Kuhmo Sawmill is 13 MW_{th}. Table 3 summarises the technical data of Kuhmo power plant.

Table 3. Technical data of Kuhmo power plant

Power generation	4,8 MW_e
Heat for district heating and process heat	12,9 MW_{th}
Thermal output	18 MW_{th}
Fuel	Industrial wood residues
Net electrical efficiency (LHV)	24 %
Total net efficiency (LHV)	88 %
Steam pressure	81 bar
Steam temperature	490 ^oC

3.3.2 Integrated gasification combined cycle in Värnamo, Sweden

The Värnamo Demonstration Plant is the first of its kind in the world. The plant is aimed at demonstrating the complete integration of a gasification plant and a combined cycle plant fuelled by biomass. The basic idea is to demonstrate the technology rather than to run a fully optimised plant /16/.

The fuel is dried in a separate fuel preparation plant, using a flue gas dryer, to a moisture content of 5 – 20 %. A simplified process diagram and a cross section of gasification plant are shown in figure 9.

The dried and crushed wood fuel is pressurised in a lock-hopper system to a level which basically is determined by the pressure ratio of the gas turbine, and is fed by screw feeders into the gasifier a few meters above the bottom. The operating temperature of the gasifier is 950 – 1000 ^oC and pressure is approximately 18 bar (a). The gasifier is of a circulating fluidized bed type and consists of the gasifier itself, cyclone and cyclone return leg.

The fuel is pyrolyzed immediately on entering the gasifier. The gas transports the bed material and the remaining char towards the cyclone. In the cyclone most of the solids are separated from the gas and are returned to the bottom of the gasifier through the return leg. The re-circulated solids contain some char, which is burned in the bottom zone where air is introduced into the gasifier. The combustion maintains the required temperature in the gasifier. After the cyclone the gas produced flows to a gas cooler and a hot gas filter. The gas cooler is of a fire tube design and cools the gas to a temperature of 350 – 400 ^oC. The gas enters the candle filter vessel where the particulate clean-up occurs. Ash is discharged from the candle filter and from the bottom of the gasifier, and is cooled before entering the de-pressurization system.

The gasifier is of an air-blown type. Thus about 10 % of the air is extracted from the gas turbine compressor, further compressed in a booster compressor, and finally injected into the bottom of the gasifier. The gas generated is burned in the combustion chambers and expands through the gas turbine, generating electricity. The turbine is a single-shaft industrial gas turbine. The fuel supply system, fuel injectors, and the combustors have been re-designed to suit the low calorific value gas (5 MJ/m^3_n).

The hot flue gas from the gas turbine is ducted to the heat recovery steam generator, where the steam is generated, along with steam from the gas cooler, is superheated and is then supplied to a steam turbine (40 bar, 455 °C). The technical data is summarised in Table 4.

Table 4. Technical data of Värnamo gasification combined cycle power plant

Power generation	6 MW_e
Heat for district heating	9 MW_{th}
Fuel input	18 MW_{fuel} (85 % ds)
Fuel	Wood chips
Net electrical efficiency (LHV)	32 %
Total net efficiency (LHV)	83 %
Gasification pressure	20 bar (a)
Steam pressure	40 bar
Steam temperature	455 °C

LHV=lower heating value

3.3.3 The Arable Biomass Renewable Energy (ARBRE) in UK

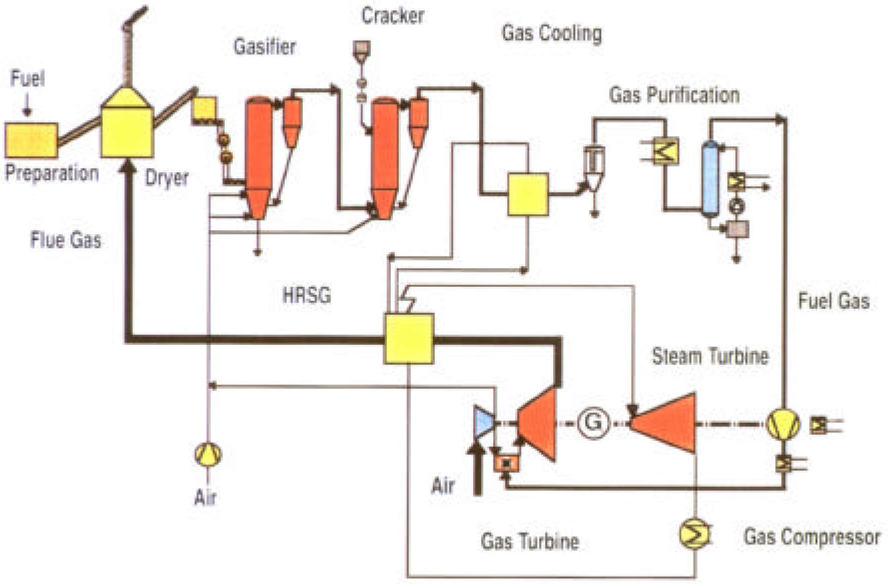


Figure 15. Process diagram of Arable plant. TPS process.

Biomass integrated gasification combined cycle (BIG-CC) employs a biomass gasifier, a gas turbine and a steam turbine using the generated by the heat from the gas turbine exhaust (Fig. 15) /16/.

Wood, being a young fuel, has a higher hydrogen/carbon ratio, and oxygen/carbon ratio than older fossil fuels. This results in a higher gasification yield of both gases and hydrocarbons such as tars. The amount and composition of the tars is depended on the fuel, the pyrolysis conditions and the secondary gas phase reactions. These tars are not problematic if they do not polymerise or condense /16/.

In the patented TPS process the tars produced in the gasifier are cracked catalytically to simpler compounds in a dolomite-containing CFB vessel located immediately downstream of the gasifier. This tar conversion process does not result in any significant reduction in the chemical energy of the gas. By converting the tar into líghter compounds the gas can be cleaned of particulates and alkalis in conventional gas cleaning equipment /16/.

The biomass gasification combined-cycle process includes:

- air blown gasification in an atmospheric pressure circulating fluidised bed (CFB)
- tar cracking by utilising a dolomite catalyst in a secondary CFB system
- final gas cooling and cleaning in a filter/scrubber unit
- gas compression in multiple stage compressor, gas combustion and expansion in a gas turbine
- exhaust gas heat recovery by steam generation and fuel drying
- electricity generation by gas turbine and steam turbine generators

Gas turbine has an output of 4.75 MW_e and the steam will power a 5.25 MW_e steam turbine. Exhaust gas will be utilised to provide heat for wood chip drying. The net electrical output of the plant shall be 8 MW with an overall net efficiency (LHV) of 30 %. At larger scale, say 30 MW, overall net efficiencies of more that of 40 % can be achieved /16/.

3.4 LARGE SCALE (10 MW_e – 240 MW_e)

3.4.1 Municipal district heating plant Forssa (BFB boiler and steam turbine including auxiliary condensing, boiler 66 MW_{th})

Figure 16. Forssa CHP plant using wood chips and wood residues /2/.

The Forssa biopower plant is the first CHP district heating power plant in Finland fuelled only by wood biomass (Fig. 16 and 17). It is a counterpressure plant with a boiler specifically adapted for the use of solid biofuels /2/.

The main fuels are residues from wood processing industry such as sawdust and bark (54%), together with forest chips (34%;), building wastes and other wood-containing substances. In addition the plant is using 4% REF fuels from the neighbouring waste treatment plant. The total use of solid fuels has been 720 TJ (200 GWh) in 1999. Wood chips are acquired from an area within a radius of 50 km from Forssa. Forest chips are harvested in integration with merchantable wood. Residues from the logging sites are heaped when cutting timber. A terrain chipper with a 10-20 m^3 bin bin chips logging residue at site. The chipper hauls the chips into lorry trailers at the roadside. The trailer lorries transport the chips to the power plant. In wintertime the moisture content of fresh wood chips is more than 50%. More than 95% of chips are less than 45 mm in size, and there are no over-sized objects or knots among the chips. Hot corrosion, possibly due to chlorine from green chips, has been studied in Forssa. Part of superheater pipes must be replaced yearly. The biofuels are mainly stored in the large storage field of the plant.

The surface area of the asphalted storage field is about one hectare. The maximum size of the stockpile is about 70 000 in the autumn, and the target is to exhaust it by the summer. The storage field also serves as quality homogenizer, as different fuels – bark, sawdust, forest chips-are stored at layers. The storage is compacted with bulldoze and this prevents heating, self-ignition and energy losses. Compacting enables lorries to drive and unload on top of the stockpile. Part of the fuels is stored unmixed in separate heaps in the storage field /2/.

.Table 5. Technical data of Forssa district heating power plant /2/.

Power generation	17,2 MW_e
Heat for district heating	48 MW_{th}
Fuel input	71,7 MW_{fuel}
Fuel	Wood chips, industrial wood residues (sawdust, bark etc.), recycled fuel
Net electrical efficiency (LHV)	24 %
Total net efficiency (LHV)	91 %
Steam pressure	62 bar
Steam temperature	510 ^oC

The fuel is burnt in a fluidised bed furnace. The height of the boiler is 20 m and the cross-sectional area 25 m^2. In the furnace the separate sand bed acts as a grate through which preheated air is blown. The fuel ignites and burns when it is supplied to the glowing fluidised sand layer. Additional air required for combustion is blown in through air ducts above the bed. One advantage of fluidised bed combustion over other is the low burning temperature (800–850 ^oC) that gives low nitrous oxide emissions. When wood fuel is used, no sulphur dioxide emissions take place. The average efficiency of the boiler was 91.5% in 1999. The total investment in the plant was 17.1 MEUR in 1996. Of this, 1.3 MEUR was due to the construction of the district heating network. Specific investment for electric power is about 925 EUR/kW_e, which may be considered relatively low for a power plant of this size class. The investment costs of fuel handling system until the feed of boiler bins were 1.1 MEUR, i.e. 7% of the total costs. The total costs of boiler delivery amounted to 4.9 MEUR, i.e. 28% of the total investment costs of the plant. The total maintenance costs of the plant range 50 000 – 67 200 EUR/a. The operation time of the plant has been on average 311 days a year in recent years /2/. The technical data is summarised in Table 5

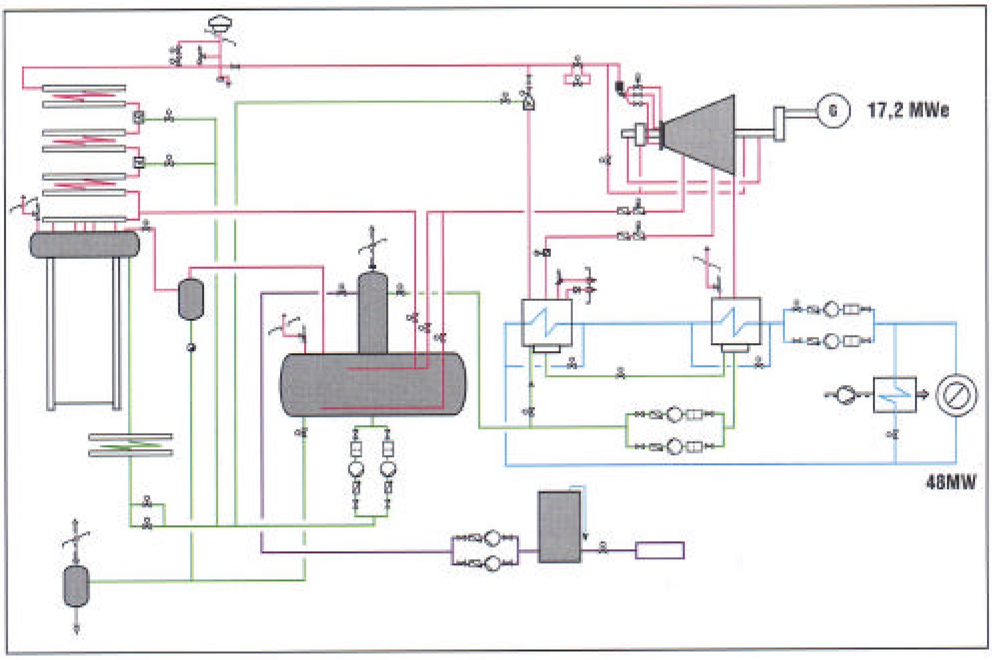


Figure 17. Process diagram of the Forssa CHP plant (Rankine power plant) /2/.

3.4.2 Grenå straw and coal-fired CFB boiler

Straw is a biomass with substantial energy potential in many countries. The 80 MW_{th} CHP plant in Grenå, Denmark is based on cofiring straw and coal. The plant, in operation since the beginning of 1992 has achieved high availability, showing that straw can be used in power generation in an efficient and environmentally acceptable manner. Straw contains high proportions of alkaline and chlorine and is accordingly classified as a difficult fuel in combustion. Severe fouling and superheater corrosion were encountered during initial operation at Grenå. The corrosion problem was solved through the adjustments in superheater equipment. The fouling tendency was checked with lowering combustion temperature and adjusting the composition of the bed to avoid alkaline accumulation /2/.

The plant has made an agreement with an association of farmers – Djursland Halmsammenslutning – for annual straw deliverance. Straw for the plant has to be compressed into bales of the physical size defines as big bales. The cross dimension of a big bale is app. 120 x 130 cm and has a length of app. 240 cm. Average weight of a big bale is app. 500 kg. The maximum acceptable moisture content is straw is 24% (usually 15-17%). The plant is also using also dry biomass fuels like pellets, residues from sunflower oil production and other agricultural residues. Total fuel utilisation is 1 917 TJ of straw represents 42%, coal 43% and dry biomass fuels 14% and oil 1%. The annual supply of straw is almost 55 000 tonnes. Straw bales are placed by the crane at the indoor storage, where each of the sections are capable to accommodate 880 bales (Fig. 18). The weighting and measuring of the moisture content of the plant is automatised. The straw is shredded into size of less than app. 5 cm /2/.

The boiler in Grenå is a circulating fluidised bed type and it is designed for operation with a fuel mixture up to 60% straw or with coal alone. The temperature in furnace is kept in the range of 820 – 830 °C in order to avoid slagging. Total investment costs of the plant were 55 MEUR in 1992 /2/. The technical data is summarised in Table 6.

Figure 18. The traversing table has picked up a bale from the right and passes it now on to a vacant feeder line to the left /2/.

Table 6. Technical data of Grenå cofired power plant /2/.

Power generation	18.6 MW_e
Process heat and district heating	60 MW_{th}
Boiler output	85 MW_{th}
Fuel	straw, coal
Net electrical efficiency (LHV)	17/(80/0,9) =19 %
Total net efficiency (LHV)	86 %
Steam pressure	92 bar
Steam temperature	505 °C
Flue gas cleaning	in-bed desulphurisation by limestone injection and electrostatic precipitator

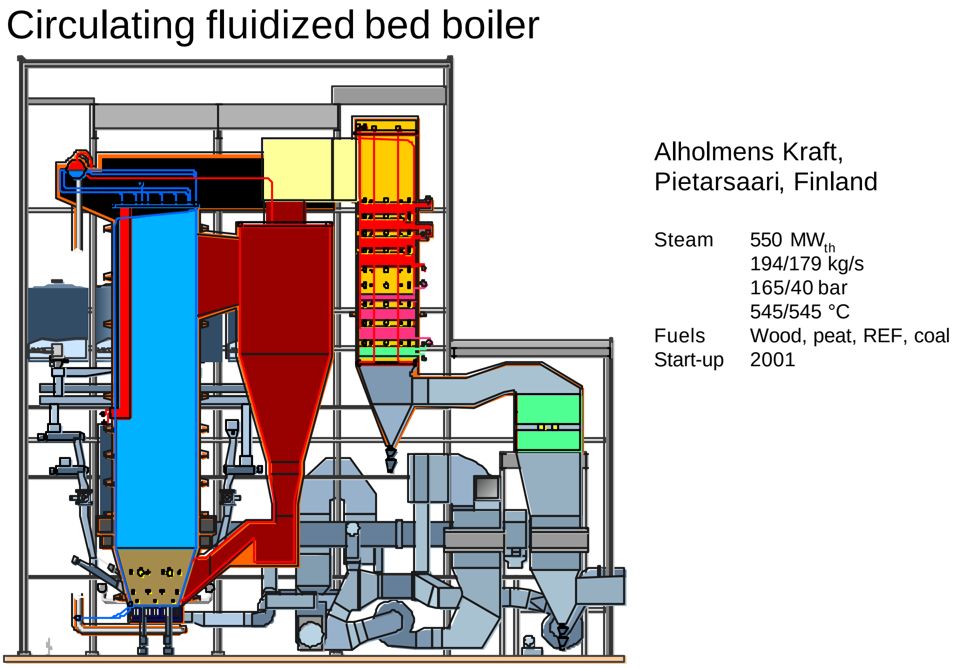
3.4.3 Alholmens Kraft (multifuel CFB boiler forest residues, industrial wood residues, peat and REF, boiler 550 MW_{th} and electricity 240 MW_e)

The world largest biofuel-fired circulating fluidised bed boiler is to be built at the new Alholmens Kraft power plant at Pietarsaari on the west coast of Finland. The power plant is combined plant for producing heat and power. It will supply process steam for the nearby UPM-Kymmene Wisaforest pulp and paper mill and for district heating in the city of Pietarsaari.

When commissioned in the autumn of 2001 the boiler will be one of the largest CFB boilers in the world and by far the world´s largest biofuel-fired CFB boiler.

The Alholmens Kraft CFB boiler is a multifuel boiler whose main fuels include bark, peat and wood residues (Fig. 19). Annual fuel utilisation is 12 600 TJ of which wood presents 40%, peat 45% and coal 15%. The plant is designed for flexible fuel utilisation (100% biomass or 100% coal).

The plant is aimed to use 150 000 – 200 000 m^3 solid of logging residue annually. The logging residues are hauled to the plant as loose material or as bales. The aim is develop new logging residue harvesting method, where the logging residues are baled in the stand (Fig 1). The main idea is use traditional timber harvesting equipment. For forest residue haulage a load of the forwarder has been increased from 4.3 m^3 solid to 7.8 m^3 solid by using a special, wider-than normal load space. A forest entrepeneur working for UPM Kymmene has acquired a baling machine (Fiberpack 370) and it is now in commercial use. It produces some 20 bales per hour. One bale has a volume of about 0.5 m^3 solid (450 – 500 kg, 3.3 metre long). An ordinary timber truck is used and it can take 60 to 70 bales at one load. The bales or loose logging residues are chipped at the plant. The production costs of the baling methods are estimated by the first research studies carried out by Metsäteho to be about 45 – 55 FIM/MWh (7.5 – 9.2 EUR/MWh) when the maximum transportation is 80 km and forest haulage 300 m. Annual working period is 10 months and working is be carried out in two shifts.



Circulating fluidized bed boiler

Alholmens Kraft,
Pietarsaari, Finland

Steam	550 MW_{th} 194/179 kg/s 165/40 bar 545/545 °C
Fuels	Wood, peat, REF, coal
Start-up	2001

Figure 19. Boiler of the Alholmens Kraft. Kvaerner Pulping.

The technical data is summarised in Table 7.

Table 7. Technical data of the Ahlholmens Kraft plant.

Power generation	240 MW_e
Heat for process heat and district heating	100 MW_{th} process steam and 60 MW_{th} district heat
Fuel input	580 MW_{fuel}
Fuels	bark, peat, wood residues, sludge, coal
Steam pressure	165/37 bar
Steam temperature	545/545 ^oC

3.4.4 Lahti, Kymijärvi municipal CHP plant (40-70 MW gasifier connected to 350 MW boiler fuelled by coal and natural gas)

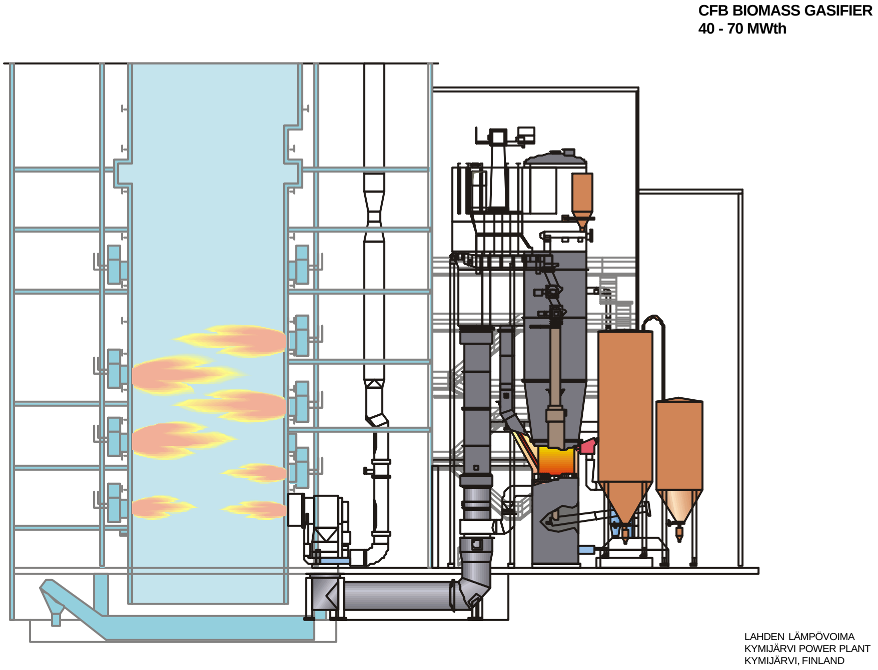


Figure 20. Biomass CFB gasifier connected to a 350 MWth steam boiler with coal and natural gas – Thermie demonstation project in Lahti , Finland. Foster Wheeler /2/.

Lahden Lämpövoima Oy is a municipal energy company. The Kymijärvi plant of Lahden Lämpövoima Oy has a coal and natural gas fired boiler with 350 MW$_{th}$ output. Boiler is Benson – type once trough boiler. The plant started THERMIE project in 1996 to demonstrate on a commercial scale the direct gasification of wet biofuel and the use of hot, raw and veerly low calorific gas immediately in the existing coal-fired boiler. The effect of the atmospheric CFB-gasifier is 40 – 70 MW$_{th}$ and the fuels are different types of solid biofuels and recycled fuel (REF) from source separated waste (Fig. 20). The capacity of the gasifier depends on moisture content of the fuel /2/.

The CFB gasifier consists of the inside refractory-lied steel vessel, where the fuel is gasified in a hot fluidized gas-solid particle suspension. In the gasifier biofuels and REF will be converted to combustible gas at atmospheric pressure at the temperature of about 850 ^{o}C. The hot gas flowing through the uniflow cyclone will be coolded down in the air preheater before it is fed into the main boiler. Simultaneously, the gasification air will be heated up in the air preheater before feeding it into the gasifier /2/.

The fuel does not need to be dried in this application, but the moisture content of the fuel can be up to 60 %. From the mechanical and piece of equipment point of view some changes compared to the standard atmospheric biomass gasifier have been made. This is due to the special nature of some of the fuel components /2/.

Concerning the product gas combustion the hot gas is led directly from the gasifier through the air preheater to two burners, which are located below coal burners in the boiler. The gas is burned in the main boiler and it replaces part of the coal used in the boiler. When the fuel is wet, the heating value of the gas is very low. Typically when the fuel moisture is about 50 %, the heat value of the gas is only approximately 2.2 MJ/kg /2/.

The boiler used about 180 000 tonnes (5760 TJ/a) coal and about 1 440 TJ natural gas. In 1999 the gasifier plant used 1249 TJ fuels of which the wood residues presented 57% and REF 42%. The recoved fuel (REF) includes plastics, wood, and paper and cardboad waste. At the moment there are 50 different fuel suppliers and approx. 100 different fuel types /2/.

The total investment was 12 MEUR. The estimated payback time is approx. 10 years. Operational and maintenance costs are approx. 0.5 million EUR/a. The maintenance costs for fuel handling are about 200 000 EUR/a and for the gasifier about 62 000 EUR/a. The operating experiences of the year 1998 and 1999 have been good. Only a few problems occurred at the gasification plant and the availability of the plant has been high since the beginning of operation in 1998. Most of problems are related to the fuel processing and feeding. The gasifier and the overall cocombustion concept have been proven to work technically very well /2/.

4 ECONOMICS OF BIOMASS CHP

CHP plants are built in Finland for financial gain. Cogeneration must be cheaper than the acquisition of corresponding amounts of power and heat with other methods. The profitability of different alternatives must be assessed for the whole life expectancy of a power plant. It is normally more costly to build but cheaper to operate a CHP plant than a plant employing other production methods. The owner of the power plant may consume the power and heat, or they may be sold to other customers /11/.

The environmental protection costs of power plants affect the economy of a CHP pant and its alternatives. Finland imposes the same environmental requirements on CHP plants as on other power or heat production plants of a corresponding size.

Cogeneration usually requires larger investments than alternate power and heat production methods. The counterbalance is a smaller consumption of primary energy. Therefore, the production costs of CHP may be lower than those of other generation forms.

The economy of a biomass fired CHP plant and the profitability of the investment in the plant depends to a great extent on local conditions such as the heat consumers, the volume and permanence of the heat load, and the price of the available fuels.

The smallest size scale for CHP plants usually based on fluidised bed combustion to be commercially viable today in Finland is usually about 20 MW of district heat, i.e. 6

MW_e of electricity. In last two years also two plants in which electricity capacity is less 1 MW_e, has been built in two mechanical wood industry sites. In these cases the State is supporting investments costs and also the electricity production is very import. In Finland the support of wood fuels are presented in table 8 /8/.

Table 8. Maximal influence for wood fuels based on the state supports in Finland in 2001. FIM/MWh (EUR/MWh) /8/.

	Heat production FIM/MWh (EUR/MWh)	Heat and power production, CHP plant FIM/MWh (EUR/MWh)		Only electricity production, condensing plants
		Municipal plants	Industry	
Wood fuel harvesting from young stands	14 (2.35)	14 (2.35)	14 (2.35)	14 (2.35)
Support of chipping	12 (2.02)	12 (2.02)	12 (2.02)	12 (2.02)
Investment support 30 %	14 – 8 (2.35 – 1.34)	12 – 9 (2.02 – 1.51)	8 – 6 (1.34 – 1.0)	8 (1.34)
Electricity production support or taxation in heat production	Energy taxes for peat 9 (1.51), coal 35.2 (5.92) heavy fuel oil 28.4 (4.78), natural gas 10.3 (1.73) and light fuel oil 37.9 (6.39)	5– 7 (0.84 – 1.18)	3 – 5 (0.50 – 0.84)	10 (1.68)
Total	40 – 34 (6.73 – 5.72)	43 – 42 (7.23 – 7.06)	37 (6.22)	44 (7.40)

The economic size limit has come down during the last 5 – 10 years due to the technological achievements and the fuel cost reduction. On example in Finland shows how the investment cost of a CHP plant has dropped to one third during the period of 1979 to 1991 (fig. 21). The price of biomass fuels (mainly wood fuels) has reduced because of the improved wood fuel harvesting technology (see fig. 22) /12,14/.

In the following cost surveys the price of wood fuel is typically 45 FIM/MWh (2.1 EUR/GJ), which is quite average fuel price of wood fuels in Finland today. In some studies also lower and higher fuel prices have been used.

In size scale of 6 MW_e with peak operating time of 4000 hours per year, investment aid is 10–20 % makes the CHP electricity generation using solid biomass fuels economically feasible. The district heat production is valued according to an optional production method of district heat. The investment cost of a 3 MW_e CHP plant is at a level of 2000 EUR/kW_e, 6 MW_e of 1500 EUR/kW_e and for a 17 MW_e 1200 EUR/kW_e. Thanks to low fuel price of industrial wood residues and the long annual operating time, the price of electricity generated at CHP plants in the forest industry can very profitable in Finland (fig. 23 and app.1 /12/). Finnish District Heating Association has studied also the real investment costs for heat production (fig. 24) /9/.

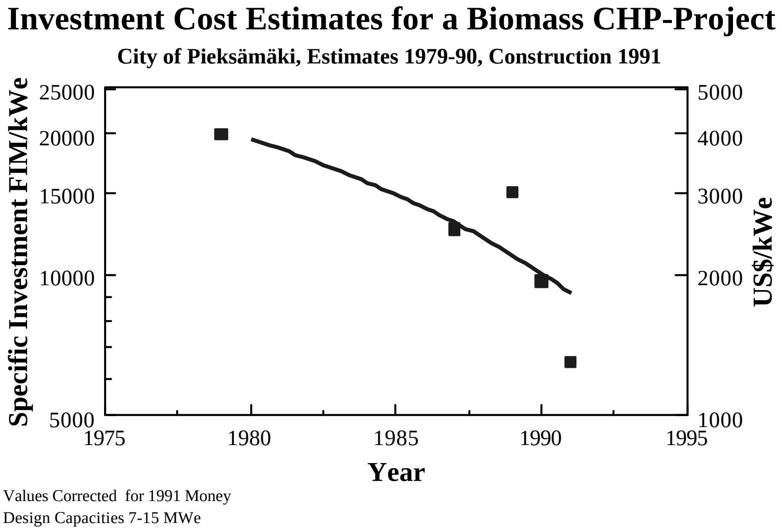


Figure 21. Reduction of investment cost in Finland – case Pieksämäki CHP plant. /17/.

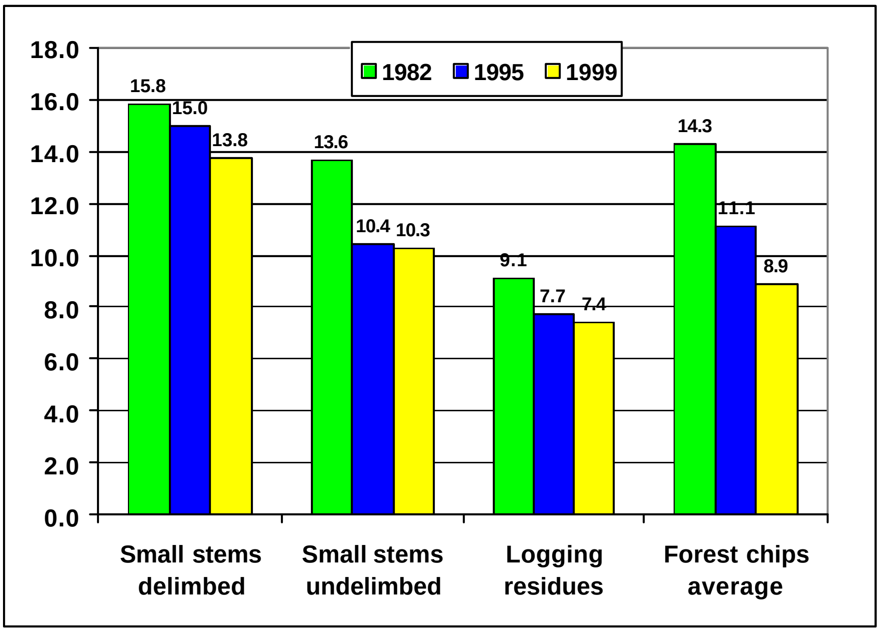


Figure 22. The development of the prices of forest chips in Finland (EUR/MWh, VAT excluding)/12/.

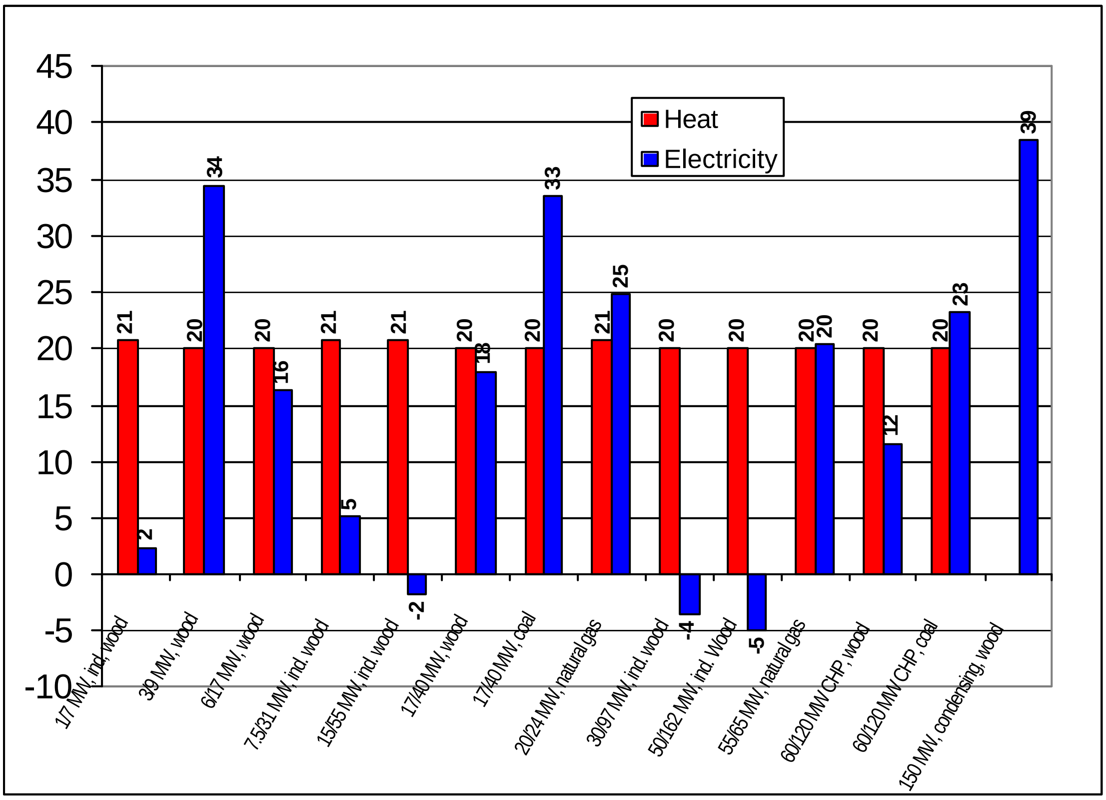


Figure 23. Production costs of electricity and heat in Finland in different CHP plants in 1999 (EUR/MWh) /14, app.1 .

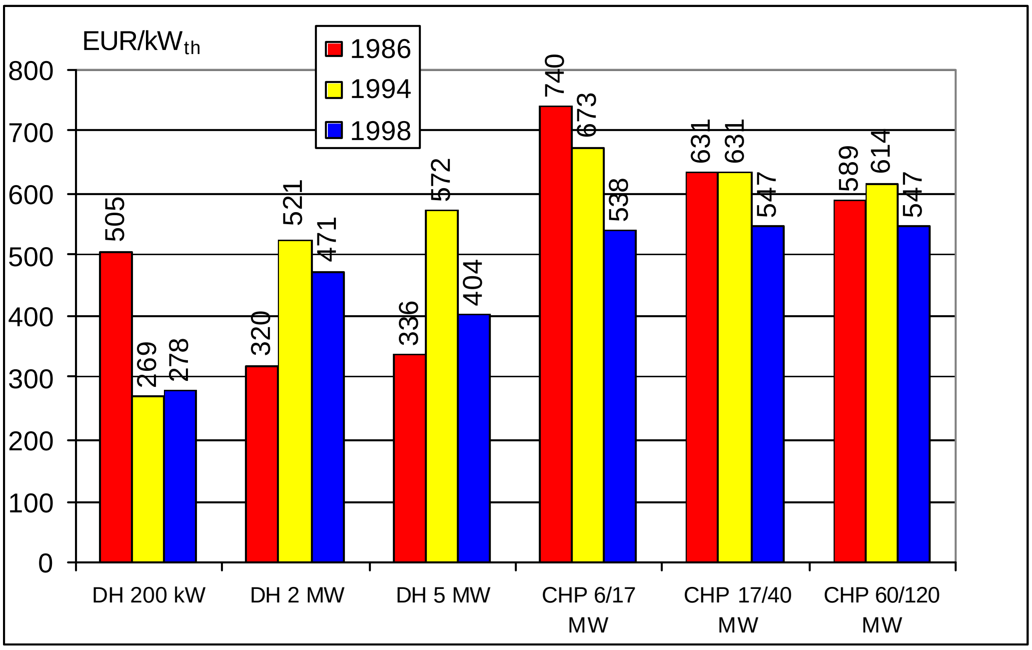


Figure 24. Specific investment costs (EUR/kW$_{th}$) of real biomass DH and CHP plants in Finland in 1986, 1994 and 1998 (1 EUR=5.94573 FIM). Source Finnish District Heating Association.

VTT Energy has also studied as a part of IEA task the CHP production costs. A study of small scale power production from woody biomass was carried out within the IEA Bioenergy Task "Techno-Economic Assessments for Bioenergy Applications". The study was carried out comparing production of electricity at 2 MW_e. The scale was selected to study /17/:

- how well the commercial steam boiler power plant competes with the new power plant concepts especially in the small scale
- what is the future estimates for cost and performance of the new concepts.

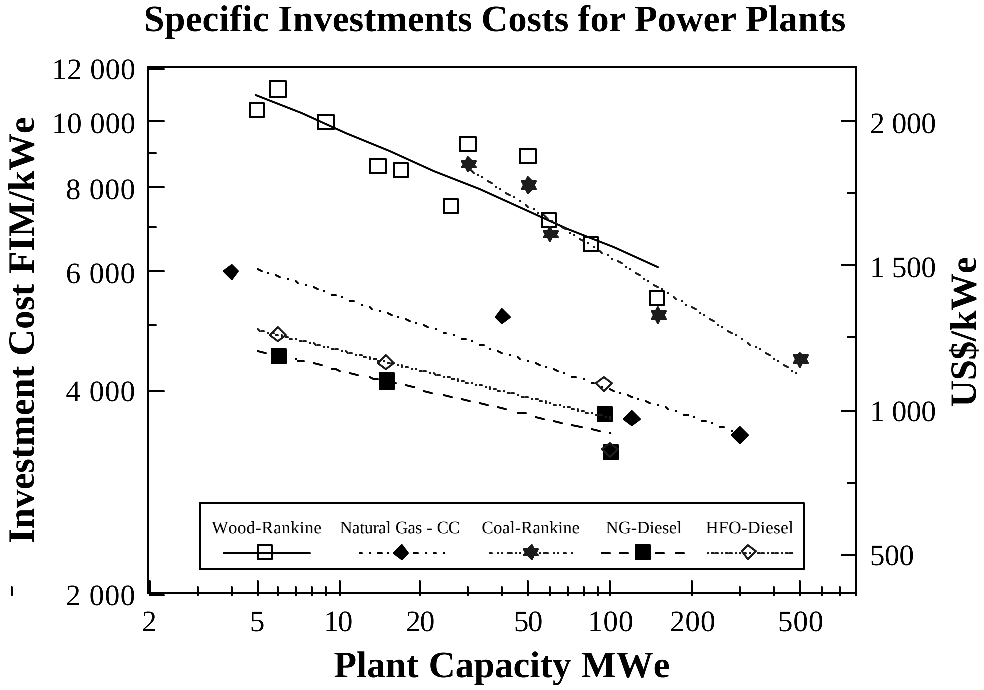
The systems compared were

- the Rankine steam boiler power plant
- the gas engine power plant using gasification fuel gas. The gasifier and the engine are integrated.
- the diesel power plant using fast pyrolysis liquid as a fuel. Liquid production and the power plant are de-coupled.

Overall efficiencies for these systems are: the Rankine cycle 17.5%, gasification - gas engine 23.9%, and pyrolysis - diesel engine 24.7%. Potential improved efficiencies for the three technologies are 23, 32.4, and 31.5%, respectively. Estimated specific investment costs for the base power plants are 2 100, 3 800, and 3 300 EUR/kW_e, respectively /17/.

It is shown that the Rankine cycle is superior compared to the gasification gas engine and pyrolysis diesel engine with current cost data. Increasing fuel cost 50% from the base value FIM 45/MWh (EUR 2.1/GJ) improves the competitiveness of new concepts, but the Rankine is continuously more economic over the whole annual operation time. At high fuel costs, the difference between the diesel and the Rankine is negligible below 4 000 h/a. In a very long-term operation time, the gas engine is not much more expensive than the Rankine power plant. Differences between the alternatives are fairly small over the whole range, where improvements for technologies are assumed valid. The range of variation with the Rankine and the least-cost new cycle is about 10%, which is not a significant difference within the accuracy of the study. It is shown that cogeneration improves the economics of small-scale power production considerably. The Rankine cycle remains as the least-cost option in all cases studied /17/.

It is concluded that for the new power plant technologies to be competitive compared to the Rankine cycle, especially capital costs have to be reduced. Without such reductions it will be hard to compete with the Rankine cycle in a small scale either in power-only or co-generation mode of operation /17/.



Costs in Finland 1994-1997

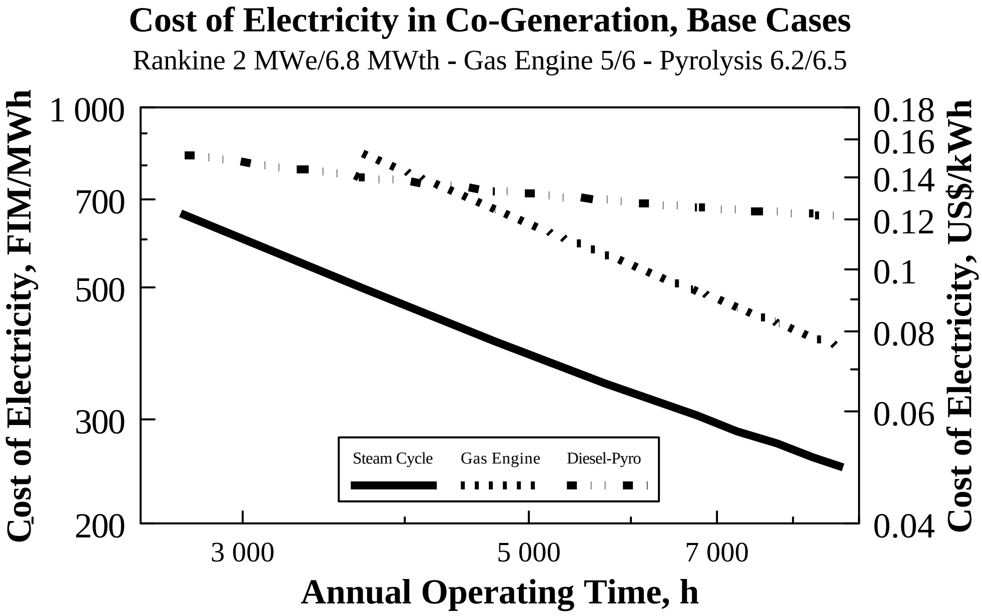
Figure 25. Specific investment costs of power plants. Costs shown for 1994-1997. Both built and planned costs shown. 1 US$=0.91 EUR) /17/.

The three technologies are also compared in combined heat and power production, CHP, Figure 26). District heat production is assumed. The heat production capacity for each case is fixed at about 6 MW_{th}, and the power production capacity is determined based on power-to-heat ratio of the individual technology. This approach for comparison is selected because the CHP plants are sized based on the heat demand /17/.

The performances of the cases are summarised in Table 9. Again, improved future concepts are shown with performance values, which are believed to be feasible in the near future /17/.

Table 9. Summary of the performance of the CHP plant concepts /17/.

	Rankine power plant		Gasification - gas engine		Pyrolysis diesel	
	Base	Future	Base	Future	Base	Future
Power production MW_e	2.0	2.0	5.0	5.0	6.2	6.2
Heat production MW_{th}	6.8	5.8	6.0	5.7	6.5	6.5
Power production efficiency %	17.5	23.0	23.9	32.4	24.7	31.5
Overall efficiency %	88.0	90.0	85.0	90.0	58.5	66.0
Power to heat ratio	0.30	0.35	0.83	0.88	0.95	0.95



Wood Fuel 45 FIM/MWh (2.3 US$/GJ), Pyrolysis Liquid 219 FIM/MWh (11.1 US$/GJ)
Heat Cost - Fixed 155 FIM/MW, a - Variable 55 FIM/MW

Figure 26. The three technologies compared in small scale cogeneration (1 US$=0.91 EUR) /17/.

VTT Energy has also calculated *economy of the different type of gasification processes* based on new fixed-bed gasification technology developed in Finland (Novel gasification) /15/. The performance and investment costs of the three size classes studied are presented in Table 10. The performance and costs of the reference conventional steam-cycle-based power plant (= Rankine) were taken directly from a study made by Electrowatt-Ekono for the Finnish market situation /14, app.1/.

The rather high electric efficiency (based on the lower heating value of biomass with 50 % moisture) of the Novel gasifier-engine plant is achieved by effective utilisation of heat recovered in gas cooling and in condensing scrubber. This heat is used primarily for preheating the gasification air and for fuel drying /15/.

The cost of electricity was then calculated as a function of the annual operation time. The prices of biomass fuel and produced heat were used as parameters. The lowest fuel price of 0 EUR/MWh corresponds to a situation where there is no other use for a biomass residue, the medium price of 5 EUR/MWh is a typical price for bark and wood residues in Finland and the highest prices of 10 EUR/MWh corresponds to specially produced high-quality energy wood chips /15/.

Two prices for the produced heat were also studied: zero price for a case that only electricity is produced and a medium price corresponding to the average price of small-scale district heating plants in Finland. Fully automatic operation was assumed both for the gasifier-engine plants as well as for the reference steam cycle power plant. The operating costs were calculated on the basis of one full-time worker. The capital costs were calculated employing 5% interest rate and 20 year service time /15/.

Table 10. The estimated performance and total investment of the Novel gasification-engine power plant in three size classes /15/.

Size, kWe	Steam cycle	580	1 200	2400
Wood input, MJ/s (LHV based)[1]	5.6	1.7	3.3	6.7
Net power output, MW_e	1.0	0.58	1.2	2.4
Heat production, kJ/s	4.0	0.87	1.73	3.55
Electricity efficiency, %	17.5	34.0	36.0	36.0
Heat efficiency, %	71.5	51.0	52.5	53.0
Total efficiency, %	89.0	85.0	88.5	89.0
Total investment, MEUR	2.84	1.8[2]	2.5[2]	3.6[2]
Relative investment, EUR/kW_e	2 840	3 100	2 100	1 500
Relative investment, EUR/fuel-kW	510	1 060	750	540

[1] based on wood with 50% moisture, drying to 20% before gasification

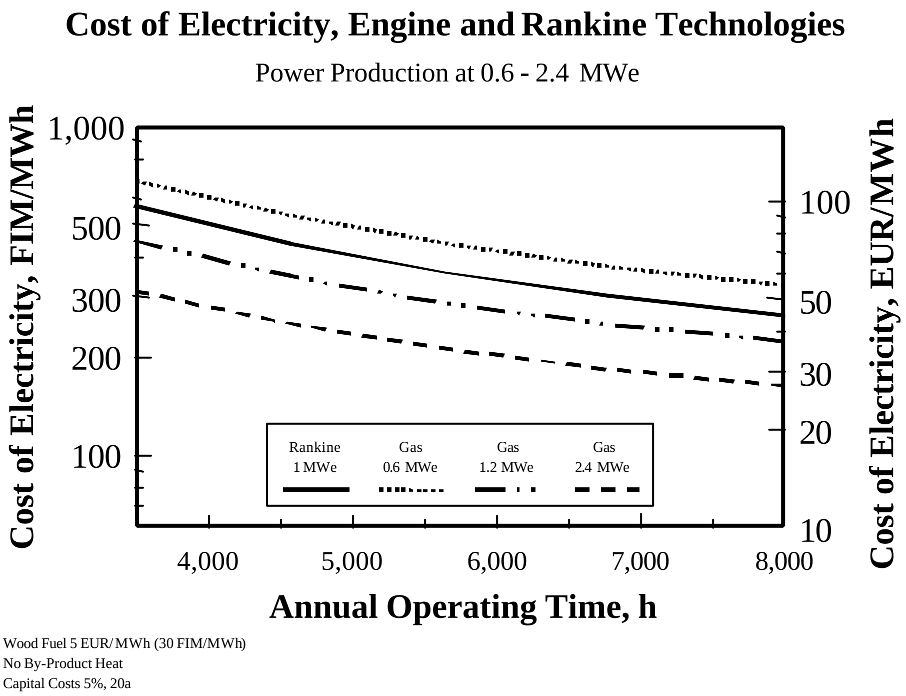
[2] total investment of first commercial plants

The results are shown in Fig. 27, Fig. 28, Fig. 29 and Fig. 30 show the effect of the income from the by-product district heat on the electricity price. These figures are based on using the medium fuel price of 5 EUR/MWh. The two larger-scale gasifier engine concepts seem to be competitive with the steam cycle when no district heat is produced. In the typical Finnish small-scale district heating case (Fig. 27), only the largest gasifier-engine concept seems to be competitive with the steam cycle.

Figure 28 illustrates the effect of higher fuel price on the competitiveness of the studied process concepts in a typical Finnish district heating application (with an average price for the produced heat). With higher fuel prices (10 EUR/MWh) the two larger-scale gasifier-engine process can compete with the steam cycle even in Finnish district heating case.

When these estimated electricity production costs are compared with the present electricity prices, none of the studied small-scale electricity production concepts (at biomass prices ≥5 EUR/MWh) is competitive with the prices paid for power producers when selling electricity to the grid. Thus, this kind of system can be competitive on the Finnish market only in two cases:

- If the produced electricity can be consumed without selling to the grid. Examples of this type of application are small sawmills, which have to pay a relatively high price (> 30 - 40 EUR/MWh) for their electricity.
- If the biomass-based power production is subsidised by an investment support, the subsidy for green electricity or taxation of fossil fuel is used for power production (at the moment only fuel for heating applications have to pay taxes).
- If feedstocks with a negative or zero price become available (e.g. due to changes in landfill regulations) and will be suitable for the new gasifier and gas cleaning process.

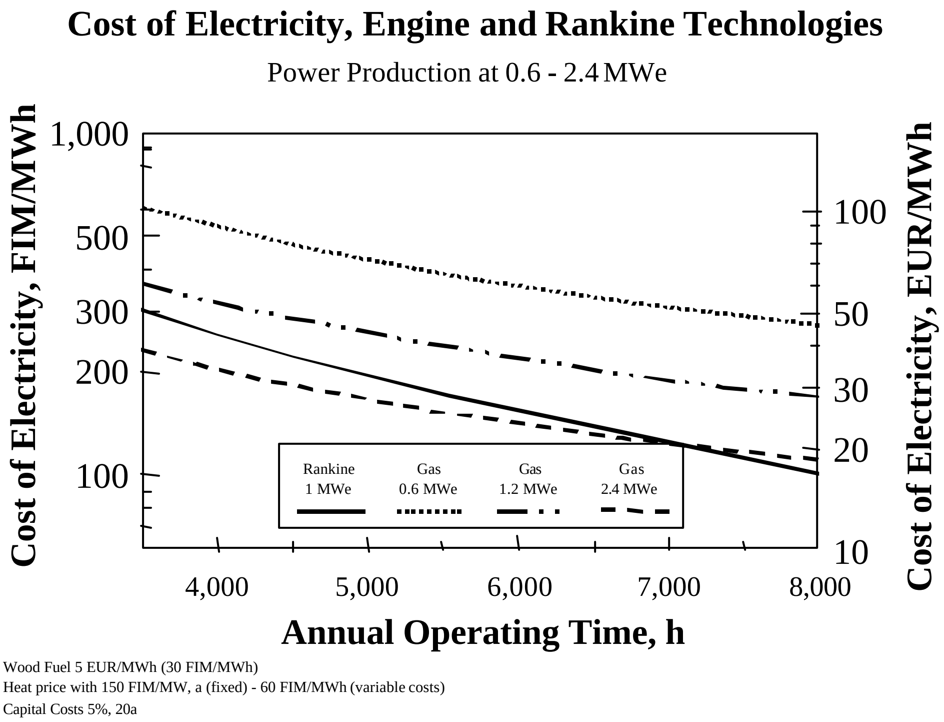


Cost of Electricity, Engine and Rankine Technologies

Power Production at 0.6 - 2.4 MWe

Wood Fuel 5 EUR/ MWh (30 FIM/MWh)
No By-Product Heat
Capital Costs 5%, 20a

Figure 27. The cost of electricity - medium fuel price (5 EUR/MWh), no by-product heat.

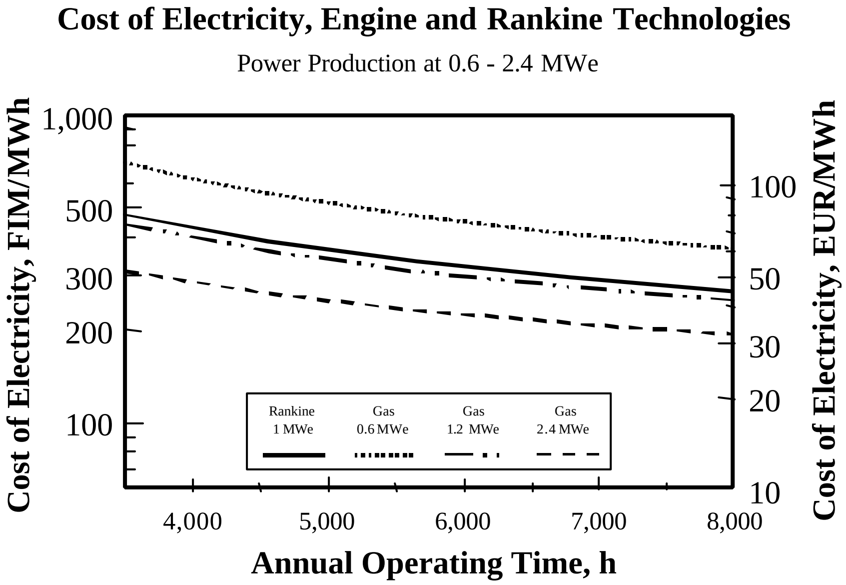


Cost of Electricity, Engine and Rankine Technologies

Power Production at 0.6 - 2.4 MWe

Wood Fuel 5 EUR/MWh (30 FIM/MWh)
Heat price with 150 FIM/MW, a (fixed) - 60 FIM/MWh (variable costs)
Capital Costs 5%, 20a

Figure 28. The cost of electricity - medium fuel price (5 EUR/MWh), medium price for the by-product heat.



Wood Fuel 10 EUR/MWh (60 FIM/MWh)
Heat price with 150 FIM/MW, a (fixed) - 60 FIM/MWh (variable costs)
Capital Costs 5%, 20a

Figure 29. The cost of electricity - high fuel price (10 EUR/MWh), medium price for the by-product heat.

Elomatic Papertech has calculated *costs of the biomass ORC cogeneration plant* in Finland. In size scale of 480 $\mathrm{kW_e}$/5 MW with peak operating time of 6850 hours per year the electricity production costs are 2.75 EUR-cents/kWh. Investment costs for electricity generation components in ORC plant is 600 000 EUR. By high investment support (30%) the electricity production costs will lower 2.2 EUR-cents/kWh. Annual electricity production is calculated to be about 3350 MWh.

Based on Danish biogas experiences, treatment costs and energy sales are presented in table 10. The calculation is based on fictive centralised biogas plant with a treatment capacity of 300 m^3 biomass per day. In the calculations an average biogas yield of 30 m^3 biogas per m^3 biomass treated is utilised, which in normal situation for biogas plants with a waste ratio of approx. 20% . The remaining biomass is slurry. The price of biogas is EUR 0.23 per m^3. A real interest rate of 5 per cent is used. Depreciation periods of 15-20 year are used for the biogas plant, 7 years for lorry chassis and 15 years for lorry cisterns. Table 11 do not include investment grants. It appears that net treatment costs, represented by the calculated deficit, amount to EUR 1.47 per m^3 biomass treated /4/.

Table 11. Treatment costs and energy sales based on Danish conditions /4/.

	EUR per m^3 total biomass treated
Biomass transportation	
- operating costs	2.01
- capital costs	0.54
Anaerobic treatment	
- operating costs	2.28
- capital costs	3.48
Total treatment costs	8.31
Energy sales	6.83
Deficit, net treatment costs	- 1.47

5 CONCLUSIONS AND FUTURE PROSPECTS

Finland has a long tradition in using biomass in CHP plants. Main reasons for a high CHP technology utilisation are the following:

- Both heat and power needed because of climate conditions and industrial structure (forest industry needs process steam and heat)
- Technology development (grate boilers for wet biomass fuels, fluidised bed boilers, district heating networks, automation etc.). Fluidised bed combustion enables to use different fuels in same boilers and especially wet biomass fuels.
- Resourses of biomass; availability of industrial wood residues like bark, sawdust etc. and large potential of forest fuels available
- Long traditions in municipal owned district heating and CHP plants; in southern Finland fuelled by coal and natural gas, in central and northern Finland with peat, wood biomass and oil.

The Finnish Ministry of the Trade and Industry has launched in October 1999 an Action Plan for Renewable Energy Sources. The use of solid wood fuels in 1997 was 1.59 Mtoe (excluding domestic use) and the expected increase from 1997 to 2010 is about 0.85 Mtoe, and then the total use will be about 2.4 Mtoe (excluding domestic use) /1,13/.

The electricity capacity of wood biomass in municipal and industrial CHP plants will increase by 860 MW$_e$ and heat capacity by 1700 MW$_{th}$ from year 1997 to 2010 (table 12). It has been estimated that more than 100 new or retrofits to biomass CHP is planned. Addition to that also 65 plants are aiming to use more wood biomass. Some plants need boiler retrofits or additional investments for fuel handling systems. /8/.

Table 12. Planned wood biomass plants from 1997 to 2010 in Finland /8/.*

Plant type	Number of plants	Electricity output, MW_e	Heat output, MW_{th}	Boiler output, MW_{th}
Municipal CHP plants	14	225	540	890
Municipal DH plants	74	0	240	275
Industrial CHP plants	13	395	990	1600
Industrial steam boilers	6	0	85	100
Alholmens Kraft	1	240	160	580
Total	108	860	2 015	3 450

* plants are mainly multifuel plants also using peat and part of the plants are retrofits of existing biomass plants.

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Fuel prices used in calculations (EUR/MWh) /14/

Plant	Milled peat heat	Milled peat, elect.	Sod peat, heat	Sod peat, electr.	Wood chips	Heavy fuel oil	Light fuel oil,	Natural gas,	Coal, inland	Coal, coast
District heating plant	8.6		9.1		7.4	15.3	23.5	12.3	12.3	11.4
Steam boilers	8.6		9.1		7.4	15.3	23.5	12.3	12.3	11.4
Municipal CHP,min	7.8-8.6	6.3-7.1	9.4	7.9	7.4-7.9	10.4	16.8	12.3	6.4	5.5
Municipal CHP,max.	7.8- 8.6	6.3-7.1	9.4	7.9	7.4-7.9	10.4	16.8	12.3	6.4	5.5
Industrial CHP,min.	7.8	6.3	9.6	7.9	7.4	10.4	16.8	12.3	6.4	5.5
Industrial CHP,max.	8.6	7.1	9.6	7.9	7.9	10.4	16.8	12.3	6.4	5.5
Condensing plants	0.0	5.7	9.6	7.9	9.6	10.4	16.8	12.3	6.4	5.5
Exctraction condensing plants,min.		6.3		7.9	7.7	10.4	16.8	12.3	6.4	5.5
Exctraction condensing plants,max.		6.3		7.9	7.9	10.4	16.8	12.3	6.4	5.5

Fuel prices in heat production includes energy taxes excluding VAT (22%).

Wood chips, 6.2 EUR/MWh (20 km transportation and 7.7 EUR/MWh 100 km transportation.

Heavy fuel oil, heat production 15.3 EUR/MWh.

Heavy fuel oil, support fuel in electricity production 10.4 EUR/MWh.

Fuel properties /14/

Fuel properties	**Milled peat**	**Sod peat**	**Wood chips**	**Heavy fuel oil**	**Light fuel oil**	**Natural gas**	**Coal**
LHV as received, GJ/t	8	11	10	40.9	42.4	48.6	25.6
LHV as received, MWh/m^3 loose min.	0.7	1.15	0.9			10	
LHV, MJ/l				40.1	35.9		
Moisture, w-%	40-56	30-47					
Bulk density, kg/m^3	325	374	325	980	847	0.74	750

Other calculation information /14/

- Investment costs are calculated by 5% interest rate and 15 years depreciation period for heating stations and 20 power plants
- Construction time for municipal CHP plants 2 –3 year, for industrial CHP plant 1.5 – 3 years.
- Annual salary of the operation staff is 42 000 EUR/a including salary and direct personnel costs.
- Service and reparation and insurance costs are 1.2 – 2 % of the investments costs of equipment, machines and building.
- Variable costs in heat and power production are mainly fuel costs
- Fixed costs for heat and power production have been calculated by comparing costs of the costs for alternative heat production unit.
- Costs of the desulfurization and NO_x reduction has been calculated based on Finnish emission regulations
- Other variable costs in heating stations 5 EUR-cents/MWh_{fuel} and in power plant 8 EUR-cents/$MWh_{fuel.}$
- Peak load utilisation hours, 5000 h/a district heating plants and 6500 h/a for industrial plants
- Water 0.84 EUR/m^3 and waste water 0.84 EUR/m^3
- Ash transportation cost 4.2 EUR/ton and waste fee 1.7 EUR/ton.
- The own electricity use of the power plant has been calculated from brutto electricity output and by using net electricity output.
- Fluidised bed boiler, bed material 0-3kg/MWh fuel, costs 200-250FIM/ton

Typical emissions and ash amounts used in calculations /14/

Fuel	gCO_2/MJ	$mgSO_2$/MJ	kg_{ash}/MWh_{fuel}
Milled peat	107	201	10
Sod peat	106	202	8
Wood fuel	114	25	4
Heavy fuel oil	77	464	0
Light fuel oil	74	85	0
Natural gas	56	0	0
Coal	94	705	14

Particulate emissions - guidelines to restrict the particulate emissions of power and boiler plants fuelled by biomass in Finland.

Primary fuel	Boilers´s fuel capacity, MW$_{th}$	Particulate emission maximum mg/MJ
Wood, straw or peat - small and medium scale (plants built before the Decision came in force in 1987, Decision of Council of State 157/87)	1 <P < 5 5 < P < 10 10 £ P £30 30 £ P £ 50	200 300 target value 120 target value 60 target value
(as of Feb, 12, 1987, Decision of Council of State 157/87)	1 < P < 5 5 £ P £ 50	200 calculated by using formula 85 - 4 (P - 5)/3
Wood, straw or peat - large scale boilers (as of 20.5.1994, Decision of Council of State 368/94)	50 < P £300 P > 300	50 mg/m^3_n 30 mg/m^3_n

The target values for boilers with a fuel capacity of over 5 MW$_{th}$. The recommended emission value for bottom-burning (grate combustion) with a fuel capacity of a minimum of 5 but below 10 MW$_{th}$ is, however, 200 mg/MJ, when wood or peat is used.

Nitrogen Emissions - Guidelines to restrict the NO$_x$ emissions of power and boiler plants fuelled by biomass in Finland.

Primary fuel	Boilers´s fuel capacity, MW$_{th}$	NO$_2$ emission maximum mg/MJ
Wood, straw or peat (plants built before 1st January 1991, Decision of Council of State 527/91)	P > 100	180 for peat using burners 150 for peat, other techniques 150 for wood or straw
(plants built after 1st January 1991, Decision of Council of State 527/91)	50 < P £ 300 P > 300	150 50

Main design values of the CHP plants using peat, wood or coal /14/.

	3/9MW	6/17MW	17/40MW	60/120MW	85/160MW	1/7MW	7.5/31MW	15/55MW	30/97 MW	50/162 MW
Boiler output, MW_{th}	12	24	59	187	253	9	39	72	131	216
Combustion technology	FB	FB	FB	FB	FB or pulverized	Sermet biograte	CFB	CFB	CFB	CFB
Steam flow, kg/s	4.5	8.2	20	75	102	3.2	16	29	52	86
Steam pressure, bar	61	61	89	114	130	30	64	84	113	130
Steam temperature, C	510	510	525	530	530	350	485	500	525	530
Electricity output, net MW_e	3	6	17	60	85	1	7.5	15	30	50
Heat output, MW_{th}	9	17	40	120	160	7	31	55	97	162
Sod peat, consumption ratio elect./heat	1.36/1.15	1.34/1.13	1.29/1.12	1.26/1.12	-	1.30/1.15	1.30/1.15	1.30/1.15	1.30/1.15	1.30/1.12
Milled peat, consumption ratio elect./heat	1.36/1.15	1.34/1.13	1.29/1.12	1.26/1.12	1.25/1.12	1.28/1.15	1.28/1.15	1.28/1.15	1.28/1.15	1.25/1.1
Wood chips, consumption ratio electr./heat	1.36/1.15	1.34/1.13	1,29/1,12	1,26/1,12	-	1.28/1.15	1.28/1.15	1.28/1.15	1.28/1.15	1.25/1.1
Coal, consumption ratio elect./heat	-	-	1.25/1.12	1.23/1.12	1.22/1.11	-	1.26/1.12	1.26/1.12	1.26/1.12	1.22/1.11
Size of building, m^3	8 900	15 200	36 000 coal 32 000	106 000 coal 100 000	140 000 coal 130 000	3000	25000 coal 20 000	39 000 coal 34 000	65 000 coal 59 000	105 000 96 000 coal
Staff, number (biomass/coal)	9	9	30/26	56/50	60/55	5	22/20	26/24	38735	45740

Investment costs (EUR) of municipal DH and CHP plants in Finland in 1999 /14/.

EUR, Total	2 MW_{th}	5 MW_{th}	15 MW_{th}	Steam 1.7kg/s (3.3MW_{th})	Steam 3.3kg/s (6.4MW_{th})	3/9MW	6/17MW	17/40MW	60/120MW	85/160MW	150 MW condensing	500 MW condensing
Sod peat	941 567	1 984 017	4 068 916	2 572 496	3 816 710	5 716 659	9 415 673	21 017 128	64 396 481			
Milled peat		1 984 017	4 068 916	2 572 496	3 816 710	5 716 659	9 415 673	21 017 128	64 396 481	83 732 238	145 270 390	
Wood chips	941 567	1 984 017	4 068 916	2 572 496	3 816 710	5 716 659	9 415 673	21 017 128	64 396 481		145 270 390	
Heavy fuel oil	269 019	538 038	1 076 077	638 921	975 195							
Natural gas	269 019	538 038	1 076 077	638 921	975 195							
Coal		1 765 439	3 614 946	2 202 595	3 345 927			20 176 443	61 370 014	78 351 854	137 199 812	406 219 052

Specific investment costs (EUR/kW) for municipal DH and CHP plants in Finland in 1999 /14/.

EUR/kW	2MW_{th}	5 MW_{th}	15 MW_{th}	Steam 1.7kg/s (3.3MW_{th})	Steam 3.3kg/s (6.4MW_{th})	3/9MW	6/17MW	17/40MW	60/120MW	85/160MW	150 MW condensing	500 MW condensing
Sod peat	486	395	271	777	597	1 932	1 565	1 234	1 073			
Milled peat		395	271	777	597	1 932	1 565	1 234	1 073	84	968	
Wood chips	301	395	271	777	597	1 932	1 565		1 073		968	
Heavy fuel oil	135	109	72	193	151							
Natural gas	135	109	72	193	151							
Coal		353	241	666	523			1 189	1 024	78	915	812

Total investment costs (EUR) for industrial plants and natural gas plants in Finland in 1999 /14/.

EUR	4/8MW	40/70MW	120/120MW	1/7MW	7.5/31MW	15/55MW	30/97MW	50/162MW	20/24MW	55/65MW
Sod peat				3 362 740	14 459 784	23 034 772				
Milled peat				3 362 740	14 459 784	23 034 772	40 857 297	68 599 906		
Wood chips				3 362 740	14 459 784	23 034 772	40 857 297	68 599 906		
Coal				3 362 740	13 282 825	21 689 676	38 503 379	62 378 836		
Natural gas	4 035 289	35 813 186	76 166 072						17 149 977	42 034 256

Specific investment costs (EUR/kW_e) for industrial plants and natural gas plants in Finland in 1999 /14/.

EUR/kW	4/8MW	40/70MW	120/120MW	1/7MW	7.5/31MW	15/55MW	30/97MW	50/162MW	20/24MW	55/65MW
Sod peat				3 430	1 939	1 538				
Milled peat				3 430	1 939	1 538	1 362	1 370		
Wood chips				3 430	1 939	1 538	1 362	1 370		
Coal				3 430	1 779	1 446	1 283	1 248		
Natural gas	1 021	894	634				857	763	857	763

Heat production costs (EUR/MWh) for municipal DH and CHP plants in Finland in 1999 /14/.

EUR/MWh	2 MW_{th}	5 MW_{th}	15 MW_{th}	Steam 1.7kg/s (3.3MW_{th})	Steam 3.3kg/s (6.4MW_{th})	4/8MW	40/70MW	120/120MW	20/24MW	55/65MW
Sod peat	27	24	20	26	23					
Milled peat		24	19	26	23					
Wood chips	25	22	18	24	21					
Heavy fuel oil	23	21	20	22	21					
Natural gas	22	19	18	19	18	20	20	20	21	21
Coal		27	23	29	26					

Heat production costs (EUR/MWh) for municipal DH and CHP plants in Finland in 1999 /14/.

EUR/MWh	3/9MW	6/17MW	17/40MW	60/120MW	85/160MW	1/7MW	7.5/31MW	15/55MW	30/97MW	50/162MW
Sod peat	20	20	20	20		21	21	21		
Milled peat	20	20	20	20		21	21	21	21	21
Wood chips	20	20	20	20		21	21	21	21	21
Coal		20		20	20	21	21	21	21	21

Peak load utilisation hours, 5000 h/a district heating plants and 6500 h/a for industrial plants. Investment rate 5%, plant operation year 15 year.
Staff annual costs 250 000 FIM/a (42 034 EUR) Operation and management, insurance costs 1,2 - 2 % of investments, Water 5 FIM/m^3 and waste water 5FIM/m^3 (0.84 EUR/ m^3
Fluidised bed boiler, bed material 0-3kg/MWh$_{fuel}$, costs 200-250 FIM/ton (33.6 – 42.1 EUR/ton)

Electricity production costs (EUR/MWh$_e$) of municipal and industrial CHP plants in Finland in 1999 /14/.

EUR/MWh$_e$	3/9MW	6/17MW	17/40MW	60/120MW	85/160MW	1/7MW	7.5/31MW	15/55MW	30/97MW	50/162MW	20/24MW	55/65MW
Sod peat	43	23	25	22		22	18	11				
Milled peat	39	17	20	16	14	14	10	4	1	-1		
Wood chips	34	16	18	12		2	5	-2	-4	-5		
Coal			35	23	20	41	25	21	17	14	25	20

Condensing power plants, EUR/MWh$_e$ /14/

Fuel	150 MW	500 MW
Milled peat	34	
Wood chips	34	
Coal	34	34

Fixed and variable operating costs of CHP plants /14/

EUR	Fixed EUR/kW,a	Variable, EUR/MWh
Municipal CHP	11.8	17.7
Ind.CHP	20.2	17.7

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