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COMBUSTION AND GASIFICATION OF SOLID BIOMASS FOR HEAT AND POWER PRODUCTION IN EUROPE – STATE-OF-THE-ART AND RELEVANT FUTURE DEVELOPMENTS

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Abstract Combined Heat and Power (CHP) technologies based on biomass combustion and gasification have been developed intensively over the past ten years. Typical fields of application for these CHP technologies are wood-processing industries, district heating systems and industries with a high process heat or cooling demand. These applications represent a great market potential in Europe as well as worldwide.

CHP technologies based on biomass combustion have reached a high level of development. For large-scale CHP plants (>2,000 kW_{el}) the steam turbine process is economically and technically feasible. In the medium-scale power range (200 - 2,000 kW_{el}) the Organic Rankine Cycle (ORC) process has proven its technological maturity. For small-scale CHP plants (<100 kW_{el}) the Stirling engine process is the only technology with the potential to meet the requirements of this market segment at present. Biomass CHP plants based on Stirling engines are expected to be available on the market within the next few years.

CHP technologies based on biomass gasification processes also represent a future potential but have not yet achieved a level of development which allows commercial application. However, several demonstration projects based on biomass gasification are already successfully in operation and are partly at the edge of commercialisation. For small-scale applications the downdraft gasification technology Pyroforce (CH) represents a promising technology for the future. The updraft gasification technology at Harboore (DK) has proven its reliability. However, the product gas contains high amounts of tars, thus requiring a complex gas cleaning system. The circulating fluidised bed biomass steam gasification process in Güssing (A) has been in successful operation for more than 32,000 hours. Due to the complexity of this technology and the comparatively high operating costs, this technology is expected to be economically feasible only for large-scale applications.

The electricity generation costs of biomass CHP technologies based on biomass combustion range between 0.13 and 0.22 €/kWh_{el}, at present, mainly depending on size (economy-of-scale), fuel price and annual full load operating hours achievable. The electricity generation costs for the gasification based processes clearly exceed those for the CHP systems based on biomass combustion with the same nominal electric power output, which is due to high investment, operating and maintenance costs of these technologies at present. For all CHP technologies mentioned above considerable R&D efforts are ongoing, mainly focusing on further technological developments in order to improve their efficiency as well as their availability.

Keywords CHP technology, solid biomass, combustion, gasification, Stirling engine, ORC, steam turbine

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INTRODUCTION

CHP technologies based on biomass combustion and gasification represent a great potential to reduce CO_2 emissions since they are based on the utilisation of renewable energy sources.

Typical fields of application for biomass CHP plants are wood-processing industries and sawmills, district heating systems (newly erected or retrofitted systems) as well as industries with a high process heat or cooling demand. These applications represent a great market potential in Europe. In order to achieve an ecological and cost-effective plant operation it is a basic requirement that not only the electricity but also the heat produced as process or district heat are utilised (heat-controlled operation of the overall system). From an ecological and economic point of view, the total annual utilisation rate (heat and electricity produced / fuel energy input [NCV]) should not be less than 60% and ideally exceed 80%. Furthermore, since the energy density of solid biofuels is relatively low, biomass CHP technologies should be primarily applied for decentralised applications.

The annual full load operating hours of the CHP plant have the largest influence on the electricity generation costs. A minimum value of 6,000 hours for an economic operation can be recommended which shows the importance of an optimal design of the CHP unit according to the annual heat output line of the district or process heating network. An additional important side constraint for biomass CHP plants are long-term supply contracts for the biofuel used.

Over the past few years, CHP technologies based on biomass combustion have been newly or further developed and plants have been successfully implemented in many European countries. Several different technologies for medium- and large-scale applications are available on the market and have proven their technological maturity. CHP technologies in the power range below 100 kW_{el} (small-scale systems) are in the demonstration stage at the moment and should be commercially available within the next few years.

CHP technologies based on biomass gasification processes also represent a future potential but have not yet achieved a level of development which allows commercial application. Several demonstration plants based on biomass gasification, however, are already in operation for several thousands of hours and partly at the edge of commercialisation. Biomass gasification is a considerably more complex process than biomass combustion but may offer higher electric efficiencies, which makes it attractive as a future option.

The objective of the paper presented is to give an overview of the state-of-development, about the operating experiences already obtained as well as about the future development potential of CHP technologies based on combustion and gasification of solid biomass. Moreover, the paper points out the economical and technical constraints which must be considered for the implementation of biomass CHP plants.

POTENTIAL AND FRAMEWORK FOR BIOMASS CHP PLANTS IN THE EUROPEAN UNION

The leading renewable energy sources in the European Union are hydropower and biomass. The electricity generation from biomass increased by a factor of 4.7 from 1990 to 2005 with an average rate of about 11% annually. The major share of this increase is attributable to wind power and CHP plants based on biomass combustion [1; 2; 3]. The largest producers of electricity from biomass in 2005 amongst the EU-27 Member States were Germany, the United Kingdom, Finland and Sweden (see Figure 1).

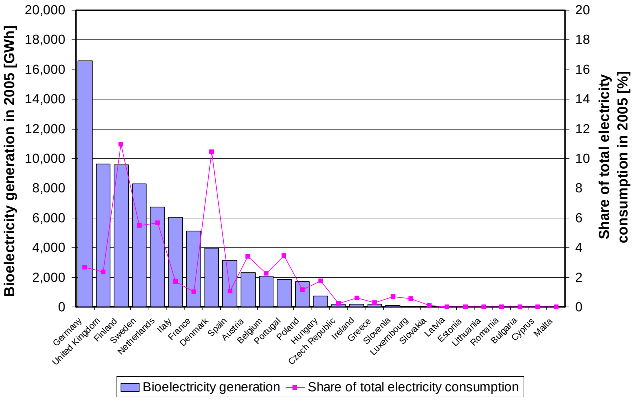

Figure 1. Electricity generation from biomass in EU-27

<u>Explanations:</u> data source [1; 2], biomass includes solid biomass, renewable MSW and biogas.

Poland and Hungary lead the new Member States in bioelectricity generation, though the quantities are significantly smaller than in the old Member States. Finland has the highest share of electricity production from biomass on the total national electricity consumption (approx. 11%), followed by Denmark, the Netherlands as well as Sweden and Austria.

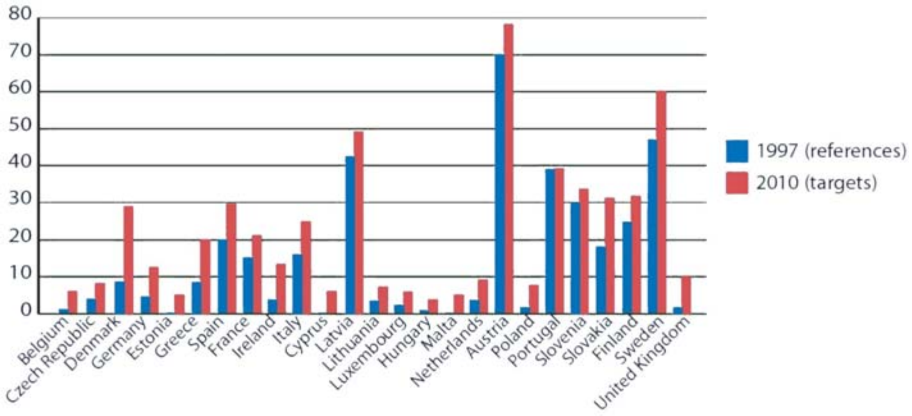

Figure 2. Defined targets regarding the electricity production from renewable energy sources in the EU-25 Member States in the year 2010

<u>Explanations:</u> share of renewable energy sources in gross national electricity consumption, in percent; the reference year for the 10 new EU Member States is the year 2000.

The Directive of the European Commission on the promotion of electricity production from renewable energy sources (RES-E Directive) requires 21% of the total electricity demand in the EU to be covered by renewable energy sources by 2010 [4]. The Member States have defined their national targets based on this Directive (see Figure 2). In order to achieve these goals, appropriate feed-in tariffs for electricity from biomass and a certain period of time over which these tariffs are guaranteed (at least 15 years) are essential. These factors form the basis for an economical operation of such systems and for the market introduction of new biomass CHP technologies.

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CHP TECHNOLOGIES BASED ON BIOMASS COMBUSTION

Description of Technologies

Various technologies are available for the electricity production based on biomass combustion: the steam turbine process, the steam piston engine process, the steam screw-type engine process, the ORC process, and the Stirling engine process.

These technologies are applicable for the following power ranges:

1. Up to 100 kW_{el}: the only applicable technology for small-scale CHP plants is the Stirling engine process which is at the demonstration phase at present.
2. From 200 – 2,000 kW_{el}: suitable technologies for medium-scale CHP plants are steam engines, steam turbines and especially the ORC process. These technologies are already available on the market.
3. Larger than 2,000 kW_{el}: the steam turbine process is the most relevant technology for large-scale CHP plants.

The steam turbine process and the steam piston engine process have been applied for many years and represent the state-of-the-art. The first biomass CHP plants based on an ORC process in the European Union was put into operation in 1999 in Admont (A) within a European demonstration project [5]. This technology was further developed and optimised during the past eight years and can now be considered as a market-proven technology. The steam screw-type engine technology was successfully demonstrated in the biomass district heating plant of Hartberg (A) in December 2003 [6]. The experiences gained in the period of about four years of operation have proven that this technology has already achieved a high level of development. The Stirling engine process is at the demonstration stage at present [7; 8; 9; 10]. A field test with several engines has been initiated and market introduction is expected within the next few years.

In the following sections two new and interesting CHP technologies based on biomass combustion for decentralised applications are described in more detail: the ORC process and the Stirling engine process.

ORC Process

The principle of electricity generation based on an ORC (Organic Rankine Cycle) process corresponds to the conventional Rankine process. The substantial difference is that an organic working medium with favourable thermodynamic properties is used instead of water [11]. A technology especially designed for biomass CHP plants was developed by TURBODEN Srl, Brescia, Italy in cooperation with the Technical University of Milan [12,13]. The nominal electric capacities of ORC modules for biomass CHP plants range from 200 to 2,000 kW at present.

The working principle and the different components of the ORC process are shown in Figure 3 and Figure 4. The ORC process is connected with the thermal oil boiler via a thermal oil cycle. The ORC unit itself operates as a completely closed process utilising a silicon oil as organic working medium. This pressurised organic working medium is vaporised and slightly superheated by the thermal oil in the evaporator and then expanded in an axial turbine which is directly connected to an asynchronous generator (see Figure 4). Subsequently, the expanded silicon oil passes through a regenerator (where in-cycle heat recuperation takes place) before it enters the condenser. The condensation of the working medium takes place at a temperature level which allows the heat recovered to be utilised as district or process heat (hot feed water temperature about 80 to 100°C). The liquid working medium then passes the feed pumps to again achieve the appropriate pressure level of the hot end of the cycle, passes the regenerator and again enters the evaporator.

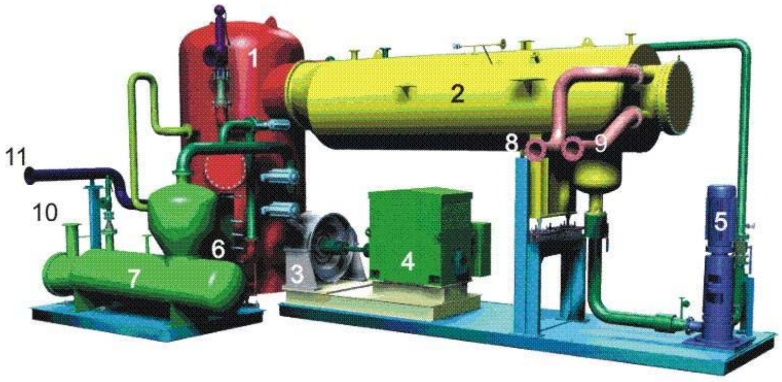

Figure 3. Schematic illustration of a 1,000 kW$_{el}$ ORC module

Explanations: 1 … regenerator, 2 … condenser, 3 … turbine, 4 … electric generator, 5 … circulation pump, 6 … pre-heater, 7 … evaporator, 8 … hot water inlet, 9 … hot water outlet, 10 … thermal oil inlet, 11 … thermal oil outlet; data source [15]

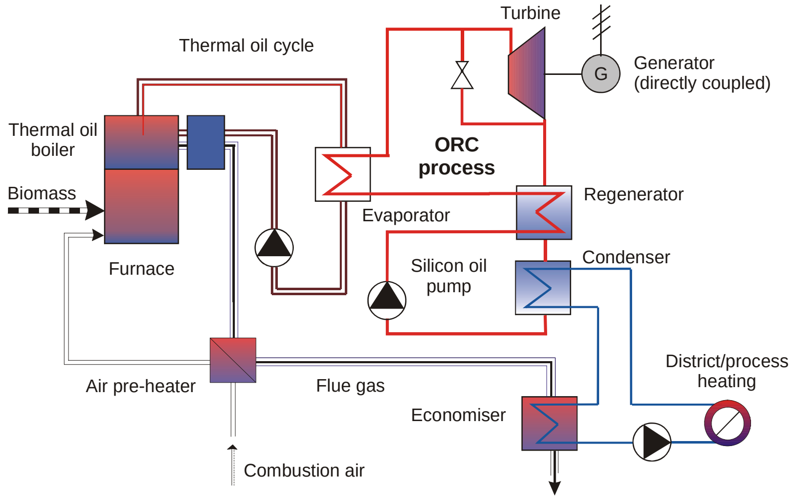

Figure 4. Schematic illustration of a biomass CHP plant based on ORC technology

In order to obtain a high electric efficiency (= net electric power produced / thermal power input) of the ORC unit itself, it is necessary to keep the back-pressure of the turbine as low as possible and thus to minimise the necessary temperature for district or process heat utilisation at the condenser of the ORC plant. This can be achieved primarily by an optimised hydraulic integration of the ORC in the district or process heating network and secondarily by optimising the operation and control of the district heating network.

ORC plants are relatively silent (the highest noise emissions occur at the encapsulated generator and amount to about 85 dB (A) at a distance of 1 m. The operating costs are low, since the ORC process is closed and thus no losses of the working medium occur. Moreover, only moderate consumption-based costs (lubricants) and maintenance costs are incurred. The lifetime of ORC units usually exceeds twenty years, which has been proven by geothermal applications. The silicone oil used as the working medium has the same lifetime as the ORC since it does not undergo any relevant ageing.

Special advantages of the ORC process are its excellent partial load and load changing behaviour, the matureness of the technology and its high availability, the high degree of automation and the low maintenance costs as well as the fact that it requires only atmospherically operated boilers (thermal oil boiler) thus reducing personal costs (no constant supervision required). The main weak points are the relatively high investment costs.

The overall electric efficiency of the CHP plant (= net electric power produced / fuel power input related to the NCV) can be considerably increased by coupling the thermal oil boiler with a thermal oil economiser and an air preheater (see Figure 4). Using this approach, the efficiency of the biomass-fired thermal oil boiler amounts to about 82% (= thermal power output / fuel power input [NCV]), which is about 10% higher than corresponding values from conventional biomass-fired thermal oil boilers [1]. This increased boiler efficiency correspondingly also raises the overall electric efficiency of the CHP plant (= net electric power produced / fuel power input related to the NCV) to about 15% (see Figure 5).

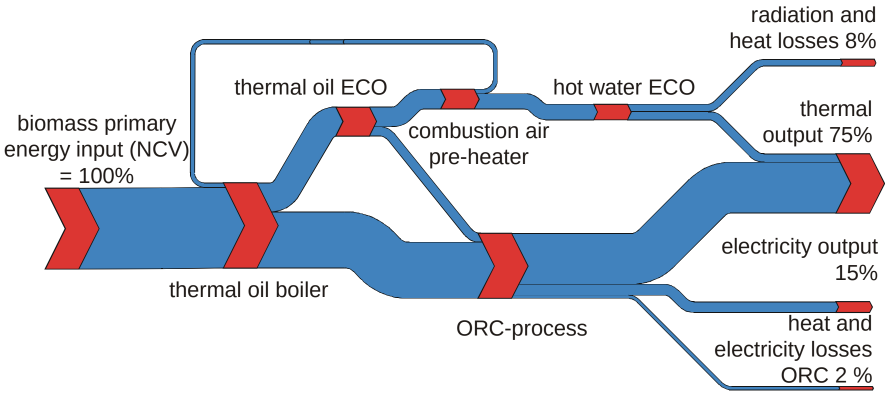

Figure 5. Energy balance of a biomass CHP plant based on ORC technology

Operating experiences have shown that the ORC technology is a technologically and economically feasible application for medium-scale biomass CHP plants. More than 50 CHP plants based on ORC technology are at the implementation stage or already in operation in Austria, Switzerland, Germany, Italy, the Czech Republic, Poland and the Netherlands. In total, an electric capacity of more than 50 MW is already installed.

Ongoing and future developments will concentrate on improving the electric efficiency [15]. In this respect, the ORC process with a branched condensate cycle is a new and interesting option to further optimise the system. This new technological approach utilises additional heat from the flue gas in a second thermal oil economiser. Calculations already performed indicate that this technology can enhance the electric plant efficiency by 4 % (same specific heat exchanger area) to 8% (increased specific heat exchanger area). An increase in the thermal oil temperature (from 300/250 to 320/270 °C) also leads to an enhanced electric plant efficiency (approx. 3%), but several components of the ORC process must be modified in order to implement this measure effectively. In summary, the measures indicated are expected to result in a 10% increase in efficiency in comparison to state-of-the-art systems within the next few years.

An interesting new application is the integration of ORC processes in large-scale biomass gasification systems to utilise the waste heat. Following this approach an increase of the electric plant efficiency by 15% to 20% in comparison to conventional gasification systems seems possible.

Stirling Engine Process

The CHP technology based on Stirling engines is a promising application for small-scale electricity production from biomass with nominal electric capacities up to 100 kW. A small-scale CHP technology based on Stirling engines for solid biomass fuels with a nominal electric power output of 35 kW and 70 kW was developed and optimised within the scope of several R&D projects in cooperation of the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GesmbH (A), BIOS BIOENERGIESYSTEME GmbH (A) and the Austrian Bioenergy Centre.

Stirling engines are based on a closed cycle, where the working gas is alternately compressed in a cold cylinder volume and expanded in a hot cylinder volume. The advantage of the Stirling engine over internal combustion engines is that the heat is not supplied to the cycle by combustion of the fuel inside the cylinder, but transferred from the outside via a heat exchanger in the same way as in a steam boiler.

Stirling engines especially designed for CHP plants using solid biomass fuels have been developed at the Technical University of Denmark [16; 18]. Helium is used as the working gas at a maximum mean pressure of 4.5 MPa. The utilisation of low molecular weight gases, like Helium, make it difficult to design piston rod seals, which keep the working gas inside the cylinder and prevent the lubrication oil from entering the cylinder. In order to avoid these problems the Danish engine is designed as a hermetically sealed unit with the generator incorporated in the pressurised crankcase, just like the electric motor in a hermetically sealed compressor for refrigeration. Only static seals are necessary and the only connections from the inside to the outside of the hermetically sealed crankcase are the cable connections between the generator and the grid.

The Stirling engine heaters (one for each cylinder) are designed as panels forming a square combustion chamber, where radiation from the combustion is transferred directly to the panels (see Figure 6). Narrow passages in the heater sections are avoided in order to adapt the system to the high dust load of flue gases from combustion systems fired with solid biomass fuels. The problems related to biomass fuel use in connection with a Stirling engine mainly occur during the heat transfer from the flue gas to the working gas. The temperature must be high to obtain an acceptable specific power output and efficiency, and the heat exchanger must be designed so as to minimise problems regarding hard deposit formation. The risk of deposit formation in biomass combustion processes is mainly due to aerosol formation and condensation of ash vapours during flue gas cooling [17].

Figure 7 shows a schematic illustration of the newly developed small-scale CHP technology. In order to enhance the electric plant efficiency, the combustion air is preheated to approx. 550 °C by an air pre-heater. The furnace is designed for temperature levels of about 1,300 °C. Due to the high temperatures in the combustion chamber, it is suitable only for wood fuels with low ash and chlorine contents, such as wood chips, sawdust and pellets. The furnace is equipped with underfeed stoker technology and operates satisfactorily at full load with fuel moisture contents ranging from 10 to 55 wt% (w.b.). The Stirling engine is mounted in horizontal position downstream of the secondary combustion chamber for convenient maintenance (see Figure 8). The air pre-heater and the economiser are placed on top of the furnace in order to achieve a compact plant design. The CHP plant does not require substantially more space than a normal biomass combustion plant with the same heat output. A pneumatic and fully automatic cleaning system has been developed and installed to remove fly ash particles from the Stirling engine heater. During test runs the plant achieved an electric efficiency (= net electric power produced / fuel power input related to the NCV) of approx. 12% and future developments are expected to raise this up to 15%.

Figure 6. Front and back view of the 35 kW_{el} Stirling engine developed for biomass CHP plants including the heater forming an interface to the combustion chamber

<u>Explanations:</u> data source [19].

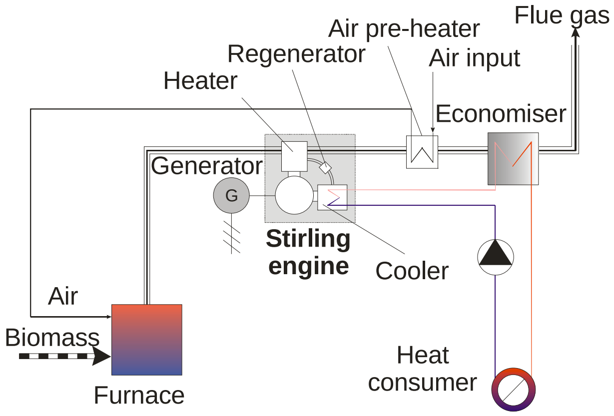

Figure 7. Schematic illustration of a biomass CHP plant based on a Stirling engine

A 35 kW_{el} pilot plant was put into operation in 2002 and was successfully tested for more than 12,000 hours (see Figure 8). A second pilot plant with a 70 kW_{el} engine has been operated for approx. 7,000 hours since autumn 2003 [19; 20]. The pilot plants work fully automatically. There are several points to be addressed in future, primarily regarding enhanced electric efficiency and mechanical stability of the engine. The pneumatic cleaning system to reduce ash depositions in the heater sections and thus to achieve a higher availability of the whole system as well as the connection of the Stirling engine to the furnace achieved already pre-series stage.

The CHP technology described above can be considered as a breakthrough in the application of Stirling engines for small-scale CHP plants burning solid biomass fuels. Currently, long-term field test runs with three further developed and optimised 35 kW_{el} Stirling engines are ongoing. It is expected that this technology will be commercially available by the end of 2008 (provided, that the long-term test runs can be finalised successfully).

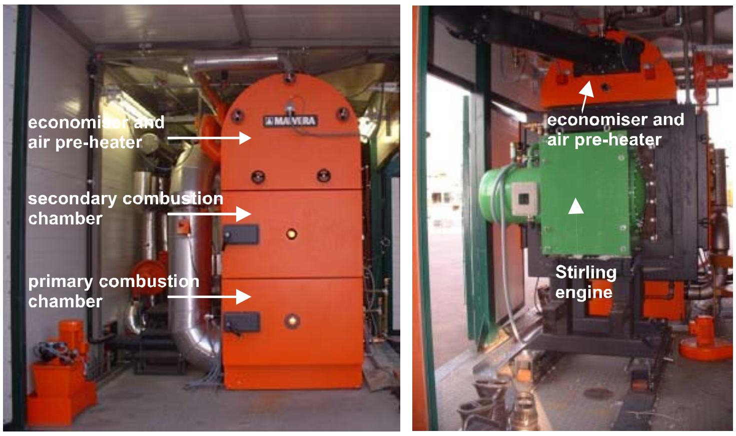

Figure 8. Pictures of the small-scale CHP pilot plant based on a Stirling engine

CHP TECHNOLOGIES BASED ON BIOMASS GASISIFICATION

Description of Technologies

CHP technologies based on biomass gasification are currently at the development and demonstration stage but have not reached market maturity yet. Several demonstration plants have been erected over the past few years and some of these are in operation for several thousands of hours [32; 33; 34].

Three different basic concepts exist regarding biomass gasification technologies: the fixed-bed gasification process (for small- to medium-scale applications), the fluidised-bed gasification process (mainly for large-scale applications) and the entrained flow gasification process (for large-scale applications). The latter system focuses on syngas production and is therefore not further considered in this paper.

Fixed-bed Gasification Process

Figure 9 shows the two basic types of fixed-bed gasifiers (the updraft and the downdraft gasifier). Both reactor types are based on gravity-fed fuel supply. The residence time of the fuel in the gasifier is long and the gas velocity is low. The traditional fixed-bed gasifiers are suitable only for sized feedstocks, whose bulk density is high enough to guarantee stable fuel flow.

In an updraft gasifier the fuel is fed at the top of the gasifier, from where it flows down slowly through drying, pyrolysis, gasification and combustion zones (see Figure 9). Ash is removed from the bottom, where the gasification air and/or steam are introduced. The products of the drying and pyrolysis zones are directly released into the product gas without secondary decomposition reactions which causes high tar contents in the product gas. The product gas temperature at the gasifier outlet is low (approx. 80-300 °C). The bottom ash is usually completely oxidised and does not contain significant amounts of unburned carbon. Furthermore, the dust content of the product gas is comparatively low resulting from low gas velocities and filtering effects of the fuel bed (drying and pyrolysis zones).

Updraft gasifiers are relatively insensitive towards varying particle size (5 – 100 mm) and towards varying moisture content of the fuel (up to 55 wt% (w.b.) possible). Stable operating conditions can usually be obtained and the partial load behaviour is good. The nominal thermal capacity of updraft gasifiers ranges from 100 kW to 20 MW.

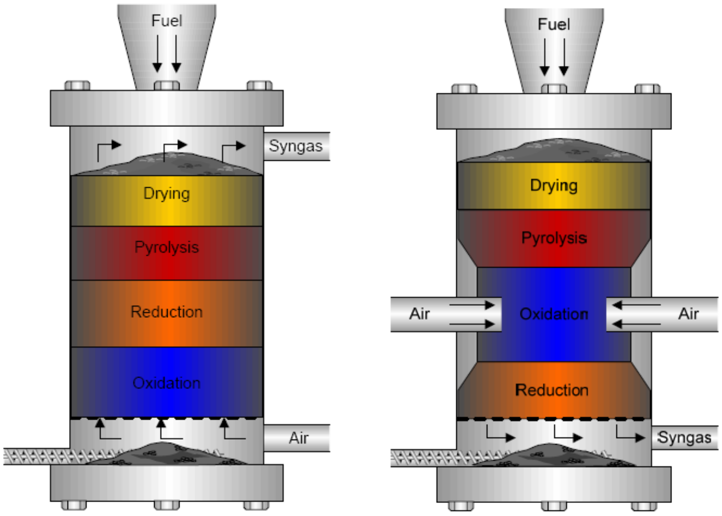

Figure 9. Scheme and operating principle of conventional fixed-bed gasifiers
Explanations: left: updraft gasifier; right: downdraft gasifier; data source [21].

The advantage of downdraft gasifiers is that the pyrolysis products must flow co-currently through the hot combustion and gasification zones, where tars are decomposed and oxidised (see Figure 9). Consequently, the tar content in the product gas is lower than in the product gas of updraft gasifiers, which allows for a simpler design of the gas cleaning and tar removal systems, if the product gas is utilised in an internal combustion engine. Downdraft gasifiers are sensitive towards varying particle size of the fuel (20 - 100 mm), require dry fuels (moisture content <20%) and their partial load behaviour is rather poor. The nominal thermal capacity of downdraft gasifiers ranges from 20 kW to 5 MW.

Several biomass CHP systems based on downdraft gasifiers and internal combustion engines have been developed during the past few decades. So far, none of these trials has resulted in the development of a commercially viable process. The main reason for this is that the ideal (low-tar) operation of downdraft gasifiers is limited to extremely high-quality sized and dry wood fuels. However, some demonstration plants based on downdraft gasifiers seem technologically promising concerning a future market introduction.

In addition, several other concepts of fixed bed gasifiers exist, specifically double fired gasifiers, which try to combine the advantages of updraft and downdraft technology and multi-stage gasifiers, where drying and pyrolysis as well as gasification and combustion are performed in separate reactors [22; 23; 24].

Fluidised-bed Gasification Process

In a fluidised bed gasifier the gasification medium (air, steam or oxygen) and biomass are mixed in a hot bed of solid material (e.g. sand). Due to the intense mixing, the different zones (drying, pyrolysis, oxidation, reduction) cannot be distinguished. The temperature is relatively uniform throughout the bed. In contrast to fixed bed gasifiers, the gasification medium to biomass ratio can be changed, which allows the bed temperature to be controlled. The product gas will always contain certain amounts of tars as well as high dust concentrations, which need to be removed. Basically two reactor designs exist: bubbling and circulating fluidised beds (see Figure 10). In circulating fluidised beds the specific throughput is considerably higher but the design is more complex. The two operating principles are allothermal and autothermal gasification. While in autothermal gasification processes usually air is used as gasification medium and the necessary energy is provided within the process, in allothermal gasification processes usually steam is used as gasification medium and the necessary heat is supplied from outside (e.g. via heated bed material).

Fluidised bed gasifiers should be operated at full load in order to maintain bed material circulation. Partial load operation is therefore limited to about 70 % of the nominal load and the gasifiers should be used for base load coverage. Furthermore, a fully automatic process control as well as a clearly defined fuel particle size range are required. Due to the complexity of the process, the plant cannot be operated without constant supervision. The technology is thus only suitable for large-scale applications where constant supervision can be provided. The advantages of fluidised bed gasifiers are relatively homogeneous operating conditions and a product gas of higher calorific value (if allothermal gasification is applied).

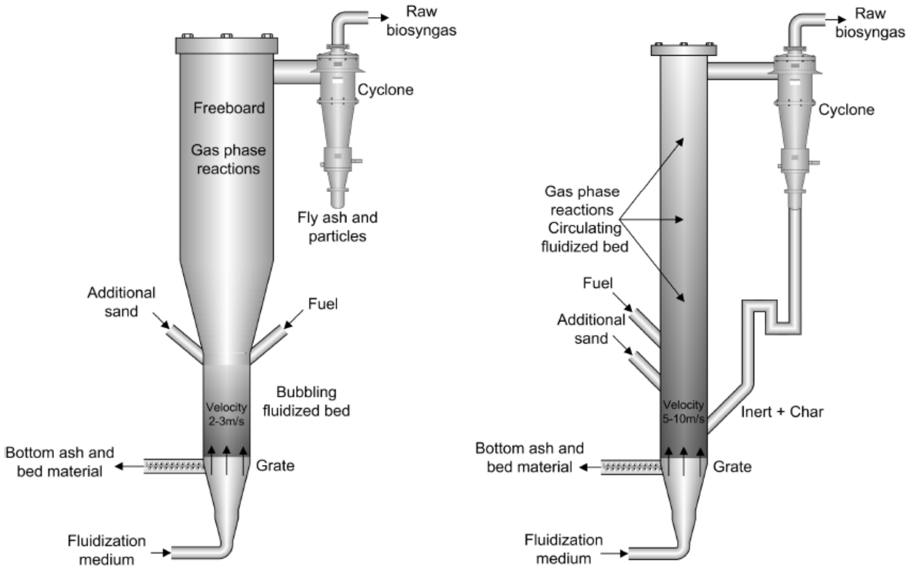

Figure 10. Schematic illustration and operating principle of fluidised bed gasifiers

Explanations: left: bubbling fluidised bed, right: circulating fluidised bed; data source [21]

The cold gas efficiency of a biomass gasifier (energy content in the product gas [NCV] / energy content of the fuel [NCV]) should be higher than 80% in order to achieve an acceptable electric efficiency of the overall CHP plant. Regardless of the gasification technology applied, the gasifier will be connected to a gas cleaning system followed by a gas engine or gas turbine unit. At present, only gas engine based biomass CHP plants are at the demonstration stage.

Gas Cleaning Technologies

Depending on the application, type of gasifier and contaminants in the fuel, a certain (usually high) level of gas conditioning (cleaning/cooling) is required if the product gas is utilised in an internal gas engine or gas turbine. The most frequent impurities in the product gas are hydrocarbons (tars), dust (particulates), ammonia, hydrogen sulphides, chlorides and alkali metals, which need to be removed or converted.

Dust is usually removed by cyclones and/or fabric filters. Ammonia, hydrogen sulphides and chlorides can be removed by scrubbers or additives. The most critical component to be handled, however, are tars. Tars can be removed from the product gas by thermal, chemical and physical methods. Thermal and chemical methods destroy the tar, physical methods only remove the tar (resulting in a tar waste stream). Figure 11 shows different tar removal and conversion concepts, more details can be found in [25].

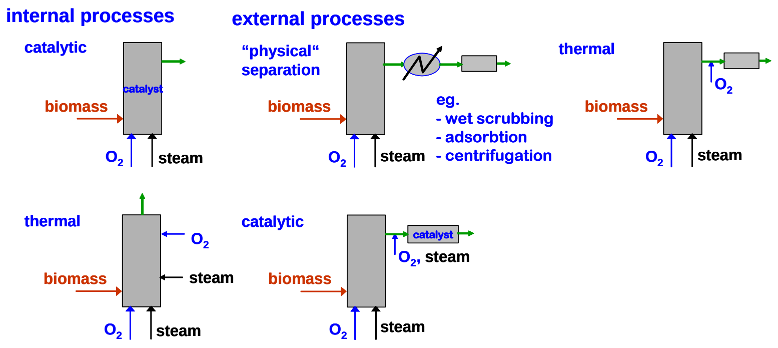

Figure 11. Tar removal/conversion concepts

In the following sections three demonstration plants based on biomass gasification, which have achieved several thousands of operating hours, are described [26].

Pyroforce technology (CH)

The Pyroforve technology has been developed by Pyroforce Energietechnologie AG (former company Hydrotest), Switzerland. The technology is based on an atmospheric air-blown downdraft (and partly cross-flow) fixed bed gasifier with round cross-section [29; 30]. Figure 12 shows the process scheme of the Pyroforce technology. Drying and pyrolysis of the fuel takes place in the upper part of the gasifier. In the following oxidation zone the products from pyrolysis are partly oxidised. The air needed for oxidation is sucked through nozzles positioned around the reactor in the middle section as well as trough a lance in the middle of the reactor. At the bottom of the gasifier the products from oxidation are reduced at the charcoal. The producer gas is removed in cross-flow via an annular gap around the reaction zone. Together with the producer gas large amounts of incompletely gasified charcoal and mineral compounds are removed. The conversion of the remaining charcoal in the reaction zone at the bottom of the gasifier is almost complete. The resulting ash (TOC < 5 wt.% d.b.) is fed into an ash container.

The tar content in the product gas leaving the gasifier is approx. 1,500 mg/Nm^3. In a first gas cleaning step major parts of charcoal and ash particles are removed in a cyclone. The removed solid residues have a high carbon content of up to 70%. Larger charcoal particles are separated and fed again into the gasifier. The remaining cyclone ash has to be disposed of or can be utilised in a biomass combustion plant. Afterwards, the producer gas is cooled in a gas-air heat exchanger, where ambient air is pre-heated. The pre-heated air is used to dry the fuel to the required moisture content. The gas-air heat exchanger is followed by a pre-coated baghouse filter. The carbon content of the filter fly ash amounts to about 25%. The baghouse filter is followed by a scrubber using RME, where the producer gas is further cooled and cleaned, before it is fed into the gas engine to produce heat and electricity. The spent RME saturated with tars from the scrubber is utilised by recycling it to the gasifier.

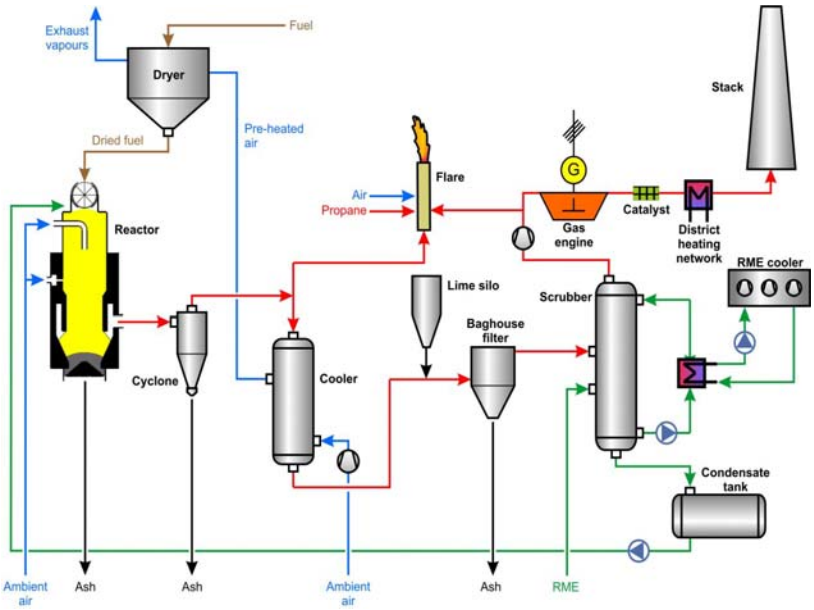

Figure 12. Process scheme and operating principle of the Pyroforce technology

Explanations: data source adapted from [29].

The Pyroforce technology has successfully been demonstrated in a demonstration plant in Spiez, Switzerland, which started operation in 2001. Since then the gasifier has been in operation for approx. 24,100 hours, the gas engine for about 16,600 hours (status 09/2007). The plant is a medium-scale gasifier with a nominal fuel power input (NCV) of approx. 580 kW. The plant can be operated fully automatically. The fuel should be wood chips G50 according to ÖNORM M 7133. The amount of fines should be below 5 wt.% and the moisture content of the fuel should be below 15 wt% (w.b.). Operating results show a cold gas efficiency of the gasifier of approx. 76% and a gross electric plant efficiency of approx. 27.4% [32]. As the heat from the producer gas cooler has usually to be used to dry the fuel and the RME must be cooled by an air cooler (due to the low temperature level), only the heat from the gas engine is available for utilisation. Therefore, the thermal plant efficiency (37.7%) as well as the overall plant efficiency (65.1%) are comparatively low. The engine has a nominal electric power output of approx. 150 kW.

The nominal electric power output of the basic concept is 150 kW$_{el}$, based on a gasifier with a nominal fuel power input (NCV) of 580 kW. Upscaling of the technology can be done by combining up to four gasifiers with one gas cleaning system and one gas engine. Therefore, units with 150, 300, 450 and 600 kW_{el} are available.

Main advantages of the technology are the comparatively high state of development and the good part load behaviour. Weak points of the technology are the carbon rich residues (energy losses and disposal costs) and its low overall plant efficiency.

The first two commercial plants have recently been installed in Austria (300 kW_{el}) and Switzerland (2 x 600 kW_{el}). At these plants the availability and long-term reliability of the system have to be proven.

Vølund Updraft Gasification Process at Harboore (DK)

The Vølund up-draft biomass gasification process at Harboore is based on a concept developed by Keramische Industrie Bedarf, Berlin [27; 28]. In December 1993 a wood chips gasifier with a nominal thermal capacity of 4 MW was built in Harboore (DK) – initially to provide district heat (see Figure 14). The gasifier itself was optimised starting in early 1994 and continuing to mid 1996.

A system for cleaning the tar-contaminated product gas was developed in the year 2000. Cooled condensers followed by a wet electrostatic precipitator to eliminate remaining tars and water droplets from the product gas are used. In April 2000, two gas engines from the Austrian manufacturer Jenbacher were installed. These natural gas fired engines with a nominal electric capacity of 1,000 kW_{el} each were down-rated to 650 kW_{el}, but one was later again up-rated to 770 kW_{el} again.

In a first step all condensate streams (from both producer gas coolers and the wet electrostatic precipitator) are filtered, where solids contained in the condensate are almost completely removed. The removed solids have to be disposed of (small amounts). The heavy tar compounds in the remaining wastewater from the gas cleaning system are removed in a conventional tar/water separator. The water cleanup system installed in 2000 also included an ultra-filtration and reverse osmosis system for removing the light (water-soluble) tar compounds prior to discharging the wastewater into the municipal sewage system. The gas cleaning system operated satisfactorily, but the system for removing the water-soluble tars failed after a few hours of operation and had to be abandoned.

By mid 2002 a proprietary water cleanup system was developed, called TARWATC (see Figure 13) [27]. The contaminated water from the tar/water separator is evaporated and the light tars are separated in a droplet separator using hot water from the engine exhaust boilers and from the exhaust steam of the TARWATC-reactor. The light tars are stored in a tank. The slightly contaminated steam is superheated in counter-flow with clean steam from the high temperature TARWATC-reactor before entering this reactor (see Figure 13). The temperature in the reactor is further increased to about 800°C by burning part of the light tars from the tank in a burner, which leads to an almost complete decomposition of the organic compounds. The steam cleaned in the high temperature reactor is in a first step cooled in a heat exchanger, where heat is transferred to the hot water circuit and in a second step condensed in a condenser connected to a district heating system and the inert gases are discharged through a flue gas stack.

The heavy tars have a gross calorific value of about 29 MJ/kg (d.b.) and are used for district heating peak load firing (see Figure 15). In future applications, the heavy tars could also be used in a biomass-fired thermal oil boiler to operate a small ORC unit producing additional electricity. This possibility is indicated in Figure 15. The light tars separated in the evaporator have a gross calorific value of 13 – 15 MJ/kg (d.b.), their energy content is usually sufficient to achieve the required temperature in the TARWATC-reactor. Only in case of unfavourable operating conditions (e.g. very high moisture content of the fuel) heavy tars are additionally required to operate the TARWATC-process. The utilisation of the tars is important in order to enhance the overall plant efficiency and to reduce waste streams. By late 2003, the water cleaning system was optimised and has operated satisfactorily since then.

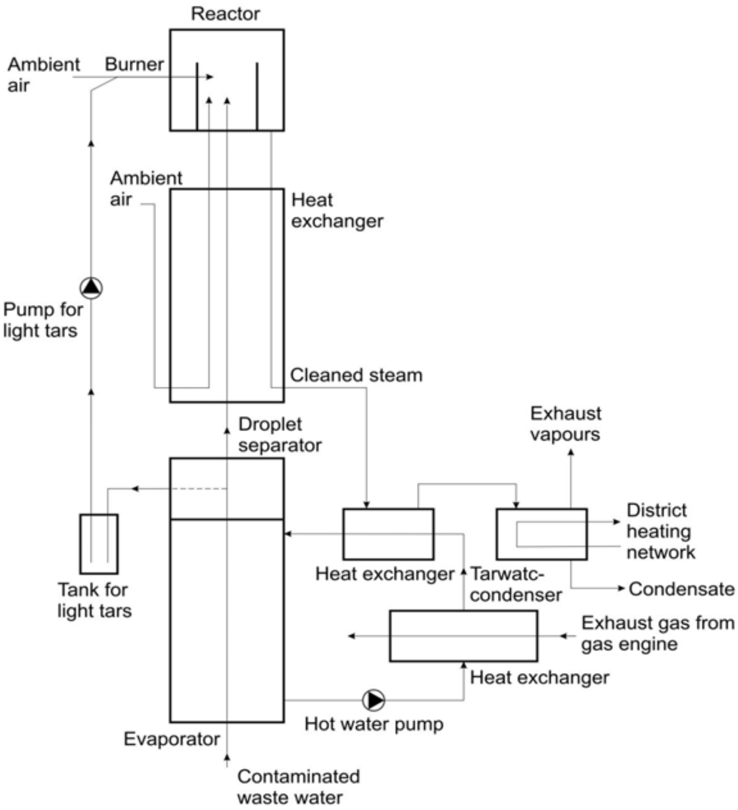

Figure 13. Simplified flow sheet of the TARWATC-process
Explanations: data source adapted from [31].

Figure 14. Picture of the updraft gasifier plant in Harboore (DK)

The plant uses wood chips from local plantations with a typical particle size of 10 to 80 mm and a moisture content varying between 35 and 55 wt% (w.b.). During a monitoring period from December 2003 to July 2004 the gas engines delivered approx. 3,700 MWh of electricity to the grid. The cold gas efficiency of the gasifier ranges between 70 and 80% in dependence of the extent of energy recovery achievable from the tars within the gasification process. The gross electric plant efficiency obtained (electric power output / fuel power input related to NCV) amounts to approx. 28.5%. The thermal plant efficiency is very high and amounts to 64.2%. The overall plant efficiency reaches 92.7%. These high efficiencies are achievable, if the heavy tars can be used to provide district heat. Overall, the Harboore gasifier has been in operation for more than 100,000 hours and the engines have operated for approx. 40,000 hours (both engines) since their installation in the year 2000 [27; 32].

The gasifier at Harboore has a proven long-term capacity of 3,700 kW_{th} fuel power input (NCV) and (when hot) it is able to modulate down to a few hundred kW_{th} and back to full load within a few minutes. The ash discharged from the system shows an organic carbon concentration below 1 wt% (d.b.). The wastewater discharged from the TARWATC condenser contains only traces of organic compounds and can usually be discharged in a sewer system.

The main advantages of the Vølund updraft gasification technology are the proven long-term operating stability, its good partial load behaviour and in particular the high overall and thermal efficiencies. The main disadvantage of this technology is the complex tar removal and water cleaning system necessary, which also increases the investment and operating costs as well as the complexity of the whole system considerably.

The standard module of the Vølund technology is available with a nominal electric power output of 2 MW_{el}, a nominal thermal power output of 3 MW_{th} and a nominal fuel power input (NCV) of about 7 MW. Units with a nominal power of 1 to 7 MW_{el} should be possible with one gasifier, but are not available yet.

A first follow-up plant of the Vølund technology with a nominal electric power output of 2 MW_{el} is currently in the start-up phase in Japan (Yamagata) [32].

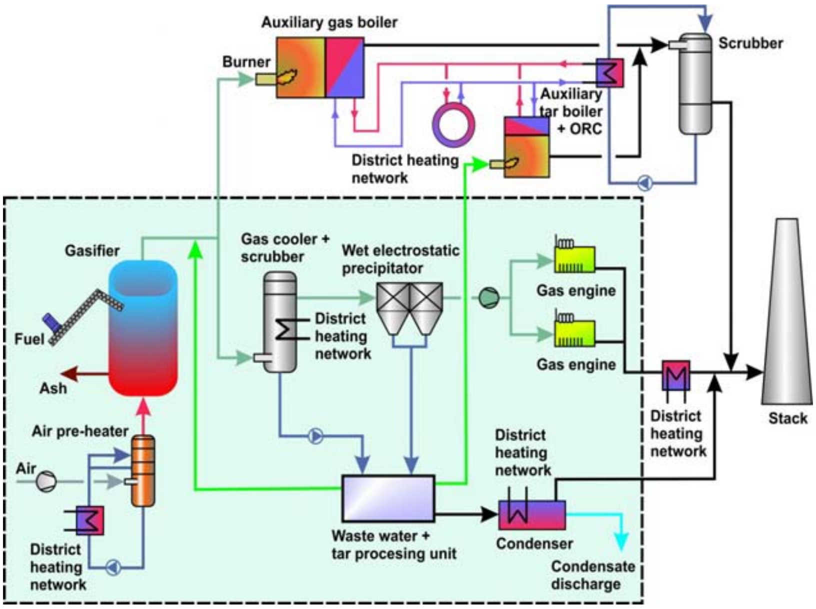

Figure 15. Simplified process scheme of the CHP plant based on an updraft gasifier in Harboore (DK)

Explanations: data source [34].

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CFB Steam Gasification Process in Güssing (A)

The Fast Internal Circulation Fluidised Bed (FICFB) biomass steam gasification process was developed by the Vienna University of Technology and the REPOTEC Umwelttechnik GmbH [35; 36; 37]. A CHP plant based on this technology with a nominal fuel power input (NCV) of 8 MW_{th} was erected in Güssing (A) and put into operation in 2001 (see Figure 16).

Biomass is gasified in a dual fluidised-bed (steam blown) reactor and the resulting gas is used to produce heat and power (see Figure 17). The fluidised bed gasifier consists of two zones, a gasification and a combustion zone. The gasification zone consists of a steam blown bubbling fluidised bed in order to achieve a nitrogen-free producer gas. The combustion zone is an air-blown circulating fluidised bed where the remaining charcoal from the gasification process is combusted. Heat is transferred from the combustion to the gasification zone by the bed material as the operating temperature of the combustion zone is about 100 °C above that of the gasifier.

Figure 16. Picture of the biomass CFB steam gasification process in Güssing (A)

The producer gas is cooled and cleaned by a two-stage cleaning system. A heat exchanger reduces the temperature from 850 to about 150 °C. The first stage of the cleaning system is a pre-coated fabric filter to remove particulates and condensed tars. In the second stage the gas is scrubbed to further remove tar compounds as well as ammonia and sulphur compounds using biodiesel as scrubbing liquid. The temperature of the product gas is reduced to about 50 °C in the scrubber. The clean gas is finally fed into a gas engine with a nominal electric capacity of 2,000 kW to produce electricity and heat. The dust from the fabric filter, the spent scrubber liquid saturated with tars, and the condensate from the scrubber are utilised by recycling them to the combustion zone of the gasifier.

The gasifier has been in operation for about 32,700 hours and the gas engine for 28,400 hours from November 2001 until September 2007. The cold gas efficiency of the gasifier amounts to approx. 71.4% and the gross electric plant efficiency to 25.6%. The thermal plant efficiency amounts to 50.9% and the overall plant efficiency to 76.5%. These efficiencies can be achieved, if fuel with a moisture content below 15 wt.% (w.b.) is used. The plant is operated with wood chips with a particle size of up to 50 mm. In order to achieve an acceptable electric efficiency the fuel moisture content should be below 20 wt.% (w.b.).

The CFB steam gasification process in Güssing (A) has already achieved a high level of development and is currently approaching the market introduction stage. Another advantage of the technology is, that an operation without problematic residues is possible. Weak points are the complex technology (high specific investment costs) and the high operating costs. This technology is thus mainly suitable for large-scale applications (>2,000 kW$_{el}$).

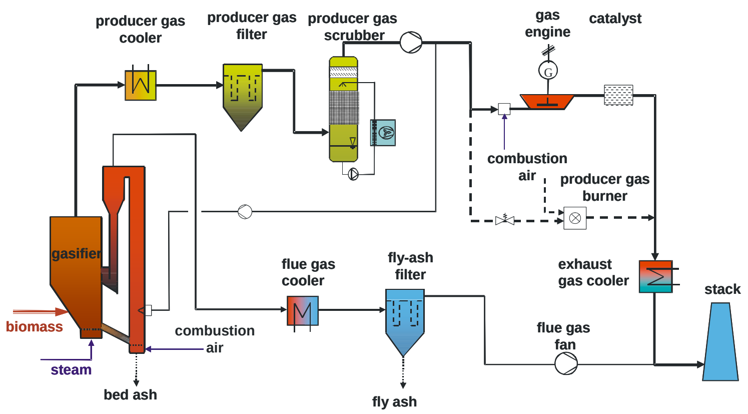

Figure 17. Simplified process scheme of the CFB steam gasification process in Güssing (A)
<u>Explanations:</u> data source [35].

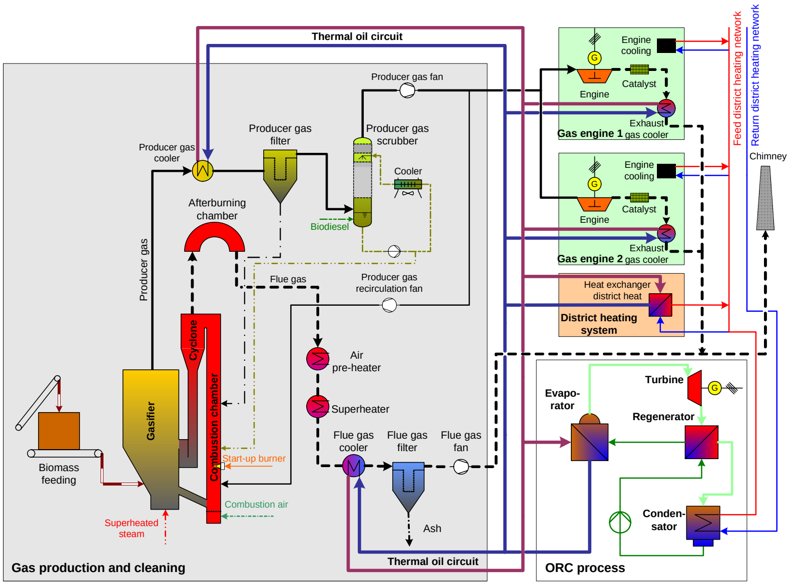

Figure 18. Simplified process scheme of the biomass CFB steam gasification process with integrated gas engines and an ORC unit
<u>Explanations:</u> data source [34].

Further development activities focus on an improvement of the cold gas efficiency by integration of a biomass dryer as well as on the integration of an ORC process to increase the gross electric efficiency of the overall process. Figure 18 shows a simplified process scheme of the new biomass CFB steam gasification process with integrated gas engines and an ORC unit. The waste heat produced in the product gas cooler, the flue gas cooler and the gas engine coolers is transferred to an ORC unit by a thermal oil cycle. Based on calculations, the innovative measures described should increase the gross electric plant efficiency to about 32.2% [15; 32]. This application is suitable for biomass CHP plants with a nominal electric capacity above 2.5 MW. Two commercial units with this combined gasification and ORC technology shall be erected in Ulm (Germany) and Oberwart (Austria).

ECONOMIC ASPECTS

Economic evaluations have been performed for five case studies of CHP plants based on biomass combustion and for three case studies based on biomass gasification. The case studies based on biomass combustion cover two Stirling engine processes (35 kW$_{el}$ and 70 kW$_{el}$), two ORC processes (650 kW$_{el}$ and 1,570 kW$_{el}$) and one steam turbine process (5 MW$_{el}$). Moreover, three case studies are based on the gasification technologies described in the previous section. All case studies evaluated are based on realised plants which are in operation (combustion systems) or on offers derived from the demonstration projects (gasification systems).

Figure 19 shows the specific additional investment costs for different biomass CHP technologies. The calculation considers only the surplus investment costs of a CHP plant as compared to a conventional biomass combustion plant with a hot water boiler and the same thermal output. This approach seems to be meaningful because decentralised biomass CHP plants primarily produce process or district heat. Electricity production is an alternative and implementation depends mainly on the profitability of the additional investment necessary.

The results show that in the case of CHP technologies based on biomass combustion the investment costs increase with decreasing nominal electric power output which clearly demonstrates the economy-of-scale effect (see Figure 19). The specific additional investment costs of the Stirling engine processes amount to approx. 5,300 €/kW$_{el}$ (35 kW$_{el}$) and approx. 4,600 €/kWh$_{el}$ (70 kW$_{el}$). The respective costs for the ORC processes investigated range from 2,600 (1,570 kW$_{el}$) to 3,600 €/kW$_{el}$ (650 kW$_{el}$) and the specific additional investment costs of for the steam turbine process investigated amount to about 2,400 €/kW$_{el}$.

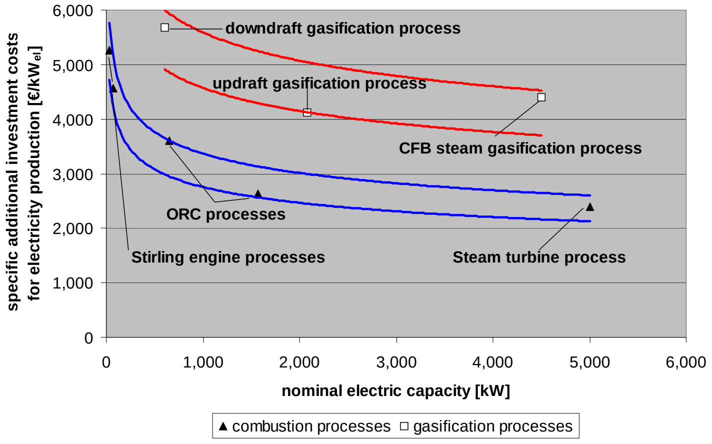

Figure 19. Specific additional investment costs for different biomass CHP technologies versus nominal electric capacity

Explanations: data source [34].

In comparison, the specific additional investment costs of the gasification processes investigated are higher and do not show a pronounced economy-of-scale-effect. This is due to the higher level of complexity and the fact that the data are based on first demonstration projects implemented (high initial costs for new technologies). A certain cost reduction potential of gasification based systems by further technological development is given.

Figure 20 illustrates the electricity generation costs for different CHP technologies depending on the electric power output. The calculation of the generation costs for electricity is based on the VDI guideline 2067. This cost calculation scheme distinguishes four types of costs: costs based on capital (depreciation, interest costs and maintenance costs), consumption-based costs (fuel, auxiliary energy, consumables), operation-based costs (mainly personnel costs) and other costs (mainly administration and insurance). The calculation of the capital costs considers only the surplus costs for electricity generation (as explained before). Furthermore, a clear distinction between heat and electricity related costs was also made for all the other cost types in order to ensure a correct calculation [38].

The specific electricity generation costs for the Stirling engine processes (nominal electric power output 35 and 70 kW) amount to approx. 0.22 €/kWh$_{el}$ and 0.19 €/kWh$_{el}$, respectively. The costs for medium-scale applications, such as ORC processes, range from approx. 0.14 to 0.17 €/kWh$_{el}$ (depending on size) and the costs for the steam turbine based process with a nominal electric power output of 5 MW$_{el}$ amounts to about 0.13 €/kWh$_{el}$.

The specific electricity generation costs of the plants based on biomass gasification are clearly higher and range between approx. 0.19 €/kWh$_{el}$ (updraft gasification process) and 0.26 €/kWh$_{el}$ (downdraft gasification processes). Again, a pronounced economy-of-scale-effect as for combustion based processes can not be seen. In this respect, high investment, operating, and maintenance costs are not compensated by the higher electric plant efficiency of this technology at present.

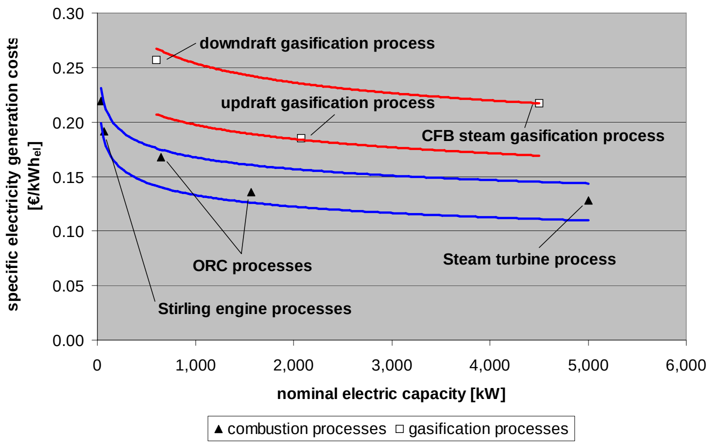

Figure 20. Electricity generation costs for different CHP technologies versus electric power output

Explanations: 6,000 annual full load hours assumed for all processes; fuel price 2.2 €Cent/kWh; no subsidies; interest rate 7%; service life 10 a, data source [34].

The results clearly show that appropriate feed-in tariffs for electricity from biomass, secured for a specific period of time (at least 15 years) in combination with investment subsidies for highly innovative concepts like small-scale combustion based and gasification based processes are needed in order to make biomass CHP plants economically competitive.

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SUMMARY AND CONCLUSIONS

Together with hydropower, biomass is the most important renewable energy source in the European Union. In the so-called RES-E Directive the European Commission has stipulated that 21% of the total electricity demand in the EU should be covered by renewable energy sources until 2010. Electricity generation from biomass represents the most important pathway to meet this objective, provided that appropriate legislative framework is available in the EU Member States.

Several state-of-the-art CHP technologies based on biomass combustion are available for medium- and large-scale applications. The steam turbine process is both economically and technically feasible primarily for large-scale CHP plants (nominal electric power output >2,000 kW). In the medium-scale power range (nominal electric power output 200 - 2,000 kW) the ORC process has proven its technological maturity. More than 50 CHP plants based on this technology are at the implementation stage or already in operation at present. The Stirling engine process is the only technology for small-scale CHP plants at present, which has the potential to meet the requirement of this market segment. Demonstration plants with nominal electric power outputs of 35 and 70 kW are in operation and a long-term test with three 35 kW_{el} engines is ongoing. It is expected that biomass CHP plants based on Stirling engines will be available on the market within the next few years.

CHP technologies based on biomass gasification are currently at the development and demonstration stage but have not yet reached a level of development which allows full commercial applications. Several promising demonstration plants, however, have been erected over the past few years and some of these are in operation for several thousands of hours, which shows the future potential of this technology. An interesting development for small-scale applications in this respect is the Pyroforce gasification system. The technology, which is based on an atmospheric air-blown downdraft fixed bed gasifier, has been demonstrated successfully, market introduction is currently starting. The updraft gasification system demonstrated at Harboore (DK) is a rather mature technology with a good partial load behaviour. The disadvantage of this technology is the fact that the product gas contains high amounts of tars, which makes a complex and expensive gas cleaning system necessary in order to utilise the gas in an internal combustion engine. The circulating fluidised bed biomass steam gasification process in Güssing (A) has proven its technological maturity and has been successfully operated with a gas engine for approx. 28,400 hours until September 2007. Weak points are the complexity of the system, the rather high operating costs and the moderate electric efficiency of the first demonstration plant. In this respect, development activities are ongoing at present in order to enhance the electric plant efficiency of the process by coupling the gasifier with an ORC unit. This technology is mainly applicable for large-scale systems (>2,000 kW_{el}).

Several side constraints are of great importance for biomass CHP plants. Due to economical as well as ecological reasons, the total annual utilisation rate (heat and electricity produced / fuel energy input [NCV]) should not be less than 60% and ideally exceed 80% which is only possible if not only the electricity but also the heat produced is utilised (heat-controlled operation of the overall system). Moreover, a high number of annual full load operation hours is a crucial factor for an acceptable economic performance of biomass CHP plants (at least 6,000 h p.a. should be achieved). In this respect, a correct design of the CHP plant is essential (dimensioning for base load coverage). In addition, a long-term supply contract for the biofuels used is recommended. Additional technical side constraints must be considered for small- and medium-scale biomass CHP plants. The technology must be robust and highly available, the plants must be designed to run in unmanned operation and a good partial load behaviour as well as the ability to handle quick load changes are necessary.

The electricity generation costs of CHP technologies based on biomass combustion range from 0.13 to 0.22 €/kWh_{el} depending on the size of the technology. The electricity generation costs for the gasification based processes clearly exceed those for the CHP systems based on biomass combustion with the same nominal electric power output. This is due to the high complexity of CHP plants based on biomass gasification resulting in high investment, operating and maintenance costs. A certain cost reduction potential is given due to the early stage of development.

Appropriate feed-in tariffs for electricity from biomass as well as a certain period of time over which these tariffs are guaranteed (at least 15 years) are essential to increase the market share of biomass CHP technologies. Moreover, investment subsidies for highly innovative concepts like small-scale combustion based and gasification based processes are needed in order to make biomass CHP plants economically competitive. These framework conditions are crucial for initiating serial production of such CHP systems, which is the most important factor for cost reduction, since the capital costs are usually the most important cost factor. In this respect, it is essential that the EU Member States define appropriate legislative side constraints on a national basis as soon as possible in order to further enhance market introduction of biomass CHP technologies which is a basic requirement to meet the EU aims regarding electricity generation from biomass.

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