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6.3 Combustion and gasification technologies

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Bioenergy conversion

There is a wide range of technologies to derive energy from biomass but, ultimately, the energy originates from combustion. Be it either the direct generation of heat or some complex process with intermediate conversion steps yielding motive power or electric energy.

The burning of wood and other solid biomass is the oldest energy technology used by man. Depending on the energy service demanded, it may be a very poor or a very good technology. A simple open-fire cooking stove has an efficiency of 10 to 15%, whereas a modern wood fired boiler utilises 85% of the energy for room heating.

Higher value energy services like motive power and electricity are derived from applying a thermodynamic cycle in a combustion engine or a turbine. We can distinguish between a direct and an indirect process, i.e. either the combustion gases serve as the working fluid in the thermodynamic process or the combustion heat is transferred to a secondary working fluid. In the direct cycle the combustion gases pass through the engine or the turbine. Modern energy conversion machines are designed and optimised for clean gaseous and liquid fuels. They are not well suited to burn biofuels and come in direct contact with the combustion products. Either the machines are adapted to burn solid biomass – which normally is not feasible – or the biomass is upgraded to a suitable liquid or gaseous fuel. Gasification is a basic step in the upgrading process – also to produce liquid fuels.

The best known indirect cycle is the steam turbine with a separate combustor and boiler. A steam power plant, however, needs to be in MW-range to be efficient and economic. In the small kW-range the Stirling engine may become a technical option.

We may identify two basic preconditions for energy production from biomass:

Firstly, biomass, mostly in solid form, is not compatible with modern energy conversion technologies like combustion engines, gas turbines etc. Therefore, biomass must be converted to a liquid or gaseous fuel or used in an indirect cycle like a steam power plant.

Secondly, biomass is a local resource and, consequently, the energy unit size is limited by the material available within a certain transport distance. Furthermore, biomass is not a standardised material and the utilisation technology will have to be adapted to the specific quality of the fuel.

The choice of conversion technology should be made in the light of the energy service demanded, i.e. heat, electricity or fuel. In Northern Europe the demand for heat is the largest end use sector, followed by transportation fuel and electricity. The overall conversion efficiency from field to final consumer is an important criteria for environmental compatibility and economics. For the future use of biomass it could serve as an indicator for the technology with the highest contribution to a sustainable energy system.

Combustion

Biomass may be used as a fuel in modern power stations and in some industrial processes to provide electrical power and heat, and in domestic stoves for cooking and heating purposes. By far most of the biomass currently used in the energy supply is converted by a combustion process, either in boilers or, mainly in developing countries, in domestic stoves. The most immediate use in Northern Europe is wood chips and pellets in domestic boilers in the residential sector. Modern boilers operate automatically and are in many regions an economic alternative, e.g. Austria and Finland.

Combustion technologies

Traditionally biomass in the form of wood, straw, and domestic, agricultural, and industrial wastes has been converted in grate or stoker type boilers. In large units a steam cycle is used to generate heat, electricity and process steam. During the last twenty years combustion technologies like suspension firing and fluidized bed have also been applied. Compared to grate fired boilers, the suspension firing technology offers higher electric power generation efficiency, lower operating costs and better load adaptation. The fluidized bed technology offers the potential for high fuel flexibility and build-in

Table 10. Global primary energy sources by 2000 (IEA “World Energy Outlook”, 2002)

Modern biomass (biomass applied in boilers)	14.900 PJ
Traditional biomass (biomass applied in stoves for cooking and heating)	30.500 PJ
Other renewable (Hydro, wind)	2.800 PJ
Conventional sources (Oil, gas, coal, nuclear)	377.500 PJ

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reduction of harmful pollutants. Grate and stoker type boilers are still used today when very problematic fuels are applied, when the boiler units are small, or when limited process and operation knowledge are available. More recent conversion technologies such as gasification or pressurized combined cycle combustion have been under development for many years. However, with respect to electric power generation efficiency and operating costs they are still typically less efficient than suspension firing boilers.

Use of biomass in simple stoves in the third world accounts for a very large fraction of the global consumption of energy (see Table 10). An increased application of modern biomass boilers in developing countries will provide both improved energy efficiency and a large reduction of harmful emissions.

Biomass applied for heat and electricity production should be converted in processes with a high efficiency and low operating costs. Furthermore the processes should be environmentally sustainable and they should provide a net reduction in CO_2 emissions. R&D can support those objectives by supporting the following type of activities:

- Increase the use of biomass by increasing the knowledge of combustion characteristics of different types of biomass.
- Improve efficiency and decrease operating costs for all types of biomass combustion units.
- Develop tools to minimize operational problems (i.e., with fuel handling, corrosion and ash deposits).
- Develop methods to remove harmful emissions and to make appropriate utilization of residual products.
- Develop methods such that biomass can be applied for power generation on high efficiency suspension fired and fluidized bed boilers.

Pretreatment of biomass

Fuel pretreatment involves the steps necessary to upgrade a harvested biomass resource to a usable fuel. It is aimed at partly at reducing storage, transport and handling costs and partly at providing a homogeneous fuel that is suitable for automatic fuel-feeding in combustion systems. The pretreatment process depends on the type of biomass as well as on the preferred combustion technology. It may involve baling (herbaceous biofuels), particle size reduction, and, if necessary, drying. Various pretreatment techniques are discussed in detail elsewhere [1].

Operational problems in biomass combustion

Biomass has a number of characteristics that makes it more difficult to handle and combust than fossil fuels. The low energy density is the main problem in handling and transport of the biomass, while the difficulties in using biomass as fuel relates to its content of inorganic constituents. The herbaceous types of biomass commonly used in Denmark contain significant amounts of chlorine, sulfur and potassium. The salts, KCl and K_2SO_4, are quite volatile, and the release of these components may lead to heavy deposition on heat transfer surfaces, resulting in reduced heat transfer and enhanced corrosion rates. Severe deposits may interfere with operation and cause unscheduled shut downs. The release of alkali metals, chlorine and sulfur to the gas-phase may also lead to generation of significant amounts of sub-micron particles (aerosols) along with relatively high emissions of HCl and SO_2.

The nature and severity of the operational problems related to biomass depend on the choice of combustion technique. In grate-fired units deposition and corrosion problems are the major concern. In fluidized bed combustion the alkali metals in the biomass may facilitate agglomeration of the bed material, causing serious problems for using this technology for herbaceous based biofuels. Fluidized bed combustors are in frequent use for biomass, e.g. wood and biogenic waste material, circulating FBC are the preferred choice in larger units. In the power range of 20 MW-el an efficiency of 30–35% is achieved with a modern steam cycle.

Application of biomass in existing boilers with suspension-firing is considered an attractive alternative to burning biomass in grate-fired boilers. However, also for this technology the considerable chlorine and potassium content in biomass, particularly in one-year crops such as straw, may cause problems due to deposit formation, corrosion, and deactivation of catalysts for NO removal (SCR). Currently wood based bio-fuels are the only biomasses that can be co-fired with natural gas; the problems of deposition and corrosion prevent the use of herbaceous biomasses. However, significant efforts are aimed at co-firing of herbaceous biomass together with coal on existing pulverized coal burners. Co-firing with coal has been successfully demonstrated and the most modern unit built in Denmark, Avedøre 2. For some problematic fuels, esp. straw a separate auxiliary boiler may be required. In addition to the concerns about to deposit formation, corrosion, and SCR catalyst deactivation, the addition of biomass in these units may impede the utilization of fly ash for cement production. In order to minimize these problems, various fuel pretreatment processes have been considered, including washing the straw with hot water or using a combination of pyrolysis and char treatment (washing or gasification or low-temperature combustion). However, during the combustion process the coal ash may capture a significant fraction of the alkali metals released from the biomass and thereby lower the problem with deposition/corrosion and SCR deactivation. Furthermore, fly ash with a certain fraction of biomass ash has now been accepted for cement production. For these reasons, pre-treatment of the straw can be avoided by choosing specific coals and keeping the straw share of the fuel mixture below a critical value. A preliminary conclusion would be that the steam cycle

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is the only commercial technology for power generation from biomass today. The units need to be in the region above 5 to 10 MW to achieve an acceptable efficiency of 25 to 30%. Higher efficiencies are achieved with co-firing, taking advantage of the good steam parameters, frequently super critical, in large power station of the 100 MW class and more.

Gasification

The gasification of wood fuel has a long tradition, especially in small units. The technology can also draw on experience gained with lignite and hard coal. Over the years a large number of gasifiers have been built and partly developed to an industrial level. In particular, a considerable effort has been made towards the use of gasification as part of CHP strategies. Further, the technology has been automated to a level approaching other biomass based power generation systems.

One reason for considering gasification is that the combustion of solid biomass is changed into the much more attractive process of burning a gas and the inorganic material present in the biomass does not enter the final combustion zone.

Modern gasification technology with high quality standards for the product gas is a complex process.

The product gas consists mainly of H_2, CO, CH_4, and CO_2 and is mostly intended for immediate use on site and the gasification unit is an integral part of the power generating plant. In the small unit size the gas is mostly used in a combustion engine and in the larger units in a gas turbine or combine cycle plant. In this way a higher efficiency of the biomass conversion can be obtained. In consequence, the size of the gasifiers and the energy conversion technology must be optimised to integrate all energy flows such as waste heat from quenching and cooling the raw gas.

Technology platforms

The gasifiers fall into three categories:

- Fixed bed gasifiers.
- Fluidised bed gasifiers.
- Entrained flow gasifiers.

The fixed bed gasifiers are mostly small scale and come in two types, either down-draft (<2 MW) or up-draft (<10 MW). They differ in the direction of gas flow through the biomass in the reactor. In the up-draft gasifiers the raw gas contains important fractions of tar which need to be removed before using the gas. The down-draft reactor enables the cracking of the high hydrocarbon fraction but a drawback is the high gas temperature at the outlet.

The fluidised bed gasifiers, either stationary, SFB, or circulating, CFB, are in the MW-range. The circulating variety, CFB, requires a size of more than 15 MW to be commercially viable. The product gas is characterized by low tar content and also sulphur and chloride may be absorbed in the bed material. Thus, fluidised bed gasifiers apparently reduce significantly the problems associated with the utilization of agricultural biomass.

Entrained flow gasifiers operate at very high temperatures, 1200 to 2000°C and require biomass in form of very finely ground particles. Again there are a number of different types. A special feature is the utilisation of the high temperature heat in the raw gas which is quenched after leaving the reactor.

The cold gas efficiency, describing the heating value of the gas stream in relation to that of the biomass stream, is in the order of 55 to 85%, typically 70%. For biomass air is mostly used as the gasifying medium. Pure oxygen or steam is seldom used as the complexity of the process scheme is hardly justified. The heating value of the gas, mostly consisting of CO and H_2, is in the region of 5 MJ/m^3 or roughly one sixth of natural gas. In comparison, biogas from anaerobic fermentation with a high methane content has a heating value corresponding to one half of natural gas.

Gas quality and environmental issues

A major challenge has been to develop gas-cleaning strategies to meet the stringent requirements of gas quality. Two methods deserve to be mentioned, namely the wet gas cleaning procedure developed by Babcock & Wilcox Volund (BWV) and the high temperature two-stage gasification as developed at the Technical University of Denmark. The methods are part of the 6 MW_{TH} CHP demonstration plant (Harboøre, Denmark) and the 75 kW staged gasifier ("Wiking") at the Technical University of Denmark, respectively [2,3].

The BWB method is based on gas cooling and wet electrostatic precipitation. A prerequisite for fuelling engines with the product gas is that the gas temperature is lowered to approximately 40°C. This temperature drop causes the release of a large quantity of a water/tar condensate. The wastewater has been a significant problem due to it's high content of light tar compounds. However, a novel process for cleaning the wastewater ensures a 99.98% cleaning efficiency and, hence, that the water can be discharged without restrictions. Furthermore, an even more compact cleaning system based on supercritical wet gasification/oxidation is currently being developed.

The main advantage of the two-stage gasification process is, that contrary to most other gasifiers, very small amounts of tar is present in the produced gas. This is the result of a highly efficient, on-line gas cleaning based on a high temperature, reactive bed. So the costs for gas cleaning before use of the produced gas in gas motors or turbines can be significantly reduced.

It is a characteristic feature that the developed procedures for gas cleaning demonstrates efficiencies well above 99.9%.

The emission from CHP gasification plants seems not to present specific problems with the exception of CO. The Danish regulations request in general CO-levels below

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500 mg/Nm^3 in the exhaust. This limit is the result of an apparent coupling of the CO emission with the emission of PAH in combustion processes. This is obviously not the case using a partly CO based fuel. On the other hand, a simple catalyst system may reduce the CO emission close to the present limits.

The ash seems to have a low carbon level and is tested negative for dioxin and PAH's and may, hence, be used as a fertiliser in agriculture/plantations.

Towards the green fuel cell

Electricity production by SOFC fuel cells is one road to obtain a high efficiency in electricity production. In order to meet this demand in a sustainable way, gasification and SOFC fuel cell conversion systems based on biomass, should obviously be considered. The most cost-effective size has been estimated to be plants up to 30 MW_E and electric efficiencies well above 50% are expected.

The highly purified gasfication gas has the potential to be used directly in SOFC cells or alternatively steam-reformed. In this case, steam gasification of biomass would directly enhance the hydrogen content in the crude gas. The biomass-hydrogen route could be a promising future technology bringing a green fuel cell to reality.

Liquefaction of biomass

Thermal conversion of biomass has been investigated for many years as a possible source of renewable liquid fuels. Fast pyrolysis is an advanced process which gives a yield of bio-fuels up to 80% on dry feed, typically, 65% liquids and 10% non-condensable gases. The characteristic features of fast pyrolysis are the very high heating and heat transfer rates, a carefully controlled pyrolysis temperature and a rapid cooling of the products. The process may advantageously be carried out on CFBs modified to operate at low temperatures. However, the technology is still at a relatively early stage.

The liquid bio-fuels are storable and have the advantage of separating the fuel production from the utilisation. They can substitute fuel oil in any stationary heating or power generating application and have a heating value of about 40% of a conventional fuel. Thus, bio-fuels may well find use at peak loads at large power plants. The dominant use of liquid bio fuels is in the transportation sector, at least on the continent. Oil from plants, especially rape seed is obtained in pressing and extraction and can be used directly in dedicated engines. In a subsequent process a methylated ester is produced with a quality comparable to diesel fuel. It is marketed as "Bio-diesel" or is blended with standard diesel.

A different approach is to convert the gas from the gasification of biomass in either a methanol synthesis process or a Fischer-Tropsch process yielding light hydrocarbons. Both products can be used as straight fuels or as blends. The efficiency of the total processing route is a critical parameter. The costs are obviously higher than similar products from mineral oil. The tax regime and the national fiscal policy are determining factors in market penetration.

Conclusion

- The combustion of solid biomass to produce heat is an established and (mostly) economic technology in the whole power range. Especially for small units in the residential sector a further market penetration would require a convenient and user friendly fuel supply and service infrastructure.
- The combustion of biomass to electricity is today technically and economically only feasible with the steam cycle in the larger MW-units, especially in co-firing.

Table 11. Qualitative comparison of technologies to produce electricity, heat and/or power from biomass. + relatively poor or low, +++ relatively good or high, # relatively cheap, #### relatively expensive.

	Technology	Economics	Environment	Market potential	Present deployment
Combustion - Heat	+++	#	+++	+++	+++
Combustion - Electricity	++(+)	##	++(+)	+++	++
Gasification	+(+)	###	+(++)	+++	
Pyrolysis	(+)	####	(+++)	++(+)	

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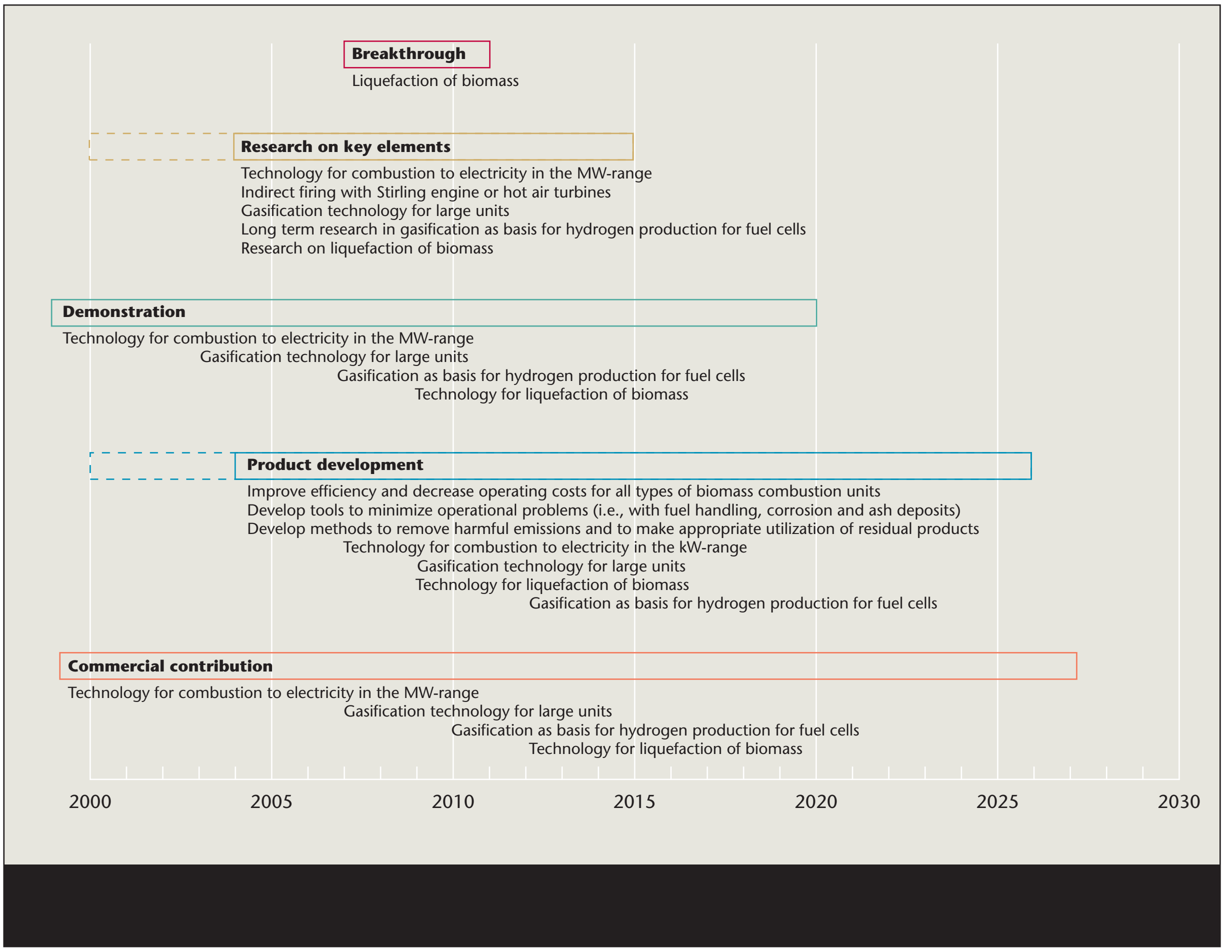

Figure 15. Time scale from breakthrough to commercial contribution

There is no technology available in the kW-range. On the longer time scale indirect firing with Stirling engine or hot air turbines appears promising.

- Thermochemical gasification allows to transform (almost) all biogenic feedstock into a low caloric gas which can be utilised in a broad range of technologies. The gasification technology is in the demonstration phase and still has technical and economic deficits, especially in small units. The potential applications are large, primarily for electricity and heat. On the longer time scale, gasification could be the basis for hydrogen production for fuel cells.
- The upgrading of biogas to a liquid fuel would open a large range of potential applications. The process chain entails, however, a number of conversion losses and does at present not appear to be the most efficient use of the biomass resource potential.