ADVANCED TECHNIQUES FOR GENERATION OF ENERGY FROM BIOMASS AND WASTE

1.   INTRODUCTION

Biomass contributes as the world's fourth largest energy source today up to 14% of the world's primary energy demand. In developing countries it can be as high as 35% of the primary energy supply. Biomass is a versatile source of energy in that it can be readily stored and transformed into electricity and heat. It has also the potential that it is used as a raw material for production of fuel and chemical feedstock. Production units range from small scale up to multi-megawatt sizes.
Development of biomass use contributes to both energy and other non-energy policies.

None energy related arguments are:
- Environmental and climate change. CO_2 is the main gas responsible for climate change, and it is observed that the gas emissions from road transport are the main contributors to the increase of the total level of emission in recent years, in spite of levelling off or even reduction of CO_2 emissions from other activities in the European Union.
- Environmental Policy: The life cycle of biomass as a renewable material has a neutral effect on CO_2 emission. It also offers the possibilities of a closed mineral and nitrogen cycle. The environmentally hazardous sulphur dioxide (SO_2), which is produced during combustion of fossil fuels, leading to acid deposition, is not a major problem in biomass systems due to the low sulphur content of biomass (< 1% compared to 1 to 5% for coal).
- Agricultural Policy: CAP (Common Agricultural Policy) and the search for alternative uses of set-aside land. It is estimated that 20 million hectares of agricultural land and 10-20 million hectares of marginal land could already be made available for non-food production by the year 2000.
- Social Policy: Estimates show that 11 jobs are created per MW of installed biomass conversion capacity so that 5% of coverage of the EU energy needs on the basis of biomass would lead to 160,000 additional jobs (Wright report).
- Regional Policy: Biomass can be used as a decentralised energy source where conversion plants are located close to the source of biomass. This would lead to stabilisation of employment in rural areas and regional development.
- Security of supply. 98% of the transport market is dependent on oil. In the case of no policy on the level of the EU, the external energy dependence will reach 70% before 2030. This dependence will be up to 90% when it concerns oil imports.

Energy related motivations for use of biomass are:
- Biomass can readily be used in boilers to produce directly heat and/or steam to generate electricity. This is being done at a small scale at remote locations and in a centralized way in large production units of more than 50 Megawatts. Co-firing with coal is an attractive option with a relatively low need for additional investments.
- Gasification is, although the technology exists already for decades, it is still being developed for advanced uses of biomass and waste. The gas which can be produced this way, a syngas, is a well known commodity in the energy generation and chemical process industry and offers excellent options for high efficiency large scale electricity production and chemicals.
- The EU has put forward the objective to substitute 20% of traditional fuels by alternatives in the road transport sector by the year 2020, which has lead to a Directive on the promotion of biofuels. This draft Directive contains a proposal for an obligation on member states to

ensure that, from 2005, a minimum share of transport fuel sold on their territory will be bio-based, whereas the individual member states sell a minimum proportion of biofuel of 2%. This level should grow by a yearly amount of 0.75% in the following years up to a level of 5.75% in 2010. In 2020 8% of the fossil fuel based transportation fuels has to be substituted by biofuels. To meet this 2020 EU-goal large scale robust, reliable and cost-effective biofuel production facilities have to be developed and implemented, with final production costs of 10 Euro/GJ.

- Biofuel currently represents 0.3% of the total diesel and gasoline consumption in the market, which is basically the result of 6 member countries amounting to a level of 700 ktons in 2000.

- Major oil companies in the EU have formulated their strategies in view of their responsibilities to contribute to a sustainable development, but also advocate a seamless introduction. This means that any replacement of conventional fuels by biofuel should not induce major changes in the current supply and distribution infrastructure. For the next decades any biofuel should have such properties that they can be blended into the current conventional fuels without major adaptation of the technological infrastructure. This means that carbon based renewable fuels are for the next decades the only option for a substantial replacement of the fuel pool.

- Obviously, there is a good chance for natural gas to become a transportation fuel, which, however, does need extensive adaptations in the supply infrastructure, but only minor modifications on the car engine. Natural gas has lower CO_2 emissions per unit of delivered mechanical energy and consequently less emission. Also dependence on supply from outside the EU is less than in the case of mineral oil. In the long run hydrogen will become important, giving other renewable energy sources a chance to contribute. However, technology is still in its infancy and a distribution and supply infrastructure is non-existent. It is believed that hydrogen will break through after the year 2020 or even later.

- The major candidates for short term replacement of fuel out of mineral oil like biodiesel (RME), pressed vegetable oils (PVO), and conventional bio-ethanol from starch and sugar crops show manufacturing costs of between 12 and 21 dollar per Gigajoule, which compares with the costs including excise duty and taxation of mineral diesel between 17 and 30 dollar per Gigajoule. This latter depends on the price per barrel of crude oil, which for this analysis is taken between 15 and 25 dollar per barrel. This means that a policy based on exemption of excise duty on biofuels, and an increase of the price of mineral oil, will create the economic conditions for replacement. In the (near) future Fischer-Tropsch diesel and bio-ethanol from lignocellulosic biomass can offer lower prices than current biodiesel and conventional bioethanol fuels.

Already a surprising number of actions are undertaken with promising results:
- In Austria, the contribution of biomass for district heating has increased 6-fold [1] in Sweden 8-fold [2] during the last decade thanks to positive stimulation at federal and local level.
- In the USA, already more than 8000 MW_e installed capacity based on biomass has been installed, primarily stimulated by the PURPA-Act [3].
- In France, direct combustion of wood represents almost 5% of the primary energy use [4].
- In Finland, bio-energy already amounts by 18% of the total energy production and if foreseen to grow to 28% by 2025 [5].

It is obvious that the above given arguments underline the dependence of the introduction of biofuels in the transportation sector on external factors like commitment of EU member states to international agreements and directives as well as local circumstances such as industrial infrastructure, crude oil price, availability and contractibility of biomass, taxation policy and choice of the best option for development of renewable energy recourses.
On the other hand, the technological development can severely influence the production costs and large-scale availability of biofuels. It is for the time being still in debate which is the best option for the conversion technology starting from biomass supply all the way to the end-use.

Further, the actual choice will depend on local circumstances such as potential set aside agricultural land in the EU, the availability of waste vegetable oil and fats and/or other derived organic waste streams.

2.   PRESENT SITUATION

This section summarises the current status of biomass technology from biomass crops, conversion technologies to end products, technologies available and end products of the conversion process.

Figure 2.1 gives an overview of the different routes from biomass to end products.

This system focuses on distributed production, which is the area where nowadays the very challenging developments are underway. However, particularly in the Netherlands, the main contribution to renewable energy generation is co-conversion with coal-fired stations and in the future with gas turbines.
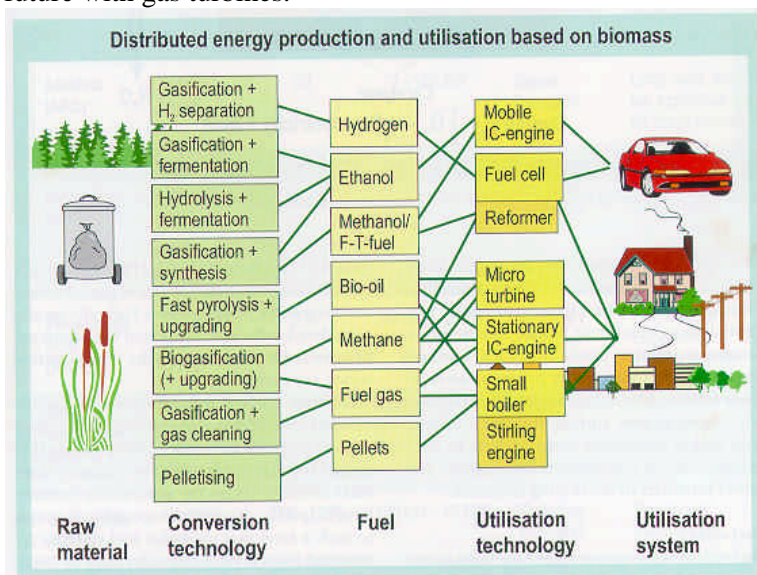

Figure 2.1 *Potential paths for biofuel-based distributed energy production (taken from "Energy Visions 2030 for Finland)[5]*

In the year 2004, some 9 PJoule of bioelectricity generated by co-firing is expected besides 20 PJoule generated in small-scale units in the Netherlands. The plans exist to achieve in 20010 34 PJoule by co-firing against 26 PJoule in small-scale operations.

Co firing in coal fired power stations is a very attractive option as the biomass or biomass derived waste is taken with the coal into the boiler. This bio-fuel can either be ground down to the size of the pulverized coal particles and mixed up with the coal, or it can be injected in separate units into the same boiler. In both cases the grinding is a critical step and can substantially influence the costs of the electricity generated due to the co-firing. For the rest, the downstream equipment remains the same and no major investments are necessary. R&D work at ECN has resulted in a thermal pre-treatment for bio-fuel (Torrefaction). [21] which gives the fuel similar properties as the coal concerning the ignitability, next to other benefits like hydofobicity and reduced weight. In the end even homogeneous properties can be given to a broad band of bio-fuels and wastes so that the specificity for fuels might become less severe. The negative side obviously is an extra process step.

The co-firing potential of current units is the limitation due to the fact that ashes with different properties than coal are mixed up which can lead to unwanted, or at least, not well understood ash behaviour in the applications which it is now being used for. A way out of this problem is to separately gasify the biomass and inject the syngas into the boiler. In this way, in principle,

more freedom exists in choosing the balance between coal and biomass input and the ashes are entirely separated. The draw back is the extra gasifier that has to be invested.
Figure 2.2 gives an example of a gasification unit for co-conversion with a 600 MW power plant.
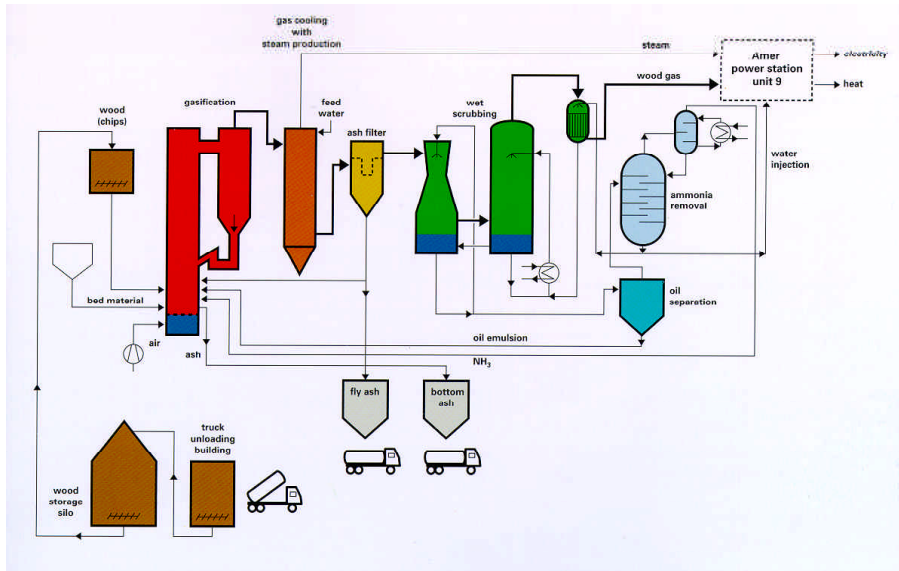

Figure 2.2 *Indirect cofiring by upstream gasification (Amer-9 power plant of Essent)*

The waste incineration area has recognized that, next to elimination of municipal waste material, the generation of electricity will become more and more interesting from both societal and economic point of view. This is also stimulated by the fact that, for instance in the Netherlands, up to 50% can be considered as renewably generated electricity which has all the benefits of selling price, tax exemption and subsidees.
In view of this up to now, some 12 Petajoules of fossil input is replaced by electricity generated from waste. The plans are to increase this amount to 20 Petajoules by the year 2010 [19].
The initiative recently taken by the "Afval Energiebedrijf " in Amsterdam envisages to build a 530.000 tons per year waste incineration unit based on grate combustion and employing flue gas recirculation, improved steam conditions in combination with advanced materials in the hot zones, adding up to an output efficiency of more than 30%.
Figure 2.3 shows a schematic of this new unit being build up along with the steam flow and conditions and some other performance factors.

2.1   Biomass material

The main biomass resources include the following: short rotation forestry (Willow, Poplar, Eucalyptus), wood wastes (forest residues, sawmill and construction/industrial residues, etc.), sugar crops (Sugar beet, Sweet Sorghum, Jerusalem Artichoke), starch crops (Maize, Wheat), herbaceous lignocellulosic crops (Miscanthus), oil crops (Rapeseed, Sunflower), agricultural wastes (straw, slurry, etc.), municipal solid waste and refuse, and industrial wastes (e.g. residues from the food industry). Current and future biomass resources in the EU are given in Table 2.1.
It can be seen from the table that in the long term, energy crops can be an important biomass feedstock. At present, however, wastes, either in the form of wood wastes, agricultural wastes, municipal or industrial wastes, are the major biomass sources and, consequently, the priority fuels for energy production. There is also an additional environmental benefit in the use of residues such as municipal solid waste and slurry as feedstocks as these are withdrawn from polluting land filling.
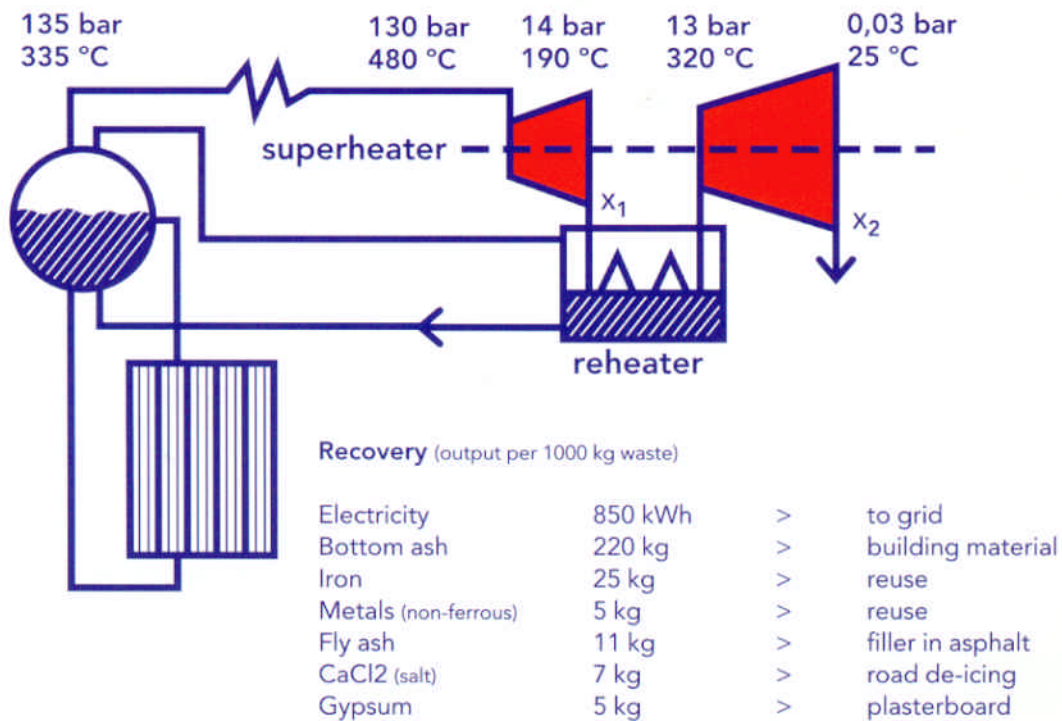
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Figure 2.3 *Flow scheme and characteristics of the new AEB Amsterdam new waste incineration unit*

Table 2.1 *Current and future EU biomass resources [6], [7], [8]*

Raw Material	Current Resources (dry) Mt./yr.	Future Resources Mt./yr.
Short Rotation Forestry	5	75 -150
Wood Wastes	50	70
Energy Crops	-	250-750
Agricultural/Wastes	100	100
MSW/Refuse	60	75
Industrial Wastes	90	100

Research on biomass energy crops is concentrating on generating reliable data on potential yield, environmental impact, limitations and economics. Developments are done through networks of research groups such as the Miscanthus Network, the Sweet Sorghum Network etc. There is also a number of other European and national projects which carry out research on a range of biomass materials.

2.2 Conversion processes

Biomass combustion or gasification?
Biomass combustion results in either heat or electricity. Biomass gasification results in a combustible gas, which can be used for the generation of different products: heat, electricity, synthetic natural gas (SNG), transportation fuels and chemicals. So only if heat and/or electricity is required, combustion and gasification are competing processes.

If heat is the only product required, combustion seems to be preferable. Small-scale heat producing plants however suffer from bad economics[1], especially if high emission standards are to be met. Large-scale generation of SNG by biomass gasification (and subsequent distribution to small-scale users where the SNG is burned to produce heat) is considered to be an attractive alternative.

If electricity is the desired product from biomass, combustion and gasification compete. Gasification however, can reach higher electric efficiencies because of Carnot's law[2]. The advantage becomes even larger if a fuel cell is added to the gasification system, since the efficiency of a fuel cell does not depend on Carnot's law. In reality, thermodynamic optimum systems cannot be made due to different losses and non-ideal behaviour. The main conclusion however remains valid: conversion by gasification leads to a higher electric efficiency than conversion by combustion. Furthermore, by gasification more products can be produced (liquid fuels like diesel, methanol and gaseous products like "natural gas" and chemicals like H_2). Even if only heat is required, gasification probably plays a crucial role by producing *SNG*, which can be stored, distributed and burned where and when heat is desired.

Combustion

Combustion can be represented by:

$$C_6H_{10}O_5 + 6\ O_2 \quad \text{------->}\quad 6\ CO_2 + 5\ H_2O + 17.5\ \text{MJ / Kg.}$$
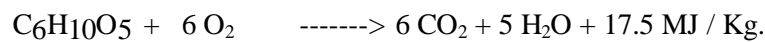
Biomass + Oxygen (air)   Carbon dioxide + water + heat.

The majority of biomass and agricultural waste derived energy comes from wood combustion. There is a constant drive to improve the combustion efficiency up to more than 30% and a reduction in pollutant emissions. The major development in this area is in large combined heat and power plants (CHP). Direct combustion processes for heat production and driving a steam cycle are commercialised already. New developments towards better overall thermodynamic efficiencies of the steam cycle and firing of biomass powder in ceramic gas turbines are envisaged.

The amount of heat produced depends on the humidity of the biomass source, the level of excess air required and whether or not complete combustion is accomplished. Today, combustion technology is extremely well advanced, permitting widespread industrial application. Two types of boiler are commonly in use:

- Boiler with fixed or travelling grates.
- Boilers with fluidised-beds.

The former type is very common, ranging from the household boiler to large scale 50 MW industrial furnaces, and can accommodate heterogeneous combustible material in terms of composition, humidity and granularity. On the other hand, load following is difficult. Figure 2.4 shows the principle of a household boiler of the Herz company in Slovakia, the capacity ranges up to 150 kW.

In a fluidised-bed, shown in Figure 2.5, the combustible particles, together with the granular bed material, are carried by a constant flow of gas in upward direction. The fuel is constantly

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[1] Small-scale generally is relatively expensive, and also small-scale heat consumers (often space heating) only need heat during the cold season, which means that the "plant" only operates limited time.

[2] Carnot's law states that the maximum efficiency from heat to work that can be obtained is equal to 1- T_{low}/T_{high}. A gas turbine is powered by gas with much higher temperatures (up to 1200°C) than the steam powered steam turbines (up to 600°C). This is the principal reason why gasification can reach higher electric efficiencies. Assume the following systems: combustion with 95% efficiency to steam and with 600°C to 100°C steam cycle and gasification with 80% gas yield with combined cycle (1200°C turbine inlet temperature to 100°C steam exit temperature) and 20% heat with steam cycle from 400 to 100°C. The theoretical maximum (thermodynamic) efficiencies are 69% and 54% for gasification and combustion respectively. If the gas from gasifier at 900°C can be used in the gas turbine directly (without intermediate cooling/steam generation), the maximum efficiency even rises to 74%. These are absolute maximum values, but it illustrates the difference between combustion and gasification.

injected into this bed. The bed itself constitutes the major heat capacity of the system and therewith stabilizes the process. In this way, effective heat and mass transfer are being taken care of. Such a system can combust a wide range of materials including fuels of non-biological origin. From an investment point of view, this fluidised-bed technology becomes attractive at plant sizes larger than 10 MW(th).
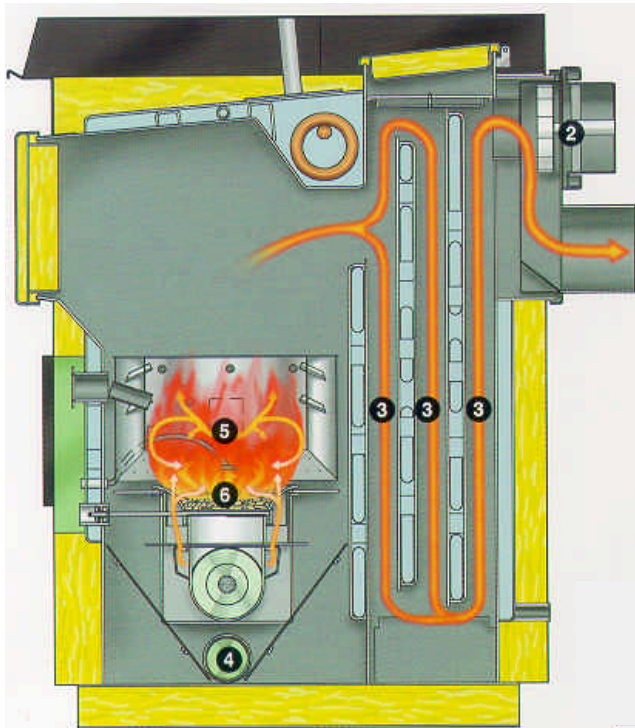
2.   Ventilator for off gases
3.   Heat exchanger
4.   Ash removal
5.   Combustion space
6.   Burner surface

Figure 2.4 *The principle of a household boiler of the Herz company in Slovakia*

Their main advantage is the possibility to use mixtures of various types of biomass (woody, non-woody) and/or to co-fire them with other fuels. Nevertheless, compared to grate-fired boilers, their operation in partial load is problematic.

As already mentioned, a promising development in combustion for efficient biomass conversion is co-combustion. This can be applied in existing coal plants of a large capacity, allowing for high efficiency of electricity production. New boiler concepts, where biomass is combusted together with coal, peat, RDF (refure-derived fuel, i.e., upgraded urban waste fractions) or other fuels can achieve high efficiencies, due scale factors and reduced risks as more than one type of fuel can be used, e.g., to compensate seasonal influences in bio-feedstock availability (see also Figure 2.2).

Gasification
As the gasification reaction itself is endothermic, heat has to be supplied to the system by external sources. This heat can be brought to the reaction zone through the wall of the reactor, by the bed material itself or through a hot process gas stream. Due to the fact that, usually, no air (or oxygen) is taken up into the process gas, a product gas with middle or high calorific value is produced (10-18 MJ/Nm^3). Such a high calorific value gas is attractive since volume streams are reduced making downstream processing like gas cleaning, compression or any kind of catalytic process relatively simple and therefore cheaper. In this respect a wealth of highly advanced processes are being developed and demonstrated or are awaiting demonstration at a sizeable scale [9], [10], [11], [16].
The other way to generate the heat necessary for the gasification reaction is to partially combust the biomass fuel giving the most direct supply of heat to the gasification process itself. The overall reaction reads:

$C_6H_{10}O_5 + 0.5O_2 = 6CO + 5H_2 + 1.85$ MJ/kg

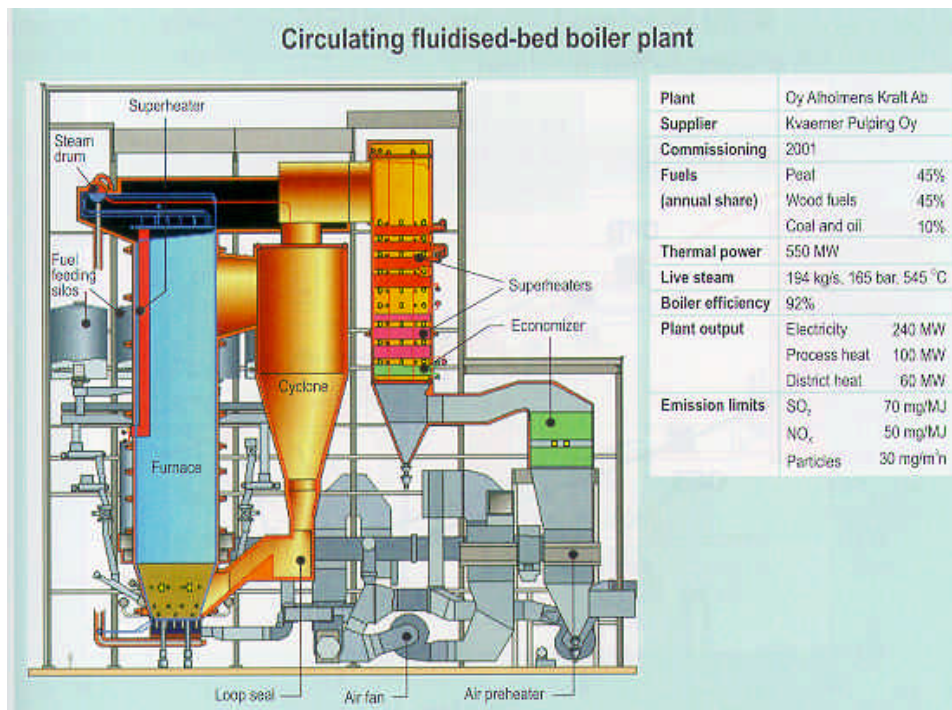but it also produces some CO_2 and H_2O in the fuel gas stream.

Figure 2.5 *Circulating fluidised-bed*

In the simplest system, air is used for the supply of oxygen, so that the syngas produced is diluted with nitrogen. Calorific values are in the range of 3- 8 MJ/Nm^3, depending on the system applied. Air gasification itself is relatively cheap, but downstream processing to clean the gas is expensive due to large volumes to be handled. Gasification with pure oxygen requires an oxygen supply, which is expensive, particularly at small scales.

Fixed bed downdraft gasification, Figure 2.6B, concerns small scale by definition, the maximum capacity is several tens of MW$_{th}$. Furthermore, the conversion generally is low. Downdraft gasifiers can also be made "slagging", which means that inert material leaves the gasifier as a liquid slag and the conversion rises to almost 100%. This generally requires oxygen in order to reach the desired high temperatures.

Fixed bed updraft gasifiers Figure 2.6A, are characterized by high conversion and high efficiency. The exit gas temperature is generally 100-300°C due to the counter current flow of solid fuel and hot gas. The product gas contains large amounts of hydrocarbons. Tar (large hydrocarbons) make up approximately 15% of the energy content of the gas. The biomass fuel specifications are mild, but there is a risk of too high-pressure drops over the bed if too much small particles are fed. Fuels with slagging tendency can cause problems in the hot bottom zone, but updraft gasifiers can also be made "slagging". This means that inert material leaves the gasifier as a liquid slag. This generally requires oxygen in order to reach the desired high temperatures.

Fluidised bed gasifiers, Figure 2.6C are characterized by the presence of an inert heat carrier like silica sand. Fluidised bed gasifiers can be separated in three types: BFB, CFB, and coupled fluidised beds (indirect). BFB (bubbling fluidised bed) is the simplest concept. It also seems suitable for applications where oxygen (and steam) must be used instead of air. CFB: circulating

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fluidised bed as shown in Figure 2.6C, reactors are often seen as the most suitable for large-scale applications. BFB as well as CFB gasifiers show a limited conversion of 90-95%. This can be increased to approximately 98% by using smaller fuel particles. Indirect gasifiers contain two reactors where gasification and combustion are separated. Two gases are produced: a N_2-free product gas and a "conventional" flue gas. Because the conversion is complete, indirect gasifiers seem to be the attractive alternative of oxygen/steam-blown fluidised beds when N_2-free gas is required.

Entrained flow reactors, Figure 2.6D, are practically empty vessels, where small fuel particles (or liquids) are converted at high temperature. It can either be slagging or non-slagging. Slagging gasifiers are preferable if biomass is used. The conversion is almost complete, but oxygen is needed to achieve the high temperatures needed. Biomass should be pulverized to a size of 1 mm. Entrained flow gasifiers are used to produce syngas to be used either as syngas or for electricity generation. This means that these gasifiers in practice operate at elevated pressure. The entrained flow technology (Figure 2.6D) is primarily developed in the petrochemical industry as a means to gasify heavy residues. It is now being used successfully for high-pressure gasification of pulverized coal and will be applied for centralized gasification of pre-treated and pulverized biomass. The high temperature reactor in the Carbo V system is an example of such an entrained flow reactor (Figure 4.2).

The gas obtained by gasification can be combusted in a diesel, gas or "dual fuel" engine, or in a gas turbine. Several biomass gasification processes have been and are being developed for electricity generation. In BIG-ISTIG (Biomass Integrated Gasifier-Steam Injected Gas turbine), steam is recovered from exhaust heat and injected back into the gas turbine. In this way, more power can be generated from the turbine at higher electrical efficiency.
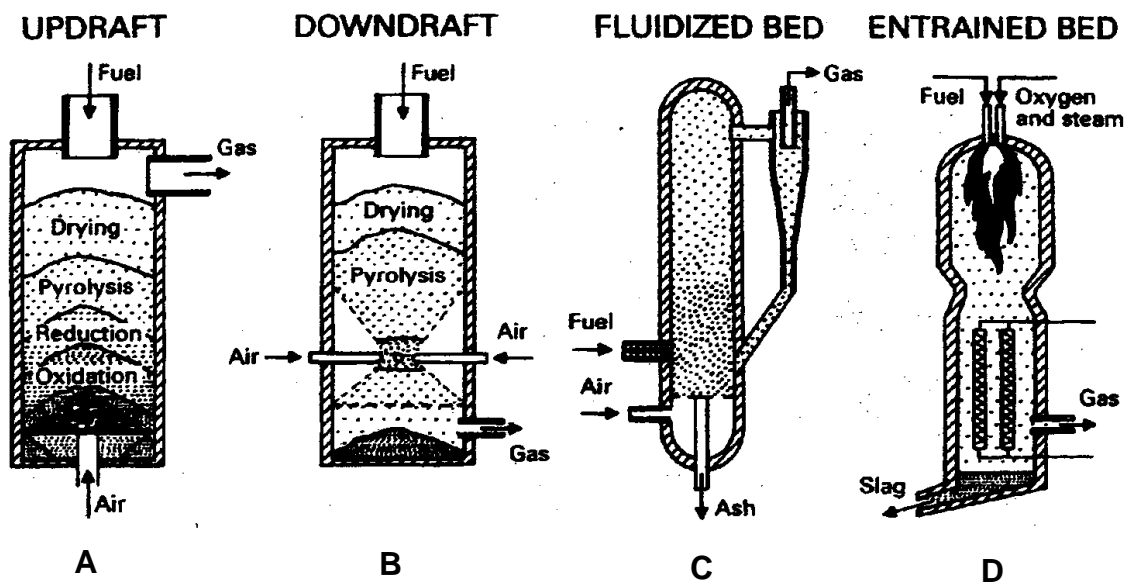

Figure 2.6 *Schematics of different direct gasification reactors*

As the gasification temperature is high (up to 2000°C) tar production is absent and a relatively pure syngas is produced which will be used for catalytic biofuel production.

Pyrolysis/Carbonisation
Pyrolysis is a process of decomposition at elevated temperature (300 to 700 ^{O}C) in the absence of oxygen. The products obtained by pyrolysis of lignocellulosic matter are: solids (charcoal), liquids (pyrolysis oils) and a mix of combustible gases. The properties of each of the products is dependent on the reaction parameters i.e. the temperature, heating rate, residence time and the

actual pressure at which the process takes place. Pyrolysis has been practised for centuries for the production of charcoal (carbonisation). This process is running at relatively low reaction temperatures and high residence times to maximise solid char yield at around 35%.

In recent years more attention has been paid to the production of pyrolysis oils, which have the advantage of being easier to handle than the starting biomass and have a much higher energy density. Yields of up to 80% by weight of liquid may be obtained from biomass material by using fast or flash pyrolysis at moderate reaction temperatures.

These liquids, currently referred to as bio-oils or biocrudes, are intended to be used in direct combustion in boilers, engines or turbines. Nevertheless, some improvements on the product are necessary to overcome unwanted properties such as poor thermal stability and heating value, high viscosity and corrosivity.

For use as a fuel for combustion engines, or even more advanced applications, extensive upgrading will be necessary liker deoxygenation by catalytic hydrotreating at high pressure or zeolite cracking at atmospheric pressure. Both processes are being developed at laboratory scale [12]. The main advantage of fast pyrolysis for the production of liquids is that fuel production can be done separated from power generation, and can be considered as a densification step to facilitate transportation and inevitable elaborate handling. Although it reduces transportation costs, the extra step of in-site pyrolysu8is offsets the costs involving direct transportation of the raw biomass [22].

Figure 2.7 shows the fast pyrolysis unit based upon the "Rotating Cone Principle" in operation at Biomass Technology Group at Enschede. This unit is now being upscaled to high capacity (> 1 MW output). Here biomass falls in hot sand, which is transported over the inner surface of a spinning cone. Sand takes care of heat transfer and residence time is determined by the cone size and rotation speed. The char is the source of heat in this reactor.
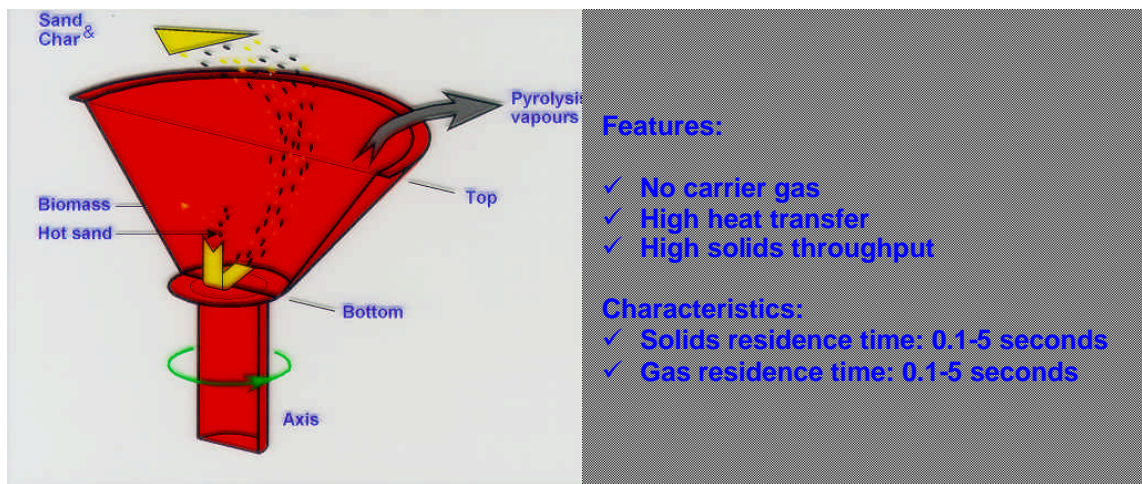

Figure 2.7 *"Rotating Cone Principle"*

Pyrolysis, either to produce a solid carbon material or a liquid can be of interest in combustion with existing systems for large-scale electricity production. If biomass fuel is to be imported, to meet national goals for introduction of renewables into the energy chain or to achieve emission reduction, it may be argued that pyrolysis is a step to be taken at the location of the biomass production, so that only highly concentrated energy carriers are transported.

Also the solid pyrolysis product (char) has properties similar to coal, and therefore can be easily accommodated as a renewable or a CO_2 emission free energy carrier, which can be mixed up with coal. Same applies to the liquid pyrolysis product, but in this case separate injection technology is to be applied with coal fired boilers.

Further, pyrolysis is applied as a means to reduce the size of waste streams, like electronic scrap, plastics etc. In some processes, even high calorific value gas is generated, precious metals are recovered and environmentally hazardous waste metals are immobilized [13].

A number of technologies combining pyrolysis and gasification are developed to overcome the drawbacks of both technologies separately by combining their respective advantages. Like in the case of advanced gasification technologies, these processes are awaiting demonstration at realistic scales [14], [15].

The largest plant built today is 2 tonnes/h but plans for 4 and 6 tonnes/h (equivalent to 6-10 MWe) are at an advanced stage of planning. Over the past years, it has become less and less obvious whether pyrolysis oil can be a viable feedstock for transportation fuel as it was believed earlier.

Liquefaction

Hydrothermal upgrading

This is a low temperature (250-500°C), high-pressure (up to 150 bar) process in which a reducing gas, usually hydrogen, is added to the slurried feed. The product is an oxygenated liquid with a heating value of 35-40 MJ/kg, compared to 20-25 MJ/kg for pyrolysis oils. Interest in liquefaction is reduced due to the high cost of pressure reactors, the need for feed preparation and problems with feeding slurries. Some R&D is being carried out on batch reactors and catalytic hydro cracking.

The so-called hydrothermal upgrading is a similar process. It takes place in a high-pressure reactor close by the critical point of water [16].

During this process biomass decomposes into CO_2 and a so-called biocrude. This latter product is easily separated from water in which it forms, but still has to be hydrogenated to become a fuel comparable with conventional ones. The work has been started to generate an alternative to the ever-increasing oil price some decades ago. Now the future of this technology looks uncertain.

Supercritical gasification

The process of supercritical gasification [24]is basically the same as Hydrothermal upgrading, but occurs at more extreme conditions in terms of temperature and pressure. Therefore the product yield will be composed of gaseous products rather than liquid in the case of HTU. Water becomes supercritical at temperatures over 374°C and a pressure of 221 bar and the distinction between gas and liquid phases disappear. Usually the reaction temperature is chosen much higher than this latter. In the phase change from sub to supercritical, the properties of water change dramatically. It becomes highly reactive and can break C-C, C-H and C-O bonds in such a way that smaller fractions are obtained if higher temperatures are applied. The selectivity and efficiency is, however, significantly enhanced by the presence of a catalyst. Under the most extreme conditions temperatures over 600C the organic molecules are split into the smallest possible entities like H_2 and CO_2, but at more moderate temperatures the selectivity towards CH_4 becomes larger. Even lower temperature than say 400°C will yield complicated waxes and higher hydrocarbons. A typical reaction reads as follows:

$$2C_6H_{12}O_6 + 7H_2O \bullet \quad 9CO_2 + 2CH_4 + CO + 15H_2 \qquad \bullet H = 1.3 \text{ MJ/kg}$$
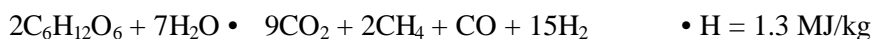
It can be seen that the water participates in the reaction, not only as an effective carrier for heat transfer to the biomass, but also as a reagent. Possibly the water is consumed in a reforming process of the large molecular fragments generated by cleavage of the biomass molecules. This might also be the explanation why a reforming catalyst is so important in the process.

A possible process is shown in Figure 2.8. Actually the process schedule is rather simple, but the problems are due to the feeding of the wet biomass and the heat exchanging. This latter heat exchanging process becomes more critical when process temperatures are increasing.

The advantages of supercritical gasification are:
- Complete transformation of all organic material
- Short residence times: .5-2 minutes
- Product gas, including CO_2 is liberated at high pressure. This CO_2 is primarily dissolved in the water phase and can be easily flashed out to a high CO_2 concentration, which will be of value when sequestration is foreseen.

- The yield is relatively clean as gaseous by-products remain dissolved in the water phase. Process costs can be high as expensive materials and reactor systems are to be used. It may well be that ultimately the process is best for producing Synthetic Natural Gas along with CO_2 storage as the economically most viable application in the long run.
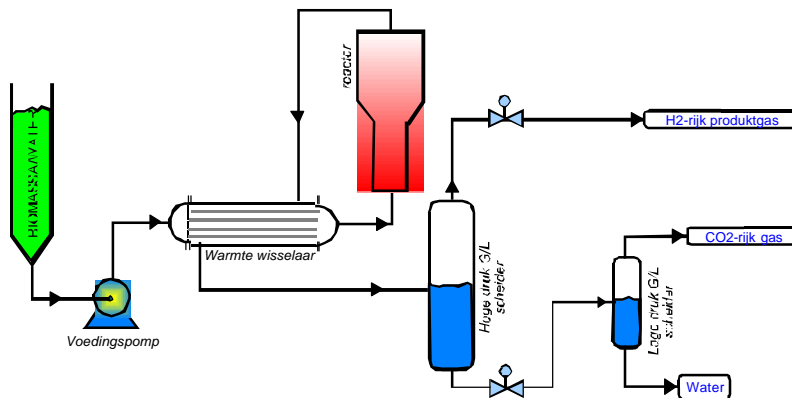

Figure 2.8 *Schematic of the supercritical gasification process*

Esterification

Esterification is the chemical modification of vegetable oils into vegetable oil esters, which are suitable for use in engines. Vegetable oils are produced from oil crops (e.g. rapeseed, sunflower) using pre-pressing and extraction techniques. The by-product of the oil production is a protein 'cake' which is a valuable feedstuff for animal feeding.

Esterification is needed to adapt the properties to the requirements of diesel engines. This process eliminates glycerides in the presence of an alcohol and a catalyst (usually aqueous sodium hydroxide or potassium hydroxide). Methyl esters are formed if methanol is used while ethyl esters are formed if ethanol is used. The most common vegetable oil ester for biofuel is RME (rape methyl ester).

The schedule of the process is represented below. This example considers an initial biomass (raw material) quantity of 3000 kg of rapeseed. During the extraction process this is converted to approx. 1000 kg of rape oil and 1900 kg of protein feedstuff. In the esterification process the rape oil is treated with methanol to produce 1000 kg RME and 110 kg of glycerine.

Extraction

Rape Seed ⟶ Feed stuff + Rape oil
(3000 kg)   (1900 kg)   (1000 kg)

Esterification

Rape oil ⟶ Glycerine + RME
(1000 kg)   (110 kg)   (1000 kg)

Vegetable oil esters can be used in mixtures with diesel fuel up to 100%.

The most promising product at present emerges as RME, a methyl ester based on vegetable oil, which is obtained from rapeseed or sunflower and further processed by cross-esterification of fatty acids and alcohol (methanol). Results from the Thermie programme on biofuel utilisation have shown that no special problem have been detected with conventional diesel engines working on mixtures of up to 50% rapeseed methyl ester.

Compared to conventional diesel, RME produces lower emissions and therefore contribute to reducing of health problems e.g. respiratory problems and cancer. Rapeseed oil doesn't produce sulphur dioxide, which impairs lung function and contributes to acid rain. There may, however, be problems with odour (similar to cooking oil) when pure RME is used as a fuel.

Biological/Biochemical Processes

Anaerobic digestion of wastes produces methane. It is a well-established technology for waste treatment. This is the natural breakdown of organic matter, such as biomass, by bacterial populations in the absence of air into biogas, i.e., a mixture of methane (40-75% v/v) and carbon dioxide. This bioconversion takes place in "digesters," i.e., sealed, airless containers, offering ideal conditions for the bacteria to ferment the organic feedstock to biogas. A simplified stoichiometry for the digestion of plant carbohydrates follows:

$$C_6H_{10}O_5 + H_2O \ ----- > 3 \ CH_4 + 3 \ CO_2$$
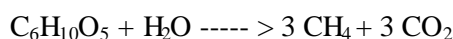
During anaerobic digestion, typically 30-60% of the input solids are converted to biogas; by-products consist of undigested fibre and various water-soluble substances.

Biogas, either raw or usually after some enrichment in methane, could be used to generate heat and electricity through gas, diesel of "dual fuel" engines, at capacities up to 10 MW(e).

The average production rate is 0.2-0.3m^3 biogas per kg dry solids. Nowadays 80% of the industrialised world 'biogas production' is from commercially exploited landfill. R&D is mainly concentrating on factors affecting microbial population growth. High solids digesters are being developed for the rapid treatment of large volumes of dilute effluents (wastes) from agro-industrial processes. This process has the advantage of a low cost feedstock and offers substantial environmental benefits as a waste management method.

Figure 2.9 shows an example of an anaerobic digestion plant in the Netherlands.

digestion: 55°C
2-3 weeks
10-15% dry matter
230 kt/y gives
92 kt/y ODW,
10 kt/y biogas,
23 kt/y digestate waste water

Figure 2.9 *Anaerobic digestion for CHP production Vagron Groningen plant*

Another product from acid and enzyme hydrolysis, fermentation and distillation is ethanol, which is used as a transport fuel, on the European level mainly in the form of ETBE (a mixture of ethanol and isobutane). The process scheme is shown in Figure 2.10. In the USA however, ethanol is used as a mixture called gasohol (ethanol mixed with gasoline), while in Brazil either pure ethanol or gasohol is used.

Presently the techniques of hydrolysis, fermentation and distribution are all commercialised for sugar and starch substrates. Acid hydrolysis for (ligno)cellulosic feedstocks is expected to be economical in about 5 to 10 years. Enzyme hydrolysis is at the pre-pilot stage. It is expected to be commercial in 5-10 years and economical in 10-15 years. The economic competitiveness will be increased by improvement of industrial productivity and efficiency. Recently, major enzyme manufacturers (Genencor, Novozymes) have claimed a 20-fold reduction of cellulosic production costs. Acid and enzymatic hydrolysis of cellulosic materials are not commercial technologies, furthermore, they need a strong R&D development before commercial demonstration.
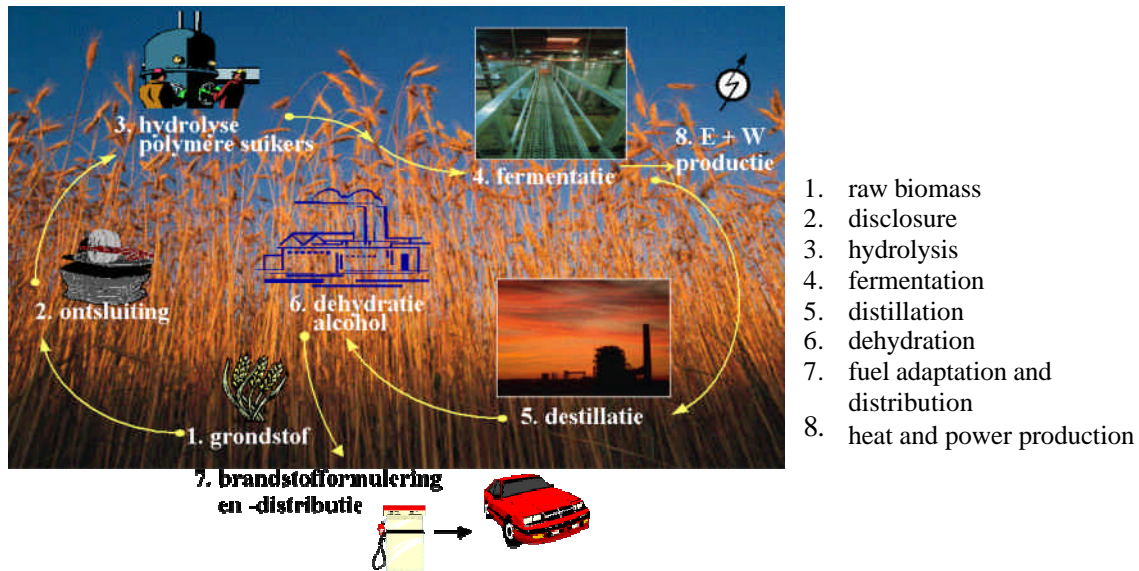
Figure 2.10 *Bio-ethanol, power and heat from biomass (waste) streams*

1. raw biomass
2. disclosure
3. hydrolysis
4. fermentation
5. distillation
6. dehydration
7. fuel adaptation and distribution
8. heat and power production

The raw materials for bio ethanol can be sugars or starch feedstocks such as wheat, sugar beet, potato, Jerusalem artichoke and sweet sorghum. Maize grain in the US and sugarcane in Brazil are the most utilised biomass material for alcohol production.

Bioethanol can be used as a pure fuel as it is applied in the Proalcool Programme in Brazil or mixed with motor gasoline. If bioethanol is used at 100%, engines should be adapted while for mixed utilisation, non-adapted engines can be used.

Since the production of bioethanol in Brazil has shown large yearly variations, the availability is experienced to be limited, or at least uncertain. This made people reluctant to invest in new cars with adapted engines. Presently new cars, which run on pure ethanol, are not produced anymore.

Ethanol can be used to substitute for MTBE (Methyl Tertiary Butyl Ether) and added to unleaded fuel to increase octane ratings. In Europe, the preferred percentage, as recommended by the Association of European Automotive Manufacturers (AEAM), is a 5% ethanol or 15% ETBE mix with gasoline.

Ethanol could in the future also be produced from lignocellulosic feedstocks.

ETBE (Ethyl Tertiary Butyl Ether) production

A new product derived from the reaction of equal parts of ethanol and the hydro carburant isobutane, which have fuel properties like octane rating, volatility, heat efficiency and corrosivity superior to bioethanol.

Instead of MTBE, ETBE can be added can be added to unleaded motor gasoline to obtain a mixture of up to 15% without technical problems. The resultant mixture exhibits the same performance characteristics and engines do not have to be modified. ETBE can be manufactured in plants currently producing MTBE. The first industrial ETBE plant came on stream in 1990 at ELF France, using bioethanol supplied by the French producers Beghin-Say and Ethanol Union.

. Gasohol is the term used in the United States to describe a maize-based mixture of gasoline (90%) and ethyl alcohol (10%). It should not be confused with gas oil, an oil product used to fuel diesel engines.

.. MTBE (Methyl Tertiary Butyl Ether). Obtained from fossil methanol (natural gas) and added to unleaded fuel to rating. MTBE output is currently growing at the rate of 10% annually in France. MTBE is the principal competitor of bioethanol and ETBE as an octane booster, with more than 10 million tonnes produced annually worldwide. The price of MTBE is linked to that of methanol, which exhibited major price fluctuations of between 95 - 190 ECU/tonne between 1987 and 1992. As a result, manufacturers may favour ETBE whose market price is generally more stable. European regulations currently specify maximum MTBE (and ETBE) content in engines as 10% by volume.

3.   ECONOMICS OF BIOMASS SYSTEMS

3.1   Cost of bio-feedstocks

The costs of biomass depend on the dynamics of local markets, as well as on agreements, such as contracts between biomass users and producers. This cost includes all necessary transportation and handling, as well as pre-treatment (drying, size changes). Exact estimates are very difficult to make, as the markets are "immature" and changes occur rapidly.
On the one end of the spectrum, we find some industrial residues, e.g., from construction sites, that have nil of even negative costs (i.e., the industry is prepared to pay to get rid of them. On the other end, we have biomass from energy plantations.
In the middle of the spectrum, forest and farm residues require the application of costly harvesting and handling operations.

According to some recent calculations the following results are derived:
- In France (1996), the cost of wood transported over a distance of 40 km to be converted to bioelectricity by advanced gasification processes - e.g., BIG-ISTIG, 20-50 MW(e) - is estimated at 1.54 €cents/kWh(e), representing between 35 and 43% of the average cost of electricity.
- A study (1998) by VTT (Finland) arrives to raw material (wood) cost figures of 2-3 €cents/kWh(e) for transportation between 20 and 40 km; this is to be increased by 30% for transportation up to 100 km.
- A Dutch study (1996) estimates the production costs of biomass in the form of organic residues as 0-45 €/dry t. Energy crops 50-80 €/dry t; to these figures we should add 10-20 €/t for transportation, and another 10-20 €/t for handling and pre-treatment.

3.2   Costs of bioelectricity

Many economic evaluations of electricity generation systems utilising biomass as a feedstock have been carried out. In the following Table, a comparison of such calculations for the main technologies available is presented.

Table 3.1   *Main technological routes for producing electricity from biomass*

Technology Applied	Efficiency (%)	Generation Capacity (MWe)		Investment (k€/kWe)	Cost cE/kWh(e)
		Present	Future		
Combustion	15 - 35	1 - 50	100	1.1 - 2.8	2.8 - 10
Co-combustion	Of existing power station	Of existing power station	Of existing power station	0.5	3.6 - 10
Gasification	20 - 35	0.1 - 25	?	1.5 - 2.0	?
Gasification * Combined cycle	30 - 47	< 12	25-120	1.3 - 2.4	4.4 - 8.4
Flash Pyrolysis * Diesel	30 - 35	15-25	50	0.8 - 1.8	3.9 - 7.8
Biogas * Urban Wastes	20 - 30	1?	< 10	9 - 15	23 - 80
Biogas * Landfills	20 - 30	< 1	?	0.5 - 1.2	2.9 - 5.6

In these calculations, the cost of feedstock is assumed to be zero only in the case of landfills; in the other cases the fuel price is assumed to be:
- combustion: 2.0 - 2.5 €cents/kWh(e);
- gasification: 1.9-2.4 €cents/kWh(e);
- pyrolysis: 37 €/t of biomass.

Combined heat and power (CHP) generation is considered to be another key potential market (see above). Table 3.2 outlines the economics involved in a CHP plant, which uses willow as a feedstock, and a fluidised-bed combustion system.

Table 3.2   *Costs of CHP plant (fluidised-bed)*

Specific Investment	1600 €/kW(e)
Lifetime	25 years
Capacity	10 MW(e) + 17 MW(th)
Biomass Costs (Short rotation, willow)	55 E/dry t
Bioelectricity Production Cost	7.6 €cents/kW(e) (bio-heat at zero cost)

Considering biofuels the Figure 3.1 gives a comparison of different commodity fuels prepared out of biomass. New products like bio-diesel will add another 20-25 $/GJ to the price of petroleum based fuel [17]. Fischer Tropsch diesel produced out of biomass will become competitive when produced centralised at large scale and with significant tax exemptions.
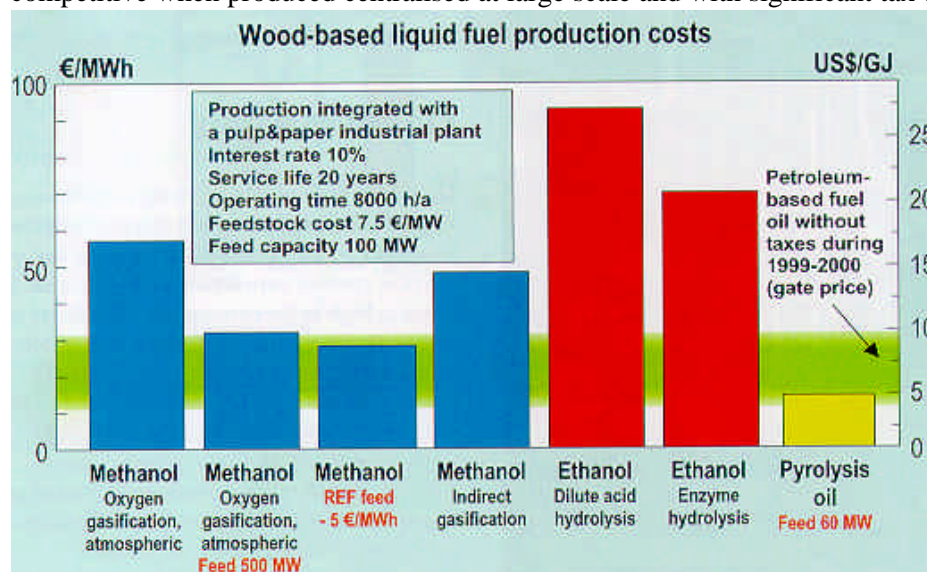

Figure 3.1   *Estimated production costs of wood-based methanol, ethanol and pyrolysis oil using various technologies (taken from "Energy Visions 2030 for Finland)[5]*

4.   CHALLENGES FOR BIOMASS R&D

4.1   Long-term goals

The long-term goal of biomass R&D is to be competitive with fossil fuels without subsidies on a level playing field of full costs, to increase its contribution to energy demand of the EU to more than 20% of the projected primary energy demand in 2025 and more than 30% in 2050. In parallel, it is necessary that the gradual increases of biomass energy contributions have to be realised in an environmentally sustainable way and accepted by the public.
Figure 4.1 shows the time path for the subsequent development steps. These will be outlined in the following section.

H.J. Veringa (ECN Biomass)

- Maximising direct/indirect cofiring in conventional coal-fired power plants
- Indirect cofiring (gasification) in natural gas-fired boilers and CCs
- Decentral CHP production (gasification, pyrolysis -> GEs, GTs, FCs)
- Gasification/methanation -> "green" natural gas (SNG, LNG)
- Hydro-Thermal-Upgrading -> "biocrude"
- Supercritical gasification -> H_2, CH_4

Implementation time

Figure 4.1 *Short and medium-term developments*

The easiest way to implement biomass as an energy resource presently is by producing process heat as it occurs to a large extent in the wood, sugar and paper industry. In Scandinavia, biomass or organic waste is combusted in large scale fluidised-bed boilers to raise steam or hot water for heat supply and to a minor extent for electricity production, basically in back pressure steam turbines. The full potential is not yet completely explored. Further, combustion units of about 50 MW(th) driving condensing steam cycles to produces mainly electricity are in a state of planning or are being started up. These systems will have to become economically viable by the fact that subsidies on the "green" electricity or heat are made available, or that customers are willing to pay extra.

As a next step, co-firing of biomass or waste (paper or sewage sludge for instance) with existing and highly optimised coal boilers is in a state of development. Presently an input of up to 10% of the calorific value of the fuel is targeted, but values of up to 35% are envisaged. This co-firing is achieved by injecting the fuel into the boiler next to the coal. In this case the biomass will have to be chipped to small particles to make injection possible. In some cases, like for sewage sludge, the waste can be co-injected with the coal. An interesting option is to pyrolyse the biomass or waste to bring it in a form, which resembles the coal so that it is easily injected. The pyrolysis gas can be injected into the system further down steam. Synergistic effect can be attained as it presents a possibility to reduce NO_x emissions from the boiler.
Another application of co-firing is to gasify the biomass and to inject the syngas into the boiler (Figure 2.2). In this case the residues from the coal-burning unit can be kept separated from the residues of the biomass. This latter technology is also foreseen to be implemented into existing gas fired combined cycle plants. This will open up an enormous potential for introducing biomass and waste into the energy-generating infrastructure.
For a county like the Netherlands, for instance, all the options of co-firing mentioned are of importance to meet the goals for CO_2 emission reduction as well as generation of energy out of renewables. So far fuel availability, but even more so, contractibility have been experienced as the main obstacle for exploitation of the large-scale potential.

Next to this co-firing, at locations where also heat has a significant economic value, stand-alone units may become attractive. Due to high potential the efficiency and attractivity of temperature levels of the process, gasification is the main candidate technology. The size and type of such plants depends on local conditions like fuel availability, its composition and morphology and the heat/power ratio required. In any case, however, gas cleaning will be the critical step. This gas cleaning is not only necessary to meet the demands of local legislation, but also, and may be even more important, to be able to combust the gas in a prime mover. At this moment it is not clear whether or not the costs for the necessary gas cleaning technology to be involved will turn out to be prohibitive for implementation. In this respect it may well be that more advanced gasification technologies giving inherently low tar levels in the product gas will ultimately be the final option for implementation.

Figure 4.2 gives an example of an advanced two-step gasification process known as the "Carbo V" process developed at the EUT in Freiberg, Germany. Here biomass is pyrolysed to char and gas. The gas is used to create a high temperature zone in which later the char is injected. This process suppresses tar formation and gives a medium calorific fuel gas.

A number of demonstration project in the EU and also elsewhere in the world are planned, started up or running to get more insight into the feasibility of the technology.
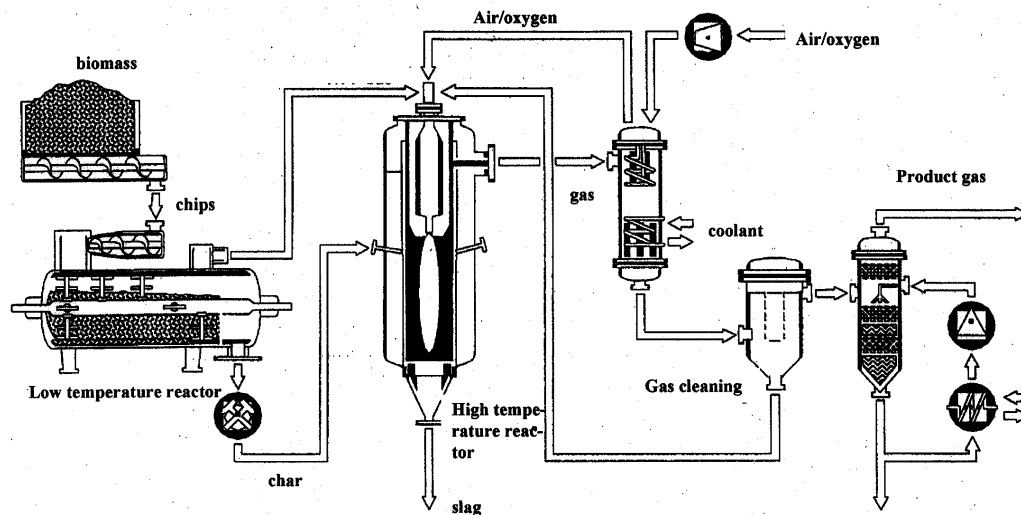

Figure 4.2 *An example of an advanced to step gasification process*

Ultimately, biomass as a feedstock will be needed to replace existing fossil recourses. Any kind of technology described here as for producing bio-oil, biogas, or routes involving catalytic chemical synthesis will be necessary to meet this future demand on chemical feedstock and transportation fuel.

It will be the main task of the biomass R&D community to make this challenge become reality in the coming decades.

Figure 4.3 shows the concept of biorefinery, the ultimate integration of biomass and waste in the energy and materials production. This will be the main way to overcome shortage in raw material to combat unwanted emissions and to guarantee a sustainable society for generations to come.
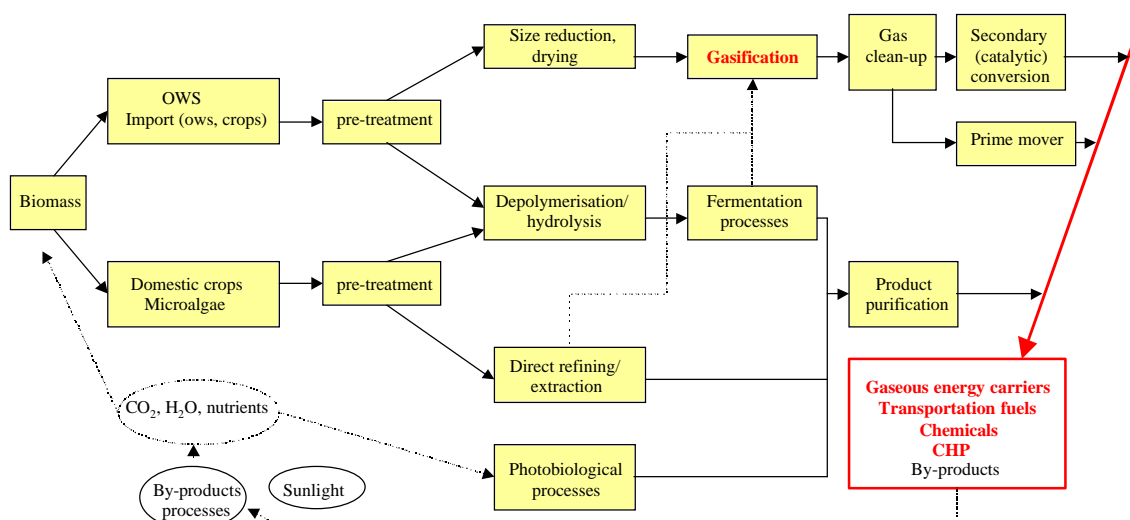
Figure 4.3 *Biorefinery concept*

4.2 Obstacles

Fuels

The major obstacle to the large-scale implementation of biomass systems will be the guaranteed supply of biomass feedstock.

In this respect distinction has to be made between availability and contractibility. As a rule, 50% of the availability is presently taken for the contractibility, but this number will have to grow to explore its potential. The commercial viability will be based on the financial margin to producer or collector (gate price or production cost). For the energy crops, this must compete with the lowest margin in conventional farming. Acceptance of new crops into the agricultural system can only be achieved if the farmer is confident with the new crop or has experience with the crop for other uses (e.g. rapeseed oil). All demonstrations and field trials should involve agricultural organisations.

Making biomass waste streams available is basically a matter of organisation or logistics. Not only the quality like the amount of inorganic material in the stream but also long term guaranteed supply is of importance in relation to the size of the plant where the biomass or waste is processed. For small plants, pre-processing or conditioning can be done on the premises, but for larger ones it can be decided as a consequence of economic optimisation, to partially pre-process the feed at the production site or on the way to the conversion plant. The extreme case is where biomass is imported as a regular fuel. Ultimately biomass is converted on the production place into char, pyrolysis oil or pellets. Local benefits may be achieved in such a case when also at the production site by products can be integrated with the local energy demand (local use of the gas as a by-product of the char production for instance).

It will be of high importance to find ways to optimise such energy chains in an environmentally and economic way to achieve a situation where biomass and organic waste is to a large extent implemented.

Energy crops

An obstacle to the growing of biomass for energy on set-aside land is the possible emergence of new crops, which will be grown for non-food and non-energy purposes (e.g. paper pulp and chemicals). These crops will be suitable for growing on set-aside land and the products may have higher value than biomass fuel, therefore, allowing the processor to pay more for the biomass. The price offered for the energy crop must compete with prices offered for other crops, which may also be grown on set aside land.

Clearly, growing of organic material for energy production needs particular insight into possible ways to maximize soil depletion. Also fertiliser and chemical constituents will have to be minimized. Of particular interest is integration of energy crop production regionally and its economics.

Wastes

Agricultural waste is a by-product and obviously not optimised towards energy production purposes. At present these 'residues' are readily available often at very low, zero, or in some situations, negative costs. Some debate exists over the use of these residues and the decision to use them is generally site-specific. Forest fires are a real threat in southern Europe thus necessitating the routine collection of forest residues, which therefore are a potential biomass fuel. However, in other more northern areas where forest fires are not a threat, residues are not harvested because they are considered to be a valuable part of the nutrient cycle of the forest and also contribute to soil structure. In these cases forest residues are usually not considered as a biomass fuel.

As a consequence, many of the steams have unfavourable properties like abrasivity, corrosivity, ash and inorganic material content. Further, local legislation leads to assignment of a certain percentage of the fuel as green fuel. This makes the total pool of organic fuel substantial but very inhomogeneous. Development of suitable fuel blends in relation with particular conversion

technologies and optimised morphology is therefore of prime importance. It may be foreseen that a new branch of economic activity will emerge: pre processed optimised fuel production with added value like pellets, briquette, chips etc. R&D into conversion technology with these new fuels is then of prime importance.

Import/Export
For highly urbanized areas, but which still have renewable energy targets, green fuel import can be important. For producing areas this can lead to new economic activity and added employment. The issue of import can mean that collection occurs over large areas. But conversion takes place highly concentrated in co-conversion or dedicated plants but with high capacity. In each particular case it has to be determined how the logistics will look like: to what extent will pre-processing be done and where. Minimization of transport costs is the main issue in this case. But also local benefits may be of importance.

4.3   Conversion Processes

Combustion
The main development has been with fluidised-bed combustors. These combustors have a high efficiency, can burn a mixture of fuels and fuels that can contain up to 60% moisture. The largest boilers are grate systems (up to 100 MW thermal), which can produce about 200 t steam/hr.
Direct combustion is commercialised at present and the firing of biomass powder in ceramic gas turbines will be commercialised in the years to come. These turbines will have a capacity of 100 kW - 500 kW. Products are heat and/or high-pressure steam, which can be used to produce power or combined heat and power.
The most promising developments in combustion for efficient biomass conversion is co-combustion. This can be done in existing coal plants of a large capacity (which allows high efficiencies for production of electricity). New boiler concepts where biomass is combined with coal, peat, RDF or other fuels offer high efficiencies because of their larger scale and low risks in the power supply since more than one fuel can be used (e.g. to compensate seasonal influences).

Most R&D is on technical aspects e.g. stoking, combustion air and fuel conveyance. There have been large improvements in combustion efficiency (>30%), in reduction of pollutant emissions (e.g. fly ash) and in the development of CHP plants. R&D will also be required for Stirling engines and pressurized combustion systems.
Main R&D tasks lay in the field of co-combustion: assessment of possibilities of co-combustion in different situations, development and demonstration of advanced boiler concepts. Specific research topics on combustion are corrosion by alkalines and chlorides and options to prevent. Further, slagging prevention and applying difficult biomass fuels such as straw, RDF, and grasses in different combustion systems is important.
The main barriers to overcome are the high cost, making use of the economy of scale. The developments will be helped if up-front investment is available. The involvement of industries in the development will be an important issue and part of the R&D should concentrate on demonstrating the environmental and energy benefits of the technologies to industries. One issue, which must be assessed in the studies, will be how well the utilities meet the CO_2 and other emission standards.

Gasification
Gasification is sensitive to changes in feedstock type, moisture content, ash content and particle size. The gas can be used for internal combustion engines provided it is cleaned of tars, carryover dusts, some of its water content, and cold enough. If cleaning does not take place, tars may precipitate on inlet valves and clog up gas/air mixers. Dust can clog carburettors, cause engine damage and act as a grinding powder between the piston and cylinder wall.

The most effective and economical use of the gaseous product is the production of electricity via gas turbines if combined with steam cycles. Gasification produces a higher yield than combustion with respect to electricity production for low power plants (50 kW to 1-10 MW) with internal combustion engines. For higher power (1-10 MW to 50-100 MW) combustion systems with steam turbines are more efficient than gasification systems. For very large-scale power plants (50-100 MW) gasification can reach exceptionally high levels of efficiency through a combined gas turbine-steam turbine system

R&D in gasification is aiming at large scale (1000t/day) oxygen and/or air blown systems. Of prime importance is the development of efficient systems for electricity production. IGCC and STIG may ultimately achieve efficiencies of 42-47%.
To reach this goal, emphasis in R&D will have to be given to:
Development of simple and cheap gas cleaning technologies for dust, NO_x or ammonia, hydrochloric acid and alkaline components. This development is needed for both large scale (>10 MW) units as well as small ones. Ultimately stringent standards for fuel quality are needed. Further, emphasis will have to be given to improving the tolerance of gasifiers to different types of biomass and operation of gas engines or gas turbines fired by low calorific gases.
Once efficient and cost effective gasification has been achieved, the synthesis gas can be used for deriving of secondary fuels like methanol or, more generally, chemical feedstock. The relative demand and cost advantages are unlikely to become evident until after 2010 when liquid fuel may increase in price or environmental requirements may restrict the use of gasoline or petroleum additives.

Pyrolysis
Flash pyrolysis will produce the largest percentage of bio-oil (60-80% by weight). Slow or conventional pyrolysis will produce more charcoal (35%-40%) than bio-oil. Flash pyrolysis is at a demonstration scale. Upgrading processes are at a far lower degree of development than pyrolysis processes.
Bio-oil is expensive as a transport fuel (especially if no environmental credits are taken into account), but as a liquid, bio-oil presents the advantage of easy handling, transport and storage. This bio-oil can be combusted for heat and electricity and therefore it may become economically attractive.
Char can be used in small gasifiers (kW range) or may become important as import fuel as a transport fuel (diesel substitute), bio-oil needs a stabilising step and maybe upgrading.

On the R&D side emphasis is to be given to:
- improving the production of bio-oil (for MW power stations) and upgrading using catalytic hydro-treatment,
- solving the corrosive and toxic problems,
- modification of diesel engines, which will be run with pyrolysis oil,
- development of recovery of fine chemicals.

Esterification
The process for the production of RME is well developed and the product is commercially available in France, Germany and Italy. EU non-food oilseed production is confined to 700,000 ha-1.2 million ha and this allocation is being quickly taken up by member states. In 1994 total EU area of oilseeds for non-food purposes was 0.62 million ha as compared to 0.2 million ha in 1993. Most of this is accounted for by rapeseed which increased to an estimated 0.4 million ha. The major producers are France and Germany with respective areas of 173,000 ha and 152,000 ha (1994).
Bio-diesel is expensive as a transport fuel (costing approx. 0.20-0.25 ECU/litre more than its mineral equivalent). In the countries where RME is commercially available, it is competitive

with fossil diesel due to tax exemptions. At the EU political life an intensive debate is going on to make biofuels economically competitive through a reduction in excise.

The main obstacles to the development of esterification processes are the high production cost of RME, the limited amount of raw material which is allowed to be grown in the EU and the opposition of some Member States and the lack of competitiveness of biofuels in comparison to fossil fuels mitigate against the injection of capital into the development of improved esterification methods.

R&D should concentrate on :

- Testing RME in different types of engines.
- Testing of engines for emissions (particulates) and reduction of odour problems.
- Improved Energy Ratios and greenhouse gas benefits.
- Reduction of production costs, especially by using more efficiently the by products (glycerine, cake).

Biological/Biochemical Conversions

Acid hydrolysis, fermentation and distillation of sugar/starch-based substrates are all commercialised at present. Enzyme hydrolysis may be commercially available in 5-10 years. Acid and enzymatic hydrolysis of cellulose-based substrates are not commercial technologies. There is still an economic gap between the price of fossil fuels (0.15 €/L) and the price of liquid biofuels (0.4-0.6 €/L for ethanol in Europe). The gap is expected to be reduced by improvement of industrial productivity and efficiency, and use of new species. Methane (used for power) and compost are other products commercially available from biochemical processes.

The main product is ethanol, which can be mixed with gasoline up to 10% in normal engines. 100% ethanol can be used in adapted engines. ETBE (a mixture of ethanol and isobutane) can be used as a lead substitute (up to 15%) in diesel/gasoline engines.

The main obstacle to the development of bioconversion technologies is the lack of investment in RD&D. In the absence of this investment co-ordination activities should be initiated, also with the USA. R&D on this topic is still in its infant phase and therefore an extensive list of topics will have to be addressed:

- Development of advanced methods for the chemical hydrolysis of cellulose and lignocellulosic materials.
- R&D in fermentation/distillation includes the use of novel yeasts, bacteria and fungi.
- Pre-treatment is being investigated to increase the ease of hydrolysis. The most cost-effective hydrolysis process developed so far is steam explosion.
- R&D in acetone-butanol fermentation is being carried out but there has been no breakthrough as yet.
- One step hydrolysis/fermentation stage where the hemicellulose and cellulose are treated at the same time.
- Niche markets should be identified and demonstrations should be established to highlight the benefits of the technologies. Example of niche markets are environmentally sensitive areas such as waterways and leisure areas.
- Development of new types of bioreactors.
- Development of new strains of microorganisms for fermentations.
- Development of cheap enzymes for enzymatic hydrolysis of lignin.

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