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DISSERTATION

Techno-Economic Assessment on the Gasification of Biomass on the Large Scale for Heat and Power Production

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Diese Dissertation haben begutachtet:

In der Wissenschaft der Gegenwart
werden immer kleinere Zimmer
immer luxuriöser und kompletter eingerichtet.

Die Naturwissenschaften sind stupid,
weil sie Antworten auf alles haben;
sie sind weise, weil sie wissen,
dass es nur vorläufige Antworten sind.

Erwin Chargaff – „Bemerkungen“ - 1951

Der energetische Imperativ:
„Vergeude keine Energie, verwerte sie!“ (1912)

„Durch ihre Strahlung sendet uns die Sonne nämlich beständig Energie, und zwar freie Energie zu, und auf Kosten dieser freien Energie geschieht so gut wie alles, was überhaupt auf der Erde geschieht....“(S.41)

„Demgemäß haben sich zunächst die Pflanzen in solchem Sinne ausgebildet, dass sie fähig sind, die strahlende Energie der Sonne in chemische zu verwandeln, und diese in Gestalt verschiedener Stoffe wie Stärke, Zucker, Fette, Proteinstoffe usw. weit über ihren unmittelbaren Bedarf hinaus anzusammeln. Die chemische Energie aus den Pflanzen ist nun das Energiekapital, aus welchem alles Leben auf Erden erhalten wird.“ (S. 42 f.)

„Wir haben es also hier mit einem Anteil unserer Energiewirtschaft zu tun, der sich etwa wie eine unverhoffte Erbschaft verhält, welche den Erben veranlasst, die Grundsätze einer dauerhaften Wirtschaft vorläufig aus den Augen zu setzen, und in den Tag hinein zu leben....“(S.44)

„Die dauerhafte Wirtschaft muss ausschließlich auf die regelmäßige Benutzung der jährlichen Strahlungsenergie begründet werden. Diese erfolgt gegenwärtig dadurch, dass man einen Teil des Landes mit Äckern, Wiesen und Wald bestockt und die dort gezogenen Pflanzen für die chemische Speicherung verwendet....“(S.44)

„Als späteres Ziel des Fortschrittes wird daher die unmittelbare Benutzung der Sonnenenergie anzusehen sein, wobei die Erde mit Apparaten bedeckt sein wird, in denen dies geschieht, und in deren Schatten die Menschen ein bequemeres Dasein führen werden....“ (S.47)

„Die spätere Menschheit wird eben die Mittel entwickeln, einen ihrem Bedarf entsprechenden größeren Anteil der jährlichen Energieeinnahme nutzbar zu machen. Dies wird einerseits durch vollständigere Fassung des Energiestromes, andererseits durch Verbesserung des Güteverhältnisses der bereits gefassten Rohenergien bei ihrer Umwandlung geschehen.“

„Auch ist es nicht unwahrscheinlich, dass künftig einmal die Menschheit einen Genuss darin finden wird, mit geringem Energieverbrauch ein anmutiges Dasein zu führen und die rohe Energiefresserei des gegenwärtigen Lebens wie eine beklagenswerte Barbarei anzusehen....“(S.50)

Wilhelm Ostwald – 1853-1932 - Nobelpreis für Chemie 1909
Wilhelm Ostwald :„Die energetischen Grundlagen der Kulturwissenschaft“
Vorlesungsmanuskript, Verlag Dr. Werner Klinkhardt, Leipzig, 1909

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To Konstanze

Kurzfassung

Die Vergasung von Biomasse bietet die Möglichkeit Strom und Wärme mit einem hohen Gesamtwirkungsgrad zu erzeugen. Dennoch befinden sich bis heute fast keine kommerziellen Anlagen in Betrieb. Ausgehend davon ist es notwendig, bereits bestehende Demonstrationsanlagen zu analysieren und damit das verfügbare Know-how zusammenzutragen, sowie entsprechende Schlussfolgerungen für zukünftige Weiterentwicklungen abzuleiten.

Die Umwandlung von Biomasse mittels Vergasung zu Strom und Wärme erfolgt in drei Prozessschritten, der Gaserzeugung, der Gasreinigung und der Gasnutzung. Für jeden dieser Bereiche wurde eine umfangreiche Hersteller- und Marktbetrachtung durchgeführt, um den Stand der Technik zu erheben und kommerziell verfügbare Systemkomponenten zu identifizieren.

Es wurden 17 Anlagen zur thermochemischen Umwandlung von Biomasse analysiert. Dazu wurden objektive Bewertungskriterien aufgestellt, die einen Vergleich der unterschiedlichen Anlagen zulassen. Durch deren Anwendung konnten jene Anlagenteile identifiziert werden, welche sich für eine Verwendung in zukünftigen Anlagen beziehungsweise für eine Weiterentwicklung eignen.

Die aus der Hersteller- und Marktbetrachtung gewonnen Erfahrungen sowie die Ergebnisse der Anlagenbewertung wurden verwendet, um vielversprechende Systemkomponenten zu identifizieren und übergeordnete Systemaspekte abzuleiten.

Aus diesen Ergebnissen können wiederum neue, auf den Erfahrungen aufbauende Anlagentypen abgeleitet werden, welche sich für eine technisch machbare und ökonomisch darstellbare thermochemische Umwandlung von Biomasse eignen.

Zur technischen Bewertung der identifizierten Konzepte wurden die Massen- und Energiebilanzen dieser Konzepte mit einem Prozesssimulationsprogramm berechnet und energetisch sowie exergetisch analysiert. Detailliert wurde der Einfluss der Trocknung auf den Gesamtprozess betrachtet. Weiters wurden die unterschiedlichen Gasreinigungssysteme anhand ihrer exergetischen Wirkungsgrade verglichen, wie auch deren Kopplungsmöglichkeit mit der nachgeschalteten Gasnutzung in einer Gasturbine oder einem Gasmotor aufgezeigt.

Abschließend wurden durch eine wirtschaftliche Bewertung die modellierten Anlagen und bereits bestehende Anlagen auf Vergasungsbasis, wie auch auf Verbrennungsbasis untersuch, um zu ermittelt, wie sich die Vergasung ökonomisch zu anderen Konversionstechnologien darstellen lässt. Dazu wurden zusätzlich Daten bestehender Anlagen erhoben und deren Wirtschaftlichkeit berechnet. Durch eine Sensitivitätsanalyse konnte der Einfluss von bestimmten Parametervariation auf die Stromgestehungskosten aufgezeigt werden konnte. Abschließend wird die Wirtschaftlichkeit der Konzepte mit anderen erneuerbaren Stromerzeugungstechnologien verglichen und ein Ausblick in die zukünftige ökonomische Entwicklung dieser Technologien gegeben.

Abstract

Gasification of biomass offers the possibility to produce heat and power at high overall efficiencies. However, only very few commercial gasification plants are in operation until today. Therefore, it is necessary to analyse existing biomass gasification plants and to collect the available knowledge in order to draw conclusions for future developments.

The conversion of biomass by gasification for heat and power production can be divided into three essential steps gasification, gas cleaning and gas utilisation. For each of these process steps a detailed technology and market analysis is carried out, to allow the characterisation of the state of the art technology and to identify suitable commercially available system components.

17 biomass gasification plants are analysed. Evaluation criteria are set up, to perform an objective comparison of different technology concepts. Components could be identified, which are promising for future use or are favourable for further development.

The results obtained from the “technology & market analysis” and from the “evaluation of the gasification plants” are used to identify promising system components to deduce guidelines for the design of new concepts.

By these results new concepts can be designed on the basis of the obtained experience, which are technically and economically feasible options for future gasification concepts.

For the technical evaluation of these concepts, mass and energy balances are calculated using a process simulation tool, which allows the energetic and exergetic analysis of these processes. Further, the influence of integrating biomass drying into a total concept is investigated and different gas cleaning systems are compared in terms of their exergetic efficiency. Additionally, the coupling with gas utilisation technologies such as gas engines and gas turbines is analysed.

These optimised concepts are assessed economically and compared to other renewable based power production technologies. Moreover, it is investigated how already existing gasification plants can compete on an economical basis with combustion based technologies. Data are collected for each plant and electricity production costs are calculated on the cash-flow basis. The influences of different parameters like fuel price or feed in tariffs for heat on the plant economy are investigated. Finally, learning curves were introduced to provide an outlook to the economic competitiveness of gasification for heat and power production in the future.

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Symbols and abbreviations

Symbols	Description	Unit
a_{el}	constant, which is specific for the individual technology	-
a_f	constant, which is specific for the individual technology	€/MWh
a_{th}	constant, which is specific for the individual technology	-
b	constant	-
c	constant	-
C_{inv}	investment costs	€
C_{prod}	electricity production costs	€/MWh
e	specific exergy	J/kg
$\dot{E}$	exergetic flow	kW/s
E_{0i}	molar standard exergy of species i	J/mol
h	specific enthalpy	J/kg
hhv	higher heating value	MJ/m_s^3
lhv	lower heating value volume referred	MJ/m_s^3
m	counting variable	-
$\dot{m}$	specific mass flow	kg/s
M	mean molar mass	kg/mol
Mtoe	million ton oil equivalent (1 Mtoe ≙ 11630 GWh)	
n	counting variable	-
N	number of built plants	-
P_{cum}	accumulated installed capacity	kW
P_{el}	electrical power	kW
P_{th}	thermal power (fuel power)	kW
$\dot{Q}$	district of process heat	kW
R	general gas constant ($R = 8.31451$)	J/(mol·K)
s	specific entropy	J/(kg·K)
T	temperature	K
wf	water free	
wt	weight	
y_i	molar fraction of species i	mol/mol

Abbreviations	Description	Unit
CFB	circulating fluidised bed	
CHP	combined heat and power	
DLL	dynamic link library	
ESP	electrostatic precipitator	
EU15	EU with 15 member states	
EU25	EU with 25 member states	
FT	Fischer-Tropsch	
IGCC	integrated gasification combined cycle	
MDK	model developer kit	
ORC	organic Rankine cycle	
PSE	process simulation environment	
RDF	refuse derived fuel	
RME	rapeseed methyl ester	
RPS	rotating particle separator	
SBCR	slurry bubble column reactor	
SFB	stationary fluidised bed	
SRF	short rotation forests	
TFBR	tubular fixed bed reactor	
TPES	total primary energy supply	Mtoe

Subscripts	Description	Unit
0	ambient conditions	
chem	chemical	
cleangas	clean product gas	
cons	consumption	
cum	cumulative	
el	electric	
ex	exergetic	
FT	Fischer-Tropsch	
Fuel	fuel (biomass)	
gross	gross value	
GC	gas cleaning	
GT	gas turbine	
GU	gas utilisation	
input	input	
inv	invest	
m	mechanic	
net	net value	
own	own consumption	
PS	useable process stream	
PG	product gas	
prod	production	
Q, q	heat	
s	isentropic	
SCR	selective catalytic reduction	
ST	steam turbine	
th	thermal	

Greek Symbols	Description	Unit
α	power to heat ratio	-
Δp	pressure drop of equipment	bar
ΔH^0	standard reaction enthalpy	kJ/mol
η	efficiency	-

1 Introduction

Biomass is widely considered to be a major potential fuel and renewable resource for the future. There are several reasons for this; first, the world has become aware of its dependence on fossil fuels and the subsequent threat to the climate; as a result, there is greater demand for renewable energy. By looking at the increase of the proven oil reserves and the increase in the oil production it becomes clear, that the growth in the production/consumption of oil is much greater than the rise of new proven oil reserves. This will lead to a shortening of the available oil resources, resulting in an oil price increase. Even if in the near future the amount of proved reserves is enlarged, their exploitation will be more expensive, since they will be of lower quality like oil shale and require expensive enhanced oil recovery methods. An increase in the oil price though, will make biomass based technologies more attractive.

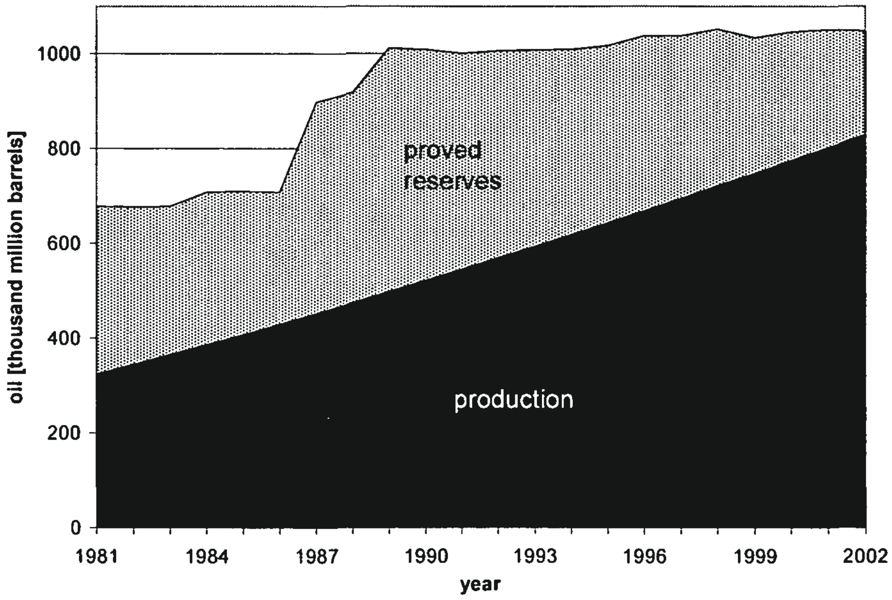

Fig. 1-1: Cumulative oil production and proved oil reserves [1]

The second main stimulus is the agriculture sector, which is producing food surplus. The therefore set aside land can provide energy crops or short rotation forest instead [2]. Biomass could play an important role, as it is available in abundant quantities around the world, throughout the year.

A European citizen requires per year about 3650 MJ of energy of nutrition, however, 175 000 MJ (2000) of primary energy in form of heat, electricity and transportation fuel, which is 48 times the requirements for nutrition [3]. The standard of living of a society is linked directly to the supply of cheap energy and the availability of technologies for their utilisation.

By comparing the energy consumption in different countries it becomes clear how dissimilar the energy consumption of the primary energy is distributed across the world. A man living in South America consumes about 46 000 MJ of energy per year, a Chinese citizen 38 000 MJ, and an African citizen only 27 000 MJ of primary energy. Since an economic development of these countries will go hand in hand with an increase in the consumption of primary energy per capita, the primary energy usage will rise strongly in the near future.

Furthermore, the world population will grow until the mid of the century from 6.2 billion to 9 - 12 billion, which will increase the primary energy consumption too. In summary the following alarming statements can be made [3]:

- Today 17 % of the world population use half of the energy supply
- If each citizen of the world would use the same amount of energy per capita as a European citizen consumes, crude oil supplies would last for about 15 years, natural gas resources for about 25 years.
- If each citizen of the world would use the same amount of energy per capita as a North American citizen consumes, crude oil supplies would last for about 8 years, natural gas resources for about 12 years.

This outlook makes clear that new sources for the primary energy supply on renewable bases have to be found. In 2001, the world total primary energy supply (TPES) was 10 038 Mtoe, of which 13.5 %, or 1 352 Mtoe, were produced from renewable energy sources. This compares to a share of 35.0 % from oil, 23.4 % from coal, 21.2 % from natural gas and 6.9 % from nuclear energy [4]. The renewable energy sources refer to IEA definition [4], and include combustible renewables and waste (solid biomass, charcoal, renewable municipal solid waste, gas from biomass and liquid biomass), hydro, solar, wind and tidal energy. Non-renewable waste sources (non-renewable industrial waste or non-renewable municipal solid waste) are not included in renewables. Due to its frequent non-commercial use in developing countries, solid biomass is by far the largest renewable energy source, representing 10.4 % of the world TPES, or 77.4 % of the global renewable energy supply. Fig. 1-2 shows the distribution of the renewable supply shares in the world regions

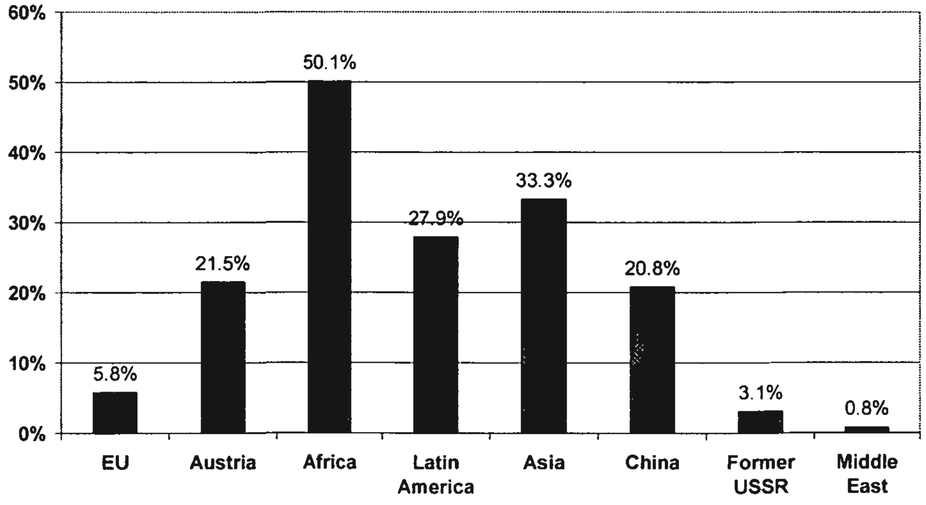

Fig. 1-2: Renewable supply shares in the world regions [4]

The European Union's (EU) share on the total renewable energy production of its TPES is a mere 5.8 %. Within the EU, Austria has one of the highest shares, of 21.5 % of its TPES. In contrast, Africa has a share of 50 % of its TPES covered by renewables, mainly non-commercial used biomass. In the European Union as well as in Austria, the main source of renewable energy is hydro power so far. The possibilities to install new hydro power plants in Europe are limited, because most of the possible sites are already in use. Wind, solar and geothermal energy production have shown high growth rates in the last years, nevertheless they cover only a small share of the energy produced from renewables (Fig. 1-3). Therefore, biomass will be the only option, which can provide a sufficient growth to take an important share in the renewable energy supply. An overview of the different kinds of biomass can be found at [2].

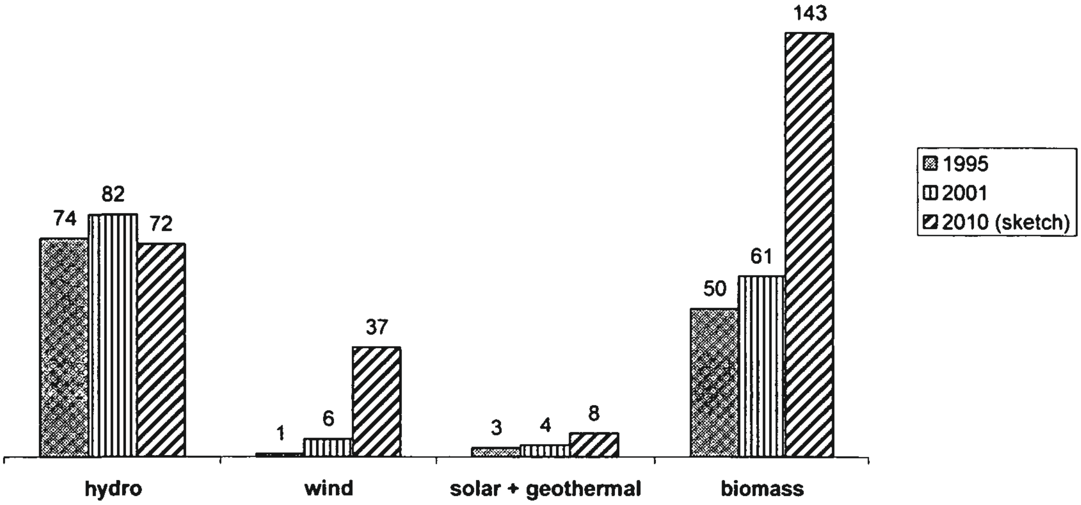

Fig. 1-3: Contribution of renewable energy sources, EU25, 1995-2001 (Mtoe) [5]

To take this into account, the European Union has set a general target in 1997, that by 2010 the renewables share of gross inland energy consumption in the EU15 should reach 12 % [6] in terms of electricity from renewable sources. This means that the share in the 25-member EU has to be increased from 14 % (2000) to 21 % (2010); translated to national target ranging from 3.6 % (Hungary) to 78.1 % (Austria) [5]. Furthermore, the share of biofuels used in the transport sector in the 25-member EU should be increased from less than 1 % (2000) to 5.75 % (2010).

Austria, as mentioned, has already a comparable high share of renewables.

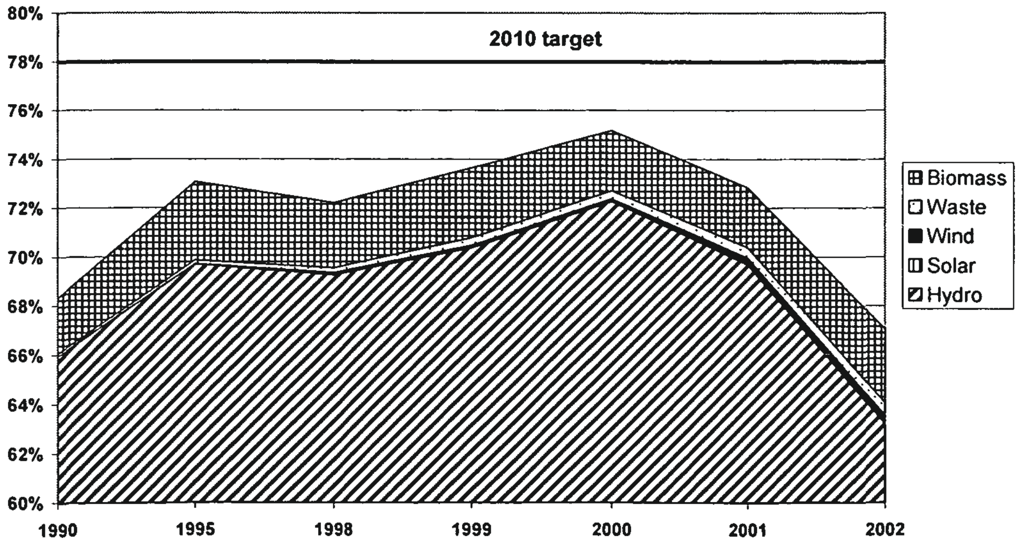

Fig. 1-4: Renewable share on the total electricity production in Austria from 1990-2002 [4]

The development on the renewable share on the total electricity production in Austria from 1990 until 2002 and the target set by the European Union can be seen in Fig. 1-4. Clearly the gap between the target and the current electricity production is obvious. In 2002 this gap even increased, due to strong decline of hydro power production by continuous drought. This gap, as already indicated, can only be filled by sustainable power production based on wind, solar and predominantly on biomass.

Produced biomass is mainly solid and difficult to use in many applications without substantial modifications. However, there is a wide range of processes available for converting biomass into more valuable fuels. These include biological processes to produce ethanol or methane, and thermal processes to produce heat, gaseous fuels, liquid fuels and solid fuels, from which a wide variety of secondary products including electricity can be produced. Fig. 1-5 shows the possibilities to convert biomass to final energy products.

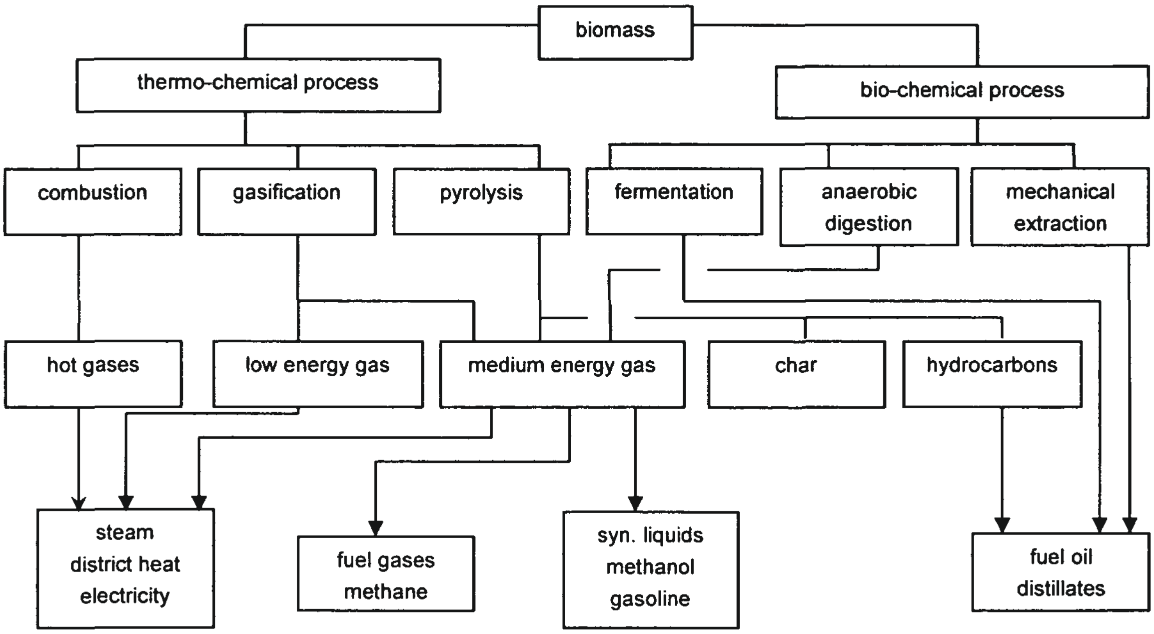

Fig. 1-5: Conversion technologies for biomass [2], [7], [8]

The application of biomass should be shifted from its traditional low-efficiency applications for heating to high-efficiency applications for combined heat and power (CHP) production [9]. In the following, only thermal conversion processes based on combustion or gasification of biomass for heat and power production shall be investigated in more detail (Fig. 1-6). Pyrolysis of biomass is considered today in terms of technology development one step behind gasification and is excluded from this analysis.

By combusting biomass, heat is yielded, that is first exchanged to a carrier media (steam, air, thermo oil) and afterwards is converted into power, whereby district heat can be produced as by-product. The conversion of heat to power can be performed according to the fuel power and the carrier media of the plant, by a steam turbine, a piston or screw steam engine, a hot air turbine, a Stirling engine [10] or an ORC-process [11]. As already mentioned, it is possible to operate these conversion technologies for pure power production or in CHP-mode.

In contrary if solid biomass is gasified, it transforms into a combustible gas, which has to be conditioned before it can be utilised. Thereby, it is often necessary to cool the product gas, the heat arising from this process step can be further utilised. The conditioned product gas can be used in gas engines, gas turbines or in future in fuel cells or as synthesis gas. Additional heat can be extracted in the gas utilisation step and from the hot flue gases. The gained heat can be used as district heat or can be further converted to power by feeding it into the already explained heat conversion technologies. In summary biomass gasification operated in CHP-mode offers the possibility to utilise the fuel power more efficient than with combustion based technologies.

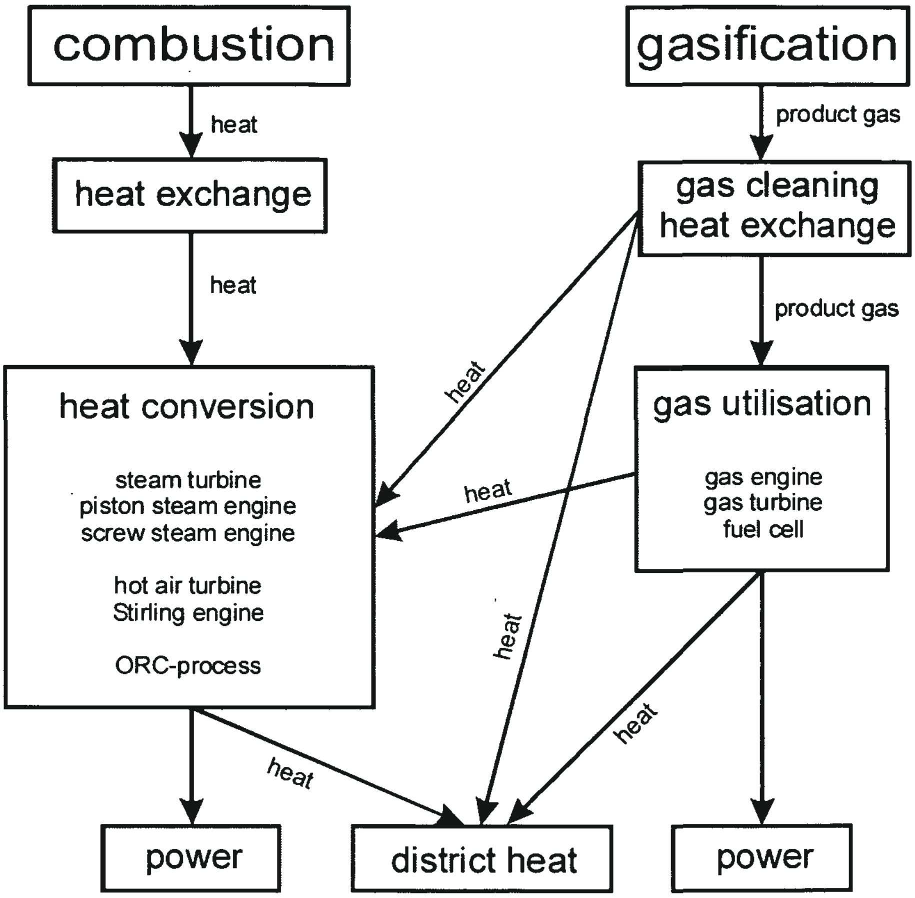

Fig. 1-6: Conversion paths of solid biomass for heat and power production

Many studies have revealed these advantages of gasification over combustion for power and heat production [12-16], which can be summarized as follows:

- High efficiency for electricity production in CHP-mode, even at a small scale.
- Cost-effective reduction of emission because of small gas flows, compared to combustion.

1.1 Aim

From the afore mentioned facts it can be seen that to fulfil the national as well as international demands for a more sustainable and renewable energy system it is vital to use and develop conversion technologies, which are able to utilise biomass with high overall efficiencies. Biomass gasification offers this advantage. Though gasification is known for some time, the technological breakthrough of this technology has not occurred so far. The aim of this thesis is to assess the state of the art of biomass gasification in technical and economical respect.

In the beginning a detailed technology and market analysis is carried out for the process steps gasification, gas cleaning and gas utilisation to identify suitable and commercial available components. The focus is laid on the gas cleaning technologies, since they represent the major challenge for a successful realisation of gasification plants. Additionally, problems are identified by an evaluation of existing gasification plants. Using this analysis, suitable system solutions can be obtained. Furthermore, these system solutions are analysed technically by a process simulation tool. Thereby, the energetic and exergetic performance of the components and the total system can be assessed.

Finally, the modelled concepts are assessed economically by calculating the electricity production costs. The obtained results are compared to other renewable power production technologies. Further, existing gasification and combustion based CHP-plants are assessed and compared to the optimised modelled CHP-concepts in terms of electricity production costs. Thereby, the existing optimisation potential of combustion and gasification based technologies can be estimated. Finally, the technical and economical status of biomass gasification can be obtained by this analysis.

1.2 Procedure

In the following section the procedure of this work is described, Fig. 1-7 shows the information flow graphically to give a better overview.

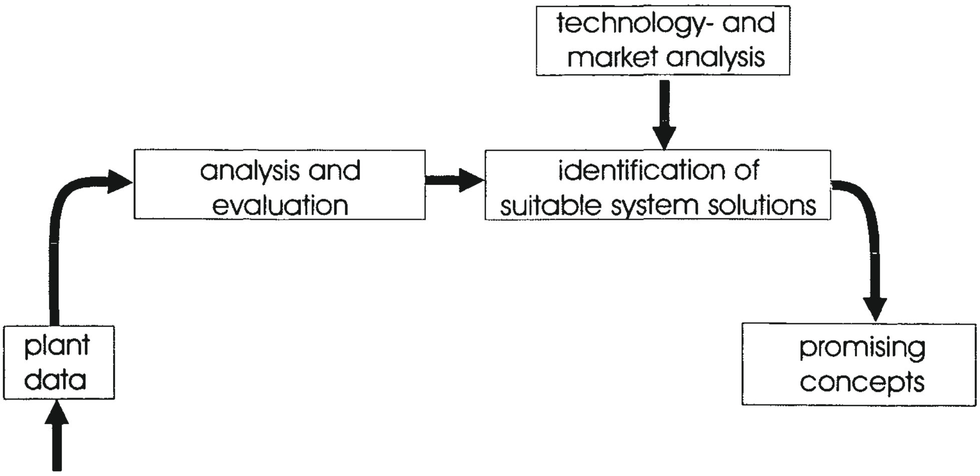

Fig. 1-7: Procedure

Initially a detailed technology and market analysis was carried out. Thereby, literature sources and information from manufacturers were used to obtain information about the process steps pre-treatment, gasification, gas cleaning and gas utilisation.

Using this information, the characteristics of the different applicable technologies for gasification have been analysed and advantages and disadvantages are identified. This analysis yielded a detail overview of the commercial available system components to allow a cost effective design of future gasification plants.

Additionally, a detailed plant analysis and evaluation of already built gasification plants is carried out to identify the suitable system components and to analyse overall aspects from operation results of "real" plants.

Serving this purpose, criteria are defined for each process step like fuel supply, gasification, gas cleaning and gas utilisation as well as criteria referring to the total plant. This allows an evaluation based on identical criteria and hence yields comparable results.

Results from the "technology and market analysis" and the "plant analysis and evaluation" are finally used for the identification of suitable system solutions. Furthermore, general aspects are concluded for a technical and economical feasible design of future gasification plants.

The identified system components are used this way to build up new promising gasification concepts, which include the learned lessons from the past.

The deduced concepts are evaluated energetically and exergetically using process simulation, to identify their performance and optimisation potentials.

This technical evaluation can provide the basis for future design of gasification plants but the economic aspect was not taken into account so far. Using the calculated data, an economic assessment of the plants can be done. The obtained results are compared to other renewable power production technologies and to an economic analysis based on data of existing plants. This allows assessing the status and competitiveness of biomass gasification in the future.

2 Technology and market analysis

One of the most important barriers to an accelerated penetration of all biomass conversion technologies is that of adequate resource supply. Fig. 2-1 depicts the technology reliability using the most important feedstocks in gasification applications.

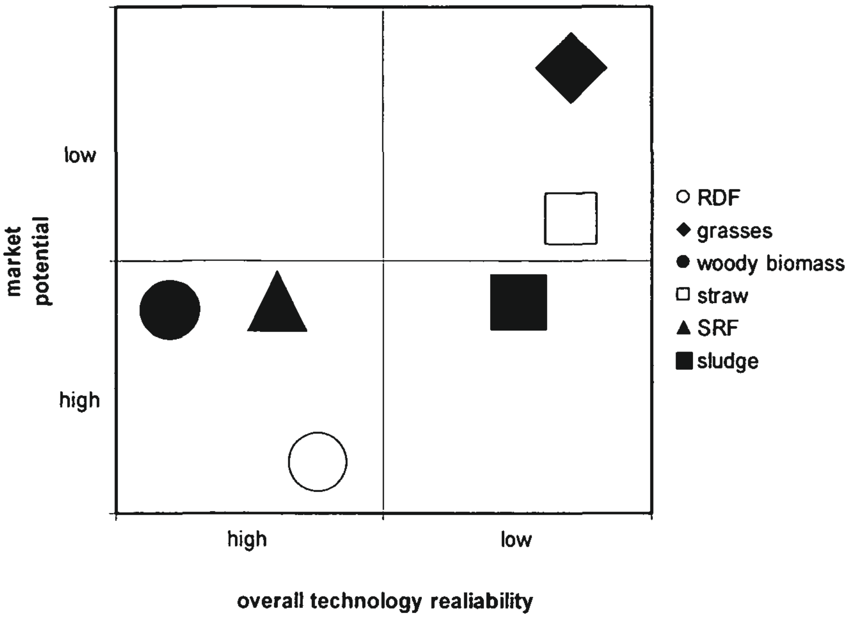

Fig. 2-1: Status of feedstock technology reliability and market potential [9]

Clean biomass feedstocks are becoming scare in many countries and there is hardly any reliable supply. In some countries like Germany, all industrial waste wood and other wood residues are consumed nearly completely [3] and there is little other clean biomass available to increase the contribution of bioenergy. Thus, the industry has been obliged to look into relative difficult fuels and feedstock, with little practical industrial experience in order to create new market opportunities. Waste recovered fuels present the advantage that they often have a negative cost associated with their disposal, which can significantly decrease the operating costs of a plant. In addition, since the last decade there has been a significant interest in energy crops and especially short rotation forestry (SRF) as a means to increase the production of biomass fuels while simultaneously creating new jobs for the farming community [9].

Woody biomass has the highest reliability in feeding into a gasifier and most problems related to bed sintering in fluidised bed gasifiers or slag formation on heat exchange surfaces are relatively well understood, which offers quite reliable operation. Furthermore, some experience for the pre-treatment operations such as drying, size reduction and storage has been obtained. The market potential of woody biomass is limited in many countries due to the fact that clean biomass is used already in various industrial or district heat applications. This fact applies not to countries with large shares of forest like Austria, Sweden or Finland.

Short Rotation Forestry has a relative good potential to be used in non arable land and provides a sustainable approach to energy [12], however, since the land has to be blocked for about 15 - 20 years, farmers in the EU are reluctant to implement SRF schemes. On the other hand, very few tests have been carried out with SRF feedstocks and there are uncertainties about this type of fuel. A sensitive area is that of heavy metals some of which are easily up taken by the plants (e.g. cadmium) [9].

Grasses have attracted interest recently since they can be cultivated on various places, even on the sides of highways, however, their market potential is still uncertain and there is relative little experience with such feedstocks. Technically grasses present problems in all pretreatment operations such as size reduction, storage, drying and even their relative fast biodegradability, which can result in significant weight loss unless dried and properly stored. Their low bulk density results in solids flow problems and can create local hot spots in the gasifier [9].

Straw has a relative low market potential for gasification applications since there is little experience with straw gasification and severe problems of ash sintering and bed agglomeration are known to exist in fluidised bed gasifiers. Due to the low bulk density it is not possible to use straw in moving bed gasifiers unless the straw has been pelletised; an expensive operation.

Refuse Derived Fuel (RDF) has significant potential for gasification applications, however, RDF is mainly a no renewable energy source. Finally, sludge can also be utilised in gasification applications and although there exists little experience, it is expected that the application with sludge may increase in the future. Technical reliability still has to be demonstrated.

From this short overview of possible feedstocks for gasification it can be seen that on the short time horizon only woody biomass and SRF seems to be a reliable and promising option, if RDF is excluded as feedstock. Therefore, this work will focus on woody biomass as feedstock.

The production of heat and power from biomass by gasification can be split up into four essential steps, fuel conditioning, gasification, gas cleaning and gas utilisation (Fig. 2-2).

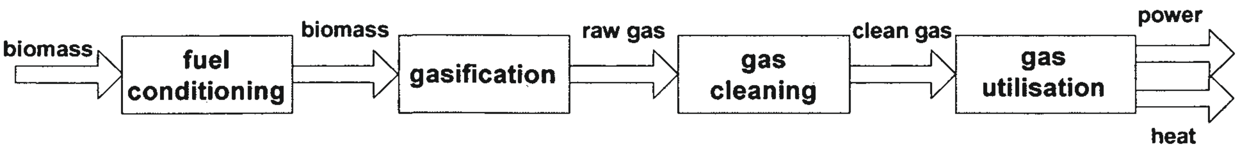

Fig. 2-2: Essential steps of biomass gasification

The *fuel conditioning* consists of apparatus to adapt the feedstock to the requirements concerning size, dryness, etc. of the gasifier and provide the feeding to the reactor. The *gasification section* includes the gasification reactor and all adjacent apparatus like gasifier feeding systems or ash discharge systems. The *gas cleaning* step conditions the raw product gas to the requirements for the gas utilisation. This includes the removal of undesired compounds and pollutants as well as the cooling of the product gas. The so cleaned gas can be converted in the gas utilisation section by internal combustion devices into the products heat and power. Each of these steps is discussed in the following in detail providing a market analysis for each component.

2.1 Gasification

Thermochemical gasification is the conversion by partial oxidation at elevated temperature of a carbonaceous feedstock such as biomass or coal into a gaseous energy carrier. This contains carbon monoxide, carbon dioxide, hydrogen, methane, trace amounts of higher hydrocarbons such as ethane and ethene, water, nitrogen (if air is used as the oxidizing agent) and various contaminants such as small char particles, ash, and tars. The partial oxidation is carried out using air, oxygen, steam or a mixture of these.

Fig. 2-3 shows the conversion paths for the formation of the different gasification products from biomass with the indication of the relevant processes in C-O-H diagram.

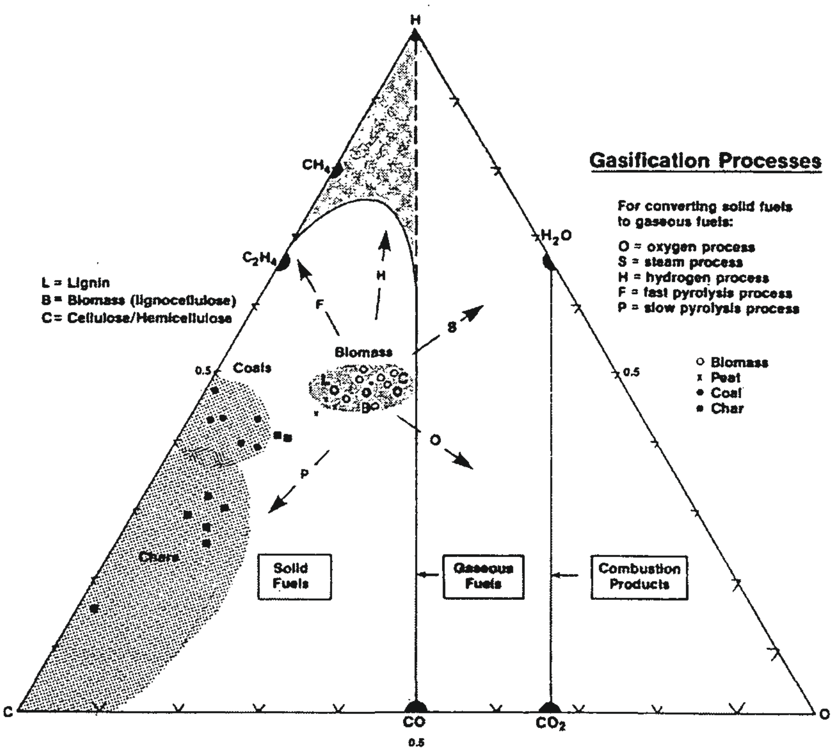

Fig. 2-3: C-O-H diagram of gasification processes [16]

If oxygen is used as gasification agent the conversion path points in the oxygen corner. This path leads to a lowering of the hydrogen content and an increase on the carbon based compounds such as CO and CO_2. If steam is used instead the path is pointing into the formation of water, which causes an increase of hydrogen in the produced compounds.

Air gasification produces a poor-quality gas in terms of heating value, 4 – 7 MJ Nm^{-3} lower heating value (lhv), suitable for boiler, engine and turbine operation due to its low energy density. Oxygen gasification produces a better-quality gas (10 – 18 MJ Nm^{-3} lhv), suitable for use as synthesis gas for conversion, for example, to methanol and gasoline. Gas of this quality can also be produced by pyrolytic or steam gasification, with the process energy being supplied by combustion of by-product char in a second reactor, e.g. a twin fluidised bed system. Gasification with air is the more widely used technology since this concept avoids the costs and hazards of oxygen production.

Principles

Gasification occurs in sequential steps, which can be found in most gasification reactors:

- drying	to evaporate moisture,
- pyrolysis	to produce gas, vaporized tars and a solid char residue, by thermal degradation
- oxidation	or partial oxidation of the solid char, pyrolysis tars and pyrolysis gases
- reduction	formation of the product gas, by a reduction of the combustion compounds on fixed carbon.

An overview of these processes gives Fig. 2-4.

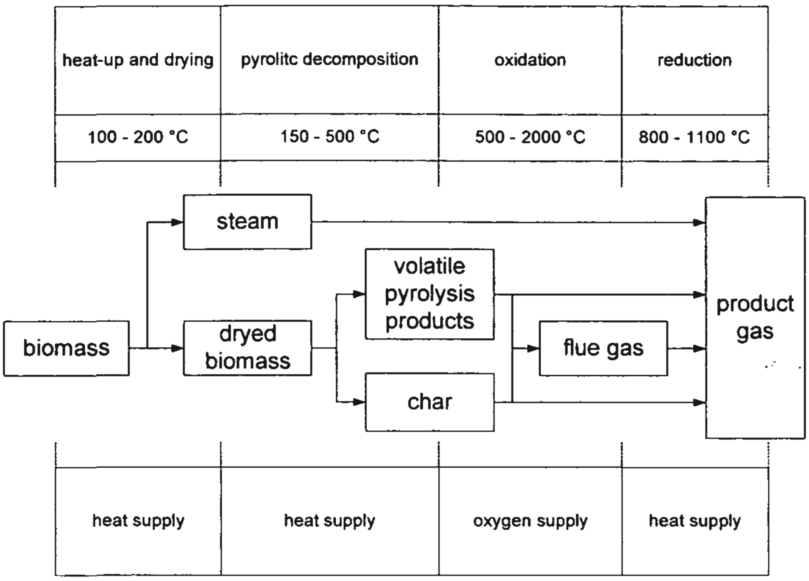

Fig. 2-4: Sequential steps of biomass gasification [17]

Once the biomass enters the reactor it is first heated up and dried, releasing its water content as steam until a temperature of about 200 °C. When the dried biomass is heated further at 150 – 500 °C in the absence of an oxidizing agent it pyrolyses to solid char and volatile pyrolysis products such as condensable hydrocarbons or tar, and gases. The relative yields of gas, liquid and char depend mostly on the rate of heating and the final temperature. Generally pyrolysis proceeds much more rapidly than the final reduction, and the latter is thus the rate-controlling step. The gas, liquid, and solid products of pyrolysis then react with the oxidizing agent at over 500 °C - usually air - to give permanent gases (CO, CO_2, H_2) and lesser quantities of hydrocarbon gases. Partially carbon is combusted at that stage too by the following reactions:

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -393{,}5\ kJ/mol \qquad \text{Equation 2-1}$$

$$C + \tfrac{1}{2} O_2 \leftrightarrow CO \qquad \Delta H = -123{,}1\ kJ/mol \qquad \text{Equation 2-2}$$

These reactions are highly exothermic and provide the necessary heat in terms of autothermal gasification. Even if biomass is gasified autothermal these reactions can take place due to the biomass bound hydrogen, although not to the extent as if an oxidising agent is added.

The oxidation is followed by a reduction, where char gasification take place. During reduction an interactive combination of several gas-solid and gas-gas reactions take place in which solid carbon is oxidized to carbon monoxide and carbon dioxide, and hydrogen is generated through the water-gas shift reaction (Equation 2-4). The gas-solid reactions of char oxidation are the slowest and limit the overall rate of the gasification process. Many of the reactions are catalysed by the alkali metal compounds present in wood ash, but still do not reach equilibrium. Endothermic reactions include the Boudouard-reaction (Equation 2-3) and the heterogeneous water-gas shift reaction (Equation 2-4):

$C + CO_2 \leftrightarrow 2CO$ $\Delta H = 159{,}9\ kJ/mol$ Equation 2-3

$C + H_2O \leftrightarrow CO + H_2$ $\Delta H = 118{,}5\ kJ/mol$ Equation 2-4

These reactions cause a volume increase and are strongly temperature dependent. At higher temperatures and decreasing pressures they shift to an increase of the CO compound. During the reduction of CO_2 and water also the homogeneous water-gas reaction takes place, which shifts at higher temperatures to the CO and H_2O-side (Equation 2-5).

$CO + H_2O \leftrightarrow CO_2 + H_2$ $\Delta H = -40{,}9\ kJ/mol$ Equation 2-5

Another important reaction is the formation of methane, which is reduced at higher temperatures and increased by higher pressures (Equation 2-6).

$C + 2H_2 \leftrightarrow CH_4$ $\Delta H = -87{,}5\ kJ/mol$ Equation 2-6

In summary it can be seen that the gas composition is influenced by many factors such as feed composition, water content, reaction temperature and pressure, and the extent of oxidation of the pyrolysis products. Fig. 2-5 shows as example the dependency of gasification reaction constants on the gasification temperature.

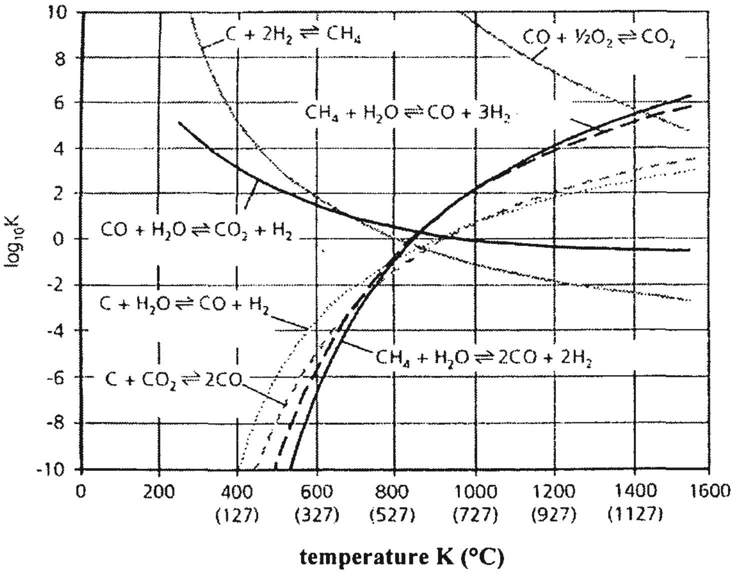

Fig. 2-5: Influence of the gasification temperature on the reaction constants

Not all the liquid products from the pyrolysis step are completely converted owing to the physical or geometrical limitations of the reactor and the chemical limitations of the reactions involved. These liquid products give rise to contaminant tars in the final product gas. Owing to the higher temperatures involved in gasification compared with pyrolysis, these tars tend to be refractory, i.e. very unreactive, and are difficult to remove by thermal, catalytic or physical processes. The basic principles of gasification can be found at [18], [19].

Comparison of pressurised and atmospheric operation

Basically, it is possible to operate gasification processes at atmospheric or pressurised conditions. Atmospheric gasifiers show the following significant features:

1. The product gas from atmospheric gasification for gas turbine applications is required to be sufficiently clean (tars, NH_3 etc.) for compression before the turbine. For engine applications the gas quality requirements are less stringent and no compression is required.
2. Atmospheric systems have a potentially much lower capital cost at smaller capacities [31].

Pressurised gasifiers have the following significant features:

1. Feeding is more complex and very costly, and has a high inert gas requirement for purging.
2. Capital costs of pressure equipment are much higher than for atmospheric equipment, although equipment sizes are much smaller [32]. This disadvantage is countered by the higher efficiency.
3. Gas is supplied to the turbine at pressure, avoiding the need for gas compression and also permitting relatively high tar contents in the gas; however, tar needs to be completely burned in the turbine combustor.
4. Hot gas cleaning with mechanical filters (such as sintered metal or ceramic candles) is often used, which reduces thermal and pressure energy losses.
5. Overall, the system efficiency is higher owing to retention of sensible heat and chemical energy of tars in the product gas and the avoidance of a fuel gas compression stage ahead of the gas turbine.

Product gas composition

The product gas composition depends on a number of different parameters, like the type and shape of the biomass feedstock (particle size, specific surface, water content, chemical composition), the type and quantity of the gasification agent (air, steam, oxygen or mixtures of those), the reactor configuration (contact intensity of the fuel and gasification agent, residence time of the fuel and so on), the gasification temperature, the presence of catalysts and the pressure conditions in the reactor [33].

In Table 2-1 typical dry product gas compositions from atmospheric gasification of woody biomass and their pollutants according to the reactor design are listed. A detailed discussion of the influence of the different parameters on the gasification process and the formation of the pollutants can be found in [2], [19] and [33].

Table 2-1: Product gas composition, pollutants, lower heating value and chemical efficiencies of different atmospheric gasifier types using the feedstock forest wood (values in brackets indicate mean values) according to [33] and [34]

		fixed bed downdraft	fixed bed updraft	CFB	twin fluidised bed
gasification agent		air	air	air	steam
H_2	Vol.-% dry	15 - 21	10 - 14	15 - 22	(38)
CO	Vol.-% dry	10 – 22	15 – 20	13 – 15	(25)
CO_2	Vol.-% dry	11 - 13	8 - 10	13 - 15	(22)
CH_4	Vol.-% dry	1 - 5	2 - 3	2 - 4	(10)
C_2+	Vol.-% dry	0.5 - 2			(2)
N_2	Vol.-% dry	rest	rest	rest	< 3
particle	g/Nm³	0.1 – 8 (1)	0.1 – 3 (1)	8 – 100 (20)	60 – 100 (50)
tar	g/Nm³	0.1 – 6 (0.5)	10 – 150 (50)	1 – 30 (8)	1 – 10 (2)
NH_3	ppm	feedstock dependent, between 120 – 1000			
HCN	ppm	feedstock dependent, between 20 - 500			
H_2S	ppm	feedstock dependent, between 70 - 150			
lhv	MJ/Nm^3_{dry}	4.0 - 5.6	3.7 – 5.1	3.6 – 5.9	12 – 15
chemical efficiency	%	65 - 75	50 - 70	70 - 85	65 – 85

2.1.1 Gasification technology

A range of reactor configurations has been developed in the past. The reactor types can be split up into four groups, fixed bed, fluidised bed, moving bed gasifiers and reactors of special design.

Table 2-2 shows an overview with a short description of each reactor type.

Table 2-2: Gasification reactor types [20]

fixed bed	
downdraft	solid moves down, gas moves down – concurrent material flow
updraft	solid moves down, gas moves up – countercurrent material flow
special constructions	stirred bed; two-stage gasifier, cross-current gasifiers
fluidised bed	
single reactor	
bubbling fluidised bed	low gas velocity, inert solid stays in reactor (stationary fluidised bed)
fast fluidised bed	inert solid is elutriated with product gas and recycled
circulating bed	inert solid is elutriated, separated and recirculated; sometimes also refers to fast fluidised bed or twin-reactor systems
entrained bed	usually no inert solid; highest gas velocity of lean-phase systems; can be run as a cyclonic reactor
twin reactor	steam gasification or pyrolysis occurs in the first reactor; char is burned in the second reactor to heat the fluidising medium for recirculation; either can be any type of fluidised bed, although the combustor is often a bubbling fluidised bed

moving bed	mechanical transport of solid; usually lower temperature processes; includes multiple heart, horizontal moving bed, sloping hearth, screw/auger kiln
other	
two-stage-gasifiers	two gasification technologies are combined to utilise the different advantages; firstly the feedstock is pyrolysed or gasified at low temperature. The products (char, tar loaded gas) are gasified in a second reactor at high temperature yielding a nearly tar free gas
rotary kiln	good gas-solid contact; careful design needed to avoid solids carryover
cyclonic reactors	high particle velocities give high reaction rates
vortex reactors	similar to cyclonic reactors

Fig. 2-6 shows typical fuel power application ranges for selected gasification reactors. On small scale fixed bed downdraft and updraft gasifiers are used, in the large scale fluidised bed gasifiers are applied.

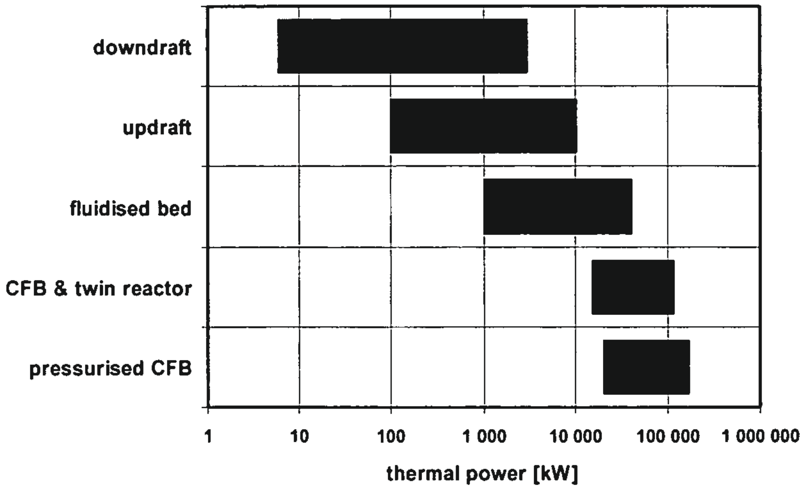

Fig. 2-6: Typical fuel power application ranges for selected gasification reactors

2.1.1.1 Downdraft gasifiers

Downdraft gasifiers (Fig. 2-7) feature concurrent flow of gases and solids through a descending packed bed. This bed is supported across a constriction known as a throat, where most of the gasification reactions occur. The reaction products are intimately mixed in the turbulent high-temperature region around the throat, which aids tar cracking. Some tar cracking also occurs below the throat in a residual charcoal bed, where the gasification process is completed. This configuration results in a high conversion of pyrolysis intermediates and hence a relatively clean gas.

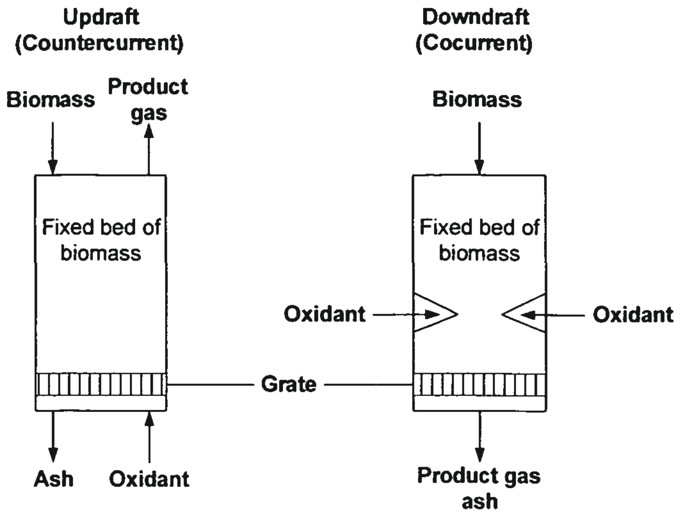

Fig. 2-7: Fixed bed gasifier types

Downdraft gasification is simple, reliable and proven for relatively dry (up to ~20 wt% moisture [2]) homogenous chipped woody fuel with a low ash content (<1 wt%) and containing a low proportion of fine and coarse particles (not smaller than ~1 cm and not larger than ~30 cm in the longest dimension [20]). Owing to the low content of tars in the gas, this configuration is generally favoured for small-scale electricity generation with an internal combustion engine. The physical limitations of the diameter and particle size relation mean that there is a practical upper limit of the capacity of this configuration of ~500 kg/h woody fuel or ~500 kW_{el}.

2.1.1.2 Updraft gasifiers

In updraft gasifiers (Fig. 2-7), the downward-moving biomass is first dried by the upflowing hot product gas. After drying, the solid fuel is pyrolysed, giving char, which continues to move down to be gasified, and pyrolysis vapours, which are carried upward by the upflowing hot product gas. The tars in the vapour either condense on the cool feedstock or are carried out of the reactor with the product gas, contributing to its high tar content. The tars condensed on the feedstock are recycled back to the reaction zones, where they are further cracked to gas and char. In the bottom gasification zone the solid char from pyrolysis and tar cracking is partially oxidized by the incoming air or oxygen. Steam may also be added to provide a higher level of hydrogen in the gas.

The product gas from an updraft gasifier thus contains a significant proportion of tars and hydrocarbons, which contribute to its high heating value. The fuel gas requires substantial cleaning if further processing is to be performed. The principal advantages of updraft gasifiers are their simple construction and high thermal efficiency: the sensible heat of the gas produced is recovered by direct heat exchange with the entering feed, which thus is dried, preheated and pyrolysed before entering the gasification zone. In principle, there is little scaling limitation, although no very large updraft biomass gasifiers have been built.

2.1.1.3 *Fluidised bed gasifiers*

These types of gasifiers take advantage of the excellent mixing characteristics and high reaction rates of this method of gas-solid contacting. The fluidising material is usually silica sand, although alumina and other refractory oxides have been used to avoid sintering. Fluidised bed reactors are the only gasifiers with isothermal bed operation. A typical operating temperature for biomass gasification is 800 - 950°C. Most of the conversion of the feedstock to product gas takes place within the bed; however, some conversion to product gas continues in the freeboard section owing to reactions of entrained small particles and particularly thermal tar cracking [20]. In most cases carbon conversion approaches 100 %, unless excessive carryover of fines takes place, which will occur with a top feeding configuration. The bubbling fluidised bed gasifier tends to produce a gas with tar contents between that of the updraft and downdraft gasifiers (Fig. 2-8).

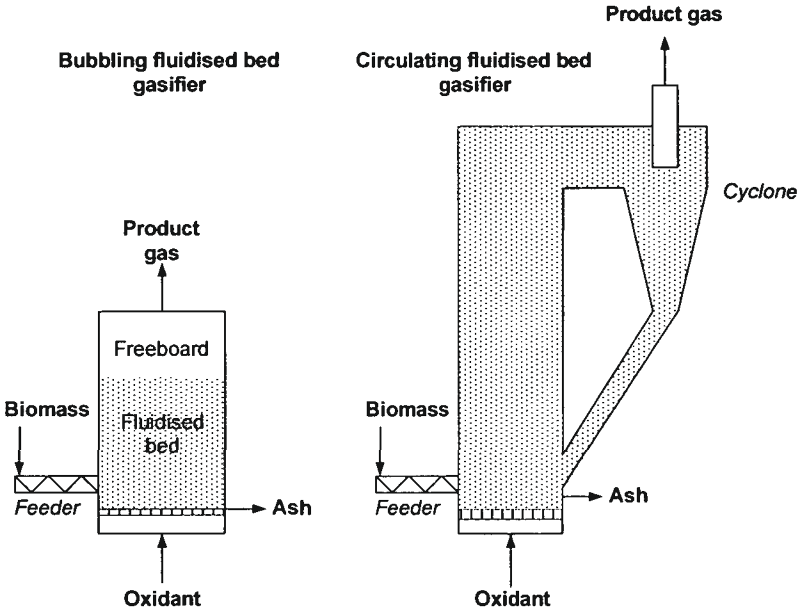

Fig. 2-8: Fluidised bed gasifier types

Fluidised beds are not economical for small-scale applications, due to higher operating (i.e. compression) costs [20]. Fluidised bed gasifiers have the advantage that they can readily be scaled up with considerable confidence. Only the fuel distribution becomes problematic in large beds, although multiple feeding is an acceptable solution. For an in situ tar reduction the bed material can be replaced by a catalyst [21], [22].

2.1.1.4 *Circulating fluidised bed gasifiers*

The fluidising velocity in the circulating fluidised bed is high enough to entrain large amounts of solids with the product gas (see Fig. 2-8). These systems were developed so that the entrained material is removed from the gas stream by a cyclone and recycled back to the fluidised bed to improve the carbon conversion efficiency compared with the bubbling fluidised bed design.

2.1.1.5 *Twin fluidised bed gasifiers*

Twin fluidised bed gasifiers are used to produce a gas of higher heating value than it is obtained from a single air-blown gasifier. The gasifier is heated with hot sand from the second fluidised bed, heated by burning the remaining product char in air before recirculation to the first reactor. Steam is usually added to enhance the shift reaction, to generate hydrogen and to increase carbon-steam reactions. This general layout is shown in Fig. 2-9.

The gasifier can be a bubbling or a circulating fluidised bed, the same applies to the combustion section. Realised configurations include gasification in a bubbling fluidised bed and combustion in a CFB-reactor [23-25] and the combination of two CBF-reactors [26-28].

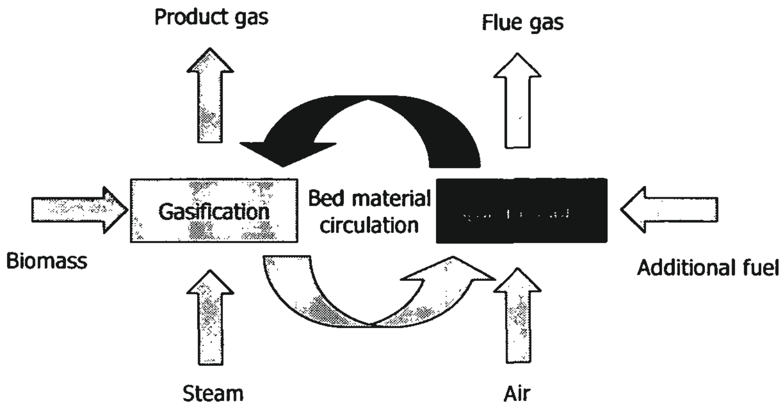

Fig. 2-9: General layout of a twin fluidised bed gasifier [23]

2.1.1.6 *Entrained gasifier*

Fig. 2-10 shows an entrained flow gasifier for biomass derived slurries as an example.

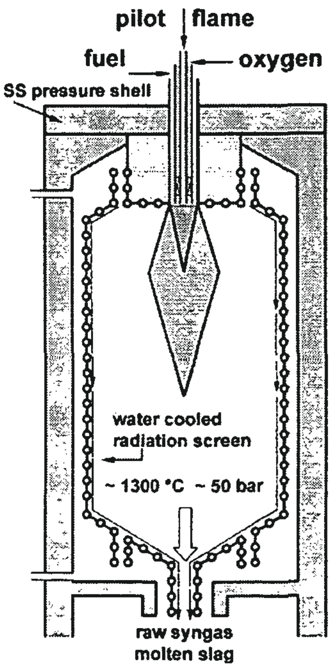

Fig. 2-10: Entrained flow gasifier for high pressures with internal water cooling radiation screen for gasification of biomass slurries [29]

In entrained flow gasifiers, no inert material is present but a finely reduced feedstock is required. Entrained bed gasifiers operated at high temperatures of 1200 – 1500 °C, depending on whether oxygen or air is used. Hence, the product gas has low concentrations of tars. However, this high temperature operation creates problems for material selection of apparatus and of ash melting. Conversion in entrained beds effectively approaches 100 % [20]. Until today there is only little experience in utilising biomass in entrained gasifiers.

2.1.1.7 Two–staged gasifiers

Recent developments are two-staged gasifiers, which aim to combine positive aspects of different technologies. When utilising the product gas a common problem faced is the tar content in the gas; this content can be lowered by passing the raw gas through a hot zone in the gasifier. A proper realisation of this task can be made using two different reactors. In the first reactor the feedstock is dried, pyrolysed or gasified at low temperature yielding the products char and a tar loaded gas. These primary products are gasified in a second reactor at high temperature whereby tars are mainly cracked, yielding a gas with very low tar concentrations. Fig. 2-11 shows the two-staged gasifier of the Technical University of Denmark, which consist of an exhaust gas heated screw pyrolysis and a fixed bed downdraft air gasifier.

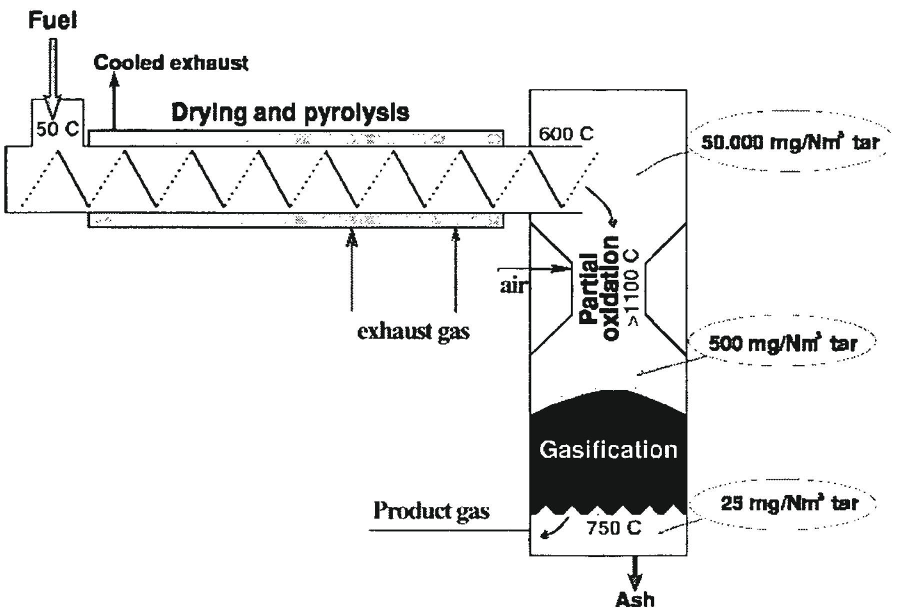

Fig. 2-11: Example of a two staged gasifier [30]

2.1.2 Market and technology analysis

In the following the results of a detailed investigation on the market and technology situation concerning gasification are presented. The market overview was carried out in a recently concluded project and can be found there in detail [35].

The analysis yielded the result that until today gasification reactors are not available off-the-peg and are more or less customer-built apparatus. This fact supports the point of view that for a successful operation of gasification plants lots of experience and knowledge in interaction of the different system components is necessary. There are only few manufacturers on the market, with no or very little experiences in long term operation of their equipment. Most of the realised plants are in the small scale, only few large scale projects have been realised. Fig. 2-12 shows the distribution of produced gasifiers of 30 manufacturers . It can be clearly seen that fixed bed gasifiers account for nearly half and fluidised bed gasifiers for one third of the produced apparatus.

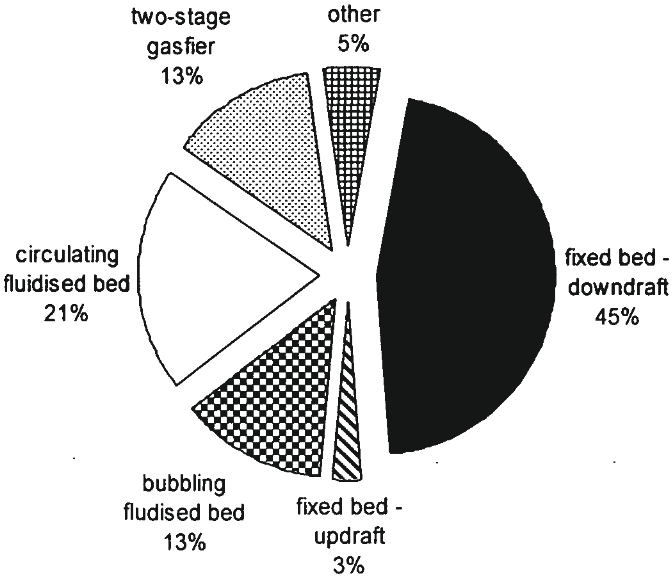

Fig. 2-12: Distribution of produced gasifiers of 30 manufacturers [35]

Fig. 2-13 indicates the distribution according to the size and type of the different gasifiers. It can be seen that most gasifiers are of fixed bed type at a scale smaller than 1 MW of fuel power. Fluidised bed gasifiers have been produced mainly at pilot scale (smaller than 1 MW fuel power) or at large scale (larger than 5 MW fuel power). Very few two-stage gasifiers are available and mainly at very small sizes, which underlines the low development stage of this technology.

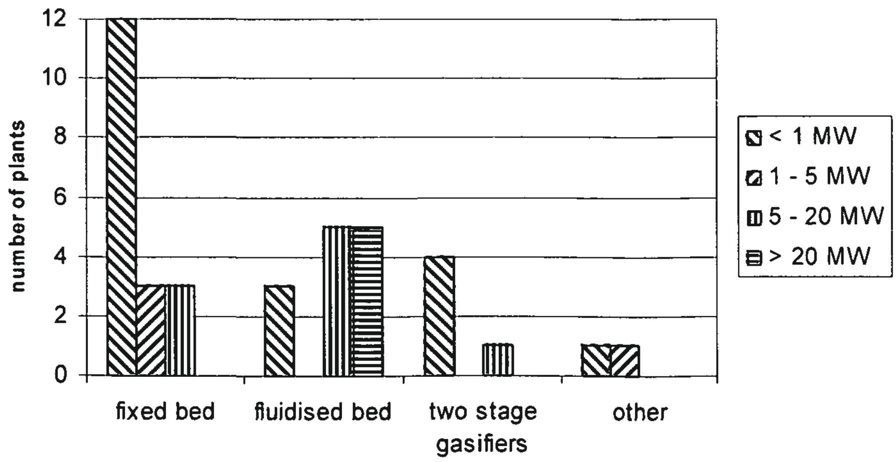

Fig. 2-13: Number of produced gasifiers sorted by type and fuel power [35]

2.2 Gas cleaning

Gas cleaning provides the linkage between gasification and gas utilisation, since the raw product gas rarely fulfils the necessary requirements for gas utilisation. Until today no sufficient primary measures (measures in the gasifier) are developed, that can avoid the necessity of a gas cleaning. The gas utilisation of the product gas strongly determines the intensity of the gas cleaning; an utilisation as co-firing fuel requires very little conditioning compared to an utilisation in a gas engine, a gas turbine or even a fuel cell.

Gases formed by gasification are contaminated by some or all of the constituents listed in Table 2-3. The level of contamination varies, depending on the feedstock, the gasifier, the process conditions and the gasification agent. Gas cleaning must be applied to prevent erosion, corrosion and environmental problems in downstream equipment. Table 2-3 summarizes the main problems resulting from these contaminants.

Table 2-3: Product gas contaminants and caused problems

contaminant	example	problems
particulates	ash, char, bed material	erosion
tars	cyclic and polycyclic hydrocarbons	clogging, depositing
alkali metal compounds	sodium and potassium compounds	hot gas corrosion, depositing
fuel nitrogen	mainly NH_3 and HCN	NO_x formation
sulphur, chlorine	mainly H_2S, HCl	corrosion, emissions

2.2.1 Gas cleaning technologies

2.2.1.1 Particles

Particles are solids, which are entrained from the gasifier by the product gas. These include inorganic ash, originating from minerals in the fuel, not fully converted biomass as coke and bed material, if available. The contamination of the product gas with particles is inevitable. Since they cause erosion, damage of the follow up components and environmental problems, particle removal is required for every gasification plant.

The requirements for the allowable particle loading in the clean gas are dependent on the gas utilisation technique; e.g. gas engines require loading below 50 mg/Nm³, gas turbines below 30 mg/Nm³ and for the utilisation as synthesis gas the loading has to be lowered to 0.02 mg/Nm³.

Standard apparatus for the removal of particles include *cyclones*, *barrier filters*, *electrostatic precipitators* and *scrubbers*. In the following the different technologies will be presented, details can be found in [35] and [36].

Cyclones: Cyclones are used for gas streams with high particle loading. As a result, they are often applied for the primary reduction of particles, because they are effective and inexpensive. In CFB reactors they are a necessary component for the recirculation of the entrained particles. Advantageous is the applicability of cyclones over a large temperature range, only limited through the used material. By a coupling of cyclones (multi-cyclone) higher separation efficiencies with a constant pressure drop can be achieved. Another development to enhance the separation efficiency is the rotating particle separator (RPS), where the centrifugal force is enhanced by rotating part of the cyclone [34]. Nevertheless, the separation of small carbon particles from a gasification gas can be sometimes problematic, as reported from Bridgewater [20].

Barrier filter: These filters can separate particles from 0.5 to 100 µm very effectively. Basically, barrier filters can be designed to separate any particle size, though the pressure drop rises strongly with smaller sizes. In technical applications particles up to 0.5 µm are removed; the cleaning is done by a pressure surge counter currently to the product gas flow. To reduce the cleaning intervals and also the operating cost, barrier filters are often combined with a cyclone for coarse particle separation.

In biomass gasification *fabric filters*, *granular bed-separators* and *candle filter* have been tested. The separation efficiency of *fabric filters* strongly depends on the thickness of the filter cake, which accounts for most of the filtering effect. Standard fabric normally can stand temperatures up to 250 °C, fabrics made from metal can be used up to 350 °C. The product gas from biomass gasification normally contains tar, which causes problems through plugging of the fabrics below temperatures of 400 °C. Therefore, tars have to be separated before the fabric filter or the filter has to be precoated. For that a filter aid is applied before the filtration, which acts as filter media and is removed again during cleaning together with the dust and tar fraction. With this type of filter dust removal efficiencies up to 99.9 % and tar removal efficiencies up to 80 % are possible [24].

In granular bed filters gas is flowing through a packed bed (e.g. sand, saw dust, ceramic spheres). It is often applied in small gasification systems for the combined removal of dust and tar. Troublesome is the waste disposal of the loaded filter material, which contains highly toxic tar compounds and has to be often handled by hand. A further development of the static granular filter is the moving granular filter. Here the loaded filter media is continuously removed and replaced with fresh one. The loaded media can be treated separately. An example of this technology is the Kawasaki granular moving bed filter [37].

Granular bed filters are resistant against corrosive gas compounds, can stand high temperatures, show low pressure drops and can be applied at a broad temperature range. However, until today there are no large scale demonstrations of these types of filters. Further, the separation of sub micron particles as well as the formation of a surface layer on the granular bed is still unsolved [38].

Candle filters are often referred to as hot gas filters, because it is possible to maintain the sensible heat in the product gas during the removal. In most cases a cyclone is located ahead of the candle filter to remove coarse particle loadings. Metal or ceramic are used as filter media, but ceramic filters have the disadvantage of possible reactions with gaseous alkali metal compounds. Problems encountered using metal as filter media range from plugged surfaces from tar compounds or problems due to the interaction of dust and highly humid product gas [39].

Promising further developments of ceramic candle filters will offer the possibility to separate dust and to catalytically remove tar and ammonia compounds at the same time. These types of filters are currently developed and tested [40].

Hot gas filters can be operated up to 900 °C, which makes them a very suitable gas cleaning technology for coupling a pressurised gasifier with a gas turbine, or with a fuel cell in the future. Candle filters are expensive apparatus, which makes it desirable to keep the gas flow to be filtered at a minimum. This can be achieve by pressurised or steam gasification.

Electrostatic precipitators can be classified in wet and dry ones. The latter one can be operated up to 500 °C; the separated dust is removed mechanically. Wet electrostatic precipitators can be operated up to a temperature of 65 °C, since collected particles are removed using a thin water film. Both types achieve high separation efficiencies for particles. The wet type can additionally separate tars and partly remove water-soluble gaseous compounds like NH_3, HCl and H_2S.

Electrostatic precipitators are characterised by a low pressure drop, high filtration rates with low operational costs and continuous operation. However, so far they were installed due to their size and investment cost only in large plants [38]. Recently, wet electrostatic precipitators have been applied successfully in the small scale of 0.5 to 1 MW_{el}, respectively [41], [42].

Scrubbers use a scrubbing liquid, in many cases water, to remove particles from a gas stream. Commonly, a venturi scrubber is used for particle removal, which achieves high separation efficiencies and low clean gas concentrations of 10 – 20 mg/Nm³, at high pressure drops of 30 to 200 mbar though. Like all wet based separation technologies the gas inlet temperature should be kept below 100 °C, which requires gas cooling before the scrubber. Scrubbers with internals are seldom used for the removal of dust, due to lower separation efficiencies and problems of plugging.

2.2.1.2 Tars

Gasifying biomass produces tar as a by-product and so it is important to reduce the tar content through primary measures in the gasifier itself. However, these primary measures are in most cases not sufficient, to reduce the tar content to levels required for the gas utilisation. Furthermore, tar in the product gas also lowers the chemical efficiency of the gasifier, since chemical energy is stored in pollutants, which have to be removed before gas utilisation. This does not apply, if the separated tar is returned into the gasifier or can be used in the gas utilisation.

Basically, the removal technologies for tar can be classified into **physical**, **thermal** and **catalytic** methods.

Physical methods: Physical methods are applied in most cases as they are proven technology. However, they require the cooling of the gas ahead.

In standard applications *scrubbers* are commonly used for the removal of tars, with the scrubbing liquid water. Using water as scrubbing liquid, moderate separation efficiencies can be achieved. The separation process is based on the coalescence of the gaseous tar compounds by cooling the gas. The tar droplets are removed by colliding them with water in the scrubber. Using aqueous scrubbers clean gas tar concentrations of 20 – 40 mg/Nm³ can be achieved. As scrubbing apparatus wash towers, rotary washers, impact washers and venturi scrubbers are used.

Non aqueous scrubber liquids have the advantage that tar can be removed also by dissolving it in the scrubber liquid. Using oil based liquids clean gas concentrations of 10 mg/Nm^3 can achieved.

A new development is the OLGA process [43]. The raw gas enters the scrubber at a temperature above the tar condensation (> 400 °C). The gas outlet temperature of the scrubber is kept above 100 °C, to avoid the condensation of water. The tar loaded, water free scrubber liquid is stripped in a second column yielding tar loaded gases, which are returned in the gasifier; a large scale demonstration of this technology is still missing.

For removal of tars wire-pipe *wet electrostatic precipitators* (ESP) are preferred to plate-ESP. The separation process of the condensed tars is similar to the removal of dust. According to the viscosity of the separated tars it may be necessary to inject water in the ESP that the collected tars can run off more easily. Advantageous is the possibility to remove tars and particles at the same time using one apparatus and to achieve high clean gas levels (< 10 mg/Nm^3).

Barrier filters are less suitable for the removal of tars, because condensed tars tend to block filter media and their cleaning is difficult. By precoating the filter it is possible to achieve moderate tar removal efficiencies and a waste water free removal [23]. Granular bed filters with sand or sawdust as filter media are only used in small scale plants.

If tar and dust is separated in *cyclones* at low temperatures it is likely that a sticky layer of particles and tar is formed. Even if particles are separated before the cyclone only poor separation efficiencies are achieved, since tar droplets are smaller than 1 μm in size and the separation efficiency of cyclones for particles of that size is poor. A possible future option could be the rotating particle separator, which allows the separation of smaller particles; for cleaning a solvent would be used.

In his thesis Joerg [44] showed the temperature dependence of tar removal (Fig. 2-14), which indicates that tar removal efficiency mainly depends on the operation temperature of the apparatus.

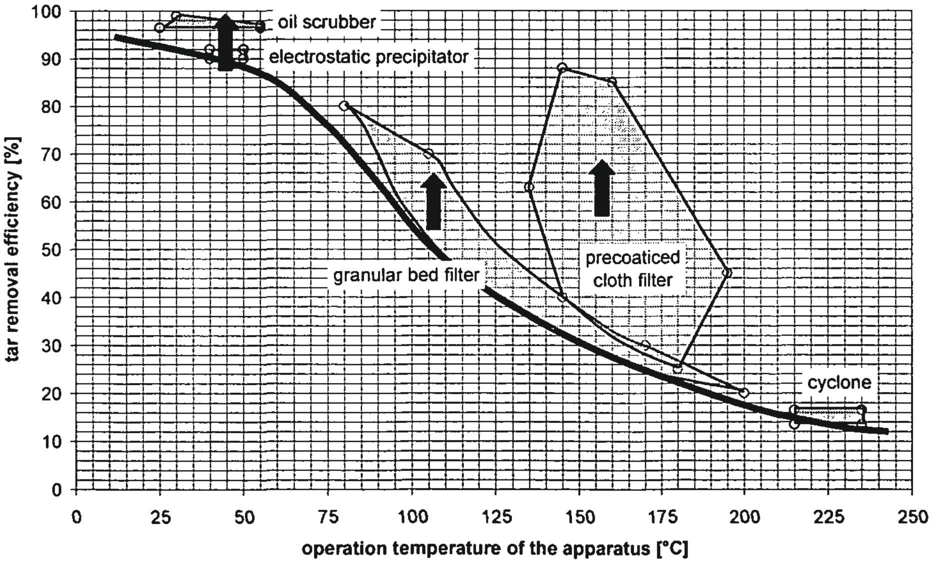

Fig. 2-14: Tar removal efficiencies of different apparatus and temperatures [44]

The bold line indicates the achievable removal efficiency due to tar condensation. Additional tar removal can be achieved using different removal technologies (marked with a grey area). Each technology can enhance the removal efficiency determined by the operation temperature to a certain extent. The removal efficiency of an electrostatic precipitator for instance can be enhanced significantly by using a scrubber with a tar soluble liquid at the same temperature level. The same applies if a precoated cloth filter is used, which partly adsorbs tar in the filter media. In general it can be seen that physical tar removal at lower temperatures is far more effective than high temperature tar removal.

Catalytic methods: Tar can be converted under the presence of a catalyst at 800 – 900 °C into stable gaseous compounds. In laboratory experiments conversion efficiencies of over 99 % are achieved. Catalysts can be used directly in the gasification reactor as additive to the bed material or in a separate apparatus. Attention has to be paid that in fluidised bed reactors attrition of the bed material can be very high; in fixed bed reactors, due to the low residence times and improper mixing, the conversion efficiency is poor. The applied catalyst has therefore to be specially designed for the desired application. Temperature control in external apparatus is easier as well as managing the attrition of the catalyst, however, in-bed catalyst avoid an additional reactor.

Non-metal catalysts are dolomite, zeolite and calcite, which are relatively cheap and resistant against pollutants. Metal catalysts tend to be more susceptible to contamination but are commercially used in the oil industry; e.g. Ni, Ni/Mo, Ni/Co/Mo, NiO, Pt, Ru. These catalysts have the advantage to be able to destruct ammonia in the product gas too [45-50].

Thermal methods: Tars can be destructed without the presence of a catalyst at very high temperatures. Biomass-derived tars though are more refractory and are harder to crack by thermal treatment alone. There are several ways of achieving thermal cracking [20]:

- By increasing residence time after initial gasification, such as in a fluidised bed reactor freeboard, but this is only partially effective.
- By direct contact with an independently heated hot surface, which requires a significant energy supply and thus reduces the overall efficiency. This is also only partly effective, owing to reliance and good mixing.
- By partial oxidation by addition of air or oxygen. This increases CO_2 levels, reduces efficiency and increases costs for oxygen use. However, it can be very effective, particularly at the high temperatures of above 1300 °C achievable with oxygen gasification.
- By cracking the tars in an electrically produced plasma arch between two electrodes; this method is available at pilot scale only [51], [52].

2.2.1.3 Alkali metal compounds

Alkali metal compounds of the biomass evaporate during the gasification process. They stay in vapour phase at high temperatures and therefore pass through particulate removal devices unless the gas is cooled. The maximum temperature that is considered to be effective for condensing alkali metal species is 600 °C. Tests on alkali metal compounds have shown that their gaseous concentrations fall with temperature to the extent that concentrations are close to turbine specifications at temperatures below 500 - 600 °C [53]. Thus it is possible that gas cooling to this level will cause alkali metal compounds to condense on entrained solids and be removed by particulate removal tools. Alkali metal compounds may also damage ceramic filters at high temperatures. Therefore, the gas needs to be cooled before cleaning, so that the alkali metal compounds condense. The alkali particles have to be removed before the gas turbine to avoid solid alkali metal compounds evaporating again in the gas turbine and causing damage on the turbine blades.

The state of the art method to **cool the product gas** for alkali condensation reduces the sensible heat of the product gas utilisable in the gas turbine. Therefore, recently a new technology for high temperature alkali removal has been developed. **Activated bauxite** is used to adsorb alkali metal compounds in the temperature range from 650 – 750 °C, yielding separation efficiencies of 95 % for potassium and 99 % for sodium, commercial applications are missing though [54].

2.2.1.4 Nitrogen compounds

50 % - 80 % of the fuel bound nitrogen is converted during gasification into ammonia, additional to small traces of other nitrogen compounds like hydro cyanide. Ammonia if combusted produces NO_x emissions, which has to be avoided due to environmental standards. Furthermore, ammonia is reported to cause problems if the producer gas needs to be compressed before utilisation.

Basically, there are two strategies to solve possible NO_x emissions; one is to remove ammonia before combustion from the producer gas and the second one is to treat the flue gas with a **selective catalytic reduction** *(SCR)* for NO_x removal. Aim of the gas cleaning should be the removal of ammonia before combustion due to smaller volume flows. The SCR-NO_x removal is a state of the art technology and will be discussed no further.

The common method to remove ammonia from the product gas is **scrubbing** with a slightly acid liquid, though for low ammonia levels water alone is sufficient. As already mentioned the gas has to be cooled before scrubbing. Additionally, every scrubbing process produces waste water, which may require extensive waste water treatment due to the presence of tar in the gas.

A future method will be hot gas removal of ammonia using **catalysts** like dolomite, nickel, and iron based catalysts, which are also applied for tar cracking. At pilot scale 99 % of the nitrogen compounds can be destroyed above 900 °C. Troublesome are catalyst poisons like sulphur and chlorine compounds as well as the missing of large scale applications.

2.2.1.5 Sulphur compounds

Sulphur compounds are not generally considered to be a problem, since biomass feeds have very low sulphur contents. The removal of sulphur compounds may therefore be only necessary if contaminated wood is used as fuel. Sulphur concentrations are lower than those produced in the combustion of fossil fuels, and hence expensive sulphur removal methods are not necessary.

Sulphur compounds can be removed by the **absorption** and **adsorption** processes.

To remove sulphur by **adsorption,** commonly a basic scrubbing liquid is used, which is a proven state of the art technology though it causes residue in terms of waste water. Higher sulphur levels can be conveniently removed by technologies used in refineries. Thereby, solvents are used (Rectisol, Purisol, DEA, MDEA), which can be regenerated in a desorption column, yielding a concentrated H_2S gas flow, which can be processed in a Claus plant to elementary sulphur. These technologies are already used for cleaning of synthesis gas from coal gasification and natural gas and have proven its suitability [55]. However, due to their high costs, these methods of removal are only applicable in large scale plants.

The second option to remove low loads of sulphur from a gas is **adsorption**. As adsorption material *zinc-oxide* can be used at 350 – 450 °C the formed zinc sulphide has to be regenerated or disposed. Advantageous are the achievable low sulphur concentrations in the clean gas (ppb range) and the fact that the sensible heat of the gas can be obtained. Instead of zinc-oxide sulphur can be adsorbed regenerative at *titan*, *iron*, *magnesium* or *aluminium* oxides at 500 °C. The obtained metal sulphide can be regenerated using steam causing H_2S contaminated flue gas [56].

A further method to remove sulphur is by adding *additives to* the gas stream *in a dry or semi-dry process*; possible additives include dolomite or lime. Lab tests have proven removal efficiencies of over 85 %. However, the disposal of residues with high CaS concentrations is troublesome. Low product gas loadings of sulphur can also be adsorbed in catalytic tar crackers, if available.

Further, active carbon can be used to remove sulphur from product gas at low temperatures; the loaded active carbon has to be regenerated or treated.

2.2.1.6 Chlorine compounds

Potential chlorine concentrations in the product gas occur if biomass feedstock with high chlorine contents or waste wood is used. At elevated temperatures chlorine causes corrosion of metals and has therefore to be removed. Removal can be done by absorption in active material like active carbon in a secondary reactor, or by dissolution in a basic wet scrubbing system. Both systems cause residues.

2.2.2 Market and technology analysis

The market for gas cleaning technologies is large and it is difficult to get an overview. Though, there are only few manufacturers, which have experience and references in cleaning product gas from gasification. Fig. 2-15 gives a distribution of 60 companies indicating their competence in the specific field. It is obvious that there is mainly knowledge available on particle separation and removal of alkali metal compounds. Removal of nitrogen, sulphur and halogen compounds can be engineered by over 40 % of the evaluated companies. The knowledge for tar removal is very low. Only 25 % of the enquired companies have indicated that they have knowledge and experience in tar removal.

To structure, assess and compare the different gas cleaning technologies it is of major importance to introduce an evaluation method based on fundamental criteria. By applying these criteria on the different gas cleaning technologies the most suitable ones can be identified for each application.

Six evaluation criteria have been specified to characterise the different technologies and identify advantages and disadvantages. Two criteria, the removal efficiency and the operating temperature, are based on technical accessible data. Therefore, they are referred to as hard criteria. Hard criteria are a characteristic of each technology. If they do not comply with the plant characteristic, the respective technology is unsuitable for this application.

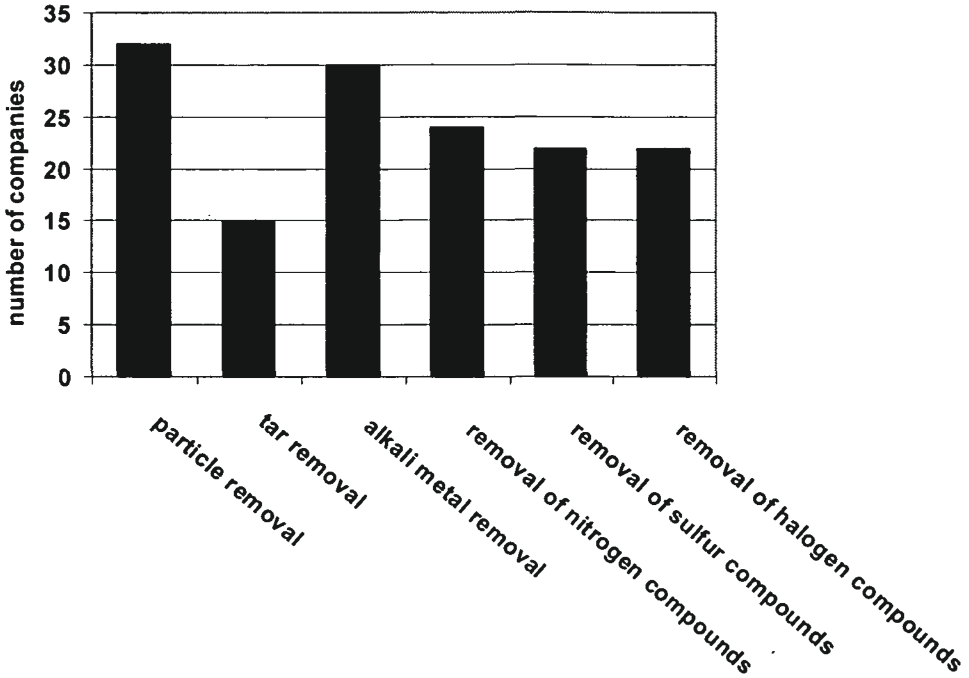

Fig. 2-15: Distribution of experience of gas cleaning companies according to the different pollutants

Nevertheless, gas cleaning technologies failed in the past, which complied in terms of hard criteria. Therefore, it is important to include so called soft criteria into the analysis. These criteria cannot be assessed by technical data, but reflect the summarised know-how of the different manufacturers on the specific gas cleaning technology. These soft criteria include the development status, the robustness, the influence on the overall plant efficiency and the residues. A gas cleaning technology for instance can have sufficient removal efficiency and operate in the proper temperature range; nevertheless, it may have a poor development status and low robustness. Such a technology is not suitable for the design of fail safe plants in the near future.

In the following the specific criteria will be characterised and explained.

- **Removal efficiency;** characterises the performance of the gas cleaning technology.
- **Operating temperature;** is an essential point for coupling the gas cleaning technology to the gas utilisation. A certain temperature can be beneficial for certain gas utilisation tools.
- **Development status;** accounts for the availability of a certain gas cleaning technology.

- **Robustness;** indicates the availability of operation of the specific technology. A high availability is beneficial and reduces the possibility of plant failure due to this specific apparatus.
- **Influence on the overall plant efficiency;** indicates the influence of the gas cleaning equipment on the overall efficiency. Most gas cleaning technologies have a negative effect on the overall efficiency.
- **Residues;** represents the influence of residues from the gas cleaning on the complexity and economy of the plant. This criterion has always to be negative. However, each gas cleaning technology produces different residues, which require different treatment and cause different waste disposal costs.

Table 2-4 gives an overview of the applied evaluation criteria.

Table 2-4: Evaluation criteria

removal efficiencies		development status		robustness		influence in the overall plant efficiency		residues	
++	> 99.9%	++	commercial available	++	very good				
+	> 99 %	+	pre-commercial	+	good	+	positive		
0	> 95 %	0	demonstration	0	average	0	no influence	0	non
-	>90 %	-	pilot scale	-	poor	-	negative	-	low
--	< 90 %	--	lab scale	--	very poor	--	strong negative	--	high

The defined criteria have been used to assess the information on the gas cleaning technologies obtained from the manufacturers for each of the relevant pollutants.

2.2.2.1 Removal of particle

Quite a progress has been made in the last years in particle removal; cyclones are used for the removal of coarse particles, scrubbers, barrier filters and electrostatic precipitators are used for fine particle removal. Furthermore, progress in hot gas cleaning was achieved using ceramic and metal filter candles. Table 2-5 gives an overview of the different particle removal technologies and their characteristics.

For high temperature applications cyclones and multi-cyclones are the best available technologies for coarse particle removal. They are robust have a high development status, a low influence on the overall plant efficiency and cause low residues. If fine particles should be removed at elevated temperatures metal and ceramic candle filter are the best choice. They are characterised by high removal efficiencies and high temperature resistance. However, the development status is lower and candle filter have a negative effect on the overall system efficiency due to their pulse cleaning. If the gas temperature can be lowered below 100 °C, a wet electrostatic precipitator offers the best performance in terms of removal efficiency, development status, robustness and effect on the overall plant efficiency.

Table 2-5: Comparison of particle removal technologies

	removal efficiency	operation temperature [°C]	development status	robustness	influence on the overall plant efficiency	residues
cyclone	--	< 900	++	++	0	-
multi-cyclone	-	< 900	++	++	0	-
RPS	0	< 500	-	-	?	-
barrier filter	++	< 350	++	+	0	-
granular bed filter	0	< 900	--	--	-	-
candle filter	++	< 900	+	+	-	-
ESP	+	< 500	++	+	-	-
wet-ESP	+	< 100	++	+	-	--
venturi scrubber	+	< 100	++	0	--	--
scrubbing tower	--	< 100	++	+	-	--

2.2.2.2 Removal of tars

The knowledge on the removal of tars from biomass has made recently tremendous progress. This is mainly due to the increased interest in gasification of biomass. Table 2-6 gives an overview of the different tar removal technologies and their characteristics.

At elevated temperature (above 800 °C) tar can be removed by catalytic and thermal crackling. Both technologies offer good removal efficiencies but they are only available at demonstration scale and the robustness is still unclear. From the manufacturers point of view, the catalytic and thermal removal of tars is still not state of the art, neither will it be in the near future.

Today, tar removal can be done securely and with high removal efficiencies at temperatures below 100 °C. Among these low temperature technologies the wet electrostatic precipitator offers the best performance in terms of removal efficiency, development status and robustness.

Comparable results are achieved with the wash tower operated with oil as solvent. The removal efficiencies are a little bit lower compared to the wet-ESP but this gas cleaning technology shows a good development status and good robustness. Further, the influence on the overall plant efficiency is low.

A new tar removal technology with good prospects for commercialisation is the OLGA technology. High removal efficiencies can be achieved at product gas inlet temperatures up to 300 °C. Since the gas exit temperature is kept above 100 °C, water condensation is avoided and therefore the disposal of waste water. Since the scrubbing liquid is recycled, the amount of residues is very low.

Table 2-6: Comparison of the different tar removal technologies

	removal efficiency	operation temperature [°C]	development status	robustness	influence on the overall plant efficiency	residues
catalytic cracking (non-metal catalyst)	++	800-900	+ / 0	+	0 / +	- / --
catalytic cracking (metal catalyst)	++	800-900	0	?	0 / +	- / 0
thermal cracking	++	1000-1200	+	+	--	0
plasma arch technology	+	>1200	--	?	?	0
cyclone	--	<900	++	++	0	-
ceramic candle	-	<900	0	-	-	-
granular bed filter – active carbon/saw dust	+	<200/<60	0	+	-	--
granular bed filter - sand	+	<900	0	+	--	--
barrier filter	-	<350	+	+	0	-
wet – ESP	++/+	<50	++	+	-	-- / -
RPS	?	?	-	-	?	--
venturi scrubber	+	<100	++	0	--	--
wash tower – water	-	<100	++	+	-	--
wash tower – oil	+	<100	+	+	0	-- / -
OLGA	++	>300/<100[1]	-	?	-	0

2.2.2.3 Removal of alkali metal compounds

Not much progress has been made in terms of new removal methods for alkali metal compounds; they are removed mainly by cooling and filtering the gas stream. For a proper removal of the condensed alkali metal compounds barrier filters and electrostatic precipitators offer good prospects. These apparatus can separate small sized particles at high efficiencies and offer good development status and robustness. At temperatures up to 650 °C candle filters could be applied with high removal efficiencies, however, they can corrode due to alkali metal compounds. Water based removal technologies, like a venturi scrubber or a wash tower, should be avoided, since they cause waste water. New high temperature technologies, which are based on adsorbing alkali metal compounds, are still under development, offering low separation efficiencies and low robustness.

Table 2-7 gives an overview of the different alkali metal removal technologies and their characteristics.

---

[1] The inlet temperature of the OLGA process should be below 300 °C, the outlet temperature above 100 °C.

Table 2-7: Comparison of the different alkali removal technologies

	removal efficiency	operation temperature [°C]	development status	robustness	influence on the overall plant efficiency	residues
cooling + cyclone	--[2]	<600	++	++	0	-
cooling + multi-cyclone	-	<600	++	++	0	-
cooling + RPS	0	<600	-	-	?	-
cooling + barrier filter	++	<350	++	+	0	-
cooling + granular bed filter	0	<650	--	--	-	-
cooling + candle filter	++	<650	+	--[3]	-	-
cooling + ESP	++	<650	++	+	-	-
cooling + wet ESP	++	<100	++	+	-	--
cooling + venturi scrubber	+	<100	++	0	--	--
cooling + wash tower	--	<100	++	+	-	--
alkali metal adsorber	0	550	--	?	?	?

2.2.2.4 *Removal of nitrogen compounds*

Table 2-8 gives an overview of the different nitrogen removal technologies and their characteristics. Most of the manufacturers suggest the removal of nitrogen compounds by scrubbers with a slightly acid scrubbing liquid at temperatures below 100 °C. Scrubbers offer good removal efficiencies combined with a good development status and robustness. However, scrubbing produces waste water, which has to be treated. The removal of nitrogen compounds using catalysts at elevated temperatures is not available at large scale and has stringent requirements for other pollutants, like sulphur. Low concentrations of nitrogen compounds in the product gas can be removed together with tars and dust in a wet-ESP.

Table 2-8: Comparison of the technologies for nitrogen removal

	removal efficiency	operation temperature [°C]	development status	robustness	influence on the overall plant efficiency	residues
non-metal catalysts	++	800-900	- / 0	?	0	- / --
metal catalyst	++	800-900	- / 0	?	0	- / 0
scrubber (acidic)	++	<100	++	++	0/-	- / --
wet ESP	0	<50	++	+	-	--

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[2] Cyclones cannot separate condensed alkali metal compounds (mainly d_p< 5μm).

[3] Ceramic and metal candle filters can corrode due to alkali metal compounds.

2.2.2.5 *Removal of sulphur compounds*

As already mentioned, sulphur removal is mainly necessary if waste wood is utilised. Table 2-9 gives an overview of the different sulphur removal technologies and their characteristics. The state of the art technology suggested by most manufacturers is the removal with a basic aqueous scrubbing liquid. This technology offers good removal efficiencies combined with a good development status and robustness. However, scrubbing produces waste water, which has to be treated.

Technologies, which are state of the art in natural gas preparation like physical scrubbing (Rectisol) or chemical scrubbing (DEA, MDEA), offer high removal efficiencies but are not applicable due to the small size of biomass gasification and the necessity for an additional Claus-plant to process the sulphuric residues. Active carbon can be used for low sulphur loadings, however, it causes high amounts of residues in form of loaded active carbon. Using dry adsorption offers good prospects in terms of removal efficiencies; however, it has not been tested in combination with biomass gasification so far.

Table 2-9: Comparison of technologies for the sulphur removal

	removal efficiency	**operation temperature [°C]**	**development status**	**robustness**	**influence on the overall plant efficiency**	**residues**
water scrubber	++	<100	++	++	0/-	- / --
solvent scrubber (DEA, MDEA, Purisol)	++	<50/-100	++	?	--	--[4]
zinc oxide filter	++	<350	++	+	?	--
metal oxide filter (regenerative)	++	<350	0	+	?	--[4]
dry adsorption	+	<500	0	?	0	-
wet-ESP	0	<50	++	+	-	--
active carbon	++	<300	++	++	0	--[5]

2.2.2.6 *Removal of chlorine compounds*

State of the art removal of chlorine compounds, mainly HCl, is basic scrubbing, which offers the already mentioned advantaged and disadvantages. Furthermore, there are dry adsorption technologies available, which have been tested at temperatures below 500 °C successfully. For small loadings active carbon can be used; however, it causes high residues. Table 2-10 gives an overview of the different removal technologies of chlorine compounds.

---

[4] Desorbing the chemical scrubbing liquids releases a sulphur loaded gas, which can be utilised in a Claus-plant.

[5] Active carbon is suitable for the removal of low sulphur loadings, however the loaded active carbon has to be regenerated or disposed.

Table 2-10: Comparison of chlorine removal technologies

	removal efficiency	operation temperature [°C]	development status	robustness	influence on the overall plant efficiency	residues
basic scrubber	++	<100	++	++	0/-	- / --
dry adsorption	+	<500	++	+	0	-
active carbon	++	<300	++	++	0	--[6]

2.3 Gas utilisation

The cleaned product gas can be utilised by various gas utilisation technologies. Fig. 2-16 shows the various possible options indicating the requirements for the gas cleaning and the overall technology reliability. It is assumed that the same feedstock is used for all technologies. Co-firing represents the simplest and therefore most reliable technology with the lowest requirements for the gas cleaning, since the operation of a plant is not fully dependent on the operation of the gasifier.

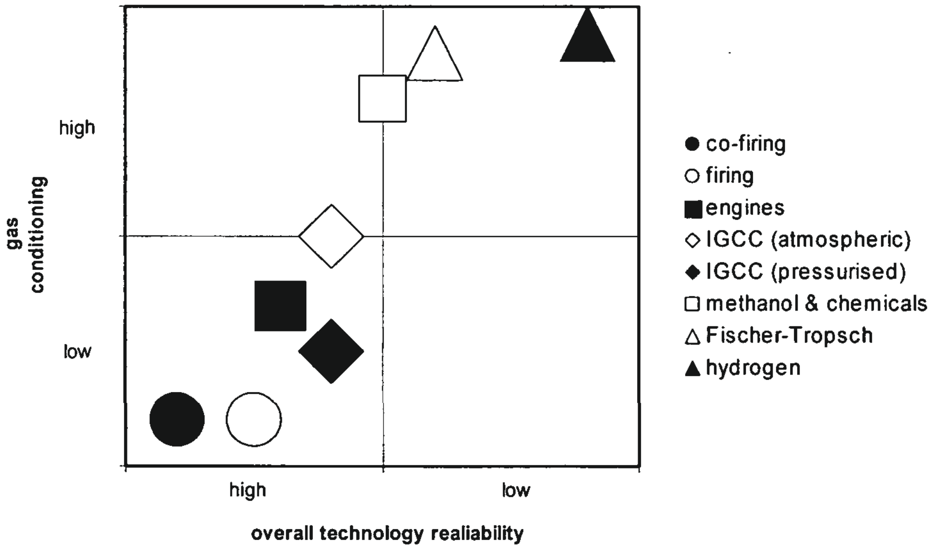

Fig. 2-16: Characterisation of different gas utilisation technologies

Firing has slightly lower technology reliability, due to the fact that the total plant is dependent on the gasification, but the required gas cleaning is still at a low level. For engine applications the necessary gas conditioning increases as for IGCC (Integrated Gasification Combined Cycle) applications. However, pressurised IGCC application have lower requirements regarding the gas cleaning as if atmospheric gasification is used and the product gas has to be pressurised before utilisation. The highest requirements in terms of gas cleaning and the

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[6] Active carbon is suitable for the removal of trace compounds, however the loaded active carbon has to be regenerated or disposed which can cause problems and high costs.

lowest overall technology reliability show technologies, which produce a storable product like Fischer-Tropsch technology, methanol synthesis and hydrogen production technology.

In the following an overview of achievable efficiencies for different gas utilisation technologies is given. Gasification combined with available internal combustion based technologies offers the possibility to convert biomass into heat and power at high efficiencies. However, this applies to realised plants only, if a high overall utilisation of the feedstock is achieved apart of a high electrical efficiency. If gasification plants are optimised for pure electricity production, combustion based technologies using a steam cycle achieve comparable efficiencies [57].

Fig. 2-17 shows the ranges of efficiencies for different technologies for combined heat and power production with an overall fuel utilisation of over 75 %.

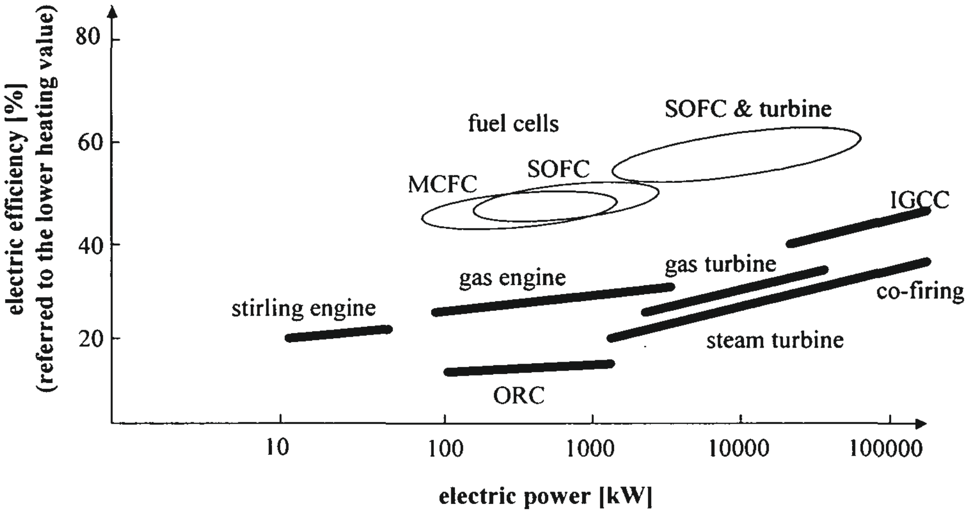

Fig. 2-17: Electric efficiencies of different biomass conversion technologies [57]

Gasification based technologies (gas engine, gas turbine) show the highest efficiencies, additional, high technical developing potential. An increase in efficiency is possible within combined cycle applications (IGCC). In the future, biomass gasification will offer the possibility to utilise fuel cells as conversion technology, which will further increase the electric efficiencies.

2.3.1 Gas utilisation technologies

At present co-firing and firing application are the easiest options for an accelerated market penetration potential of biomass gasification. The overall costs for co-firing are relatively low due to the usage of the power cycle for instance in coal fired power plants. In addition, co-firing has the advantage over co-combustion (where un-gasified biomass fuels are mixed with coal before or during the combustion process) that the biomass residual ash is not mixed with the coal ash, which has an existing market for instance as a construction material. Direct firing of the producer gas in cement kilns represents another reliable possibility for gas utilisation. Within both technologies the technical risks are low as the gas is utilised hot and therefore no tar problem occurs. However, co-firing and firing have low conversion efficiencies from biomass to power and are far less promising options than if the product gas is utilised directly in an internal combustion engine and will therefore be excluded from further consideration within this work.

Internal combustion engines like gas turbine or gas engine, fuel cell or synthesis technologies have far higher requirements on the gas conditioning as co-firing. These requirements are summarised in Table 2-11, however, until today some of the requirements have not been specified.

Table 2-11: Minimum requirements of the producer gas for different gas utilisation technologies (not all requirements have been specified so far) [33]

		gas engine	gas turbine	methanol synthesis	fuel cell
particle-loading	mg/Nm³	< 50	< 30	< 0,02	
particle size	µm	< 3	< 5		
tar-loading	mg/Nm³	< 100		< 0,1	< 1
alkali metals-loading (K, Na)	mg/Nm³		< 0,25		
NH_3-loading	mg/Nm³	< 55		< 0,1	< 0,1
H_2S-loading	mg/Nm³	< 1 150		< 1	< 1

It can be seen that internal combustion based technologies have requirements, which are 100 to 1000 times higher than for fuel cell or methanol synthesis applications. The additional effort for dust and tar removal, to condition producer gas suitable for internal combustion devices compared to the requirements for use in FT-synthesis, can be seen in Fig. 2-18.

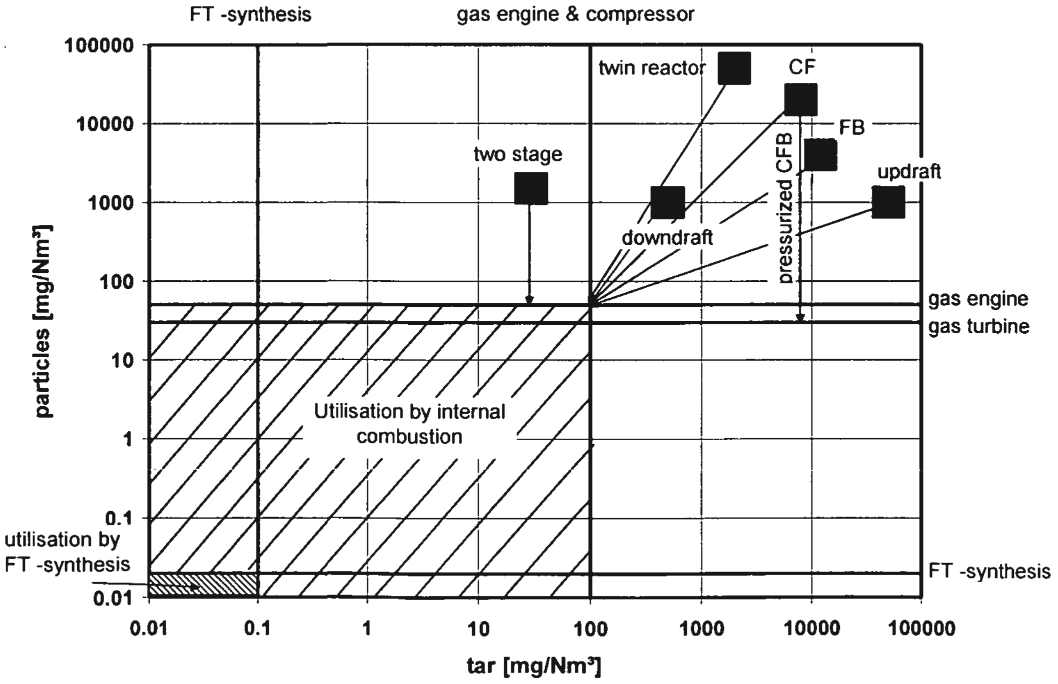

Fig. 2-18: Particle and tar loading of the different gasification systems compared to the necessary clean gas requirements of internal combustion engines and Fischer-Tropsch synthesis

Different gasification systems require different needs for gas cleaning; two stage gasifiers can produce a gas without the need for additional tar removal for engine or turbine application; particle removal is still necessary. All other gasification systems require particle and tar removal in the producer gas to a different extent. Only pressurised CFB-applications in combination with a gas turbine can dispense with tar removal before the turbine.

2.3.1.1 Gas engines

In the last decade gas engines mainly designed for natural gas or diesel have been adapted or further developed to combust low calorific value gases [58], [59]. The product gas from gasification, which has to fulfil the requirements given in Table 2-11, is quite well suited for the combustion in gas engines concerning laminar flame speed and knock resistance; however, the high hydrogen content in the gas requires special adjustments, which slightly reduce the power output and efficiency of the gas engine. Three gas engine types are used today [35]:

- Gas Otto-engine at $\lambda \sim 1$ with a three-way catalyst.
- Gas Otto-engine at $\lambda \sim 1.4 - 1.7$ operated in lean mode with or without flue gas treatment (thermal / catalyst).
- Ignition jet engine like the diesel principle with ignition oil usage of 3 to 20 %.

These types differ according to their combustion technique, investment costs, efficiencies, life expectations, emissions and maintenance requirements. The lowest emissions can be achieved using a gas-Otto-engine, achieving electrical efficiencies up 38 %. Using a lean operating engine with turbocharger even higher efficiencies of up to 42 % can be achieved. Ignition jet engines can perform equally well; however, they show high emissions of NO_x, CO and unburned hydrocarbons. Gas engines are currently applied in a power range from 50 kW_{el} to 10 MW_{el}.

2.3.1.2 Gas turbines

The requirements for the product gas to be combustible in gas turbines are given in Table 2-11. However, not all limits have been specified until today. The major advantages of gas turbines are lower emissions in terms of CO and NO_x. If the plant should be operated in IGCC-mode, gas turbines offer the advantage due to the higher flue gas temperature of high steam parameters and therefore better efficiencies. Disadvantageous is the lower efficiency at small scale and the poor partial load behaviour. Recently, attempts have been made to solve this problem by decoupling the shaft of the turbine from the given net frequency using an inverter, which resulted in the development of the micro gas turbine with high rotation speeds. This new technology has proven its qualities using natural gas as fuel, though until today no experiments with product gas from a gasifier have been made.

Standard gas turbines are currently applied in a power range of 0.4 – 340 MW_{el}, micro-gas turbines in a power range of 20 – 350 kW_{el}.

2.3.2 Market and technology analysis

The Projektgemeinschaft Biomasse [35] has carried out a survey concerning the utilisation of low calorific gas from gasification in internal combustion engines like gas engines, gas and micro-gas turbines. The results will be briefly presented together with an evaluation of the current status and requirements of those technologies.

2.3.2.1 Gas engines

In Europe there are over 40 manufacturers of gas engine based CHP-plants but only 15 engine manufacturers. In general, the interest for the application of gas engines in the gasification sector is limited due to the small expected market. Only few manufacturers are willing to invest in this market and to perform active research and development. However, most manufacturers demand specific requirements of the fuel gas in terms of pollutants and regard it as the responsibility of the gasifier and gas cleaning manufacturers to provide suitable gas qualities [35].

The requirements of the engine manufacturers are summarised as following

- Secure constant flow of the product gas with low range of variations in the heating value.
- Low content of pollutants including tars, particles and acid compounds.

2.3.2.2 Gas turbines

Currently gas turbine manufacturers are not very interested in the biomass gasification market, even less than the manufacturers of gas engines. Two manufacturers could be identified in Europe, which have experience in the combustion of gasification gas; however, there is only little interest at the present for cooperations. Currently there are no applications of micro-gas turbines with gasification gas, from which it can be concluded that further research and development is required [35].

Comparison of evaluated gas utilisation technologies

In the following the different gas utilisation technologies will be compared in terms of their application properties. The product gas requirements already have been specified in Table 2-11, the results are given in Table 2-12. It can be seen that gas engines and micro gas turbines are applied mainly in the lower power range and are well suitable for atmospheric applications, gas turbines are best applied at large scale and pressurised gasification, since no compression of the product gas is required. Gas turbines can meet the CO emission limits, gas engines require CO reduction methods of the flue gas because of a certain product gas slip through the engine. Furthermore, lower NO_x emissions can be achieved with gas turbines, where gas engines operate right on the legal limit. The main advantages of gas engines are higher efficiencies and better partial load behaviour at electrical power ranges below 2 MW as well as the greater experience with the utilisation of biomass gasification gas. Gas turbines at large scale offer similar efficiencies as gas engines, although due to their higher flue gas exit temperature it is recommended to include a steam cycle in the plant to enhance the electric efficiency.

Table 2-12: Comparison of different gas utilisations

	gas engines	gas turbines	micro gas turbine
power application range	50 kW – 10 MW_{el}	0.4 – 350 MW_{el}	20 – 350 kW_{el}
atmospheric application[7]	++	-	+
pressurised application	--	++	--
emissions CO[8]	--	+	+
emissions NO_x[8]	-	+	+
electric efficiency (< 2 MW_{el})[9]	++	--	+
electric efficiency (> 2 MW_{el})[9]	+	+	n.a
noise emissions [dBA]	80 – 120	60 -90	60 -75
experience with gasification gas[10]	++	+	--

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[7] ++ well suitable; - suitable, -- unsuitable

[8] -- emissions to high, require stringent flue gas treatment; - emissions are just below the emissions limits; + emissions limits can be kept without post treatment

[9] these evaluations are done by comparing the different technologies: ++ high electrical efficiency and good partial load behaviour; + medium electrical efficiency and partial loading behaviour; -- poor electrical efficiency and partial loading behaviour

[10] ++ applications and experience available; + only few applications and little experience; -- currently no experience available

3 Plant analysis and evaluation

The current state of the art of biomass gasification technology allows only to a certain extent the utilisation of commercially available system components. Therefore, in the following a methodological approach is presented, which permits the identification and specification of appropriate system components. The basis for this is formed by an analysis of existing gasification plants.

3.1 Methodological approach

Existing gasification plants are characterised by the use of a multitude of different technologies, which are all characterised by a lack of operating experience and the need for further development. The analysis in this study is based on the know-how and operating experience of existing gasification plants. This evaluation is done on two levels: the unit operation level, respectively the system components and the process level, here referred as the arrangement or combination of the components in an overall system.

For the analysis of the system components, i.e. fuel conditioning and feeding, gasification, gas cleaning and gas utilisation, on a fundamental basis, it is important to base the assessment on real plant operating data. On that basis the different apparatuses can be evaluated and it is possible to compare different gasifiers for instance on the impurity content of the product gas or the reactor complexity. Similarly, for the gas cleaning different criteria like removal efficiency for different pollutants or the amount of residues can be used. Important criteria for the gas utilisation include the pollutant tolerance, the electrical efficiency and the flue gas emissions.

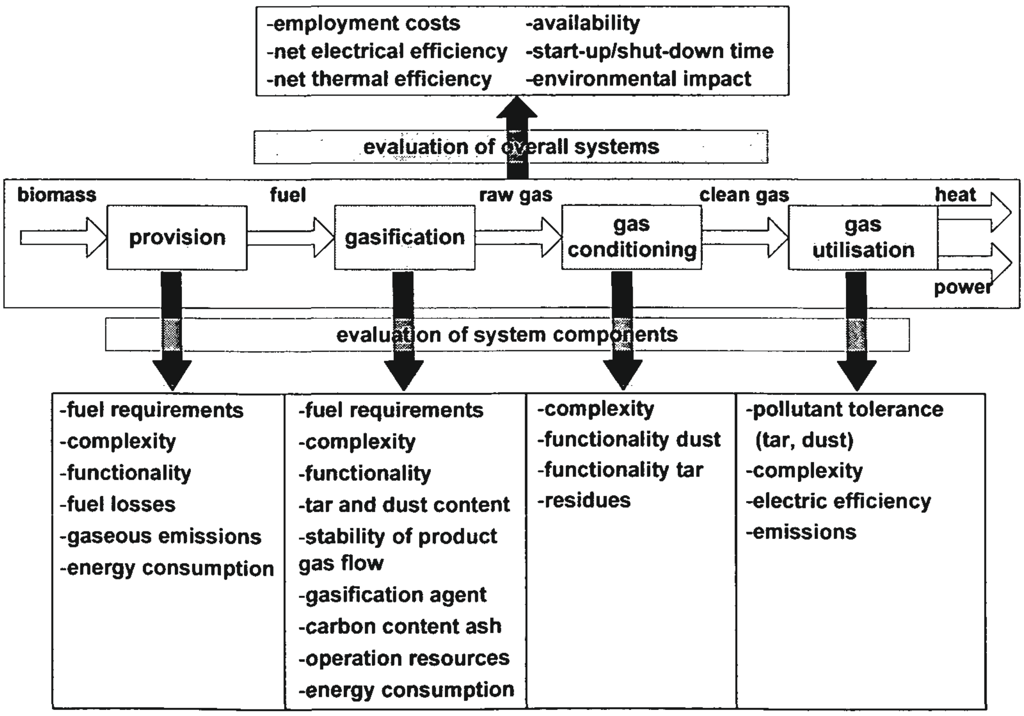

Fig. 3-1: Methodological approach [60], [61]

Experience has shown in the past that individually well designed process steps may cause problems when used in combination with other system components. Therefore, in addition to the evaluation of single system components it is important to assess suitable combinations and possible interactions of these unit operations. For the overall plant evaluation criteria like the type of technology, equipment availability and total efficiency have been defined and used.

The application of this concept and combination of the gained information enables the improvement of existing gasification processes and the development of new concepts for biomass gasification.

A detailed evaluation method, which meets the aforementioned requirements, is shown in Fig. 3-1.

3.2 Investigated plants

Many gasification plants, both at small and large scale, have been developed over the past decade, but there are only few of them successfully running as commercial gasifiers today [62]. Data from 17 different plants have been collected to obtain a detailed view of the different applied gasification, gas cleaning and gas utilisation technologies [63]. These plants were grouped into three categories: fixed-bed gasification plants, fluidised bed gasification plants, and plants using multi-stage gasification with separated reaction zones. Table 3-1 gives an overview of the investigated plants.

Table 3-1: Overview of the investigated plants

fixed bed gasification plants	fluidised bed gasification plants	multi-stage gasification plants
Domsland	ARBRE	Blauer Turm (DM2)
Espenheim	Güssing	Carbo-V
Harboore	Umsicht	Carbo-Compact
Hengelo	Värnamo	DTU -Viking
Pyroforce	Vermont	
Siebenlehen		
Wr. Neustadt		
Xylowatt		

In the following, the fixed bed and fluidised bed gasification plants are characterised briefly. For further information literature sources are given. A detailed overview including the multi-stage gasifiers can be found in the report of the “Projektgemeinschaft Biomassevergasung” [63].

The investigated plants are summarised according to their main process characteristics in order to give a better overview of the different applied technologies. Table 3-2 shows the investigated fixed bed gasifiers for small scale applications, Table 3-3 gives the overview of fluidised bed gasifiers for large scale applications. In the following sections of this work these gasification plants will be referred to by the names given in Table 3-2 and Table 3-3.

Table 3-2: Overview of the evaluated fixed bed gasification plants

	Domsland	Espenheim	Harboore	Hengelo	Pyroforce	Siebenlehen	Xylowatt	Wr. Neustadt
plant data								
fuel power [kW]	800	4000	10000	600	?	10000	225	2000
net electric power [kW]	150	700	1500	200	200	1750	50	580
district heating [kW]	320	-	5000	-	260	4500	108	720
gasification reactor								
single stage gasification	X	X	X	X	X	X	X	X
autothermal	X	X	X	X	X	X	X	X
allothermal								
pressure (a... atmospheric, p...pressurised)	a	a	a	a	a	a	a	a
gasification agent (a...air, s...steam, o...oxygen)	a	a	a	a	a	a	a	a
gas cleaning								
dry gas cleaning		X		X	X	X	X	
wet gas cleaning	X	X	X	X	X		X	X
cyclone		X		X	X		X	
catalytic gas cleaning								
barrier filter				X	X		X	
wet electrostatic precipitator			X					X
scrubber	X	X		X	X		X	
gas utilisation								
gas engine	X	X	X	X	X		X	X
gas turbine						X[11]		
CHP-plant	X		X		X	X	X	X
combined cycle (IGCC)								
status								
current plant status o.....continuous operation to....temporarily operated, no...not operated sd...shut down, dismantled	to	sd	co	to	co	to	co	to
literature sources								
	[64]	[65-68]	[42], [62], [69]	[62]	[70]	[71-76]	[65], [77-79]	[41]

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[11] Product gas is combusted and used in a hot gas turbine.

Table 3-3: Overview of the evaluated fluidised bed gasification plants [12]

	Värnamo	Umsicht	ARBRE	Güssing	Vermont
plant data					
fuel power [kW]	18000	500	27000	8000	32000
net electric power [kW]	5800	43	8100	1700	-
district heating [kW]	8900	-	-	4500	-
gasification reactor					
single stage gasification	X	X	X	X	X
autothermal	X	X	X		
allothermal				X	X
pressure (a... atmospheric, p...pressurised)	p	a	a	a	a
gasification agent (a...air, s...steam, o...oxygen)	a	a	a	s	s
gas cleaning					
dry gas cleaning	X	X			
wet gas cleaning			X	X	X
cyclone			X		
barrier filter	X	X	X	X	
electrostatic precipitator					
scrubber			X	X	X
gas utilisation					
gas engine		X		X	■
gas turbine	X		X		
CHP-plant	X			X	
Combined cycle (IGCC)	X		X		
status					
current plant status co.....continuous operation to....temporarily operated, no...not operated sd...shut down, dismantled	no	to	sd	co	to
literature sources					
	[62] [80-82]	[16], [18], [62], [83]	[62] [84-86]	[23-25] [87-89]	[26-28] [62]

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[12] Black areas indicate not existing components.

3.3 *Evaluation criteria*

3.3.1 Fuel conditioning and feeding

The section of fuel conditioning and feeding covers the area between the fuel storage facilities and the lock feeding system of the gasifier. The lock feeding system is considered as part of the gasifier and evaluated in the gasifier section.

The fuel conditioning enables the preparation of the fuel characteristics according to the requirements of the subsequent gasification reactor. It can consist of physical processing, like a change in particle size or water content or of transportation and storage operations. This group includes feeding systems like conveyor belts or screw conveyors, systems for altering the size of the fuel like sieves, mills or choppers and systems to dry the fuel like rotary kiln dryers or fluidised bed dryers.

The analysis leads to the formulation of the following criteria for the evaluation of existing fuel conditioning. The criterion *fuel requirements* characterises the demand on the biomass fuel concerning size, dryness and size distribution, the criterion *complexity* specifies the requirements on machinery, conveyors, and dryers necessary to achieve the specified fuel conditions. *Functionality* is a criterion, which relates the actual performance of a process component to the performance as expected from design values. The criterion *fuel loss identifies* the losses of fuel through conveyors and conditioning. *Gaseous emissions* specify gaseous emissions originating for instance from fuel drying. Finally, the criterion e*nergy consumption* characterises the energy requirements of the fuel conditioning equipment referred to the gross electric power production of the plant.

For each criterion an evaluation split into five grades is defined, which can be found in Table 3-4. These definitions allow the comparable evaluation of different fuel conditionings.

Table 3-4: Overview of the evaluation for fuel conditioning and feeding

evaluation	fuel requirements	complexity	functionality	fuel losses	gaseous emissions	energy consumption
5	log	very low (conveyor)	100 %	< 1 %	none	< 1 %
4	wood chips	low (screw conveyor)	>80 %	1 ≤ 5 %	-	1 ≤ 5 %
3	wood chips pre-dried	middle (additional sieving or drying)	>50 %	5 ≤ 10 %	Yes	5 ≤ 10 %
2	wood chips dried or classified	high (additional sieving and drying)	> 50 %	10 ≤ 20 %	-	10 ≤ 15 %
1	wood chips dried and classified	very high (additional chopping)	> 50 % and negative influence on the follow up components	≥ 20 %	-	≥ 15 %

3.3.2 Gasification

The analysis of the gasification section includes the fuel feeding into the reactor, the reactor itself and all equipment directly belonging to the reactor. The following criteria can be formulated:

The criterion *fuel requirements* characterises the requirements of the reactor on the biomass feedstock concerning size, dryness and size distribution, the criterion *complexity* specifies the equipment necessary to operate the gasifier, like locks, fuel feeding screws or ash discharge systems. *Functionality* is a criterion, which relates the actual performance of a process component to the performance as expected from design values. The criterion *dust content* and *tar content* both indicate the pollutant content in the producer gas. Further criteria are the *stability of the product gas flow,* which is essential for follow-up components, and the *gasifying agent*. The *carbon content ash* specifies the carbon content in the fly ash and the bottom ash of the gasifier. The *consumption of operating resources* characterises the use of catalysts, bed material, nitrogen, and other resources, for the operation of the gasifier. Finally, the *energy consumption* characterises the energy requirements of the gasifier referred to the gross electrical power of the plant.

For each criterion an evaluation split into five steps is defined, which can be found in Table 3-5.

Table 3-5: Overview of the evaluation for the gasifier

evaluation	fuel requirements	complexity	functionality	dust content	tar content
5	wood chips	fixed bed, no lock system	100 %	< 500 mg/Nm^3	low
4	wood chips pre-dried	fixed bed	> 80 %	-	-
3	wood chips dried or classified	fixed bed with rotating equipment	> 50 %	500 – 5000 mg/Nm^3	middle
2	wood chips dried and classified	fluidised bed	> 50 %	-	-
1	sawdust dried and classified	pressurised fluidised bed	> 50 % and negative influence on the follow up components	> 5000 mg/Nm^3	high

evaluation	stability of product gas flow	gasification agent	carbon content ash	operating resources	energy consumption
5	none	air	< 10 %m	very low	< 1 %
4	low	-	10 ≤ 20 %m	low	1 ≤ 4 %
3	middle (problems with follow up components)	steam	20 ≤ 40 %m	medium	4 ≤ 6 %
2	high (partial operation possible)	-	40 ≤ 80 %m	high	6 ≤ 8 %
1	very high (no constant operation possible)	oxygen	≥ 80 %m	very high	≥ 8 %

3.3.3 Gas cleaning

The gas cleaning section includes the section between the gasifier exit and the gas utilisation system. In this section the performance of the applied gas cleaning technology is assessed according to the following criteria.

Complexity indicates the quantity and effort in the gas cleaning equipment to achieve the required gas conditions for the gas utilisation technology. Each additional gas cleaning step increases the complexity of the plant and therefore the risk of a failure of a system component. The criterion *functionality dust* describes how well the dust separation in reality works referred to the design state. The *functionality tar* indicates the same issue referred to tar separation. Finally, possible *residues* are assessed, which give an insight to the produced residues and their further processing of the specific gas cleaning technology. Due to unavailability of data concerning pollutants like alkali metal, sulphur, nitrogen, and chlorine compounds no evaluation of these pollutants could be performed.

An overview about the evaluation criteria can be found in Table 3-6.

Table 3-6: Overview of the evaluation criteria for the gas cleaning

evaluation	complexity	functionality dust	functionality tar	residues
5	heat exchange (HE)	very good	very good	none
4	HE and one gas cleaning step (GCS)	good	good	utilisation
3	HE and two GCS	fair	fair	disposal
2	HE and three GCS	low	low	treatment before disposal
1	HE and more than three GCS	very low	very low	special disposal

3.3.4 Gas utilisation

The section of gas utilisation includes all apparatus for the conversion of the clean producer gas into heat, power or both products. An overview of the evaluation criteria can be found in Table 3-7.

Table 3-7: Overview of the evaluation for the gas utilisation

evaluation	pollutant tolerance dust	pollutant tolerance tar	complexity	electrical efficiency	emissions
5	robust co-firing	co-firing	co-firing	IGCC	<< TA-Luft without treatment
4	co-firing	gas turbine without compressor after the gasifier	gas engine	gas engine adapted	< TA-Luft without treatment
3	gas engine, gas turbine	gas turbine, gas engine	gas turbine	gas turbine adapted	< TA-Luft with treatment
2	fuel cell	fuel cell	fuel cell	gas engine not adapted	> TA-Luft
1	synthesis gas	synthesis gas	IGCC	gas turbine not adapted	>> TA-Luft

TA-Luft: Technische Anleitung zu Reinhaltung der Luft vom 24.Juli 2002

The criterion *pollutant tolerance dust* is difficult to evaluate. However, in general gas engines tolerate higher dust loadings than gas turbines in the evaluated plants. The same applies to the criterion *pollutant tolerance tar*, since there are marginal tolerance differences between the gas engine and the gas turbine. Therefore, all processes are evaluated equally. Only the gas turbine of Värnamo, which can burn tars as well, is assessed better. The criterion *complexity* indicates the complexity of the apparatus for the electricity production. Finally, insight is given by the criterion *electrical efficiency* on the gross efficiency of the gas utilisation technology (produced electrical power referred to the fuel power) and by the criterion *emissions* on the necessary treatment of the flue gas leaving the gas utilisation technology.

3.3.5 Overall plant

This criteria group describes the overall performance and gives some indications of the plant economy.

The criterion *employment costs* evaluates the personnel costs necessary to operate the plant. The *net electrical efficiency* indicates the performance of the total plant in terms of electricity production defined as produced electrical power reduced by own power consumption referred to the fuel power. The *net thermal efficiency* is a criterion for the net thermal efficiency of the plant defined as the produced usable thermal power reduced by internal thermal power consumption referred to the fuel power. The criterion *availability* indicates the availability of operation of the total plant, which is an important parameter for an economic operation of a plant. *Start-up / shut-down time* shows the flexibility of the plant. The criterion *environmental impact* accounts for the impact the plant has on the surrounding environment. For the evaluation gaseous and noise emissions as well as liquid residues and odours of the plant are considered.

In the following the different criteria are presented (Table 3-8).

Table 3-8: Criteria for the overall plant evaluation

evaluation	employment costs	net electrical efficiency	net thermal efficiency	availability	start-up/ shut-down time	environmental impact
5	unmanned operation	≥ 35 %	> 50 %	< 95 %	automatic	very low
4	1 man shift	35 ≥ 30 %	50 ≥ 40 %	95 ≥ 80 %	semiautomatic (short time)	low
3	2 man shift	30 ≥ 25 %	40 ≥ 30 %	80 ≥ 60 %	semiautomatic (long time)	medium
2	3 man shift	25 ≥ 20 %	30 ≥ 20 %	60 ≥ 40 %	manual (short time)	high
1	manual - operation	< 20 %	≥ 20 %	≥ 40 %	manual (long time)	very high

3.4 Results

In the following the results of the evaluation are presented. For each criterion bars are drawn, whereby the length of the different bars indicates the quality of the specific criterion. Longer bars indicate a better performance, whereas shorter bars indicate a poorer one. The evaluation of the plants is, similarly as before, limited to fixed bed and fluidised bed gasification plants. The focus in this work is given on large scale applications and, hence, only fluidised bed gasifiers are of importance. However, it is still necessary to assess fixed bed gasifiers. This is, because significant progress has been made recently for gas cleaning and gas utilisation at small scale. This is explained mainly by the lower investment costs for small plants, and, thus, newly developed technologies are applied much faster than on the large scale. However, not all technologies suitable for small scale applications can be applied on the large scale too. Therefore, in each case an assessment of the obtained results is necessary.

3.4.1 Fixed bed gasification plants

3.4.1.1 Fuel conditioning and feeding

Fig. 3-2 shows the graphical evaluation of the fuel conditioning and feeding section for different fixed bed gasification plants. It can be seen easily that there are large differences in some of the criteria, which reflect the various fuel conditioning processes. Organic gaseous and particles emissions can be found in plants with integrated drying, like in Pyroforce, Domsland and Wr. Neustadt. If a dryer is used, the energy consumption rises too, which can be easily seen.

Generally, there are problems within the functionality of the fuel conditioning system, a point where improvements are still to be made. Further, it can be seen that the fuel requirements rise complementary to the fuel losses, since fuel conditioning always causes fuel losses.

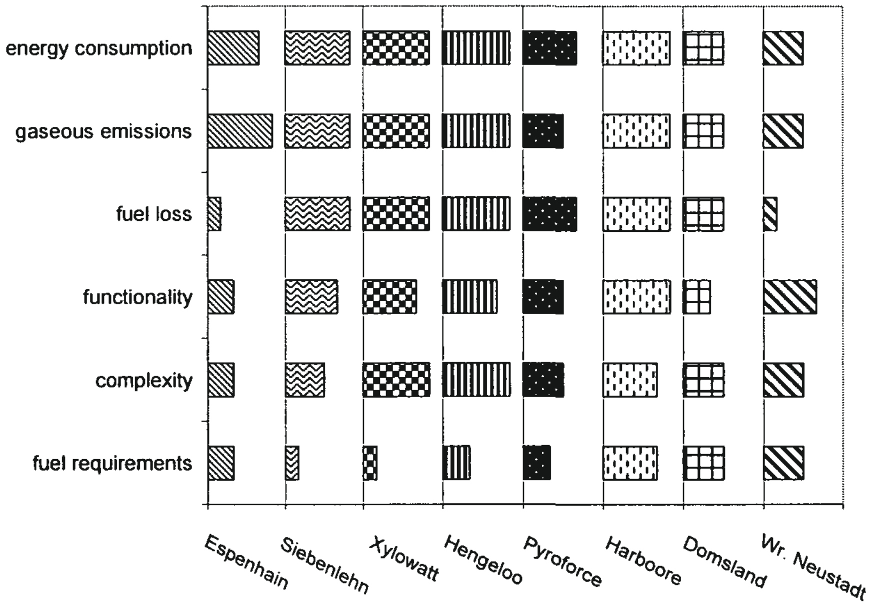


Fig. 3-2: Evaluation results of the fuel conditioning and feeding for fixed bed gasifiers

From Fig. 3-2 it can be seen that old plants like Espenheim are poor in terms of fuel requirements as well as in terms of complexity in comparison with other evaluated plants. This indicates that at least some lessons have been learned from the past. Finally, a connection between the fuel requirements and the complexity of the plants can be found. Generally spoken, fuel requirements decrease with an increase in the complexity of the fuel conditioning.

3.4.1.2 Gasifier

Fig. 3-3 shows the graphical evaluation of the fixed bed gasification reactors. Looking at the fuel requirements it can be seen that the Harboore plant has the lowest requirements and achieves also the best evaluation result. This plant can operate with chopped wood of various size and humidity, which indicates the advantages of updraft-gasifiers over downdraft gasifiers in terms of fuel requirements.

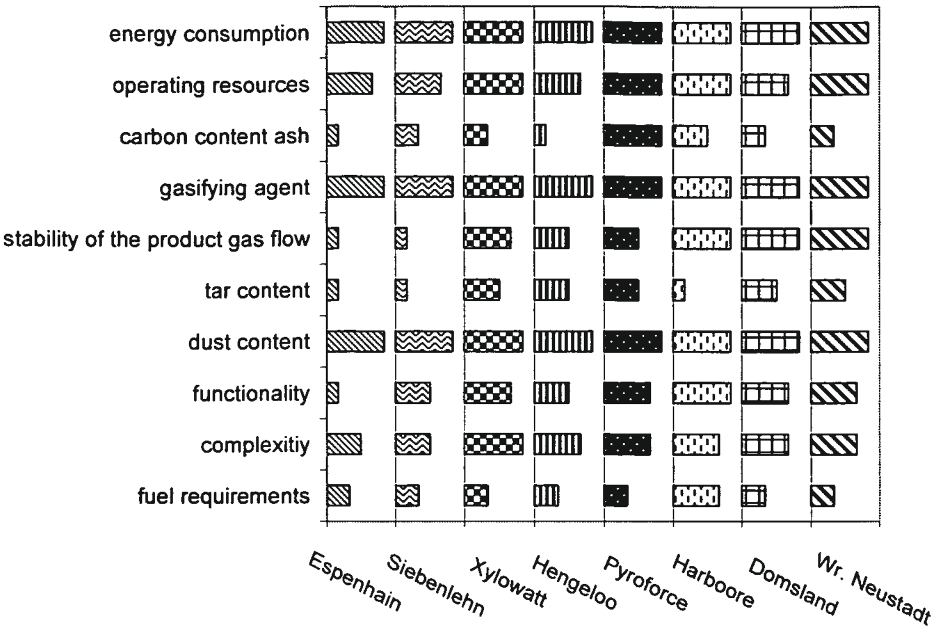


Fig. 3-3: Evaluation results for fixed bed gasification reactors

The development of the fixed bed reactors can be seen clearly: the last three plants in Fig. 3-3 have been recently constructed and are capable to produce the most steady product gas flow and show the highest functionality.

Due to the fact, that all fixed bed gasifiers use air as gasifying agent no difference can be seen in this evaluation criterion. The same applies on the energy consumption, which is almost equal at all evaluated gasifiers. Further, the different fixed bed gasifiers cannot be distinguished concerning dust content, due to a lack of measurement data.

The difference of the tar contents in the product gas can easily be seen; downdraft gasifiers produce much lower tar contents as updraft gasifiers. Concerning carbon content in the ash, the plant Pyroforce achieves good values, due to the installation of a separate ash post gasification unit.

3.4.1.3 Gas cleaning

The evaluation of the gas cleaning is given in Fig. 3-4. In terms of residues the plant Domsland and Wr. Neustadt can be seen as positive example. All other plants produce a residue, which has to be treated or disposed and leads to higher operation costs or environment concerns. Furthermore, it can be seen that plants using an electrostatic precipitator, like Harboore and Wr. Neustadt achieve sufficient tar reduction. All other plants can not fulfil the requirements on tar for gas engines. The dust requirements are easily reached in all plants, since state of the art technology is used. In terms of the criterion complexity the evaluated plants differ little; the plant Siebenlehen performs best, due to the non existing gas cleaning.

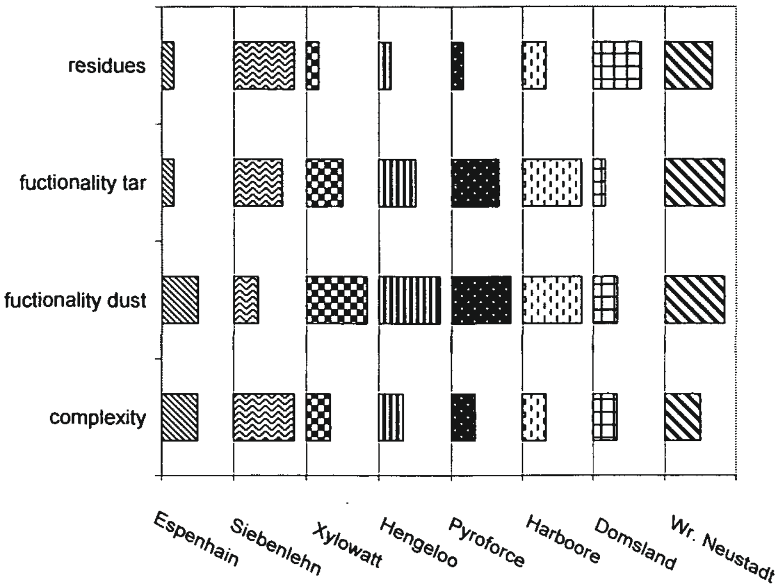


Fig. 3-4: Evaluation results for the gas cleaning for fixed bed gasifiers

3.4.1.4 Gas utilisation

Due to the fact that the gas is utilised at all evaluated fixed bed gasifiers in gas engines, (exception: Siebenlehen) the evaluation result of the gas utilisation does not differ much. This applies to the criteria pollutant tolerance dust and tar as well as on the complexity of the gas utilisation. Great difference can be found in the electrical efficiency of the applied gas engines, which results from the various engine types used. Gas engines developed for the use of low calorific gas or modified gas engines achieve much better electrical efficiencies than standard gas engines. The high CO-emissions of the gas engines are problematic in terms of the legal emissions standards, though they can be kept low using a flue gas catalyst (Pyroforce, Harboore) or post combustion (Wr. Neustadt).

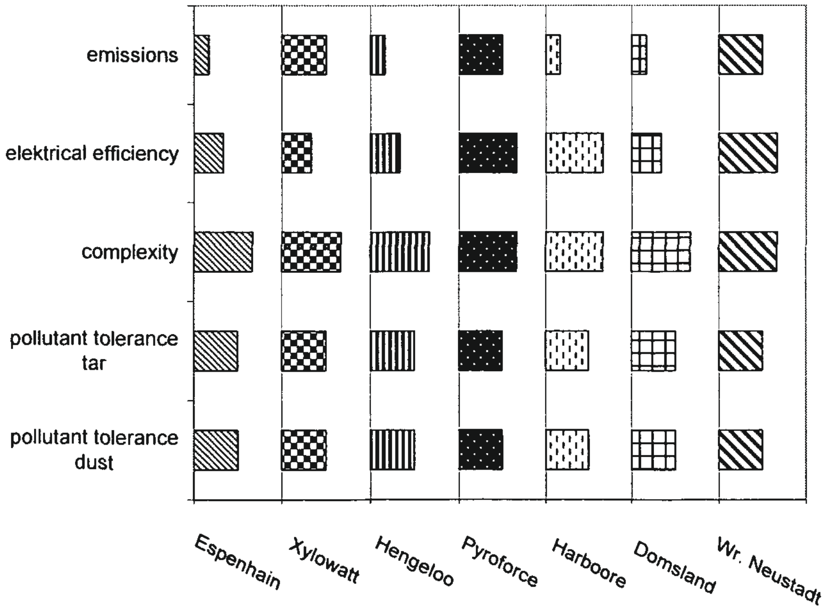


Fig. 3-5: Evaluation of the gas utilisation for fixed bed gasifiers

3.4.1.5 *Overall plant*

Fig. 3-6 shows the evaluation of the overall plant for fixed bed gasification plants. Large differences can be seen in the employment costs, which result from the different development status of the investigated plants: Harboore and Wr. Neustadt are designed for commercial operating conditions and show higher grades of automation, whereas pilot plants like Domsland have much higher personnel requirements. Differences concerning the electrical efficiency and the start-up / shut-down time are minor. The produced heat is utilised in all plants but Hengelo as district heat. Concerning the criterion availability the plants Xylowatt, Harboore and Wr. Neustadt perform well because they have been recently erected or undergo continuous development.

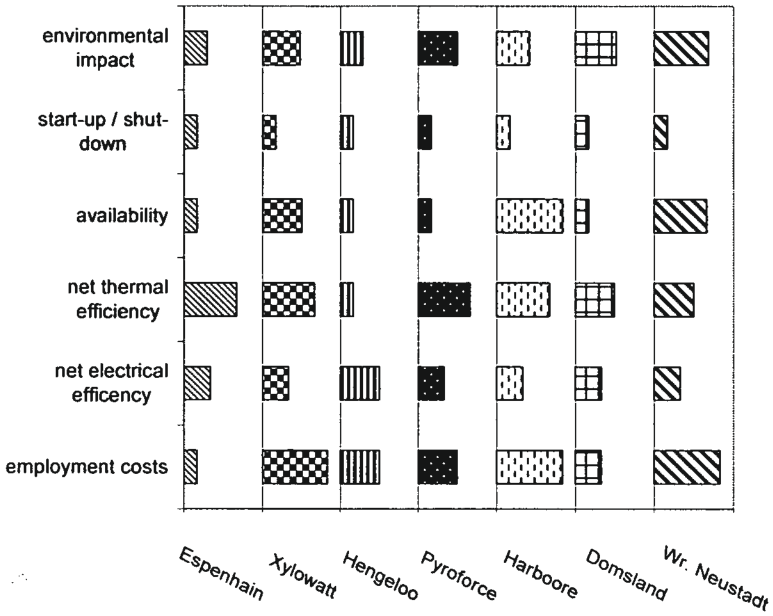


Fig. 3-6: Evaluation result for the overall plant for fixed bed gasifiers

3.4.2 Fluidised bed gasification plants

3.4.2.1 *Fuel conditioning and feeding*

Fig. 3-7 shows the graphical evaluation of the fuel conditioning and feeding section of the different fluidised bed gasification plants. Striking is the high energy consumption (lowest evaluation result) in the case of Värnamo, which is caused by the very complex fuel conditioning system. Gas emissions have to be considered in plants with integrated drying, i.e. Umsicht, Vermont and Arbre.

Fuel losses of fluidised bed gasifiers are low, since fuel conditioning is less stringent. That is the case because fluidised bed reactors are far more tolerant to variations in the fuel size than fixed bed gasifiers. It can be seen that the functionality of the fuel conditioning reaches in most cases good to average values, due to the fact that the fuel conditioning for fluidised bed gasifiers is less complex than for fixed bed gasifiers. The plant Värnamo can be seen hereby as an exception, which has a fuel conditioning plant that can process nearly every fuel to the specifications for the gasification reactor. This can be easily seen in the graphical evaluation, since this plant has the highest complexity but on the other hand then lowest requirements on the feedstock. The Umsicht plant has slightly higher requirements on the feedstock than other plants, since the usage of a catalytic tar removal for gas cleaning which is sensitive to certain pollutants (mainly sulphur) in the feedstock.

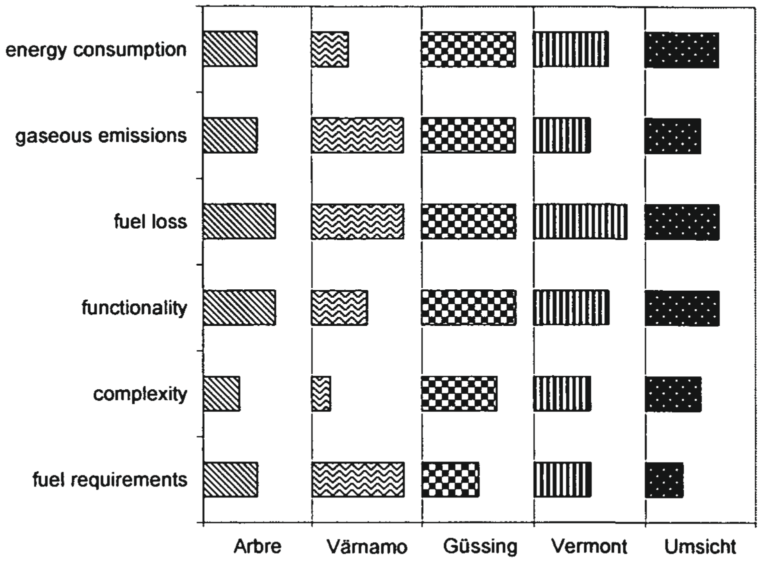


Fig. 3-7: Evaluation results for the fuel conditioning and feeding for fluidised bed gasifiers

3.4.2.2 *Gasifier*

Fig. 3-8 shows the graphical evaluation for fluidised bed gasification reactors. Two of the evaluated plants are operated with steam (Güssing, Vermont) the others are operated with air as gasification agent. The remaining carbon content in the ash of the plants differs little. The high requirements of the Värnamo plant in terms of energy and operating resources can be easily seen. In terms of product gas supply all the evaluated plants perform satisfactorily. Further, no difference can be seen concerning the dust loading of the plants.

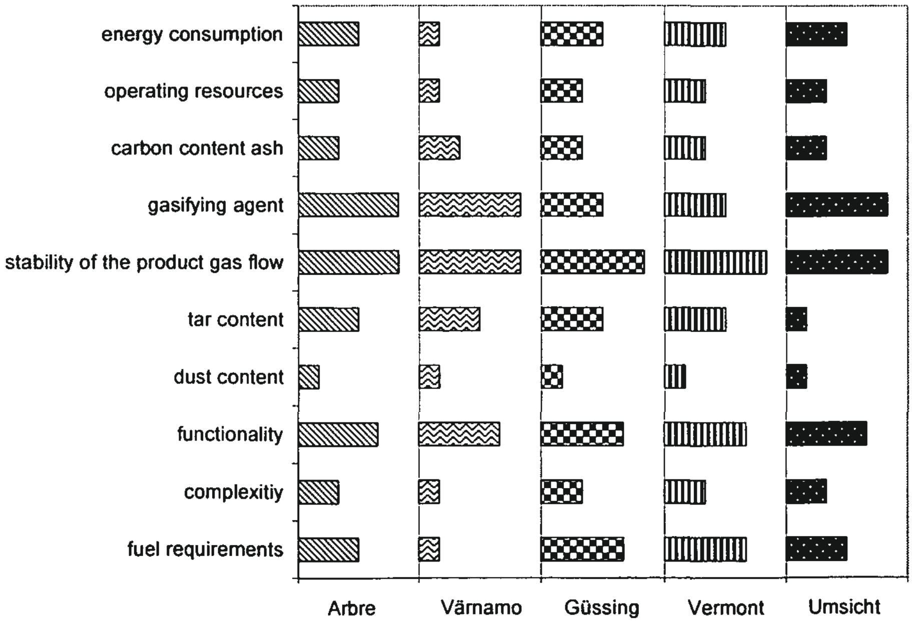


Fig. 3-8: Evaluation results for fluidised bed gasification reactors

However, the loading is much higher than the loading at fixed bed gasifiers. This also applies in terms of tar loading with the exception of the Umsicht plant, which uses a catalytic bed material and achieves much lower tar loadings than downdraft gasifiers. The complexity of the plants differs little, though in general the complexity is much higher than for fixed bed gasifiers. Värnamo has the highest complexity due to pressurised operation. It can be recognised that all fluidised bed gasifiers have much lower fuel requirements than fixed bed gasifiers (exception Värnamo plant).

3.4.2.3 Gas cleaning

The results of the evaluation for the gas cleaning are shown in Fig. 3-9. Four of the five evaluated plants have an installed gas cleaning, for the Vermont plant the installation of a gas cleaning is planned in the future. Concerning complexity Värnamo performs best with one installed gas cleaning step (candle filter). Arbre has the highest complexity (cyclones, tar cracker, filter, and scrubbers). By looking on the criteria for the removal of dust and tar it can be seen that Arbre could not achieve the clean gas requirements. However, this evaluation is based on few operation experiences so far. Further, there is still an unsolved waste water problem in Arbre. The other three plants operated waste water free.

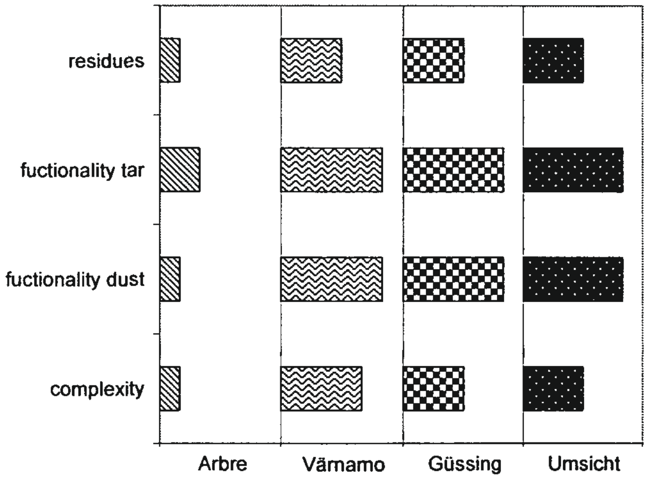


Fig. 3-9: Evaluation results for the gas cleaning for fluidised bed gasifiers

3.4.2.4 Gas utilisation

Fig. 3-10 shows the evaluation results for the gas utilisation. It has to be considered that two plants (Värnamo, Arbre) are IGCC plants, whereas in the CHP-plants Güssing and Umsicht gas engines are used for power production. IGCC based power plants can achieve much higher electrical efficiencies, since waste heat can be converted partially to electricity too. In terms of emissions Umsicht is not performing satisfactorily, due to the lack of a flue gas catalyst after the gas engine. The same applies for Güssing, where emission limits can be fulfilled because of the mixing of the flue gas stream of the gas engine with the flue gas stream of the combustion section of the twin-fluidised bed gasifier. The increase in efficiency by IGCC operation in the Värnamo and Arbre plant causes an increase in the complexity of the plant design. In the Arbre plant the increase in efficiency is low, since power is necessary for the compression of the product gas before the gas turbine. Concerning the evaluation of tar tolerance Värnamo plant performs best, since the tar in the product gas can be combusted in the gas turbine and used for electricity generation too. No differences could be identified in dust and tar tolerances by gas engines and gas turbines.

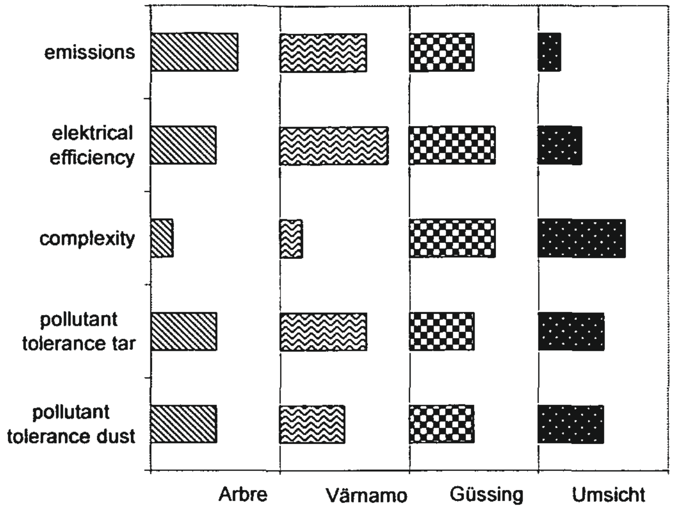


Fig. 3-10: Evaluation results for the gas utilisation for fluidised bed gasifiers

3.4.2.5 *Overall plant*

Fig. 3-11 shows the evaluation of the overall plant. It can be seen that Umsicht is not designed for commercial operating conditions, since it requires long start-up / shut-down times and has poor availability. Certainly, the size of the plant is a reason for this, which is the smallest of the four evaluated plants. Värnamo achieves the lowest environmental impact, because of tar utilisation and nearly residue free operation. Värnamo, Güssing and Arbre are designed for commercial operation. Arbre achieves low evaluation results in terms of availability, since so far only limited operation was possible, due to technical and financial problems. Concerning thermal efficiency the plants Arbre (condensing turbine) and Umsicht (no district heat coupling) have the lowest evaluation results. Most of the fluidised bed plants are operated automatically; therefore, there are only minor differences in the employment costs.

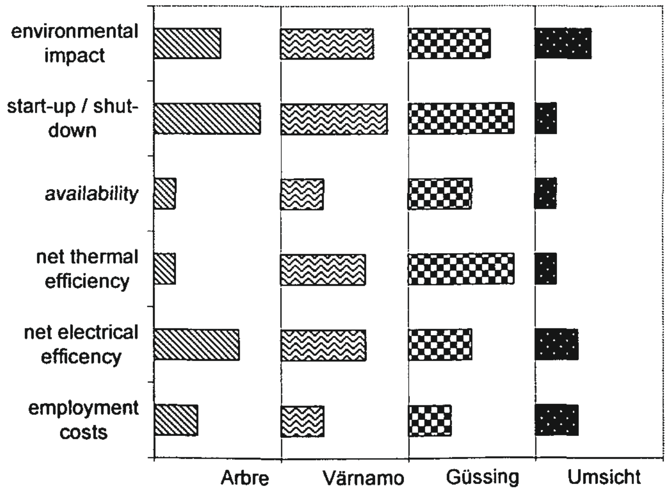


Fig. 3-11: Evaluation results of the overall plant for the fluidised bed gasifiers

4 Identification of suitable solutions

So far, suitable technical solutions for gasification, gas cleaning, and gas utilisation have been identified by a technology and market analysis. Further, a detailed plant analysis and evaluation was done to identify suitable system compounds and promising overall plant concepts. By using this information conclusions are obtained for system compounds and for their appropriate combination.

4.1 Fuel supply and conditioning

Fuel supply is an important process step for “fail-safe” operation of a gasification plant. Although it is considered to be state of the art technology it has caused problems in many plants. A detailed analysis can be found in [90]. In the following the main problems are summarised and solutions are presented.

The main problems result from the *inaccurate definition of the biomass feedstock* and improper conditioning of the feedstock to the requirements of the gasifier. This causes problems during operation if feedstock conditions change. This is hardly the case in gasification plants that are capable to process a variety of different feedstocks without changes in the fuel conditioning and feeding, like in the Värnamo plant. In general problems are caused by an improper reduction of the water content, changing fuel sizes or an increase in interferents in the feedstock. By a change for instance in feedstock from forest wood to waste wood, metal separation may become necessary and higher ash contents can cause problems in the ash discharge system of the gasifier. Further, changes in fuel size can make a sieving and removal of smaller particles necessary for “fail-safe” reactor operation. However, the residue wood fraction from sieving has to be utilised or disposed, wherefrom costs arise.

Further, problems are often caused by the *fuel transport system* for instance by blocking, caused by the inhomogeneous feedstock.

Finally, problems originate frequently from *fuel drying* predominantly, by an improper design of these apparatus. Results are poor drying or gaseous emissions from dryers. However, the occurrence of these effects depends largely on the applied gasifier type.

The following conclusions can be drawn from the results of the market and technology analysis and the results of the plant evaluation for design of future fuel preparation systems:

- Exact determination of feedstock conditions in terms of chemical as well as mechanical properties is required.
- Design of the feedstock transport system must consider the inhomogeneous fuel properties of biomass.
- The fuel supply systems must be integrated into the plant by waste heat utilisation and residue avoidance.

4.2 Gasification

The gasification reactor represents the core of a gasification plant where all the other compounds are dependent on. The aforementioned feedstock supply and conditioning depend on the requirements of the gasification reactor. However, it is difficult to summarise problems and solutions in general, due to many different designs of gasification reactors. Further, feasible solutions for gasification reactors with fuel powers of several MW are not easily applied to small scale gasification reactors around 1 - 2 MW fuel power due to the economy of scale. However, some general statements on existing technical barriers can be made:

- Most of the evaluated gasifiers operate as demonstration or even as pilot plant. Commercial applications in economic operation are hardly found, which is mainly caused by today's development status and the small scale of biomass gasification.
- Pollutants in the raw gas from the gasifier are too high for internal combustion applications and have to be reduced by gas cleaning. This applies mainly for dust and tar as well as other feedstock dependent pollutants such as nitrogen and sulphur compounds. Dust separation is state of the art and even high particle loadings, like in product gas from fluidised beds, cause no problems. High tar contents, like from updraft gasifiers, can cause problems in their removal. They reduce the cold gas efficiency of the gasifier, if the separated tar cannot be utilised in the system.
- Feedings systems for gasification reactors have caused problems by plugging due to improper feedstock specifications and gas leakage, and require further research and development.
- The carbon content of gasification ash originating from fixed bed gasifiers exceeds the limits for disposal in most European countries. Therefore, post-treatment is necessary.
- Secure operation of fixed bed downdraft gasifiers is only possible if the feedstock is proper conditioned in terms of size and fine particle content.

For “fail safe” design of gasification reactors it is necessary to acquire more operation experience on demonstration and large scale. This applies mainly for staged gasifiers, which have been demonstrated so far on pilot scale only. Furthermore, “fail safe” and reliable fuel feeding systems have to be developed, which are designed especially for biomass usage and can combine a “fail-safe” long-term operation with low requirements of operating resources. Thereby, in particular the inhomogeneous conditions of biomass compared to coal or other solid fuels have to be taken into account. The same applies to ash discharge systems, which are the main causes for operation problems concerning the gasifier.

The research and development of in-situ tar reduction methods by catalytic materials has to be intensified alongside large scale long term testing in demonstration plants.

By considering these general conclusions possible problems can be avoided already at the design stage of a gasifier.

It was already mentioned that the plant size has an essential influence on the choice of the applied gasification reactor. In large scale concepts, fluidised bed gasifiers and staged gasifiers (fixed bed pyrolysis and entrained gasification) are favourable, due to higher fuel flexibility and better upscaling potential. However, staged gasifiers at fuel powers of above 10 MW have so far not been demonstrated. The expected advantages in terms of efficiency and technical simplicity compared to fluidised bed systems could not be verified until today, since no secure data for the evaluation of such plants are available.

4.3 Gas cleaning

Gas cleaning can be done using various technologies, depending on the gasification technology, the gas utilisation and the plant size. Therefore, it is not easy to identify suitable gas cleaning technologies, which are applicable in general in gasification plants.

By evaluation of the gasification plants and the market and technology analysis major problems have been identified. One of the most important issues is the **poor tar removal** in the gas cleaning apparatus. Problems were caused as well by plugging of the **heat exchanger** and by **costs and expenses for the disposal of residues** from the gas cleaning. Other identified problems include **poor removal efficiency for ammonia** and **dust** as well as high use of **operating resources** and **man power** for plant operation.

In the following the identified problems will be discussed and possibilities for their solution or avoidance given.

4.3.1 Tar removal

As already mentioned tar in the product gas causes problems in the gas cleaning and the gas utilisation. Condensed tars can block filters and can cause fouling of scrubbers and pipes.

In the following technologies are identified, which are capable of removing tars from the raw product gas to the levels required for gas utilisation. Furthermore, these technologies should be of robust design and cause little residues.

Ta removal can be separated into two technology groups; cold and hot gas cleaning, which are treated separately in the following sections.

4.3.1.1 Cold gas cleaning

Technologies for tar removal, which have been used in existing plants, are scrubbers and wet electrostatic precipitators. However, scrubbers were operated mainly with water as scrubbing liquid, where the removal efficiency depends on the condensation and collision of tar droplets with the scrubbing liquid. Therefore, removal efficiencies are low and do not fulfil the requirements of most gas utilisation technologies. Another disadvantage of water as scrubbing liquid is the required low temperature for tar condensation, causing a loss of sensible heat.

This problem can be overcome by using a solvent as a scrubbing liquid, which can additionally remove condensed tars by physical solution in the liquid. Good clean gas conditions can be achieved, which has been successfully demonstrated at the Güssing plant, using rape methyl ester (RME) as solvent. Tar loadings, which are even below the tar condensation in the clean gas, can be achieved by a new scrubber system called “OLGA”. This system has been already described before.

Another technology suitable for tar removal, even at high loadings originating from a fixed bed updraft gasifier is the wet electrostatic precipitator. It has proven in two commercial operating plants (Harboore, Wr. Neustadt) that it is technically feasible. The application of a wet electrostatic precipitator requires the cooling of the gas before its inlet, which is frequently done by using a quench. In the past, only fixed bed gasifiers were considered to be suitable for the application of an electrostatic precipitator, since the variation of the product flow is low. Recent tests have proven the applicability for this gas cleaning in combination with fluidised beds too.

4.3.1.2 *Hot gas cleaning*

Today, hot gas removal of tars is considered to be in the pilot and demonstration stage, since applicable catalyst are not available on industrial scale and long term experience is still missing. Therefore, most engineering companies rely on state of the art tar removal technologies based on cold gas cleaning.

Basically, catalysts can be used in a fluidised or in a fixed bed. Fluidised beds offer the advantage to utilise relatively cheap catalysts, which have a high specific surface. However, high cost can arise for the replacement of catalysts by attrition and catalyst losses. The first reactor of this kind in industrial scale was build in the Arbre plant but so far no operating experiences are available due to technical and economical problems in the operation of the plant. Good results have been obtained if the catalyst is used directly in the gasifier, which has been demonstrated in Güssing.

Fixed bed catalysts for instance in honey comb construction style have the advantage of low operation costs and an easy usage. However, they have a lower specific surface and require therefore longer residence times for conversion and larger construction volumes.

Advantageous of catalyst technology is the possibility of a residue free tar removal but most catalysts require gas temperatures of 800 – 900°C to achieve high tar conversion rates. Therefore, in most cases it is necessary to heat-up the raw product gas from the gasifier, which can be achieved by adding small amounts of an oxidising agent like air. This partial combustion reduces the heating value. Furthermore, the combustion products and the nitrogen intake in case of air, results in a dilution of the product gas. Using pure oxygen instead of air can reduce this dilution but the provision of pure oxygen is costly. Additionally, catalysts tend to be sensitive on high H_2S concentrations in the product gas, which are caused for instance by feedstocks like waste wood. Recent tests from Pall-Schuhmacher [40] have indicated that catalysts applied on the inside of hot ceramic filters can stand at 900 °C H_2S concentrations of up to 100 ppm without deactivation. This technology of combined dust and tar removal seems a promising solution in the future. However, long term experience is missing and the application will be limited to large scale applications due to the expected high costs.

4.3.1.3 *Conclusions*

It can be concluded that it is possible to provide secure tar removal with present available technology for gas engine and gas turbine applications. A secure removal combined with a robust design and relatively low residues can be achieved by **a wet electrostatic precipitator** and a **solvent scrubber with RME.** The mentioned OLGA-technology will be demonstrated in the near future, which will give insight about its technical feasibility and reliability.

Hot gas cleaning, beside of in-situ tar reduction in the fluidised bed gasifier, still requires further research and development. However, fixed bed catalysts and catalytic hot gas filters are promising options for the future. But today's development stage and the high costs make a commercial application in the near future doubtful.

4.3.2 Heat exchange

In most cases the raw product gas from the gasifier has to be cooled before gas cleaning or gas utilisation. However, the unclean product gas has often high dust and tar loadings, which can cause problems by clogging/fouling of heat exchangers. In many gasification plants cooling of the product gas was considered as a state of the art operation and therefore not too much significance was laid on its careful design.

In general, it can be concluded that cooling a dust and tar laden gas causes deposits on flue gas-tube type heat exchangers but the mutual influence is not yet well investigated. Clogging problems in the Güssing plant could be avoided by an increase in the dust content of the raw product gas, which can be explained by a catalytic cleaning effect of the dust particles in the gas stream.

From today's view it is of vital importance to operate flue gas-tube heat exchangers in a way that the surface temperature of the heat exchanger stays above 400 °C, the beginning of the tar condensation. However, this results in a minimum gas outlet temperature after the heat exchanger of around 400 °C, which is too high for most gas cleaning applications. Therefore, further cooling is required, which should be done for instance by a quench. To maintain the surface temperature of the heat exchanger at temperatures of 400 °C, a heat exchanger medium different from water must be used, since water causes a surface temperature of about 100 °C. Suitable exchanger media include thermo-oils, which can be operated at temperatures up to 400 °C.

As already mentioned for a further reduction of the gas temperature after the flue gas-tube heat exchanger a quench would be a feasible option. Using water as medium can cause problems in terms of residues. Furthermore, the exchanged heat cannot be used as district heat, due to the low temperature level. However, a water quench is a well demonstrated secure method to cool down a raw gas stream.

Using oil based media instead of water, offers the possibility to operate the quench at higher temperatures and, therefore be able to utilise the exchanged heat as district heat. However, this option has been so far not been demonstrated.

There are two options available for a robust and technical feasible for cooling of raw product gas:

- A water quench offers robust operation and provides a good option if the exchanged heat is not utilised.
- Staged cooling by a flue gas-tube heat exchanger with a thermo-oil based media and a water quench offers a good possibility to combine partial heat utilisation with a fail-safe operation.

4.3.3 Dust removal

Dust removal is rarely a problem since it is even for gasification a state of the art technology. However, in some plants problems have been reported if unsuitable technologies for the dust removal were applied. If barrier filters are used, a precoating is necessary to prevent clogging of the filter by condensed tar compounds. It can be concluded that:

- Cyclones are a suitable technology for the removal of high dust loads and should be applied due to their robust design for the primary dust removal.
- Precoated cloth filters can remove particles from tar loaded gases at high efficiencies and show good operational behaviour at moderate gas temperatures.
- Wet electrostatic precipitators have high removal efficiencies for dust and tar combined with a robust design but operate at low temperatures.
- Hot gas candle type filters are suitable for the removal of dust at high temperatures but are expensive and, thus, economically feasible only for large scale pressurised gasification.

4.3.4 Ammonia removal

Ammonia removal is from the technical point of view not a problem, since technologies for its removal exist. However, since gasification plants for biomass are built mainly at small scale, an installation of an ammonia removal increases investment costs and was therefore often neglected in the past.

Fuel bound ammonia, which is converted during gasification mainly to NH_3, causes problems if the gas needs to be compressed before utilisation and causes NO_x emissions after combustion.

The necessity for an ammonia removal depends on the nitrogen content of the feedstock and, hence, the loading of the raw product gas. Therefore, it is of great importance to specify the feedstock of a gasification plant before its construction, to identify the need of an ammonia removal. Biomass feedstock from short rotation forests for instance has much higher nitrogen contents as standard forest wood. Using forest wood, it is often possible to avoid an ammonia removal.

State of the art removal for ammonia is by a slightly acidic scrubber but at low ammonia levels in the product gas water is sufficient too. Therefore, it is possible to use an existing quench for ammonia removal when, the quench water is treated periodically to remove the dissolved ammonia.

Another method of removal is by catalytic destruction, since most tar removal catalysts can convert NH_3 to elementary nitrogen. However, since the technology is not well developed further research and development is necessary before an industrial application.

4.3.5 Disposal of residues

Residues from gas cleaning do not represent a problem in terms of technical functionality of a plant. However, residues cause high costs for their disposal and are therefore an economic problem. Residues from gas cleaning can be of solid and liquid nature. If residues cannot be avoided their amount should be reduced to a minimum and, hence, the concentrations of the pollutants in the residue must be increased. Polluted water for instance should be concentrated by filtering to reduce the necessary amount of disposal. Furthermore, residues in solid form are more desirable, since they can be easier handled.

Fly ashes from gasification have to be recycled or treated by post combustion, to reduce the carbon content before disposal. Waste water originating from gas cleaning is often polluted by organic compounds and has to be treated before being acceptable for discharge to a sewage system.

To minimize or avoid possible residues from gas cleaning the following measures should be taken:

- Using dry gas cleaning (not in all cases applicable).
- Integration of the gas cleaning into the total process.
- Closed circuit operation of the gas cleaning.
- Operation of the plant in a way that water is released as steam in the flue gas of the stack and not in form of a residue as condensed water loaded with pollutants.

4.3.6 Operating resources and man power

Though, operating resources and high demands for man power for the operation of a plant cause no technical problems, they are essential for an economical operation of a plant. However, since most plants are operating at demonstration stage they have not undergone an optimisation process yet. This result in high consumes of operating resources, such as bed material or scrubbing liquids. Furthermore, most plants lack a sufficient automation, which applies predominantly for small scale plants. This economic burden can be dissolved by optimising demonstration plants and by increasing the automation of future plants.

4.3.7 Possible gas cleaning concepts

In the following, possible gas cleaning concepts are described and discussed in detail. Thereby, different gasifiers and gas utilisation technologies like gas engines and gas turbines are considered.

Concepts

Concepts one to five are designed for the utilisation of the cleaned product gas in a gas engine but compressing the gas and utilising it in a gas turbine is possible too. Concept six is designed for pressurised gasification and gas turbine usage, concept seven for the application of a feedstock with high pollutant levels.

Concept 1: In this concept the hot raw product gas is first cleaned by a catalytic hot gas filter, which removes dust and tar from the gas stream at 800 – 900 °C. After that it is possible to cool the product gas without problems since tar condensation is avoided. This would be an easy and robust option for gas cleaning but would be only an economical option for large scale plants, preferably in pressurised operation since the filtering surface can be kept small (Fig. 4-1).

Concept 2: In this concept a catalytic tar cracker is used for the tar removal, which requires a partial oxidation of the product gas for optimum operation. The dust loaded gas can be cooled down easily, since tar is already removed. Dust can be removed at low temperatures with a bag house filter, before supplied to a gas engine (Fig. 4-1).

Concept 3: In this concept staged cooling of the product gas is used to avoid tar condensation during cooling and the sensible heat of the product gas can be partly recovered. For the first cooling step a conventional flue gas-tube heat exchanger is used to cool the gas to about 400 °C using thermo oil as heat exchanging media. The second cooling staged should be designed with an easy cleanable heat exchanger before the gas is filtered in a precoated barrier filter. The remaining tar is removed by a solvent scrubber. Necessary operating resources include precoat material for the filter and solvent for the scrubber. Residues originate from the filter in form of dust and tar loaded precoat material and loaded scrubbing liquid (Fig. 4-1).

Concept 4: Concept four is an extension of the concept quench - wet electrostatic precipitator by an additional heat exchanger before the quench to increase the district heating power of the plant. This heat exchanger should be operated with thermo-oil as coolant above 400 °C to reduce the risk of plugging by condensed tars. The concept of quench and electrostatic precipitator has proven its suitability in two demonstration plants (Fig. 4-1).

Concept 5: In this concept thermal tar cracking is applied. The pyrolysis gas from the low temperature gasifier is combusted at high temperature, were all tars are destructed. The gas is quenched by blowing carbon from the pyrolysis in the reactor, which reacts with the hot combustion gases and form the desired product gas. The obtained gas can be cooled very easily since it has very low tar content and requires only a dust removal before gas utilisation (Fig. 4-1).

Concept 6: This gas cleaning concept is only suitable for pressurised gasification combined with a gas turbine. There is no need for tar removal from the product gas and therefore only dust removal and cooling of the gas to about 400 °C is necessary. To avoid problems in the heat exchanger it should be operated with thermo-oil to maintain heat exchanger surface temperatures above 400 °C (Fig. 4-1).

Concept 7: This concept represents a coupling of an atmospheric gasification with gas utilisation in a gas turbine. Since the gas needs to be compressed before the compressor stage, tars have to be removed thoroughly from the gas. This is done using a catalytic tar cracker with a partial oxidation for a temperature increase, followed by a heat exchanger, dust removal and a scrubber to remove nitrogen and sulphur compounds. The cleaned gas is compressed and utilised in a combined cycle (Fig. 4-1).

The hot compression of the product gases is not taken into account since the resulting higher compression work, which causes most of the electricity consumption in a plant. Fig. 4-1, gives a graphical overview of the different concepts indicating the required process steps.

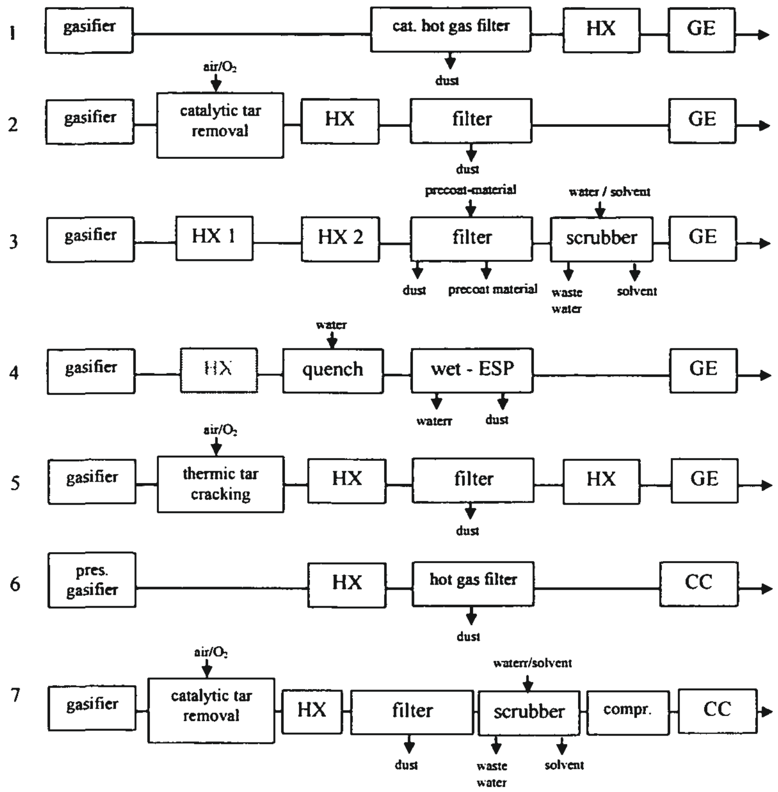
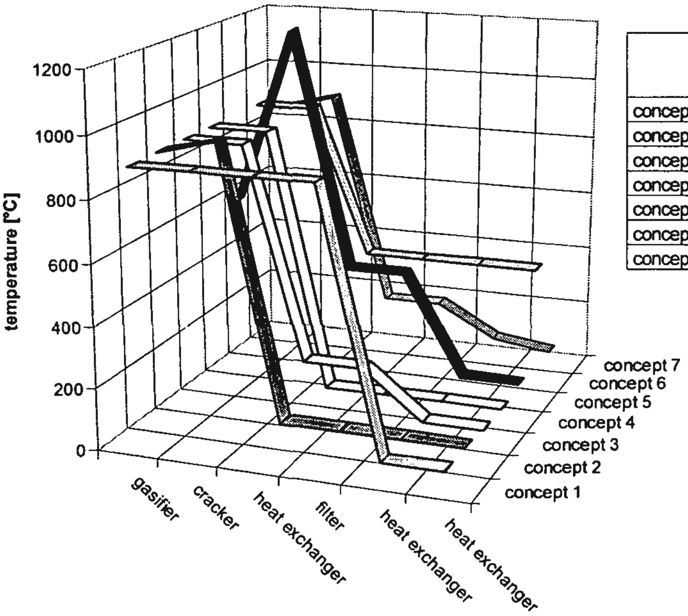


Fig. 4-1: Possible gas cleaning concepts

(HX...heat exchanger; GE... gas engine, ESP...electrostatic precipitator; compr...compressor, CC...combined cycle; cat...catalytic)

Fig. 4-2 shows the expected temperature profiles of the different gas cleaning concepts



	gasifier outlet [°C]	tar cracker [°C]	heat exchanger [°C]	filter [°C]	heat exchanger [°C]	gas utilisation [°C]
concept1	900	900	-	900	60	60
concept 2	900	950	60	60	-	60
concept 3	900	-	200	200	45	45
concept 4	900	-	45	45	-	45
concept 5	600	1200	400	400	60	60
concept 6	900	-	400	400	-	400
concept 7	850	900	180	180	75	45

Fig. 4-2: Temperature profiles of different gas cleaning concepts

Concept comparison

Since the applied gas cleaning highly depends on the type of gasifier and the gas utilisation technology, an analysis has to be done in every single case. In the large power range expensive apparatus have, due to the effect of economy of scale, a lower influence on the investment costs as in small scale plants.

A catalytic hot gas filter would be an optimum solution, since the residues are low and the required gas cleaning steps are reduced to one, which also puts the high investment cost into perspective (dust and tar removal in one step, NH_3 reduction expected). However, the development stage of this technology has not yet reached a sufficient state, which can change in the near future, since demonstration experiments are on the way.

If gas engines are used for gas utilisation the product gas needs to be cooled, which makes the concept of quench and wet electrostatic precipitator a favourable one. Hot gas cleaning is in that case not advantageous and causes higher costs. If the water circuit is operated in closed mode, it is possible to reduce the amount of residues from the gas cleaning, by feeding the concentrated residues (dust-tar-water) back into the gasifier or a separated combustor. Additionally, continuous ammonia removal seems possible when the circulating quench water is treated periodically. This type of gas cleaning has been applied already successfully in two gasification plants and can be addressed as state of the art technology.

If a gas turbine is used it has to be distinguished between pressurised or atmospheric gasification. In contrary to an engine application it is possible to utilise product gas at temperature up to 400 °C in gas turbines. Using pressurised gasification a compression of the product gas before the utilisation in the turbine is not required; hence, only dust removal is necessary. This technology is state of the art and has been successfully demonstrated. The higher investment costs must be seen in relation to the simple gas cleaning in one step, where only solid residues remain.

If the product gas is produced atmospherically, additionally to the gas cleaning a tar removal has to be installed for a secure operation of the compressor. To reduce the work of compression low inlet temperatures are necessary, which reduce the advantages of a hot gas cleaning. From today's point of view a staged cooling, as described before, with a thermo-oil heat exchanger and a quench combined with a wet electric precipitator seems to be the most promising option.

This evaluation has revealed the difficulties in identifying a general gas cleaning concept without considering the applied gasification and gas utilisation technology.

4.4 Gas utilisation

The gas utilisation focuses on the production of heat and power from the cleaned product gas of biomass gasification. Co-combustion, due to the low achievable efficiencies and fuel cells, due to their poor development state are not included in this investigation. The focus is given on internal combustion engines like the gas engines and the gas turbines.

From the evaluation of the different gasification plants it is clear that gas engines have been preferred in the past as conversion technique, which is because engines are available at smaller scale being more suitable for gasification plants of pilot and demonstration scale.

Only two of the evaluated plants used gas turbines as conversion devices but operation experience was reported from one plant only.

In general it can be stated that manufacturers of internal combustion engines do not see it as their responsibility to produce apparatus with less stringent purity requirements on the gasification gas, since the gasification market is assessed as too small. Therefore, in the past apparatus were operated at higher pollutant levels as required from manufacturers, which caused in most cases the loss of warranty. Further optimisation and development was rarely done by involving the manufacture but often just by the operator of the plant. Another general problem is that only few plants run under commercial operating conditions because the main objective was the demonstration of the gas utilisation devices. Therefore, little long-term experience exists that can be used as basis for further development.

4.4.1 Gas engines

One of the major problems of gas engines is the fuel gas slip of 1 – 1.5 % through the gas engine, which due to the high CO content in the product gas causes CO emissions that are above the legal limit. Additionally, the same percentage of slow combustible compounds like methane is emitted too.

4.4.1.1 CO and hydrocarbon emissions

CO emissions from a gas engine operated on gasification gas range between 2500 – 4500 mg/Nm³ referred to 5 % O_2 compared to the legal emission limit of 650 mg/Nm³ (engine fuel power > 3 MW, ref. to 5 % O_2). Additionally, a small percentage of other hydrocarbon compounds are expected to pass the gas engine unburned but exact measurements on this are not available so far. This slip is caused by the overlap in the valve opening times of the gas engine and can be hardly reduced.

However, to reduce the CO and hydrocarbon emissions a catalytic or thermal treatment of the flue gases is necessary, which is commercially available on the market. Thermal treatment is a robust method to remove any CO and hydrocarbon emissions from the flue gas but it requires more energy input than catalytic treatment. Also, they are not yet fully developed and optimised in terms of sensitiveness on pollutants and long-term performance.

4.4.1.2 Oil operating life

Since the engine oil gets into contact with the product gas in the gas engine pollutants can be dissolved in the oil, which can cause a reduced operating life of the oil and, hence the necessity for plant shut down or a burn off the gases during oil exchange. Further, the operating cost of a gas engine rise by frequent oil exchanges.

So far it is very difficult to predict oil operating life time since it highly depends on the concentration of the pollutants in the clean product gas and possibly also on the hydrogen content in the product gas. Very low operating times have been reported being around several hundred hours in the worst cases to up to over 2000 hours in recent, more promising results.

In some plants, like in Güssing, engine manufacturers and the oil industry work on the development of motor oils, which can stand higher pollutant levels in the product gas without loosing its lubricity. Furthermore, online oil exchange seems to be a promising option to reduce the idle time of the gas engine.

4.4.1.3 NO_x - emissions

NO_x emissions of gas engines are due to the NH_3 concentrations in the product gas, which in most cases remain within the emission limit of 500 mg/Nm³ (TA-Luft; engine fuel power > 3 MW, ref. to 5 % O_2). Since the mainly used lean combustion engines have low thermal NO_x formation the main nitrogen source is by fuel bound nitrogen. Although catalytic reduction of NO_x emissions in the flue gas is possible and also state of the art technology, it involves high investment costs and should therefore be avoided. A more suitable option is the reduction of the NH_3 concentration in the product gas before the combustion to fulfil the emission limits.

4.4.2 Gas turbines

Like already mentioned, operating experience from gas turbines using biomass gasification gas as fuel is only available for one plant. Since biomass gasification is situated in the small to medium power range standard gas turbines of 500 MW electrical are not applicable for biomass gasification. Therefore, only technology from an earlier technology state with low efficiencies is available.

Generally, gas turbines can be easily modified for using of low calorific gases. This can be realised by adding an external combustion chamber for continuous operation. Furthermore, CO emissions can be minimised and NO_x emissions reduced by staged combustion. Unfortunately, very few operation experiences exist so far.

4.4.2.1 Availability and efficiencies

The main problem using gas turbines is the availability of low calorific value gas turbines capable of burning product gas of about 5 MJ/Nm³ without supplementary fossil fuels.

So far only two manufacturers (General Electric and Alstom) have adapted standard turbines for combusting gasification gas. However, since available technology was used the achievable electric efficiencies for this gas turbine range from 20 – 25 %. Due to the higher flue gas temperatures of gas turbines operation in a combined cycle mode is preferable.

4.4.2.2 Gas compressor

Since standard gas turbines operate at about 20 bar the product gas has to be compressed before combustion or has to be produced by a pressurised gasifier. Compression of gases requires high energy inputs, which can account to 10 - 20 % of the total energy output of the plant. Furthermore, gas compressors are sensitive to pollutants like dust, tar, nitrogen and sulphur based compounds, and, thus, stringent gas cleaning is required before compression. Pressurised operation of the gasifier eliminates this problem. However, the gasifier and the gas cleaning have to be designed for pressurised operation, which increases the investment costs.

For the small power range of 200 – 500 kW electrical recuperative micro-gas turbines would be a promising option but they have not yet been developed to utilise gasification gas and show even lower efficiencies than gas engines. Further research and development in this field is necessary.

To reduce the energy consumption for compression of the product gas the development of recuperative gas turbines, which can operate at 5 bar with good efficiencies seems to be necessary. Additionally, gas turbine manufacturers have to be encouraged to increase their research activities for low calorific applications.

4.5 Overall system aspects

Finally, overall system aspects, which are important for the design of new gasification plants, shall be discussed. Thereby, the interaction of different system solutions is taken into account, and the link from the single point of view to the integrated one for entire concepts is provided. The following strategies for the design of new gasification plants have been identified:

- The entire concept should consist of a minimum of components and of robust design. Since gasification of biomass is a relatively new technology the emphasis should be given on the functionality and availability of the components more than on complex design.
- The interaction of different system components drying, gasification gas cleaning and gas utilisation have to be considered to eliminate any possible negative effects.
- For new designs the potential conflict between technical and economic feasibility of a concept must be kept in mind.
- Residues should be avoided or fed back into the process for reducing disposal costs.
- If drying of the feedstock is necessary it should be integrated into the process, both, in terms of heat demand and drying-related residues.
- Fluidised bed gasification plants should be built in a power range of 5 – 20 MW electrical to operate economically. Furthermore, operation in CHP or combined cycle mode is favourable to achieve higher fuel conversion efficiencies.

4.6 *Promising concepts*

Gasification technology was so far assessed by a "market and technology analysis" as well as by an "evaluation of existing gasification plants". Thereby, problems and possible solutions have been identified. The preceding chapters have revealed suitable system components for process steps gasification, gas cleaning and gas utilisation. Here, the focus is given on the interaction of components to deduce technically suitable, economically and environmentally sound concepts. The graphical presentations indicate the necessary process steps in the concepts and show important characteristics (like tar-dust recycle) but do not represent a complete flow diagram including all process streams, which can be found in chapter 5.

The design of new concepts requires a definition of the application field, since not all technologies are technical and economical feasible in each power range. In this work, concepts for large scale applications are investigated, which are based on further developments of existing biomass based power plants.

The major aim is to optimise the electrical net output and the electrical efficiency, since at large scale district heating customers with high demands are seldom found. Therefore, these concepts are focused on maximising the electricity production. Clearly, the production of district heat must be considered as possible option (concepts marked with the extension "dh"). If district heat is produced, the steam turbine is operated in back-pressure mode, to reach suitable temperatures in the condenser for district heat production. Further, the waste heat of the gas engine, if installed, is used as well.

On this basis all the evaluated concepts operate in combined cycle mode with a net electric power output of 20 MW, considering legal emission standards.

4.6.1 Concept I

In this concept an autothermal pressurised fluidised bed gasifier is used for the production of raw product gas, which can be utilised without further compression in a gas turbine. Therefore, tar removal is not necessary since tar even acts as additional fuel in the gas turbine. This concept is further developed on the results of the Värnamo gasification plant.

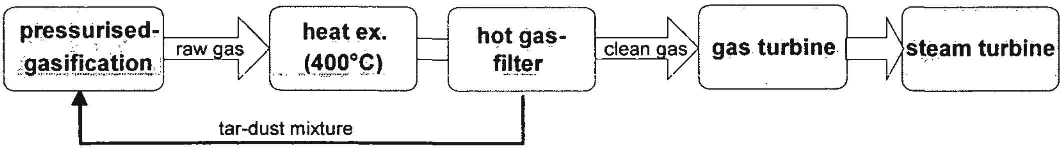


Fig. 4-3: Process scheme of concept I

Gas conditioning and cleaning consists only of a heat exchanger to cool the product gas to 400 °C before dust is removed by a hot gas filter. Since the removed dust has high carbon content, it is returned into the gasifier. However, this possibility was not demonstrated in the Värnamo plant so far. The cleaned product gas is combusted in a gas turbine, which also supplies the gasification reactor with pressurised air from its compressor. The remaining heat is utilised in a steam cycle operated in condensed mode.

4.6.2 Concept II

Autothermal atmospheric gasification in a circulating fluidised bed is used to produce raw product gas, which is cooled down to 400 °C in a heat exchanger operated with thermo-oil to prevent any tar condensation. The necessary additional cooling to about 50 °C is done in a quench, before the gas is cleaned in a wet electrostatic precipitator from dust and tar loadings.

Concept II-gt

In concept II-gt a gas turbine is used as gas utilisation device. Therefore, before the atmospheric gas can be utilised in the gas turbine, it has to be compressed according to the pressure requirements of the turbine. The flue gas heat of the gas turbine and from the heat exchanger is used in a steam cycle to enhance the electricity production. The steam turbine is operated in condensed mode. To avoid wet residues, the waste water from the quench is recycled after tar and dust is removed. The residues from the filter are returned into the gasifier or are combusted separately.

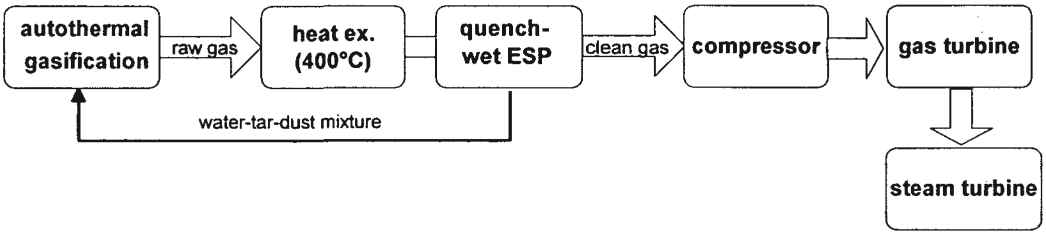


Fig. 4-4: Process scheme of concept II-gt

Concept II-ge

This concept differs from concept II-gt by the gas utilisation technology; instead of a gas turbine a gas engine is used. Hence, no compression of the cleaned product gas before gas utilisation is required, which lowers the own power consumption of the plant.

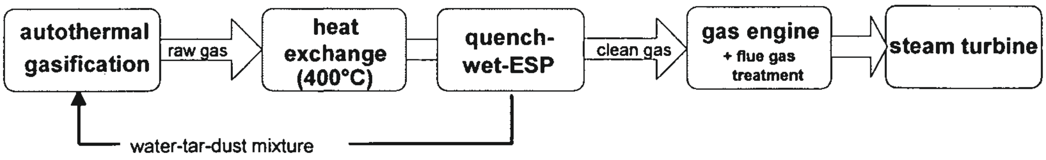


Fig. 4-5: Process scheme of concept II-ge

The flue gases from the gas engine have to be treated catalytically or thermally to reach the CO emission limits. The remaining heat is used in a steam cycle.

4.6.3 Concept III

The raw product gas, which originates from an autothermal fluidised bed gasifier, is catalytically cracked in a fixed bed before it is cooled down and dedusted in a fabric filter. Since tar is removed before cooling the product gas no problems are expected by plugging or clogging of the heat exchanger.

Concept III-gt

In concept III-gt the cleaned gas is compressed and utilised in gas and steam turbines in the same way as described in concept II. This concept is advantageous since only dust is produced as residue and tar is converted into combustible gaseous compounds.

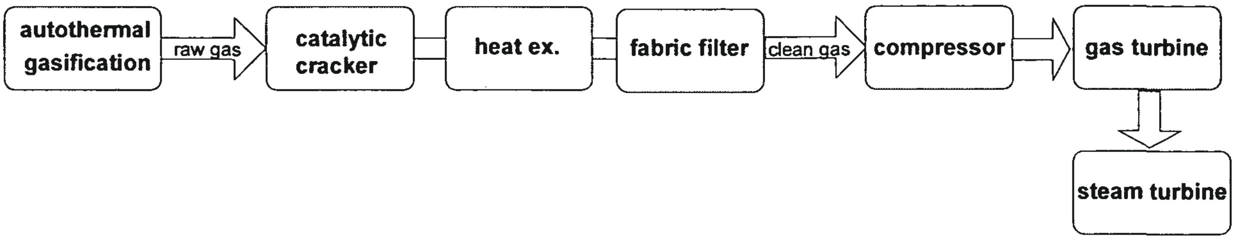


Fig. 4-6: Process scheme of concept III-gt

Concept III-ge

Concept III-ge differs from the above mentioned concept by a different gas utilisation technique. Instead of a gas turbine a gas engine is used, which avoids a compression stage before the gas utilisation. The combined cycle usage is equivalent to concept II.

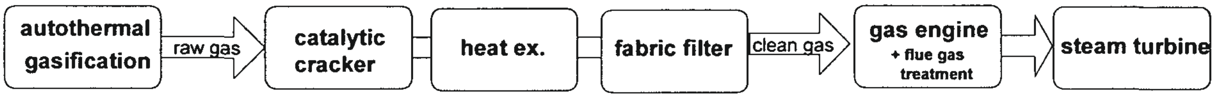


Fig. 4-7: Process scheme of concept III-ge

4.6.4 Concept IV

The raw product gas, originating from an autothermal fluidised bed gasifier, is first cooled and than dedusted by a precoated bag house filter. Tar is removed by a solvent scrubber. The cleaned gas is compressed and utilised in a gas and steam turbine in the same way as described in concept II. The loaded scrubbing liquid together with the removed dust is separately combusted.

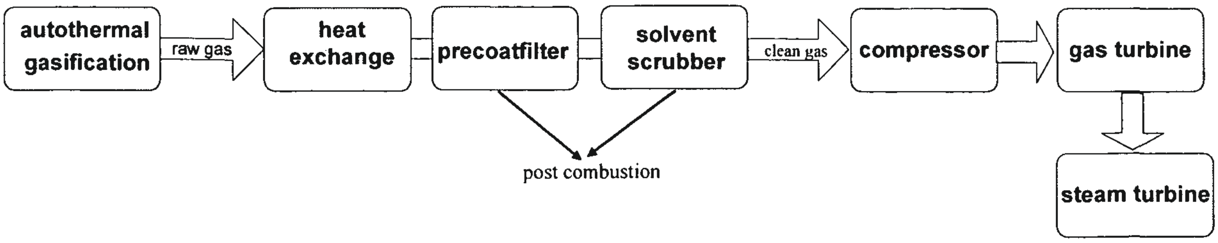


Fig. 4-8: Process scheme of concept IV

4.6.5 Concept V

In this concept a dual fluidised bed steam gasifier is used. The raw product gas, which is nitrogen free, is first cooled, dedusted in a precoated bag house filter and cleaned from tar using a solvent scrubber.

Concept V-gt

This concept uses a gas turbine for gas utilisation. Since the gas is free of nitrogen, the power consumption of the compressor before the turbine is lower than for product gas from gasifiers operating on air. The flue gas from the combustion zone of the gasifier as well as from the gas turbine is used for the production of steam for the steam cycle, operated in condensed mode.

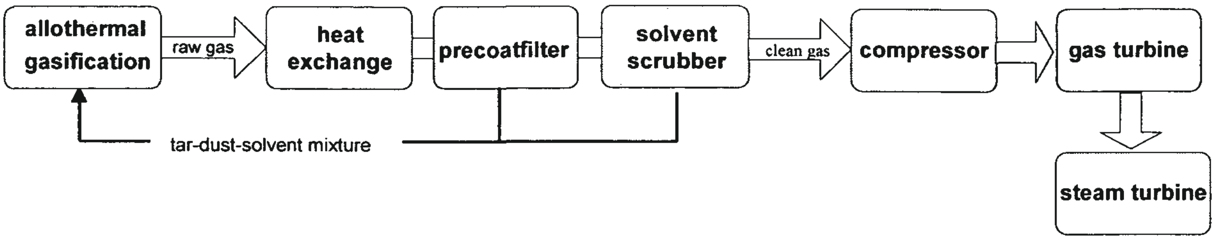


Fig. 4-9: Process scheme of concept V-gt

Concept V-ge

Concept V-ge differs from the above mentioned concept by the gas utilisation technology. Instead of a gas turbine a gas engine is used, which dispenses with the compressor before the gas utilisation. The combined cycle usage is equivalent to the above described concept.

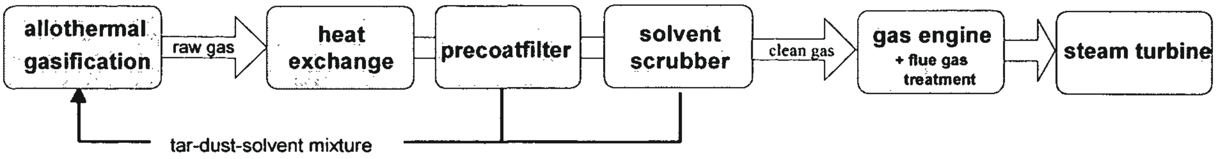


Fig. 4-10: Process scheme of concept V-ge

In the following these concepts are further investigated and technically assessed using the process simulation tool IPSEpro.

5 Technical assessment

Using the data from the evaluation of the different gasification plants it is possible to investigate the technical optimisation potential. To assess the developed concepts technically it is important to define objective and comparable criteria. Therefore, energetic and exergetic efficiencies are set up to be able to compare simulation results among the concepts and to other results. To obtain mass and energy balances for the evaluated concepts a modelling is done using a process simulation tool, IPSEpro. Hence, process simulation is briefly discussed and boundary conditions as well as general aspects are explained. It is essential to base a technical assessment on the same parameters to achieve comparable results. On that basis different fuel drying concepts are evaluated to identify the most suitable solution, which will be used in all concepts. Thereafter, the results of the different concepts are presented. To obtain a benchmark for the gasification concepts a conventional steam cycle is modelled as well. Further, an exergetic analysis of the different applied gas cleaning and gas utilisation technologies as well as their interaction is carried out. Finally, the overall systems are assessed by comparing them among each other and to the performance of a conventional steam cycle.

5.1 Efficiency definitions

For evaluation in process technology main efficiencies are defined, which should provide a possibility for the comparison of different processes. However, for a proper comparison these characteristic efficiencies have to be defined precisely. For the evaluation of the processes evaluated in this work the following characteristic efficiencies are defined:

5.1.1 Definition of electrical efficiencies

The gross electrical efficiency is calculated as the fraction of the produced electrical power referred to the fuel power of the feedstock entering the plant (e.g. before a possible fuel preparation).

$$\eta_{el,gross} = \frac{P_{elGT} + P_{elST}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \qquad \text{Equation 5-1}$$

The net electrical efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus to the fuel power of the feedstock entering the plant before the dryer (before a possible fuel preparation).

$$\eta_{el,net} = \frac{P_{elGT} + P_{elST} - P_{elCons}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \qquad \text{Equation 5-2}$$

5.1.2 Definition of the thermal efficiency

The thermal efficiency of a plant is calculated as the fraction of the produced heat (district or/and process heat) referred to the fuel power of the feedstock entering the plant (before a possible fuel preparation).

$$\eta_Q = \frac{\dot{Q}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}}$$ Equation 5-3

5.1.3 Definition of the fuel utilisation

The gross fuel utilisation is calculated as the fraction of the produced electrical power and heat (district or process heat) to the fuel power of the feedstock entering the plant (before a possible fuel preparation).

$$\eta_{fuel,gross} = \frac{P_{elGT} + P_{elST} + \dot{Q}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}}$$ Equation 5-4

The net fuel utilisation is calculated as the fraction of the produced electrical power and heat (district or process heat) reduced by the electrical consumption of the apparatus to the fuel power of the feedstock entering the plant before the dryer (before a possible fuel preparation).

$$\eta_{fuel,net} = \frac{P_{elGT} + P_{elST} - P_{elCons} + \dot{Q}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}}$$ Equation 5-5

5.1.4 Definition of the cold gas efficiency

Especially for the characterisation of gasification processes the chemical efficiency is a widely used parameter.

The chemical efficiency is generally defined as the amount of chemical energy, which can be transferred from fuel power in the feedstock into the fuel power of the product gas of a thermo-chemical conversion process:

$$\eta_{chem} = \frac{\dot{m}_{PG} \cdot lhv_{PG}}{\sum \dot{m}_{Fuel} \cdot lhv_{Fuel}}$$ Equation 5-6

where $\dot{m}_{PG}$ represents the mass flow of the product gas, lhv_{PG} the lower heating value of the product gas, $\dot{m}_{Fuel}$ the mass flow of the fuel into the gasification reactor and lhv_{Fuel} the lower heating value of the feedstock.

Definition of the chemical efficiency of the gasifier

This definition is very well suited for the characterisation of a gasifier. The fuel power of the product gas includes the combustible compounds including tars and higher hydrocarbons, which leave the gasifier. However, this efficiency does not indicate the quality of the gasification process, but only expresses the ratio between the lower heating value of the gaseous compounds at the exit of the gasifier and the fuel power of the feedstock. Therefore, the chemical efficiency of the gasifier does not indicate its usability in the gas utilisation. The term $\dot{m}_{PG} \cdot lhv_{PG}$ in Equation 5-6 refers to the conditions of the product gas at the exit of the gasifier, however, at that stage the quality of the gas is not suitable for direct gas utilisation in most cases. The term $\sum \dot{m}_{Fuel} \cdot lhv_{Fuel}$ refers to the total fuel input into the gasifier. Since the system boundary is set around the gasifier, any additional fuels recycled from the gas cleaning e.g. in form of tars or char have to be considered as external streams too. Fig. 5-1 demonstrates the system boundary for the calculation of the chemical efficiency for the gasifier.

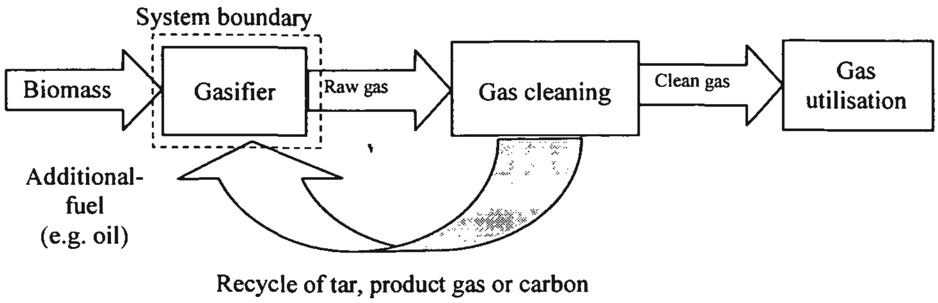


Fig. 5-1: System boundary for the calculation of the chemical efficiency for the gasifier

Definition of the chemical efficiency for a gasification plant

For the evaluation of gasification plants though, the definition of the chemical efficiency for the gasifier is not very well suited since the quality of the product gas is neglected. By including the gas cleaning into the system boundary the quality of the product gas can be taken into account in the analysis. Thereby, the mass flow and the lower heating value of the product gas at the inlet to the gas utilisation are taken. Therefore, only usable combustible compounds are assessed, tars or char are not included anymore. Possible feedbacks from the gas cleaning into the gasifier are treated as internal streams, since they do not leave the system boundary. The system boundary for the calculation of the chemical efficiency of a plant is given in Fig. 5-2.

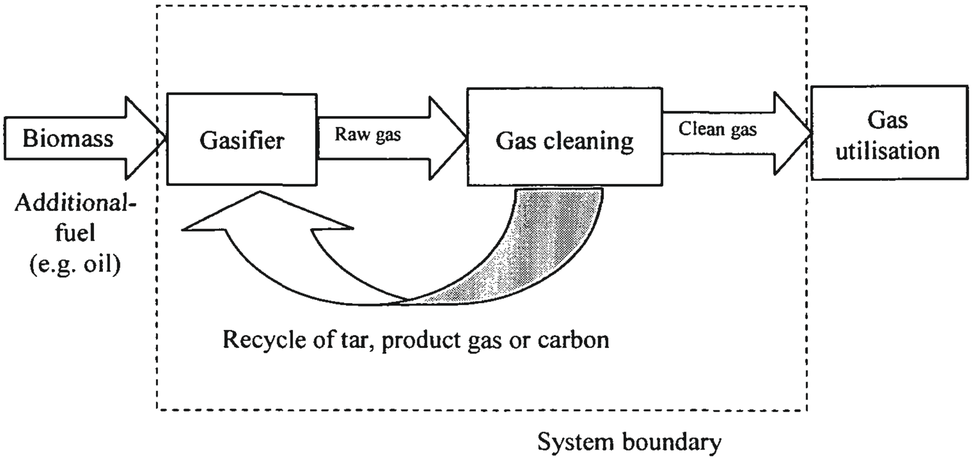


Fig. 5-2: System boundary for the calculation of the chemical efficiency for a plant

5.1.5 Definition of power to heat ratio

The gross power-to-heat-ratio is calculated as the fraction of the produced electrical power to the produced heat (district and/or process heat).

$$\alpha_{gross} = \frac{P_{elGT} + P_{elST}}{\dot{Q}} \qquad \text{Equation 5-7}$$

The net power-to-heat-ratio is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus to produced heat (district and/or process heat).

$$\alpha_{,net} = \frac{P_{elGT} + P_{elST} - P_{elCons}}{\dot{Q}} \qquad \text{Equation 5-8}$$

5.1.6 Definition of the exergy efficiencies

In general the overall exergetic efficiency can be defined as the total sum of all usable exergy flows in desired products, leaving the plant (power, heat, etc.) to the sum of all exergy inputs into the plant, like electric power or fuel.

$$\eta_{ex} = \frac{\sum \dot{E}_{prod}}{\sum \dot{E}_{input}} \qquad \text{Equation 5-9}$$

For the exergetic evaluation of the gas cleaning, it is of major interest how much of the exergy in the raw product gas can be kept in the clean gas to be converted into electricity. For this the exergetic gas cleaning efficiency can be defined by the ratio of the exergy flow in the cleaned product gas to the exergy flow in the raw product gas.

$$\eta_{ex,GC} = \frac{\dot{E}_{cleangas}}{\dot{E}_{rawgas}} \qquad \text{Equation 5-10}$$

The calculation of an exergetic efficiency to investigate the quality of the combination of gas cleaning and gas utilisation is difficult, since it is not easy to determine the correct system boundary. This is explained in the following example. Product gas originating from an atmospheric gasification needs to be compressed before being utilised in a gas turbine, which requires electrical power. In contrary, pressurised product gas can be utilised without further compression. Hence the definition of comparable efficiencies is not easy.

To compare different gas utilisation options an exergetic efficiency can be defined in a similar way as the net electric efficiency is calculated. The net exergetic efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus plus the produced useable exergy flows to the sum of exergy of the product gas and the exergy of the combustion air.

$$\eta_{ex,GU,net} = \frac{\dot{E}_{el,brut} - \dot{E}_{el,own} + \dot{E}_{PS}}{\dot{E}_{PG} + \dot{E}_{air}} \qquad \text{Equation 5-11}$$

If the gas utilisation does not consume any electric power, this distinction is irrelevant.

5.2 Process simulation

Basically programs for the simulation of processes can be separated into stationary simulation tools und programs to solve in-stationary, dynamic processes. In this work only stationary processes are considered, since it is the aim to calculate mass and energy balances for stationary operation of those plants.

In stationary simulation tools processes are modelled as a network of process streams, with process units located in their knots. Process units include reactors, stream splitters, turbines, etc., which are mathematically modelled by mass and energy balances and by thermodynamic principles. Hence stationary behaviour is assumed and only few parameters of construction are included in the simulation. According to the type of solving algorithm simulation programs can be divided into sequential modular and equation based structures [91].

5.2.1 Sequential modular based programs

The solving algorithm is structured in a way that process units are calculated step by step, which corresponds to the arrangement in the flow chart of the program. The obtained results of a converged process unit are the input values for the following one. This makes it easy to follow the calculation path.

In most cases the calculation of a closed process does not converge in one run, which requires an iterative solution. The reasons for iterative solutions are given in the following:

- In chemical processes streams are often returned or mixed with input streams, which corresponds to a feedback of information. This changes the composition of the input stream into the process unit and therefore has an effect on the outlet concentration as well. Such iteration loops are done as long as program internal parameters, so called design specifications, or user-set criteria are reached.
- The second reason, which makes iterations necessary, is that certain process parameters have to be fulfilled in process units. This can be achieved by so called design specifications. Iteration is done on the outer loop by adjusting free parameters in a way that the set design characteristics are met.

On that basis the following advantages and disadvantages can be identified:

Advantages

- By the block wise calculation of process units the procedure of the calculations can be easily followed and errors can be easily identified.
- Hence only one process unit is calculated at a time, it is possible to model them in a detailed and complex way.

Disadvantages

- Complex systems cause problems in outer loops convergence.
- Therefore, in large and strongly linked flow charts a calculation in a reasonable time frame even with strong computing power is not possible.

5.2.2 Simultaneous or equation based programs

The solving algorithm is structured in a way that the flow chart is transformed into an equation system of *n* equations with *n* variables in form of a (*n* x *n*) – Matrix and this system is solved simultaneously. The structure of equation based programs allows more flexibility, than of modular based ones; hence, any parameter can be specified as long as they are independent from each other. Therefore, it is not important if an inlet or outlet stream of a process unit is defined, since the solution process does not change. Also recycle streams do not cause an increase in the necessary calculation performance. However, the simulation path is not as easy to be followed and to be understood as of sequential, modular programs. On that basis the following advantages and disadvantages can be identified:

Advantages

- Flexibility in terms of parameter settings and design specifications of the process units.
- Possibility to calculate complex flow charts with many recycle streams without convergence problems
- Fast computing algorithm, hence no external loops have to be calculated.

Disadvantages

- The sequence of the calculations cannot be followed, hence it is difficult to identify and find possible errors
- The possibilities for a detailed modelling of process units is limited compared to the possibilities of a modular concept, since the number of equations and units, which have to be solved at the same time is limited.

5.2.3 Simulation tool IPSEpro

IPSEpro is an example of an equation oriented process simulation environment with a modular structure to offer flexible handling of process units. This process simulation tool solves the modelled process by forming a non-linear equation system, which is solved by a Newton-Raphson-algorithm. An essential advantage of this tool is the modular set up, shown in Fig. 5-3.

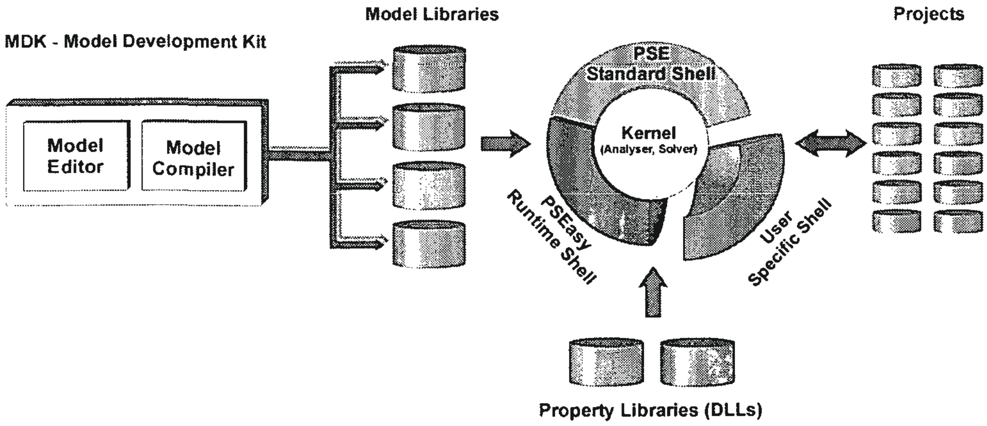


Fig. 5-3: Structure of the simulation environment

The process simulation environment (PSE) with the equation solver (Kernel) refers to a model library, with the information about the utilised apparatus. This model library can be edited with a special editor called model developer kit (MDK), which allows the implementation of user-defined models. The thermodynamic and physical data for the calculations are provided by external property libraries (DLLs). The standard software package IPSEpro® [92], which is designed to model standard power plant processes, has been greatly enlarged to model and describe gasification processes; dryers, gasifiers and gas cleaning equipment have been implemented, by mass- and energy balances, including possible chemical reactions and empirical correlations from measurements of real gasification plants. A detailed description of the models can be found in [93] and [94].

Exergy calculations

One essential feature of the so designed process simulation tool is the possibility of analysing a process using an exergetic evaluation. Conventionally the performance of a process is described in terms of the energetic performance, referred to lower heating value of the fuel and sensible heat. This evaluation method has the disadvantage to neglect the convertibility of the energy forms.

A possibility to include this into the calculation is to introduce the exergy, the part of the energy, which can be transformed into all forms of energy. This offers the possibility to investigate processes in terms of their exergetic behaviours and efficiencies.

When the original software was enlarged this value was included in the calculation. Since it will be used for an evaluation of the plant performance it is important to describe the calculation principles. Using these calculations it is possible to obtain an exergetic flow diagram of the process, which can help to identify possible optimisation potential.

The exergy of a stream consists of heat exergy and chemical exergy (Equation 5-12) [95].

$$e = e_q + e_{chem} \qquad \text{Equation 5-12}$$

For ideal gas mixtures, the specific exergy is defined by:

$$e_q = h - h_0 - T_0 \cdot [s - s_0] \qquad \text{Equation 5-13}$$

$$e_{chem} = M^{-1} \cdot \left[\sum_i (y_i \cdot E_{0i}) + R \cdot T_0 \cdot \sum_i (y_i \cdot \ln y_i) \right] \qquad \text{Equation 5-14}$$

The heat exergy in Equation 5-13 can be calculated as a function of the enthalpy *h*, entropy *s* and the ambient conditions (index *0*) and is a property of the gas mixture. The thermal environment defined for the present study is 298.15 K, 1.0 bar. For the calculation of the chemical exergy the molar exergy of pure substances [95] based on an equilibrium environment by [96] is used. The standard exergy of chemical compounds can be calculated from elemental exergy and standard free enthalpy [95]. For pure water and steam the exergy is defined using IAPWS-IF97 data [97], for solid mixtures it is expressed in analogy to ideal gases, neglecting the pressure dependency. For organic mixtures the chemical exergy is set equal to the higher heating value [98].

5.2.4 General conditions of the simulation

In the following the ambient conditions, the efficiencies of the specific apparatus and the biomass feedstock are given. All simulation work is based on these conditions. The specific ambient conditions and the general set-up can be found in Table 5-1.

Table 5-1: Ambient conditions and general plant data

Ambient conditions	
temperature	15 °C
relative humidity	60 %
ambient pressure	1.013 bar
General set-up	
stack temperature	120 °C
high pressure steam	84 bar / 450 °C
low pressure steam	18 bar / 450 °C
condenser conditions	80 mbar / 41.5 °C
Δp heat exchangers (PG-, flue gas-, air side)	10 mbar
Δp evaporators steam side	0.1 bar
Δp pre-heater steam side	3 bar
Δp reheat steam side	2 bar
Δp super heater steam side	0.1 bar

The implemented efficiencies for the specific apparatus can be seen in Table 5-2.

Table 5-2: Efficiencies of the specific apparatus

	η_s	η_m
high pressure turbine	0.84	0.99
low pressure turbine	0.82	0.99
compressors	0.75	0.99
pumps	0.75	0.99
gas turbine	0.88	0.985
compressor gas turbine	0.85	0.985

	η_{el}	η_m
motors, generators	0.98	0.98

As fuel for the different simulations, biomass with the characteristics given in Table 5-3 is used. For the investigations forest wood and a fuel mix of 80 % waste wood with 20 % residue wood are used.

Table 5-3: Biomass feedstock characteristics

component		forest wood	residue wood	waste wood
ash wf	[wt%]	5.0	7.69	7.5
C wf	[wt%]	46.71	44.75	43.97
H wf	[wt%]	6.02	5.95	5.95
O wf	[wt%]	41.93	41.00	40.54
N wf	[wt%]	0.293	0.465	1.830
S wf	[wt%]	0.030	0.093	0.137
Cl wf	[wt%]	0.012	0.056	0.082
water content	[wt%]	40	35	20
lhv wf	[kJ/kg]	17391	16784	16651
lhv	[kJ/kg]	9457	10054	12832

5.3 Results

In the following the results of the technical assessment will be presented, starting with the results from the identification of the most suitable drying concept, which is used for all concepts. Consequently the layout and the main process parameters of the different concepts are presented.

5.3.1 Identification of suitable drying concepts

In this chapter the possibilities of integrating biomass drying into a pressurised IGCC-concept are investigated to evaluate the most suitable, energy efficient drying technology for the following concepts. Three solutions for the implementation are considered using steam and exhaust gas as heat sources. These concepts are evaluated in terms of their exergetic performance and discussed in detail.

Description of the investigated process

The investigated process is based on a large pressurised IGCC concept with a net electrical power output of 20 MW. The basic outline of the plant is a pressurised gasification in a circulating fluidised bed with hot gas conditioning, coupled with a gas turbine and a two stage steam cycle in condensation mode. The flow diagram is shown in Fig. 5-4.

Biomass is pressurised in a lock hopper system and enters a **C**irculating **F**luidised **B**ed (CFB) reactor with 21 bar operating pressure. Air is used as gasification agent, which is extracted as side stream from the compressor of the gas turbine (about 10 % of the mass flow) at turbine operating pressure, cooled in an evaporator, pressurised and reheated again to 250 °C. The additional compression is necessary to cover pressure drops, which occur in the gasifier and the gas conditioning before the combustion chamber of the gas turbine. The product gas is cooled, first with a reheat to about 700 °C and second with an evaporator to 400 °C before it is dedusted in a hot gas filter. The fly ash of the filter has high carbon content, and is therefore recycled into the gasification reactor.

The cleaned product gas is combusted in the combustion chamber of the gas turbine with the remaining air of the gas turbine compressor and leaves the turbine at about 520 °C. The gas is further cooled in the waste heat recovery consisting of a superheater, an evaporator and a feed water preheater (economiser), before released to the atmosphere at 120 °C. The steam cycle consists of a two-stage turbine (84 bar / 18 bar).

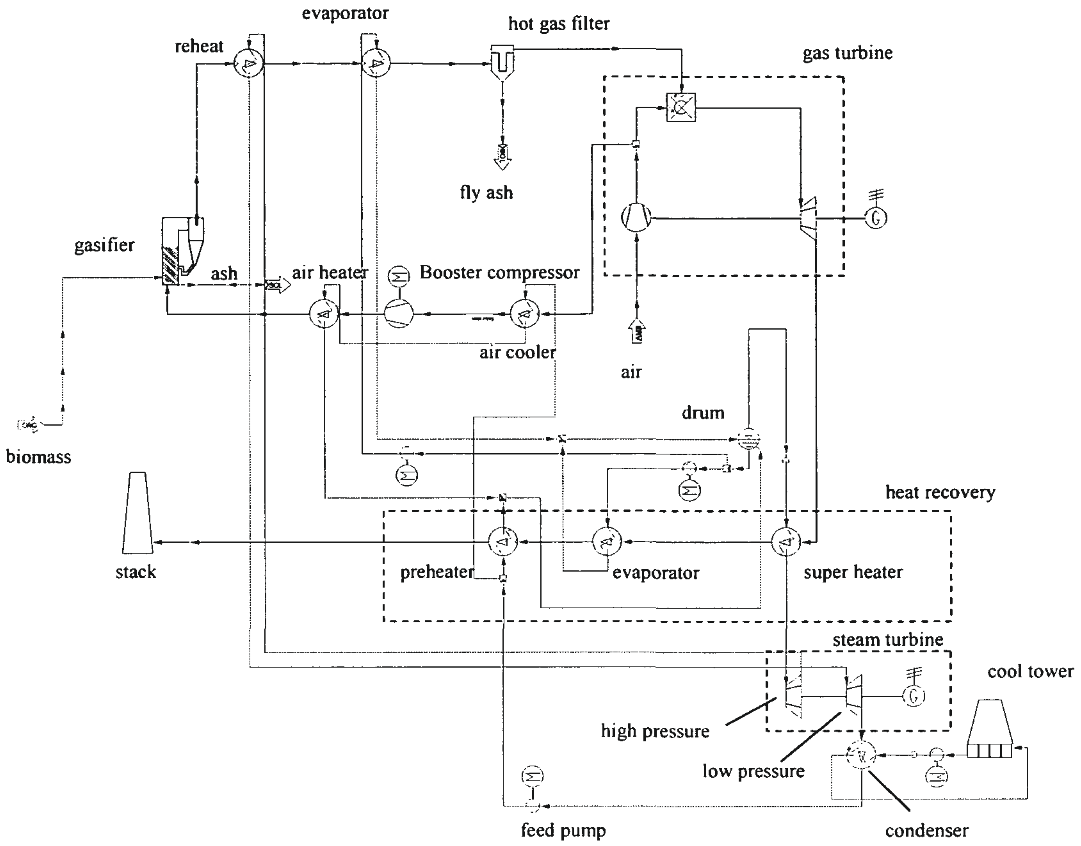


Fig. 5-4: Flow diagram of the IGCC process

Influence of the biomass water content

In the following the influence of the water content on the process will be discussed. Fig. 5-5 shows the effect of the variation of the water contents from 40 % to 10 %, when the total power output of the plant is kept constant. It can be clearly seen, that the reduction of the water content from 40 % to 10 % results in an increase of the net electrical efficiency of over 2.5 %. Furthermore, the effect on the chemical efficiency of the gasifier can be seen; an increase of 20 % can be obtained if the water content is reduced to the above mentioned values.

In Fig. 5-6 the influence of different biomass water contents on the exergy losses of different apparatus at constant total power output of 20 MW_{el} is given.

The highest sensitivity can be seen for the gasifier, where the water in the fuel has to be evaporated. The heat for the evaporation has to be produced by partial combustion of the fuel, which has a strong influence on the exergy loss, due to the irreversibility of the combustion. The necessary additional combustion dilutes the product gas with inert combustion gases and additional nitrogen from the gasification air. This results in a reduction of the lower heating value and thereby, the exergy content of the product gas.

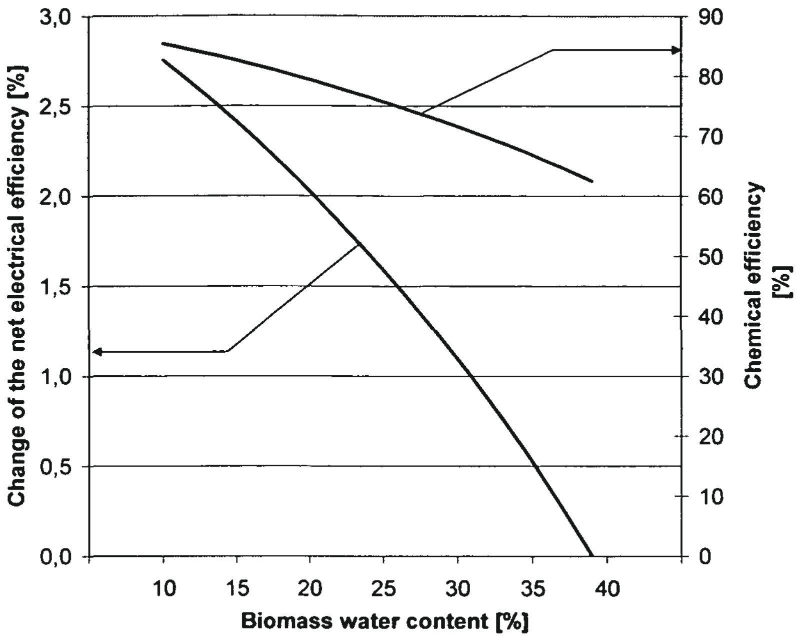


Fig. 5-5: Influence of the biomass water content

Therefore, wet fuel reduces the power of the gas turbine due to the lower heating value of the product gas. This results also in a decline of the exergy losses in the gas turbine. In total it can be concluded that in terms of electrical efficiency as well as in terms of exergy losses the use of dry wood gives considerable advantages. For the further simulations a biomass water content after the dryer of 15 wt% is assumed.

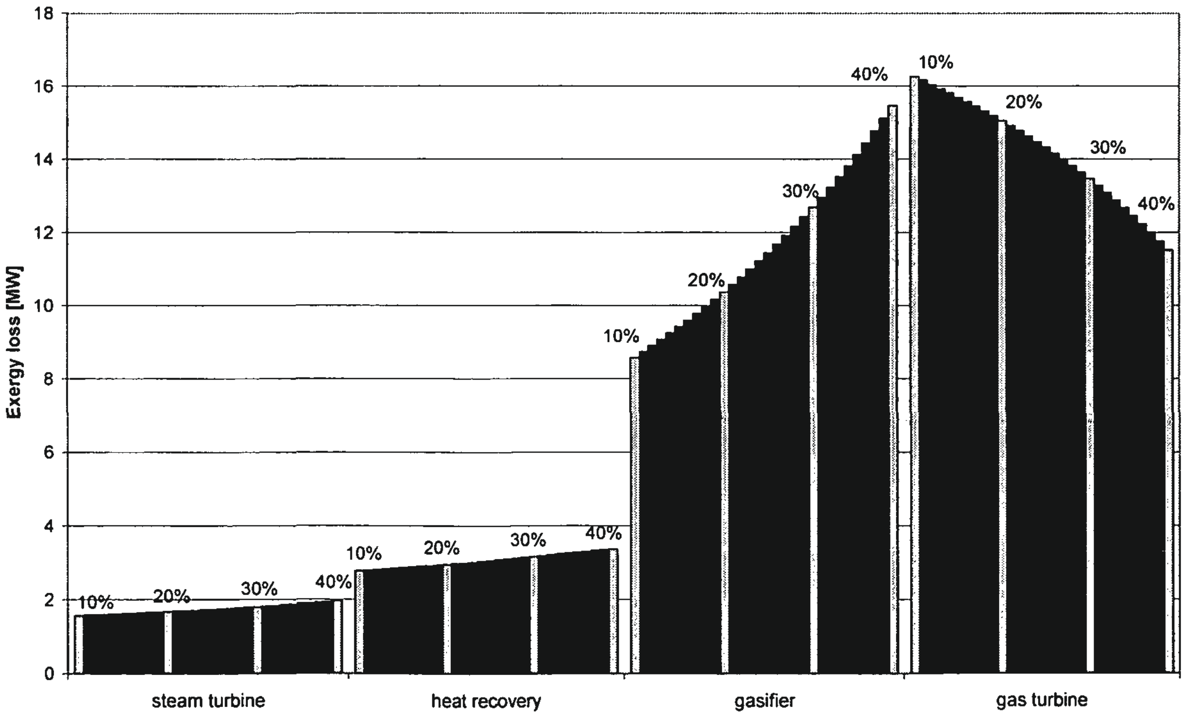


Fig. 5-6: Exergy losses of different apparatus at different biomass water contents (10% - 40%, marked by grey lines)

Drying of biomass

If biomass is dried the water content is reduced, though according to the drying temperature organic emissions can occur [99-101]. In the temperature range from 80 °C to 120 °C according to Rupar [102] oak shows a carbon loss of 0.04 % to 0.08 %. If superheated steam is used (3 bar, 133 °C) according to Münster [103] a loss in the lower heating value of 1.2 %, corresponding to an average carbon loss of 1 % using wood as a fuel, occurs. With an increase in the drying temperature from 190 °C to 350 °C a rise in the carbon loss from 1 % to 10 % for pine wood and up to 17 % for birch wood has been measured [104].

It can be easily seen that the carbon loss at low drying temperatures (<120 °C) can be nearly neglected. To investigate the influence of the carbon loss on the electrical and chemical efficiencies of the process the loss was varied from 0 % to 8 %, which can be seen in Fig. 5-7. Up to a carbon loss of 1 % the influence on the electrical efficiency is rather low (0.4 %), but even small carbon losses can cause undesired gaseous emissions. If only particle removal is installed, the temperature in the dryer should be kept below 100 °C.

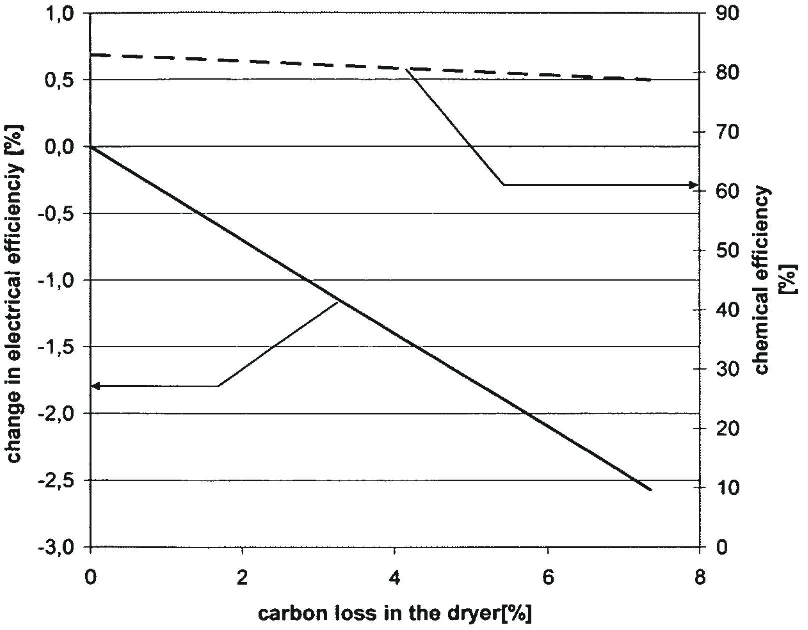


Fig. 5-7: Influence of the carbon loss in the dryer

Until today few experiences for drying of biomass for gasification exist. The applicable drying technologies can be separated into systems with *direct* and *indirect* heat transfer.

Using *direct drying*, rotary drum dryers have been successfully utilised; a warm gas stream (flue gas, heated up air) is fed counter currently to the biomass into the drum. The rotary drum itself provides the transport and mixing of the biomass.

Other types of dryers suitable for low temperature direct drying are the conveyor and the vibro dryer. The conveyor dryer uses a porous belt, which carries the biomass over the cross flow feed of warm gas; the vibro dryer uses a porous metal surface, which is vibrating for better fuel mixing. Warm gas is fed again in cross flow to the biomass through the porous metal surface.

Indirect heat transfer *drying technologies* transfer the necessary heat indirectly through heat exchangers into the drying equipment; therefore, the released drying gases can be separately drawn off. For fast drying of beet slices a pressurised fluidised bed dryer, with internal steam recirculation is often used. This dryer has been successfully applied on the drying of biomass wood chips too [104]. A more detailed description will follow at the relevant concept discussion.

Evaluated concepts

Flue gas drying: For low temperature drying of biomass, especially wood chips, the rotary drum dryers, the conveyor dryer and the vibro dryer are suitable types. The process is equal to the one described above, additionally the dryer is added (Fig. 5-8). The flue gas after the preheater is mixed with recycled gas from the dryer outlet to reduce the energy demand of the dryer and to adjust the dryer inlet temperature. The necessary heat for the drying is drawn from the product gas. This raises the necessary temperature after the preheater and therefore has a negative effect on the power output of the steam cycle.
Air drying: Further reduction of the organic emissions can be achieved by using ambient air (15 °C), heated up by flue gas. This gives the advantage, that the dryer can be operated at temperatures below 100 °C. The flue gas of the dryer is partially recycled to reduce the necessary heat demand.

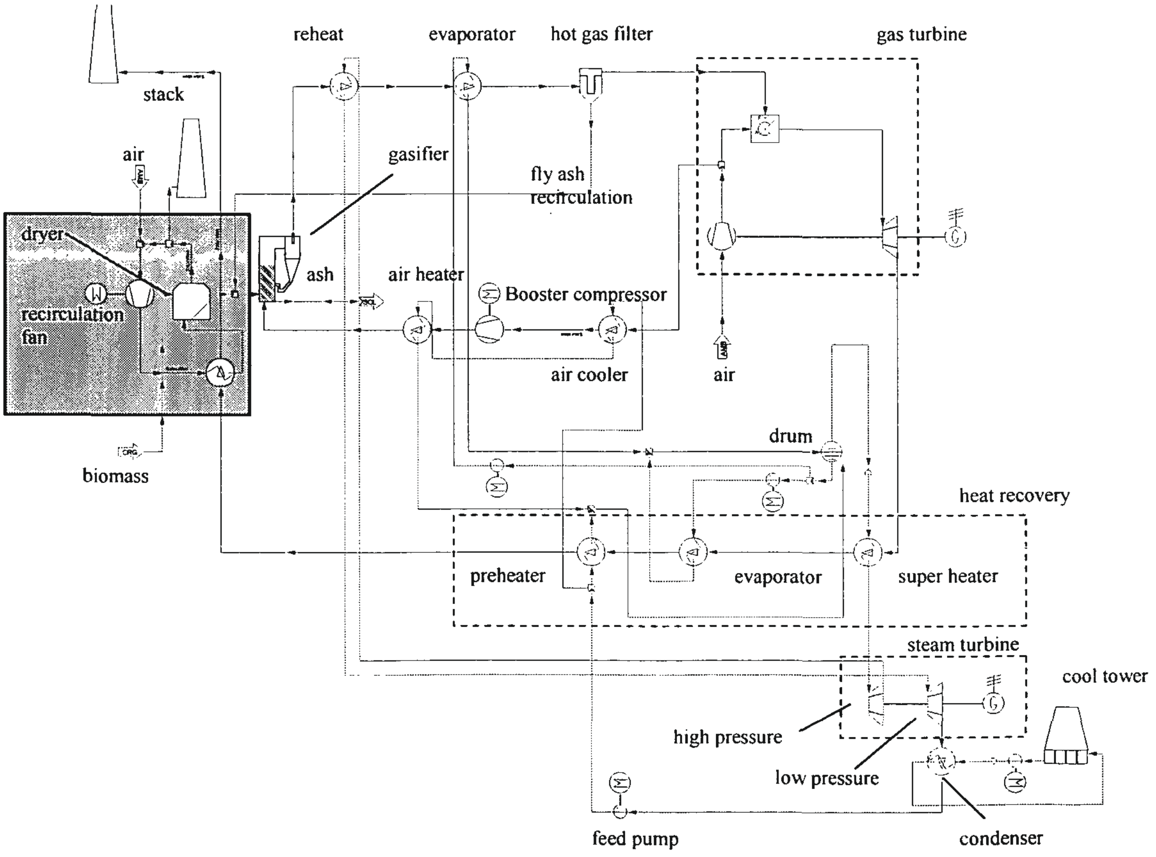


Fig. 5-8: Flow chart with integrated air drying

Steam drying: Finally, a concept using medium pressure steam as heat source will be investigated. A detailed description of a fluidised bed steam dryer is given by Jensen [105]. The dryer uses partly the recirculated steam from the biomass to fluidise the chopped wood. The heat for the drying is drawn from steam, extracted after the high pressure steam turbine from the process, which is condensed in an internal heat exchanger thereby heating up the recirculated steam. The steam leaving the dryer is condensed; the yielded heat is fed back into the steam circle. The wastewater from the condenser has to be treated, because it contains organic compounds.

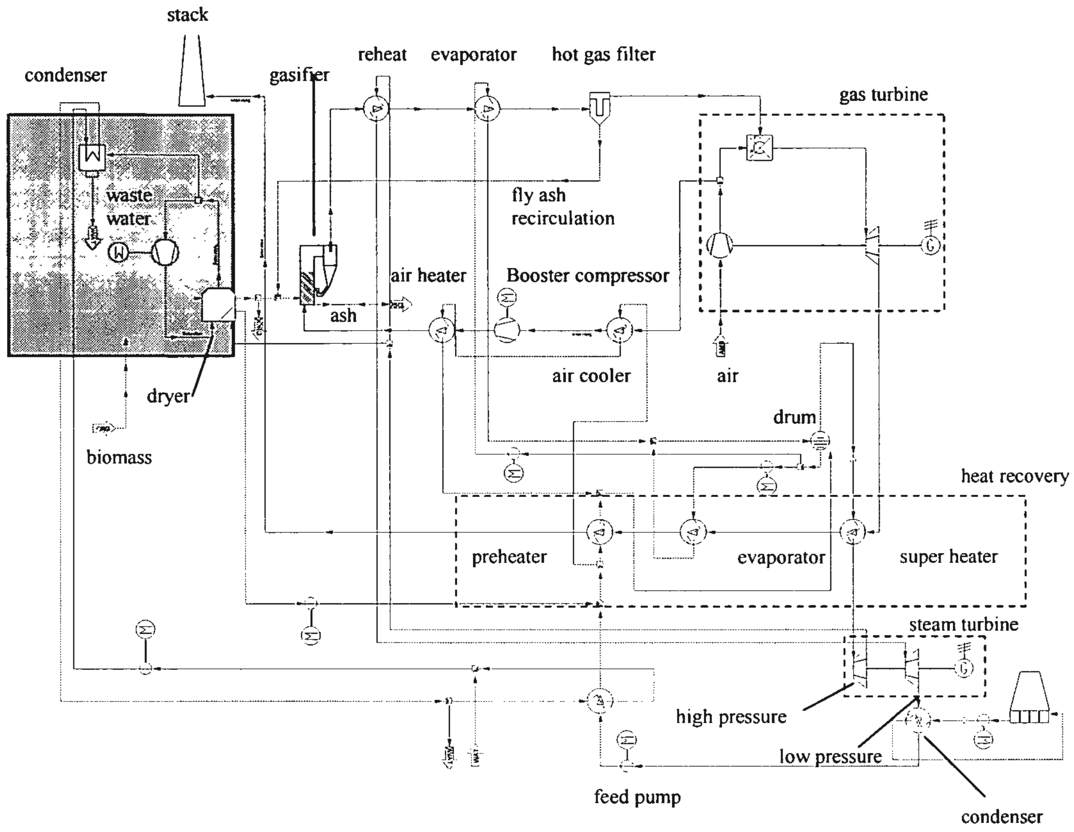


Fig. 5-9: Flow chart with integrated steam drying

A detailed description of each concept can be found in [106].

Concept comparison

Fig. 5-10 gives a comparison of the different concepts in terms of their electrical efficiencies. It can be seen, that steam drying achieves the highest net electrical efficiency and shows a low own consumption of electricity. In a real plant this little benefit in electrical efficiency (0.1 %) compared to the flue gas drying concept has to be set into relation to the costs for the wastewater treatment.

Using air as drying medium the net electrical efficiency is 1.2 % lower as if steam is used, because of the higher flue gas recirculation rate the compressor power increases the own electrical consumption of this concept. Organic emissions can be largely avoided due to the low drying temperature of the wood, so the loss in efficiency may be compensated by the lower post treatment cost of the dyer exhaust.

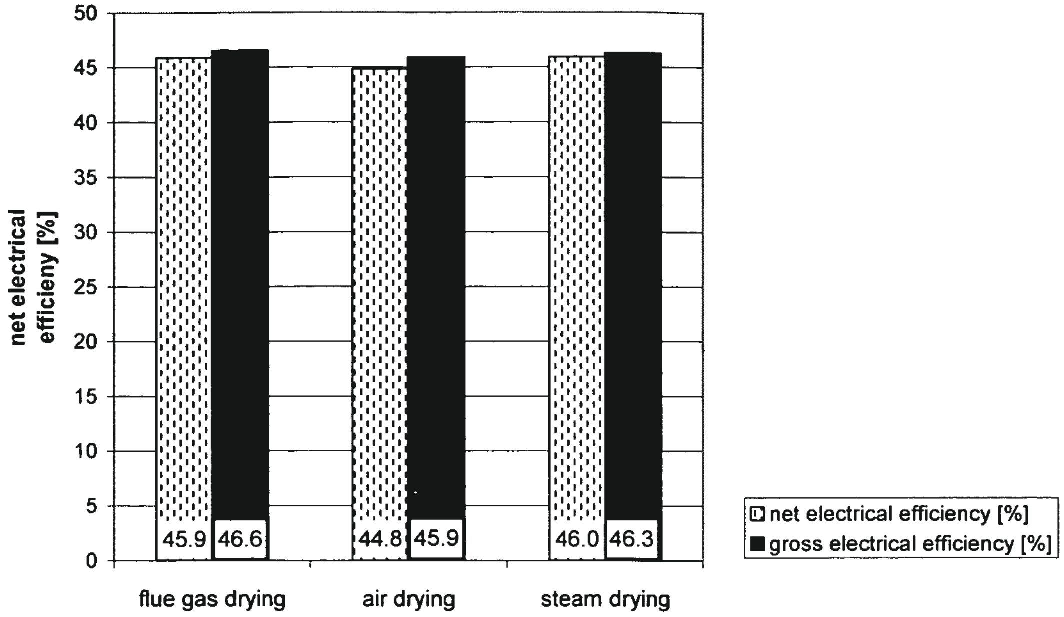


Fig. 5-10: Comparison of the efficiencies of the different concepts [106]

Operating the dryer using flue gases equal results in efficiency (45.9 %) compared to the steam drying concept can be achieved. The advantage is that no waste water is produced. Interestingly these three concepts show also different sensitivities, if the water content of the biomass is varied. Steam drying shows a lower sensitivity on the water content of the biomass, equal to air drying than flue gas drying (Fig. 5-11).

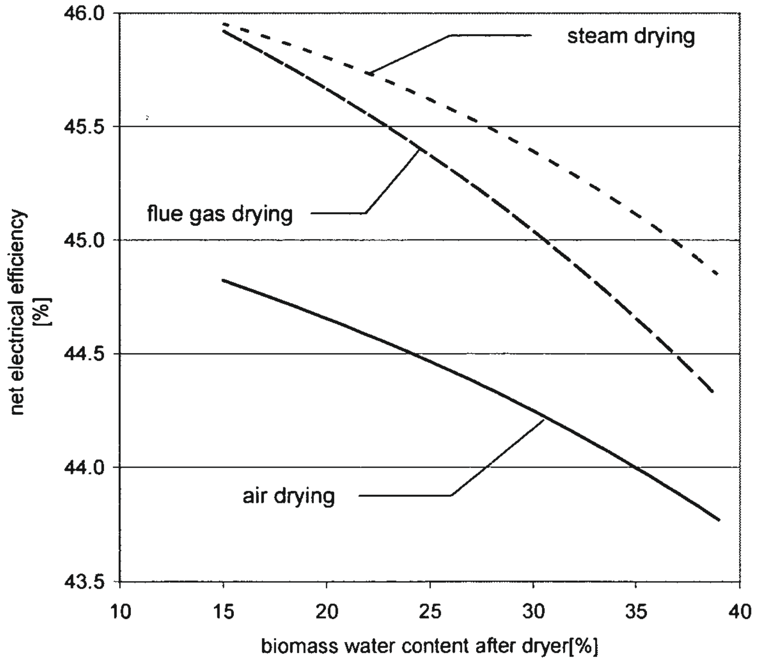


Fig. 5-11: Sensitivities on the efficiencies of the concepts on a variation of different water contents [106]

By comparing the exergy losses of the three different concepts at constant power outputs of 20 MW electrical (Fig. 5-12), it can be seen that using the steam drying concept the exergy losses in the gas turbine and the gasifier can be reduced whereas the losses raise strongly in the dryer. This can be explained by the higher temperature gradient between biomass and steam as well as by the carbon losses in the steam dryer. Since the overall power output is kept constant the reintegration of heat from the condenser after the dryer has a positive effect on the exergy losses in the gasifier and the gas turbine. The two concepts based on the heat from flue gas show only minor differences in their exergy losses.

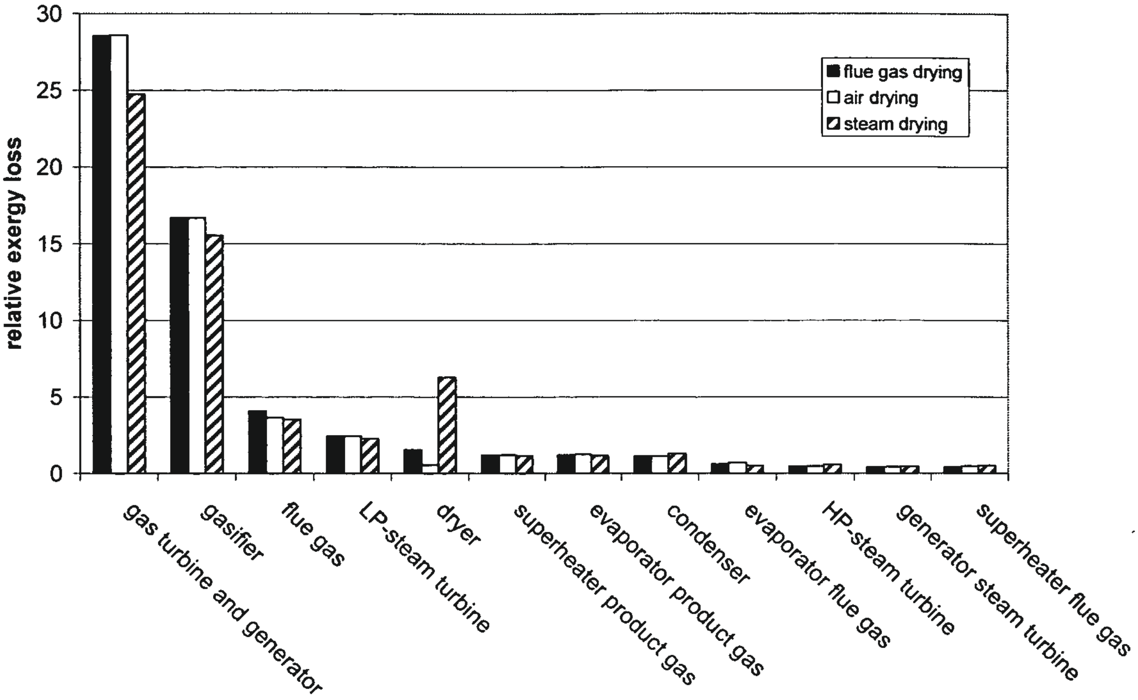


Fig. 5-12: Comparison of the exergy losses [106]

In the following, the exergy inputs into the dryer are investigated. The exergy input is defined as the exergy necessary to dry the fuel to the desired water content. This exergy is provided by hot flue gas after the economiser in the concepts of flue gas drying and air drying and in the steam drying concept by steam drawn from the steam cycle. A comparison of the exergy inputs can be found in Fig. 5-13.

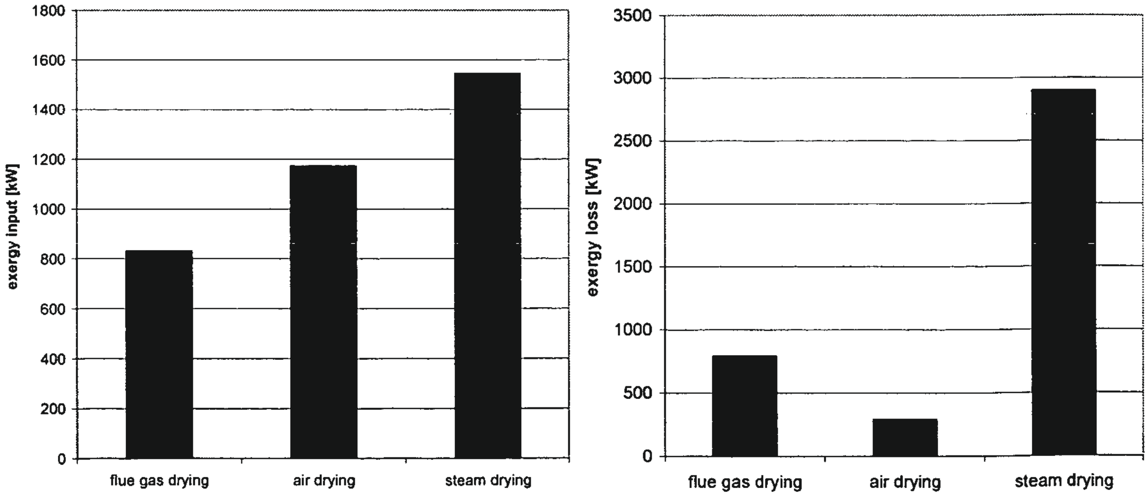


Fig. 5-13: Comparison of the exergy inputs (left) and exergy losses (right) [106]

The dryer in the flue gas concept needs the lowest exergetic input (heat from the flue gas), which means it uses less valuable energy for drying the biomass. The larger exergetic input in the air drying concepts is mainly due to the use of ambient air, which has to be heated up and needs more energy than using hot flue gas. Drying the biomass using steam as heat source requires the largest exergetic input, due to the fact that steam (20 bar, 280 °C) has still a high exergetic value and therefore is more valuable in terms of energy than hot flue gas at 180 °C.

The detailed exergetic losses in the dryer are given in Fig. 5-13. Steam as drying medium shows the largest exergetic losses, which include also the carbon losses of 5 % of the biomass in the dryer exhaust gas. Due to the lower temperature difference and the lower carbon loss, the exergetic loss in the flue gas drying concept is considerable lower, reaching the minimum if heated ambient air is used.

Conclusion

The reduction of the biomass water content can contribute significantly to the electrical efficiency of the biomass based IGCC processes. Improvements of 2.5 % in electrical efficiency referred to the fuel power can be achieved if wood with a water content of 15 % instead of 40 % is used. Using low temperature heat from the flue gas for the drying process gives the significant advantage of a low exergetic input into the dryer as well as low organic emissions. Furthermore, the waste water formation is avoided. The concept with integrated flue gas drying can achieve net electrical efficiencies of up to 46 %, which is high for biomass options and offers the best compromise between efficiency and residual treatment.

For future biomass based IGGC plants the integration of the fuel drying into the entire concept is a proper method to increase the fuel flexibility and offers the advantage to operate the plant at optimum conditions. Therefore, for the following technical assessment flue gas drying is used to condition biomass to the requirements of the gasification reactor.

5.3.2 Concept I

This process is based on a large pressurised IGCC concept with a net electrical power output of 20 MW. Since the specified feedstock has a water content of 40 % (forest wood) or 23 % (fuel mix), which would cause high energetic and exergetic losses during gasification (compare 5.3.1), the investigated flue gas drying is installed

Biomass is delivered to the plant and dried in a flue gas dryer with tail gas recirculation. It leaves the dryer at about 40 °C and is mixed with solid residues from the hot gas filter, before it is pressurised in a lock hopper system and enters a **C**irculating **F**luidised **B**ed (CFB) reactor with 21 bar operating pressure. The rest of the process is equal to the one described in 5.3.1 and consist of a hot gas cleaning, gas utilisation in a gas turbine and additional heat utilisation in a steam cycle. The flow diagram is shown in Fig. 5-14.

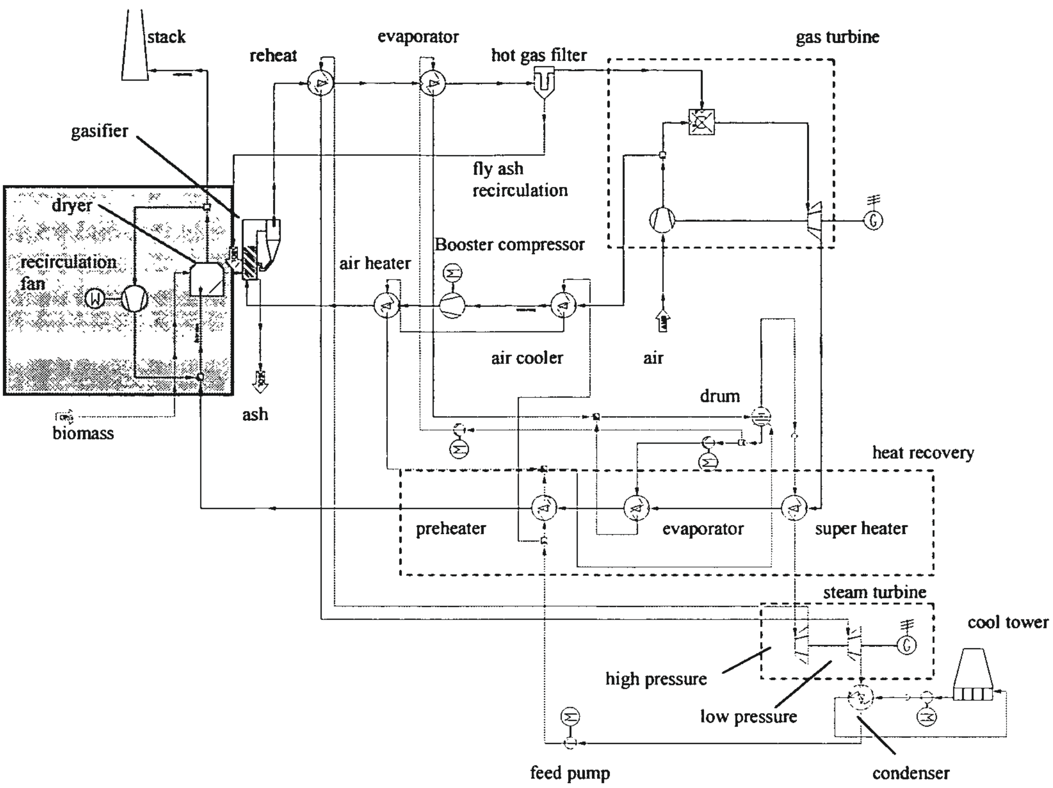


Fig. 5-14: Flow diagram of the IGCC process with integrated biomass drying with flue gas

By returning the fly ash back into the gasifier, residues are reduced and the carbon conversion efficiency of the gasifier is increased. Moreover, low temperature heat in the flue gas, which has low potential for conversion to electricity, is used for drying the wet biomass. This reduces the amount of the biomass, which has to be combusted in the gasifier to evaporate the incorporated water. Concept I-dh differs from the original concept only by the production of district heat and therefore the steam turbine is operated in back-pressure mode. The main process data of these four concepts are given in Table 5-4.

Table 5-4: Overview of the main process data

powers				
	I		I-dh	
	forest wood	fuel mix	forest wood	
fuel power	45.66	46.49	49.14	MW
chemical power product gas	37.45	35.59	38.98	MW
district heat	-	-	18.86	MW
electric gross power	20.30	20.15	20.29	MW
own consumption	299	147	292	kW
electric net power	20.00	20.00	20.00	MW
efficiencies				
$\eta_{el,gross}$	44.5	43.3	41.3	%
$\eta_{el,net}$	43.8	43.0	40.7	%
$\eta_{Q,dh}$	-	-	38.4	%
$\eta_{chem,plant}$	82.0	76.6	79.3	%
$\eta_{fuel,gross}$	44.5	43.3	79.7	%
$\eta_{fuel,net}$	43.8	43.0	79.1	%
α_{gross}	-	-	1.08	-
α_{net}	-	-	1.06	-

Comparing the efficiencies of the feedstock "forest wood" and the feedstock "fuel mix", it can be seen that although "forest wood" has higher water content than "fuel mix" higher electrical efficiency can be achieved. This phenomenon looks at the first glace as a paradox, but can be understood by the following analysis: The electric gross power output of the plant is kept constant at 20.0 MW and the water content of the feedstock after the dryer is fixed to 15 %. Hence biomass feedstock with higher water content also requires a higher heating power of the dryer. The heat for the dryer is taken from the flue gas of the gas turbine, after the pre-heater. Fig. 5-15 shows this arrangement:

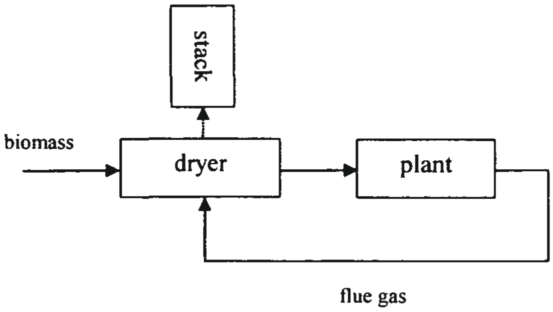


Fig. 5-15: Block-flow chart of the plant

Looking at Fig. 5-16 it can be seen, that the fuel power before the dryer declines slightly with an increasing water content, if the gross electric production of the plant is kept constant. This corresponds to a slight reduction in efficiency.

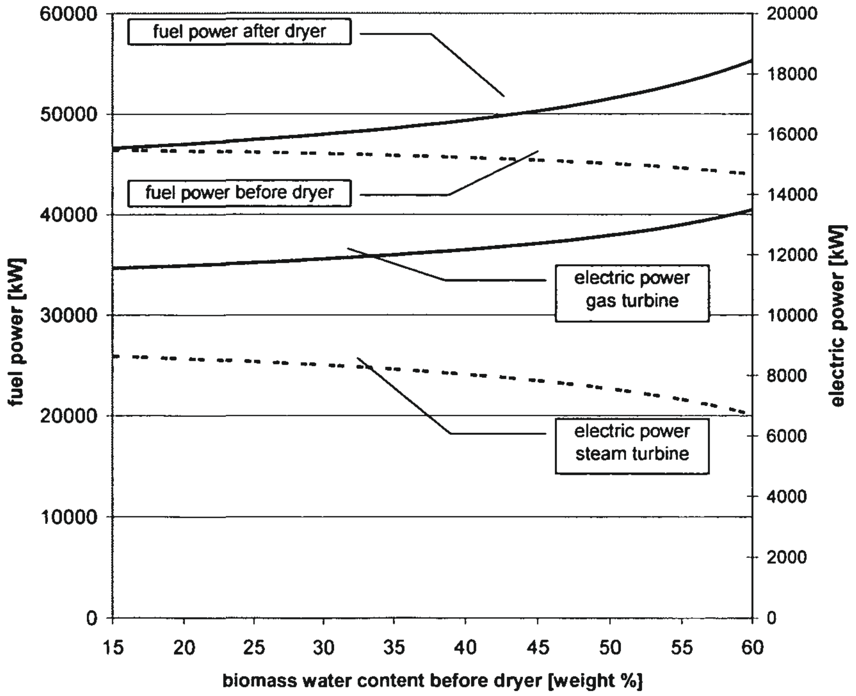


Fig. 5-16: Influence of different water contents of the feedstock on the fuel and electric power of the plant

However, by drying the biomass the calorific value is raised in the dryer quite significantly. This "upgrading" of the fuel is done with low temperature heat from the flue gas after the preheater. Further, the power output of the gas turbine is increased by the higher fuel power, but the electric power of the steam turbine declines, since for the evaporation of higher water contents more heat has to be drawn from the flue gas.

The gain in efficiency can be explained by partial conversion of heat from a low temperature level in chemical bound energy with high conversion potentials, since the "increase" of the calorific value of the feedstock in the dryer can be converted to electricity using the combined cycle.

To indicate the possibilities for investigating optimal plant design, the energy and exergy flow diagrams of this concept are presented as an example in the following.

Fig. 5-17 shows the energetic flow diagram of this concept. In power plant technology, the energy is referred to the lower calorific value of the feedstock, hence, water in condensed form would have negative energy, which is not a realistic approach. Therefore, the energy streams of the steam cycle cannot be drawn true to scale compared to the fuel bound energy streams. Instead of that the sensible heat flows are shown.

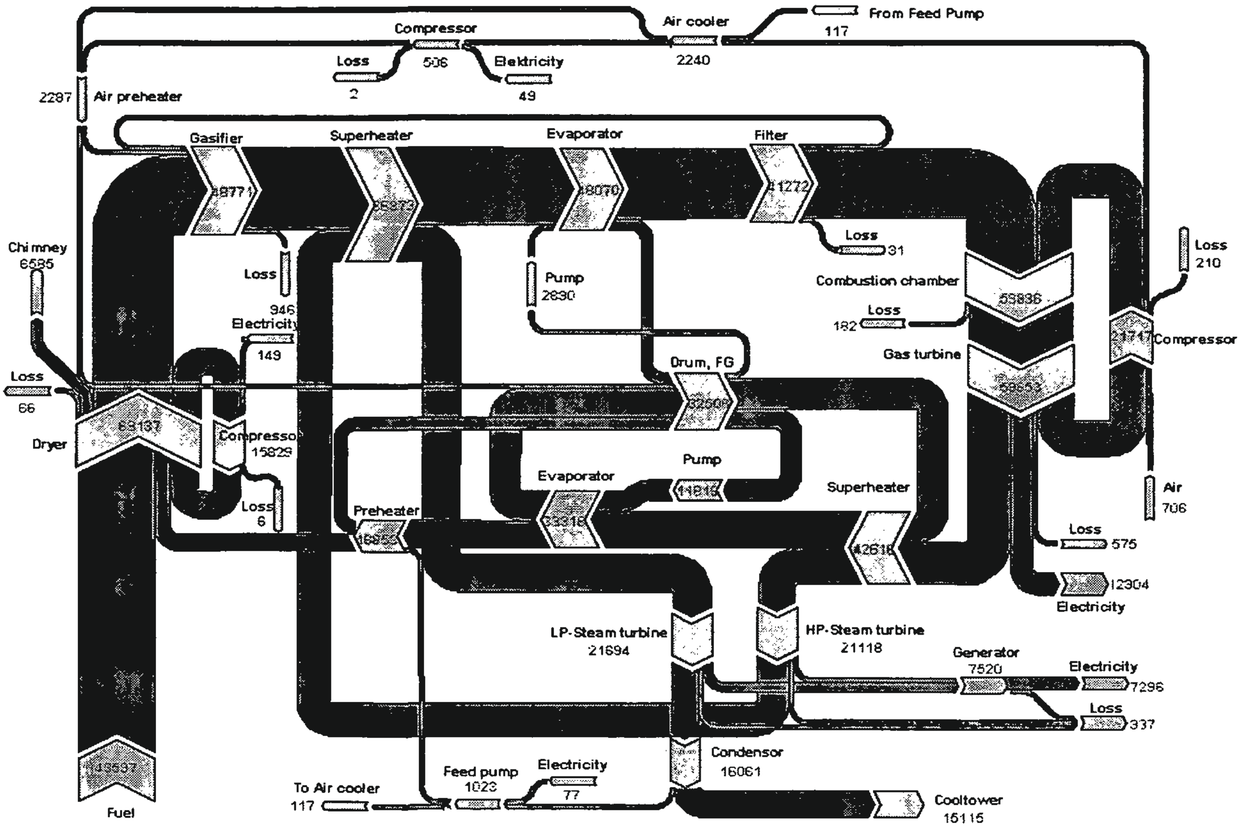


Fig. 5-17: Energetic flow diagram of process I for forest wood (value in kW)

These restrictions do not occur if the exergy is used as an evaluation basis, since as reference point a standard environment is used. The exergy flow diagram is shown in Fig. 5-18. Using this diagram the exergy flow of the feedstock can be followed through the plant. The exergy can thereby be interpreted as the part of the energy, which can be converted into all energy forms. Hence, exergy indicates the quality of energy. It can be seen that most of the chemical exergy of the feedstock is converted into chemical exergy of the product gas and thereafter into electricity. Due to the fact that steam has a lower exergy (no chemical energy) the exergetic flows in the steam cycle are much smaller than in the energetic flow diagram. Therefore, it should be the aim to maintain as much exergy of the feedstock in chemical form as fuel for the gas turbine to reduce exergetic losses, since the conversion to an intermediate medium, like steam and thereafter into electricity increases the exergetic losses.

Clearly it can be seen, that the highest exergetic losses origin from the combustion and gasification step. Further, the high power consumption, indicated by a large exergetic flow for the compression of the combustion air of the gas turbine, can be seen.

Additionally, the before mentioned paradox is not valid if the exergy is used as an evaluation bases. If the overall exergetic efficiency of the plant (produced electric power referred to fuel exergy) is compared for the different feedstocks, the fuel “forest wood” achieves, due to the higher water content, an about 1 % lower exergetic efficiency as if the “fuel mix” is used.

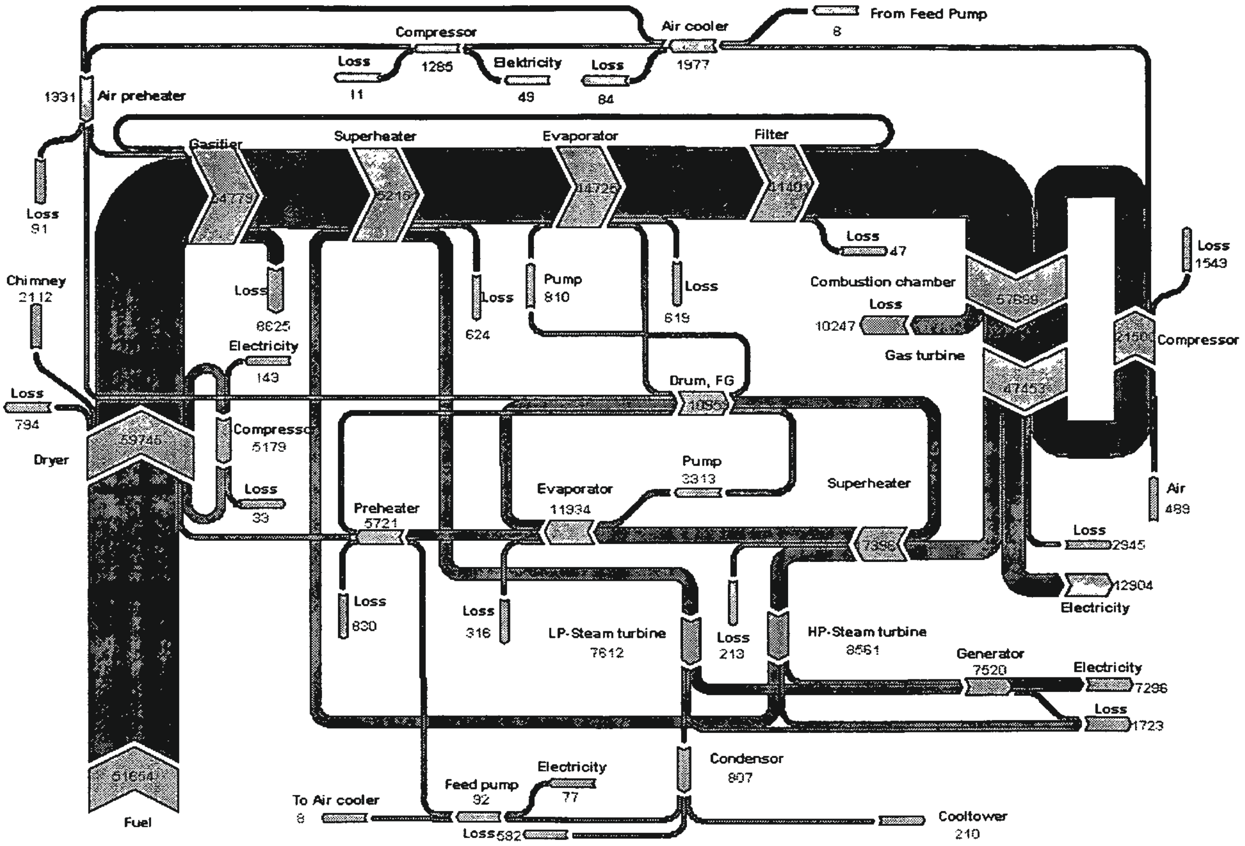


Fig. 5-18: Exergetic flow diagram of process I for forest wood (values in kW)

A better analysis of the different exergetic losses can be gained from Fig. 5-19, where they are referred to the feedstock exergy. The highest exergetic losses occur in the gasifier and the gas turbine, due to irreversibility of combustion and gasification processes, as already mentioned. These can only be reduced, if the efficiency of the gas utilisation is increased or other gas utilisation technologies, such as fuel cells are used. Further, the difference in the exergetic losses in the dryer of different fuels can be seen. The feedstock “forest wood” causes much higher exergetic losses in the dryer, since more water has to be evaporated as the feedstock “fuel mix”.

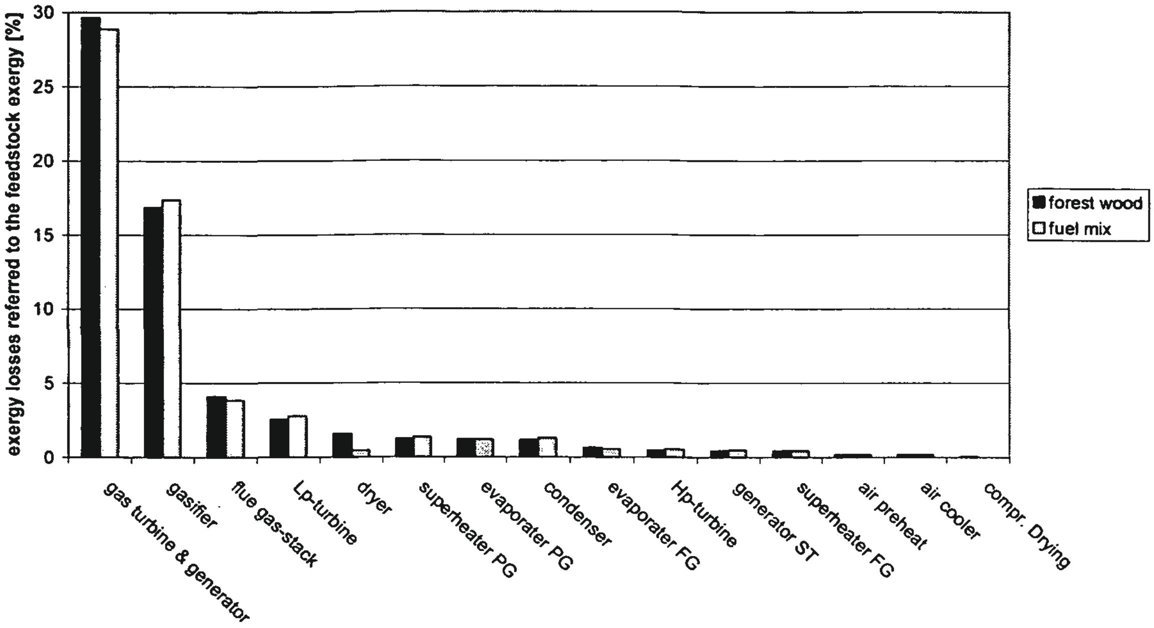


Fig. 5-19: Exergetic losses of the different apparatus referred to the exergy of the biomass feedstock

In summary the feedstock “forest wood” has a lower exergetic performance than the dryer feedstock “fuel mix”. If the lower heating value and hence an energetic evaluation is used it is the opposite case. A plant with integrated low temperature drying increases its efficiency with wetter feedstock, which makes a comparison of different plants only valid if the same feedstock is used.

5.3.3 Concept II

The evaluation of the pressurised gasification discussed before has shown for the feedstock “forest wood” and the “fuel mix” similar results with only minor differences in the efficiency (about 0.7 %). Therefore, for the following concepts and for their comparison “forest wood” will be used as feedstock.

Concept II-gt

Biomass with a water content of 40 wt% is dried in a flue gas dryer to 15 wt% and leaves the dryer at about 40 °C. It is fed to the gasifier, where it is converted with hot air at 900 °C to raw product gas. The raw product gas is dedusted in a cyclone before it is cooled by an evaporator and air preheater to 400 °C. After that, the product gas is cooled further by a quench to the required inlet conditions for the electrostatic precipitator (45 °C), where it is cleaned from dust and tar loads. Waste water from the quench and the wet electrostatic precipitator is filtered; its residues are fed to a combustor. Since the heating value of this residue is to low for combustion, additional biomass is added to the combustor.

After the electrostatic precipitator the product gas is compressed in a multi-stage compressor with intermediate cooling, before it is combusted in a gas turbine. The flue gas after the gas turbine (about 520 °C) is mixed with the hot flue gases from the biomass combustor and used to raise steam at 84 bar in a waste heat recovery system. After the preheater the flue gas has a temperature of about 190 °C, which is sufficient to dry the wet feedstock. To reduce the dryer inlet temperature and therefore the organic emissions, the dryer is operated in recirculation mode. The flue gas leaves the dryer at about 120 °C. The produced steam is converted in a two-stage steam cycle to electricity. Fig. 5-20 shows the process flow diagram of concept II-gt, the main process data can be found in Table 5-5.

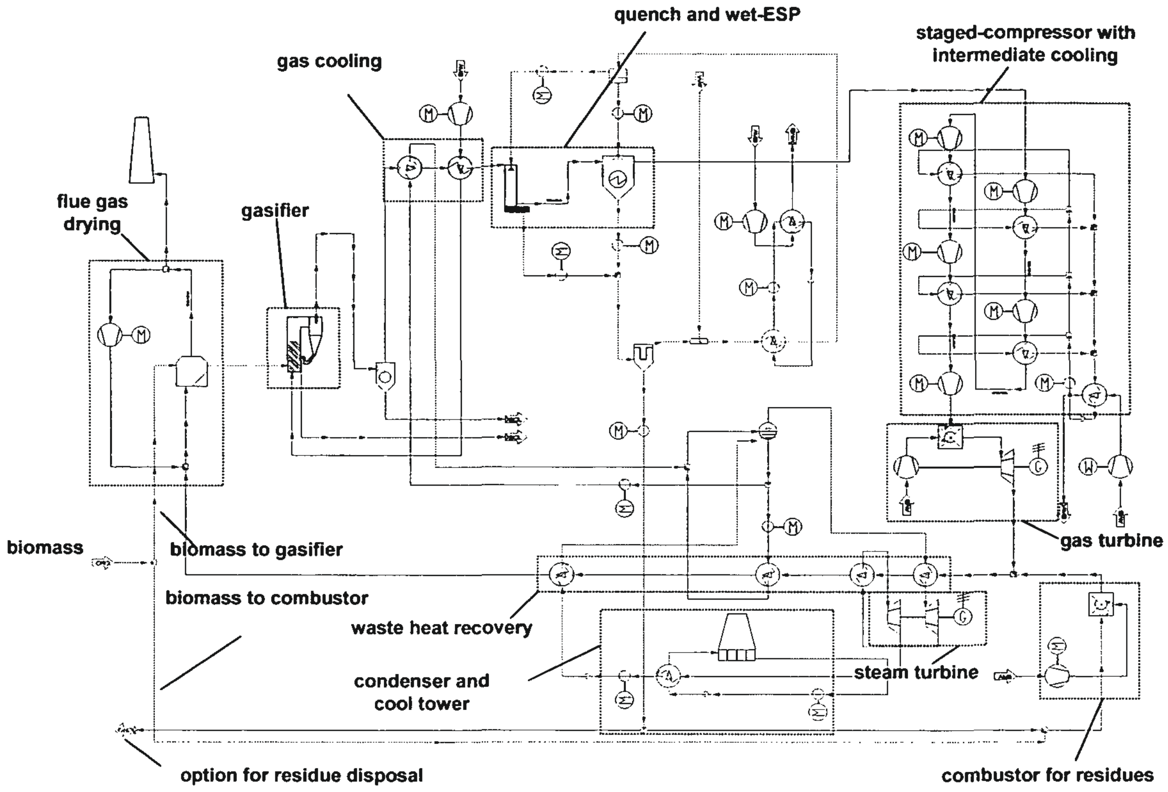


Fig. 5-20: Flow diagram of the IGCC process with integrated biomass drying with flue gas

Certain parameters have a strong influence on the performance of the process and need therefore to be carefully set considering technical and operational constraints. As an example in the following the influence of the gas temperature before the multi-staged compressor is discussed briefly.

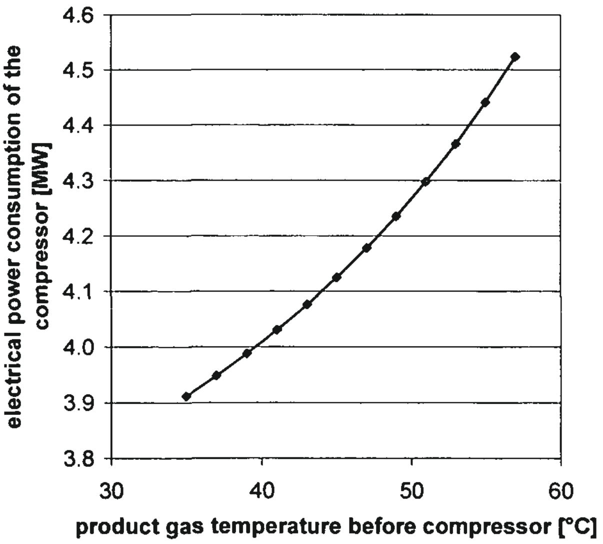


Fig. 5-21: Influence of product gas temperature before compressor on its power consumption

Fig. 5-21 shows this dependence. It can be seen that by a temperature increase of 20 °C the power consumption of the compressor rises by 700 kW, which is 3.5 % of the total power output of the plant. Therefore, lower temperatures are favourable to reduce the own power consumption of the plant. However, at lower temperatures more water condenses in the quench, which increases the amount of waste water for disposal. Another constraint is given by the ambient temperature, since the quench water is cooled by ambient air. Therefore, in this concept the gas temperature before the compressor is set to 45 °C.

Concept II-ge

Concept II-ge uses a different gas utilisation technology, instead of a gas turbine gas engines are used, hence no compressor is needed. Fig. 5-22 shows the flow diagram of the adapted process using nine gas engines instead of one gas turbine. The heat of the cooling water of the gas engines is additionally used in the steam cycle. The main process data can be found in Table 5-5. The grey area marks the difference to Fig. 5-20.

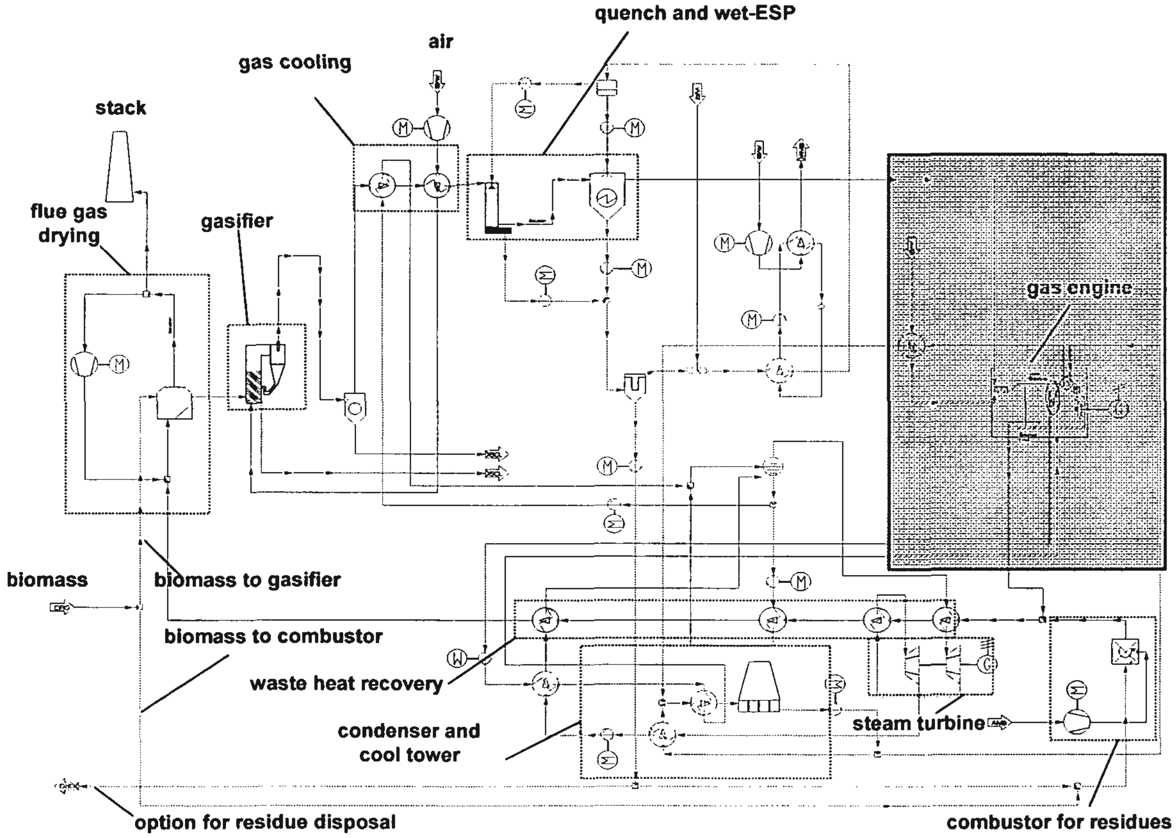


Fig. 5-22: Flow diagram of the IGCC process using nine gas engines (grey area marks the difference to Fig. 5-20)

Concept II-gt-dh, concept II-ge-dh

So far concepts are optimised to maximise the electric power output. To investigate the influence on the plant efficiency both concepts are adapted, to operated in combined heat and power mode. The necessary changes can be seen in Fig. 5-23, the main process data can be found in Table 5-5. In concept II-gt-dh the turbine is operated in back pressure mode and district heat is produced in a heat exchanger after the low pressure turbine. In concept II-ge-dh additional to the already mentioned changes district heat is produced by the gas engines as well.

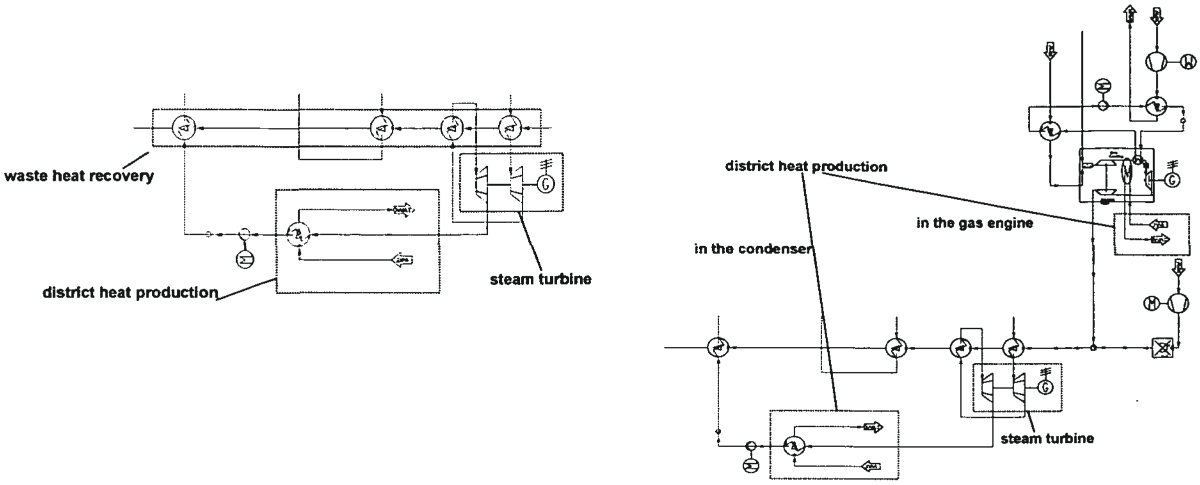


Fig. 5-23: Changes for combined heat and power operation (left side concept II-gt-dh, right side concept II-ge-dh)

The main process data of these four concepts are given in Table 5-5.

Table 5-5: Overview of the main process data

powers					
	concept II-gt	concept II-gt-dh	concept II-ge	concept II-gt-dh	
fuel power	58.04	61.79	57.33	60.67	MW
chemical power product gas	43.99	46.84	43.27	45.96	MW
district heat	-	22.11	-	24.78	MW
electric gross power	24.61	24.91	20.92	20.97	MW
own consumption	4614	4913	916	973	kW
electric net power	20.00	20.00	20.00	20.00	MW
efficiencies					
$\eta_{el,gross}$	42.4	40.3	36.5	34.6	%
$\eta_{el,net}$	34.5	32.4	34.9	33.0	%
$\eta_{Q,dh}$	-	35.8	-	40.8	%
$\eta_{chem,plant}$	75.8	75.8	75.5	75.8	%
$\eta_{fuel,gross}$	42.4	76.1	36.5	75.4	%
$\eta_{fuel,net}$	34.5	68.1	34.9	73.8	%
α_{gross}	-	1.13	-	0.85	-
α_{net}	-	0.90	-	0.81	-

Comparing these four concepts it becomes clear, that all concepts have about the same net electrical efficiency, though the gross electrical efficiency of the gas turbine based concepts is about 6 % higher than the one of the gas engine based ones. Furthermore, it is interesting to see, that power plants operating in CHP-mode can achieve fuel utilisations of about 70 %, which represents an increase of about 35 % compared to plants for pure power production. However, this additional heat production lowers the electrical efficiency of the plants only by one to two percentage points.

5.3.4 Concept III

The basic outline of concept III differs from afore mentioned concept II in the applied gas cleaning. The same dryer and gasifier are used; therefore, the description focuses mainly on the differences in the gas cleaning.

Concept III-gt

The raw product gas leaves the gasifier with 860 °C, and it is firstly dedusted by a cyclone. After that, the product gas is partially combusted adding air and enters the catalytic tar cracker with 900 °C. The catalytic cracker converts tars into stable gaseous compounds. The tar-free gas is cooled in an evaporator and in the air preheater of the gasifier to 190 °C. The cooled gas is dedusted using a fabric filter and cooled to 45 °C by an air cooler.

The clean product gas is compressed in a multi-stage compressor with intermediate cooling, before being combusted in a gas turbine. The flue gas leaves the gas turbine at about 520 °C and produces steam in a waste heat recovery system. After the preheater the flue gas has a temperature of about 190 °C, which is sufficient to dry the wet feedstock. To reduce the dryer inlet temperature, the dryer is operated in recirculation mode. The flue gas after the dryer leaves the stack at about 120 °C. The produced steam is converted in a two-stage steam cycle to electricity. Fig. 5-24 shows the process flow diagram of this concept, which is similar to the ARBRE plant. The main process data are given in Table 5-6.

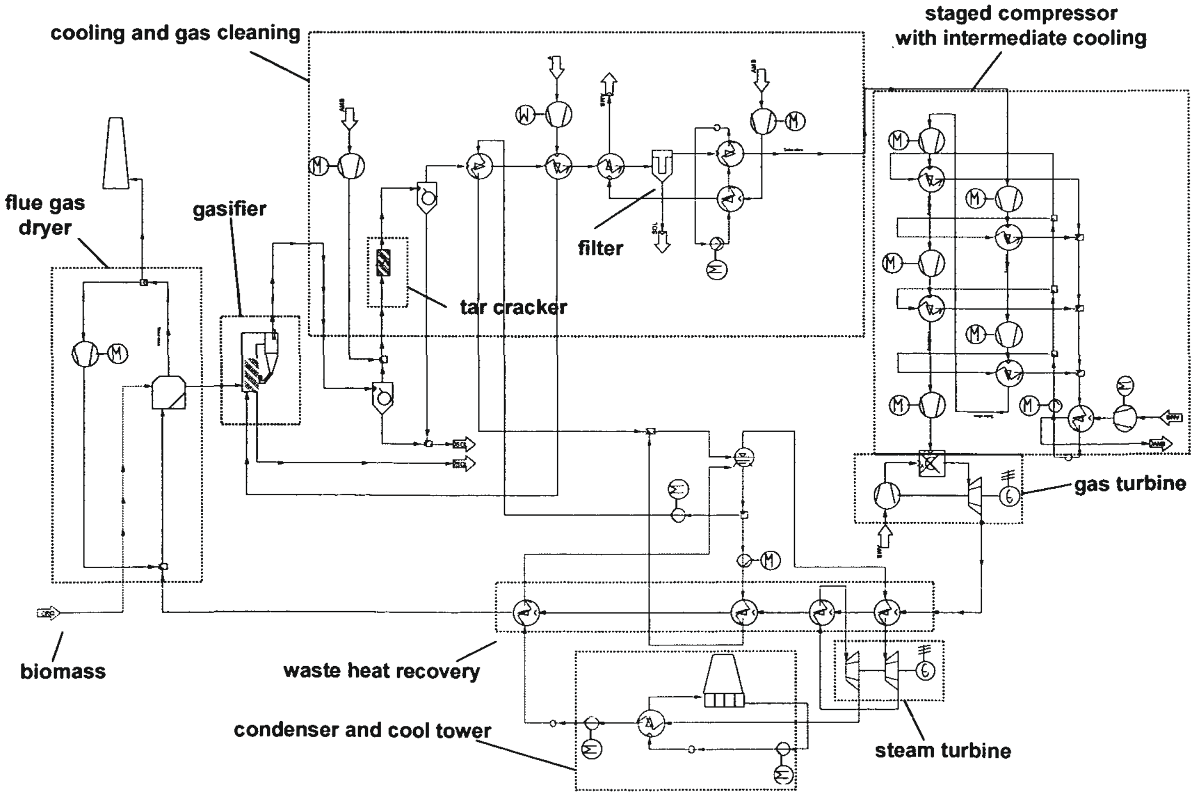


Fig. 5-24: Flow chart of concept III-gt with integrated biomass drying with flue gas

Concept III-ge

Concept III-ge uses a gas turbine instead of gas engines, hence no compressor is needed. Fig. 5-25 shows the flow diagram of the adapted process using nine gas engines instead of one gas turbine. The main process data are given in Table 5-6.

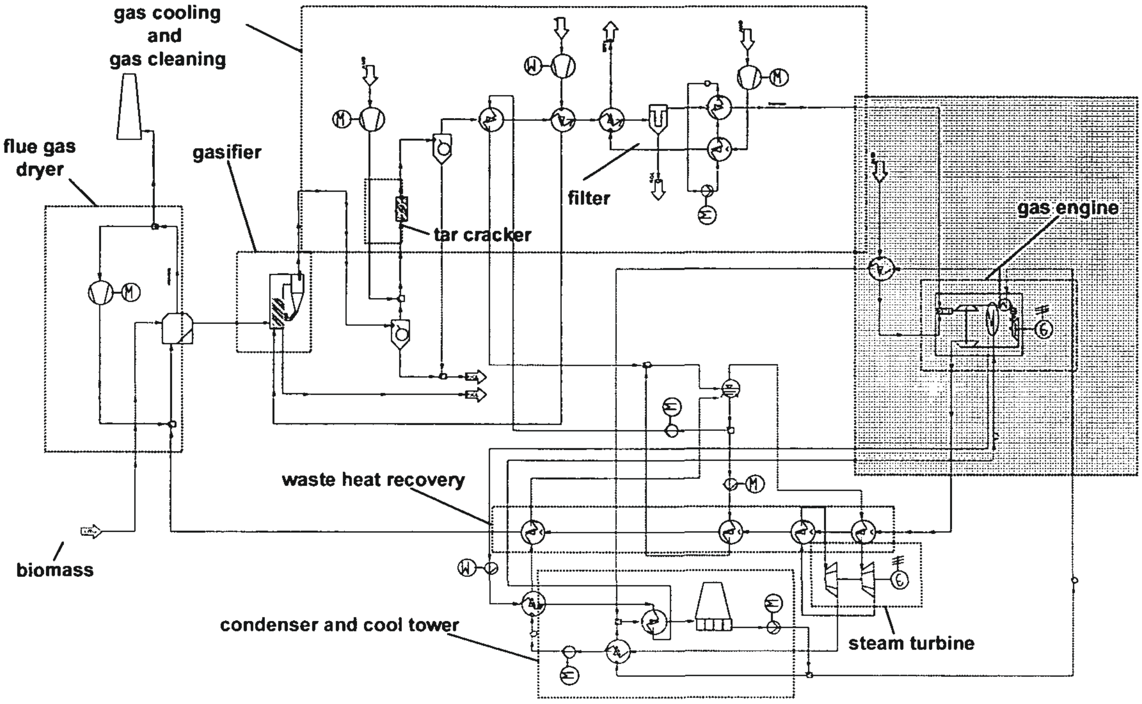


Fig. 5-25: Flow diagram of the IGCC process using a gas engine (grey area marks the difference to Fig. 5-24)

Concept III-gt-dh, concept III-ge-dh

To operate these two concepts in combined heat and power mode the same modifications are done as already shown in Fig. 5-23. The main process data of these four concepts are given in Table 5-6.

Table 5-6: Overview of the main process data

powers	concept III-gt	concept III-gt-dh	concept III-ge	concept III-ge-dh	
fuel power	58.62	63.25	54.74	59.60	MW
chemical power product gas	42.72	46.07	39.87	43.41	MW
district heat	-	23.69	-	25.64	MW
electric gross power	26.38	26.86	20.76	20.88	MW
own consumption	6375	6861	761	881	kW
electric net power	20.00	20.00	20.00	20.00	MW
efficiencies					
$\eta_{el,gross}$	45.0	42.5	37.9	35.0	%
$\eta_{el,net}$	34.1	31.6	36.5	33.6	%
$\eta_{Q,dh}$	-	37.4	-	43.0	%
$\eta_{chem,plant}$	72.9	72.8	72.8	72.8	%
$\eta_{fuel,gross}$	45.0	79.9	37.9	78.1	%
$\eta_{fuel,net}$	34.1	69.1	36.5	76.6	%
α_{gross}	-	1.13	-	0.81	-
α_{net}	-	0.84	-	0.78	-

Comparing the different concepts it can be seen that the turbine based concepts achieve in this arrangement lower net electric efficiencies than the gas engine based ones. This can be explained by the fact that the product gas volume flow is increased by the partial combustion before the catalytic cracker and hence the compression power before the gas utilisation in the gas turbine is increased. In this arrangement the difference in the net electric efficiency between CHP-mode and power production is one percentage higher than in concepts II. This can be explained by the fact that due to the partial combustion before the catalytic cracker the chemical efficiency of the product gas is lowered and converted into heat. This heat is used in the steam cycle, which shows a strong dependence in electrical efficiency if operated in back-pressure or condensed mode.

5.3.5 Concept IV

Concept IV differs in the gas cleaning technology from concept III. In this concept a combination of a precoated fabric filter and a solvent scrubber is used for dust and tar removal.
The raw product gas leaves the gasifier with 860 °C, is cooled in an evaporator and further in an air preheater to 180 °C. The raw product gas is cleaned in a precoated fabric filter from dust and partly from tars. The final tar removal is done in a solvent scrubber using oil as scrubbing liquid. The loaded oil as well as the dust from the filter is fed to a combustor, where the hot flue gases are used in the waste heat recovery.

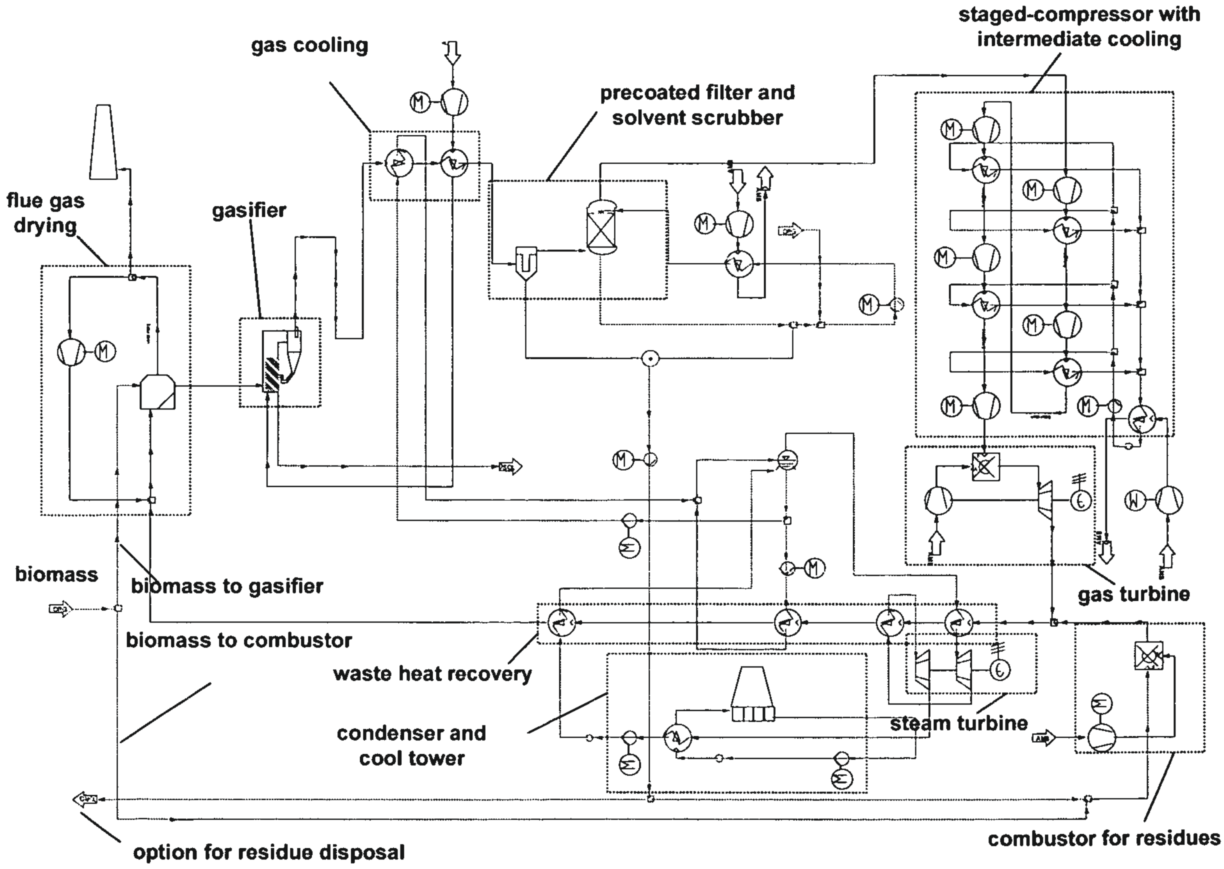


Fig. 5-26: Flow chart of concept IV-gt

The clean product gas with a temperature of 45 °C is compressed in a multi-stage compressor with intermediate cooling, before being combusted in a gas turbine. The flue gas after the gas turbine has a temperature of about 520 °C, is mixed with the hot flue gases of the biomass combustor and is used to produce steam in a waste heat recovery system. After the preheater the flue gas has a temperature of about 190 °C, which is sufficient to dry the wet feedstock. To reduce the dryer inlet temperature, the dryer is operated in recirculation mode. The flue gas after the dryer leaves the stack at about 120 °C. The produced steam is converted in a two-stage steam cycle to electricity. Fig. 5-26 shows the process flow diagram, the main process data of this concept are given in Table 5-7.

Table 5-7: Overview of the main process data

powers		
fuel power	58.75	MW
chemical power product gas	42.69	MW
district heat	-	MW
electric gross power	24.35	MW
own consumption	4425	kW
electric net power	20.00	MW
efficiencies		
$\eta_{el,gross}$	41.4	%
$\eta_{el,net}$	33.9	%
$\eta_{Q,dh}$	-	%
$\eta_{chem,plant}$	72.7	%
$\eta_{fuel,gross}$	41.4	%
$\eta_{fuel,net}$	33.9	%
α_{gross}	-	-
α_{net}	-	-

5.3.6 Concept V

Concept V is an adaptation of concept IV, utilising the same gas cleaning technology. Instead of an autothermal fluidised bed gasifier an allothermal steam gasifier is used for gasification.

Concept V-gt

In concept V-gt the raw product gas leaves the gasifier at 860 °C, is first cooled in a reheater and a preheater before being filtered in a precoated filter and a solvent scrubber like in concept IV. Since the allothermal steam gasifier has a combustion zone already integrated, no external combustor is necessary. The residues from the gas cleaning can be fed back to the combustion zone of the gasifier, where they are thermally destructed.

The cleaned product gas is compresses in a multi staged compressor and fed to a gas turbine (Fig. 5-27). The flue gas from the combustion section of the gasifier is firstly used for steam production for the gasifier and than fed together with the flue gas from the gas turbine to the waste heat recovery. A detailed description of the applied gasification and gas cleaning technology can be found in [94]. The main process data of this concept are given in Table 5-8.

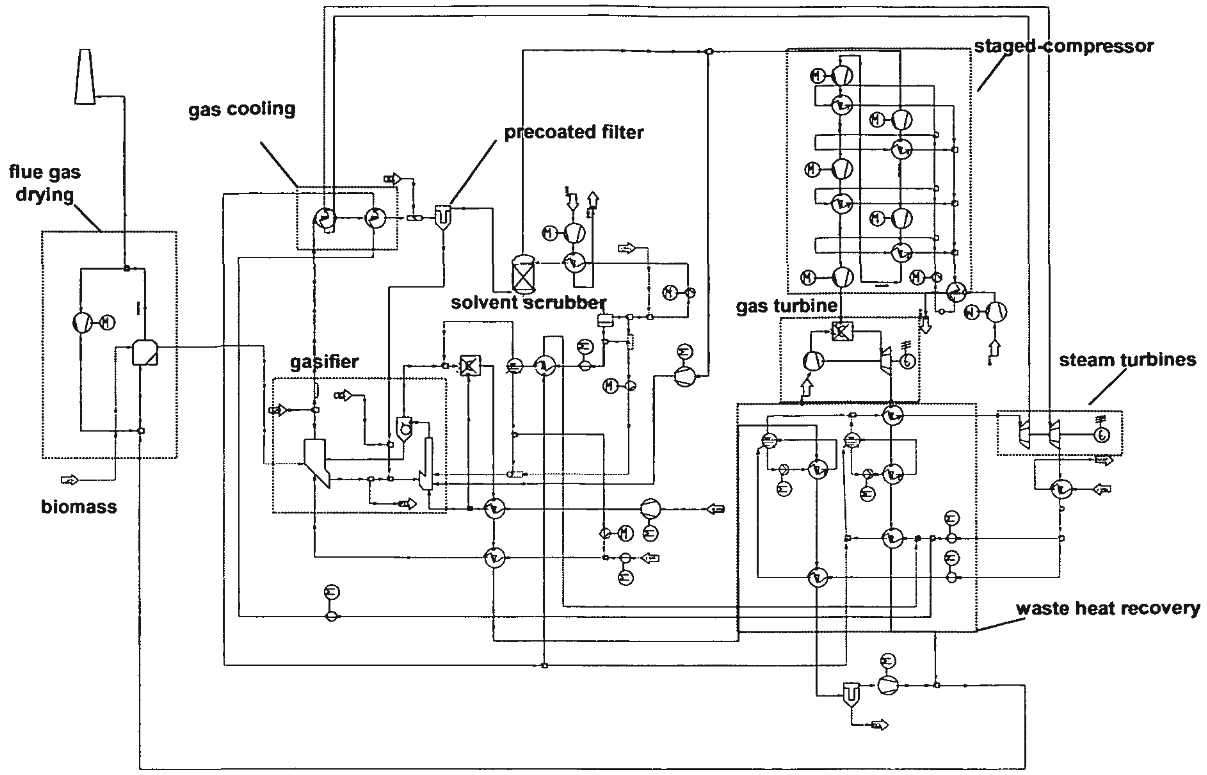


Fig. 5-27: Flow chart of concept V-gt with integrated drying using flue gas

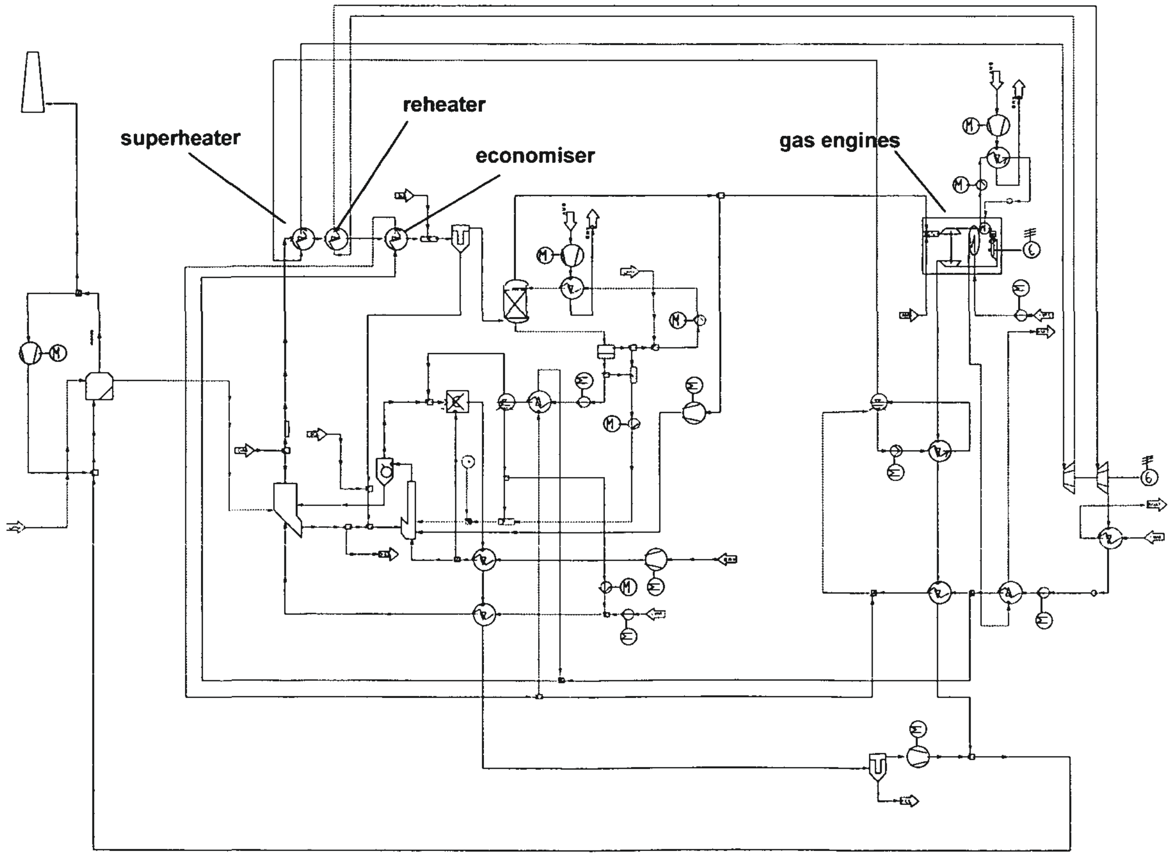


Fig. 5-28: Flow chart of concept V-ge with integrated drying using flue gas

Concept V-ge

In concept V-ge no compressor is necessary since gas engines are used for gas utilisation shown in Fig. 5-28. Furthermore, this concept differs from the already mentioned one that additionally a superheater is situated in the product gas stream, since the flue gas temperature of the gas engine is too low to achieve the desired steam parameters of 450 °C and 84 bar.

The main process data of this concept are given in Table 5-8.

Table 5-8: Overview of the main process data

powers			
	concept V-gt	concept V-ge	
fuel power	57.25	57.65	MW
chemical power product gas	42.11	42.41	MW
district heat	-	-	MW
electric gross power	22.68	20.53	MW
own consumption	2684	531	kW
electric net power	20.00	20.00	MW
efficiencies			
$\eta_{el,gross}$	39.6	35.6	%
$\eta_{el,net}$	34.9	34.7	%
$\eta_{Q,dh}$	-	-	%
$\eta_{chem,plant}$	73.6	73.6	%
$\eta_{fuel,gross}$	39.6	35.6	%
$\eta_{fuel,net}$	34.9	34.7	%
α_{gross}	-	-	-
α_{net}	-	-	-

Comparing these concepts it can be seen that quite similar net electrical efficiencies can be achieves, which can be explained by the reduction in the own power consumption compared to the autothermal concepts. This is caused by the fact, that the product gas from the allothermal gasification does not contain nitrogen, which accounts for about 50 % of the autothermal product gas composition.

5.3.7 Steam cycle

Additionally, a steam cycle with integrated flue gas drying was modelled for comparison to the gasification concepts. The same outline of the steam process was used as for the combined cycle application of the gasification concepts. The parameters can be found in chapter 5.2.4.

Biomass with 40 wt% water content enters a flue gas dryer, of the same type already described. The water content is reduced to 15 wt% before fed to the combustor. Here the dried biomass is combusted with preheat air from the flue gas after the heat recovery. The hot flue gases are cooled by a reheat, a superheater, an evaporator and a water preheater. The produced steam is utilised in a two stage steam cycle with 84 / 18 bar. For power only production the low pressure turbine is operated in condensed mode at 80 mbar, if district heat is produced as well the turbine is operated in back pressure mode.

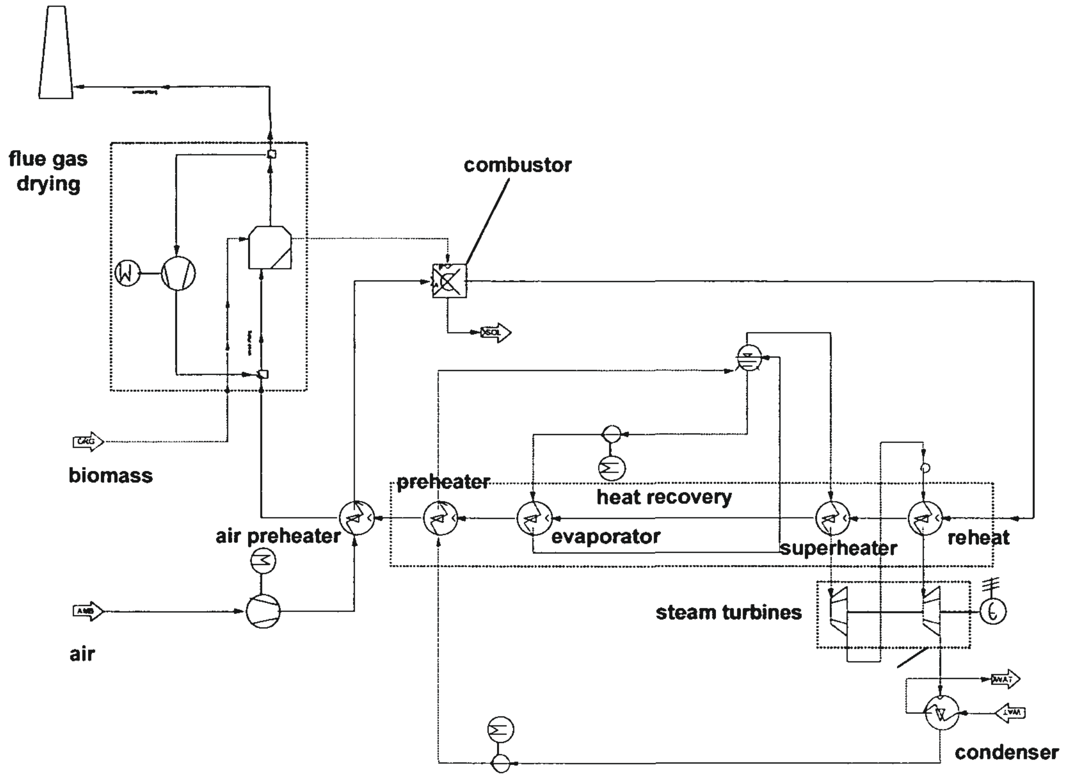


Fig. 5-29: Flow chart of steam cycle with integrated drying using flue gas

The main process data of this concept are given in Table 5-9.

Table 5-9: Overview of the main process data

powers			
	steam cycle	steam cycle-dh	
fuel power	72.13	81.18	MW
district heat	-	49.90	MW
electric gross power	21.00	21.15	MW
own consumption	999	1150	kW
electric net power	20.00	20.00	MW
efficiencies			
$\eta_{el,gross}$	29.1	26.1	%
$\eta_{el,net}$	27.7	24.6	%
$\eta_{Q,dh}$	-	61.5	%
$\eta_{fuel,gross}$	29.1	87.5	%
$\eta_{fuel,net}$	27.7	86.1	%
α_{gross}	-	0.42	-
α_{net}	-	0.40	-

5.4 *Concept comparison*

In the following the different concepts are compared according to efficiencies defined in chapter 5.1. First, the different gas cleaning and gas utilisation technologies as well as their combination are assessed by an exergetic analysis. Finally, the overall systems are analysed and compared among each other by the defined efficiencies.

5.4.1 Exergetic analysis of the gas cleaning

In the following different gas cleaning technologies of the described concepts are compared by their exergetic performance. Fig. 5-30 gives an overview of these concepts. Three concepts based on atmospheric gasification are evaluated, with different gas cleaning technologies using a combination of precoated cloth filter - a solvent scrubber, quench - wet electrostatic precipitator and catalytic cracker – cloth filter. For gas utilisation in all these concepts the gas has to be compressed before combustion in a gas turbine. The fourth concept uses pressurised gasification, which requires only hot gas particle cleaning before gas utilisation.

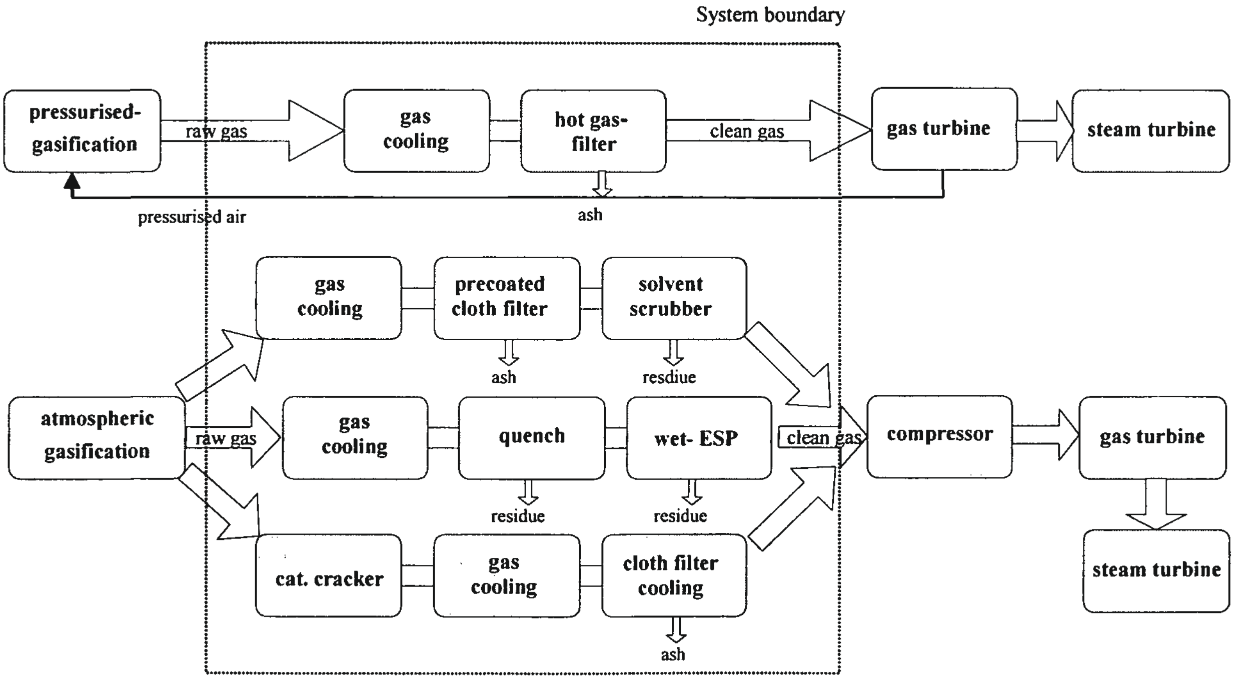


Fig. 5-30: Overview of the evaluated concepts [107]

The result of this evaluation is shown in Fig. 5-31 using Sankey-diagrams. To compare these gas cleaning concepts in each case the raw product gas is taken as basis and therefore considered as 100 %. In the gas cleaning, this raw product gas stream splits up into clean gas, useable exergy streams, losses and residue streams. Aim of the gas cleaning is to preserve as much exergy as possible in the clean product gas. The production of useable exergy stream, mostly heat, is acceptable, but these streams cannot be converted into electricity at the same efficiency as product gas. Losses stand for exergetic losses due to heat losses or to exergetic losses in heat exchangers. However, they do not cause any follow up costs like for disposal. Residues represent exergetic streams like ashes or tar loaded water streams, which cause exergetic losses from the gas cleaning as well as cost for their treatment or disposal.

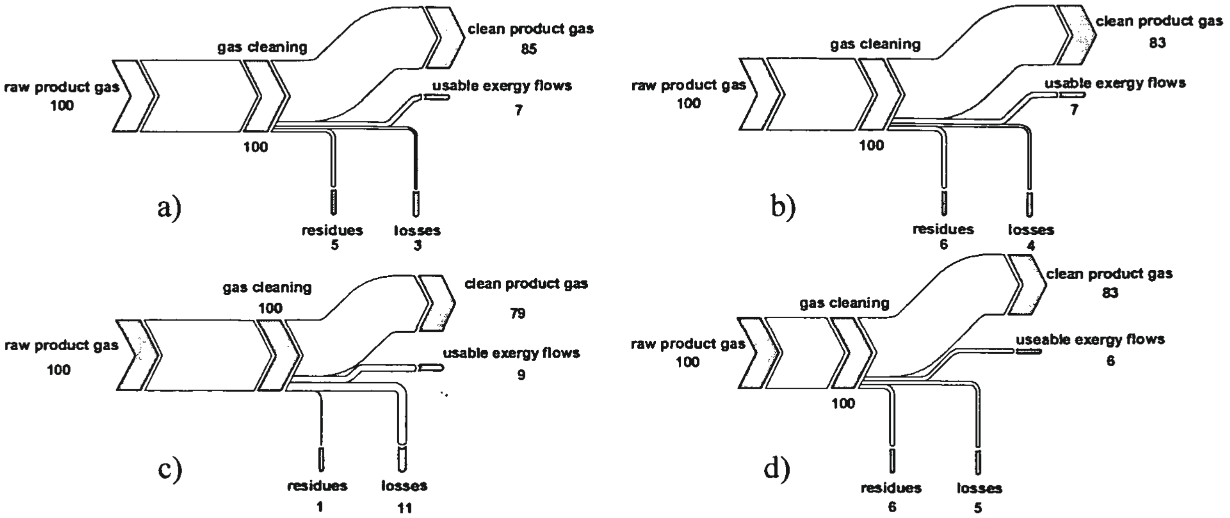


Fig. 5-31: Sankey-Diagrams of the different gas cleaning concepts: a) hot has filter; b) pre-coated cloth filter – solvent scrubber; c) catalytic cracker – cloth filter; d) quench – wet-ESP [107]

It can be clearly seen by looking at the Sankey-diagrams that up to 21 % of the exergy in the raw product gas is lost during the gas cleaning. The highest exergetic efficiency can be achieved by the hot gas cleaning (pressurised gasification), where 85 % of the exergy from the raw product gas can be obtained. Furthermore, 7 % of the raw gas exergy can be converted into usable exergy streams (steam). Together this accounts for an overall exergetic efficiency of 92 %. Atmospheric based gasification systems, which require more stringent gas cleaning, achieve exergetic efficiencies, which are 2 % lower in the best case, using a solvent scrubber (b) or a wet electrostatic precipitator (d), and even lower if a catalytic cracker is used (c). The concept of the catalytic cracker has the lowest residue streams (about 1 % of the exergy of the raw product gas), since tars are converted into stabile gaseous compounds. However, for a complete conversion of tars, as already mentioned, high temperatures of about 900 °C are necessary. This requires the raw product gas to be heated up, which is done in most cases by partial combustion of the product gas adding an oxidising agent, in most cases air. Thereby, the heating value of the gas is reduced, since it is partly combusted and diluted by combustion products. However, the useable exergy flows are increased, since more heat is available. Furthermore, since combustion is an irreversible process, the exergy losses increase.

Fig. 5-32 shows the comparison of the overall exergetic efficiencies of the different gas cleaning concepts. The dark grey bars account for the exergy of the clean product gas, the light grey bars on the top for the usable exergy flows, like produced steam. The sum of both bars represent the exergetic efficiency of the gas cleaning.

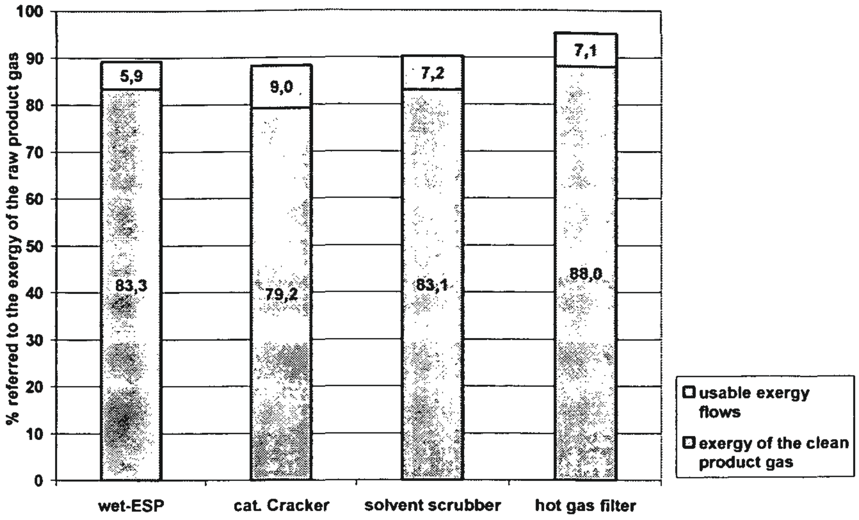


Fig. 5-32: Exergetic efficiencies of different gas cleaning technologies [107]

Fig. 5-33 shows the losses and the residues of the different gas cleaning technologies. The cracker has the highest non-usable exergy flows (sum of losses and residues), however, the share of the residues is very low. Since residues can account for high disposal costs, it can be useful in some cases to take higher exergy losses into account to avoid high amounts of residues. The technologies wet-ESP and solvent scrubber show equal values in terms of residues, however, in total the scrubber shows better results. The technology with the lowest losses is hot gas cleaning in combination with pressurised gasification; though even in this case higher amounts of residues are produced than with the catalytic cracker.

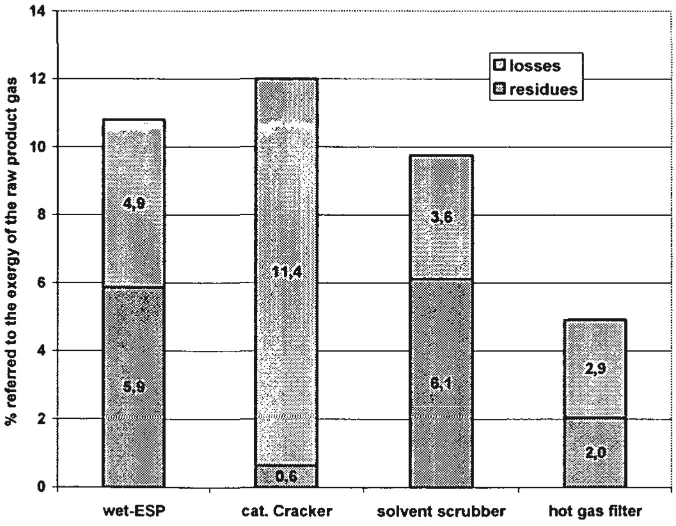


Fig. 5-33: Exergetic losses and residues from the different gas cleaning technologies [107]

5.4.2 Exergetic analysis of the gas cleaning and gas utilisation

In the following the suitability of coupling different gas cleaning technologies with different gas utilisation technologies will be investigated. Therefore, the system boundary has to be extended onto the gas utilisation. This can be done in a straight forward approach for the atmospheric based systems with gas turbine or gas engine for gas utilisation. However, for pressurised systems, like the one which was evaluated, compressed air from the gas turbine is used as gasification agent in the gasifier, which is outside the system boundary. Therefore, a careful analysis of internal and external streams is necessary.

Input streams are the raw product gas from the gasifier, electricity (for a possible compression) and air for combustion. Output streams are the produced electricity, useable exergy flows, like the heat in the flue gas after the combustion, losses and residues. An overview can be seen in Fig. 5-34.

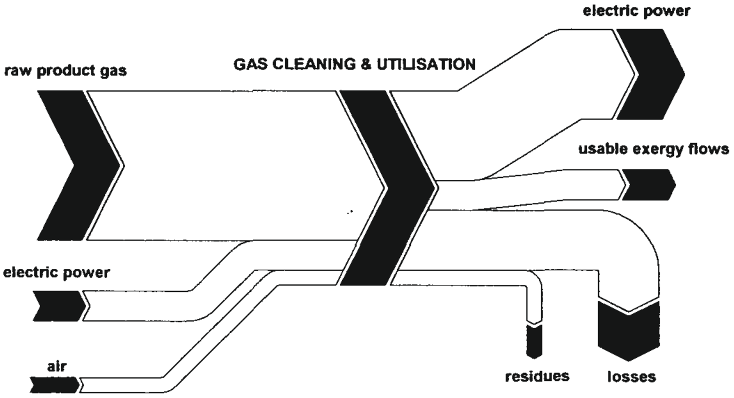


Fig. 5-34: Diagram of the balanced streams for the gas cleaning and utilisation

Fig. 5-35 summarises the net exergetic efficiencies for power and usable exergetic flows for different gas cleaning and utilisation technologies.

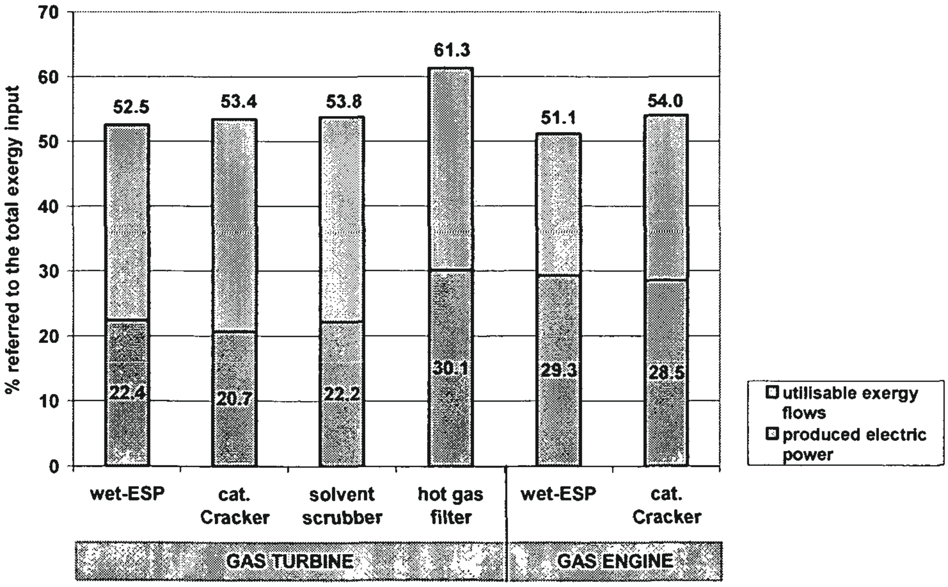


Fig. 5-35: Net exergetic efficiencies for power and useable exergetic flows [108]

Only little differences can be seen between the technologies wet-electric precipitator and solvent scrubber in terms of the electric exergetic efficiency if a gas turbine is used as gas utilisation technology. The gas cleaning technology catalytic cracker coupled with a gas turbine achieves the lowest electric exergetic efficiency. A substantial increase in efficiency can only be made if pressurised gasification is used in combination with a hot gas filter and a gas turbine.

Furthermore, it can be seen that using gas engines instead of gas turbines as gas utilisation technologies, higher exergetic efficiencies can be achieved using the same gas cleaning technology, which are close to the efficiencies achievable using a pressurised concept.

5.4.3 Analysis of the overall systems

In the following the overall systems will be evaluated and compared among each other with the efficiencies defined in chapter 5.1.

Fig. 5-36 shows the net and gross electrical efficiencies of the different gasification concepts and of the conventional steam cycle. The net electrical efficiencies are marked grey, the gross electrical efficiencies are only indicated, since power plants have to cover their own consumption themselves.

It can be clearly seen that concept I using a pressurised system can obtain the highest electrical efficiencies. In this concept only the gasification air has to be pressurised and not the whole product gas after the gasifier for gas utilisation. Furthermore, tars can be combusted in the turbine as well. This concept has also the lowest own power consumption of the evaluated systems.

Concept III-ge (catalytic gas cleaning – gas engines) achieves the highest net electrical efficiency of the atmospheric operated concepts and shows the lowest own consumption. The other concepts for power production have about the same net electrical efficiencies, however, the gross efficiencies differ significantly.

Comparing concept-IV-gt and V-gt, which use the same gas cleaning and gas utilisation technologies, it can be seen that by steam gasification the power consumption of the plant can be reduced quite significantly. Additionally slightly higher net electrical efficiencies are obtained. The trend of higher net electrical efficiencies using gas engines instead of gas turbines, if the same gas cleaning is used, cannot be seen with the allothermal steam gasification (Concept-V-gt and V-ge). This can be explained by the fact that the own electrical consumption of the plant is significantly lower due to the lack of nitrogen in the product gas, resulting in a lower volume flow compared to the concepts II-gt, III-gt, IV-gt.

Concept II-gt differs from concept II-ge only in the applied gas utilisation technology. Since the gas turbine requires high power inputs for compression (concept II-gt) the advantages of a higher gross efficiency is reduced. The same applies for concept III-gt, which would achieve the highest gross electrical efficiency. However, this efficiency is achieved by an increase in the volume flow through the partial combustion of the product gas and the catalytic tar cracker. Therefore, a higher gas flow needs to be compressed onto the turbine pressure, which accounts for a very high own consumption.

Compared to the atmospheric gasification concepts, the steam cycle can achieve a net electrical efficiency, which is about 7 % lower, if only power is produced.

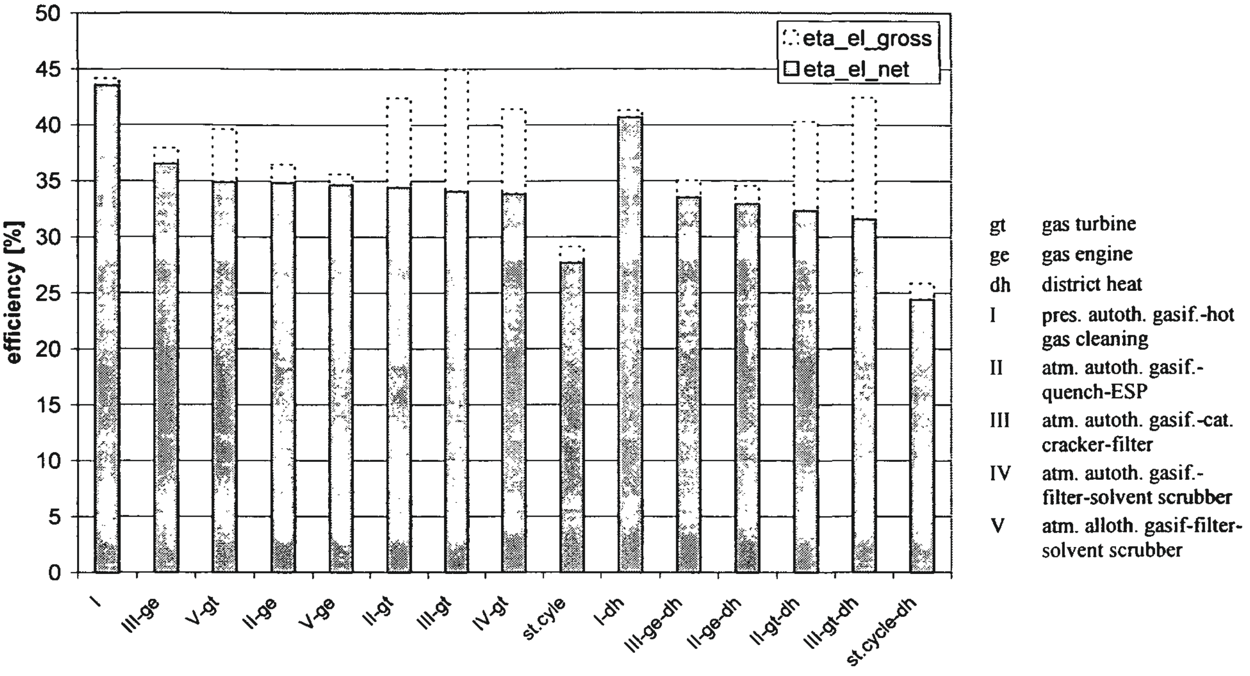


Fig. 5-36: Comparison of the gross and net electric efficiencies of the different concepts

The concepts marked with the extension "dh" on the right hand side of Fig. 5-36 are operated in combined heat and power mode. Again, using pressurised operation the highest net electrical efficiencies can be achieved with the lowest own consumptions. Concepts III-ge-dh and II-ge-dh, both using gas engines, achieve slightly higher electrical efficiencies than turbine based concepts II-gt-dh and III-gt-dh. The difference resulting from the gas cleaning is small. Again, the steam cycle operated in back-pressure mode achieves the lowest net electrical efficiency at about 25 % if operated in CHP-mode. Furthermore, the steam process with district heat production shows a stronger decline in the net electrical efficiency (about 4 %) as the gasification processes (about 2 %).

Fig. 5-37 shows the comparison of different chemical plant efficiencies. The highest chemical efficiency can be obtained in concept I, since tars can be combusted too. Using a wet electrostatic precipitator for gas cleaning, like in concepts II, efficiencies around 75 % can be achieved. This efficiency drops a little bit, using an oil scrubber (concept IV&V) since the loaded oil is used as combustion fuel and has therefore to be included in the fuel power.

By using a catalytic cracker the heating value of the product gas is reduced and therefore also the chemical efficiency of the system, which can be seen in concepts III.

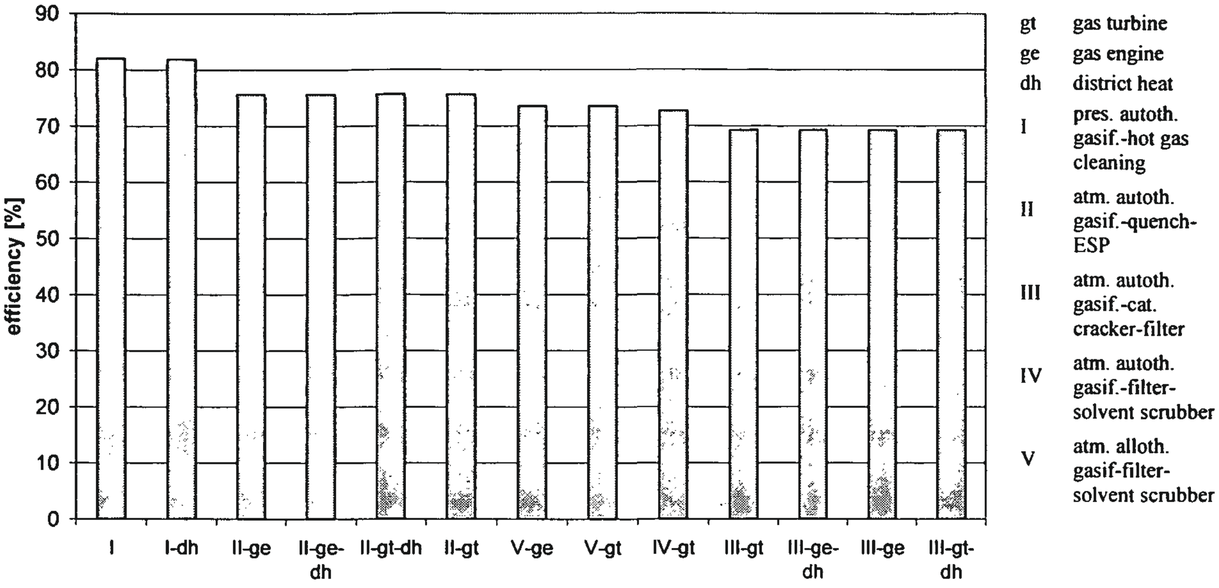


Fig. 5-37: Comparison of the chemical efficiencies of the different concepts

Fig. 5-38 gives a comparisons of the different thermal efficiencies of the different combined heat and power concepts. It can be seen that the highest thermal efficiencies can be achieved by using a steam cycle. The highest thermal efficiencies among the gasification concepts can be achieved by using gas engines (concepts marked with "ge"). Furthermore, if a catalytic converter is used for gas cleaning the additional heat accounts for a better thermal efficiency as if the heat is lost by quenching, like in concept II-ge. In general, turbine based concepts I-dh, III-gt-dh, II-gt-dh achieve lower thermal efficiencies, since the cooling water of the gas engines is used for district heat only.

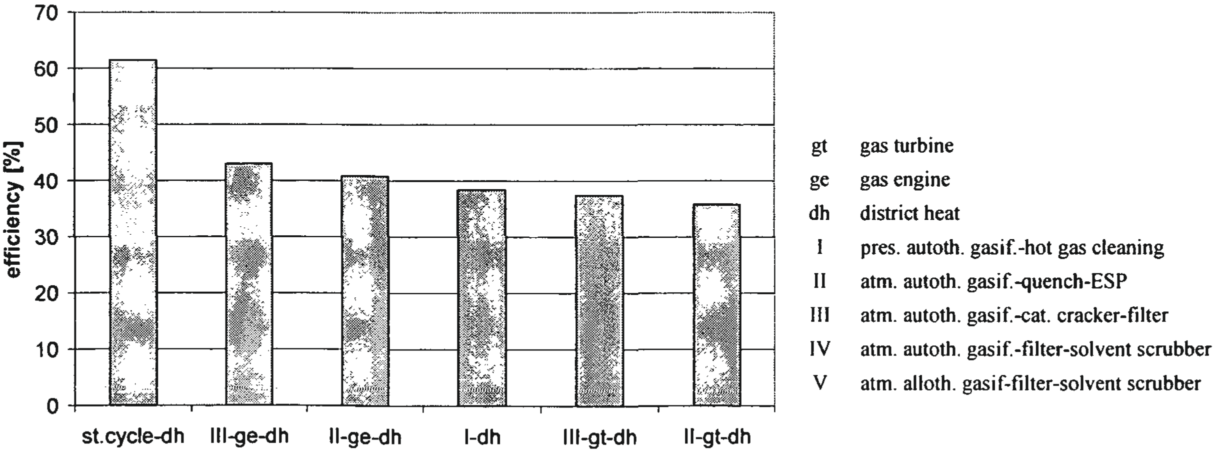


Fig. 5-38: Comparison of the thermal efficiencies of the different concepts

If the electrical and the thermal efficiencies are added, the fuel utilisation is obtained.

An overview of the different efficiencies can be found in Fig. 5-39. The steam process operated in CHP-mode achieves the highest efficiency of nearly 90 %, however, with a poor power-to-heat ratio. Gasification concepts operating in combined heat and power mode can utilise the fuel up to 80 %, nearly double the value that can be obtained using pure power production. The highest grades can be achieved by using pressurised gasification, followed by the catalytic cracking and the wet-ESP in combination with a gas engine. The net fuel utilisation of afore mentioned concepts using a gas turbine are similar, however, differ greatly on their gross basis.

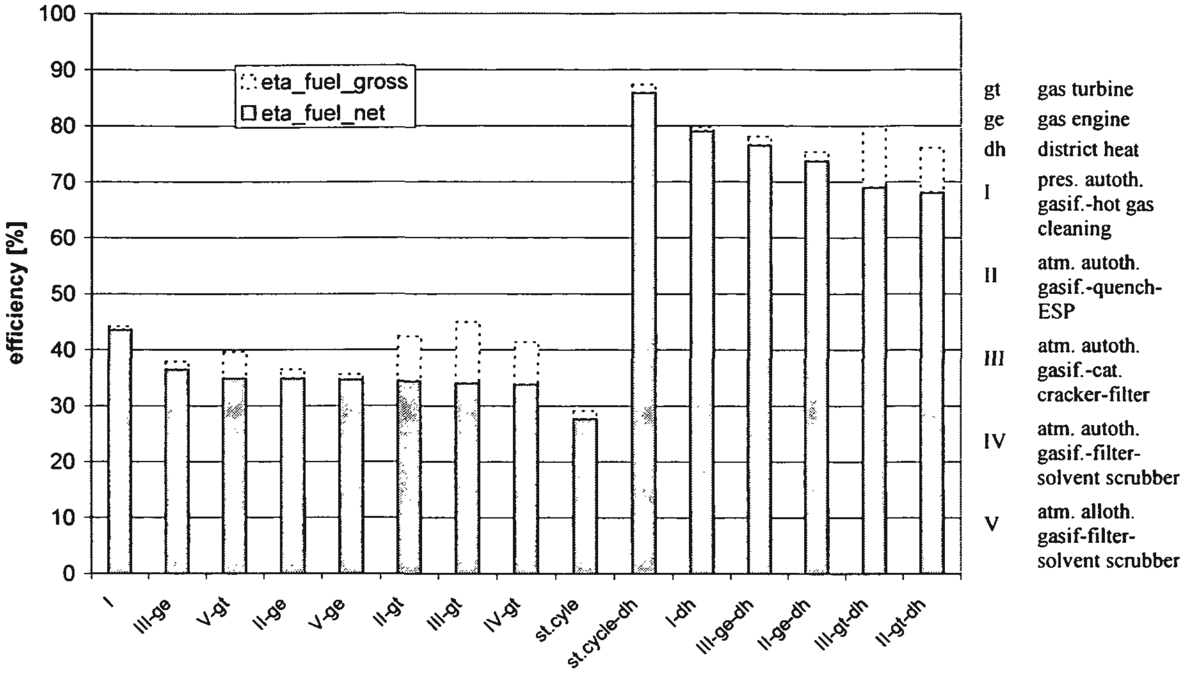


Fig. 5-39: Comparison of the gross and net fuel utilisation efficiencies of the different concepts

Finally, the power-to-heat ratio (alpha-values) of the different combined heat and power concepts are compared in Fig. 5-40. The steam cycle achieves only half the alpha value of the gasification technologies. Great differences can be found comparing the gross and net alpha values of the different concepts, depending on the gross and net power outputs. The highest ratios can be achieves using gas turbines for gas utilisation, wherefrom the pressurised operation performs best. Second best values can be achieved by using a wet electrostatic precipitator (concept II-a-dh), mainly since not all heat can be utilised from the product gas in the quench. The remaining three concepts achieve equal power to heat ratios of about 0.8.

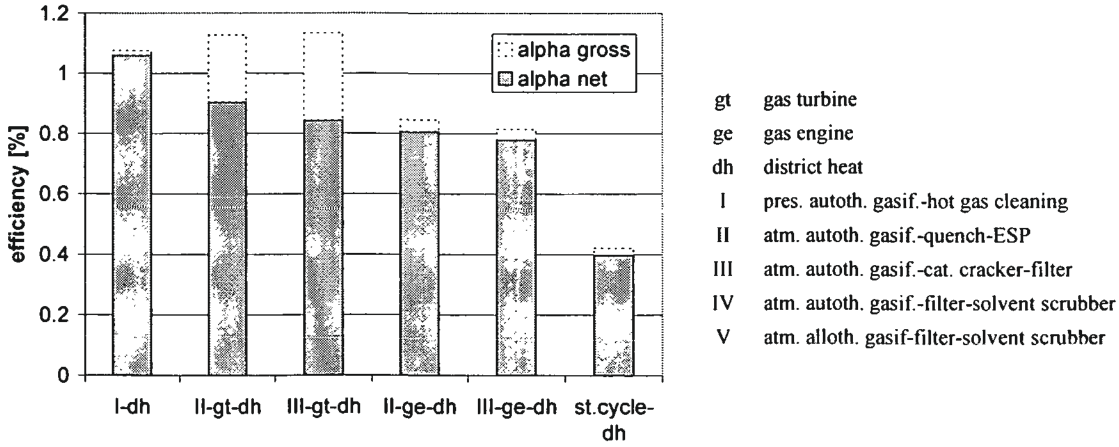


Fig. 5-40: Comparison of the gross and net power to heat ratios (alpha values) of the different concepts

5.5 Conclusion

Using the process simulation tool IPSEpro the identified concepts could be analysed according to their mass and energy balances. Furthermore, different system aspects, like the drying, the gas cleaning and the gas utilisation technologies could be investigated.

By analysing the influence of the biomass water content a significant effect to the electrical efficiency of the biomass based IGCC process could be identified. Improvements of 2.5 % in electrical efficiency referred to the fuel power can be achieved if wood with a water content of 15 % instead of 40 % is used. The usage of low temperature heat from the flue gas is favourable for the drying process. This gives the significant advantage of a low exergetic input into the dryer as well as low organic emissions. Furthermore, the waste water formation is avoided.

The exergetic analysis of the gas cleaning has revealed hot gas cleaning in a pressurised system as the most favourable option. Using atmospheric gasification the wet electrostatic precipitator and the solvent scrubber are favourable in terms of exergetic efficiencies and commercial availability. Catalytical cracking achieves lower efficiencies, however, produces the lowest residues.

From the exergetic point of view pressurised gasification in combination with a gas turbine and atmospheric gasification with gas engines achieve considerable higher exergetic efficiencies than atmospheric systems using a gas turbine.

Summarising the energetic comparison of the analysed concepts, it can be concluded that pressurised gasification with a hot gas cleaning and a gas turbine offers for power and CHP operation the highest achievable electrical efficiencies.

In atmospheric mode gas engines can achieve higher electrical efficiencies than gas turbines. This can be explained by the necessary compression before gas turbine usage. The different concepts do not differ much in their net electric efficiencies, however, their own consumption varies strongly. An atmospheric gasification concept for pure power production can achieve about 7 % higher net electric efficiencies compared to a conventional steam cycle. Furthermore, the gasification concepts show a much lower dependence of the electric efficiency if operated in CHP-mode.

From today's point of view, gas cleaning using a wet-ESP and a solvent scrubber is favourable. Catalytic tar cracking is still not state of the art and its robustness is still unclear.

In terms of the fuel utilisation a CHP operation of the gasification concepts is favourable since up to 80 % of the energy content of the fuel can be converted into usable products. If only power is produced this value ranges from 33 % to 40 %. The steam process can achieve higher values (88 %), however, with a poor power-to heat ration.

Finally it can be concluded that all gasification concepts operated in CHP mode achieve power to heat rations between 0.8 and 1.0, whereas the steam cycle yields values of about 0.4.

From the technical point of view, the most promising concept is the one of pressurised gasification with a gas turbine (concept I), since the highest net electrical efficiencies can be achieved. To identify a favourable concept among the atmospheric gasification plants is difficult, since the net electric efficiencies are more or less equal. However, since the catalytic gas cleaning (concepts: III-ge, III-gt) does not give any significant advantages and is still not state of the art (see chapter 4) its application is doubtful. Using the quench with a wet-ESP combines a fail-safe proven gas cleaning technology with comparable net electric efficiencies.

Among the CHP-concepts the pressurised gasification offers the highest net electric efficiencies (concept I-dh). The atmospheric gasification concepts do not differ much in the net electrical efficiencies, however, concept II-ge-dh and concept II-gt-de seem favourable, since the use a state of the art technology.

The following economic assessment of these concepts will help to refine this analysis.

6 Economic assessment

So far, the technical analysis yielded promising concepts for future gasification plants, but it is still unclear if gasification technologies can compete economically with state of the art combustion based technologies. Therefore, the electricity production cost of the modelled IGCC-concepts are calculated and compared to the electricity production costs of a conventional steam cycle. The evaluation is split into concepts, designed for pure power production and into concepts for combined heat and power production. Furthermore, an analysis of existing CHP-plants was carried out to determine the current economic status of biomass based plants and calculated today's electricity production costs. These costs are finally compared to the electricity production costs of the optimised gasification concepts, to determine the existing optimisation potential.

6.1 Economic assessment of modelled concepts

In this chapter the technical assessed process will be evaluated economically by calculating the electricity production costs. An evaluation basis has been defined to obtain comparable results. The investment costs of the different concepts have been estimated. The necessary operating resources have been analysed and estimated for the different concepts. Finally, the electricity production costs are calculated for plants designed for pure power production and for CHP-operation.

6.1.1 Evaluation basis

To evaluate the simulated concepts economically, the interest rate was calculated on a cash-flow basis, assuming an utilisation period of the plants of 13 years. This is in accordance with the decree of Austrian government from December 2002, which fixes the electricity feed in tariffs for a period of 13 years [110]. The rate of interest was chosen in conformity with other techno-economical assessments at 6 % [7], [111].

The evaluation was based on the net electric efficiency of the plants, since power plants must cover their own consumption themselves. The inflation rate was fixed at 2 %. Commissioning of the plant is assumed in the year 2006, with the same interest rate (6 %) during the construction. The plants for pure power production are designed for 7,600 full load operation hours a year without district heat production. For plants operating in CHP-mode the full load hours are assumed lower, since heat has to be sold throughout the year. In reality, electricity production is not strictly linked to the heat demand, because it can be economically advantageous to operate a plant during summertime even if the produced heat cannot be sold. Therefore, 6000 full load operation hours/a are assumed for electricity production, whereas only 4000 hours/a are assumed for heat production for CHP-plants. The district heat feed in tariffs are fixed at 20 €/MWh and defined at the intersection of the CHP-plant and the district heating grid.

Six start-up/shut-down procedures are about to occur during one year. Forest wood with a price of 14 €/MWh and the feedstock “fuel mix” with 1.8 €/MWh are evaluated as fuel.

Costs for operating resources include lime stone with 70 €/t, char coal with 220 €/t, RME with 500 €/t, inert gas with 1000 €/t and supplementary fuel (oil) with 0.4 €/l.

For IGCC plants of the considered size, a staff of 18 people is necessary at costs of 40,000 € per year and person. The maintenance costs are assumed to be 2 % of the investment costs, insurance costs to be 1 % of the investment costs per year and additional costs (tax, inspection, etc.) to be 0.75 % of the investment costs per year.

Costs for residues include grate ash with 30 €/t, fly ash 50 €/t and waste water 20 €/t. The construction area of the plant is assumed to 3 hectares. The final investment costs are increased by the percentage of unexpected costs, which accounts for possible risks during the erection of the plant. This percentage is chosen in that case to 8 % of the final investment costs.

An overview of the conditions for pure power and CHP-operation used in this economic evaluation can be found in Table 6-1.

Table 6-1: Evaluation basis

period of amortisation	13	a
interest rates	6	% p.a.
inflation rate	2	%
commissioning in year	2006	
interest rate during erection	6	%
full load operation		
power production	7,600	h/a
CHP-operation: power	6,000	h/a
CHP-operation: heat	4,000	h/a
CHP-operation: heat sales	20	€/MWh
shut downs	6	per year
fuel costs:		
forest wood	14	€/MWh
fuel mix	1.8	€/MWh
operating resources:		
limestone	70	€/t
char coal	220	€/t
supplementary fuel (oil)	0.40	€/l
inert gas	1,000	€/t
RME	500	€/t
staff	18	people
staff costs	40,000	€/a
maintenance costs	2	% invest cost
insurance	1	% invest cost/a
additional costs (tax,..)	0.75	% invest cost/a
residues:		
grate ash	30	€/t
fly ash	50	€/t
waste water	20	€/t
construction area	3	hectare
unexpected costs	8	% invest cost

6.1.2 Investment costs and operating resources

The investment costs include all necessary apparatus, supplementary apparatus, piping, erection, commissioning and documentation (Table 6-2). Concepts operating in CHP-mode need additional equipment, necessary for district heat production. Therefore, 200 000 € are added in that case to the sum of the investment costs. Comparing the investment costs it can be seen that the steam cycle is about 7 million € cheaper than the pressurised gasification concept (concept I). Gas turbine based concepts (extension-gt) have in general lower investment cost than gas engine based concepts (extension-gt). Additionally, the installed gas cleaning has a major impact on the investment costs.

Table 6-2: Investment costs for the different concepts

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

apparatus	investment costs [million €]								
	I	II-gt	II-ge	III-gt	III-ge	IV-gt	V-gt	V-ge	steam cycle
fuel storage, feeding, preparation	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
gasifier, heat exchangers, waste heat recovery, product gas cleaning	22.00	16.50	16.50	21.50	21.50	18.50	22.50	22.50	11.00
gas turbine /engine – generator	8.00	8.00	12.60	8.00	12.60	8.00	7.50	12.60	6.30
flue gas treatment, ash and waste water treatment, (additional firing)	2.20	2.90	2.90	2.90	2.90	2.90	2.90	2.90	7.80
electrical input supply, controlling	6.20	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.20
construction	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80
supplementary systems, building service engineering, office, workshop	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
sum	49.30	44.55	49.15	49.55	54.15	46.55	50.05	55.15	42.20

In Table 6-3 the necessary operating resources are listed for the different concepts. Some values have been estimated from comparable plants, since no data have been available.

Table 6-3: Operating resources for the different concepts

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

operating resources	amount									
	I	I-fuel mix	II-gt	II-ge	III-gt	III-ge	IV-gt	V-gt	V-ge	steam cycle
additional fuel for one start-up (oil) [1000 l]	10		10	10	10	10	10	10	10	10
inert gas [kg/h]	50				50	50	50	50	50	
ammonia water [kg/h]		60								
limestone for gas cleaning [kg/h]		200					200	200	200	
bed material [kg/h]	40	40	40	40	40	40	40	40	40	
water intake [m³/h]			1	1						
char coal [kg/h]		20								
RME [kg/h]							85	85	85	

6.1.3 Electricity production costs

For the period of amortisation (13 years) the yearly costs for fuel, operating resources, staff costs, maintenance, insurance, etc. are calculated. These represent the yearly operating expenditures, which increase per year by the assumed inflation. The investment costs of the plant, costs for land and the percentage for the unexpected costs give the overall project costs. For the economic evaluation, the interest rate during erection has to be added to the overall costs, which are the imputed investment costs.

Finally, the yearly cash-flow is calculated by a cost and revenues analysis, wherefrom the interest rate of the overall project can be obtained. By a variation of the feed in tariff for electricity the interest rate is iteratively calculated until the desired value of 6 % is achieved. These results for the different concepts are given in Fig. 6-1 for pure power production, in Fig. 6-3 for heat and power production.

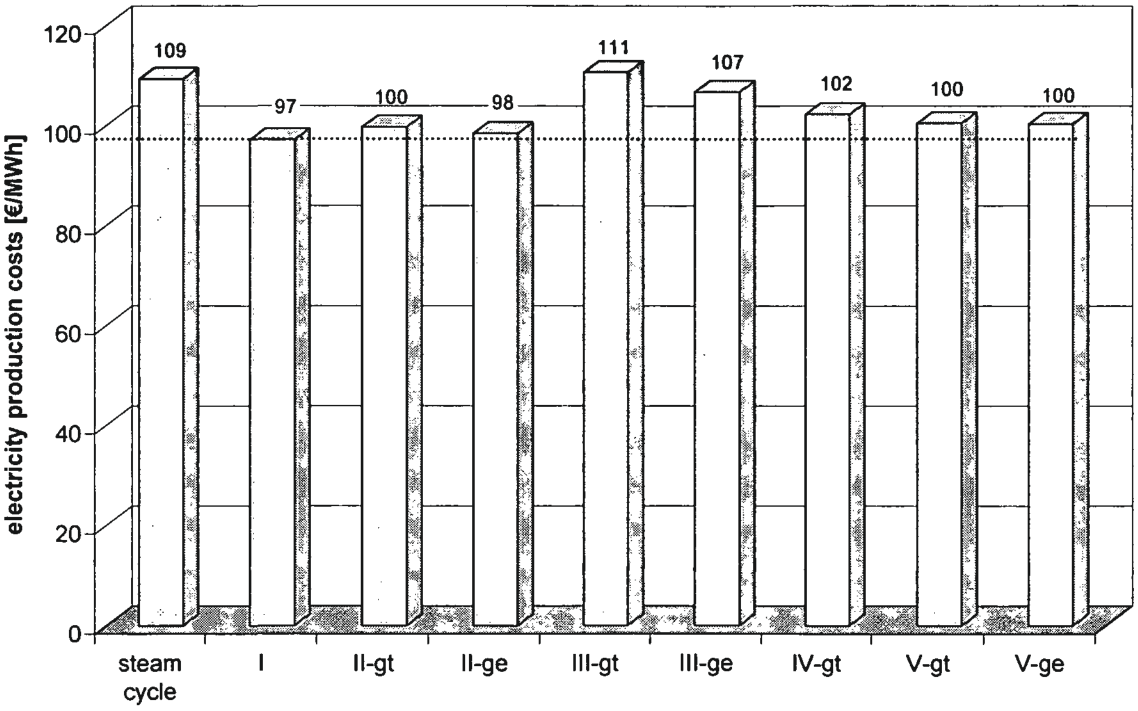


Fig. 6-1: Electricity production costs for the different concepts operated in power mode

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

The pressurised gasification concept (concept I) achieves the lowest electricity production costs of about 97 €/MWh. This value is also indicated by the dotted line for easier comparison to the other concepts. Interestingly, the electricity production costs do not differ significantly although higher net electrical efficiencies can be obtained using pressurised compared to atmospheric gasification. Most of the gasification based technologies can achieve electricity production cost, which are lower by 5 – 10 €/MWh referred to the combustion based steam cycle.

Comparing the different atmospheric concepts it can be seen, that lower electricity production costs can be achieved if gas engines are used for gas utilisation. Gas turbine based concepts show higher electricity production costs, although gas engines have much higher investment cost compared to gas turbines. The applied gas cleaning technology has a strong influence on the electricity production costs. Concept II, using a physical gas cleaning can achieve much lower production costs (around 98 €/MWh for concept II-gt) than concept III using a catalytic gas cleaning (111 €/MWh for concept III-gt). This is mainly caused by the higher investment costs and the limited operation life time of the applied catalyst. Although concept IV-gt and V-gt use the same gas cleaning, a precoat filter and solvent scrubber, electricity production costs differ. Concept V-gt can obtain lower production costs than concept IV-gt, although the investment costs of the latter one are lower. The reason for this is that concept IV-gt uses an autothermal gasifier and concept-V-gt an allothermal steam gasifier, which reduces the electric consumption for the gas compression to about half the value.

Additionally, the influence of different feedstocks was investigated. Therefore, the pressurised gasification concept, which was modelled for the fuel “forest wood” and “fuel mix” was economically assessed. The result can be seen in Fig. 6-2. If “fuel wood“ is used as feedstock, the electricity production costs decline strongly by about 27 €/MWh, although additionally apparatus and operating resources for the flue gas cleaning are necessary. This strong economic dependency has to be taken into account in advance if a plant is designed for a specific fuel.

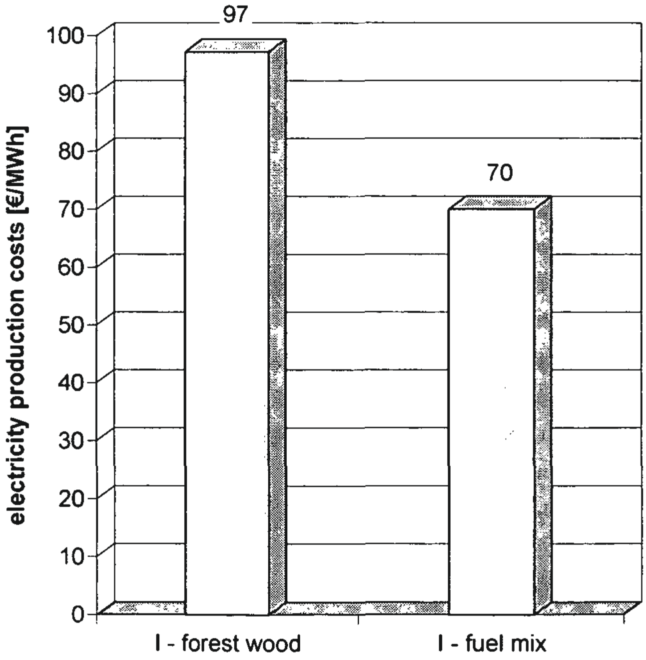


Fig. 6-2: Electricity production costs for the same gasification concept and the feedstock forest wood and fuel mix

Fig. 6-3 shows the comparison of economically evaluated gasification plants compared to a conventional steam cycle, both operated in CHP-mode. Interestingly, the electricity production costs of the steam cycle decline and the costs of the gasification concepts rise, operated in CHP-mode compared to pure power production. This can be explained by the fact, that the steam cycle has a much higher district heat output than the gasification concepts. Since the heat sales have a large impact on the economy of a CHP-plant the steam cycle can improve the electricity production costs even though the net electric efficiency declines stronger compared to the gasification concepts.

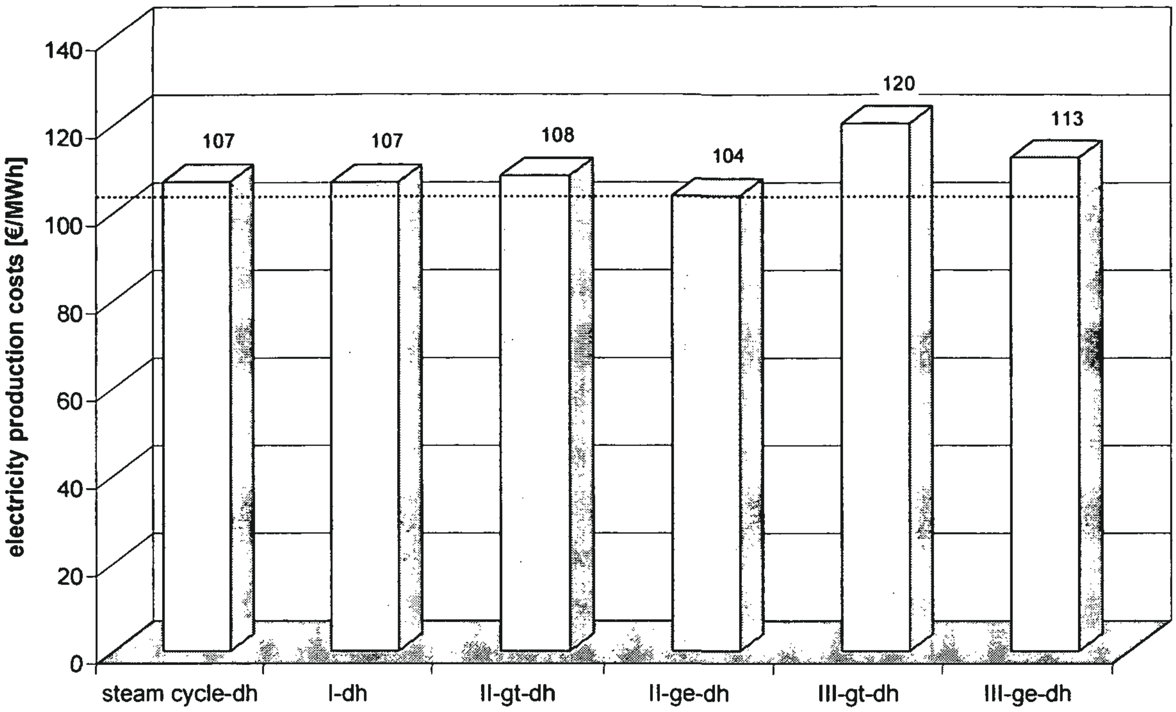


Fig. 6-3: Electricity production costs for the different concepts operated in CHP-mode

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

The pressurised gasification concept (I-dh) achieves equal electricity production costs as the steam cycle. The atmospheric gasification concept using a physical gas cleaning and a gas engine can achieve the lowest electricity production costs of about 104 €/MWh. The production costs increase slightly if a gas turbine is used instead, and strongly if a catalytic gas cleaning is applied.

6.2 Economic assessment of existing gasification and combustion based CHP-plants

In the previous chapter combustion based and gasification based CHP-concepts have been evaluated using data from a technical assessment, like it has been done in many other analyses of that kind [20], [112-114]. However, it is still unknown if these plants can economically perform in reality in the way they have been designed.

To investigate that, existing and operating plants are evaluated, to obtain "real" costs and performances for evaluation of the gasification technology at present and in the future. Six technologies for conversion of biomass to energy are assessed; conventional combustion based technologies, like steam turbine, steam engine, ORC-process or Stirling engine are looked at on the one hand and gasification-based technologies, like fixed and fluidised bed gasification combined with gas engines on the other hand.

From the economical point of view, it is problematic to assign costs to two coupled products electricity and heat. Many authors [7], [31], [115-117] assume that the main reason for the erection of a CHP-plant is the heat demand. Therefore, they only assign costs to heat production, which would arise for heat-only production in an equivalent hot-water boiler; all additional costs of the CHP-plant are assigned to the electricity production. This point of view justifies to a certain extent the practise of plant operators to sell all electricity produced to the grid and to draw their own consumption from the grid for standard rates. It is estimated that the own consumption would also arise if only heat was produced. Therefore, the complete generator output is sold as "green" electricity.

A second approach towards the assignment of costs considers the CHP-plant to be a power plant with the goal of maximising the total energy output. Generally, all caloric power plants produce large quantities of heat in the condenser/cooler of the thermodynamic cycle. If the electric efficiency is maximised, the available heat is at a temperature level close to the ambient temperature and is lost from the economic point of view.

The economic value of heat strongly depends on the temperature level, which usually is 90 to 110°C in common district heating grids. Therefore, two aspects have to be considered if a standard power plant should be operated as CHP-plant: Heat has to be drawn at a temperature level high enough and heat consumers must be located in vicinity of the plant. This consideration takes the electricity production as part of the total concept, which makes a separation of produced electricity and own consumption unjustifiable. Therefore, the own consumption of the plant is subtracted from the generator power in order to get the net electricity output of the plant. For this kind of evaluation the so-called net efficiencies apply.

Therefore, in this evaluation CHP-plants are treated as power plants with net power and heat output. That allows a comparison of the results to the analysis of the modelled concepts. In order to compare the electricity production costs, the price for decoupled heat must be fixed for all plants at the same level. The evaluated plants prove this approach by the fact that the investigated feed in tariffs for district heat do not differ significantly.

6.2.1 Evaluation basis

For this assessment the same evaluation basis has been used as already described in the previous chapter. An overview can be found in Table 6-1.

6.2.2 Investment costs and operating resources

In order to obtain data for the different technologies, eight plants have been visited and the specific data collected. Table 6-4 gives an overview of the characteristic data of the evaluated plants. Further, descriptions of the different technologies can be found in [25], [41], [118-120]. Additionally, an overview on the specific costs of each considered technology in a typical application size can be found in Table 6-4. The costs are related to the fuel power of each plant in order to give a better impression of the necessary plant size.

Table 6-4: Overview of the characteristic data of the evaluated plants

	unit	grate firing Stirling engine 0.9 MW_{th}	grate firing steam engine 4.3 MW_{th}	fixed bed air gasifier gas engine 2.0 MW_{th}	grate firing ORC-process 8.0 MW_{th}	fluidised bed steam gasifiers gas engine 8.0 MW_{th}	grate firing back pressure steam turbine 18.5 MW_{th}
fuel power	kW_{th}	900	4,300	2,000	8,000	8,000	18,500
gross el. power	$kW_{el,gross}$	50	580	580	1,130	2,000	2,700
el. proper consumption	kW	30	80	100	180	300	200
net el. power	$kW_{el,net}$	20	480	480	950	1,700	2,500
usable district heat	kW_Q	800	3,050	720	6,100	4,500	12,000
investment cost (machinery, building)	€/$kW_{el,gross}$	8,784.00	3,775.56	5,172.41	4,630.09	5,000.00	2,637.96
investment cost (machinery, building)	€/kW_{th}	488.00	509.26	1,500.00	654.00	1,250.00	385.00

In CHP-plants, chemical energy is converted into two usable energy forms, heat and electricity. This conversion cannot be performed without energy conversion losses. By looking at the economics of energy conversion, the basic rule applies that the produced energy has to be of greater economic value than the energy input in terms of kilowatt hours of biomass fuel. In addition to that, the investment and operation costs of the power plant have to be covered by the difference between the revenues and the fuel price. A steam turbine power plant operated in condensing mode has to cover all expenses by earnings from the electricity sales, because the remaining heat cannot be utilised due to the low temperature level. In CHP-plants, the earnings from heat significantly contribute to the total economy. The quality of a power plant is often characterised through efficiencies, which have to be defined precisely in order to be comparable. It is of major importance, whether the own electricity consumption of the plant is considered or not.

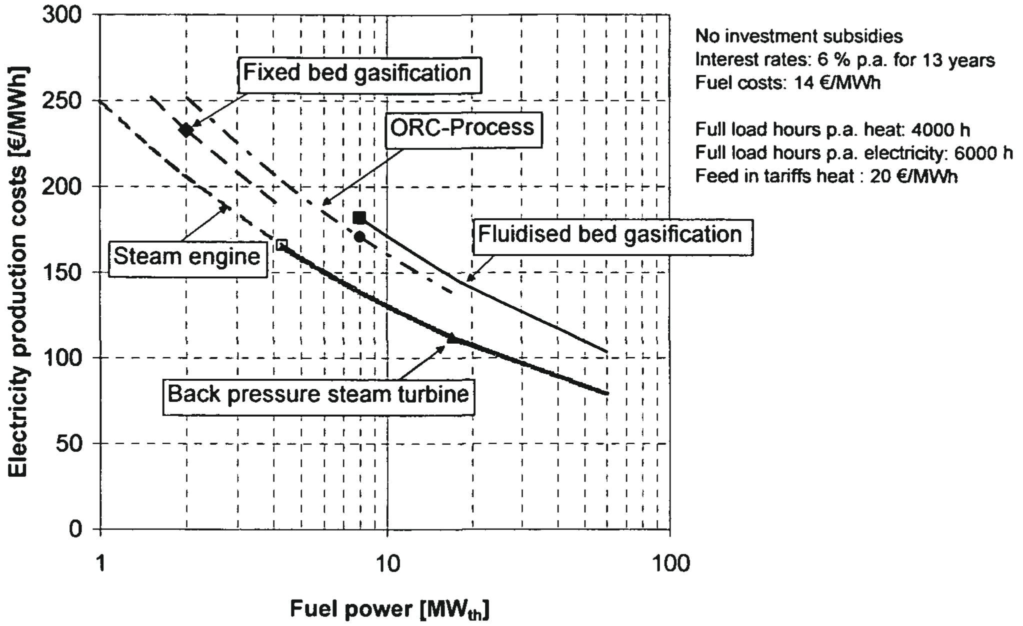
Comparing combustion based technologies to gasification technologies, it can be seen that gasification yields much higher electric efficiencies. This is of major importance as electricity is an energy form of higher exergetic value than district heat and can be transported much easier.

6.2.3 Electricity production costs

The electricity production costs are calculated from the net electric output, taking the own electric consumption into account. Costs arise through operation and payback of investment rates, earnings are yielded from the district heat sold [121].

Fig. 6-4 shows the electricity production costs of the evaluated technologies indicated with a point a the appropriated plant size. The electricity production costs of the Stirling engine, which range at about 700 €/MWh for a 50 kW_{el} (900 kW_{th}) plant, are not shown in the diagram. It is important to notice that at this stage the different development status of the technologies is not taken into account.

It can be clearly seen that today gasification technologies have higher electricity production costs than state of the art technologies. The ORC-Process, a technology on the edge of the state of the art, is situated in terms of electricity production costs between the fluidised bed gasifier and the back pressure steam turbine.



No investment subsidies
Interest rates: 6 % p.a. for 13 years
Fuel costs: 14 €/MWh

Full load hours p.a. heat: 4000 h
Full load hours p.a. electricity: 6000 h
Feed in tariffs heat : 20 €/MWh

Fig. 6-4: Electricity production costs of different technologies in terms of the fuel power

To compare different biomass CHP-plants, their size is of major importance, due to the economy of scale. This applies to the evaluated data, which reflect only one specific plant size of this technology. Large plants have considerably lower electricity production costs. Schaidhauf [111] has compared technologies of different sizes and found a correlation between electrical capacity and electricity production costs as

$$C_{prod} = a_{el} \cdot P_{el}^{b} \qquad \text{Equation 6-1}$$

where C_{prod} represents the electricity production cost, P_{el} the net electrical power output of the plant and a_{el} is a factor, which is specific for the individual technology and has been calculated from the collected data. The exponent b in Equation 6-1 is in the range between -0.3 and -0.2 according to Schaidhauf [111]. In this work, an exponent of -0.28 has been chosen for all plants. This exponent is kept constant even if the correlation is applied to the thermal capacity, which is shown in Equation 6-2 to Equation 6-5:

With

$$P_{el} = \eta_{el} \cdot P_{th} \qquad \text{Equation 6-2}$$

where P_{th} represents the fuel power and η_{el} the electrical efficiency.

Equation 6-2 can be transformed with Equation 6-3 to

$$C_{prod} = a_{el} \cdot \eta_{el}^{b} \cdot P_{th}^{b}$$ Equation 6-3

This equation can be further transformed with Equation 6-4

$$a_{th} = a_{el} \cdot \eta_{el}^{b}$$ Equation 6-4

to

$$C_{prod} = a_{th} \cdot P_{th}^{b}$$ Equation 6-5

which proves that the correlation in Equation 6-1 is also valid if applied to the fuel power of a plant. The new factor a_{th} can be calculated from the specific electricity production costs and the specific fuel power of the evaluated plants and ranges between 100 and 900.

Using Equation 6-5, the different technologies are scaled in their typical application range of size, which can be seen in Fig. 6-4.

Based on a reference case, variations of specific parameters are carried out. In order to compare the technologies two typical plant sizes are defined:

- The fuel power for a small sized plant is set to 3 MW_{th} for the fixed bed gasifier, the steam engine and the ORC-process.
- The fuel power for the large sized plant is set to 20 MW_{th} for the back pressure steam turbine and the fluidised bed gasification.

Fig. 6-5 shows variations of different full loading hours per year. The full load hours for heat have been set to 2/3 of the total full load hours. It can be seen that the electricity production costs strongly depend on the total full load hours. To obtain competitive electricity production costs all plants should operate for more than 6000 h/a.

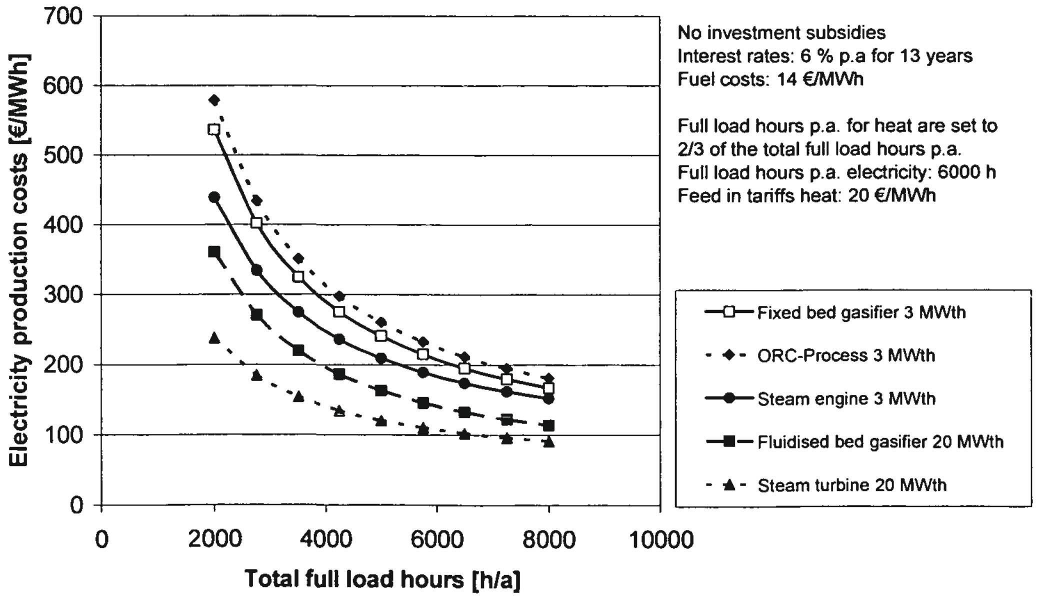


Fig. 6-5: Variation of the total full load yearly operation hours

Fig. 6-6 shows the greater dependence of the combustion technologies on the feed in tariffs for heat, whereas low heat earnings have only a minor effect on the economy of gasification technologies. The higher electrical efficiency of gasification technologies has advantages during periods of lower heat sales or discontinuous heat demand.

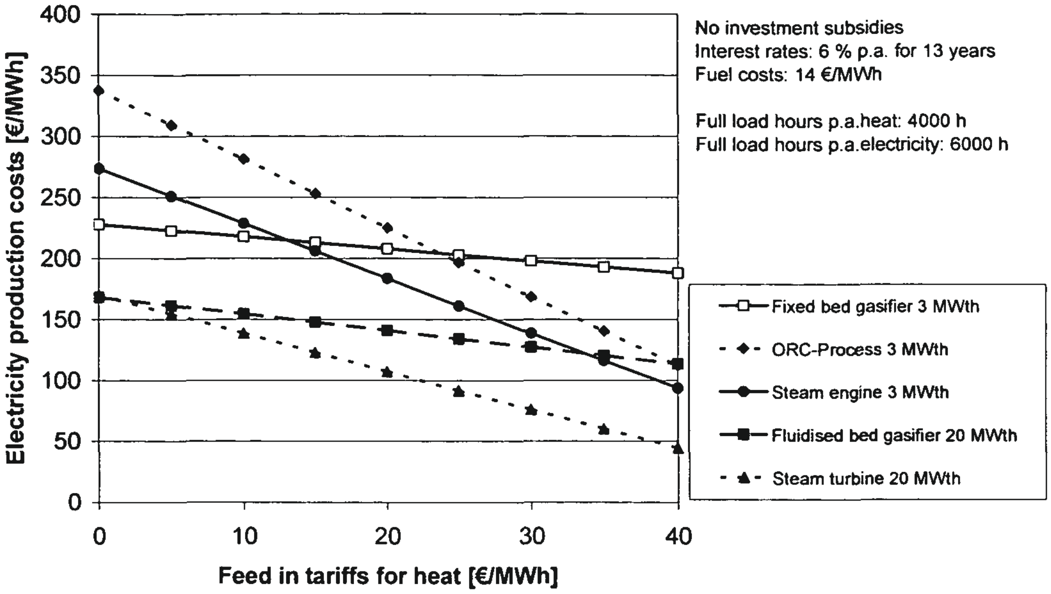


Fig. 6-6: Variation of the feed in tariffs for heat

The variation of the investment subsidies can be found in Fig. 6-7. A slightly stronger dependence of the gasification technologies on the percentage of subsidies can be seen, which is understandable because of the higher investment costs.

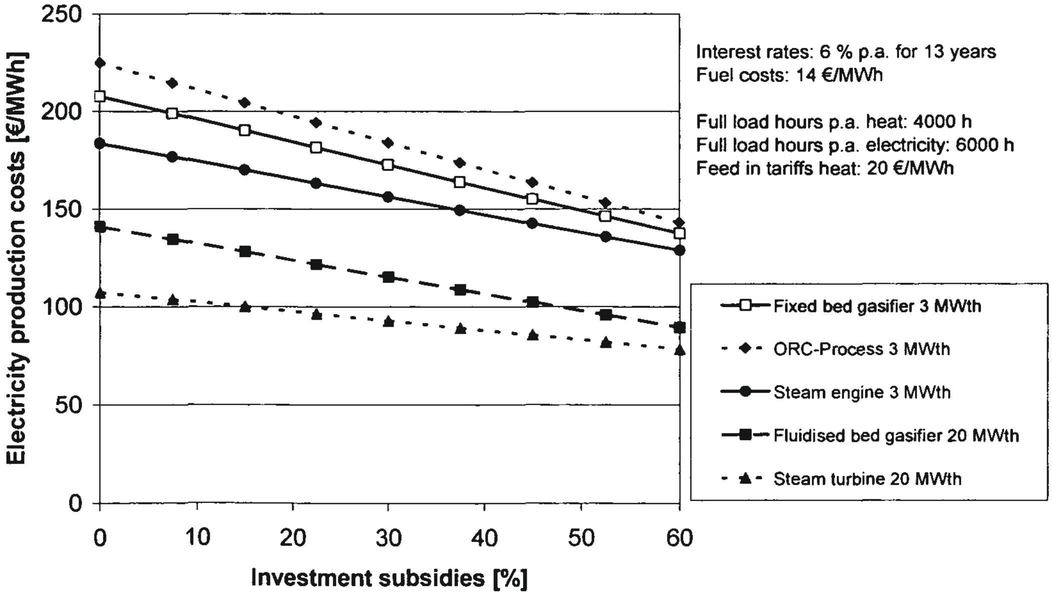
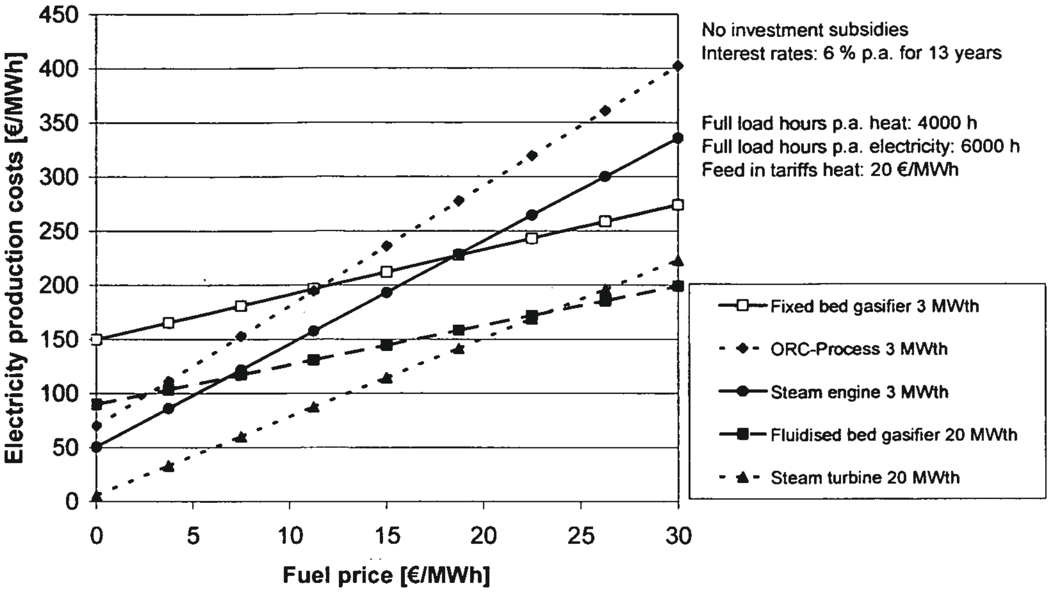


Fig. 6-7: Variation of the investment subsidies

Higher fuel prices are advantageous for gasification technologies (Fig. 6-8). Even at the current technological development status, gasification technologies can compete at a higher fuel price with state of the art technologies. This is of major importance because the fuel price has already increased due to encouraged use of woody biomass and will further rise in the near future.

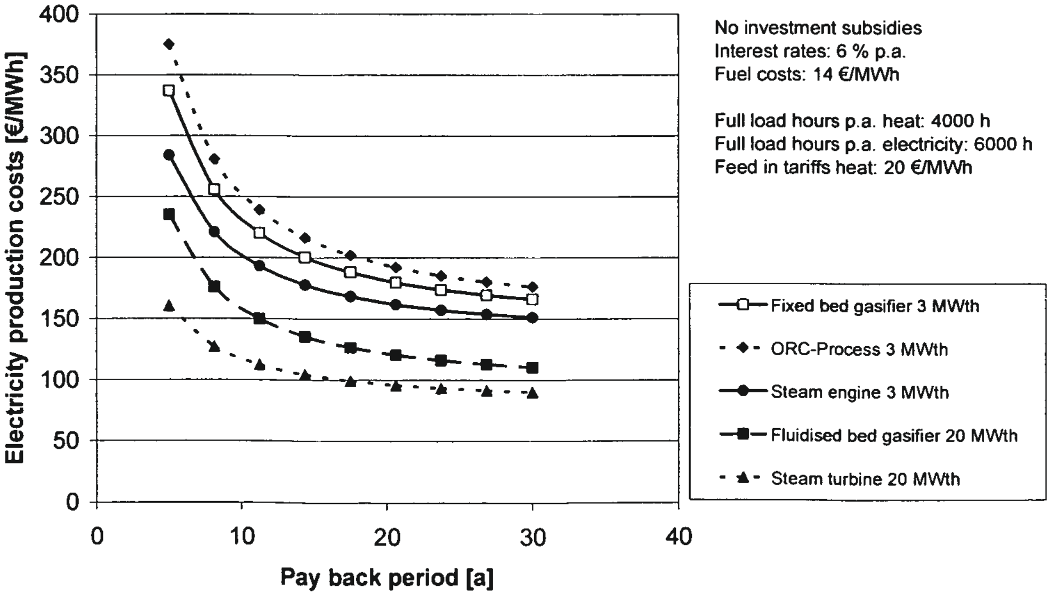


No investment subsidies
Interest rates: 6 % p.a. for 13 years

Full load hours p.a. heat: 4000 h
Full load hours p.a. electricity: 6000 h
Feed in tariffs heat: 20 €/MWh

Fig. 6-8: Variation of the fuel price

In Fig. 6-9 the influence of the pay back period on the electricity production costs is shown. The costs decline strongly up to a pay back period of 13 years. After 20 years the influence of the pay back period has only a minor effect on the electricity production costs.



No investment subsidies
Interest rates: 6 % p.a.
Fuel costs: 14 €/MWh

Full load hours p.a. heat: 4000 h
Full load hours p.a. electricity: 6000 h
Feed in tariffs heat: 20 €/MWh

Fig. 6-9: Variation of the pay back period

6.2.4 Electricity production cost for future plants

Technologies, which are suitable for standardisation and for exploitation of economic of scale, tend to follow a learning-by-doing pattern. With a growth in the cumulative production or the life cycle stage of a product, the productivity will increase, and thus lower specific production costs will result. The performance, and in particular the production costs, follow a so called learning curve [122].

Not all technologies evaluated within the present work have the same development status. So far, the effect of experience in engineering and operation, which is basically different for each technology, has not been considered. A certain learning effect can be expected for not fully matured technologies. The impact of experience is estimated to agree with the effect found in series production compared to the production costs of a prototype. Rogner [123] and Tseng [124] have shown that this effect could be found as well in power plant technology. In general learning curves have the following form:

$$C_{inv} = a_{inv} \cdot P_{cum}^{n} \qquad \text{Equation 6-6}$$

where C_{inv} represents the investment costs, P_{cum} the accumulated installed capacity or the number of installed plants. n represents a negative dimensionless exponent, which accounts for the quantity of cost reduction for a newly installed plant. The factor a_{inv} is technology specific and is computed for each technology from the collected data.

In order to calculate the future electricity production costs of the different evaluated technologies further information additional to the investment cost reduction is needed. Reduction potential can be found as well in the enhanced conversion efficiency, the possible usage of lower quality and therefore cheaper fuel, the usage of operating resources and the staff requirements. This reduction potential was accounted for by adopting Equation 6-7 to the following form:

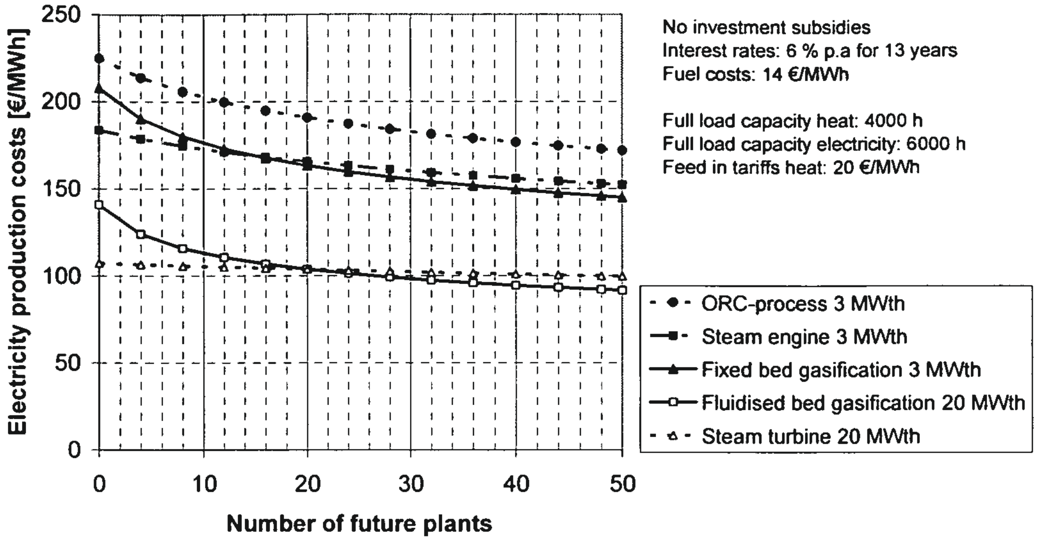
$$C_{el} = a_{f} \cdot N^{c} \qquad \text{Equation 6-7}$$

where C_{el} represents the future electricity production cost of plant number N. The plant number depends on the development status of the technology, the specific factor a_f is calculated from the collected data.

Constant c, necessary to model the cost reduction, is obtained through detailed studies on the reduction potential of the fluidised bed gasification plant in cooperation with the owner and constructor. Reduction potentials in terms of investment, operational and staff costs and an increase in the plant efficiency have been considered. The expected electricity production cost for the next, the 5th, the 10th, the 15th, the 20th, the 30th and the 50th gasification plant are calculated. This evaluation yields a value of -0.15 for the factor c. The gasification technology has certainly, because of its development status, the highest cost degression of all evaluated technologies. Due to a lack of cost estimating data for the other technologies, the same factor c is used for them.

The development status of each technology is different. Stirling engines and fixed bed gasifiers are known for quite a long time, though they are not well developed in terms of commercial application. This applies also for fluidised bed gasification plants. The ORC-process is available as packaged unit on the market, as well as the steam engine. The highest developed technology is the steam turbine, with large capacities installed and little development potential.

Taking these considerations into account, future electricity production costs can be estimated for the next 50 plants to be built. Again, the two defined standard sizes are used for the application on the learning curves. The results can be found in Fig. 6-10 for 3 MW$_{th}$ and 20 MW$_{th}$, respectively.



No investment subsidies
Interest rates: 6 % p.a for 13 years
Fuel costs: 14 €/MWh

Full load capacity heat: 4000 h
Full load capacity electricity: 6000 h
Feed in tariffs heat: 20 €/MWh

Fig. 6-10: Development of the electricity production costs for future plants

Today's electricity production costs of these technologies (no new plants built) can be seen on the left side of each curve. Depending on the development status of the varying technologies different slopes exist for each one.

Looking at the small plant size (3 MW$_{th}$), it can be seen that on the long term electricity production costs of 150 €/MWh$_{el}$ can be achieved. For the larger scale, the fluidised bed gasification can reach the plant cost level of the steam turbine and might even achieve values below. In the large scale applications electricity production costs of 90-100 €/MWh$_{th}$ are realistic in the future.

It is important to keep in mind, that this approach is based on the standard case, which assumes a district heat demand of 4000 full load hours a year. In cases where a high heat demand is guaranteed during summer, the heat-dependent combustion technologies may show better results than in Fig. 6-10. An advantage of gasification-based technologies is the possibility of lower heat production compared to combustion-based technologies of the same size. This indicates also the higher power-to-heat-ratio (α) for gasification-based technologies: Combustion technologies can achieve α-value form 1:6 to 1:10 whereas gasification technologies can provide α-values of 1:2. Therefore, gasification technology produces a higher power output at the necessary heat supply than combustion based technologies, if at a location a certain heat demand exists.

6.3 Conclusions

The economic evaluation of the modelled concepts for power production indicates that electricity production costs of 97 – 110 €/MWh can be achieved by gasification (IGCC) based biomass conversion technologies, compared to 109 €/MWh using a conventional combustion based steam cycle. The pressurised gasification concept shows the lowest production costs (97 €/MWh). Looking at atmospheric gasification, the concept using physical gas cleaning combined with gas engines can achieve the lowest electricity production costs of 98 €/MWh. In general gas engine based concepts showed lower electricity production costs than gas turbine based concepts. Of major influence on the economy of the evaluated concepts are the costs for the applied feedstock.

To given an impression of the competitiveness of the modelled concepts for pure power production the calculated electricity production costs are compared to other renewable technologies using literature values [125]. This comparison can be found in Fig. 6-11. The light grey bars on the top represent thereby the range of the electricity production costs.

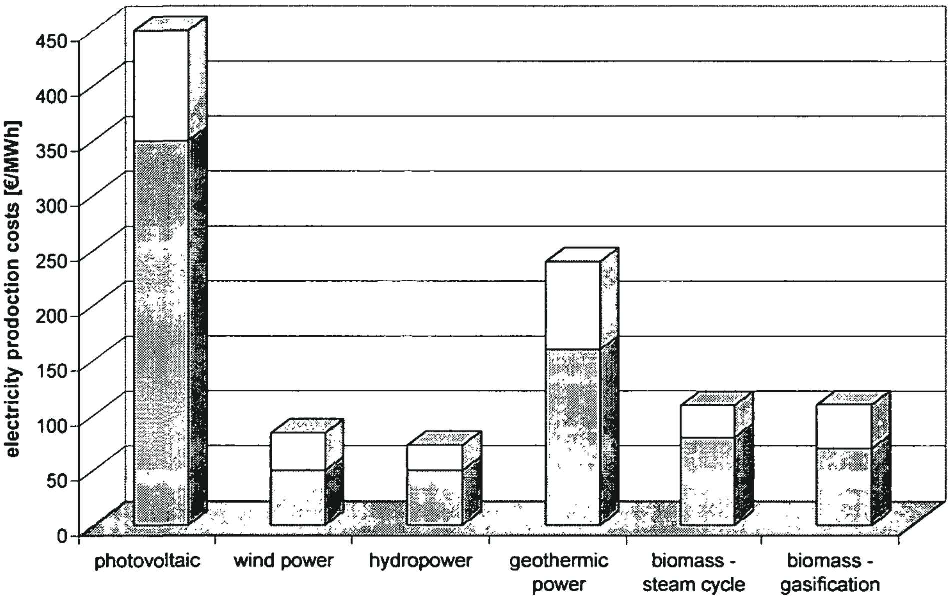


Fig. 6-11: Comparison of the electricity production costs of different renewable energy technologies

Power generation by photovoltaic (350 – 440 €/MWh) represents the most expensive form of energy production followed by the geothermic power production (160 -220 €/MWh). Both generation methods have higher electricity production costs than the biomass based technologies. The lowest production costs can be achieved by hydropower (49 – 73 €/MWh) and wind power (48 – 84 €/MWh). The evaluated biomass technologies, based on a steam cycle and gasification, achieve electricity production cost, which are in the average 25 €/MWh more expensive than wind or hydro based generation technologies.

If the modelled concepts are operated in CHP-mode, the electricity production costs of the steam cycle decline and the costs of the gasification concepts rise. The pressurised gasification concept can achieve equal electricity production costs as the steam cycle (107 €/MWh). The atmospheric gasification concept using a physical gas cleaning and a gas engine can achieve the lowest electricity production costs of about 104 €/MWh. These costs increase slightly if a gas turbine is used instead, and strongly if a catalytic gas cleaning is applied.

The performed evaluation of existing plants shows that the economy of CHP-technologies highly depends on the revenues from district heat. Future plants will have to focus on having large district heat consumers in their vicinity. Furthermore, these consumers should have a constant heat demand throughout the year, to achieve a high percentage of full load heat consumption. High loads on the heat production can compensate on even low electrical efficiencies and can maintain an economical operation. In general, gasification technology is more suitable if sales of district heat are limited.

The size of a CHP-plant has a great influence on the electricity production costs. The general tendency is a reduction of costs with increasing plant size. Therefore, future biomass based-CHP-plants should be built at the largest possible size that allows regional fuel supply and high full load hours on district heat.

By combining of today's technological status with characteristic learning curves, the direction of the development of these technologies has been drawn. In the future, gasification technologies in their range of size have the potential to achieve lower electricity production costs then combustion based technologies.

By comparing the average economic performance of existing CHP-plants to the modelled concepts a reduction potential of electricity production costs can be estimated, which is shown in Fig. 6-12. It can be seen that the decline of the electricity production costs for the gasification are three times higher than for the steam cycle technology. This is also an indication for the technological development status. The steam cycle is well developed and therefore shows a low reduction potential, whereas the existing gasification technologies have still a high optimisation potential.

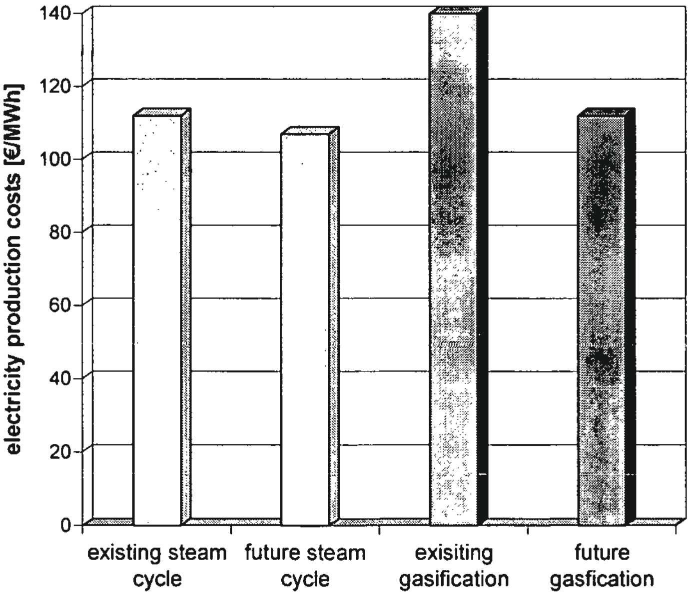


Fig. 6-12: Comparison of the average electricity production costs of combustion - steam cycle and gasification based technologies

It can be concluded that biomass gasification can compete with combustion based technologies, however, has higher production costs than hydropower and wind power.

7 Conclusion and outlook

Gasification of biomass offers the possibility to produce heat and power at higher overall efficiencies compared to combustion based technologies. Despite of these advantages, gasification technology for biomass is still under development. In the past a broad variety of process elements as well as overall systems have been developed. However, until today none has reached technical maturity and only few are operated under commercial conditions.

Based on these facts, an extensive evaluation was carried out, which on the one hand identified problems associated with biomass gasification and on the other hand promising solutions. Concepts have been developed and assessed on this basis.

A market analysis was carried out for the process steps gasification, gas cleaning and gas utilisation. Gasifiers are available at almost all power ranges and for different feedstocks on the market. However, most of the gasification reactors are prototypes. Air is commonly used as gasification agent, and most of the evaluated gasifiers are operated at small scale applications (below 1 MW_{th}). The produced raw gas is not suitable for direct use in internal combustion devices, like gas engine or gas turbine.

Looking at the gas cleaning step, different systems are available, but most of them work on conventional wet basis. There is little experience and few companies have references in the field of “wood-gas”-cleaning. Many technologies are available for dust separation, only a few for tar separation. For the separation of other compounds like S-, N- or Cl-compounds, conventional technologies are available. However, especially for biomass gasification designed technologies (e. g. hot gas cleaning) are still under development.

With respect to gas utilisation, it can be concluded that gas engines and gas turbines can be adapted to the combustion characteristics of the product gas. Gas engines are available for the small (< 2 MW_{el}), gas turbines for large power ranges. To promote further development of these technologies the market is considered too small by most companies. Therefore, an adaptation to higher tar-, S-, N- or Cl-compound levels is not taken as the responsibility of the manufacturers. It can be concluded that all components for electricity generation via gasification are in general commercially available, but the know-how is shared by only a few companies.

The analysis of different gasification plants and their system components yielded the result, that for the fuel provision of future plants it is important to define the fuel requirements of the gasifier, assure the fuel properties by a quality-management-system, prevent emissions and integrate the fuel preparation into the entire system.

For the system component “gasification” it can be concluded that fixed bed gasifiers are well advanced and CFB-gasifiers are state-of-the-art. However, for biomass usage both systems require further optimisation. Most gasifier types produce tar containing raw gas, only two-staged gasifiers promise a “tar-free” raw gas production, but are not well developed. Depending on the application range, CFB-gasification is most suitable for large scale applications.

In gas cleaning, wet as well as dry technologies are available to achieve suitable clean gas conditions. Suitable gas cleaning technologies for dust are the precoated bag house filter, ceramic or metallic candle filters as well as a combination of quench and wet-electrostatic precipitator. For tar separation suitable, fail-safe components include wet-electrostatic precipitators and solvent scrubbers. Catalytic tar removal has not reached fail-safe operation so far.

For large scale systems, gas turbines are the "standard technology", however, available turbines have low efficiencies in the applicable power ranges and in most cases require compression of the product gas. Therefore, it can be more feasible to use several gas engines instead of one gas turbine at medium power ranges.

Based on this analysis promising concepts for power production and CHP-operation in the power range of 20 MW are identified and modelled using the process simulation tool IPSEpro. The highest electrical efficiencies (about 43 %) can be obtained using a pressurised system with hot gas cleaning coupled to a gas turbine. In this concept gas utilisation requires only the compression of the gasification air and hence not the whole product gas after the gasifier. Furthermore, tar can be combusted in the turbine as well. This concept also has the lowest own power consumption of the evaluated systems.

The concept catalytic gas cleaning – gas engines offers the highest net electrical efficiency (about 36 %) among the atmospherically operated concepts and requires the lowest own consumption. The other concepts (gas cleaning using a quench - wet ESP and a precoated filter – solvent scrubber in combination with gas engines or gas turbines in combined cycles) offer about the same net electrical efficiencies in the range of 34 – 35 %. A combustion based steam cycle concept operated in condensed mode can achieve net electrical efficiencies of about 28 %.

Operating these concepts in combined heat and power mode the net electric efficiencies decrease by 2 %, while the fuel utilisation efficiency can be raised to 70 – 80 %. In a comparable power plant based on a steam cycle the net efficiency would decrease by about 5% if district heat is produced. Gasification technologies offer in addition a high power-to heat ratios (> 0.8) compared to steam based technologies (~ 0.4).

The economic evaluation of the modelled concepts indicated that gasification based biomass conversion technologies allow electricity production costs of 97 – 110 €/MWh, compared to 109 €/MWh using a conventional steam cycle. The pressurised gasification concept shows the lowest production costs (97 €/MWh). Looking at atmospheric gasification, the concept using physical gas cleaning combined with gas engines can achieve the lowest electricity production costs of 98 €/MWh. In general, gas engine based concepts showed lower electricity production costs than gas turbine based concepts. Of major influence on the economy of the evaluated concepts are the costs for the applied feedstock.

Fig. 7-1 shows the technical (net electrical efficiency) and economical (electricity production costs) summary of this work. The net electrical efficiency indicates the technical quality of the conversion process. A higher efficiency represents a better fuel utilisation of the biomass and should therefore be preferred. The opposite applies for the electricity costs, which indicate the economic performance of the plant. Here lower values represent economically better concepts. Plants, which combine both advantages are to be preferred and can be found in the upper left corner.

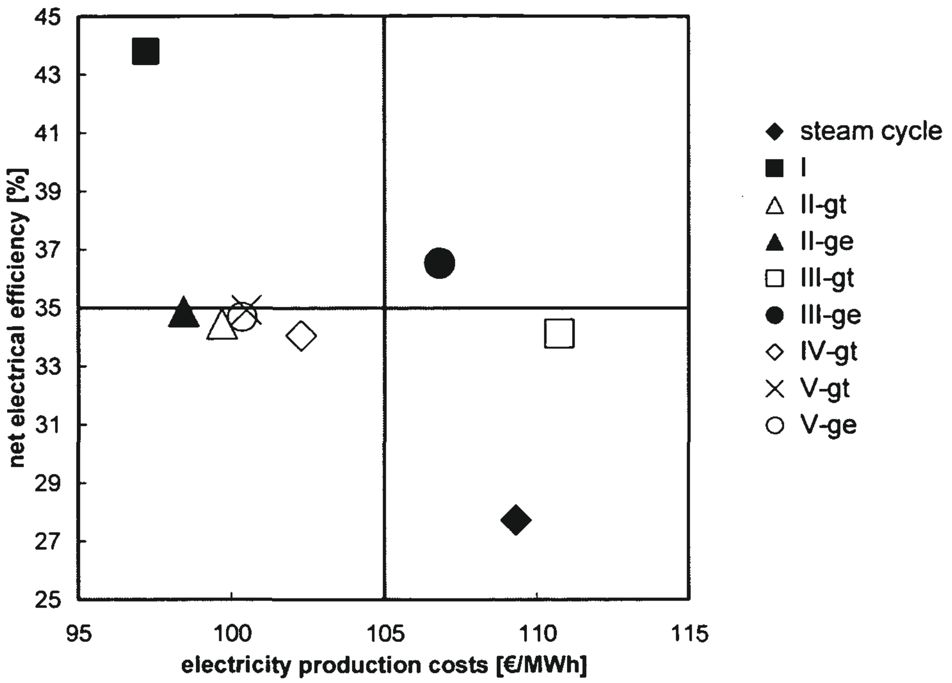


Fig. 7-1: Net electrical efficiency versus electricity production costs of concepts for power production at 20 MW net electrical output

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

It can be seen that the pressurised gasification concept (concept I) achieves the highest net electrical efficiencies and the lowest electricity production costs. The atmospheric gasification concepts have lower net efficiencies, but differ in their electricity production costs only minor. Concepts based on physical gas cleaning (II, IV, V) are grouped around 100 € MWh, whereas catalytic gas cleaning has much higher electricity production costs. The steam cycle shows the lowest net electrical efficiency and high electricity production cost.

If these concepts are operated in CHP-mode, the electricity production costs of the steam cycle decline and the costs of the gasification concepts rise. The pressurised gasification concept can achieve equal electricity production costs as the steam cycle (107 €/MWh). The atmospheric gasification concept using a physical gas cleaning and a gas engine can achieve the lowest electricity production costs of about 104 €/MWh in CHP-mode. These costs increase slightly if a gas turbine is used instead, and strongly if a catalytic gas cleaning is applied.

The economic comparison of existing combustion and gasification based technologies shows that the economy of CHP-based technologies highly depends on the revenues from district heat. Due to the fact that transportation of district heat is expensive and transportation costs rapidly increase with distance, future plants will have to focus on having sufficient market for district heat in their vicinity. High loads of heat production can even compensate low electrical efficiencies and can assure an economical operation. In general, gasification technologies depend less on the sales of district heat as combustion based technologies. Since gasification technology has higher electrical efficiencies the revenues are shifted from heat towards electricity.

A strong influence of the size of CHP-plants on the electricity production costs was identified. The general tendency is a reduction of costs with increasing plant size. Considering two different plant sizes, a smaller one with 3 MW_{th}, and a larger one with 20 MW_{th}, typical electricity production costs were calculated. Smaller plants have about 50 % higher electricity production costs (about 180 – 230 €/MWh) than large plants (110 – 140 €/MWh). Since the development state of the evaluated technologies significantly differs, it can be expected that further cost reduction can be achieved. To account for this effect, learning curves were introduced. In the future, gasification technologies in the respective range of size have the potential to achieve lower electricity production costs than combustion based technologies.

Fig. 7-2 shows the techno-economic analysis for modelled and existing combined heat and power plants. Again the pressurised gasification can achieve the best performance concerning net electrical efficiencies and electricity production costs. The net electrical efficiencies of all concepts operated in CHP-mode decrease slightly since additional fuel is used for the heat production. The steam cycle can improve its performance in terms of electricity production costs significantly due to the higher heat sales.

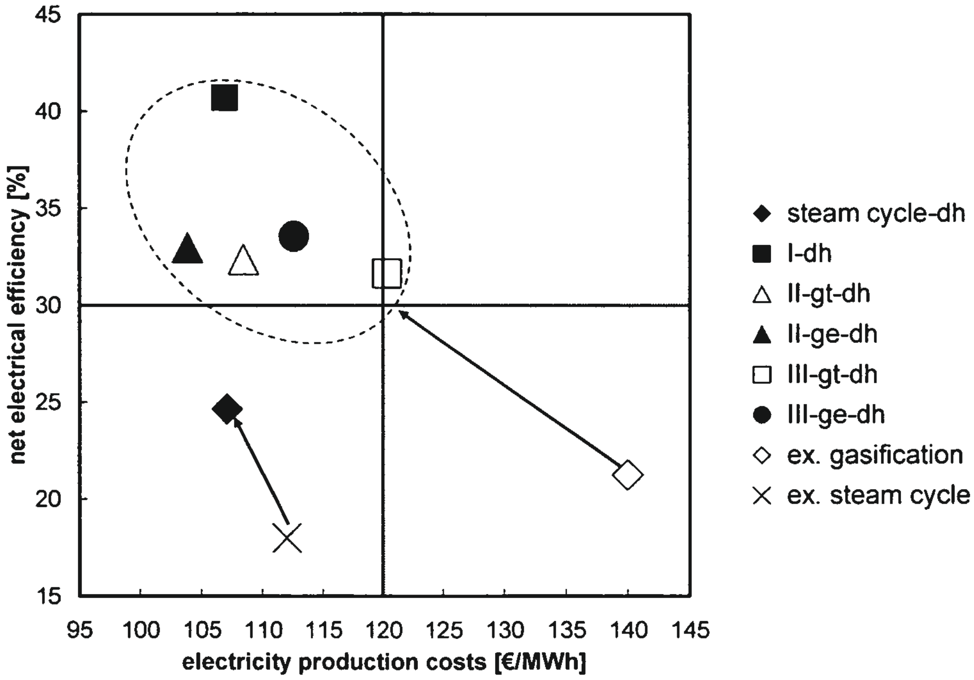


Fig. 7-2: Net electrical efficiency versus electricity production costs of concepts for heat and power production

gt...gas turbine, ge...gas engine, dh...district heat, I...pres. autoth. gasif.-hot gas cleaning, II...atm. autoth. gasif.-quench-ESP, III...atm. autoth. gasif.-cat. cracker-filter, IV...atm. autoth. gasif.-filter-solvent scrubber, V...atm. alloth. gasif.-filter-solvent scrubber

Additionally, the performance of an existing steam cycle and gasification plant is indicated in the graph. It can be seen that the steam cycle offers low improvement potential compared to the state of the art technology, whereas gasification based technologies offer still quite significant improvement potential (modelled plants are marked with a circle). This agrees well with the results of the learning curves in chapter 6.2.4.

It can be concluded, that gasification has a significant advantage in terms of fuel utilisation, achieving about 10 % higher net electrical efficiencies as combustion based systems. Since biomass resources are limited, the technology with the higher conversion efficiency, gasification, should be favoured.

For successful realisation of gasification projects in the future some important points should be considered:

- Pressurised gasification can achieve the lowest electricity production cost combined with the lowest fuel consumption and represents the most favourable concept.
- For atmospheric concepts similar net electrical efficiencies can be achieved with gas engines and gas turbines even at large scale. Gas engines are well developed and offer more flexibility and good partial load behaviour.
- In future concepts the integration of the feedstock drying should be considered right from the start of the project, since higher electrical efficiencies can be obtained and low temperature heat can be utilised.
- CHP-operation affects the net electrical efficiencies only to a minor extent but increases the overall fuel utilisation significantly. Since biomass is a valuable and expensive feedstock, with limited resources, CHP-based power production should be preferred to pure power production. This requires careful planning of the construction site of the CHP-plant, since local heat demands are necessary throughout the year.

In the future, the development of the gasification technology will require scientifically supported pilot and demonstration projects integrated into a network of plant operators and constructors, like successfully demonstrated by the RENET Austria network. The network should act as an exchange of obtained information, experience and learned lessons to be used in future applications.

On this basis a significant contribution to the renewable production of electricity by the production of heat and power via gasification can help to fulfil the European White Papers.

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9 Papers

This appendix includes the papers, which have been published in journals, presented at conferences or are about to be published. The papers are arranged in the order of their usage in this thesis.

1. Bolhàr-Nordenkampf, M.; Rauch, R.; Hofbauer, H.; "Biomass CHP Plant Güssing – Using Gasification for Power Generation", Proceedings of the 2nd RCETCE Conference; Phuket, Thailand, Feb 2003, 567–572.
2. Bolhàr-Nordenkampf, M.; Aichernig, C.; Hofbauer, H.; "Scale-up of a 100kW$_{th}$ pilot FICFB-gasifier to a 8 MW$_{th}$ FICFB-gasifier demonstration plant in Güssing (Austria)"; Proceedings of the 1st Ukrainian Conference on Biomass and Energy, Kiev, Ukraine, Sept. 2002, 728-736.
3. Bolhàr-Nordenkampf, M.; Jörg, K.; Baaske, W.; Schmoll, J.; Herdin, G.; Hofbauer, H.; " Extension of a biomass district heating plant with a twin-fire fixed bed gasifier"; Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.
4. Bolhàr-Nordenkampf, M.; Hofbauer, H.; "Gasification Demonstration Plants in Austria", Proceedings of the 4th International Slovak Biomass Forum, Bratislava, Slovakia, Feb. 2004, 99-103.
5. **Bolhàr-Nordenkampf, M.; Jörg, K.; „Gasreinigung – Stand der Technik", Proceedings of the international Meeting Biomasse-Vergasung – Der Königsweg für effiziente Strom- und Kraftstoffbereitstellung?, FNR-Schriftenreihen, Leipzig, Germany, Okt. 2003, 84-107.**
6. **Bolhàr-Nordenkampf, M.; Vogel, A.; „Bewegtbett-Vergaser zur Stromerzeugung - Lessons learned"; Proceedings of the international Meeting Biomasse-Vergasung – Der Königsweg für effiziente Strom- und Kraftstoffbereitstellung?; FNR-Schriftenreihe, Leipzig, Germany, Okt. 2003, 250-267.**
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9. **Bolhàr-Nordenkampf, M.; Vogel, A.; Kübel, M.; Detering, M.; Weigand, P.; Hofbauer, H.; Kaltschmitt, M.; "Analysis and Evaluation of Biomass Gasification Plants - Developments of New Concepts"; Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.**

10. **Bolhàr-Nordenkampf, M.; Hofbauer H.; "Biomass Gasification Combined Cycle Optimisation Using Integrated Drying", Proceedings of the Conference Turboexpo 2004, Vienna, Austria, June 2004, CD-publication.**
11. **Bolhàr-Nordenkampf, M.; Fürnsinn, S.; Hofbauer H.; „Exergetic and Energetic Evaluation of Biomass Based IGCC Processes", Proceedings of the 16th International Congress of Chemical and Process Engineering CHISA 2004, Prag, Tschechoslowake, Aug. 2004, paper in press.**
12. **Bolhàr-Nordenkampf, M.; Fürnsinn, S.; Hofbauer H.; „Exergetische Analyse und Bewertung von Gasreinigungsverfahren zur Staub- und Teerabscheidung aus Produktgas der thermo-chemischen Umwandlung", Proceedings of the DGMK-Meeting „Energetische Nutzung von Biomasse - Velen VI", Velen, Germany, April 2004, 169-176.**
13. **Bolhàr-Nordenkampf, M.; Pröll, T.; Hofbauer, H.; "Techno-Economical Assessment of Combined Heat and Power Production from Biomass", Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.**
14. **Bolhàr-Nordenkampf, M.; Vogel, A.; Hofbauer, H.; Kaltschmitt, M.; "Analysis and Evaluation of the Production of Fischer-Tropsch-Fuels from Biomass", Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.**
15. **Vogel, A.; Bolhàr-Nordenkampf, M.; Hofbauer, H.; Kaltschmitt, M.; „Vergasung biogener Festbrennstoffe zur Produktion von Fischer-Tropsch-Kraftstoffen", BWK, 2004, 56, 3, 57–62.**
16. **Vogel, A.; Kaltschmitt, M.; Bolhàr-Nordenkampf, M. Hofbauer, H.; „Vergasung zur Kraftstoffbereitstellung- Grundsätzliche konzeptionelle Überlegungen"; Proceedings of the international Meeting Biomasse-Vergasung – Der Königsweg für effiziente Strom- und Kraftstoffbereitstellung?; FNR-Schriftenreihe, Leipzig, Germany, Okt. 2003, 268-297.**

In the following the most important papers (marked bold in the listening) are attached.

I. PAPER

Bolhàr-Nordenkampf, M.; Jörg, K.

„Gasreinigung – Stand der Technik“

Proceedings of the International Meeting Biomasse-Vergasung – Der Königsweg für effiziente Strom- und Kraftstoffbereitstellung?

FNR-Schriftenreihen, Leipzig, Germany, Okt. 2003, 84-107.

Biomasse-Vergasung – Internationale Tagung Leipzig, Oktober 2003

Gasreinigung – Stand der Technik

Markus Bolhàr-Nordenkampf , Klaus Jörg
Technische Universität Wien

Kurzfassung

Holzgas kann im allgemeinen ohne Aufbereitung außer durch Mitverbrennung nicht direkt energetisch genutzt werden. Die derzeit eingesetzten Aggregate Gasmotor und Gasturbine stellen gewisse Anforderungen an die Gasqualität. Dieser Vortrag soll einen Überblick über die Möglichkeiten der Aufbereitung des Holzgases geben. Dabei liegt der Fokus vor allem auf der Partikel- und Teerabscheidung für eine abschließende motorische Nutzung des gereinigten Holzgases.

Durch die thermochemische Umwandlung des Holzes entstehen je nach Reaktorart unterschiedliche Mengen an Schadstoffen im Produktgas. Die wichtigsten stellen dabei Partikel und Teer dar. Weitere häufige gasförmige Komponenten sind Stickstoffverbindungen, Schwefelverbindungen, Halogenverbindungen und Alkalien.

Im Prinzip kann zwischen zwei Arten der Reinigung unterschieden werden: Der kalten Gasreinigung und der heißen Gasreinigung.

Systeme der kalten Gasreinigung: Hier wird unterschieden zwischen trockenen und nass arbeitenden Verfahren. Nasse Gasreinigungsverfahren (Wäscher, Nasselektrofilter) ermöglichen neben der Partikelabscheidung auch eine sehr gute Abscheidung von Teeren und der weiteren Schadstoffe. Zu der trocken arbeitende Verfahren zählen filternde Abscheider (Schüttschichtfilter, Schlauchfilter) und Fliehkraftabscheider (Zyklon). Diese scheiden zwar Partikel und Alkalien im ausreichenden Masse ab, die weiteren Schadstoffe werden allerdings nur bedingt abgeschieden.

Systeme der heißen Gasreinigung: Diese sind vor allem bei der Verwertung des Gases in einer Gasturbine oder Brennstoffzelle (MCFC,

SOFC) bei Druckvergasung sinnvoll, da hier das Gas ohne wesentliche Abkühlung gereinigt und in die Brennkammer der Turbine eingeleitet werden kann. Eine Technologie zur Reduktion der Teere (und zum Teil auch des Ammoniaks) aus dem Heißgas ist der Einsatz von Katalysatoren. Allerdings sind diese meist auch anfällig gegenüber der weitern Schadstoffe wie Schwefel und Chlor. Eine Partikel- und Alkalienabscheidung ist wiederum durch entsprechende filternde (Keramikkerzenfilter) oder Fliehkraftabscheider (Heißgaszyklon) möglich. Generell muss allerdings der Abscheider aufgrund des größeren Gasvolumenstromes bei atmosphärischem Betrieb größer gebaut werden, was wiederum größere Kosten verursacht.

Für die gemeinsame Entfernung von Teer und Partikel aus dem Produktgas eignet sich der Nasselektrofilter von den betrachteten kalt arbeitenden Gasreinigungssystemen am besten. Dieser ermöglich neben einer fast vollständigen Partikelabscheidung auch eine für den Motoren- und Turbinenbetrieb ausreichende Teerabscheidung. Bei einer Heißgasreinigung des Gases konnten bis heute nur auf der Partikelseite die Anforderungen erfüllt werden. Eine zufriedenstellende Reinigung durch eine katalytische Zersetzung der Teere konnte bis heute noch nicht erfolgreich demonstriert werden. Für die Nutzung des Holzgases in einer Turbine wäre diese Art der Reinigung aus energetischer Sicht vorteilhaft.

Einleitung

Die Gasreinigung stellt das Bindeglied zwischen der Gaserzeugung und der Gasnutzung dar. Meistens erzeugen Gaserzeuger ein Produktgas einer Qualität, die sich nicht für eine direkte Gasnutzung zur Stromerzeugung eignet. Bis heute konnten keine passenden Primärmaßnahmen (Maßnahmen im Vergaser selbst) gefunden werden, die ein Produktgas mit so niedrigen Verunreinigungen garantieren, welches eine Gasreinigung obsolet machen würde.

Der Aufwand der Gasreinigung hängt sehr stark von dem eingesetzten Brennstoff, dem Vergasungsverfahren, den Prozessparametern und der nachgeschalteten Gasnutzung ab. So verursacht zum Beispiel ein Wirbelschichtvergaser eine deutlich höhere Staubbeladung im Produktgas als ein Festbettvergaser, ein Luftvergaser einen deutlich größeren Produktgasstrom (aufgrund des Stickstoffes im Produktgas) als ein Vergaser, der mit Dampf oder Sauerstoff fluidisiert wird. Auch gibt es je nach Verfahren unterschiedliche Teer, Ammoniak und H_2S Gehalte im Produktgas, sowie anderen Verunreinigungen. All diese Faktoren haben natürlichen einen Einfluss auf die für eine bestimmte Produktgasqualität notwendigen Gasreinigungsverfahren, deren Baugröße und damit auch auf die Kosten und die Wirtschaftlichkeit der Gesamtanlage.

Die Gasnutzung bestimmt den Reinheitsgrad des benötigten Produktgases. Wird das Gas als Brennstoff in Zementmühlen oder als Zufeuerung in Kraftwerken verwendet, kann meist vollständig auf eine Gasreinigung verzichtet werden. Soll das Gas hingegen zur Stromerzeugung herangezogen werden. so ist eine mehr oder minder aufwendige Gasreinigung notwendig.

Eine Gasturbine zum Beispiel fordert zum einen für den sicheren Betrieb des Kompressors niedrige Teerwerte, zum anderen, um Heißgaskorossion an den Schaufeln zu vermeiden, äußerst niedrige Alkalienwerte. Weiter sind, um einen hohe Wirkungsgrade zu erreichen, eine hohe Eintrittstemperatur und ein hoher Druck des Produktgases wünschenswert. In diesem Fall hätte eine heiße Gasreinigung durchaus Vorteile.

Ein Gasmotor hingegen benötigt ein Gas mit einer niederen Temperatur, um die notwendige Gasmenge in den Verbrennungsraum zu bringen. Auch sollten die Ammoniakbeladungen niedrig sein, da vermutet wird, dass Ammoniak die Schmierfähigkeit des Motoröls herabsetzt. Wie man sieht, hätte bei motorischer Gasnutzung eine Kaltgasreinigung keine Nachteile, sondern sogar Vorteile.

Bei einer etwaigen zukünftigen Nutzung des Produktgases in einer Brennstoffzelle oder gar zur Synthesegasproduktion werden die Anforderungen, welche an die Gasreinigung gestellt werden, noch um einiges höher.

Wie aus der Einleitung leicht ersichtlich, ist die Auswahl der passenden Gasreinigung eine Aufgabe von großer Komplexität und durchwegs nicht trivial. Im Folgenden sollen die kommerziell verfügbaren und die in Entwicklung befindlichen Verfahren beschrieben werden und die Ergebnisse der Hersteller- und Marktrecherche präsentiert werden.

Verunreinigungen und Gasreinigungsverfahren

Das Ziel die Verunreinigungen des Produktgases bereits im Vergaser soweit zu reduzieren, dass die geforderte Produktgasqualität erreicht werden kann, ist meist nicht möglich. Daher benötigen fast alle Systeme eine zusätzliche Gasreinigung, sofern eine Nutzung des Gases im Motor oder in der Turbine gewünscht wird. Diese besteht meistens aus mehreren Schritten durch Hintereinanderschalten von Komponenten wie Zyklone, Wäscher oder Filter, die jeweils einen oder mehrere Verunreinigungen abscheiden.

In Abb. 1 sind die wichtigsten Verunreinigungen des Produktgases dargestellt.

Abbildung 1: Verunreinigungen des Produktgases

Diese Verunreinigungen und die Möglichkeiten der Entfernung werden im Folgenden im Detail besprochen. Zusätzlich zur Entfernung dieser Verunreinigungen muss für die Nutzung als Synthesegas auch die Gaszusammensetzung bestimmten Voraussetzungen genügen. Die Gaskomponenten Methan und Ethan, die für den Einsatz von Produktgas als Brennstoff durchaus gewünscht sind, stellen für die Synthesegasproduktion unerwünschte Komponenten dar, da sie eine niedrigere Reaktivität besitzen. Zusätzlich muss für den Synthesegaseinsatz auch das molekulare Verhältnis zwischen Wasserstoff und Kohlenmonoxid eingestellt werden.

Partikel

Als Partikel werden Feststoffe verstanden, welche mit dem Rohproduktgas aus dem Vergaser ausgetragen werden. Dazu zählen anorganische Asche, die aus den Mineralien im Brennstoff stammt, nicht umgesetzte Biomasse in Form von Koks und Bettmaterial. Partikelverunreinigungen im Produktgas sind unvermeidlich, jedoch höchst unerwünscht, da diese zu Erosion und Beschädigung von nachgeschalteten Anlagenteilen, wie auch zu Problemen mit den vorgeschriebenen Emissionsgrenzwerten führen. Daher benötigt nahezu jede Großanlage zur Biomassevergasung eine Partikelreinigung des Produktgases.

Partikelentfernung

Die notwendige Reinheit in punkto Partikel hängt vom Einsatzgebiet des Produktgases ab. Zum Beispiel muss für einen Einsatz des Produktgases in einem Gasmotor die Partikelbeladung unter 50 mg/Nm³, für den Einsatz in einer Gasturbine unter 15 mg/Nm³ (5 µm) und für den Einsatz in Synthesegas bis auf unter 0,02 mg/Nm³ gesenkt werden. Folgende Standardkomponenten können für die Partikelentfernung eingesetzt werden:

- Zyklone
- Filter mit Filtermedium
- Elektrostatischer-Filter
- Wäscher

Die einzelnen Technologien werden im Folgenden besprochen.

Zyklone

Zyklone stellen einen gute Möglichkeit dar, hohe Partikelbeladungen aus einem Gasstrom abzuscheiden. Sie werden daher meist für die Erstreinigung eingesetzt, da sie effektiv und relativ kostengünstig im Bau und Betrieb sind. In zirkulierenden Wirbelschichten oder Flugstromreaktoren sind sie sogar ein integraler Bestandteil des Systems, um das zirkulierende Bettmaterial und die Partikel vom Produktgas abzuscheiden und rückzuführen.

Zyklone sind besonders bei großen Partikeln effektiv und können über einen weiten Temperaturbereich eingesetzt werden, welcher im Prinzip nur durch die eingesetzten Materialien bestimmt wird. Werden mehrere Zyklone parallel, so genannte Multiklone (Abb. 2), eingesetzt, können für Partikeldurchmesser größer als 5 µm Abscheidegrade von über 90 % bei einem Druckverlust von ungefähr 10 mbar erzielt werden. Eine Abscheidung von Partikel zwischen 1 bis 5 µm ist teilweise möglich, allerdings geht die Abscheideleistung drastisch zurück. Problematisch stellt sich der äußerst schlechte Abscheidegrad kleiner kohlenstoffhaltiger Partikel dar, wie sie häufig bei der Vergasung entstehen. Hierbei kann es passieren, dass selbst Hochleistungszyklone nur eine Reduktion der Staubgehalte auf unter 5-30 g/Nm³ erreichen /Bridgwater, 1995/. Ein Vorteil ergibt sich aus dem der Tatsache, dass Zyklone bei hohen Temperaturen betrieben werden können, womit die fühlbare Wärme weitgehend erhalten werden kann, welches vor allem bei der Druckvergasung von Bedeutung ist.

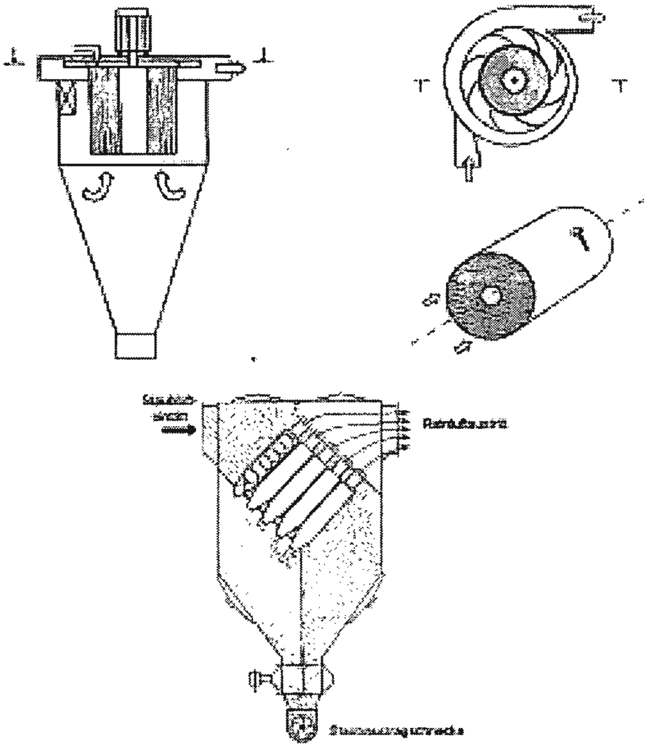

Abbildung 2: Multiklon und Rotierender Partikelabscheider

Eine Weiterentwicklung auf dem Zyklonsektor stellt der Rotierende Partikel Separator (RPS) dar (Abb. 2). Das zentrale Element dieses neuartigen Trägheitsentstaubers besteht aus einem rotierenden Wabenelement mit durchgehenden Kanälen. Durch die hohe Drehgeschwindigkeit dieses Wabenelementes wird die Abscheidewirkung für feine Partikel verbessert. Die Abgase werden hier in einen zyklonähnlichen Abscheideraum eingeleitet und dort vorentstaubt. Statt eines Tauchrohres ist dieses um seine Längsachse rotierende wabenförmige Element in der Mitte eines zyklonartigen Gehäuses angebracht. Durch die parallel verlaufenden Längskanäle strömt das mit Feinstaub beladene Abgas. Aufgrund der durch die Rotation aufgezwungenen Fliehkräfte werden die Partikel in diesen kleinen Röhren abgeschieden. Das gereinigte Gas verlässt den Abscheider, während das an den Wänden der Röhren angesammelte Material durch periodische Druckluftstöße abgereinigt wird.

Filter mit Filtermedien

Diese Filter können kleine Partikel in der Größeordnung von 0,5 bis 100 µm sehr effektiv entfernen. Sie können so ausgelegt werden, dass sie nahezu jede Partikelgröße abscheiden, sogar submicrone Partikel mit dem Nachteil eines stark ansteigenden Druckverlustes. Daher werden aus technischen und wirtschaftlichen Gründen in Vergasungssystemen solche Filter nur zur Entfernung von Partikel bis 0,5 µm eingesetzt, da in Vergasungssystemen meist große Volumenströme zu reinigen sind. Diese Filter werden meistens mittels eines Druckstoßes abgereinigt, der entgegen der normalen Anströmrichtung wirkt. Um die Abreinigungsintervalle und somit die Betriebskosten gering zu halten werden solche Filter meist in Kombination mit Zyklonen, welche den Grobanteil der Partikel vorabscheiden, eingesetzt.

Gewebefilter

Die Abscheideleistung von Gewebefiltern ist stark von der Dicke des Filterkuchens abhängig, der den Großteil der Filterwirkung darstellt. Die Abreinigung der Filter erfolgt durch einen Druckstoß oder durch Rütteln. Gewebefilter aus Standardmaterialien können üblicherweise bis zu einer Temperatur von 250 °C, Filter aus Metallgeweben bis 350 °C eingesetzt werden. Da das Vergasungsgas vor der Reinigung abgekühlt wird, eignet sich dieses Verfahren hauptsächlich für Anlagen, in denen es nicht wichtig ist die fühlbare Wärme im Gas zu erhalten. Teer im Produktgas führt bei Gewebefilter zu Problemen, da diese zum Verkleben des Filtermediums führen. Teere müssen daher vorher abgeschieden werden oder es darf die Kondensationstemperatur der Teere nicht unterschritten werden. Eine Methode sowohl Teere als auch Staub gleichzeitig zu entfernen und dabei ein Verkleben des Filtertuches zu verhindern kann durch eine Precoatisierung des Filtermediums erreicht werden. Dabei wird vor der Filtration auf das Filtermedium eine dünne Schicht eines Filterhilfsmittels aufgebracht, welches die Filterwirkung übernimmt und danach mit dem Staub-Teerkuchen abgereinigt wird. Mit einem Filter dieser Bauart lässt sich neben einer sehr hohen Staubabscheidung auch eine Teerabscheidung von bis zu 80 % erzielen. Dieses wurde erstmals in Güssing (A) in einer Demonstrationsanlage von der Firma Austrian Energy erfolgreich eingesetzt.

Schüttschichtfilter

Bei dieser Filterart durchströmt das Gas ein Bett, das aus unterschiedlichen Materialien bestehen kann (Sand, Sägespäne oder auch keramische

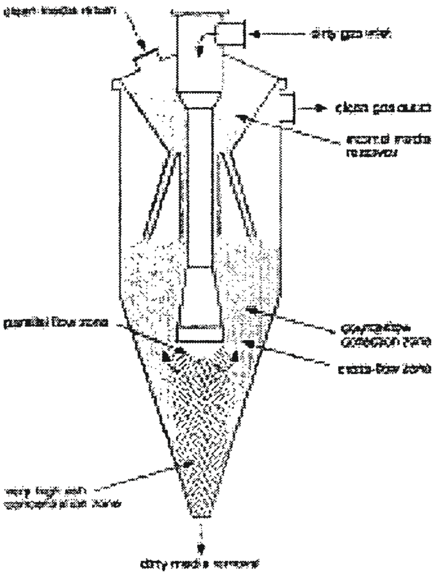

Abbildung 3: Kawazaki Wanderbettfilter

Kugeln). Diese Filterart wird in kleinen Vergasern hauptsächlich zur kombinierten Staub und Teerabscheidung eingesetzt. Problematisch stellt sich dabei die Entsorgung des beladenen Filtermaterials dar, da dies aufgrund der Teerbeladung hochgiftig ist und teuer entsorgt werden muss. Eine Weiterentwicklung des diskontinuierlichen Schüttschichtfilters stellt der Wanderbettfilter dar. Bei diesem wird das beladene Filtermaterial kontinuierlich abgezogen und durch frisches ersetzt. Das beladene Filtermaterial kann extern aufbereitet werden. Ein Beispiel für einen solchen Filter ist der Kawazaki-Wanderbettfilter, der in Abb. 3 dargestellt ist.

Schüttschichtfilter sind weitgehend unempfindlich gegen korrosive Gasbestandteile, können bei hohen Temperaturen eingesetzt werden, besitzen einen niedrigen Druckverlust und können ein einem weitem Druckbereich eingesetzt werden. Jedoch fehlen bei Wanderbettfiltern die großtechnischen Demonstration und brauchbare Regenerationskonzepte. Auch die Abscheideleistung von submicronen Partikel, sowie bei Schüttschichtfiltern die Ausbildung einer Oberflächenschicht auf dem Filterbett stellen ein Problem dar /Abatzoglou et al., 2001/.

Kerzenfilter

Kerzenfilter werden manchmal auch als Heißgasfilter bezeichnet, da sie eine Möglichkeit darstellen, die fühlbare Wärme im Produktgas zu erhalten (Abb. 4). In den meisten Fällen wird ein Zyklon als Grobpartikelab-

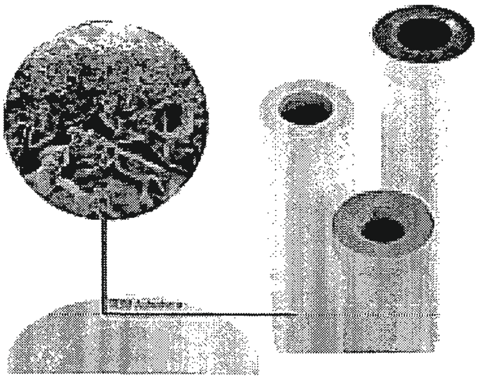

Abbildung 4: Keramischer Kerzenfilter

scheider den Kerzenfilter vorgeschaltet. Diese Filter erreichen sowohl für große als auch kleine Partikeldurchmesser einen sehr hohen Abscheidegrad. Als Filtermittel werden Keramik oder Metall eingesetzt. Keramik hat dabei den Nachteil, dass Reaktionen mit Alkalien zur Zersetzung oder zur Verstopfung der Filterkerzen führen können. Bei Metallfiltern wurden von Herstellern Probleme durch verkleben der Oberfläche durch Teer oder zu hohe Feuchte in Verbindung mit Staub genannt /Alvin, 1998/. Vielversprechende Weiterentwicklungen auf dem Gebiet der keramischen Filter in Zukunft eine gleichzeitige Staub und katalytische Teer und Ammoniakabscheidung an einem Filter erlauben. Derzeit befinden sich katalytische Keramikfilter allerdings erst im Versuchs- und Demonstrationsstadium. Die anfänglichen Probleme bei Keramikfiltern auf rasche Temperaturwechsel konnte weitgehend in den Griff bekommen werden. Diese Filter können bis zu 900 °C betrieben werden und eignen sich daher vor allem für die Kopplung der Vergasung mit einer Gasturbine und in der Zukunft mit einer Hochtemperaturbrennstoffzelle. Da die Filterkerzen sehr teuer sind, ist es wünschenswert den zu filternden Gasstrom und damit die Anzahl der benötigten Filterkerzen möglichst klein zu halten, welches entweder mittels einer Druckvergasung oder durch eine Dampf-/Luftvergasung erreicht werden kann.

Elektrostatische Filter

Je nach Abreinigungsmethode unterscheidet man zwischen trockenen Elektrofiltern und nassen Elektrofiltern. Beim trockenen Elektrofilter wird der gesammelte Staub mechanisch durch Klopfen periodisch entfernt. Diese Filter können bei Temperaturen bis über 500 °C betrieben werden. Nasse Elektrofilter, welche die gesammelten Partikel mittels eines dünnen Wasserfilmes entfernen, können nur bis zu einer Temperatur von 65 °C betrieben werden. Sowohl mit trockenen als auch nassen Elektrofiltern können sehr hohe Abscheidegrade für Partikel erreicht werden. Weiter ist mit Nasselektrofiltern eine gleichzeitige Staub und Teerentfernung möglich, wie auch eine teilweise Abscheidung von NH_3, HCl und H_2S[1] sofern diese Komponenten in abgeschiedenen Wassertröpfchen gelöst sind.

Elektrofilter zeichnen sich durch einen niedrigen Druckverlust und hohe Filtrationsraten, bei niedrigen Betriebskosten und kontinuierlichem

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[1] Nach Angaben der Firma Beth

Betrieb aus. Allerdings liegt der Einsatzbereich aufgrund ihrer Größe und Kosten meist in Mittel- und Großanlagen /Abatzoglou et al., 2001/. In letzter Zeit wurden jedoch auch in den Anlagen Harboore und Wr. Neustadt im Leistungsbereich von 1 bzw. 0,5 MW_{el} ein Nasselektrofilter eingesetzt.

Wäscher

Wäscher benutzen eine Waschflüssigkeit, meist Wasser, um Partikel aus dem Gasstrom zu entfernen. Der häufigst angewandte Wäschertyp zur Partikelentfernung ist der Venturiwäscher, der zwar eine hohe Partikelabscheiderate, jedoch auch einen hohen Druckverlust von 30 bis 200 mbar aufweist. Außerdem braucht dieser, wie alle Nassverfahren eine Eintrittstemperatur unter 100 °C, welches eine Kühlung des Gases erfordert. Dem Venturiwäscher ist meist ein Demister nachgeschaltet, um die mitgerissenen Flüssigkeitströpfchen abzuscheiden. Mit einem Venturiwäscher lassen sich Reingaskonzentrationen von 10-20 mg/Nm³ erzielen. Wäscher mit Einbauten werden aufgrund ihrer geringen Abscheiderate und wegen der Verstopfungsgefahr für die Staubentfernung nur selten eingesetzt.

Teer

Teer ist eine komplexe Mischung aus oxydierten organischen Verbindungen. In dieser Arbeit werden alle Komponenten mit einem Molgewicht größer als Benzen (78 g/mol) als Teer bezeichnet. Teer führt zu Problemen, wenn das Gas vor der Nutzung gekühlt oder komprimiert werden muss. Die Menge an Teer im Produktgas hängt stark von der Vergasungstemperatur, bei niedrigen Temperaturen entstehen bedeutend größere Teermengen als bei hohen, vom Reaktordesign, von der eingesetzten Biomasse und von der Prozessführung ab.

Teerentfernung

Alle Biomassevergasungssysteme produzieren Teer, daher ist es wichtig bereits im Vergaser durch Primärmaßnahmen zu versuchen den Teergehalt zu minimieren (Reaktordesign, Prozessführung, Katalysatoren). Meist reicht die Reduktion durch diese Primärmaßnahmen nicht aus, daher müssen weitere Gasreinigungsstufen nachgeschaltet werden. Jedoch stellt Teer nicht nur ein Problem bei der Gasreinigung und Gasnutzung dar, sondern dieser reduziert auch den Kaltgaswirkungsgrad der Anlage, sofern der abgeschiedene Teer nicht rückgeführt wird. Problematisch stellt sich auch die Entsorgung des anfallenden Teers dar.

Zur Entfernung des Teers stehen im Prinzip zwei Wege offen:

- Meistens werden **physikalische Methoden** angewandt um diesen abzuscheiden. Dazu werden meist Wäscher oder Elektrofilter eingesetzt. Diese Methode erfordert allerdings eine Kühlung des Gases vor der Abscheidung der Teere in kondensierter Form.
- Zwei andere Möglichkeiten stellen die **thermische** oder **katalytische Teerentfernung** dar, wobei der Teer zu stabilen Gaskomponenten umgewandelt wird. Die gebildeten Gaskomponenten können den Heizwert des Gases erhöhen.

Physikalische Teerentfernung

Im Folgenden werden die spezifischen Verfahren besprochen, wobei nur mehr die Unterschiede der Verfahren zur Staubentfernung erwähnt werden.

Wäscher

Der Wäscher stellt die am häufigsten angewandte Methode der Teerentfernung dar, obwohl dieser, mit Wasser betrieben, keine guten Abscheidegrade erreicht. Wie bereits eingehend erwähnt, muss der gasförmige Teer zur Koalieszenz gebracht werden. Dazu wird das Gas gesättigt und gekühlt, die entstandenen Teertröpfchen werden im nachfolgenden Wäscher durch Kollision mit Wasser vergrößert, bevor diese vom Gasstrom abgetrennt werden. Damit können Teerwerte im Reingas von 20-40 mg/Nm^3 erreicht werden. Für die Teerentfernung werden die unterschiedlichsten Wäschertypen eingesetzt: Waschtürme, Rotationswäscher, Prallwäscher und Venturiwäscher. Vor kurzem wurde das erste Mal ein Ölwäscher erfolgreich zur Teerabscheidung betrieben. Dieser hat den Vorteil, dass sich der Teer im Gegensatz zu Wasser in Öl zusätzlich löst, womit man Reingaswerte um die 10 mg/Nm^3 erreicht.

Eine Neuentwicklung auf diesem Gebiet stellt der OLGA Prozess dar. Dabei wird anstatt Wasser ein organisches Lösungsmittel eingesetzt. Die Eintrittstemperatur in den Wäscher muss über der Kondensationstemperatur der Teere liegen und befindet sich um die 400 °C. Die Austrittstemperatur soll, um einen Abwasseranfall im Wäscher zu vermeiden, höher als die Kondensationstemperatur von Wasser sein (>100 °C). Das Lösungsmittel wird in einer zweiten Kolonne gestripped, das teerreiche Gas in den Vergaser rückgeführt. Der Vorteil in diesem Verfahren liegt darin, dass kein weiterer Abfallstrom anfällt und die Kondensationstemperatur der Teere im Reingas sehr tief ist (bis -17 °C). Diese nachhaltige Entfernung ermöglicht einen guten Einsatz des gereinigten Gases für Synthesegasanwendungen, allerdings steht die großtechnische Erprobung dieses Verfahrens noch aus.

Nasselektrofilter

Für die Teerentfernung werden Draht-Röhrenelektrofilter Plattenelektrofiltern vorgezogen. Das Gas wird vor Eintritt mit Wasser gesättigt, die entstanden Flüssigkeitströpfchen und Partikel danach im Elektrofilter abgeschieden. Zur Entfernung des kondensierten Teeres von den Elektroden wird meist Wasser eingesetzt, wobei die Menge je nach Teerart variiert. Wie von der Firma Beth berichtet reicht meist die Fließfähigkeit des Teeres aus, um von den Elektroden abzutropfen, wodurch keine zusätzliche Wassereindüsung im Filter notwendig ist.

Ein großer Vorteil dieses Gasreinigungsverfahrens ist die Möglichkeit einer kombinierten Staub und Teerabscheidung, wobei sehr hohe Reinheitsgrade erreicht werden können (<10 mg/Nm^3).

Filter mit Filtermedium

Durch die Kondensation der Teere zur klebrigen Partikeln ist die Abreinigung von teerbeladenen Filtermedien schwierig. Noch problematischer stellt sich die Abreinigung eines Filterkuchens der aus Partikeln und kondensierten Teeren besteht dar, welches meist der Fall ist. Neuerdings konnte durch Precoatisierung eines Gewebefilters das erste Mal in einer Biomassevergasung gezeigt werden, dass die Abreinigung trotzt Teer-Staubfilterkuchen problemlos möglich ist (Firma Austrian Energy).

Schüttschichtfilter mit Sand, Sägemehl und ähnlichem werden hauptsächlich bei Kleinanlagen eingesetzt. Ihre Anwendung ist aber aufgrund der Rückstände und deren Entsorgung problematisch. In Großanlagen werden sie aufgrund des aufwendigen Betriebes und der damit verbundenen hohen Kosten nicht eingesetzt. Eine mögliche Lösung bieten kontinuierlich arbeitende Schüttschichtfilter (siehe Partikelabscheidung), die sich aber noch im Entwicklungsstadium befinden.

Zyklone
Werden in Zyklonen Teer und Partikel gleichzeitig abgeschieden, so entsteht ein klebriger Belag, der sehr schwer zu entfernen ist. Auch wenn Partikel vor den Teeren abgeschieden werden, ist es schwierig Zyklone zur Teerabscheidung einzusetzen, da diese eine schlechte Abscheideleistung von Partikeln unter 1 µm aufweisen. Eine Weiterentwicklung, die sich allerdings noch im Versuchsstadium befindet, ist der Rotierende Partikel Separator (siehe Partikelabscheidung), welcher kleinere Partikel abscheiden kann und mit Lösungsmittel rückgespült wird.

Katalytische Teerabscheidung
Bei der katalytischen Teerabscheidung wird der Teer mittels eines Katalysators bei 800-900 °C umgesetzt und zerstört. Dabei wurden im Labor Umsatzraten von über 99 % erreicht. Es gibt die Möglichkeit den Katalysator direkt im Vergasungsreaktor oder in einem externen Reaktor einzusetzen. Bei direktem Einsatz in einem Wirbelschichtvergaser kann es durch Abrieb zu hohen Katalysatorverlusten führen, während bei Festbettvergasern aufgrund der geringen Verweilzeit der Umsatz meist nicht vollständig erfolgen kann. Der verwendete Katalysator muss daher genau auf das System abgestimmt sein. Ein extern angeordneter Reaktor ermöglicht eine bessere Temperatureinstellung und auch ein besseres Kontrollieren des Abriebs. Dieses wird allerdings mit einem deutlich höheren apparatetechnischen Aufwand erreicht.

Nicht metallische Katalysatoren wie zum Beispiel Dolomite, Zeolithe und Kalkspat sind relative kostengünstig und sind gegenüber Verunreinigungen nicht so empfindlich. Metallische Katalysatoren werden kommerziell in der Petrochemie eingesetzt. Typische Vertreter sind Ni, Ni/Mo; Ni/Co/Mo; NiO, Pt, Ru Katalysatoren /Corella et al., 1995/ /Corella et al., 1998/ /Corella et al., 1999a/ /Corella et al., 1999b/ /Caballero et al., 2000/ /Delgado et al., 1996/ /Delgado et al., 1997/. Diese Katalysatoren haben den Vorteil, dass sie neben Teer, auch in der Lage sind, den im Produktgas vorhandenen Ammoniak zerstören, jedoch ist die Lebensdauer dieser Katalysatoren in der Biomassevergasung noch nicht ausreichend getestet und sie sind teuer.

Thermische Teerzerstörung
Teere können auch ohne Katalysatoren thermisch zerstört werden, wofür sehr hohe Temperaturen erforderlich sind. Allerdings ist es schwer Teere

aus Biomassevergaser vollständig thermisch zu cracken. Durch die erforderlichen hohen Temperaturen ist der Spagat zwischen Wirtschaftlichkeit, Betrieb und völliger Teerzerstörung fast nicht zu bewerkstelligen /Bridgwater, 1995/.

Prinzipiell gibt es drei Möglichkeiten Teere thermisch zu zerstören:

- Durch eine Erhöhung der Verweilzeit nach der Vergasung, zum Beispiel im Freeboard bei Wirbelschichtvergasern.
- Durch direkten Kontakt mit einer heißen Oberfläche. Die Beheizung der Oberfläche, benötigt viel Energie, welches sich negativ auf den Wirkungsgrad der Anlage auswirkt, weiter wird meist nur eine unvollständige Zersetzung des Teers erreicht.
- Durch die partielle Oxidation des Produktgases mit Luft oder Sauerstoff bei über 1200 °C, welches den CO_2 Anteil im Produktgas erhöht, den Wirkungsgrad erniedrigt und bei Sauerstoffeinsatz hohe Kosten verursacht.

Eine weitere Möglichkeit der thermischen Teerzersetzung bietet der elektrisch erzeugte Plasmabogen, bei dem zwischen zwei Elektroden in einem Plasmabogen /Neeft, 1999/, /Heesch van et al., 1998/ die notwendige Temperatur zur Teerzerstörung erreicht wird. Dieses Konzept befindet sich allerdings noch im Versuchsstadium.

Alkalien

Über 800 °C verdampfen die in der Biomasse enthaltenen Alkalien und können auf kühleren Flächen im Gasstrom Ablagerungen bilden. Verdampfte Alkalien kondensieren ab einer Temperatur von 600 °C wieder in Form kleiner Partikeln (<5 µm) auf kalten Oberflächen.

Gasförmige Alkalien können Heißgasfilter wie zum Beispiel Keramikfilter beschädigen, weshalb das Gas vor einer Filtration unter 600 °C abgekühlt werden sollte. Die kondensierten Alkalien müssen abgeschieden werden, da diese bei hohen Temperaturen wie zum Beispiel in Gasturbinen wieder verdampfen und dann zu Heißgaskorrosion der Turbinenschaufeln führen, da sie deren schützende Oxidschicht entfernen.

Alkalienentfernung

Stand der Technik der Alkalientfernung ist, das Produktgas auf unter 600 °C abzukühlen und dann die entstandenen Partikel mit den Methoden der Staubabscheidung (siehe Partikelabscheidung) zu entfernen. Diesem Verfahren haftet allerdings der große Nachteil an, dass durch die Kühlung des Gases fühlbare Wärme verloren geht, welches den Wirkungsgrad der Anlage vermindern kann.

Eine sich noch im Versuchstadium befindliche Heißgasreinigung nutzt die Möglichkeit, Alkalien mit aktiviertem Bauxit zu adsorbieren. Dieser Filter lieferte, bei ersten Tests im Temperaturbereich zwischen 650 und 750 °C, Abscheidegrade für Kalium und Natrium von 95 beziehungsweise 99 % /Stevens, 2001/.

Stickstoffverbindungen

50-80 % des brennstoffgebunden Stickstoffes wird bei der Vergasung in Ammoniak umgewandelt, kleinere Anteile auch in andere Stickstoffverbindungen wie zum Beispiel Hydrogencyanid.

Eine Entfernung beziehungsweise Reduktion von Stickstoffverbindungen (meist NH_3) ist in vielen Fällen notwendig, da diese, wenn das Produktgas verbrannt wird, zu NO_x umgewandelt werden und die NO_x-Emissionen meist einem Grenzwert unterliegen. Weiter wird vermutet, dass NH_3 die Schmierfähigkeit des Motoröls bei motorischer Nutzung des Produktgases herabsetzt und sollte aus diesem Grund entfernt werden.

Entfernung von Stickstoffverbindungen

Grundsätzlich gibt es folgende Möglichkeiten Stickstoffverbindungen im Gasstrom zu vermeiden oder zu entfernen:

- Als Standard zur Entfernung aus dem Produktgasstrom wird heutzutage die Nasswäsche eingesetzt, welches ein kommerzielles erprobtes Verfahren darstellt. Dabei wird das Produktgas zuerst gekühlt und dann mittels eines Wäschers von den Stickstoffverbindungen gereinigt.

- Auf katalytischem Weg mittels Katalysatoren ähnlich derer, welche auch für das Teercracken eingesetzt werden. Dabei können Dolomite, Nickel- und Eisen-basierende Katalysatoren im gleichen Temperaturbereich eingesetzt werden, in denen diese auch Teer cracken können. In Versuchen konnten bei 900 °C über 99 % der Stickstoffverbindungen zerstört werden, welches allerdings bis jetzt nur im Labormaßstab nachgewiesen wurde. Problematisch stellen sich dabei Katalysatorgifte (Schwefel, Halogene) dar, die den Katalysator schädigen. Großtechnische Erfahrungen fehlen, wobei eine gleichzeitige Entfernung von Teer und Stickstoffverbindungen durchaus wünschenswert wäre.

Schwefelverbindungen

Da der Schwefelgehalt in frischem Holz normalerweise niedrig ist, wird, sofern das Produktgas für Verbrennungszwecke eingesetzt wird, meist auf eine Entfernung von Schwefelverbindungen verzichtet (meist H_2S). Für Brennstoffzellen und Synthesegasanwendungen ist allerdings in jedem Fall eine Schwefelentfernung notwendig, da diese Gasnutzungstechnologien Konzentrationen von unter 1 ppm beziehungsweise 0,1 ppm Schwefel im Produktgas erfordern. Auch beim Einsatz von kontaminiertem Holz ist meist eine Abtrennung der Schwefelverbindungen notwendig.

Entfernung von Schwefelverbindungen

Eine Entfernung der Schwefelverbindungen kann mittels zweier Verfahrensarten erfolgen:
- Absorptive Verfahren
- Adsorptive Verfahren

Absorptive Verfahren
Zur Entfernung der Schwefelverbindungen kann ein **basischer Wäscher** verwendet werde. Dabei handelt es sich um eine erprobte Technologie, die allerdings Reststoffe in Form von Abwasser, welches aufgearbeitet werden muss, verursacht.

Für die Abtrennung größerer Schwefelmengen im Produktgas sollten regenerative **Technologien der Kohlevergasung** beziehungsweise der

Synthesegasproduktion herangezogen werden, in denen durch ein Lösungsmittel der Schwefel entfernt wird (Rectisol, Purisol, DEA, MDEA). Die abgeschiedenen Schwefelverbindungen in Form eines H_2S-haltigen Gases werden meist in einer Clausanlage zu elementarem Schwefel aufgearbeitet. Aufgrund des Aufwandes ist es leicht ersichtlich, dass sich diese Verfahren nur bei Großanlagen ökonomisch rechnen beziehungsweise bei Anlagen die in einen Chemieverbund integriert sind.

Adsorptive Verfahren

Ein kommerzieller Prozess der sich auch für kleine Schwefelfrachten eignet, ist Schwefel in einem **Zink-Oxid-Bett** bei 350–450 °C zu adsorbieren. Das Zinksulfid, welches bei der Adsorption entsteht, muss entsorgt werden. Dieser Prozess hat den Vorteil neben dem Erreichen von äußerst niedrigen Schwefelkonzentrationen im ppb-Bereich, die fühlbare Wärme des Gases weitgehend zu erhalten. Allerdings ist auch dieser Prozess nicht reststofffrei.

Ein weiterer Prozess, der sich derzeit im Versuchstadium befindet, ist die regenerative Adsorption von Schwefel an **Metall-Oxid-Pellets**. Dabei wird bei 500 °C der Schwefel an Oxiden aus Titan, Eisen, Magnesium oder Aluminium gebunden. Das entstehende Metallsulfid muss mit Dampf regeneriert werden, wobei H_2S als Abgas entsteht /Berg et al., 1996/.

Eine weitere Methode ist das sogenannte **Trockenadditivverfahren**, bei dem ein Feststoff wie zum Beispiel Dolomit oder Kalk zum Adsorbieren des Schwefels in das Produktgas eingebracht wird. Dieses Verfahren befindet sich allerdings erst im Versuchstadium, wobei Abscheidegrade von über 85 % im Labor erreicht werden. Problematisch stellt sich das Deponieren des gebrauchten Materials dar, wenn die CaS-Konzentrationen zu hohe Werte erreichen. Auch der Vergasung nachgeschaltete Teercracker mit Dolomit als Bettmaterial können die Schwefelwerte im Produktgas deutlich senken.

Weiter kann noch **Aktivkohle** zur Entfernung des Schwefels eingesetzt werden. Dieses Verfahren eignet sich nur bei geringen Konzentrationen von Schwefel im Produktgas, da die beladene Aktivkohle entweder unter Abgabe eines schwefeligen Gases regeneriert oder entsorgt werden muss.

Halogenverbindungen

Die Konzentration an Halogenverbindungen ist, wie auch die der Schwefelverbindungen, gering, sofern frische Biomasse eingesetzt wird. Daher kann bei Verwendung des Produktgases für die motorische Nutzung meist auf eine Entfernung der Halogenverbindungen (hauptsächlich HCl) verzichtet werden.

Entfernung von Halogenverbindungen

Sollen dennoch die vorhandenen Halogene entfernt werden, so wird meist ein **Wäscher** eingesetzt. Diese Technologie ist kommerziell verfügbar und erprobt.

Auch kann die Entfernung gleichzeitig mit den Schwefelverbindungen erfolgen, dabei können **Sorptionsmittel** wie zum Beispiel Kalk eingesetzt werden. Auch diese Technologie ist erprobt und verfügbar. Beide Technologien liefern allerdings einen Rückstand der entsorgt beziehungsweise aufgearbeitet werden muss.

Betriebserfahrungen RENET

Zum Abschluss sollen noch Betriebserfahrungen von RENET mit unterschiedlichen Abscheidesystemen an Anlagen der TU-Wien, in Güssing und in Wr. Neustadt dargestellt werden.

Bei der Anlage der TU-Wien handelt es sich, wie auch bei der Anlage in Güssing, um einen Wirbelschichtdampfvergaser. An dieser Anlage wurden unterschiedliche Gasreinigungssysteme hinsichtlich ihrer Partikel- und Teerabscheidung getestet. Als erste Reinigungsstufe (Partikelabscheidung) wurden ein Schüttschichtfilter (mit unterschiedlichen Bettmaterialien), ein Zyklon und ein Schlauchfilter (mit unterschiedlichen Precoatmaterialien) getestet. In folgender Tabelle sind die gemessenen Abscheidegrade der getesteten Systeme dargestellt. Die angegebene Reingaskonzentration wurde aufgrund der Schwankungen bei den einzelnen Messwerten aus dem Abscheidegrad und einer typischen Rohgaskonzentration (15 g/Nm^3) errechnet.

Ebenfalls in dieser Tabelle dargestellt ist die Partikelabscheidung der Quenche, welche bei der Anlage in Wr. Neustadt zur Produktgasabkühlung und als erste Reinigungsstufe eingesetzt wird. Aufgrund dessen, dass es sich bei dieser Vergasungsanlage um einen Festbettvergaser handelt (Zweizonenvergaser), ist auch die Rohgaskonzentration an Partikel wesentlich niedrigerer als bei einer Wirbelschicht (35 mg/Nm³).

Tabelle 1: Partikelabscheidung (1 Technikum, 2 Güssing, 3 Wr. Neustadt)

Abscheider	**Abscheidegrad**	**Reingaskonzentration**
Schüttschichtfilter[1]	90 %	1,5 g/Nm³
Zyklon[1]	90 %	1,5 g/Nm³
Schlauchfilter[1,2]	> 99 %	< 25 mg/Nm³
Quenche[3]	40 %	20 mg/Nm³

Mit den eben erwähnten Abscheidern konnte neben der Partikelkonzentration auch die Teerkonzentration im Produktgas reduziert werden. Allerdings ist diese Teerabscheidung für die Nutzung des Produktgases in einem Gasmotor unzureichend. Daher ist eine zweite Teerabscheiderstufe erforderlich. Im Falle der Technikumsanlage und der Güssinger Anlage ist dies je ein Lösungsmittelpackungswäscher. In Wr. Neustadt kommt ein nass arbeitender Elektrofilter zum Einsatz. Auch hier wurde wiederum für die Partikelabscheiderstufe ein typischer Wert für die Rohgasteerkonzentration von 4 g/Nm³ für die Technikums- und die Güssinger Anlage und 400 mg/Nm³ für die Wr. Neustädter Anlage angenommen und mit dieser und dem gemessenen Abscheidegrad die Reingaskonzentration errechnet. Für den Wäscher wurde eine Rohgaskonzentration von 1,7 g/Nm³ angenommen.

Der Abscheidegrad für Teere wird allerdings von mehreren Parametern beeinflusst. So ist beispielsweise, wie auch Abb. 5 zeigt, der Abscheidegrad des Schlauchfilters vom verwendeten Precoatmaterial und von der Betriebstemperatur des Filters abhängig.

Zusammenfassend kann gesagt werden, dass eine zufrieden stellende Partikel- und Teerabscheidung mit den Gasreinigungssystemen, wie sie bei den beiden Anlagen in Güssing (Schlauchfilter und Lösungsmittelwäscher) und Wr. Neustadt (Quenche und Nasselektrofilter) eingesetzt werde, sichergestellt ist.

Ein direkter Vergleich zeigt, dass sowohl ein höhere Druckverlust, als auch die höheren Betriebskosten bei der Güssinger Gasreinigungsanlage

Tabelle 2: Teerabscheidung (1 Technikum, 2 Güssing, 3 Wr. Neustadt)

Abscheider	Hilfsmittel	Temperatur	Abscheide-grad	Reingas-konzentration
Schüttschichtfilter[1]	Olivin	150 °C	30 %	2,8 g/Nm³
	Al_2O_3	150 °C	50 %	2 g/Nm³
Zyklon[1]	-	220 °C	14 %	3,4 g/Nm³
Schlauchfilter[1,2]	Steinmehl	150 °C	40 %	2,4 g/Nm³
	Kalkhydrat	150 °C	57 %	1,7 g/Nm³
	Sorbalit	150 °C	78 %	880 mg/Nm³
	Aktivkohle	150 °C	87 %	520 mg/Nm³
Wäscher[1]	HEL, RME	25 °C, 55 °C	97 %	50 mg/Nm³
Quenche[3]	Wasser	40 °C	20 %	325 mg/Nm³
Nasselektrofilter[3]	Wasser	50 °C	92 %	25 g/Nm³

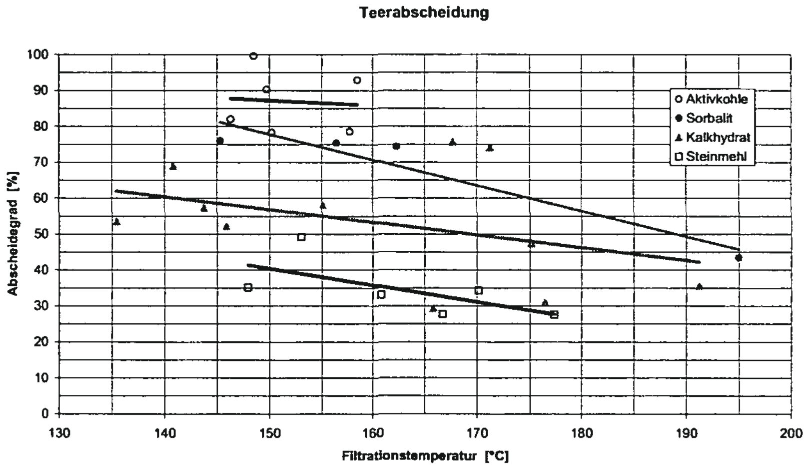

Abbildung 5: Teerabscheidung bei Schlauchfilteranlage (Technikum)

anfallen. Allerdings wird bei der Güssinger Anlage durch Vorschalten eines Produktgaskühlers (von 850 °C auf 150 °C) zusätzlich Wärme aus dem Produktgas entnommen, welche, im Gegensatz zur Kühlung des Produktgases in Wr. Neustadt mittels einer Quenche (von 650 °C auf 50 °C), in das Fernwärmenetz eingespeist werden kann.

Zusammenfassung

Zusammenfassend kann über den derzeitigen Stand der Gasreinigung in der Biomassevergasung gesagt werden, dass mit den heute verfügbaren Technologien eine Reinigung des Rohgases auf die für die Gasnutzung notwendigen Anforderungen technisch machbar ist.

Viele Firmen bieten hierfür Gasreinigungssystemen an, jedoch meist auf konventioneller Basis mittels nasser Gasreinigung. Diese Systeme sind jedoch nicht immer zielführend, da auch die meisten Firmen wenig Erfahrung auf dem Gebiet der Reinigung von Holzgas besitzen. Weiteres können die meisten Firmen auch keine Referenzen auf diesem Gebiet vorweisen.

Aufgrund der gemachten Erfahrung sollte beim Bau von neune Vergasungsanlagen auf bereits erprobte Technologien zurückgegriffen werden. Hier haben sich der precoatisierte Gewebefilter, der keramisch oder metallische Kerzenfilter, und die Kombination Quench-Nasselektrofilter für die Staubabscheidung, der RME-Wäscher wie auch der Nasselektrofilter bei der Teerabscheidung bewährt. In letzter Zeit sind zwar interessante neue Technologien auf dem Markt der Gasreinigung aufgekommen, jedoch gibt es bei diesen noch keine ausreichende großtechnische Erfahrung. Diese Technologien bedürfen noch intensiver Untersuchungen. Dabei ist vor allem deren Langzeitverhalten wichtig, damit diese erfolgversprechend und ökonomisch in neuen Anlagen eingesetzt werden zu können.

Bei der Integration der Gasreinigung in Gesamtkonzepte sollte auf die Abstimmung dieser mit den restlichen Anlagenkomponenten größter Wert gelegt werden. Auch sollte die Rückführung etwaiger anfallender Reststoffe in den Prozess von Anfang an versucht werden. Dadurch können die Entsorgungskosten gesenkt und leichter ein wirtschaftlicher Betrieb erreicht werden.

Abschließend ist festzustellen, dass die Gasreinigung sich in der schwierigen Position befindet mit möglichst geringen Kosten ein ausreichend sauberes Produktgas der Gasnutzung zur Verfügung zu stellen. Nur durch die konsequenten Weiterentwicklung und Kostensenkung der Technologie können ökonomisch arbeitende Vergasungsanlagen geschaffen werden.

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II. PAPER

Bolhàr-Nordenkampf, M.; Vogel, A.

„Bewegtbett-Vergaser zur Stromerzeugung - Lessons learned“

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Bewegtbett-Vergaser zur Stromerzeugung – Lessons learned

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Kurzfassung

Die thermochemische Vergasung von Biomasse bietet die Möglichkeit Strom und Wärme mit einem hohen Gesamtwirkungsgrad zu erzeugen, dennoch sind bis heute nur Demonstrationsanlagen in Betrieb. Ausgehend davon ist es notwendig, bereits bestehende Demonstrationsanlagen zu analysieren und damit das verfügbare Know-How zusammenzutragen, sowie entsprechende Schlussfolgerungen für zukünftige Weiterentwicklungen abzuleiten.

Daher wurden in dieser Untersuchung, getrennt nach den Bereichen Gaserzeugung, Gasreinigung und Gasnutzung, vielversprechende Systemkomponenten der betrachteten Anlagen identifiziert. Ausgehend von diesen identifizierten Systemkomponenten werden für zukünftige Anlagen vielversprechende Konzepte abgeleitetet, dabei ist auf eine sinnvolle und machbare Kombination der Komponenten zu achten.

Durch die Weiterverfolgung dieser Ansätze sollte eine kommerzielle und wirtschaftliche Umsetzung der Bewegtbettvergasung bereits in den nächsten Jahren möglich sein.

Einleitung

Die thermochemische Vergasung von Biomasse erreicht, im Vergleich zu konventionellen Technologien auf Verbrennungsbasis zur Umwandlung von Biomasse, einen deutlich höheren elektrischen Wirkungsgrad bei gleichzeitiger Möglichkeit der Auskopplung von Wärme und somit eine sehr hohe Brennstoffausnutzung. Die Technologie der Vergasung stellt daher, wegen der hohen technischen Potenziale an Bio-Brennstoffen, eine vielversprechende Möglichkeit zur Ausweitung des Anteils an erneuerbare Energie am Strom- und Wärmemarkt dar.

Obwohl die Technologie der Vergasung von fossilen Brennstoffen schon während des zweiten Weltkrieges einen großen Entwicklungsschub durchgemacht hat und auch nachfolgend stetig weiterentwickelt wurde (Kohlevergasung), konnte diese Technologie beim Einsatz von Biomasse als Brennstoff bis heute nicht die geforderte Marktreife erreichen. Dieses zeigt auch der Umstand, dass bis heute weltweit keine kommerziellen Anlagen in Betrieb sind.

Zahlreiche Forschungsanlagen und Demonstrationsanlangen wie die Anlage Umsicht, Värnamo, Vermont, ARBRE, Güssing, Carbo-V, Blauer Turm wurden in den letzten 20 Jahren errichtet und teilweise betrieben, jedoch konnten die meisten Anlagen nach beendetem Demonstrationsbetrieb nicht kontinuierlich weiterbetrieben werden. Die Gründe hierfür sind häufig in Problemen der Wirtschaftlichkeit und weniger in unlösbaren oder ungelösten technischen Problemen zu finden. Diese Anlagen bieten bereits eine Reihe von vielversprechenden Systemaspekten, allerdings auch eine Vielzahl von offenen technischen und systemtechnischen Fragen.

Zur erfolgreichen Weiterentwicklung und Optimierung der Biomassevergasung, bei gleichzeitiger wirtschaftlicher Darstellung, ist es daher erforderlich, die bestehenden Verfahren detailliert zu analysieren und vielversprechende Systemaspekte und -ansätze zu identifizieren. Dies ist insofern notwendig, als dass die bei den bisherigen Projekten bereits gemachten Erfahrungen wenig Einfluss gefunden haben und bereits bestehendes Wissen nicht genutzt wurde. Die Zusammenführung des verfügbaren Know-how ist notwendig, um Fehler der Vergangenheit zu umgehen und kommerzielle Anlagen zu schaffen, die sowohl technisch als auch wirtschaftlich darstellbar sind.

Ziel dieser Analyse ist es somit, die gemachten Erfahrungen auszuwerten und darzustellen. Dazu werden basierend auf dem Stand der Technik der Bewegtbettvergasung zunächst für die Systemelemente der Vergasung, Gasreinigung und Gasnutzung Evaluierungen und Bewertungen durchgeführt. Diese Teilsystembewertungen werden durch eine

Evaluierung von Gesamtsystemen ergänzt, um Systemansätze und Konzepte für die Weiterentwicklung der Bewegtbettvergasung zu liefern.

Einteilung der Verfahren

Die Bewegtbettvergasung kann in *ein-* und *mehrstufige* Verfahren unterteilt werden, wobei weiter zwischen der *autothermen* und der *allothermen* Vergasung unterschieden wird.

Bei der *autothermen* Vergasung wird die für die endotherme Vergasungsreaktion notwendige Energie durch eine Teilverbrennung des Brennstoffes mit dem Vergasungsmedium (Luft oder Sauerstoff) im Reaktor selbst erzeugt.

Bei der *allothermen* Vergasung wird die notwendige Energie extern zugeführt. Dies kann durch Wärmetauscher, deutlich zweckmäßiger aber durch zirkulierendes Bettmaterial oder andere Wärmeträger erfolgen, welches extern aufgeheizt wird. Als Vergasungsmedium kommt hier Wasserdampf zum Einsatz. Durch die Vermeidung der Teilverbrennung des Brennstoffes im Reaktor, vor allem aber durch das (im Gegensatz zu Luft) stickstofffreie Vergasungsmittel Wasserdampf kann ein deutlich höherer Heizwert des Produktgases erreicht werden.

Bei den *mehrstufigen* Verfahren erfolgt die Pyrolyse des Brennstoffes getrennt von der Vergasung in einem eigenen Reaktor, wobei diese extern oder ebenfalls durch Teilverbrennung beheizt wird. Die Pyrolyseprodukte (teerhaltiges Gas und Koks) werden in einem zweiten Reaktor mit einem Vergasungsmedium (Luft/Sauerstoff) oder allotherm unter Energie- und Dampfzufuhr zu Produktgas umgesetzt. Die mehrstufigen Verfahren liefern ein äußerst teerarmes Gas.

Die Übersicht über diese Verfahren ist in Abb. 1 dargestellt, weitere Grundlagen zur Bewegtbettvergasung sind in Kaltschmitt /1/ zu finden.

Methodik

Um aus bestehenden Anlagen Probleme wie auch die vielversprechenden Ansätze zu identifizieren, bedarf es zunächst einer geeigneten Bewertungsmethodik, die im Folgenden dargestellt werden soll. Nach der Erhebung der Daten an ausgewählten Anlagen wurden diese einer Analyse

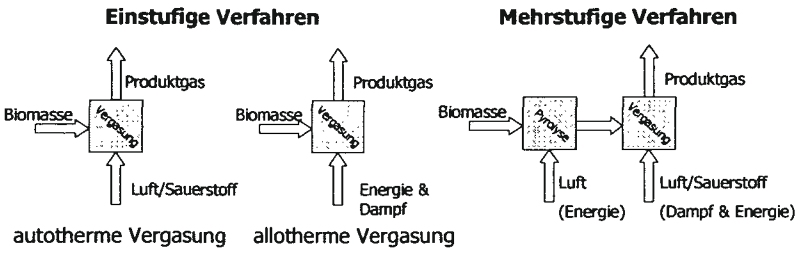

Abbildung 1: Einteilung der Verfahren

unterzogen. Diese umfasst die Einteilung und Aufschlüsselung der Verfahren. Danach wurden die einzelnen Systemkomponenten, bestehend aus Vergasung, Gasreinigung und Gasnutzung bewertet (Abbildung 2).

Abbildung 2: Systemkomponenten bei der Vergasung

In diese Bewertung flossen zudem relevante Ergebnisse ein, die aus einer umfassenden Hersteller- und Marktbetrachtung der einzelnen Systemkomponenten gewonnen wurden. Abschließend erfolgte die Bewertung des Gesamtsystems beziehungsweise des Gesamtkonzeptes, um systemkomponenten-übergreifende Aspekte zu erfassen.

Aus den gewonnen Erkenntnissen ist es nun möglich, aus vielversprechenden Systemkomponenten und der Evaluierung der Gesamtlösungen, die Grundlagen für neue, vielversprechende Verfahren zu schaffen, die auf den bisher gemachten Erfahrungen aufbauen und somit die „lessons learned" beinhalten. Mit diesen Konzepten sollte es möglich sein, alte Fehler zu vermeiden, bewerte Komponenten weiterzuentwickeln und einen Schritt in Richtung wirtschaftlichen Betrieb einer Anlage zu gehen.

Der Ablauf der beschriebenen Methodik ist in Abb. 3 nochmals dargestellt.

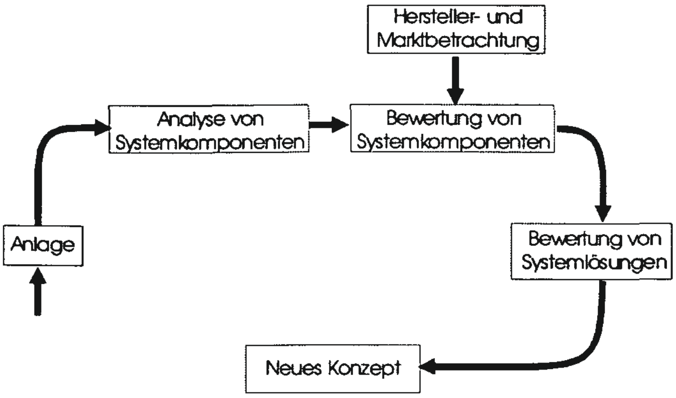

Abbildung 3: Methodik der Bewertung

Betrachtete Anlagen

Dieser Analyse und Evaluierung liegen Verfahren der autothermen, der allothermen und der mehrstufigen Verfahren zu Grunde. Als Beispiel der autothermen Vergasung wurden die Anlagen Värnamo, Umsicht und ARBRE betrachtet. Bei der allothermen Vergasung wurden die Anlagen Güssing und Vermont, bei der mehrstufigen Vergasung die Anlagen Blauer Turm und Carbo-V evaluiert. In Tabelle 1 findet sich ein Überblick über die charakteristischen Eigenschaften der jeweiligen Verfahren.

Analyse der Systemkomponenten

Ausgehend von der oben beschriebenen Methodik werden nun die einzelnen Systemkomponenten analysiert, um Charakteristika aufzuzeigen und Problemfelder zu identifizieren. Dieses erfolgt nach der in Abb. 2 dargestellten Abfolge Vergasung, Gasreinigung und Gasnutzung.

Systemkomponente Vergasung

Wie bereits unter „Einteilung der Verfahren" erläutert, kann die Bewegtbettvergasung in Untergruppen eingeteilt werden. Die Systemkompo-

Tabelle 1: Überblick der betrachteten Verfahren

	Värnamo	Umsicht	ARBRE	Güssing	Vermont	Carbo-V	Blauer Turm
Literaturstelle	2-4	5	6	7,8	9-11	12	12
Vergasungsreaktor							
Einstufig	X	X	X	X	X		
Mehrstufig						X	X
Autotherm	X	X	X			X	
Allotherm				X	X		X
Betriebsart (a... atmosphärisch, d....druck)	d	a	a	a	a	a	a
Vergasungsmittel (L...Luft, D.... Dampf, S...Sauerstoff)	L	L	L	D	D	L/S	D
Gasreinigung							
Trocken	X	X					
Nass			X	X	X	X	
Katalytisch		X	X				
Filter	X	X	X	X		X	
Wäscher			X	X	X	X	
Gasnutzung							
Gasmotor		X		X		X	
Turbine	X		X				
KWK	X	X		X			
GuD	X		X				

(X...bezeichnet vorhandene Komponenten)

nente Vergasung selbst wurde schon erfolgreich in vielen Bereichen angewandt und erprobt. So existieren Beispiele in der Mitverbrennung von Biomasse nach vorangegangener Vergasung. Die Bewegtbettvergasung ist im Gegensatz zur Festbettvergasung eine Technologie, die deutlich weiter fortgeschritten ist und in der auf einen deutlich höheren Erfahrungsschatz zurückgegriffen werden kann. Die Charakteristika der jeweiligen Technologie sollen im Folgenden dargestellt werden.

Einstufige Vergasung

Autotherme Vergasung
- mittlere Teergehalte im Produktgas
- hohe Staubgehalte im Produktgas
- geringer technischer Aufwand
- erprobte Technologie
- Möglichkeit der Reststoffrückführung
- Einsatz von katalytischem Bettmaterial möglich

Allotherme Vergasung
- mittlere Teergehalte im Produktgas
- hohe Staubgehalte im Produktgas
- Produktion eines stickstofffreies Produktgas mit hohem Heizwert ohne Sauerstoffeinsatz
- mittlerer technischer Aufwand
- Einsatz von katalytischem Bettmaterial möglich
- Möglichkeit der Reststoffrückführung
- kohlenstofffreie Asche möglich

Mehrstufige Vergasung
- sehr niedrige Teergehalte
- niedrige Staubgehalte
- hoher technischer Aufwand
- Entwicklungs- / Demonstrationsstadium

Als problematische Komponenten sind bei allen drei Technologiearten die Brennstoffzuführung und der Ascheaustrag zu nennen. Hier können vor allem Probleme mit Gasemissionen am Brennstoffeintrag sowie Probleme durch nicht funktionsfähige Ascheaustragsysteme auftreten.

Bei der mehrstufigen Vergasung muss – je nach gewählter Technologie – zusätzlich zu den bereits genannten Problemfeldern der Scale-Up bewältigt werden. Da hier meist mit indirekt eingebrachter Wärme gearbeitet wird, ist eine Maßstabsvergrößerung nicht ohne weiteres möglich, da das Volumen zur dritten Potenz, die Flächen zum Wärmeeintrag aber nur mit dem Quadrat wachsen.

Systemkomponente Gasreinigung

Die Gasreinigung stellt das Bindeglied zwischen der Vergasung und der Gasnutzung dar. Bei den Gasreinigungssystemen der betrachteten Anlagen fällt zunächst auf, dass keine der betrachteten Anlagen das gleiche Gasreinigungssystem verwendet. Dieses deutet schon darauf hin, dass die Entwicklung der passenden Gasreinigung für die Vergasung noch nicht abgeschlossen ist. Jeder Anlagenbauer hat versucht, das seiner Meinung nach vielversprechendste System umzusetzen. Die meisten dieser Ansätze führten jedoch nur teilweise oder gar nicht zum gewünschten Ziel, der Aufbereitung des Rohproduktgases auf die Anforderung der Gasnutzungstechnologie.

Aus der Analyse können folgende vielversprechenden Komponenten beziehungsweise Kombinationen identifiziert werden (in Klammern ist die bevorzugt abgeschiedene Schafstoffkomponente angeführt)

- Kombination Quench-Nasselektrofilter (Staub & Teer)
- Precoatisierte Gewebefilter (Staub)
- Lösungsmittel Wäscher (Teer)
- Heißgasreinigung mittels metallischem Kerzenfilter (Staub, Druckvergasung)

Weiterhin wurde auch Komponenten identifiziert, die noch nicht den notwendigen Entwicklungsstand erreicht haben.

Der katalytische Teercracker, sei es als Festbett oder als Bewegtbett eingesetzt, konnte bis heute noch nicht den Nachweis einer betriebsicheren, schadstofftoleranten Technologie liefern, und kann daher aus heutiger Sicht nicht als ausgereifte Technologie bezeichnet werden. Reine Wasserwäscher wurden in vielen Anlagen eingesetzt, lieferten jedoch mangelhafte Abscheidegrade (vor allem in bezug auf die Teerabscheidung) und verursachen einen großen Aufwand bei der Aufbereitung des anfallenden Abwassers. Besondere Aufmerksamkeit gilt den Wärmetauschern, die noch nicht soweit ausgereift sind, dass sie problemlos in

Systeme integriert werden können. Hier führt die Beladung des Rohgases mit einer Staub-Teerfracht immer wieder zu Problemen.

Systemkomponente Gasnutzung

Die Gasnutzung stellt – als letztes Glied des Gesamtsystems – bestimmte Anforderungen an die Qualität des Reingases. Je nach Leistungsgröße ist entweder der Einsatz eines Gasmotors (~ < 5 MW_{el}) oder einer Gasturbine (~ > 10 MW_{el}) sinnvoll, da Gasmotoren heute nur bis zu einer Leistungsgröße von 2 MW_{el} für Holzgas angeboten werden. Die Charakteristika der jeweiligen Technologie sind in der folgenden Übersicht dargestellt:

Gasmotor

- hoher elektrischer Wirkungsgrad
- CO-Nachbehandlung erforderlich
- Beschränkung in der Leistungsgröße

Gasturbine

- im kleinen Leistungsbereich geringerer Wirkungsgrad als der Gasmotor
- keine Abgasnachbehandlung notwendig
- gute Eignung für den GUD-Betrieb

Bewertung der Systemkomponenten

Im Folgenden soll die Bewertung und Evaluierung der Systemkomponenten erfolgen, wobei zuerst auf die Ergebnisse eingegangen und nachfolgend notwendige Entwicklungen aufgezeigt werden sollen:

Evaluierungsergebnisse Vergasung

- Die meisten Systeme befinden sich Demonstrationsstadium, einige noch im Entwicklungsstadium.
- Das Rohgas von Bewegtbett-Vergasungssystemen hat eine hohe Partikelbeladung (bei mehrstufigen Verfahren ist diese etwas geringer), die jedoch für alle Verfahren eine Abscheidung erforderlich macht.

- Der Teergehalt im Rohgas muss – ausgenommen bei mehrstufigen Verfahren – mittels Gasreinigungstechnologie gesenkt werden.
- Die meisten Systeme befinden sich Demonstrationsstadium, einige noch im Entwicklungsstadium.

Notwendige Entwicklungen und Vorgehensweisen:

- Scale-up der mehrstufigen Verfahren und Demonstration im großen Leistungsbereich
- Entwicklung von betriebsicheren und effizienten Brennstoffzufuhrsystemen
- Entwicklung von betriebsicheren Ascheaustragsystemen
- Weiterführende Untersuchungen zur Teerreduktion mittels katalytischem Bettmaterial

Evaluierungsergebnisse Gasreinigung

- Eine Konditionierung des Rohgases auf die Anforderungen der Gasnutzung mittels trockener oder nasser Gasreinigung ist möglich.
- Katalytische und Heißgassysteme befinden sich noch im Entwicklungsstadium.
- Die Integration der Gasreinigung in das Gesamtkonzept wurde bei den meisten Anlagen nicht realisiert.

Notwendige Entwicklungen und Vorgehensweisen:

- Zukünftige Gasreinigungen sollten aus wenigen, einfach aufgebauten Komponenten bestehen
- Weiterentwicklung von Heißgas- und katalytischer Reinigung um betriebsichere, schadstofftolerante Systemkomponenten zu schaffen; Nachweis des Langzeitverhaltens der Komponenten
- Entwicklung von reststoffarmen Gasreinigungssystemen
- Bessere Integration der Gasreinigung in die Anlage zur Minimierung des Reststoffanfalls und der Entsorgungskosten durch das Schließen von Stoffkreisläufen
- Je nach Gasnutzungstechnologie sollte versucht werden das Temperaturniveau der Gasreinigung auf die Gasnutzung abzustimmen
- Schaffung von technisch machbaren und ökonomisch realisierbaren Technologien

Evaluierungsergebnisse Gasnutzung

- Gasmotoren für den kleinen Leistungsbereich (2 MW_{el}), Gasturbinen für den großen Leistungsbereich (> 4 MW_{el}) sind am Markt vorhanden.
- Gasturbinen sollten zum Erreichen höherer elektrischer Wirkungsgrade im GUD-Betrieb gefahren werden.
- Die CO-Emissionen des Gasmotors können durch thermische oder katalytische Systemen reduziert werden.

Notwendige Entwicklungen, Vorgehensweisen und Zielsetzungen:

- Erhöhung der Schadstofftoleranz der Gasnutzungssysteme
- Entwicklung von kostengünstigen Systemen zur Senkung der CO-Emissionen des Gasmotors
- Steigerung des elektrischen Wirkungsgrades auch bei Holzgasanwendungen
- Schaffung von einfachen, betriebssicheren Gasnutzungssystemen
- Reduktion des Betriebsmittelverbrauches (vor allem beim Gasmotor)

Bewertung von Systemlösungen

Abschließend erfolgt nun die Bewertung von Systemlösungen. Dabei werden übergeordnete Strukturen und Rahmenbedingungen betrachtet und somit das Zusammenspiel der einzelnen Systemkomponenten und die Integration dieser bewertet. Folgende Kriterien wurden dabei zugrunde gelegt:

- Die Konzepte sollten aus wenigen, einfach aufgebauten Komponenten bestehen.
- Stoffkreisläufe sollten möglichst geschlossen sein, um einen Reststoffanfall und damit Entsorgungskosten zu minimieren.
- Ist eine Trocknung des eingesetzten Brennstoffes notwendig, sollte diese möglichst in den Prozess integriert werden, um anfallende Niedertemperaturwärme zu nutzten.
- Bewegtbettprojekte sollten sich aus heutiger Sicht in einem Leistungsbereich von 5-20 MW_{el} befinden, um wirtschaftlich darstellbar zu sein.

- Um möglichst hohe Stromausbeuten zu erzielen, ist es sinnvoll im oberen Drittel dieses Leistungsbereiches GuD-Konzepte einzusetzen.

Ableitung neuer Konzepte

In den vorangegangenen Ausführungen wurden Systemelemente und Gesamtsystemlösungen analysiert und die notwendigen Anforderungen aufgezeigt. Unter Beachtung dieser lassen sich neue Konzepte formulieren, die durch die Weiterentwicklung einen technischen und wirtschaftlichen Betrieb ermöglichen sollten. Fünf vielversprechende Konzepte sollen im Folgenden dargestellt werden, wobei sich die ersten drei auf eine Kraft-Wärme-Kopplung der Vergasung beziehen, während die letzten zwei Konzepte ein Maximierung der Stromproduktion durch die Erweiterung des Konzeptes um einen GuD-Prozess verfolgen.

Konzept I: autotherme Vergasung

Bei diesem Konzept soll die erprobte Technologie der autothermen Vergasung mit einer erprobten Gasreinigungstechnologie gekoppelt werden und das gereinigte Gas in einem Gasmotor verstromt werden. Das Rohgas wird nach dem Austritt aus dem Vergasungsreaktor bis auf 400 °C abgekühlt, um eine Kondensation der Teerfracht des Rohgases im Wärmetauscher zu vermeiden. Die notwendige weitere Abkühlung des Gases auf die Gasmotoreintrittstemperatur von rund 50 °C erfolgt durch einen Wasserquench. Das aufgesättigte Gas wird danach in einem Nasselektrofilter von dem verbleibenden Staub und Teer gereinigt und im Gasmotor verstromt. Das Abgas des Gasmotors muss aufgrund der verbleibenden hohen CO-Werte katalytisch oder thermisch nachbehandelt werden. Um

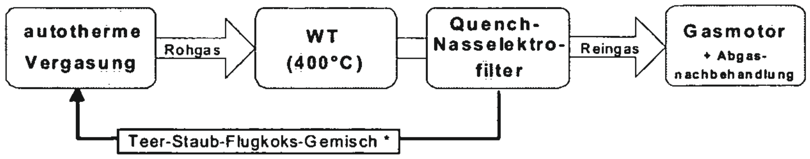

Abbildung 4: Flussdiagramm Konzept autotherme Vergasung

einen Anfall an Reststoffen zu vermeiden wird das Abwasser aus dem Quench und Nasselektrofilter rezirkuliert, wobei die Staub und Teerfracht in den Vergasungsreaktor rückgeführt werden sollte. Da es für diese Prozessvariante noch keine Realisierung gibt, sollte diese Rückführung vor der Implementierung noch untersucht werden (durch einen Stern in der Grafik gekennzeichnet).

Konzept II: allotherme Vergasung

Beim Konzept der allothermen Vergasung wird für die Vergasung ein Reaktor nach dem System Güssing eingesetzt, womit durch Wasserdampfvergasung der Biomasse ein Produktgas mit hohem Heizwert erzeugt wird. Der nach der thermochemischen Umwandlung verbleibende Koks wird in einer weiteren Wirbelschicht verbrannt, wobei das Bettmaterial aufgeheizt wird, um die Energie für die endotherme Vergasungsreaktion zu liefern. Weiterhin kann in dieser Wirbelschicht auch der anfallende Reststoff aus der Gasreinigung thermisch entsorgt werden, womit ein reststofffreier Betrieb möglich ist.

Zur Aufbereitung des Rohgases kann hier entweder auf das in Güssing erfolgreich demonstrierte Konzept precoatisierter Gewebefilter und Lösungsmittelwäscher oder auf die in Konzept 1 eingesetzte Gasreini-

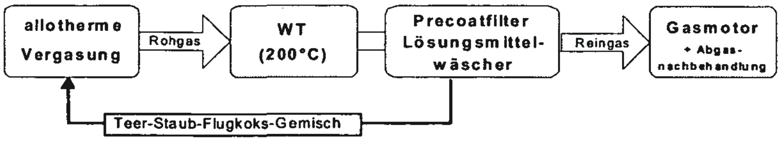

Abbildung 5: Flussdiagramm Konzept allotherme Vergasung (precoatisierter Gewebefilter - Lösungmittelwäscher)

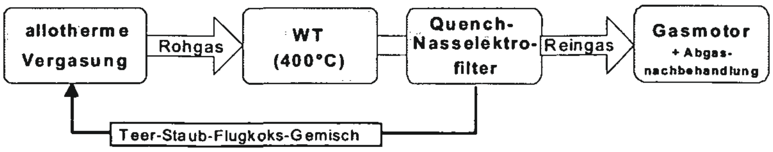

Abbildung 6: Flussdiagramm Konzept allotherme Vergasung (Quench-Nasselektrofilter)

gung zurückgegriffen werden. Bei der Kühlung des Gases auf 200 °C muss allerdings darauf geachtet werden, dass der Teergehalt im Rohgas nicht zu hoch ist und das ein Wärmetauscher mit geringer Verschmutzungsneigung eingesetzt wird.

Konzept III: mehrstufige Vergasung

Die mehrstufige Vergasung nimmt eine Sonderstellung gegenüber den zwei besprochenen Konzepten ein, ist sie doch als einzige eine Technologie, die sich noch im Entwicklungsstadium befindet und bei der noch Langzeiterfahrungen ausstehen. Dennoch bietet diese Technologie, durch die Vergasung der aus der vorgeschalteten Pyrolyse erhaltenen Produkte, den Vorteil eines nahezu teerfreien Gases. Dieses ermöglicht eine deutlich unkritischere Abkühlung des Produktgases, da es aufgrund der niedrigen Rohgasteerwerten zu keinen Staub-Teer Agglomerationen kommt. Daher ist bei genügender Brennstoffqualität (z. B. Einsatz von Hackschnitzeln aus Waldholz) nur mehr eine Entstaubung notwendig, wobei der anfallende Staub deponiert werden muss. Die Verstromung des gereinigten Produktgases erfolgt analog zu den obigen Konzepten in einem Gasmotor mit nachgeschalteter Abgasbehandlung.

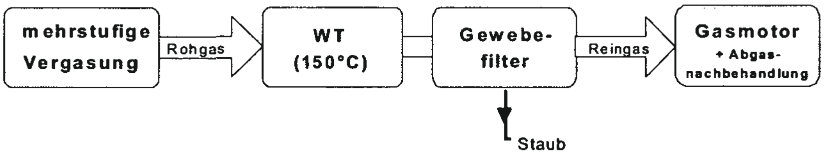

Abbildung 7: Flussdiagramm Konzept mehrstufige Vergasung

Konzept IV: GuD > 10 MW$_{el}$

Dieses Konzept ist auf eine Maximierung der Stromausbeute ausgerichtet und wird daher im GuD-Betrieb gefahren. Bei elektrischen Leistungen über 10 MW macht der höhere Aufwand der autothermen Druckvergasung Sinn, da höhere elektrische Wirkungsgrade erreicht werden können. Die Vergasung der Biomasse erfolgt daher unter Druck, der, abzüglich der Druckverluste der Gaskonditionierungsstrecke, auch dem Eintrittsdruck der Gasnutzung entspricht. Durch die Möglichkeit Produktgas mit einer Temperatur von 400 °C in der Gasturbine zu nutzen, sofern es vorher komprimiert wurde, muss der im Gas vorhanden Teer nicht abgeschieden werden. Dieser dient vielmehr in gasförmiger Form als Zusatzbrennstoff in der Turbine. Daher ist zur Konditionierung des Rohgases nur eine Kühlung auf 400 °C und eine anschließende Heißentstaubung notwendig. Der aus der Filtration anfallende Reststoff sollte, wegen des hohen Flugkoksanteiles, wieder in den Vergasungsreaktor rückgeführt werden, jedoch steht auch hier noch ein Beweis der Realisierung aus (Kennzeichnung durch einen Stern). Das so gereinigte Produktgas wird in einer Gasturbine verbrannt, wobei ein Teilstrom der Verbrennungsluft (rund 10 %) der Turbine als Fluidisierungsluft des Vergasungsreaktors dient. Zur Erhöhung der Stromausbeute ist der Gasturbine ein Abhitzekessel nachgeschaltet, dessen Wärme und die ausgekoppelte Wärme aus dem Produktgas für den Betrieb einer Dampfturbine genutzt wird.

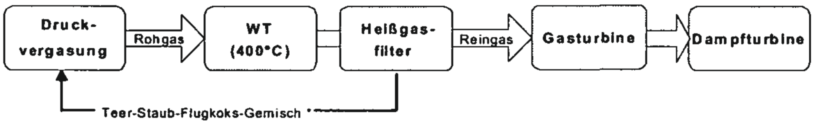

Abbildung 8: Flussdiagramm Konzept GUD: > 10 MW$_{el}$

Konzept V: GuD < 5 MW$_{el}$

Im kleineren Leistungsbereich unter 5 MW elektrischer Leistung macht die Druckvergasung, wegen des hohen Aufwandes den Brennstoff auf Druck zu bringen beziehungsweise der hohen Anforderungen an die Auslegung der Apparate, keinen Sinn. Daher kommt, aus wirtschaftlichen Überlegungen, nur eine drucklose Vergasung in Frage.

Die angewandte Gasreinigung hängt von der Gasnutzung ab. Zur Nutzung des Produktgases in einer Gasturbine ist es notwendig das Gas sehr gut zu reinigen um den Kompressor, der das Brenngas auf den Gasturbinendruck bringt, nicht zu beschädigen. Die notwendige Kompressorleistung, um das drucklose Gas auf 20 bar zu bringen ist sehr groß (rund 15-20 % der produzierten elektrischen Leistung), daher macht die Nutzung in einer Turbine keinen Sinn. Aus diesem Grund werden in diesem Konzept zwei Gasmotoren eingesetzt, woraus die notwendige Kühlung mittels Wärmetauscher (WT) und Quench resultiert. Die Reinigung

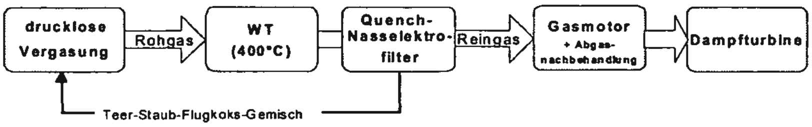

Abbildung 9: Flussdiagramm Konzept GUD: < 5 MW_{el}

des Produktgases erfolgt wiederum mittels eines Elektrofilters, wobei die Rückstände möglichst in den Reaktor rückgeführt werden sollten. Um den elektrischen Wirkungsgrad zu steigern, wird auch in diesem Konzept die Abwärme in einem Dampfprozess genutzt (MUD-Konzept).

Schlussfolgerungen und Zusammenfassung

Der Schwerpunkt bei nationalen und EU-Förderprogrammen wurde in letzter Zeit auf die Seite der Herstellung von flüssigen Kraftstoffen verschoben; die Stromproduktion mittels Vergasung rückt mehr und mehr in den Hintergrund. Diese Situation ist auf zahlreiche Rückschläge bei Projekten zurückzuführen, die die Vergasung als schwer beherrschbare und technisch nicht ausgereifte Technologie dargestellt haben.

Ungeachtet dessen stellt die Bewegtbettvergasung eine vielversprechende Variante zur Bereitstellung von Strom und/oder Wärme aus Biomasse dar. Der Grund für Scheitern oder den Stillstand einzelner Projekte ist dabei meist in der mangelnden Zusammenarbeit zwischen Wissenschaft und Industrie und weniger in der technologischen Machbarkeit zu finden. Bei den meisten Projekten fehlten die fundierte wissenschaftliche Begleitung und die Sicherung der Bereitstellung von finanziellen Mitteln über den Zeitpunkt der Inbetriebnahme hinaus. Der Erfolg einer neuen, noch nicht ausgereiften Technologie hängt immer entscheidend davon ab, ob an der Anlage gemachte Erfahrungen und Verbesserungen umgesetzt werden können oder nicht. Zur Umsetzung dieser Maßnahmen müssen Rücklagen reserviert werden, wie es in den meisten Fällen nicht gegeben war – von einer Technologie im Demonstrationsstadium kann nicht das gleiche „Maß an Ausgereiftheit" erwartet werden wie von einer konventionellen Technologie.

Die Entwicklung der Vergasungstechnologie erfolgte meist ohne Erfahrungsaustausch und ohne Koordination – jeder der Forschungsgelder erhalten hatte, baute „seine Anlage". Um die thermochemische Umwandlung zur Stromerzeugung weiterzuentwickeln und wirtschaftlich darstellbar zu machen bedarf es jedoch einem konzertierten Vorgehen. Dazu ist es notwendig Kompetenz- und Technologiezentren zu schaffen, in denen die gemachten Erfahrungen ausgetauscht werden können und somit eine Weiterentwicklung der Vergasung ermöglichen. Hier muss auch die Einbindung der Industrie und eine Verknüpfung dieser mit der Wissenschaft erfolgen, um es Konzepten aus der Wissenschaft zu ermöglichen umgesetzt zu werden und es der Industrie zu ermöglichen bei Problemen bei der Umsetzung auf das Know-How und die Forschung der wissenschaftlichen Partner zurückzugreifen.

Generell kann gefolgert werden, dass die Produktion von Wärme und Strom aus Biomasse mittels Vergasung der konventionellen Produktion mittels einer Kombination Verbrennung-Dampfturbine durch den höheren elektrischen Wirkungsgrad überlegen ist. Es ist daher wichtig diese Technologie weiter zu fördern, um die Bewegbettvergasung unter Einbeziehung der gemachten Erfahrungen im großen Leistungsbereich technisch zur Marktreife zu führen und wirtschaftlich darstellbar zu machen.

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III. PAPER

Bolhàr-Nordenkampf, M.; Vogel, A.; Kübel, M.; Detering, M.; Weigand, P.; Hofbauer, H.; Kaltschmitt, M.

"Analysis and Evaluation of Biomass Gasification Plants - Developments of New Concepts"

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ANALYSIS AND EVALUATION OF BIOMASS GASIFICATION PLANTS DEVELOPMENTS OF NEW CONCEPTS

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ABSTRACT: Gasification offers several advantages compared to the other possibilities for electricity generation from biomass e. g. by a high technical potential and high achievable efficiency. Despite these advantages biomass gasification is still under development although lots of efforts have been carried out to integrate biomass gasification into the energy system.

On that background an extensive evaluation of biomass gasification was carried out wherefrom new, improved concepts have been deducted. These concepts have been assessed on technical and economical parameters. From this the conclusion can be drawn that the gasification technology for electricity generation is competitive to combustion technology and will be available on commercial scale in the near future.

Keywords: *gasification, biomass, evaluation*

1 INTRODUCTION

Looking at the different possibilities of electricity generation from biomass gasification is a technology with good prospects; compared to biomass combustion high electrical as well as overall efficiencies can be achieved.

Despite of these advantages gasification technology for biomass as input material is still under development. In the past a broad variety of system elements as well as overall systems have been developed. Some of them are quite promising but until today none of the gasification systems available in Europe are technically mature and only a few are operated under commercial conditions.

Based on these facts, an extensive evaluation was carried out which on the one hand identified problems associated with biomass gasification and on the other hand also promising solutions. Based on this promising concepts have been developed for potential niches on the market and assessed in the following.

2 BIOMASS GASIFICATION FOR ELECTRICITY GENERATION

Gasification of biomass is the conversion of solid and liquid residues derived from the thermochemical decomposition of organic matter at high temperatures to gaseous fuel by adding oxidising agent. The main objective of gasification is to transfer the maximum usable chemical energy from the feedstock into the product gas in order to receive high yields of gas usable e. g. for electricity production.

2.1 Overall system

The process of gasification (figure 1) can be divided into several functional steps. Biomass passes the fuel provision first, where it is adapted to the conditions of the gasification reactor. In the gasification reactor raw gas is produced, which needs to be cleaned afterwards according to the conditions of the gas utilisation step (electricity production).

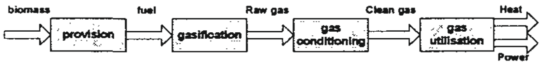

Figure 1: Process chain for the electricity generation from biomass

2.2 System components

Suitable technologies usable as system components will be discussed in the following:

Fuel provision. The fuel provision enables adaptations of the fuel characteristics according to the requirements of the gasification reactor and can be divided into

- conditioning, i.e. adjustment of the particle size,
- storage, i.e. storage of a required quantity,
- transport, i.e. from delivery to the gasifier and
- drying, i.e. adjustment of a specific water content.

If theses steps are treated individually, they can be considered as state-of-the-art and not as a “gasification-specific” problem. Hence, a detailed consideration is carried out at a later stage (chapter3).

Gasification. Over the years, a considerable number of different biomass gasifiers have been developed, constructed and tested, which can be distinguished by different criteria such as:

- reactor type (fixed bed, fluidised bed or entrained flow gasifier),
- gasification agent (air, oxygen or steam gasification),
- heat supply (allothermal or autothermal),
- reactor pressure (atmospheric or pressurised gasification).

Since each reactor type offers certain advantages and disadvantages, a universal applicable gasifier does not exist and probably will not exist in the foreseeable future. The market situation can be summarised as follows:

- in principle gasifiers are available at almost all power ranges and feedstocks,
- most of the gasification reactors are prototypes, hence several constructions exist and no data are public available,
- mainly air is used as gasification agent and almost half of the evaluated gasifiers are operated at small scale applications (below 1 MW_{th}),
- the raw gas is not suitable for direct use e. g. in combustion engines.

Gas cleaning. The raw gas from biomass gasification is polluted by condensable organic compounds, char, ash carry-over and other fuel contaminants like H_2S and NH_3. Consequently the necessary gas cleaning is determined by the raw gas characteristics and by the requirements of the gas utilisation. The market situation of such systems can be summarised as follows:

- cleaning systems are offered by many companies, but most of them are working on conventional wet based technology,
- most of these companies lack of experiences or references in the field of "wood-gas"-cleaning,
- for dust separation many technologies are available, however, only a few for tar separation,
- for the separation of further compounds (e. g. S-, N- or Cl-compounds) conventional technologies are available; however especially for biomass gasification designed technologies (e. g. hot gas cleaning) are still under development.

Gas utilisation. To reach high electrical efficiencies the usage of gas engines or gas turbines is the most common technology at present. Besides this, micro turbines are available on the (US-) market for small scale application (30 to 120 kW_{el}), but are not applied for product gases from gasification yet. In summary it can be concluded, that

- in principle the necessary adaptations on combustion due to the gas characteristics are possible,
- gas engines and gas turbines can cover all power ranges of biomass gasification,
- to promote these adaptations the market is considered to be too small for most of the engine or turbine companies, since only few are engaged in this area,
- an adaptation to higher tar-, S-, N- or Cl-compounds is not seen as the responsibility of the manufactures.

Result. In summary it can be concluded that in general all components for electricity generation via gasification are commercially available. But only some companies on the market have sufficient experiences so far.

3 ANALYSIS AND EVALUATION

For deduction of fail-safe concepts aside of the market overview experiences from existing projects are important and therefore have been analysed and evaluated.

3.1 Method

For an objective analysis of different technologies which are characterised by different development stages it is necessary to consider

- the components of the system separately as well as
- the combinations of them, i. e. overall systems.

Practical experiences as well as data from existing plants have been integrated into this analysis. 17 existing biomass gasification plants have been evaluated:

Fixed bed gasifiers	Fluidised bed gasifiers	Staged gasifiers
Espenhain Siebenlehn Xylowatt Hengelo Pyroforce Harboore Domsland Wiener Neustadt	Arbre Värnamo Güssing Vermont Umsicht	Carbo-V Carbo-Compact Viking DTU Blue Tower (DM2)

Figure 2: Overview of the evaluated plants

The method of evaluation, which is used for the following considerations, is shown in figure 3. Starting from an extensive analysis of these plants and components suitable criteria were used for their evaluation. For example, gasification can be evaluated according to tar- or dust-content in the raw gas; for gas cleaning separation efficiency or residues are important. Experiences from the past have shown that an individual well designed process step can cause problems in combination with other components. Beyond this evaluation of singular system components it is important to assess also the combination of them. Consequently, criteria like "technical concept", availability, total efficiency etc. have been evaluated for each plant.

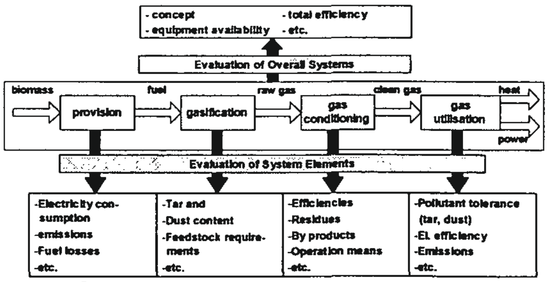

Figure 3: Evaluation method

By combining the information gained from this evaluation new or improved concepts can be developed. Hence, the results of the evaluation will be discussed according to the individual components as outlined below.

3.2 Results

Fuel provision. Fuel provision is due to the development stage of biomass gasification (demonstration stage) often partially neglected. Thus, problems caused by the fuel provision occur frequently and cause problems in follow-up components like e. g. gas instabilities in the gasification reactor. For new concepts it is important that the

- requirements of the gasifier are defined,
- the fuel properties are characterised and assured by a quality-management-system,
- emissions are prevented (dust, smell etc.),
- installed driers are better integrated into the entire system,

- and residues are prevented or their energy content recovered in the plant.

Gasification. For the system component gasification it can be summarised that fixed bed gasifiers are well advanced, but not yet optimised. CFB-gasifiers are state-of-the-art but not optimised for biomass yet. Both gasifier types produce a tar containing raw gas; only two-staged gasifiers promise a "tar-free" raw gas but are not highly-developed.

In total gasification is still not fully developed in some aspects like fuel-feeding and ash-discharge systems. Furthermore, the mechanisms of tar formation or effects of catalytic materials are not well examined for biomass. However, if suitable feedstock is used, gasification is not to be considered a critical component. Depending on the size of a plant a

- CFB-gasification for large scale or a
- twin-fire fixed bed gasifier or a two-staged gasifier for small scale

are promising solutions..

Gas cleaning. For gas cleaning wet as well as dry technologies are available to achieve suitable clean gas conditions. Water scrubbing used in many plants does not achieve satisfactory separation efficiencies concerning tar. For dry cleaning only a few suppliers are on the market; dry tar separation was not demonstrated on commercial stage so far. By analysis of the gas cleaning technologies suitable components for dust removal could be identified:

- precoated baghouse filters,
- ceramic or metallic candle filters as well as
- the combination of quench and wet-electrostatic precipitator

For tar separation suitable components include

- wet-electrostatic precipitators or
- solvent scrubbers

Gas utilisation. Electricity generation in most of the evaluated plants is carried out by a gas engine. Hence, a considerable knowledge is available on this technology. Nevertheless, some effects (e. g. interaction of NH_3 with the engine oil) are still unclear. For utilization of gas turbines so far only experiences from one plant exists. Hence, effects of pollutants are still unclear. For an application of micro gas turbines experiences are missing in general.

For new concepts in small scale only the application of an gas engine is a feasible option. The application of micro turbines is not to be expected within the near future. For large scale systems gas turbines are the "standard technology", whereby realisation of new projects of biomass gasification is necessary to obtain more experiences and operation results in this field.

4 DEDUCTION OF NEW CONCEPTS

From the evaluation it can be seen that biomass gasification is still under development, however promising components are available for the design of new concepts. Due to the current stage of biomass-use in general as well as because of the development stage of gasification new concepts can only succeed on the liberalised market with additional support.

4.1 Fields of application

An adequate application of biomass gasification in at the small scale e. g. for hospitals, public buildings as well as for agriculture and forestry companies for combined heat and power production in the range of 500 kW_{el} can be the market. At the large scale gasification could be used as an improvement of conventional combustion based plants. Therefore an application for power production in the range of 20 MW_{el} is suitable. For these potential markets concepts could be identified, which are described in the following.

4.2 Improved concepts

Small scale. One promising option for a small scale concept is the combination of a twin-fire fixed bed gasifier with a wet cleaning method and a gas engine (figure 4). The raw gas is cooled to 400 °C by an oil heat exchanger to avoid tar condensation and further by a water quench. After that the gas is cleaned by a wet electrostatic precipitator according to the engine requirements. The tar-water mixture from the gas cleaning is burned in a combustor for the production of heat for the drying.

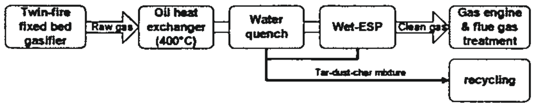

Figure 4: Twin-fired fixed bed gasification system

Alternatively the gasification can be realised by a two-staged gasifier. The product gas can be cooled easily by a heat exchanger to the temperature conditions of the baghouse filter, since the product gas is nearly tar free. (figure 5). As in the previous system the electricity is generated with an engine with flue gas treatment (CO-reduction).

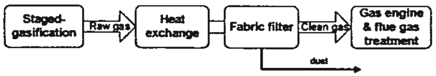

Figure 5: Two-staged gasification system

Large scale. For power generation at large scale the pressurised CFB-gasification is one of the most promising technologies (figure 6). The raw gas from the gasifier is cooled down to 400 °C and afterwards cleaned by a hot gas filter where. Since no tar condensation occurs up to this temperature a tar removal is not necessary. The product gas can be used in a combined cycle process, whereby the tar content is even increasing the power output in this concept. Dust from the filter can be recirculated to the gasification process.

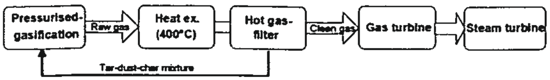

Figure 6: Pressurised CFB-gasification system

Another possibility is the CFB-gasification at ambient pressure (figure 7). Since for electricity generation at that power range only gas turbines are suitable for electricity production. A compression after atmospheric gasification to the pressure level of the turbine is required. For this system a quench-electrostatic-precipitator-combination is the most promising solution.

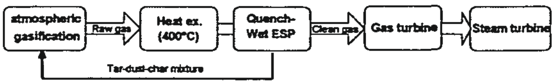

Figure 7: Atmospheric CFB-gasification system

4.3 Concept assessment

To assess these concepts with respect to a commercial implementation an evaluation in technical as well as economical terms is required.

Technical assessment. For technical evaluation mass- and energy balances of the concepts have been calculated using a process simulation tool (IPSEpro®). By this tool energy and exergetic flows can be calculated (figure 8) and optimised, as for example shown in figure 8.

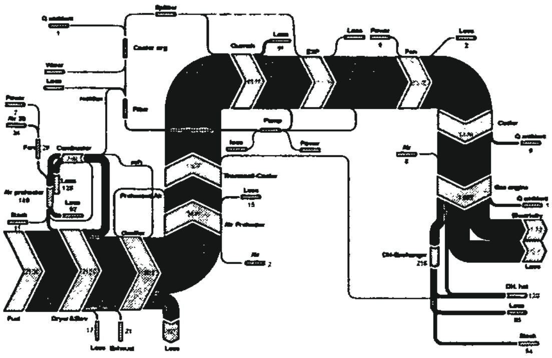

Figure 8: Example of an exergetic consideration

A comparison of the these optimised concepts is given in table 1

Table 1: Comparison of the concepts in terms of efficiency

	gross electric efficiency	net electric efficiency	thermal efficiency	total efficiency (net)	power to heat ratio (net)
500 kW					
twin-fire fixed bed gas.	27,60	26,70	38,20	64,90	0,70
staged gasification	31,30	31,00	38,00	69,10	0,82
20 MW					
pressurised CFB-gas.	42,90	42,60	0,00	42,60	-
atmospheric CFB-gas.	42,53	35,10	0,00	35,10	-
conventional combustion	42,54	34,10	0,00	34,10	-

At small scale staged-gasification reaches the highest electrical efficiencies. In comparison the fixed-bed gasification reaches lower electrical but only slightly higher thermal efficiencies. On the large scale it is interesting that both gasification concepts compared to conventional combustion process with steam cycle have similar gross electrical efficiencies. In contrast to this pressurised gasification represents a significant improvement regarding net electrical efficiencies, since it has a significant lower own power consumption.

Economic assessment. In previous steps gasification has been assessed mainly by technical criteria. Therefore in the following the economic opportunities of electricity generation by biomass gasification on market conditions are evaluated.

This was done by calculating the interest discount on the plants cash flow over the plant life. The results of this calculation for each concept are shown in figure 9.

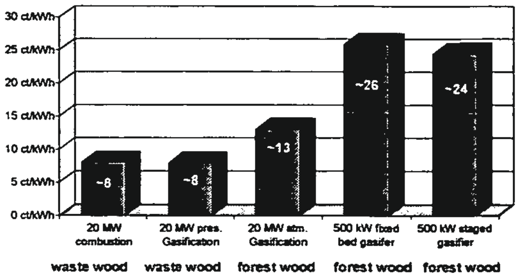

Figure 9: Electricity production costs of the investigated concepts

These results reflect that

- the fuel price (forest wood: 60 €/t, waste wood: 6 €/t) has a major impact on electricity production costs,
- even high optimised concepts at small scale applications leads to high electricity generation costs,
- large scale applications can in principle be competitive to nowadays combustion systems.

5 CONCLUSION

By a detailed market and technology analysis of gasification processes as well as an evaluation of several gasification plants problems associated with biomass gasification as well as suitable technologies for overall systems could be identified. Based on this, promising concepts for two power ranges have been developed, optimised and assessed technically as well as economically.

It can be concluded that high overall efficiencies of small scale applications (almost 70 %) could provide good usage of the valuable biomass. However, the applied technology is quite complex and thus expensive. Because of high specific investment costs of small systems, no commercial gasification systems are expected to be built in small scale without funding within the next years.

For large scale systems the situation is different. The production costs of electricity are significantly lower, but due to the necessary further development still not economically attractive yet. However, higher net electrical efficiencies (app. 40 %) compared to conventional technologies (app. 30 %) offer promising opportunities for further power plant developments.

Hence, the development of fail-safe gasification systems is important to verify these theoretical results of this study and to utilise the advantages of biomass gasification on a commercial application.

6 Sources

Project „Analysis and Evaluation of Plants and Systems of biomass gasification“ on behalf of the German Federal Ministry of Consumer Protection, Food and Agriculture (BMVEL); April 2002 – May 2004

IV. PAPER

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BIOMASS GASIFICATION COMBINED CYCLE THERMODYNAMIC OPTIMISATION USING INTEGRATED DRYING

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ABSTRACT

The conversion of solid fuels such as biomass into a combustible gas provides the opportunity to enhance the efficiency of biomass based power systems. It allows solid fuels to be used in high efficiency power generation processes such as Integrated Gasification Combined Cycle (IGCC). Using woody biomass with high water content without drying has negative effects on the overall efficiency of the process. The option of using dryer biomass is limited by the higher fuel costs. Drying with low temperature heat is the link between the usage of wet low price fuel and optimum process conditions.

In this paper, the possibilities of integrating fuel drying into a pressurized IGCC process and the effects on the efficiencies are discussed. For this purpose, an equation oriented process simulation environment with a modular structure is used. Different dryer types are integrated into this tool. Several solutions for the implementation of a drying into an IGCC process are investigated using steam and exhaust gas as heat sources. The obtained results are analyzed by the means of an exergetic analysis. Finally an optimum concept with a high electrical efficiency was obtained which will also meet the environmental regulations.

Integrating drying into a biomass based IGGC concept can be an essential step for the economic operation of a plant.

Keyword: biomass, gasification, IGCC, drying

INTRODUCTION

During recent years, the interest on biomass utilization for power generation has increased since it has significant environmental benefits. It is a renewable energy resource that is CO_2 neutral and provides low SO_2 emissions, being a positive contribution to limit the greenhouse effect. Currently 14 % of the total world energy consumption is covered by biomass [1].

However, there is even a much bigger potential to produce, for instance, at least 50 % of Europe's total energy requirement on the basis of biomass fuels [2]. The technologies for the primary thermal conversion of biomass for electricity production are combustion, gasification, and pyrolysis. An overview of existing technologies is given by Bain et al. [1]. Gasification combined with a gas engine or gas turbine has the advantage of having a higher electric efficiency and will in the future achieve lower electricity production costs than direct combustion [2]. Kwant [3,4] give an overview of principles and practice of biomass gasification.

Fluidized-bed gasifiers provide excellent mixing and gas/solid contact, causing high reaction rates and conversion efficiencies. Further, there is the possibility of addition of catalysts to the bed material to influence the product gas composition and reduce its tar content [5]. Since the gasification reactions are endothermic, the process must be supplied with energy. This can be done by partial combustion of the biomass within the gasifier using a hypostoichiometric amount of air as gasification agent. Air gasification produces a gas with low heating value (around 4-7 MJ/m^3, lower heating value (lhv)); gasification with pure oxygen, produces a high quality gas (around 10-18 MJ/m^3, lhv), requires, however, additional costs for oxygen production. A gas of similar quality can be produced by using a dual fluidized-bed-system. The gasification zone is fluidized with steam, yielding a nitrogen free gas with a lhv around 12-14 MJ/m^3. The necessary heat in the gasification reactor is supplied by hot circulating bed material [6]. The latter is heated up in a second fluidized bed reactor by combustion of residual char. In this study only autothermic air gasification is looked at.

Two power plants based on biomass IGCC concepts have been built during the last decade. The first one, Vaernamo [7,8] located in Sweden, is a pressurized IGCC, with a separated fuel preparation and drying plant. The second one was ARBRE [9], located in UK. It was an atmospheric based IGCC; sadly the ARBE project failed due to financial problems.

In this work possibilities of integrating the drying of biomass into pressurized IGCC concepts are investigated. Several solutions for the implementation are looked at using steam and exhaust gas as heat sources. Theses concepts are evaluated in terms of their exergetic performance and discussed in detail.

NOMENCLATURE

CFB	circulating fluidized bed	
DLL	Dynamic Link Library	
e	specific exergy of a stream	$\mathrm{J \cdot kg^{-1}}$
E_{0i}	molar standard exergy of species i	$\mathrm{J \cdot mol^{-1}}$
h	specific enthalpy of a stream	$\mathrm{J \cdot kg^{-1}}$
IGCC	integrated gasification combined cycle	
LHV	molar lower heating value	$\mathrm{J \cdot mol^{-1}}$
lhv	specific lower heating value	$\mathrm{J \cdot kg^{-1}}$
$\dot{m}$	specific mass flow	$\mathrm{kg \, s^{-1}}$
M	mean molar mass of a stream	$\mathrm{kg \cdot mol^{-1}}$
MDK	model developer kit	
PSE	process simulation environment	
P_{el}	electric power	W
R	general gas constant (R = 8.31451)	$\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$
s	specific entropy of a stream	$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
T	temperature	K
wf	water free	
wt	weight	
y_i	molar fraction of species i	$\mathrm{mol \cdot mol^{-1}}$
Greek symbols:		
Δp	pressure drop of equipment	
η	energetic efficiency	1
Subscripts:		
cons	consumption	
chem.	chemical	
el	electric	
Fuel	fuel (biomass)	
gross	gross value	
GT	gas turbine	
m	mechanic	
net	net value	
PG	product gas	
Q, q	heat	
s	isentropic	
ST	steam turbine	
0	ambient conditions	

SIMULATION TOOL

Calculations are performed in an equation oriented process simulation environment (IPSEpro®) with a modular structure to offer flexible handling of unit operations. This process simulation tool solves the modeled process by forming a non-linear equation system, which is solved by a Newton-Raphson-algorithm. An essential advantage of this tool is the modular set up, shown in Fig. 1.

The process simulation environment (PSE) with the equation solver (Kernel) refers to a model library, with the information about the utilized apparatus. This model library can be edited with a special editor called model developer kit (MDK), which allows the implementation of user-defined models. The thermodynamic and physical data for the calculations are provided by external property libraries (DLLs). The standard software package IPSEpro®, which is designed to model standard power plant processes, has been greatly enlarged to model and describe gasification processes; Dryers, gasifiers and gas cleaning equipment have been implemented, by mass- and energy balances, including possible chemical reactions and empiric correlations from measurements of real gasification plants [10].

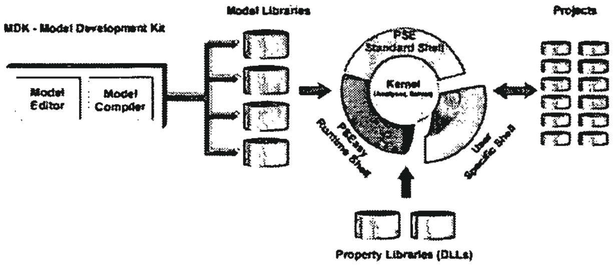

Fig. 1 Structure of the simulation environment

Conventionally the performance of a process is described in terms of the energetic performance, referred to lower heating value of the fuel and sensible heat. This evaluation method has the disadvantage to neglect the convertibility of theses energy forms.

A possibility to include this into the calculation is to introduce the exergy, the part of the energy which can be transformed into all forms of energy. This offers the possibility to investigate processes in terms of its exergetic behavior and efficiency.

The exergy of a stream consists of the exergy of heat and chemical exergy [11].

$$e = e_q + e_{chem} \tag{1}$$

For ideal gas mixtures, the specific exergy is defined by:

$$e_q = h - h_0 - T_0 \cdot \left[s - s_0 \right] \tag{2}$$

$$e_{chem} = M^{-1} \cdot \left[\sum_i \left(y_i \cdot E_{0i} \right) + R \cdot T_0 \cdot \sum_i \left(y_i \cdot \ln y_i \right) \right] \tag{3}$$

The exergy of the enthalpy in Eq. (2) can be calculated as a function of the enthalpy h, entropy s and the ambient conditions (index 0) and is a property of the gas mixture. The thermal environment defined for the present study is 298.15 K, 1.0 bar. For the calculation of the chemical exergy the molar exergy of pure substances [11] based on an equilibrium environment by Diederichsen et al. [12] is used. The standard exergy of chemical compounds can be calculated from element exergy and standard free enthalpy [11]. For pure water and steam the exergy is defined using IAPWS-IF97 [13] data, for solid mixtures it is expressed in analogy to ideal gases, neglecting the pressure dependency. For organic mixtures the chemical exergy is set equal to the higher heating value [14].

DISCRIPTION OF THE PROCESS

The process is based on a large pressurized IGCC concept with an electrical power output of 20 MW, using biomass with water content of 40 % as fuel feedstock.

The basic outline of the plant is a pressurized gasification with hot gas conditioning, coupled with a double stage steam cycle in condensation mode. Fig. 2 shows the flow diagram.

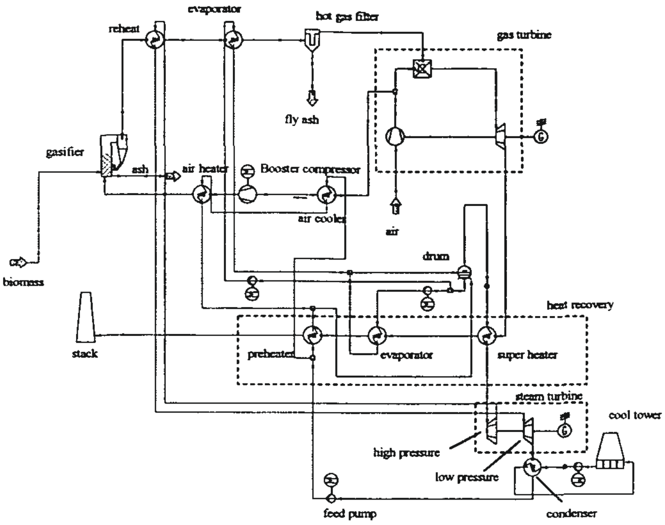

Fig. 2 Flow diagram of the IGCC process

Biomass is pressurized and enters the Circulating Fluidized Bed (CFB) reactor with 21 bar. Air is used as gasification agent, which is extracted as a side stream from the gas turbine (about 10% of the mass flow), cooled in an evaporator, pressurized and reheated again to 250 °C. The additional pressurization is necessary to cover the pressure drops which occur in the gasifier and the gas conditioning until the combustion chamber of the gas turbine. The product gas is cooled, firstly with a reheat to about 700 °C and secondly with an evaporator to 400 °C before it is dedusted in a hot gas filter. The fly ash of the filter has high carbon content, and is therefore recycled into the gasification reactor.

In the combustion chamber of the gas turbine the cleaned product gas is combusted with the remaining air of the gas turbine compressor and leaves the turbine at about 470 °C. The gas is further cooled in the heat recovery, with a superheater, an evaporator and a feed water preheat, before released to the atmosphere at 120 °C. The steam cycle consists of a two-stage turbine (84 bar/18 bar). Heat for the steam cycle is obtained from the product and the flue gas.

For the evaluation of the process three characteristic efficiencies are defined:

The gross electrical efficiency is calculated as the fraction of the produced electrical power referred to the fuel power before the dryer.

$$\eta_{gross} = \frac{P_{elGT} + P_{elST}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{4}$$

The net electrical efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus referred to the fuel power before the dryer.

$$\eta_{net} = \frac{P_{elGT} + P_{elST} - P_{elCons}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{5}$$

The chemical efficiency refers to the amount of chemical energy which can be transferred from the biomass into the product gas:

$$\eta_{chem} = \frac{\dot{m}_{PG} \cdot lhv_{PG}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{6}$$

SIMULATION OF THE PROCESS

The simulation of the process is based on the ambient conditions and the general set-up given in Table 1.

Table 1
Ambient conditions and general set-up

Ambient conditions	
temperature	15 °C
relative humidity	60 %
ambient pressure	1.013 bar
General set-up	
stack temperature	120 °C
high pressure steam	84 bar / 450 °C
low pressure steam	18 bar / 450 °C
condenser conditions	80 mbar / 41.5 °C
Δp heat exchangers (PG-, flue gas-, air side)	10 mbar
Δp evaporators steam side	0.1 bar
Δp pre-heater steam side	3 bar
Δp reheat steam side	2 bar
Δp super heater steam side	0.1 bar

The implemented efficiencies for the specific apparatus can be found in Table 2.

Table 2
Efficiencies of the specific apparatus

	η_s	η_m
high pressure turbine	0.84	0.99
low pressure turbine	0.82	0.99
compressors	0.75	0.99
pumps	0.75	0.99
gas turbine	0.88	0.985
compressor gas turbine	0.85	0.985
	η_{el}	η_m
motors, generators	0.98	0.98

As fuel biomass with the following feedstock characteristics is used, given in Table 3.

Table 3
Biomass feedstock characteristics

ash wf	3.0	[wt%]
C wf	47.6	[wt%]
H wf	6.2	[wt%]
O wf	42.9	[wt%]
N wf	0.293	[wt%]
S wf	0.031	[wt%]
Cl wf	0.013	[wt%]
water content	40	[wt%]
lhv wf	17760	[kJ/kg]
lhv	9680	[kJ/kg]

INFLUNCE OF THE BIOMASS WATER CONTENT

In the following the influence of the water content on the process shall be discussed.

Fig. 3 shows the effect of the variation of the water contents from 40 to 10 %, when the total power output of the plant is kept constant. It can be clearly seen, that the reduction of the water content from 40 % to 10 % results in an increase in the net electrical efficiency of over 2.5 %. Furthermore, the strong effect on the chemical efficiency of the gasifier can be seen; an increase of 20 % can be obtained if the water content is reduced to the above mentioned values.

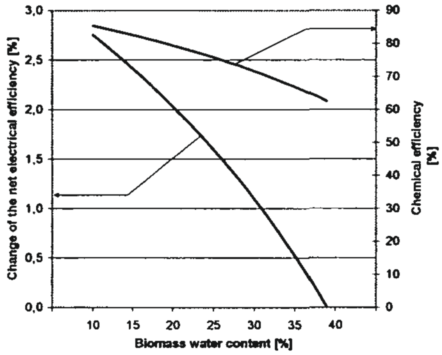

Fig. 3 Influence of the biomass water content

In Fig. 4 the influence of different biomass water contents on the exergy losses of different apparatus at constant total power output of 20 MW electrical is given.

The greatest sensitivity can be seen for the gasifier, where the water in the fuel has to be evaporated. The heat for the evaporation has to be produced by partial combustion of the fuel, which has a strong influence on the exergy loss, due to the irreversibility of the combustion. The necessary additional combustion dilutes the product gas with inert combustion gases and additional nitrogen from the gasification air. This results in a reduction of the lower heating value and thereby the exergy flow of the product gas. Wet fuel reduces the power of the gas turbine due to the lower heating value of the product gas. This results also in a decline of the exergy losses in the gas turbine. In total it can be concluded that in terms of electrical efficiency as well as in terms of exergy losses the use of dry wood gives considerable advantages. For the further simulations a biomass water content after the dryer of 15 wt% is assumed.

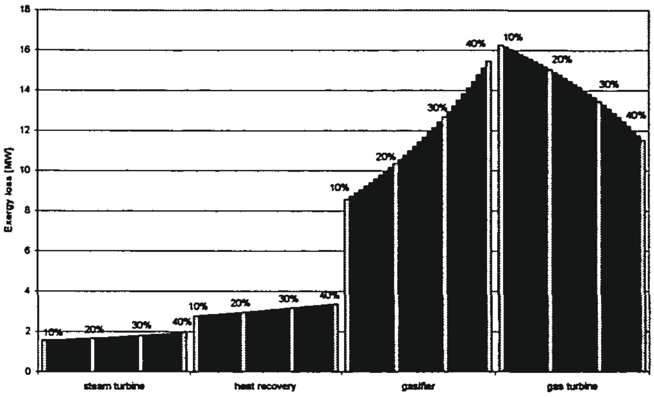

Fig. 4: Exergy losses of different apparatus at different biomass water contents (10% - 40%, marked by gray lines)

DRYING OF BIOMASS

If biomass is dried the water content is reduced, though according to the drying temperature organic emissions occur [15-17]. In the temperature range from 80 - 120 °C according to Rupar [18] oak shows a carbon loss of 0.04 – 0.08 %. If superheated steam is used (3 bar, 133 °C) according to Münster [19] a loss in the lower heating value of 1.2 %, corresponding to an average carbon loss of 1 % using wood as a fuel, occurs. With an increase in the drying temperature from 190 °C to 350 °C a rise in the carbon loss from 1 % to 10 % for pine wood and up to 17 % for birch wood has been measured [20].

It can be easily seen that the carbon loss at low drying temperatures (<120 °C) can be nearly neglected. To investigate the influence of the carbon loss on the electrical and chemical efficiencies of the process the loss was varied from 0 to 8 %, which can be seen in Fig. 5. Up to a carbon loss of 1 % the influence on the electrical efficiency is rather low (0.4 %), but even small carbon losses can cause undesired gaseous emissions. If only particle removal is installed, the temperature in the dryer should be kept below 100 °C.

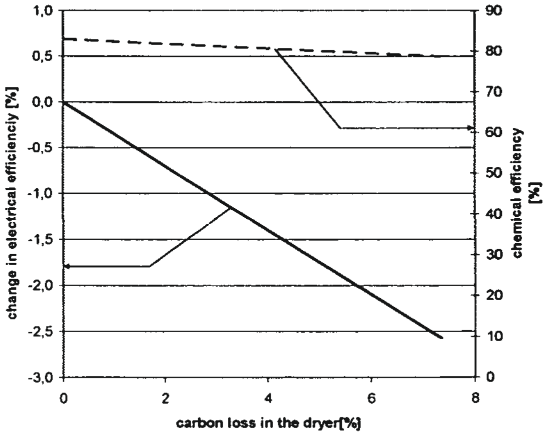

Fig. 5 Influence of the carbon loss in the dryer

Drying of biomass for gasification is until today not a state of the art technology. The applicable drying techniques can be separated into systems with direct and indirect heat transfer.

Using direct drying, rotary drum dryers have been successfully utilized; a warm gas stream (flue gas, heated up air) is fed counter currently to the biomass into the drum. The rotary drum itself provides the transport and mixing of the biomass.

Another type of dryer suitable for low temperature direct drying is the conveyor and the vibro dryer. The conveyor dryer uses a porous belt, which carries the biomass over the cross flow feed of warm gas; the vibro dryer uses a porous metal surface, which is vibrating for better fuel mixing. Warm gas is fed again in cross flow to the biomass through the porous metal surface.

Indirect heat transfer drying techniques transfer the necessary heat indirectly through heat exchangers into the drying equipment; therefore the released drying gases can be separately drawn off. For fast drying of beet slices a pressurized fluidized bed dryer, with internal steam recirculation is often used. This dryer has been successful applied on the drying of biomass wood chips too [20]. A more detailed description will follow at the relevant concept discussion.

RESULTS AND DISCUSSION

In the following, three concepts with integrated drying will be analyzed and evaluated and compared in terms of their efficiencies and their exergy.

Process concept with flue gas drying

For low temperature drying of biomass, especially wood chips, the rotary drum dryers, the conveyor dryer and the vibro dryer are suitable types. This concept is shown in Fig. 6.

The process is equal as the one described above, though the dryer is added. The flue gas after the preheater is mixed with recycled gas from the dryer outlet to reduce the energy demand of the dryer and to adjust the dryer inlet temperature. The necessary heat for the drying is drawn from the product gas. This raises the necessary temperature after the preheater and therefore has a negative effect on the power output of the steam cycle.

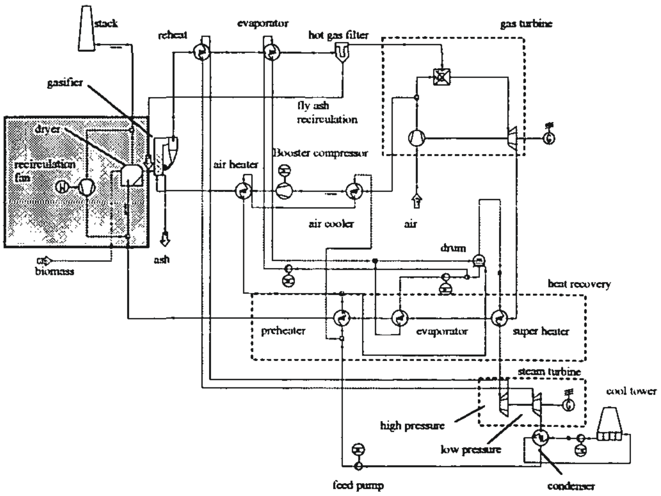

Fig. 6 Flow diagram - flue gas drying

Fig. 7 shows the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively. The total net electric efficiency declines with higher water contents as does the power output of the gas turbine, whereas the power output of the steam turbine increases due to the lower dryer heat demand and the higher volume flow through the heat recovery.

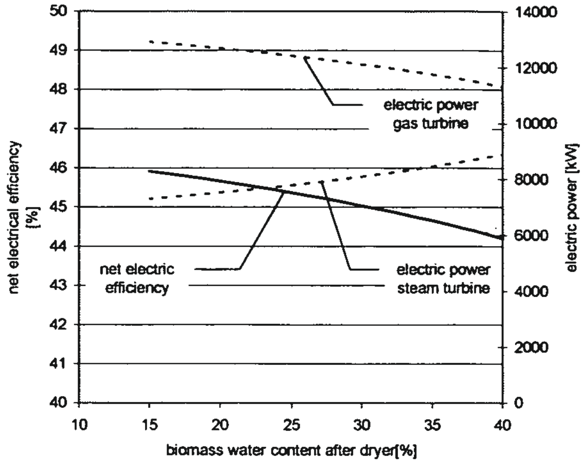

Fig. 7 Influence of different water contents

The theoretical potential for improvement of a certain process unit can be quantified by its exergy loss, though there are avoidable and unavoidable exergy losses. In the gasifier for instance, an avoidable exergy loss would be the heat loss, which can be reduced through further insulation of the gasifier. The irreversibility of the thermo chemical conversion of the biomass is an example for an unavoidable exergy loss.

An evaluation of the exergy losses can be used for the optimization of the process if the avoidable exergy losses are compared with the related cost of their possible improvement. As an example Fig. 8 shows the relative exergy losses of different units and streams of the process referred to the total fuel exergy input.

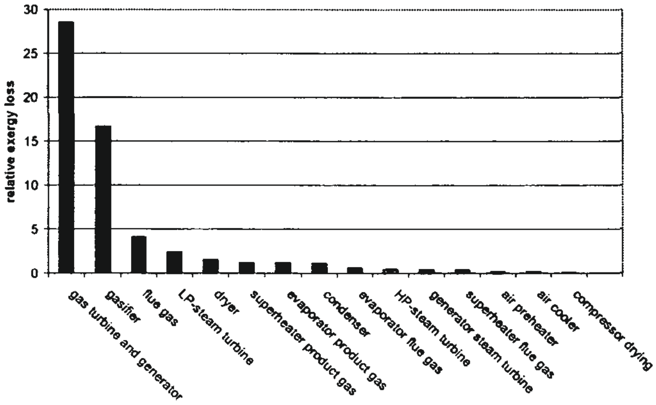

Fig. 8 Relative exergy losses of different units and streams referred to the total fuel exergy input

The highest exergy losses in the described process occur in the gas turbine and the gasifier, mainly due to the irreversibility of the combustion. These could only be reduced if different means of conversion are used, for instance a fuel cell instead of a gas turbine. Further optimization potential can be seen in the flue gas outlet temperature and the quality of the steam turbine.

Fig. 9 shows the exergy flows of the total process, with the exergy of the streams calculated according Eqs. (1)-(3), whereby electricity is considered as pure exergy.

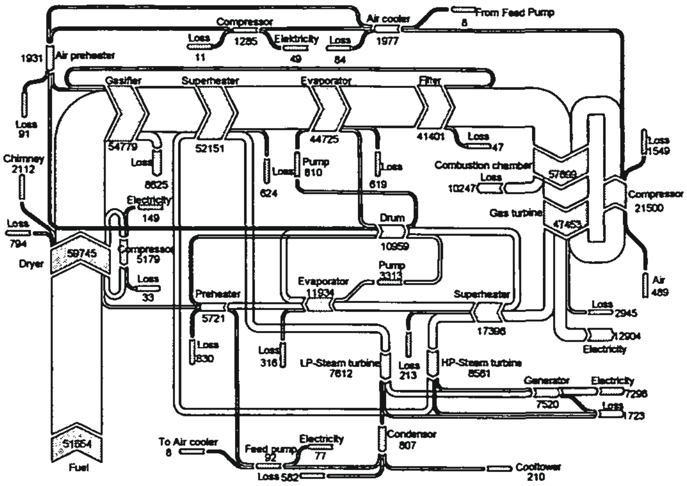

Fig. 9 Sankey-diagramm of the exergy flows – flue gas drying concept

Process concept with air drying

A further reduction of the organic emissions can be achieved using ambient air (15 °C), heated up by flue gas. This gives the advantage, that the dryer can be operated at temperatures below 100 °C. The flue gas of the dryer is partially recycled to reduce the necessary heat demand. This concept is shown in Fig. 10.

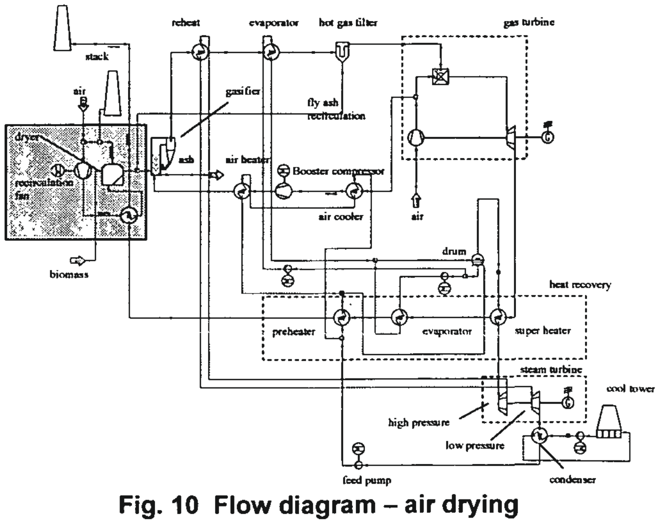

Fig. 10 Flow diagram – air drying

Fig. 11 shows the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively. The total net electric efficiency shows a lower sensitivity towards different biomass water contents as in the flue gas drying concept (Fig. 7).

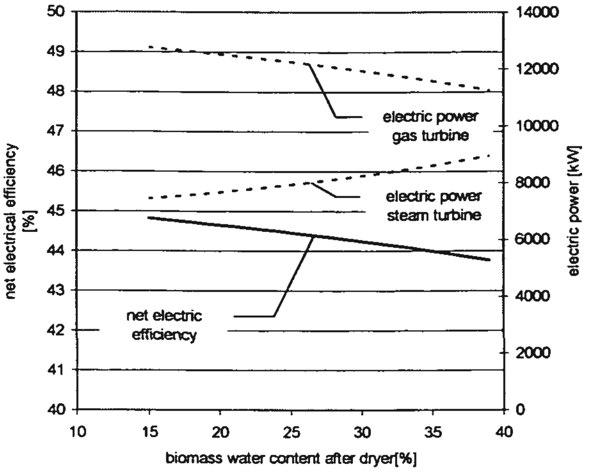

Fig. 11 Influence of different water contents

Process concept with steam drying

Finally, a concept using medium pressure steam as heat source shall be looked at. A description of a fluidized bed steam dryer is given by Jensen [21]. The dryer uses partly the recirculated steam from the biomass to fluidize the chopped wood. The heat for the drying is drawn from steam, extracted after the high pressure steam turbine from the process. The steam is condensed in an internal heat exchanger and the recirculated steam heated up. The steam leaving the dryer is condensed; the yielded heat is fed back into the steam circle. The wastewater from the condenser has to be treated, because it contains organic compounds. The flow diagram with the integration of the fluidized bed dryer can be found in Fig. 12.

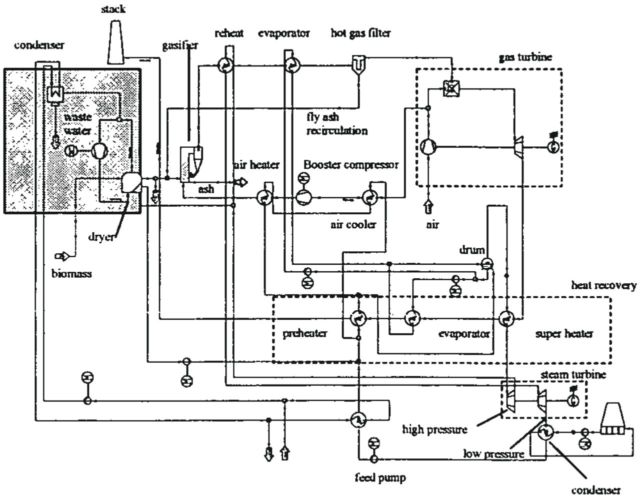

Fig. 12 Flow diagram – steam drying

Fig. 13 shows again the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively.

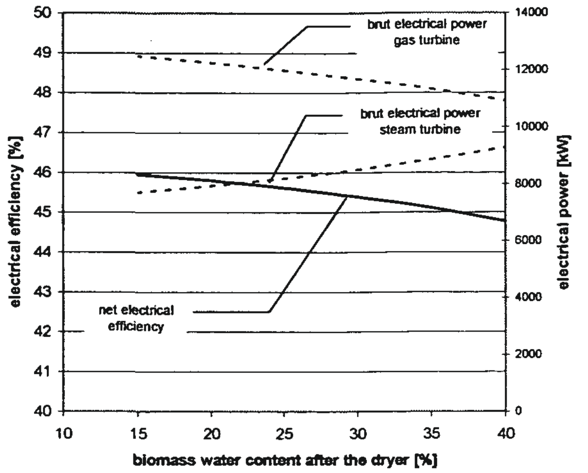

Fig. 13 Influence of different water contents

COMPARISON OF THE CONCEPTS

Fig. 14 gives a comparison of the different concepts in terms of their electrical efficiencies.

It can be seen, that steam drying achieves the highest net electrical efficiency and shows a low own consumption of electricity. In a real plant this little benefit in electrical efficiency (0.1 %) compared to the flue gas drying concept has to be set into relation to the costs for the wastewater treatment.

Using air as drying media the net electrical efficiency is 1.2 % lower as if steam is used, because of the higher flue gas recirculation rate the compressor power increases the own electrical consumption of this concept. Organic emissions can be largely avoided due to the low drying temperature of the wood, so the loss in efficiency may be compensated by the lower post treatment cost of the dyer exhaust.

Fig. 14 Comparison of the efficiencies of the different concepts

To operate the dryer using flue gases directly gives equal results in efficiency (45.9 %) as the steam concept, with the advantage, that no waste water is produced.

Interestingly the three concepts show also a different sensitivity, if the water content of the biomass is varied. Steam drying shows a lower sensitivity, equal to air drying than flue gas drying (Fig. 15).

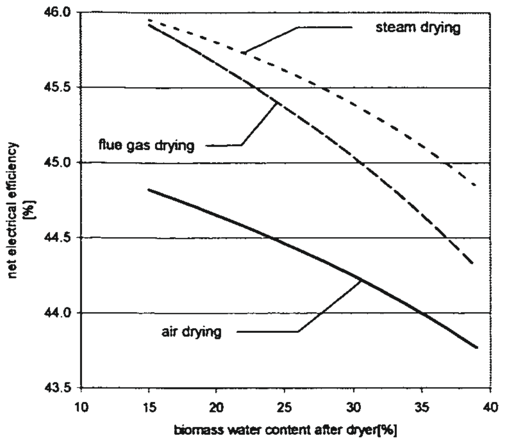

Fig. 15 Sensitivities on the efficiencies of the concepts on a variation of different water contents

Comparing the exergy losses of the three different concepts at constant power output of 20 MW electrical, (Fig. 16) it can be seen that using the steam drying concept the exergy losses in the gas turbine and the gasifier can be reduced whereas the losses raise strongly in the dryer. This can be explained by the higher temperature gradient between the biomass and the steam as well as with the carbon losses in the steam dryer. Because the overall power output is kept constant the reintegration of the heat yielded from the condenser after the dryer has a positive effect on the exergy losses in the gasifier and the gas turbine. The two concepts based on the heat from the flue gas show only minor differences in their exergy losses.

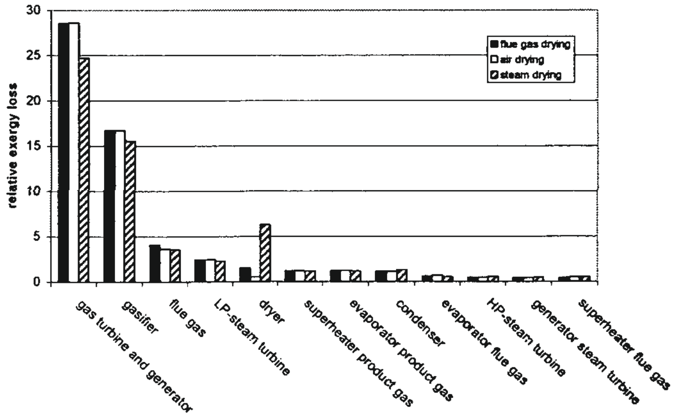

Fig. 16 Comparison of the exergy losses

In the following, the exergy inputs into the dryer shall be investigated. The exergy input is defined as the exergy necessary to dry the fuel to the desired water content. This exergy is provided at the concept of the flue gas drying and the air drying by hot flue gas after the economizer and at the steam drying concept by steam drawn from the steam cycle. A comparison of the exergy inputs can be found in Fig. 17.

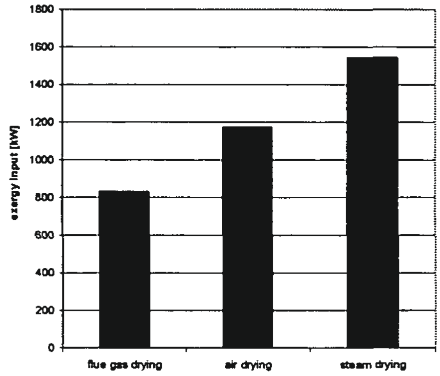

Fig. 17 Comparison of the exergy inputs in the dryer

The dryer in the flue gas concept needs the lowest exergetic input. This means it uses less valuable energy. The larger exergetic input in the air drying concepts is mainly because ambient air has to be heated up which needs more energy than using hot flue gas. Drying the biomass using steam as heat source requires the largest exergetic input, due to the fact that steam (20 bar, 280 °C) has still a high exergetic value and therefore is in terms of energy more valuable than hot flue gas at 180 °C.

The detailed exergetic losses in the dryer are given in Fig. 18. Steam as drying media shows the largest exergetic losses, including the carbon losses of 5 % in the dyer exhaust gas. Due to the lower temperature difference and the lower carbon loss, the exergetic loss in the flue gas drying concept is considerable lower, reaching the minimum if heated ambient air is used.

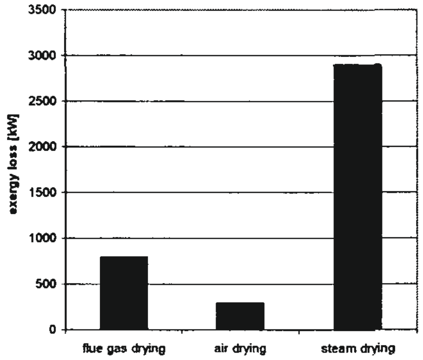

Fig. 18 Comparison of the exergy losses in the dryer

CONCLUSION

The reduction of the biomass water content can contribute significantly to the electrical efficiency of the biomass based IGCC process. Improvements of 2.5 % in electrical efficiency referred to the fuel power can be achieved if wood with a water content of 15 % instead of 40 % is used. Using low temperature heat from the flue gas for the drying process gives the significant advantage of a low exergetic input into the dryer as well as low organic emissions. Furthermore the waste water formation is avoided. This concept can achieve net electrical efficiencies of up to 46 % which is high for biomass options and offers the best compromise between efficiency and residual treatment.

For future biomass based IGGC plants the integration of the fuel drying into the total concept is a proper method to increase the fuel flexibility and offers the advantage to operate the plant at optimum conditions.

ACKNOWLEDGMENTS

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V. PAPER

Bolhàr-Nordenkampf, M.; Fürnsinn, S.; Hofbauer H.

„Exergetic and Energetic Evaluation of Biomass Based IGCC Processes"

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Exergetic and Energetic Evaluation of Biomass Based IGCC Processes

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ABSTRACT

The conversion of solid fuels such as biomass into a combustible gas provides the opportunity to enhance the efficiency of biomass based power systems. It allows solid fuels to be used in high efficiency power generation processes such as Integrated Gasification Combined Cycle (IGCC).

However, the raw gas exiting the gasifier requires conditioning before fed into the gas utilisation devices, like in a gas engine or a gas turbine. In this paper the performance of gasification processes with different gas cleanings and gas utilisations are assessed using a process simulation tool. The original tool has been extended to model gasification processes and includes the calculation of exergetic balances of the total gasification plant.

In this paper different gasification concepts are assessed energetically and exergetically. From this analysis conclusions can be drawn about the suitability coupling different technologies and asses their effect in terms of residues and performance.

Keyword: biomass, gasification, IGCC, exergetic analysis, energetic analysis

1 Introduction

During recent years, the interest on biomass utilization for power generation has increased since it has significant environmental benefits. It is a renewable energy resource that is CO_2 neutral and provides low SO_2 emissions, being a positive contribution to limit the greenhouse effect. Currently 14 % of the total world energy consumption is covered by biomass [1].

However, there is even a much bigger potential to produce, for instance, up to 50 % of Europe's total energy requirement on the basis of biomass fuels [2]. The technologies for the primary thermal conversion of biomass for electricity production are combustion, gasification, and pyrolysis. An overview of existing technologies is given by Bain et al. [1]. Gasification combined with a gas engine or gas turbine has the advantage of having a higher electric efficiency and will in the future achieve lower electricity production costs than direct combustion [3]. Kwant [4,5] gives an overview of principles and practice of biomass gasification.

Fluidised-bed gasifiers provide excellent mixing and gas/solid contact, causing high reaction rates and conversion efficiencies. Further, there is the possibility adding catalysts to the bed material to influence the product gas composition and reduce its tar content [6]. Since the gasification reactions are endothermic, the process must be supplied with energy. This can be done by partial combustion of the biomass within the gasifier using a hypostoichiometric amount of air as gasification agent. Air gasification produces a gas with low heating value (around 4-7 MJ/m^3, lower heating value (lhv)); gasification with pure oxygen, produces a high quality gas (around 10-18 MJ/m^3, lhv), requires, however, additional costs for oxygen production. A gas of similar quality can be produced by using a dual fluidised-bed-system. The gasification zone is fluidised with steam, yielding a nitrogen free gas with a lhv around 12-14 MJ/m³. The necessary heat in the gasification reactor is supplied by hot circulating bed material [7]. The latter is heated up in a second fluidised bed reactor by combustion of residual char.

In this study only autothermical air gasification is looked at, whereon the exergetic and energetic effects of different gas cleaning and gas utilisations are investigated using a process simulation tool. Thereby the influence of pressurised and atmospheric gasification is assessed. In terms of gas cleaning "hot gas filtering", the combination of "a catalytic tar cracker and a filter", a "quench and a wet electrostatic precipitator" and a "filter and a solvent scrubber" are investigated. The net power output of the designed concepts is fixed at 20 MW electrical. For gas conversion a gas turbine and gas engines are investigated, with an additional option for the production of district heat.

2 Simulation Tool

Calculations are performed in an equation oriented process simulation environment (IPSEpro®) with a modular structure to offer flexible handling of unit operations. This process simulation tool solves the modelled process by forming a non-linear equation system, which is solved by a Newton-Raphson-algorithm. An essential advantage of this tool is the modular set up, shown in **Fig. 1**.

The process simulation environment (PSE) with the equation solver (Kernel) refers to a model library, with the information about the utilized apparatus. This model library can be edited with a special editor called model developer kit (MDK), which allows the implementation of user-defined models. The thermodynamic and physical data for the calculations are provided by external property libraries (DLLs). The standard software package IPSEpro®, which is designed to model standard power plant processes, has been greatly enlarged to model and describe gasification processes; Dryers, gasifiers and gas cleaning equipment have been implemented, by mass- and energy balances, including possible chemical reactions and empiric correlations from measurements of real gasification plants [8].

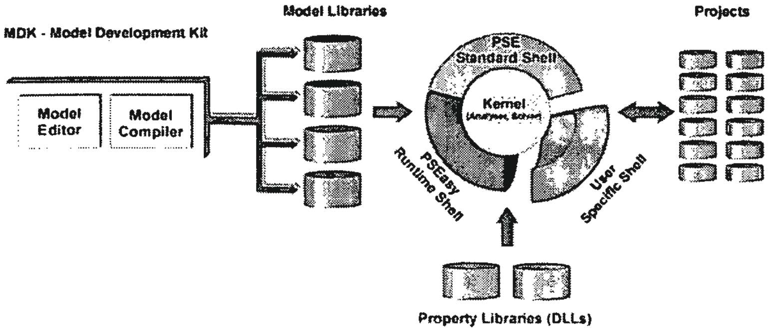

Fig. 1: Structure of the simulation environment

Conventionally the performance of a process is described in terms of the energetic performance, referred to lower heating value of the fuel and sensible heat. This evaluation method has the disadvantage to neglect the convertibility and therefore the quality of theses energy forms. A possibility to include this into the calculation is to introduce the exergy, the part of the energy which can be transformed into all forms of energy. This offers the possibility to investigate processes in terms of its exergetic behaviour and efficiency.

The exergy of a stream consists of the exergy of heat e_q and chemical exergy e_{chem} [9].

$$e = e_q + e_{chem} \tag{1}$$

For ideal gas mixtures, the specific exergy is defined by:

$$e_q = h - h_0 - T_0 \cdot [s - s_0] \tag{2}$$

$$e_{chem} = M^{-1} \cdot \left[\sum_i (y_i \cdot E_{0i}) + R \cdot T_0 \cdot \sum_i (y_i \cdot \ln y_i) \right] \tag{3}$$

The exergy of the enthalpy in Eq. (2) can be calculated as a function of the enthalpy h, entropy s and the ambient conditions (index 0) and is a property of the gas mixture. The thermal environment defined for the present study is 298.15 K, 1.0 bar. For the calculation of the chemical exergy the molar exergy of pure substances [9] based on an equilibrium environment by Diederichsen et al. [10] is used. The standard exergy of chemical compounds can be calculated from element exergy and standard free enthalpy [9]. For pure water and steam the exergy is defined using IAPWS-IF97 [11] data, for solid mixtures it is expressed in analogy to ideal gases, neglecting the pressure dependency. For organic mixtures the chemical exergy is set equal to the higher heating value [12].

3 Efficiency definitions

For evaluation in process technology mainly efficiencies are defined, which provide a possibility for the comparison of different processes. However, for a proper comparison these characteristic efficiencies have to be defined precisely. For the assessment of the processes evaluated in this work the following characteristic efficiencies are defined:

3.1 Definition of electrical efficiencies

The gross electrical efficiency is calculated as the fraction of the sum of produced electrical power referred to the fuel power of the feedstock entering the plant (e.g. before a possible fuel preparation).

$$\eta_{el,gross} = \frac{P_{elGT/GE} + P_{elST}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{4}$$

The net electrical efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus to the fuel power of the feedstock entering the plant before the dryer (before a possible fuel preparation).

$$\eta_{el,net} = \frac{P_{elGT/GE} + P_{elST} - P_{elCons}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{5}$$

3.2 Definition of the thermal efficiency

The thermal efficiency of a plant is calculated as the fraction of the produced heat (district or process heat) referred to the fuel power of the feedstock entering the plant (e.g. before a possible fuel preparation).

$$\eta_Q = \frac{\dot{Q}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{6}$$

3.3 Definition of the fuel utilisation

The gross fuel utilisation is calculated as the fraction of the produced electrical power and heat (district or process heat) to the fuel power of the feedstock entering the plant (e.g. before a possible fuel preparation).

$$\eta_{fuel,gross} = \frac{P_{elGT} + P_{elST} + \dot{Q}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{7}$$

The net fuel utilisation is calculated as the fraction of the produced electrical power and heat (district or process heat) reduced by the electrical consumption by the apparatus to the fuel power of the feedstock entering the plant before the dryer (before a possible fuel preparation).

$$\eta_{fuel,net} = \frac{P_{elGT} + P_{elST} - P_{elCons} + Q}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{8}$$

3.4 Definition of the chemical efficiency for a gasification plant

For evaluation of gasification plants, the definition of the chemical efficiency referred to the gasifier is not well suited, since the quality of the product gas is neglected. The possibility to include quality of the product gas into the analysis is by including the gas cleaning into the system border. Thereby the mass flow and the lower heating value of the product gas at the inlet to the gas utilisation are taken. Therefore only usable combustible components are assessed, tar or char is not included anymore. Possible recycles from the gas cleaning into the gasifier are treated as internal streams, since they do not leave the system boarder. The system border for the calculation of the chemical efficiency of a plant is given in Fig. 2.

$$\eta_{chem} = \frac{\dot{m}_{PG} \cdot lhv_{PG}}{\sum \dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{9}$$

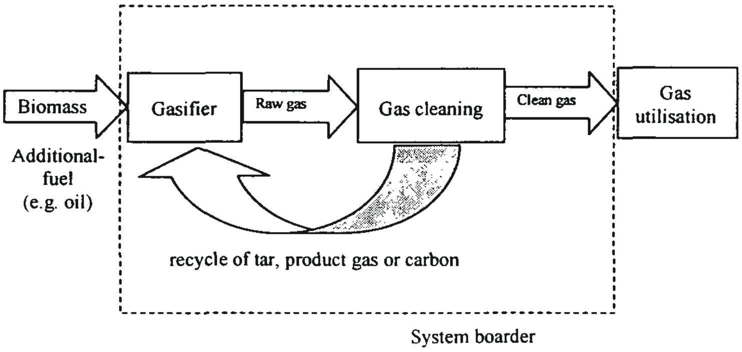

Fig. 2: System boarder for the calculation of the chemical efficiency for a plant

3.5 Definition of power to heat ratio

The gross power-to-heat-ratio is calculated as the fraction of the produced electrical power to the produced heat (district or process heat).

$$\alpha_{gross} = \frac{P_{elGT} + P_{elST}}{\dot{Q}} \tag{10}$$

The net power-to-heat-ratio is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus to produced heat (district or process heat).

$$\alpha_{net} = \frac{P_{elGT} + P_{elST} - P_{elCons}}{\dot{Q}} \tag{11}$$

3.6 Definition of the exergy efficiencies

In general the overall exergetic efficiency can be defined as the total sum of all usable exergy flows in desired products, leaving the plant (power, heat, etc.) to the sum of all exergy inputs into the plant, like electric power or fuel.

$$\eta_{ex} = \frac{\sum \dot{E}_{prod}}{\sum \dot{E}_{input}} \tag{12}$$

For the exergetic evaluation of the gas cleaning, it is of major interest how much of the exergy in the raw product gas can be kept in the clean gas to be converted into electricity in the gas utilisation device. For this the exergetic gas cleaning efficiency can be defined by the ratio of the exergy in the cleaned product gas to the exergy in the raw product gas.

$$\eta_{ex,GC} = \frac{\dot{E}_{cleangas}}{\dot{E}_{rawgas}} \tag{13}$$

To compare different gas utilisations an exergetic efficiency can be defined in a similar way as the net electric efficiency is calculated. The net exergetic efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus plus the produced useable exergy flows to the sum of exergy of the product gas and the exergy of the combustion air.

$$\eta_{ex,GU,net} = \frac{E_{el,brut} - E_{el,own} + E_{PS}}{E_{PG} + E_{air}} \tag{14}$$

4 Process simulation

The simulation of the processes is based on the ambient conditions and the general conditions. Furthermore the implemented efficiencies for the specific apparatus can be found in Table 1. The gas engine is dependent on the operating conditions and is modelled according to the data of the Jenbacher company. Therefore the electrical efficiency of the gas engine ranges from 33 % to 37 %.

Table 1: Ambient conditions, general conditions and efficiencies of the specific apparatus

Ambient conditions	
temperature	15 °C
relative humidity	60 %
ambient pressure	1.013 bar
General set-up	
stack temperature	120 °C
high pressure steam	84 bar / 450 °C
low pressure steam	18 bar / 450 °C
condenser conditions	80 mbar / 41.5 °C
Δp heat exchangers (PG-, flue gas-, air side)	10 mbar
Δp evaporators steam side	0.1 bar
Δp pre-heater steam side	3 bar
Δp reheat steam side	2 bar
Δp super heater steam side	0.1 bar
district heating feed	90 °C
district heating drain	110 °C

	η_s	η_m
high pressure turbine	0.84	0.99
low pressure turbine	0.82	0.99
compressors	0.75	0.99
pumps	0.75	0.99
gas turbine	0.88	0.985
compressor gas turbine	0.85	0.985
	η_{el}	η_m
motors, generators	0.98	0.98

As fuel biomass with the following feedstock characteristics is used, given in Table 2.

Table 2: Biomass feedstock characteristics

ash wf	3.0	[wt%]
C wf	47.6	[wt%]
H wf	6.2	[wt%]
O wf	42.9	[wt%]
N wf	0.293	[wt%]
S wf	0.031	[wt%]
Cl wf	0.013	[wt%]
water content	40	[wt%]
lhv wf	17760	[kJ/kg]
lhv	9680	[kJ/kg]

5 Evaluated concepts

In the following the different evaluated concepts will be presented, all based on combined cycle operation with a net electric power output of 20 MW, considering emission standards. An overview of the different concepts is given in Fig. 3.

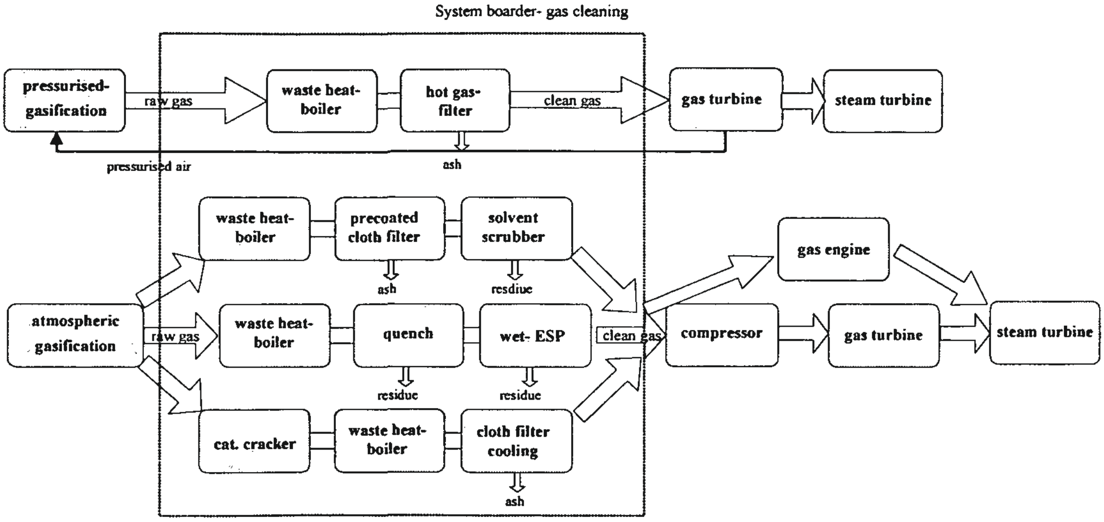

Fig. 3: Overview of the different evaluated concepts

Concept I

In this concept an autothermal pressurised fluidised bed gasifier is used for the production of raw product gas, which can be utilised without further compression in a gas turbine. Therefore, tar removal is not necessary since tar even acts as additional fuel in the gas turbine.

Gas conditioning and cleaning consists only of a heat exchanger to cool the product gas to 400 °C before dust is removed by a hot gas filter. Since the removed dust has high carbon content from the fly ash, it is returned into the gasifier. However, this possibility is not demonstrated in a real plant so far. The cleaned product gas is combusted in a gas turbine, which also supplies the gasification reactor with pressurised air from its compressor. The remaining heat is utilised in a steam cycle operated in condensed mode.

Concept II-a

Autothermal, atmospheric gasification in a circulating fluidised bed is used to produce raw product gas, which is cooled down to 400 °C in a heat exchanger operated with thermo-oil to prevent any tar condensation. The necessary additional cooling is done in a quench to about 50 °C, before the gas is cleaned in a wet electrostatic precipitator from dust and tar loadings. Before it can be utilised in a gas turbine it has to be compressed according to the pressure requirements of the turbine. The flue gas heat of the gas turbine and from the heat exchanger is used in a steam cycle to enhance the electricity production. The steam turbine is operated in condensed mode. Too avoid wet residues waste water from the quench is recycled after tar and dust is separated. The residues from the filter are returned into the gasifier or are combusted.

Concept II-b

This concept differs to concept II by the gas utilisation technology; instead of a gas turbine a gas engine is used. Hence, no compression of the cleaned product gas before gas utilisation is required, which lowers the own power consumption of the plant.

The flue gases from the gas engine have to be treated catalytically or thermally to reach the CO emission limits. The remaining heat is used in a steam cycle.

Concept III-a

The raw product gas, which originates from an autothermal fluidised bed gasifier, is catalytically cracked before it is cooled down and dedusted. Since tar is removed before cooling the product gas no problems are expected by plugging or clogging of the heat exchanger. The cleaned gas is compressed and utilised in gas and steam turbines in the same way as described in concept II. This concept is advantageous since only dust is produced as residue and tar is converted into combustible gaseous components.

Concept III-b

Concept III-b differs from the above mentioned concept by a different gas utilisation technique. Instead of a gas turbine a gas engine is used, which dispenses with the compressor before the gas utilisation. The combined cycle usage is equivalent to the above described concept.

Concept I-dh, II-a-dh, II-b-dh, III-a-dh & III-b-dh

These concepts differ from the original concepts in a way that district heat is produced as well. Therefore, the steam turbine is operated in back-pressure mode, to achieve suitable temperatures for the district heat production and the waste heat of the gas engine, if installed, is used as well.

Concept IV

The raw product gas, originating from an autothermal fluidised bed gasifier, is first cooled and than dedusted by a precoated bag house filter. Tar is removed by a solvent scrubber. The cleaned gas is compressed and utilised in a gas and steam turbine in the same way as described in concept II. The laden scrubbing liquid together with the removed dust is separately combusted.

6 Energetic concept comparison

In the following the different concepts are compared according to efficiencies defined in chapter 3. Fig. 4 shows the net and gross electrical efficiencies of the different concepts. The net electrical efficiencies are marked in grey, the gross electrical efficiencies are only indicated by dotted lines, since power plants have to cover their own consumption themselves.

It can be clearly seen that concept I using a pressurised system can obtain the highest electrical efficiencies. In this concept only the gasification air has to be pressurised and not the whole product gas after the gasifier for gas utilisation. Furthermore tar can be combusted in the turbine as well. This concept has also the lowest own power consumption of the evaluated systems.

Concept III-b (catalytic gas cleaning – gas engines) achieves the highest net electrical efficiency and the lowest own consumption of the atmospheric operated concepts. The other concepts for power production have about the same net electrical efficiencies, however the gross efficiencies differ significantly.

Concept II-a differs from concept II-b only in the applied gas utilisation technology. Since the gas turbine requires for compression high power inputs (concept II-a) the advantages of a higher gross efficiency is reduced. The same applies for concept III-a, which would achieve the highest gross electrical efficiency. However this efficiency is achieved by an increase in the volume flow through the partial combustion of the product gas and the catalytic tar cracker. Therefore a higher gas flow needs to be compressed onto the turbine pressure, which accounts for a very high own consumption.

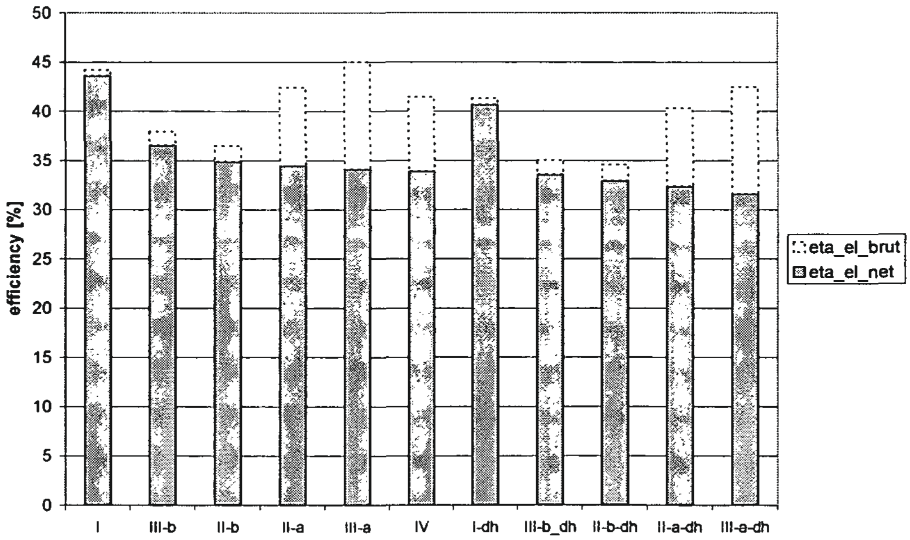

Fig. 4: Comparison of the gross and net electric efficiencies of the different concepts

The concepts marked with the extension "dh" on the right hand side of Fig.4 are operated in combined heat and power mode. Again, using pressurised operation the highest net electrical efficiencies can be achieved with the lowest own consumptions. Concepts III-b-dh and II-b-dh, both using gas engines, achieve slightly higher electrical efficiencies than turbine based concepts II-a-dh and III-a-dh. The difference resulting from the gas cleaning is little.

Fig. 5 shows the comparison of different chemical plant efficiencies. The highest chemical efficiency can be obtained in concept I, since tars can be combusted too. Using a wet electrostatic precipitator as gas cleaning, like in concepts II, efficiencies around 75 % can be achieved. This efficiency drops a little, using the oil scrubber (concept IV) since the loaded oil is used as combustion fuel and has therefore be included in the fuel power. By using a catalytic cracker the heating value of the product gas is reduced and therefore also the chemical efficiency of the system, which can be seen in concepts III.

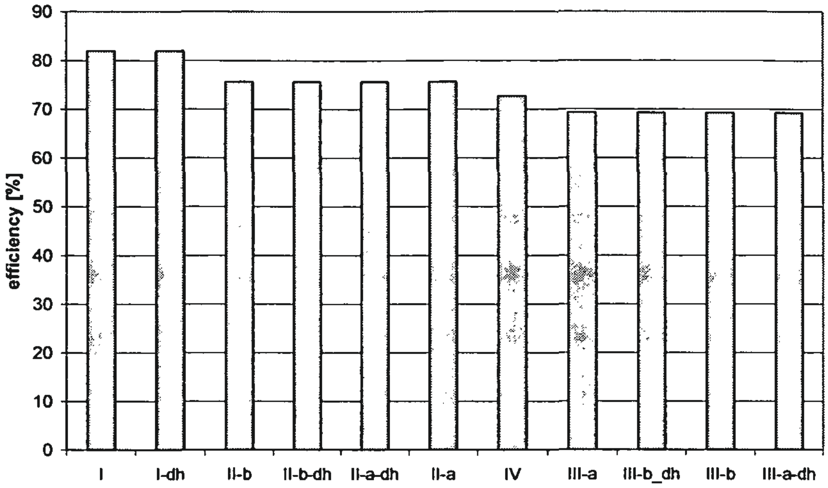

Fig. 5: Comparison of the chemical efficiencies of the different concepts

Fig. 6 gives a comparison of the different thermal efficiencies of the concepts operated in combined heat and power mode. It can be seen that the highest thermal efficiencies can be achieved using gas engines (concepts marked with "b"). Furthermore if a catalytic converter is used for gas cleaning the additionally heat accounts for a better thermal efficiency as if the heat is lost by quenching, like in concept II-b. Turbine based concepts I-dh, III-a-dh, II-a-dh achieve in general lower thermal efficiencies, since all the waste heat of the flue gas is used in the steam cycle, whereas the low temperature heat from the gas engine is used directly as district heat.

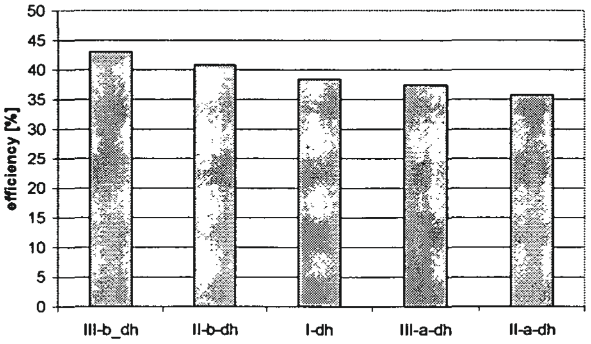

Fig. 6: Comparison of the thermal efficiencies of the different concepts

If the electrical and the thermal efficiency is summarised, the fuel utilisation is obtained.

An overview of the different fuel utilisation efficiencies can be found in Fig. 7. Concepts operating in combined heat and power mode can utilise the fuel up to 80 %, nearly double the value that can be obtained using power production only. The highest values can be achieved using pressurised gasification, followed by the catalytic cracking and the wet-ESP in combination with a gas engine. The net fuel utilisation of afore mentioned concepts using a gas turbine are nearly similar, however, differ greatly on their gross basis.

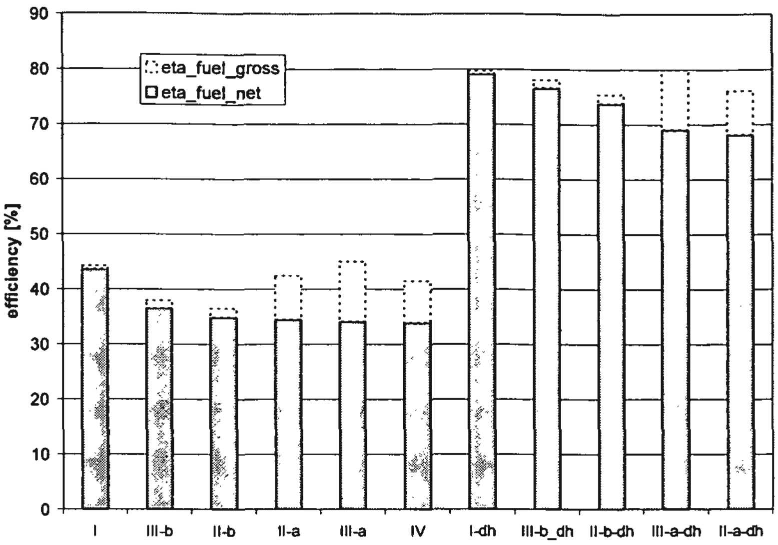

Fig. 7: Comparison of the gross and net fuel utilisation efficiencies of the different concepts

Finally the power to heat ratio of the different combined heat and power concepts are compared in Fig. 8. Great differences can be found comparing the gross and net alpha values of the different concepts, depending on the gross and net power outputs. The highest ratios can be achieved using gas turbines for gas utilisation, wherefrom the pressurised operation performs best. Second best values can be achieved using a wet electrostatic precipitator (concept II-a-dh), mainly since not all heat can be utilised from the product gas in the quench. The remaining three concepts achieve equal power to heat ratios of about 0.8.

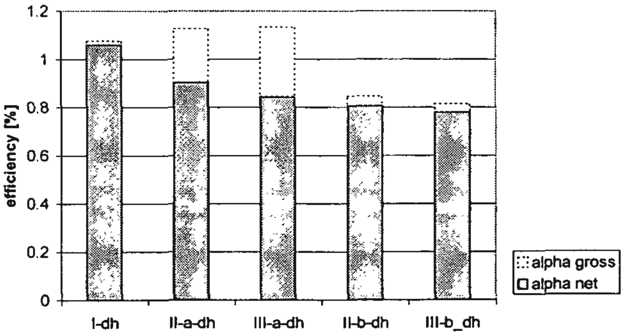

Fig. 8: Comparison of the gross and net power to heat ratios (alpha values) of the different concepts

7 Exergetic evaluation of the gas cleaning

In the following different gas cleaning technologies of the developed concepts are compared by their exergetic performance. Fig. 2 gives an overview of these concepts and the applied system boarder.

The result of this evaluation is shown in Fig. 9 using Sankey-diagrams. To compare these gas cleaning concepts the raw product gas is taken in each case as basis and set therefore as 100 %. In the gas cleaning, this raw product gas stream splits up into clean gas, useable exergy streams, losses and residue streams. Aim is to preserve as much exergy as possible in the clean product gas. The production of useable exergy stream, mostly heat, is acceptable, but these streams cannot be converted into electricity at the same efficiency as product gas. Losses stand for exergetic losses due to heat losses or to exergetic losses in heat exchangers, however do not cause any follow up costs like for disposal. Residues represent exergetic streams like ashes or tar laden water streams, which cause exergetic losses from the gas cleaning as well as cost for their treatment or disposal.

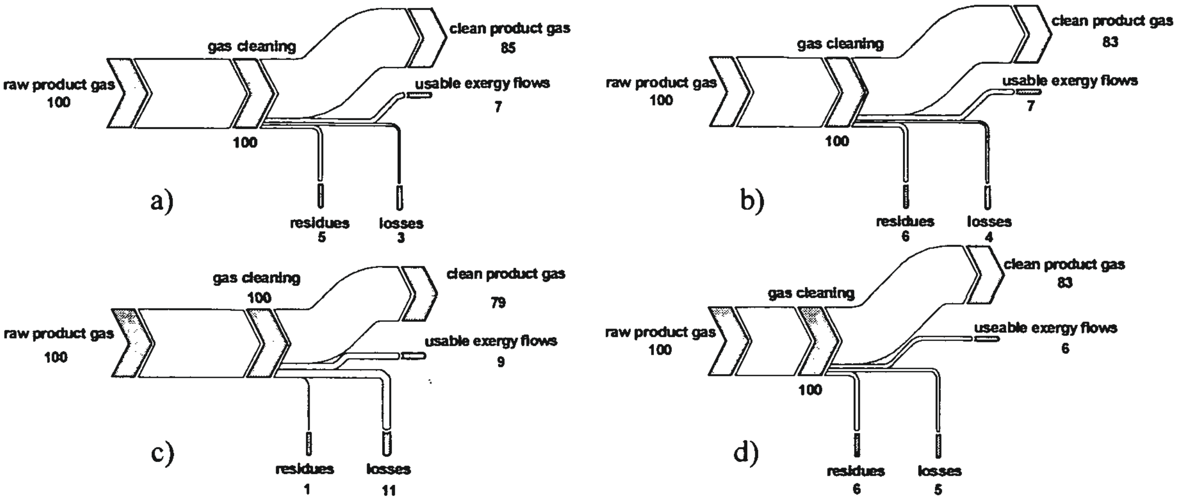

Fig. 9: Sankey-Diagrams of the different gas cleaning concepts: a) hot has filter; b) precoated cloth filter – solvent scrubber; c) catalytic cracker – cloth filter; d) quench – wet-ESP

It can be clearly seen by looking at the Sankey-diagramms that up to 21 % of the exergy in the raw product gas is lost during the gas cleaning. The highest exergetic efficiency can be achieved by the hot gas cleaning (pressurised gasification), where 85 % of the exergy from the raw product gas can be obtained. Furthermore 7 % of the raw gas exergy can be converted into usable exergy streams (steam). Together this accounts for an overall exergetic efficiency of 92 %. Atmospheric based gasification systems which require more stringent gas cleaning achieve exergetic efficiencies, which are 2 % lower in the best case, using a solvent scrubber (b) or a wet electrostatic precipitator (d), and even lower if a catalytic cracker is used (c). The concept of the catalytic cracker has the lowest residue streams (about 1 % of the exergy of the raw product gas), since tars are converted into stabile gaseous components. However, for a complete conversion of tars, as already mentioned, high temperatures of about 900 °C are necessary. This requires the raw product gas to be heated up, which is done in most cases by partial combustion of the product gas adding an oxidising agent, in most cases air. Thereby the heating value of the gas is reduced, since it is partly combusted and diluted by combustion products. However, the useable exergy flows are increased, since more heat is available. Furthermore, since combustion is an irreversible process, the exergy losses increase.

Fig. 10 shows the comparison of the overall exergetic efficiencies of the different gas cleaning concepts. The dark grey bars account for the exergy of the clean product gas, the light grey bars on the top for the usable exergy flows, like produced steam. The sum of both bars represents the exergetic gas cleaning efficiency of the gas cleaning.

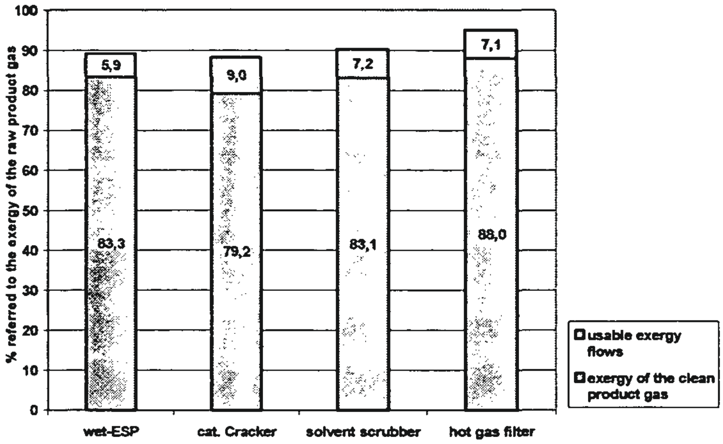

Fig. 10: Exergetic efficiencies of different gas cleaning technologies

Fig. 11 summarises the losses and the residues of the different gas cleaning technologies. The cracker has the highest non-usable exergy flows (summary from losses and residues), however the share of the residues is very low. Since residues can account for high disposal cost, it can be useful in some cases to take higher exergy losses into account to avoid high amounts of residues. The technologies wet-ESP and solvent scrubber show equal values in terms of residues, however in total the scrubber shows better results. The technology with the lowest losses is hot gas cleaning in combination with pressurised gasification, though even in this case higher amounts of residues are produced than with the catalytic cracker.

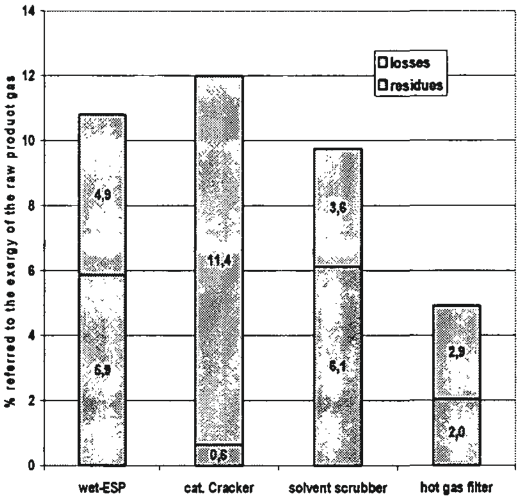

Fig. 11: Exergetic losses and residues from the different gas cleaning technologies

8 Exergetic investigations in the gas cleaning and gas utilisation

In the following the suitability of coupling different gas cleaning technologies with different gas utilisation technologies will be investigated.

Therefore the system boundary has to be extended onto the gas utilisation. This can be done in a straight forward approach for the atmospheric based systems with gas turbine or gas engine for gas utilisation. However for pressurised systems, like the one which was evaluated, compressed air from the gas turbine is used as gasification agent in the gasifier, which is outside the system boundary. Therefore a careful analysis of internal and external streams is necessary.

Input streams are the raw product gas from the gasifier, electricity (for a possible compression) and air for combustion. Output streams are the produced electricity, useable exergy flows, like the heat in the flue gas after the combustion, losses and residues. An overview can be seen in Fig. 12.

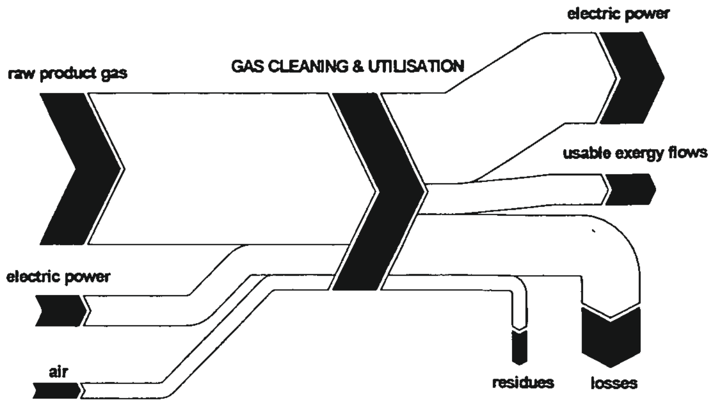

Fig. 12: Diagram of the balanced streams for the gas cleaning and utilisation

Fig. 13 summarises the net exergetic efficiencies for power and usable exergetic flows for different gas cleaning and utilisation technologies. Only little differences can be seen between the technologies wet-electric precipitator and solvent scrubber in terms of the electric exergetic efficiency if a gas turbine is used as gas utilisation technology. The gas cleaning technology catalytic cracker coupled with a gas turbine achieves the lowest electric exergetic efficiency. A substantial increase in efficiency can only be made if pressurised gasification is used in combination with a hot gas filter and a gas turbine.

Furthermore it can be seen that using gas engines instead of gas turbines as gas utilisation technologies, higher electric exergetic efficiencies can be achieved using the same gas cleaning technology, which are close to the efficiencies achievable using a pressurised concept.

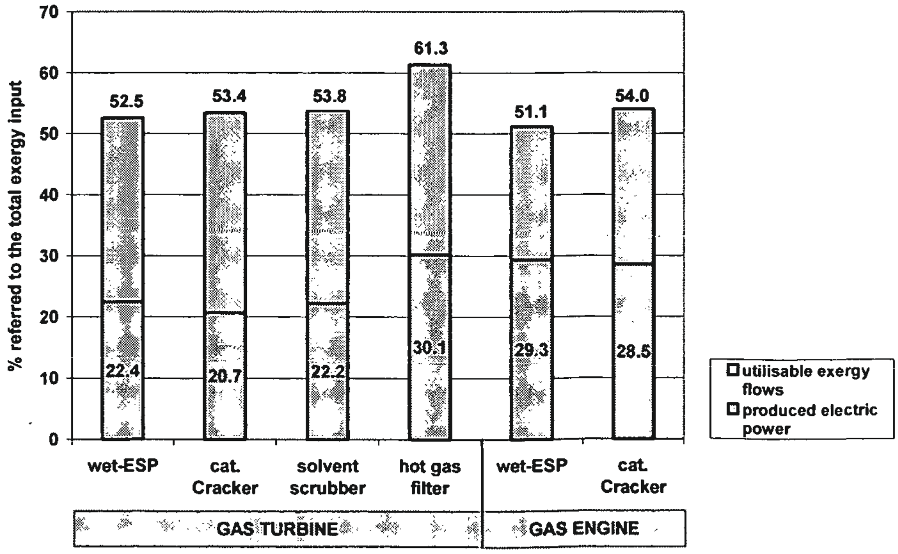

Fig. 13: Net exergetic efficiencies for power and useable exergetic flows

9 Conclusion

Using the process simulation tool IPSEpro different gasification concepts could be analysed according to their energetic and exergetic efficiencies.

Summarising the energetic comparison of the analysed concepts, it can be concluded that pressurised gasification with hot gas cleaning and gas utilisation in a gas turbine offers the highest achievable electrical efficiencies for power and CHP operation.

In atmospheric mode gas engines can achieve higher electrical efficiencies than gas turbines. This can be explained by the necessary compression before gas turbine usage. The different concepts do not differ much in their net electric efficiencies, however their own consumption varies strongly. From today's point of view, gas cleaning using a wet-ESP and a solvent scrubber is favourable. Catalytic tar cracking is still not state of the art and its robustness is still unclear.

In terms of the fuel utilisation a CHP operation is favourable since up to 80 % of the energy content of the fuel can be converted into usable products. If only power is produced this value ranges from 33 % to 40 %.

Finally it can be concluded that all concepts operated in CHP mode achieve power to heat rations between 0.8 and 1.0.

The exergetic analysis of the gas cleaning has revealed the hot gas cleaning in a pressurised system as the most favourable option. Using atmospheric gasification the wet electrostatic precipitator and the solvent scrubber are favourable in terms of exergetic efficiencies and commercial availability. The catalytically cracking achieves lower efficiencies, however produces the lowest residues.

From the exergetic point of view pressurised gasification in combination with a gas turbine achieves considerable higher exergetic efficiencies than atmospheric systems using a gas turbine.

For future developments in the 20 MW electrical and above power range pressurized gasification with hot gas cleaning seems to be the most promising option from the energetic and exergetic point of view. At smaller scale atmospheric systems using a wet ESP or a solvents scrubber coupled with a gas engine are favorable.

10 Symbols

	Description	Unit
CFB	circulating fluidised bed	
CHP	combined heat and power	
DLL	Dynamic Link Library	
e	specific exergy of a stream	$\mathrm{J\cdot kg^{-1}}$
$\dot{E}$	exergetic flow	$\mathrm{kW\cdot h^{-1}}$
E_{0i}	molar standard exergy of species i	$\mathrm{J\cdot mol^{-1}}$
h	specific enthalpy of a stream	$\mathrm{J\cdot kg^{-1}}$
hhv	higher heating value	$\mathrm{MJ\ m_s^{-3}}$
IGCC	integrated gasification combined cycle	
lhv	lower heating value volume referred	$\mathrm{MJ\ m_s^{-3}}$
$\dot{m}$	mass flow	$\mathrm{kg\ s^{-1}}$
MDK	model developer kit	
P_{el}	electrical power	kW
P_{th}	thermal power (fuel power)	MW
PSE	process simulation environment	
$\dot{Q}$	District of process heat	kW
R	general gas constant ($R = 8.31451$)	$\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$
s	specific entropy of a stream	$\mathrm{J\cdot kg^{-1}\cdot K^{-1}}$
T	temperature	K

Subscripts		
chem.	chemical	
cleangas	clean producer gas	
cons	consumption	
el	electric	
ex	exergetic	
Fuel	fuel (biomass)	
gross	gross value	
GC	gas cleaning	
GE	gas engine	
GT	gas turbine	
GU	gas utilisation	
input	input of fuel or feedstock	
net	net value	
th	thermal	
PS	useable process stream	
PG	product gas	
prod	production	
own	own consumption	
Q, q	heat	
rawgas	raw, uncleaned producer gas	
s	isentropic	
ST	steam turbine	
0	ambient conditions	

Greek-Symbols	Description	
α	power to heat ratio	-
η	efficiency	%

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VI. PAPER

Bolhàr-Nordenkampf, M.; Fürnsinn, S.; Hofbauer H.

„Exergetische Analyse und Bewertung von Gasreinigungsverfahren zur Staub- und Teerabscheidung aus Produktgas der thermo-chemischen Umwandlung“

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Exergetische Analyse und Bewertung von Gasreinigungsverfahren zur Staub- und Teerabscheidung aus Produktgas der thermo-chemischen Umwandlung

Einleitung

Die Gasreinigung stellt das Bindeglied zwischen der Gaserzeugung und der Gasnutzung dar, da sich meistens die Qualität des Produktgases aus der Biomassevergasung nicht für eine direkte Gasnutzung zur Stromerzeugung eignet. Bis heute konnten keine passenden Primärmaßnahmen (Maßnahmen im Vergaser selbst) gefunden werden, die ein Produktgas mit so niedrigen Verunreinigungen garantieren, dass eine zusätzliche Gasreinigung entfallen könnte.

Der Aufwand der Gasreinigung hängt stark vom eingesetzten Brennstoff, dem Vergasungsverfahren, den Prozessparametern und der nachgeschalteten Gasnutzung ab. So verursacht zum Beispiel ein Wirbelschichtvergaser eine deutlich höhere Staubbeladung im Produktgas als ein Festbettvergaser, ein Luftvergaser einen deutlich größeren Produktgasstrom (aufgrund des Stickstoffes im Produktgas) als ein Vergaser, der mit Dampf oder Sauerstoff betrieben wird. Auch die Teer-, Ammoniak- und H_2S-Gehalte im Produktgas hängen vom Brennstoff und dem jeweiligen Verfahren ab, ebenso wie die Gehalte aller anderen Verunreinigungen. Die Mengen und die Art der Verunreinigungen beeinflussen die zur Erreichung einer bestimmten Produktgasqualität notwendigen Gasreinigungsverfahren, deren Umfang und damit auch Kosten und Wirtschaftlichkeit der Gesamtanlage.

Der geforderte Reinheitsgrad wird durch die jeweilige Gasnutzung bestimmt. Bei einer Verwendung des Produktgases als Brennstoff in Zementanlagen oder als Zufeuerung in Kraftwerken kann meist vollständig auf eine Gasreinigung verzichtet werden. Soll das Gas hingegen zur Stromerzeugung mittels Gasmotor oder Gasturbine herangezogen werden, ist eine mehr oder minder aufwendige Gasreinigung notwendig, die bei einer zukünftigen Nutzung von Produktgas in einer Brennstoffzelle oder gar als Synthesegas noch deutlich umfangreicher würde.

Offensichtlich ist die Auswahl der passenden Gasreinigung nicht trivial. Neben der technischen Funktionalität muss die Gasreinigung auch wirtschaftliche Kriterien erfüllen und möglichst geringe energetische und exergetische Auswirkungen auf den Gesamtprozess haben.

Verunreinigungen und Gasreinigungsverfahren

In Abbildung 1 sind die wichtigsten möglichen Verunreinigungen des Produktgases dargestellt. Diese Verunreinigungen und entsprechende Entfernungsmöglichkeiten werden im Folgenden kurz dargestellt, für eine ausführlichere Darstellung und Analyse sei auf [1] verwiesen. Zusätzlich zur Abscheidung von Verunreinigungen muss für die Nutzung des Produktgases als Synthesegas auch die Gaszusammensetzung bestimmten Voraussetzungen genügen. Die Gaskomponenten Methan und Ethan, die für den Einsatz von Produktgas als Brennstoff durchaus gewünscht sind, stellen für die Synthesegasproduktion unerwünschte Komponenten dar, da sie nicht umgesetzt werden können. Zusätzlich muss für den Synthesegaseinsatz auch das molekulare Verhältnis zwischen Wasserstoff und Kohlenmonoxid eingestellt werden.

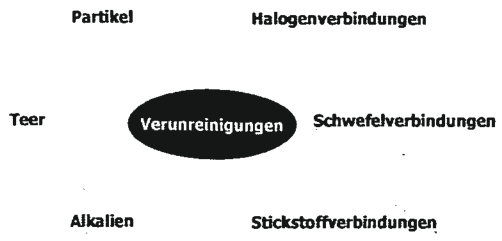

Abbildung 1: Verunreinigungen des Produktgases

Partikelentfernung

Unter Partikeln werden Feststoffe verstanden, welche mit dem Rohproduktgas aus dem Vergaser ausgetragen werden. Dazu zählen anorganische Asche, die aus den Mineralien im Brennstoff stammt, nicht umgesetzte Biomasse in Form von Koks sowie Bettmaterial. Die notwendige Reinheit bezüglich Partikel hängt vom Einsatzgebiet des Produktgases ab. Zum Beispiel muss die Partikelbeladung für einen Einsatz des Produktgases in einem Gasmotor unter 50 mg/Nm³, für den Einsatz in einer Gasturbine unter 15 mg/Nm³ (5 µm) und für den Einsatz als Synthesegas bis auf unter 0,02 mg/Nm³ gesenkt werden. Folgende Standardkomponenten können für die Partikelentfernung eingesetzt werden:

- Zyklone
- Filter mit Filtermedium
- Elektrofilter
- Wäscher

Zyklone stellen einen gute Möglichkeit dar, hohe Partikelbeladungen bei hohen Temperaturen aus einem Gasstrom abzuscheiden.

Filter mit Filtermedien können effektiv Partikel in der Größenordnung von 0,5 bis 100 µm und sogar submircrone Partikel entfernen, mit einem stark ansteigenden Druckverlust bei kleineren Partikeln. Als Filtertyp haben sich Gewebe- und Kerzenfilter bewährt. Gewebefilter aus Standardmaterialien können üblicherweise bis zu einer Temperatur von 250°C, Filter aus Metallgeweben bis 350°C eingesetzt werden und müssen, um Verklebung des Filtermaterials mit Teer zu vermeiden, precoatisiert werden. Kerzenfilter aus Metall oder Keramik werden auch als Heißgasfilter bezeichnet, da sie eine Möglichkeit darstellen, die fühlbare Wärme im Produktgas zu erhalten. Vielversprechende Weiterentwicklungen auf dem Gebiet der keramischen Filter könnten in Zukunft eine gleichzeitige Staub-, katalytische Teer- und Ammoniakabscheidung erlauben.

Eine weitere Art der Reinigung mit sehr hohen Abscheidegraden bietet der trockene oder der nasse *Elektrofilter*. Beim trockenen Elektrofilter (T<500°C) wird der gesammelte Staub mechanisch, beim nassen Elektrofilter (T<70°C) mittels eines dünnen Wasserfilmes entfernt. Nasselektrofilter können gleichzeitig Staub und Teer entfernen und dabei auch andere Schadstoffe wie NH_3, HCl und H_2S abscheiden. Elektrofilter zeichnen sich durch einen niedrigen Druckverlust und hohe Filtrationsraten bei niedrigen Betriebskosten und kontinuierlichem Betrieb aus.

Wäscher benutzen eine Waschflüssigkeit, meist Wasser, um Partikel aus dem gekühlten Gasstrom (meist mittels eines Quench) zu entfernen, wobei ein hoher Druckverlust von 30 bis 200 mbar zur Erreichung von Reingaskonzentrationen von 10-20 mg/Nm³ notwendig ist (Venturiwäscher).

Teerentfernung

Teer ist eine komplexe Mischung aus organischen Verbindungen. Dieser führt oft zu Problemen, wenn das Gas vor der Nutzung gekühlt oder komprimiert werden muss. Es ist wichtig, bereits im Vergaser durch Primärmaßnahmen zu versuchen, den Teergehalt gering zu halten (Reaktordesign, Prozessführung, Katalysatoren). Meist reicht diese Reduktion nicht aus, sodass weitere Gasreinigungsstufen nachgeschaltet werden müssen. Teer stellt nicht nur ein Problem bei der Gasreinigung und Gasnutzung dar, sondern reduziert auch den Kaltgaswirkungsgrad der Anlage, sofern der abgeschiedene Teer nicht rückgeführt wird.

Zur Entfernung des Teers stehen im Prinzip zwei Wege offen. Meistens werden *physikalische Methoden* angewandt, wozu oft Wäscher oder Elektrofilter eingesetzt werden, die eine Kühlung des Gases erfordern. Die andere Möglichkeit ist die *chemische* Teerentfernung, wobei der Teer thermisch oder katalytisch in stabile Gaskomponenten umgewandelt wird.

Physikalische Teerentfernung

Mit Wasser betriebene *Wäscher* stellen die am häufigsten angewandte Methode der Teerentfernung dar, obwohl diese keine guten Abscheidegrade erreichen. Für die Teerentfernung werden die unterschiedlichsten Wäschertypen eingesetzt: Waschtürme, Rotationswäscher, Prallwäscher und Venturiwäscher. Durch den Einsatz von Lösungsmittelwäschern auf Ölbasis anstatt Wasser können Teerreingaswerte von 10 mg/Nm³ erreicht werden [2], [3]. Eine Neuentwicklung auf diesem Gebiet stellt der OLGA Prozess [4] dar, wo Teer mittels eines Lösungsmittels bei höheren Temperaturen (300°C) entfernen werden kann. Dabei wird das gesättigte Lösungsmittel regeneriert und die gestrippten Teerdämpfe in den Prozess rückgeführt.

Für die Teerentfernung mittels *Nasselektrofilter* werden Röhrenelektrofilter den Plattenelektrofiltern vorgezogen. Die Technologie ermöglicht eine kombinierte Staub und Teerabscheidung mit sehr hohen Reinheitsgraden (<10 mg/Nm³), wobei die im gesättigten Gas entstanden Flüssigkeitströpfchen, kondensierte Teere und Partikel an den Elektroden abgeschieden werden.

Filter mit Filtermedium: Durch die Kondensation der Teere zur klebrigen Partikeln ist die Abreinigung von teerbeladenen Filtermedien schwierig. Diese müssen daher precoatisiert werden, ermöglichen aber dennoch nur eine mäßige Teerabscheidung. Schüttschichtfilter mit Sand, Sägemehl und ähnlichem werden hauptsächlich bei Kleinanlagen eingesetzt. Ihre Anwendung ist aber aufgrund der Rückstände und deren Entsorgung problematisch.

Katalytische Teerumwandlung

Bei der katalytischen Teerumwandlung wird der Teer mittels eines Katalysators bei 800-900°C in stabile Gaskomponenten umgesetzt. Es besteht die Möglichkeit, den Katalysator direkt im Vergasungsreaktor oder in einem externen Reaktor einzusetzen. Nicht-metallische Katalysatoren wie zum Beispiel Dolomite, Zeolithe und Kalkspat sind relativ kostengünstig und gegenüber Verunreinigungen nur wenig empfindlich. Metallische Katalysatoren werden kommerziell in der Petrochemie eingesetzt. Typische Vertreter sind Ni, Ni/Mo; Ni/Co/Mo; NiO, Pt, Ru Katalysatoren [5-8]. Diese Katalysatoren haben den Vorteil, dass sie in der Lage sind, neben Teer auch den im Produktgas vorhandenen Ammoniak in Stickstoff zum Teil umzuwandeln.

Bisher ist die Lebensdauer dieser Katalysatoren in der Biomassevergasung jedoch noch nicht ausreichend getestet. Ein weiterer Nachteil ist ihr hoher Preis.

Thermische Teerumwandlung

Teere können auch ohne Katalysatoren thermisch zerstört werden, wofür jedoch sehr hohe Temperaturen erforderlich sind, wodurch eine wirtschaftliche Teerabscheidung schwer möglich ist [9].

In weiterer Folge werden unterschiedlichen Gasreinigungsverfahren für die Abscheidung von Teer und Staub exergetisch untersucht.

Analyse der Gasreinigungsverfahren

Aus der Analyse der Gasreinigungsverfahren ergeben sich drei vielversprechende Gasreinigungssysteme zur Entfernung von Staub- und Teerkomponenten aus dem Rohproduktgas: mittels einer Kombination Quench - Nasselektrofilter, mittels einer Kombination precoatisierter Gewebefilter - chemischer Wäscher und mittels einer Kombination katalytischer Teercracker - Gewebefilter. Die ersten beiden Systeme sind bereits großtechnisch erprobt, das letzte stellt ein vielversprechendes zukünftiges Verfahrenskonzept dar. Beim Einsatz einer Druckvergasung ist die Gasreinigung insgesamt deutlich einfacher, da auf die Abscheidung von Teer verzichtet werden kann, sodass nur eine einfache Heißgasreinigung notwendig ist. Diese vier Verfahren wurden mittels des Simulationsprogramms IPSEpro® auf ihre Güte untersucht. IPSEpro® ist ein gleichungsorientiertes, stationäres Fließbild-Simulationsprogramm, das ursprünglich für die Kraftwerkstechnik konzipiert wurde. Gleichungsorientiert bedeutet, dass mit Hilfe der Informationen aus dem Fließbild nichtlineare Gleichungssysteme aufgestellt werden, welche dann nach einem bestimmten Algorithmus (z.B. Newton-Raphson) in einem Schritt gelöst werden. Stationär heißt, dass keine zeitlichen Veränderungen abgebildet werden können. Dieses Programm, ursprünglich für die Modellierung von Kraftwerksprozessen gedacht, wurde für die Abbildung von Vergasungsprozessen umfangreich weiterentwickelt.

Eine Bewertung der passenden Gasreinigungstechnologie kann nur im Umfeld mit dem Reaktortyp und der angewendeten Gasnutzung erfolgen. In Abbildung 2 sind mögliche Kombinationen abzuscheidender Verunreinigungen dargestellt.

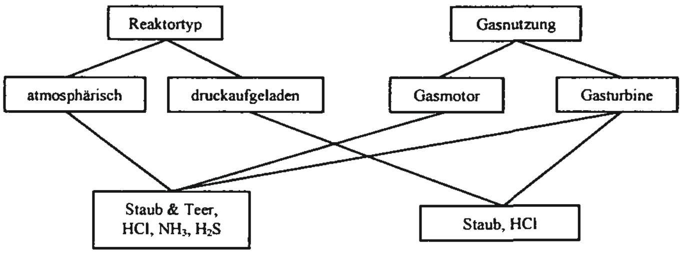

Abbildung 2: Mögliche Kombinationen von Gasreinigung und Gasnutzung

Muss das Gas vor der Nutzung verdichtet werden, so müssen etwaig vorhandene Chlor-, Stickstoff-, und Schwefelverbindungen noch vor der Verdichtung abgeschieden werden, wobei der Gasmotor aufgrund des geringeren Verdichtungsverhältnisses geringere Anforderungen an die Gasqualität stellt als die Gasturbine. Bei einer Druckvergasung müssen nur die Chlorverbindungen, welche Heißgaskorrosion in der Turbine verursachen, entfernt werden. Die anderen Schadkomponenten können auch nach der Gasnutzung aus dem Rauchgas abgetrennt werden. In dieser Arbeit wird nur die Gasnutzung in einer Gasturbine betrachtet.

In Abbildung 3 sind die untersuchten Reinigungsverfahren nochmals grafisch als Blockflussdiagramm dargestellt. Beim ersten Konzept wird ein Teilstrom der Verbrennungsluft der Gasturbine nach dem Verdichter entnommen und für die Druckvergasung genutzt. Das Produktgas befindet sich daher bereits auf dem für die Nutzung in der Gasturbine notwendigen Druck und muss nicht mehr komprimiert werden. Bei der atmosphärischen Vergasung hingegen liegt das Produktgas nach dem Reaktor praktisch mit Atmosphärendruck vor und muss nach der Gasreinigung zur Nutzung in der Gasturbine verdichtet werden. Für die atmosphärische Vergasung wurden drei Varianten der Gasreinigung untersucht: Reinigung mittels eines chemischen Wäschers, Reinigung mittels Nasselektrofilter und mittels katalytischer Teerabscheidung.

Im ersten Fall wird die fühlbare Wärme des Produktgases genutzt und dieses soweit abgekühlt, dass es im Gewebefilter entstaubt werden kann. Danach wird das Produktgas in einem Wäscher mittels eines chemischen Lösungsmittels von Teer gereinigt. Als Reststoffe fällen Asche aus dem Gewebefilter sowie das teerbeladene Lösungsmittel aus dem Wäscher an.

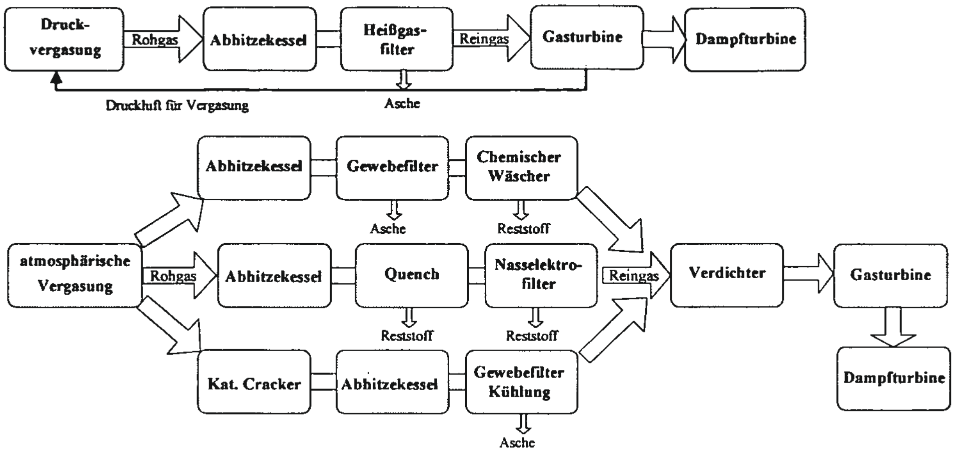

Abbildung 3: Mittels Prozesssimulation untersuchte Anlagenverschaltungen

Im zweiten Konzept wird das Produktgas nach der primären Abkühlung in einer Abhitzestrecke weiter in einem Quench auf die für den Nasselektrofilter notwendige Temperatur abgekühlt und in diesem von Staub und Teer gereinigt. Dabei fallen in beiden Aggregaten verunreinigte Wasserströme an.

Im dritten Konzept wird das Gas mittels eines katalytischen Crackers von Teerkomponenten gereinigt, das Gas in einer Abhitzestrecke gekühlt und mittels eines Gewebefilters entstaubt. Zur Reduktion der Verdichterleistung wird die Temperatur des Gases mittels eines Luftkühlers noch weiter gesenkt. Bei diesem Konzept fällt als Reststoff nur die Asche aus dem Gewebefilter an.

Ergebnisse der Analyse

Im Folgenden werden die vorgestellten Konzepte anhand der Exergie analysiert und bewertet. Die Exergie stellt dabei jenen Teil der Energie dar, welche uneingeschränkt in anderen Energieformen umwandelbar ist. So ist zum Beispiel Wärme nicht vollständig in andere Energieformen umwandelbar, Strom hingegen stellt eine Form reiner Exergie dar. Damit ist es möglich, die Güte eines Prozesses fundiert zu bewerten. In Abbildung 4 sind die Sankey-Diagramme der unterschiedlichen Gasreinigungstechnologien dargestellt.

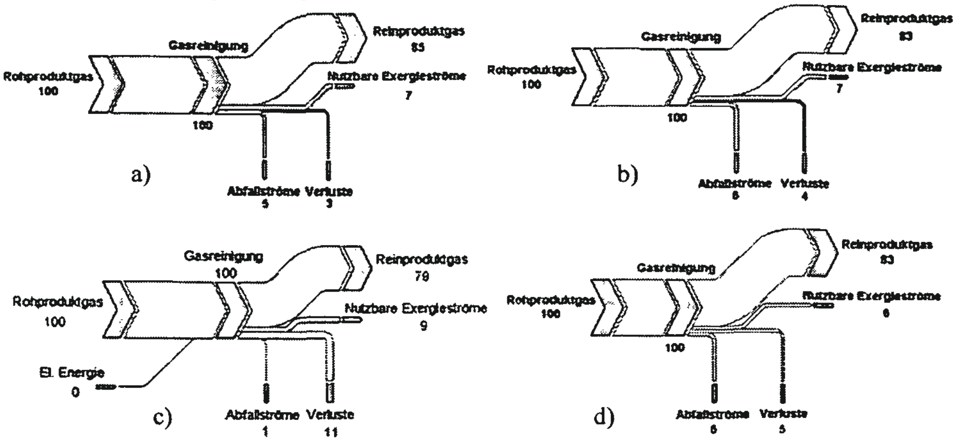

Abbildung 4: Sankey-Diagramme der unterschiedlichen Gasreinigungskonzepte a) Heißgasfilter b) Gewebefilter–chem. Wäscher c) katalytischer Cracker-Gewebefilter d) Quench–Nasselektrofilter

Wie man aus den Diagrammen ersehen kann, gibt es deutliche Unterschiede in der nach der Gasreinigung im Reinproduktgas enthaltenen Exergie. Den höchsten exergetischen Wirkungsgrad erreicht die Heißgasentstaubung (Druckvergasung), bei der 85 % des Rohproduktgases zur Gasnutzung zur Verfügung stehen und zusätzlich weitere 7 % in nutzbare Exergieströme umgewandelt werden. Dies entspricht einem gesamtexergetischen Wirkungsgrad von 92 %. Bei Verfahren, die auf der atmosphärischen Vergasung basieren und grundsätzlich eine aufwendigere Reinigung erfordern, liegen die Reinigungsverfahren mittels chemischen Wäschers (b) und mittels Nasselektrofilters mit einem 83 %igen Erhalt der Rohproduktgasexergie gleich auf. Diese Verfahren unterscheiden sich auch bei den zusätzlich auskoppelbaren Exergieströmen um nur einen Prozentpunkt. Interessanterweise hat das Verfahrenskonzept der thermischen Crackung den schlechtesten exergetischen Wirkungsgrad (bezogen auf das Rohproduktgas). Hier wird der Teer in stabile Gaskomponenten umgewandelt, weshalb auch ein deutlich geringerer Abfallstrom anfällt (nur 1 % der Exergie), jedoch bedarf die katalytische Umsetzung hoher Temperaturen (900 °C), weshalb das Produktgas teilweise oxidiert werden muss. Dadurch wird auch der Heizwert und somit die chemische Exergie vermindert. Durch den höheren Wärmeinhalt im Produktgas steigen jedoch auch die Anteile der nutzbaren Exergieströme (hauptsächlich in Form von Dampf) an. In Abbildung 5 sind die gesamtexergetischen Wirkungsgrade der jeweiligen Gasreinigung (nutzbare Exergieströme und Exergie des Reingases bezogen auf die Exergie des Rohproduktgases und die zugeführte elektrische Leistung) nochmals deutlich ersichtlich.

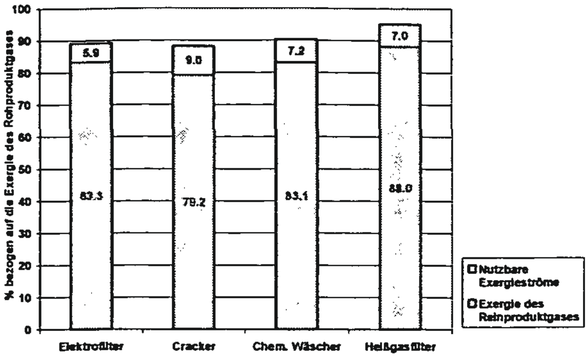

Abbildung 5: Exergetische Wirkungsgrade der jeweiligen Gasreinigungstechnologien

Abbildung 6 zeigt die Verluste und Abfallströme der jeweiligen Gasreinigungstechnologie. Dabei fällt auf, dass der Cracker am meisten nicht-nutzbare Exergieströme (Summe der Verluste und Abfallströme) aufweist, jedoch der Anteil der Abfallströme äußerst gering ist. Da Abfallströme jedoch bei der Entsorgung hohe Kosten verursachen, kann es sinnvoller sein, einen höheren Exergieverlust in Kauf zu nehmen und die Abfallströme zu minimieren. Die Technologien Elektrofilter und chemischer Wäscher liegen bezüglich der Abfallströme praktisch gleich auf, insgesamt ist jedoch der chemische Wäscher etwas besser einzustufen. Die Technologie mit den geringsten Verlusten und Abfallströmen stellt der Heißgasfilter bei der Druckvergasung dar, jedoch fallen auch hier höhere Abfallströme als beim Einsatz des katalytischen Crackers an.

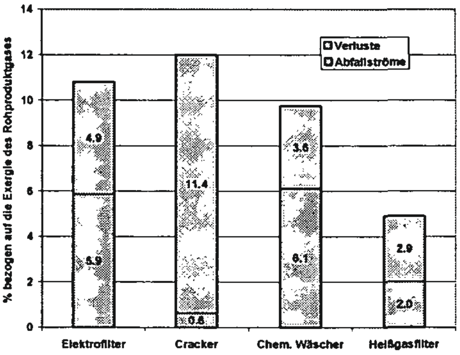

Abbildung 6: Exergetische Verluste und Abfallströme der jeweiligen Gasreinigungstechnologien

In Abbildung 7 sind die Verhältnisse der nutzbaren Exergieströme bezogen auf die Exergie des Rohproduktgases bei Kopplung der jeweiligen Gasreinigungstechnologien mit einer Gasturbine dargestellt. Die Unterschiede der Technologien Elektrofilter und chemischer Wäscher fallen gering aus. Die Technologie des katalytischen Crackers gekoppelt mit einer Gasturbine liegt sowohl bei der produzierten elektrischen Leistung als auch bei den gesamten nutzbaren Exergieströmen etwas schlechter. Eine deutliche Verbesserung der Nutzung der Rohproduktgasexergie kann nur mittels eines Heißgasfilters beim Einsatz einer Druckvergasung erreicht werden.

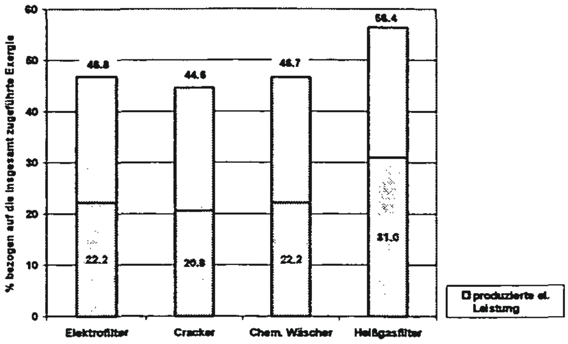

Abbildung 7: Nutzbare Exergieströme bezogen auf die insgesamt zugeführte Exergie

Zusammenfassung und Ausblick

Bis heute stellt die Reinigung des Rohgases aus der thermochemischen Umwandlung von Biomasse eine kritische Komponente dar. In diesem Paper wurden die Unterschiede in den erzielbaren exergetischen Wirkungsgraden der Gasreinigung alleine, wie auch in Kombination mit der Gasnutzung dargestellt. Dabei hat sich gezeigt, dass eine singuläre Betrachtung der Gasreinigung nicht zielführend ist.

Aus heutiger Sicht stellen die Technologien Elektrofilter und chemische Wäscher erprobte, robuste Lösungen für die Abscheidung von Teer- und Staubkomponenten dar. Das katalytische Cracken der Teere ist aufgrund der niedrigen Abfallströme eine interessante Technologie für die Zukunft, jedoch fehlt derzeit noch die Langzeiterfahrung. Eine deutlich bessere Nutzung des Exergieinhaltes des Rohproduktgases kann nur mittels der Druckvergasung, allerdings bei höheren Investkosten, erreicht werden.

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VII. PAPER

Bolhàr-Nordenkampf, M.; Pröll, T.; Hofbauer, H.

"Techno-Economical Assessment of Combined Heat and Power Production from Biomass"

Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.

TECHNO ECONOMICAL ASSESSMENT OF COMBINED HEAT AND POWER PRODUCTION FROM BIOMASS

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ABSTRACT: Even at small scale combined heat and power production from biomass can achieve high overall efficiencies referred to the fuel power input. In the present work, six technologies are evaluated; conventional combustion based technologies, like steam turbine, steam engine, ORC-process (Organic Rankine Process) or Stirling engine on the one hand and gasification-based technologies, like fixed and fluidised bed gasification combined with gas engines on the other hand. Plant data are collected to assess the different technologies and to calculate their electricity production costs. To obtain comparability for each plant the costs are calculated using a reference case. The influence of scale is considered in order to compare electricity production costs for plants of different sizes. Furthermore, variations are carried out to show the influence of different parameters. Finally, learning curves are applied to calculate electricity production costs for future plants. Revenues from heat sales are of major importance for the economy of current CHP-Plants (Combined Heat and Power). In the future, gasification technologies will close the gap to conventional technologies with respect to the costs of electricity production.

Keywords: combined heat and power generation (CHP), economic aspects, feasibility studies.

1 INTRODUCTION

Biomass is one of the renewable resources that could play a substantial role in a more diverse and sustainable future energy mix. Biomass, a renewable source of fixed carbon, is generally used to describe plant material such as wood, wood residues, agricultural crops and their residues.

In the near future electricity generation is considered the most lucrative opportunity for commercial exploitation of biomass, by virtue of the high value of electricity due to new legislations [1]. Furthermore, electricity production from biomass can contribute to the reduction of CO_2 emissions from fossil carbon.

While biomass-fired plants for heat supply have already become common in countries with high biomass availability like Austria, electricity production has not been able to attract major interest of investors during the last decades. This can be related to the fact that standardised technical solutions have not been available for small scale applications. Impulses through electricity feed in tariffs, reflecting the real costs for electricity production, have been rare. In some cases the feed in tariffs for district heat are even higher than for the produced electricity.

Biomass to electricity schemes provide today only 9 GW_{el} (about 2 %) of world-wide generating capacity [2]. Most of these systems burn various biomass and wastes (mainly wood) in boilers to raise steam that is used to drive a steam turbine. Generating capacities are constrained by the local availability of feedstock. Another constraint is the fact that steam turbines are inefficient generators with high capital costs at low plant sizes [3], [4].

Keeping in mind the Kyoto target, the situation is currently changing in Austria. Encouragements for investments in the biomass energy sector are given in form of higher and fixed feed in tariffs for electricity by the government. Due to economics and the aim of high overall efficiencies, the combined heat and power generation is the preferred type to be realised. Small to medium sized plants located close to heat consumers are required because of the limited transportation range of low level heat. The basic requests for such systems are a high availability as well as good partial load behaviour. Further, operational costs should be low. Provided the produced heat can be utilised, combined heat and power production can achieve fuel utilisation rates up to 90 % even for small plant sizes.

Some studies have investigated the cost of CHP-plants, based on calculated costs for the different technologies [5-8]. All of these studies are based on calculated design cases. In the present work, six technologies for the conversion of biomass to energy are assessed based on operation data and costs of real plants; conventional combustion based technologies, like steam turbine, steam engine, ORC-process or Stirling engine are looked at on the one hand and gasification-based technologies, like fixed and fluidised bed gasification combined with gas engines on the other hand.

2 ECONOMIC EVALUATION

2.1 Cost assignment

From an economical point of view, the problem is to assign the costs to two coupled products, electricity and heat. Many authors [9-12], [17] assume that the main reason for the erection of a CHP plant is the heat demand. Therefore, they only assign costs to heat production, which would arise for heat-only production in an equivalent hot-water boiler; all additional costs of the CHP plant are assigned to the electricity production. A second approach towards the assignment of costs considers the CHP plant to be a power plant with the goal of maximizing the total energy output. The economic value of heat strongly depends on the temperature level, which usually is 90 to 110 °C in district heating grids. Therefore, two aspects have to be

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considered if a standard power plant should be operated as CHP plant: Heat has to be drawn at a temperature level high enough and heat consumers must be located in vicinity of the plant. This consideration takes the electricity production as part of the total concept, which makes a separation of produced electricity and own consumption not justifiable. Therefore, the own consumption of the plant is subtracted from the generator power in order to get the net electricity output of the plant. For this kind of evaluation the so-called net efficiencies apply.

In this paper the CHP-plants are treated as power plants with net power and heat output. In order to compare the electricity production costs, the price for decoupled heat must be fixed for all plants at the same level. The evaluated plants prove this approach by the fact that the investigated feed in tariffs for district heat do not differ significantly.

2.2 Evaluated technologies

In order to obtain data for the different technologies, eight plants haven been visited and the specific data collected. The evaluation includes a Stirling engine, one steam engine, a fixed bed gasifier, two Organic Rankine Cycles (ORC) equal in size, a fluidised bed gasifier and two steam turbine processes equal in size too. The capacities of these plants are highly important if the production costs of different technologies should be compared. Table I gives an overview of the characteristic data of the evaluated plants. Descriptions of the different technologies can be found elsewhere [13], [14].

Table I: Characteristics plant data

Process	Biomass fuel power [kW]	Electrical gross power [kW]	Electrical own consumption [kW]	District heating power [kW]
Stirling engine	900	50	30	800
Steam engine	4,310	500	100	3,050
ORC	8,000	1,130	180	6,100
Steam turbine process	17,000	2,700	260	12,000
Fixed bed gasifier	2,000	580	100	720
Fluidised bed gasifier	8,000	2,000	300	4,500

2.3 Technology specific costs and general setup for technology comparison

In order to compare the electricity production cost of different technologies, the investment and operation costs have to be known for a specific plant size. An overview on the specific costs of each considered technology in a typical application size can be found in Table II.

The costs are related to the fuel power of each plant to give a better impression of the necessary plant size. Other expenses are calculated as a relative value of the investment costs according to VDI-Guideline 2067 [15]. Employment costs for one person are considered with 40,000 €/a, as an average value.

Table II: Characteristic plant data

	Investment cost [€/$kW_{el,brut}$]	Investment cost [€/kW_{th}]	Maintenance [% invest. p.a.]	standing expenses [% invest. p.a.]	Staff costs [k€/a]	Utilities[€/MWh_{th}]
striling engine	8,784	488	1.0	0.2	40	0.12
steam engine	3,775	509	2.5	0.2	40	1.03
fixed bed gasifier	5,172	1,500	3.0	0.2	40	1.00
ORC-process	4,630	654	2.0	0.2	60	0.20
fluidised bed gasifier	5,000	1,250	3.0	0.2	160	1.70
steam turbine	2,637	385	2.0	0.2	120	0.14

Aside of the technology specific costs the general setup costs like working capacity, fuel price and district heat revenues have to be considered. These conditions are summarised for the chosen reference case in Table III.

Table III: Assumptions for the assessment

Full load operation hours in terms of electricity production	6,000	h/a
Full load operation hours in terms of district heat production	4,000	h/a
Period of amortisation	13	a
Calculatory interest rates	6	% p.a.
Fuel costs including ash disposal costs	14	€/MWh
Feed in tariffs for district heat	20	€/MWh_Q

Electricity production is not linked strictly to the heat demand, because it can be economically advantageous to operate a plant during summertime even if the produced heat cannot be sold. Therefore, 6000 full load operation hours/a are assumed for electricity production whereas only 4000 hours/a are assumed for heat production. The period of amortisation is set to 13 years, which is in accordance with a decree of the Austrian government from December 2002, which fixes the electricity feed in tariffs for a period of 13 years [16]. The rate of interest was chosen in conformity with other techno economical assessments [17], [18]. The fuel costs refer to wood chips and include the ash disposal, which accounts for about 5% of the costs for untreated woody biomass. The district heat feed in tariff is defined at the intersection of the CHP plant and the district heating pumps.

3 RESULTS

3.1 Electricity production costs

The electricity production costs are calculated from the net electric output, taking the own electric consumption into account. Costs arise through operation and payback of investment rates, earnings are yielded from the district heat sold.

Figure 1 shows the electricity production costs referred to the plant size. The different technologies are scaled in their typical application range of size. The evaluated case is indicated as point on the curves. The electricity production costs of the Stirling engine, which range at about 700 €/MWh for a 50 kW_{el} (900 kW_{th}) plant, are not shown in the diagram. It is important to notice that at this stage the different development status of the technologies is not taken into account.

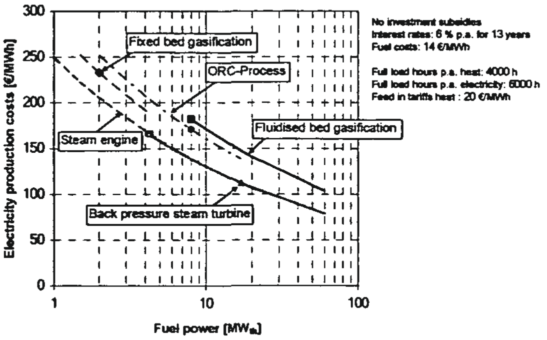

Figure 1: Electricity production cost for different technologies

Starting from the reference case variations of parameters are carried out. In order to compare the technologies two typical plant sizes are defined:

The fuel power for a small sized plant is set to 3 MW_{th} for the fixed bed gasifier, the steam engine and the ORC-process.

The fuel power for the large sized plant is set to 20 MW_{th} for the back pressure steam turbine and the fluidised bed gasification.

Figure 2 shows the greater dependence of the combustion technologies on the feed in tariffs for heat, whereas low heat earnings have only a minor effect on gasification technologies. Higher electrical efficiencies are generally advantageous during periods of lower heat sales or discontinuous heat demand.

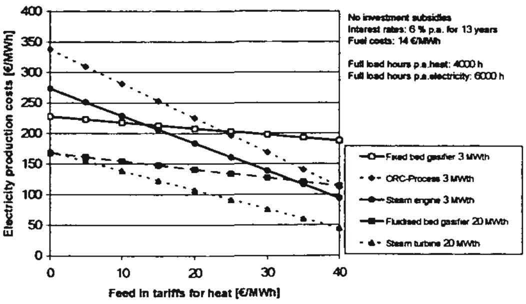

Figure 2: Influence of the feed in tariffs for heat on the electricity generating cost

High fuel prices are also favouring the gasification technologies (Figure 3).

Even at the current technological development status gasification technologies can compete at a high fuel price with state of the art technologies. This is of major importance because increases in the fuel price have occurred already and will also occur in the near future due to encouraged woody biomass usage.

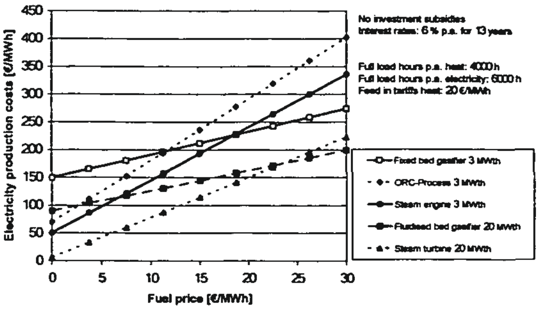

Figure 3: Influence of the fuel price on the electricity generating costs

3.3 Electricity production cost for future plants

Technologies which are suitable to standardisation and to the exploitation of economic of scale tend to follow a learning-by-doing pattern; increased productivity, and thus lower specific production costs, result in a function of cumulative production or life cycle stage. Their performance, and in particular their production costs, follow a so called learning curve [19].

Not all technologies evaluated within the present work have the same development status. The effect of experience in engineering and operation, which is basically different for each technology, has not been considered above. A certain learning effect can be expected for not fully mature technologies. The impact of experience is estimated to agree with the effect found in series production compared to the production costs of a prototype. Rogner [20] and Tseng [21] have shown that this effect could be found as well in power plant technology.

In order to calculate the future electricity production costs of the different evaluated technologies further information additional to the investment cost reduction is needed. Reduction potential can be found as well in the conversion efficiency, the possible usage of lower quality and therefore cheaper fuel, the usage of operation means and the staff requirements.

The development status of each technology is different. Stirling engines and fixed bed gasifiers are known for quite a long time, though they are not well developed in terms of commercial application. This applies also for fluidised bed gasification plants. The ORC process is available as packaged unit on the market, as well as the steam engine. The highest developed technology is the steam turbine, with large capacities installed and therefore little development potential.

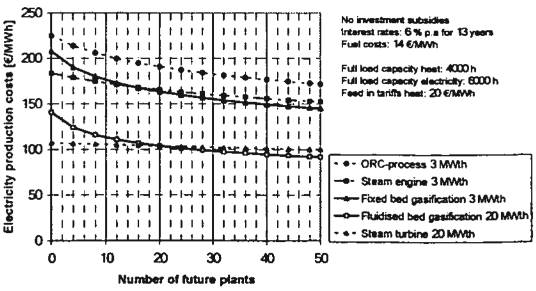

Figure 4: Development of the electricity production costs for future plants

Taking these considerations into account, the future cost of electricity production can be estimated for the next 50 plants to be built. Again the two defined standard sizes are used for the application on the learning curves. The results can be found in Figure 4 for 3 MW_{th} and 20 MW_{th}, respectively.

Today's electricity production costs of these technologies (no new plants built) can be seen on the left side of each curve. Dependent on the development status of the technologies under consideration different slopes exist for each one.

Looking at the small plant size (3 MW_{th}), it can be seen that on the long term electricity production costs of 150 €/MWh_{el} can be achieved. The differences between the combustion/steam engine or turbine technology and gasification/gas engine technology are within the accuracy of this evaluation.

For the larger plant scale, the fluidised bed gasification can reach the plant cost level of the steam turbine and might even achieve values below. In the large scale applications electricity production costs of 90 - 100 €/MWh_{el} are realistic in the future.

4 CONCLUSION

The performed evaluation shows that the economy of CHP-technologies highly depends on the revenues from district heat. Due to the fact that transportation of district heat is expensive and transportation costs are rapidly increasing with the distance, future plants will have to focus on having large district heat consumers in their vicinity. Furthermore, these consumers should have a constant heat demand throughout the year to achieve a high percentage of full load heat decoupling. High loads on the heat production allow economical operation also for low electrical efficiencies. In general, technologies with high electric efficiencies are more suitable if the sales of district heat are limited. The incomes are shifted from heat towards electricity because of the higher electrical efficiency.

The size of a CHP plant has a great influence on the electricity production costs. The general tendency is a reduction of costs with increasing plant size. In reality, limits arise for biomass-CHP because of logistic problems in biomass supply and in heat distribution. In case of limited heat demand, the plant size can be increased for concepts tending to electricity production. That results in lower specific costs due to economy-of-scale.

The development status of the evaluated technologies differs a lot, mainly between the well established combustion and the still developing gasification technologies. The Stirling engine is though a long known technology still not proper developed in terms of commercial applications.

By combining of today's technological status with characteristic learning curves, the direction of the development of theses technologies has been drawn. Considering two different plant sizes, a smaller one with 3 MW_{th} and a larger one with 20 MW_{th}, the typical application range of these technologies was paid attention. It reveals that smaller plants have 50 % higher electricity production cost than larger installations. In the future, gasification technologies in their range of size have the potential to achieve lower electricity production costs then combustion based technologies.

For specific on site conditions a first estimation is possible by using the variations of parameters followed by detailed costs calculations.

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VIII. PAPER

Bolhàr-Nordenkampf, M.; Vogel, A.; Hofbauer, H.; Kaltschmitt, M.

"Analysis and Evaluation of the Production of Fischer-Tropsch-Fuels from Biomass"

Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, May 2004, paper in press.

ANALYSIS AND EVALUATION OF THE PRODUCTION OF FISCHER-TROPSCH-FUELS FROM BIOMASS

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ABSTRACT: The conversion of biomass into liquid biofuels is considered to play an important role in the future supply of liquid fuels, since the supply is based on a CO_2-neutral and sustainable technology. The aim of this assessment is the identification of suitable gasification techniques for the production of synthesis gas from biomass suitable for Fischer-Tropsch-synthesis.
Hence Fischer-Tropsch-synthesis is analysed concerning technological specifications and requirements to yield a suitable synthesis gas from biomass. On that background suitable gasification technologies were assessed on technical, economical and ecological basis. From that evaluation conclusions can be drawn for the deduction of new overall systems for the coupling of gasification and Fischer-Tropsch-synthesis as well as further development strategies for this technology.
Keywords: gasification, bio-syngas, Fischer-Tropsch

1 INTRODUCTION

The utilisation of biomass for the production of energy is on national as well as on international level an essential contribution for a sustainable substitution of fossil fuel in the future. At the same time a substantial contribution for the reduction of the CO_2-emissions can be made.

The thermochemical conversion of biomass has proven so far to be a technical feasible option for the generation of heat and power at high overall efficiencies. However the demonstration of the production of liquid biofuels on larger scale as well as long term experience is still missing.

Therefore in the following section the various gasification technologies of biomass feedstock, suitable for the production of synthesis gas used in the Fischer-Tropsch (FT)-synthesis, are evaluated. Furthermore overall systems for the conversion of biomass to liquids are investigated to identify strategies for the future development of the FT-synthesis.

2 FISCHER-TROPSCH-SYNTHESIS

FT-synthesis was developed in 1925 in Germany for the production of liquid hydrocarbons from coal. In 1938 the commercial utilisation started which gained peak in the Second World War with nine installed plants with a total capacity of 660,000 t/a [1], [2]. After the Second World War utilisation of the FT-synthesis declined strongly, because of decreasing oil prices. Today this technology has again attained interest due to the expected limitations of the oil resources and political incentives.

2.1 Reactions

FT-synthesis can be described by the overall reaction given below, however it consists of a number of series reactions.

$$nCO+\left(\frac{n+m}{2}\right)H_2 \longrightarrow C_nH_m+nH_2O \qquad (1)$$

The firstly formed CH_2-branches grow further to form hydrocarbon chains, which represent a spectrum of different FT-products [3], [4]. Since the chain growth probability is dependent on the chain length no normal distributed product spectra is produced [3].

2.2 Process technology

Basically two process technologies exist for FT-synthesis.

- High temperature FT-synthesis (**HTFT**) between 300 and 350°C
- Low temperature FT-synthesis (**LTFT**) between 200 and 240°C

The **HTFT**-process is very well suited for the petrol production, however a petrol selectivity of only 36 % is achieved [5], which requires extensive product recovery.

The **LTFT**-process produces long-chain hydrocarbons (waxes) which have to be treated further by hydrocracking. Thereby high quality diesel is produced [6]. Two different apparatus are used for LTFT, a tubular fixed bed reactor (TFBR) and a slurry bubble column reactor (SBCR) [7]. Due to the fact that biomass gasification is used at smaller scale than coal gasification, HTFT is therefore not evaluated any further. Additionally FT-plants can be divided according to the tail gas utilisation [4] into

- full conversion operation – tail gas is recycled into the process to yield a maximum output of liquid FT-products
- and once trough operation – tail gas is utilised for the production of electricity and heat in a gas turbine or combined cycle.

2.3 Technical parameters

FT-synthesis can be influenced by numerous parameters, mainly by the catalyst and operating parameters [7].

One of the main parameters is the operation temperature, where the production capacity of FT-synthesis is highly dependent. Another major effect on the product yield has the type of catalyst employed for the synthesis.

Iron catalysts are more flexible in their usage than cobalt based catalysts [1], [8]. They slower process the hydrogenation and produce therefore less methane and can also catalyse the water-gas-shift reaction [8-10].

Cobalt catalysts are more active compared to iron based catalysts, however they can only be used at lower temperatures, because of formation of methane at higher temperatures [9]. Water is supposed to have only a slightly oxidising effect in contrast to the iron catalysts. Therefore cobalt catalysts are favoured in once-through applications of FT-synthesis, to achieve high product yields and at high water contents in the synthesis gas.

Common to all FT-catalysts is

- the sensitivity to insufficient syngas qualities, mainly for sulphur components [11],
- sintering and
- the coke formation on the catalyst surface [2].

2.4 Synthesis gas specifications

The synthesis gas specifications are determined by the FT-process. The main properties of the syngas are the purity specifications and the necessary H_2/CO ratio.

Purity specification: Apart from sulphur the knowledge of the effect of pollutants in the syngas is very limited. However, it is important to separate chlorine and nitrogen based pollutants from the syngas as well since they are supposed to cause corrosion on the catalyst. CO_2 interacts with cobalt catalysts only by diluting the syngas; iron catalysts have the capability to reform CO_2 with H_2. However the content of CO_2 should be lower than 10 Vol%, so that the partial pressure of the other components is not lowered significantly. Tars have to be removed from the syngas to a level that no condensing takes place [12]. Nitrogen acts as an inert component, however, lowers the partial pressure of other components.

In Table I references from literature are compared to a recent 750 h experiment at ECN with a cobalt catalyst. It can be seen that the specifications for the pollutants in the gas could be exceeded significantly and no deactivation of the catalyst was recognized.

Table I: Syngas specifications for the FT-synthesis

	literature values [4]	LTFT, fixed bed, Co [12-13]
CO_2	< 5 Vol %	< 5 Vol %
ash, particles	?.	< 0,1 mg/Nm³
N (HCN, NH_3)	< 20 ppb_V	< 1 ppm_V
S (H_2S, COS)	< 10 ppb_V	< 1 ppm_V
alkali metals	< 10 ppb_V	< 10 ppb_V
Cl (HCl)	< 10 ppb_V	< 10 ppb_V
Br, F	?.	< 10 ppb_V
tar	< tar condensation	< tar condensation

H_2/CO-ratio: The H_2/CO-ratio of the synthesis gas differs among various FT-processes. A summary of the different conditions can be found in Table II.

Table II: Summary of the H_2/CO-ratios for different catalyst and reactors [2], [4], [12], [14-16]

reactor type	H_2/CO with Fe catalyst	H_2/CO with Co catalyst
TFBR	min. ~0,6	>2
SBCR	optimal >1,35	optimal 2,15

3 GASIFICATION OF BIOFUELS

3.1 Theoretical analysis

Figure 1 shows the process chain for the production of FT-liquids from biomass. Biomass is first conditioned to the requirements of the gasification process, where the so called raw gas is produced. This gas has to be conditioned to syngas requirements before it can be converted by FT-synthesis to liquid biofuels.

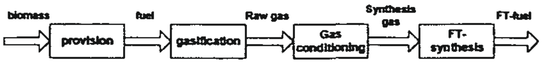

Figure 1: Process chain for the production of FT-liquids from biomass

Factors of influence: By the principles of thermochemical biomass conversion the quality of the raw gas is dependent on the following parameters:

- type , size, and shape of the fuel
- reactor type and design
- type and ratio of gasifying agent
- gasification temperature
- operating pressure
- applied catalysts [17], [18].

Apart from the reactor type, which is discussed in detail in [17], the gasification agent can have an important effect to bring syngas requirements closer to the properties of the raw product gas from gasification.

Process comparison: By comparing the theoretical product yields determined by the applied gasification agent conclusions can be drawn according to its suitability.

For an estimation of the maximum product yield from biomass, the conversion from woody biomass to $-CH_2-$ fragments (approximation for Diesel) can be analysed:

- woody biomass: $C_{4,2}O_{2,8}H_6$ → H:C ≈ 1.5
- FT-liquid (Diesel): $-CH_2-$ → H:C ≈ 2

It can be seen that hydrogen is the limiting element, since the liquid product has higher hydrogen to carbon ratios than the feedstock. By looking at the overall FT-reaction, it can be seen for a complete carbon conversion to FT-liquid four H-atoms for each C-atom are required.

$$C\,(wood) \xrightarrow{gasification.} CO \xrightarrow[+2H_2]{Fischer-Tropsch} -CH_2- + H_2O$$

On this basis gasification using oxygen or steam is compared:

Oxygen gasification: In this case only fuel (biomass dry) bound hydrogen is used for the formation of $-CH_2-$ fragments. To an ideal case stoichiometric needed oxygen is added for a total conversion to CO and H_2.

$$C_{4,2}O_{2,8}H_6 + 0,7\,O_2 \longrightarrow 4,2\,CO + 3\,H_2$$

The product yield of this ideal conversion is **210 g Diesel**/kg dry wood.

Steam gasification: In this case hydrogen is also provided by the gasification process, this increases the amount of hydrogen available for the carbon conversion. The corresponding equation can be expressed as:

$$C_{4,2}O_{2,8}H_6 + 1,4\,H_2O \longrightarrow 4,2\,CO + 4,4\,H_2$$

It can be seen that more hydrogen is produced, by a factor of 4.4 / 3 = 1.47. The product yield of this ideal conversion is 308 **g Diesel**/kg dry wood.

In summary it can be drawn that synthesis gas from steam gasification compared to pure oxygen gasification has advantages due to the higher H_2/CO-ratio. Therefore for the production of a suitable synthesis gas with high product yield only steam or steam-oxygen gasification is a suitable technology.

3.2 State of the art gasification technology

The State of the art concerning biomass gasification can be summarised in the following way:

- The main gasification development referred to biomass was focussed on the production of heat and power, therefore requirements of FT-synthesis were neglected.
- Most of the gasification plants have not reached a trouble-free operation yet, though heat and power production has lower demands for the quality of the product gas than FT-synthesis has.

Table III shows the pollutant levels of different gasifiers compared to syngas requirements.

Table III: Gas qualities of different gasification systems compared to the requirements on the syngas

		downdraft gasifier[2]	updraft gasifier[2]	fluidised bed gasifier	two-stage gasifier	syngas
H_2/CO	[-]	0.88	0.66	1.52[4]	1[2], 2[3]	>1.35
inert components [1]	[%]	64	53	25	69[2], 19[3]	< 10 %
particles	[mg/m³]	<20	200	5,000 – 10,000	<50	< 0.1
tar	[mg/m³]	100 – 150	12,000	2,000	<50	< 0.01
alkali metals	[mg/m³]	?	?	?	?	< 0.01
sulphur components	[mg/m³]	?	?	76 - 152	?	< 0.15
nitrogen components	[mg/m³]	20 – 140	?	1,200 – 1,500	?	< 0.015

[1]inert components = N_2&CO_2 in Vol.-%$_{dry}$, gasification age t [2]air, [3] oxygen, [4]steam

It can be summarised that product gas from biomass gasification requires extensive treatment before being suitable for FT-application.

3.3 Deduction of suitable gasification systems

By analysing the state of the art of FT-synthesis and of suitable gasification techniques the following conclusions can be drawn:

- Fixed bed downdraft gasifiers are basically suitable, if a steam-oxygen mixture is used as a gasification agent, however due to their limited upscale possibilities an economic operation is questionable.
- Fixed bed updraft gasifiers (gasifying agent air) are suitable for combined heat and power applications, however have high tar contents in the raw gas.
- Fluidised bed and two-stage gasifiers are more complex in terms of gasification technology; however they provide good possibilities for a coupling with FT-technology. Two-stage gasifiers have the advantage to achieve very low tar contents in the product gas, which is advantageous, however require oxygen as gasification agent.
- All gasification systems utilising the gasification agent air or oxygen have in common that they are less suitable for coupling with FT-synthesis, due to the high inert gas component in the syngas.

4 OVERALL SYSTEMS

For the design of an overall system the following aspects have to be considered too:

- type of the feedstock
- technology of the thermochemical conversion
- location of biomass to liquids plant

4.2 Feedstock

For the deduction of suitable overall systems it is of major importance if the feedstock is of blade or wood type. Although blade biomass has high potentials as feedstock, on the short time horizon woody biomass is more suitable, due to the lower pollutant contents (mainly alkali and chlorine). Even woody feedstock requires further development to provide a secure technology. For a further development of this technology in the near future woody biomass should be favoured.

4.2 Thermochemical conversion techniques

Using pyrolytic decomposition before the gasification, also called staged gasification, three utilisable products can be used as a feedstock, coke, pyrolytic gases, and both components.

If wood is pyrolitically decomposed approximately 80 m% volatile matter and 20 m% coke is produced, with an energy content of the volatile matter near 10 to 15 MJ/kg$_{gas}$ and a energy content of the coke about 20 to 30 MJ/kg$_{coke}$. This means that 68 % of the energy content is available as volatile matter and 32 % as coke [19].

The following conclusions can be drawn by looking at this analysis aiming at a complete conversion of the fuel energy. Suitable technologies include

- direct gasification of biogenic solid fuels in fluidised beds
- or staged gasification with a utilisation of the volatile and carbon matter.

However this conclusion is only valid if heat production is not taken into consideration. If this option is included in the assessment steam reforming of the volatile pyrolisis products is feasible, if coke is used as heating agent.

4.3 Location of the fuel conversion

If staged gasification shall be utilised two different systems of conversion are possible, centralised fuel conversion and decentralised fuel conversion and centralised gasification.

TableTable IV shows the energy densities of different biogenic feedstock's and pyrolytic products.

Table IV: Energy densities of solid and liquid bio fuels and pyrolytic products [20-23]

Fuel	wood	straw	coke	pyrolisis oil	slurry
Energy density [MJ/m³]	3,600	1,488	4,650	22,496	26,875

Evaluation basis wood, straw: dry and storage density, evaluation basis straw: heating value in MJ/Nm³, evaluation basis slurry: information from FZK (23 - 26 % coke in the pyrolisis oil), evaluation basis coke: bulk density 15 kg/m³

By looking at Table IV it can be seen that decentralised conversion of wood to coke is due to a marginal increase in energy density not very promising. An increase in energy density and the utilisation of the total energy content at the same time is only possible by producing an oil slurry.

5 POSSIBLE SOLUTIONS FOR OVERALL SYSTEMS

As a result of this evaluation two promising overall solutions can be identified, the allothermal gasification in the small power range of 20 to 100 MW fuel power and the autothermal gasification in the large power range of 500 MW fuel power.

Allotherme gasification: For the commercial realisation of FT-synthesis gasification plants a fuel power of 20 MW is considered to be the lowest level, since the specific investment costs rise at small fuel powers significantly. The upper limit is to be drawn at 100 MW fuel power, since the costs for the fuel provision rise significantly due to a large catchment area.

The main characteristics for such systems are:

- feedstock: wood
- allothermal gasification with a fluidised bed steam gasifier
- renouncement on oxygen as gasification agent
- renouncement on the separation of CO_2 in the gas conditioning due to economic aspects
- LTFT-synthesis in once-through operation, since no CO_2 separation is necessary
- utilisation of a Cobalt catalyst
- tail gas utilisation by a gas turbine or a combined cycle process

Autothermal gasification: In the large power range above 500 MW fuel power the specific cost for an oxygen plant and a CO_2 capture are reduced. The plant location is suitable only in the vicinity of a harbour, which can provide large biomass fuel streams of about 100 t per hour at a cost effective level. For this type of production fluidised bed reactors with a steam-oxygen mixture would be utilised. From today's perspective allotherme gasification processes with steam as gasification agent are suitable up to fuel powers of 100 MW.

The main characteristics for an overall system are:

- feedstock: wood
- autothermal gasification in a fluidised bed gasifier
- steam-oxygen mixture as gasification agent
- separation of CO_2 in the gas conditioning
- LTFT-synthesis in recycle operation
- utilisation of a Cobalt catalyst
- installation of a steam turbine for waste heat utilisation

In the fuel power range above 500 MW the gasification of products from pyrolisis becomes an additional option. This technology when compared to the fluidised bed technology has the advantage that all bio feedstock can be utilised. By considering the results of the location assessment a pyrolysis plant with attached entrained gasification seems promising. For the set-up of an overall system the same conclusion are valid as for the 500 MW fuel power plant. If the feedstock shall be pyrolysed decentralised, only the gasification of slurry makes sense, to enlarge the biomass catchment area. The necessary fast pyrolysis plants are not available in the required scale today. Since they are available only at lab scale so commercial availability in the next year seems unlikely.

Another alternative would be the coupling of the gasification technology with existing refinery structures to co-process the bio-syngas with oil based one. However, this would require an agreement on the judicial situation of the compensation of renewable based syngas.

6 CONCLUSION

Aim of this analysis was to evaluate the suitability of gasifying solid biofuels for the production of synthesis gas useable for FT-technology. From an analysis of FT-technology the possibilities to couple this technology with a synthesis gas production from biomass seems possible.

On this basis technically and economically feasible overall systems for the production of FT-diesel from biomass have been deducted:

- Allothermal gasification of solid biofuels in the scale of 20 to 100 MW fuel power, using steam as gasification agent, dispense with CO_2-seperation and tail gas utilisation by a gas turbine.
- Autotherme gasification of solid biofuels (pyrolysis product as feedstock possible) in the scale above 500 MW fuel power, using steam-oxygen as gasification agent, CO_2-separation and tail gas recirculation.

For a successful realisation of such a concept the partial concepts of gasification, gas cleaning, and conditioning and FT-synthesis have to be evaluated in detail in terms of their chemical and physical bases as well as in terms of their process coupling.

On that basis scientific supported pilot and demonstration plants utilising different technical options shall be realised. Starting from this premise FischerTropsch-synthesis can have in the future a significant contribution on the production of renewable fuel in Europe and can help to fulfil the European Biofuel Directive.

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IX. PAPER

Vogel, A.; Bolhàr-Nordenkampf, M.; Hofbauer, H.; Kaltschmitt, M.

„Vergasung biogener Festbrennstoffe zur Produktion von Fischer-Tropsch-Kraftstoffen“

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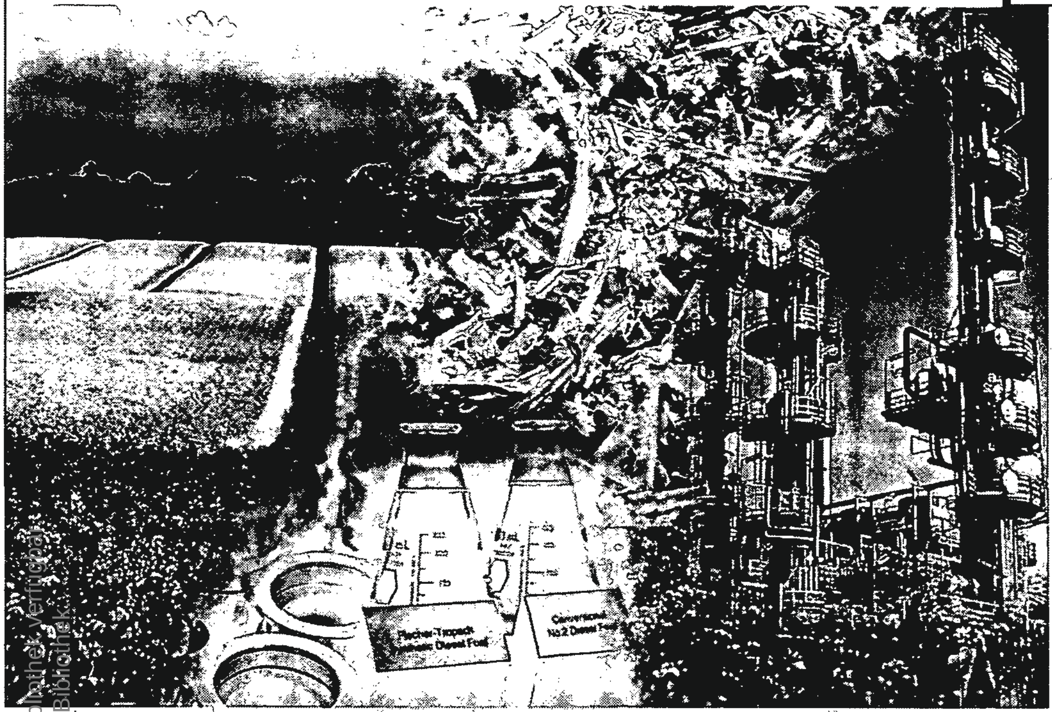

Vor dem Hintergrund der politischen Zielvorgaben einer möglichst CO_2-neutralen und ressourcenschonenden Energiewandlung gilt die Vergasung biogener Festbrennstoffe unter anderem auch im Bereich der Kraftstofferzeugung als Schlüsseltechnologie. Auf der Grundlage geeigneter Vergasungsverfahren für die Fischer-Tropsch-Synthese werden vielversprechende Systemkonzepte zur Produktion von Biokraftstoffen diskutiert.

Systemkonzepte für die Produktion von Fischer-Tropsch-Biokraftstoffen

Der Einsatz biogener Festbrennstoffe zur Energieerzeugung stellt eine wichtige Möglichkeit zur Substitution und Schonung fossiler Energieressourcen dar. Gleichzeitig kann damit ein Beitrag zur Minderung des anthropogenen CO_2-Ausstoßes geleistet werden. Im Bereich der Stromerzeugung konnte die Vergasung biogener Festbrennstoffe als technisch realisierbare Option bereits nachgewiesen werden. Für die ebenfalls mögliche Kraftstoffbereitstellung aus biogenen Festbrennstoffen durch Vergasung mit anschließender Fischer-Tropsch-Synthese steht ein Nachweis der großtechnischen Machbarkeit und ein Langzeiteinsatz derartiger synthetisierter Kraftstoffe in Kraftfahrzeugen allerdings noch aus. Im Folgenden wird daher analysiert, welche Anforderungen das Rohgas für die FT-Synthese zu erfüllen hat, welche Verfahren zur Vergasung biogener Festbrennstoffe hinsichtlich dieser Anforderungen als günstig einzustufen sind und welche Systemlösungen als vielversprechende Option für eine zukünftige Produktion von Biokraftstoffen in Frage kommen.

Fischer-Tropsch-Synthese

Als Verfahren zur Gewinnung flüssiger Kohlenwasserstoffe aus Kohle wurde die Fischer-Tropsch-Synthese im Jahr 1925 am Kaiser-Wilhelm Institut für Kohleforschung in Mühlheim an der Ruhr entwickelt. Im Jahr 1938 begann der industrielle Einsatz des Verfahren, der sich Hand in Hand mit dem Ölpreis entwickelte [1]. Speziell in Deutschland ist das Verfahren heute unter anderem wegen der politischen Vorgaben zum Klimaschutz und der daraus abgeleiteten Forderung nach einer verstärkten Nutzung von Biotreibstoffen wieder von Interesse, da das Synthesegas, das als Ausgangsmedium für die Kraftstoff-Synthese dient, auch durch eine Vergasung biogener Festbrennstoffe gewonnen werden kann. Im Folgenden werden die Techniken der FT-Synthese dargestellt und die sich daraus ergebenden Anforderungen an das Synthesegas abgeleitet.

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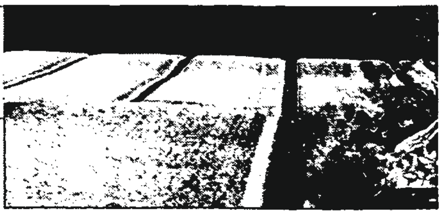


Fischer-Tropsch-Katalysator	Betriebsparameter
☐ Metall	☐ Reaktortyp
☐ Trägermaterial	☐ Temperatur
☐ Herstellung (Promotoren, etc.)	☐ Druck
☐ Vorkonditionierung, Aktivierung	☐ Raum-Zeit-Geschwindigkeit
☐ Alter	☐ Rückführrate

Tabelle 1

Einflussfaktoren auf die FT-Synthese [6].

Chemische Reaktionsgleichung

Die FT-Synthese lässt sich durch die folgende chemische Reaktionsgleichung beschreiben:

$$nCO + \left(n + \frac{m}{2}\right)H_2 \rightarrow C_nH_m + nH_2O \qquad (1)$$

Ausgehend von dieser Reaktionsgleichung werden einzelne Teilreaktionen unterschieden. Die Basisreaktion, durch die CH_2-Molekülsequenzen aufgebaut werden, ist stark exotherm [2]:

$$CO + 2H_2 \rightarrow -CH_2- + H_2O \qquad (2)$$

$$\Delta H^{o}_{FT} = -165\ kJ/mol$$

Daher kommt der Wärmeabfuhr aus dem Prozess eine große Bedeutung zu. Aus den CH_2-Molekülsequenzen bildet sich ein Spektrum unterschiedlicher Kohlenwasserstoffketten aus [3; 4].

Technische Umsetzung

Bei der FT-Synthese wird zwischen Hoch- und Niedertemperaturverfahren unterschieden:

- *Hochtemperaturverfahren* arbeiten bei Temperaturen von 300 bis 350 °C und sind speziell für die Benzinproduktion geeignet. Allerdings ist die Benzinselektivität mit 36 % [5] eher gering, so dass nachträglich eine intensive Produktaufarbeitung erforderlich wird. Deshalb sind diese Verfahren für Anlagen im kleineren Leistungsbereich, wie sie bei der Biomassevergasung im Unterschied zu FT-Verfahren auf der Basis fossiler Gase zu erwarten sind, eher nachteilig und werden hier nicht weiter betrachtet.
- *Niedertemperaturverfahren* arbeiten bei Temperaturen von 200 bis 240 °C. Aus dem Synthesegas entstehen langkettige Kohlenwasserstoffe (Wachse), die nach einem zusätzlichen Hydrocracking-Prozess Dieselkraftstoffe hoher Qualität liefern können [6]. Die Verfahren sind auch im kleineren Leistungsbereich einsetzbar.

Ferner können FT-Anlagen je nach Restgasverwendung durch die folgenden Betriebsarten klassifiziert werden [4]:

- Beim *Full-Conversion-Betrieb* wird das noch nicht umgesetzte Synthesegas für die Maximierung der Flüssigfraktion in den FT-Prozess zurückgeführt.
- Beim *Once-Through-Betrieb* werden die Restgase zur Erzeugung elektrischer Energie in einer Gasturbine oder zur Wärmeerzeugung genutzt.

Einflussfaktoren

Der Verlauf der FT-Synthese wird hauptsächlich durch die Temperatur und die Art des Katalysators beeinflusst (**Tabelle 1**). Hohe Reaktionstemperaturen begünstigen eine in der Regel nicht erwünschte Bildung von Methan und Aromaten, die zu Koksablagerungen am Katalysator führen können (speziell bei Eisenkatalysatoren [1; 7]) sowie kürzere Kettenlängen und damit eine geringere Treibstoffausbeute (vor allem Diesel) [7]. Daher ist die Möglichkeit der Steigerung der Reaktionsgeschwindigkeit durch Temperaturerhöhungen begrenzt.

Für die Katalyse der FT-Reaktion sind wegen der geringeren Methanbildung und vergleichsweise niedriger Preise vor allem Eisen- und Kobalt-Katalysatoren geeignet [1; 7; 8]. Diese unterscheiden sich durch folgende Eigenschaften:

- Eisen-Katalysatoren sind vielfältiger einsetzbar als Kobalt-Katalysatoren. Sie katalysieren in geringerem Ausmaß die Hydrogenierung und produzieren daher weniger Methan [9]. Außerdem katalysiert Eisen die Wassergas-Shiftreaktion. Allerdings wird die Katalysatoraktivität im FT-Prozess durch Wasser stark gehemmt [7; 10; 11].
- Kobalt ist im Vergleich zu Eisen der aktivere Katalysator, der allerdings nur bei niedrigen Temperaturen verwendet werden kann [9], da die (unerwünschte) Methanproduktion bei hohen Temperaturen steigt. Im Gegensatz zu Eisen wirkt Wasser auf Kobalt nur sehr leicht hemmend. Daher ist Kobalt vor allem bei der Once-Through-FT-Synthese zu bevorzugen, bei der möglichst hohe Umsätze bei einmaligem Durchlauf im Reaktor erzielt werden sollen und viel Wasser im Gleichgewicht vorliegt.

Allen FT-Katalysatoren ist jedoch die Empfindlichkeit gegenüber Gasverunreinigungen, vor allem Schwefelverbindungen (dauerhafte Vergiftung) [12], gemein. Ferner sind Sinterprobleme durch Hitzeentwicklung und die Bildung von Koksablagerungen als kritisch einzuschätzen [1].

Anforderungen an das Synthesegas

Je nach eingesetztem FT-Verfahren unterscheiden sich die Anforderungen, die an ein Synthesegas zu stellen sind. Entscheidend sind aber die notwendige Gasreinheit und das H_2/CO-Verhältnis. Über die Auswirkungen der im Synthesegas auftretenden Verunreinigungen auf die FT-Synthese ist abgesehen vom Schwefel bislang sehr wenig bekannt. Typische Literaturangaben für einzelne Komponenten sind in der **Tabelle 2** den Ergebnissen eines 750-h-Versuchs mit einem Kobalt-Festbettkatalysator gegenübergestellt [4; 13 bis 15]. Demnach wurden die Literaturangaben im Versuch deutlich überschritten, ohne dass am Katalysator ein Aktivitätsverlust festgestellt werden konnte. Insgesamt sind jedoch generell sehr geringe Gehalte an Schadstoffen, unter anderem Chlor- und Stickstoff-Verbindungen, sicher zu stellen [12; 13].

Auch beim H_2/CO-Verhältnis gibt es je nach Verfahren und Katalysators diverse Anforderungen [1; 4; 11; 16 bis 18]. So ist für Kobalt-Katalysatoren ein H_2/CO-Verhältnis oberhalb von 2,0 erforderlich; (Optimalwert: 2,15). Bei einem Einsatz von Eisen-Katalysatoren sind hohe H_2/CO-Verhältnisse demgegenüber nicht erforderlich, da zusätzlich das Wassergasgleichgewicht zu berücksichtigen ist:

Tabelle 2

Rohgas-Anforderungen für die FT-Synthese. [4; 14; 15].

Verunreinigung im Synthesegas	Literaturangaben [4; 15]	Messdaten eines Kobalt-Festbettkatalysators [14]
CO_2	weniger als 5 Vol.-%	weniger als 5 Vol.-%
Asche, Partikel	k.A.	weniger als 0,1 mg/Nm³
Stickstoff (HCN, NH_3)	weniger als 20 ppbv	weniger a 1 ppmv
Schwefel (H_2S, COS)	weniger als 10 ppbv	weniger als 1 ppmv
Alkalien	weniger als 10 ppbv	weniger als 10 ppbv
Chlor (HCl)	weniger als 10 ppbv	weniger als 10 ppbv
Brom, Fluor	k. A.	weniger als 10 ppbv
Teer	unterhalb des Taupunktes	unterhalb des Taupunktes

ppbv: parts per billion volumetric (Volumenmischungsverhältnis)
ppmv: parts per million volumetric (Volumenmischungsverhältnis)

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (3)$$

Wird Gl. (3) in Gl. (2) eingesetzt, ergibt sich folgende Reaktionsgleichung:

$$2CO + H_2 \rightarrow -CH_2- + CO_2 \qquad (4)$$

Statt des stöchiometrischen H_2/CO-Verhältnisses von 2,0 für die FT-Reaktion wäre demnach lediglich ein Wert von 0,5 notwendig; dieser Wert entspricht auch praktisch dem mehrfach gefundenen minimalen H_2/CO-Verhältnis für Eisen-Katalysatoren von etwa 0,6.

Fazit

Hinsichtlich einer Auswahl prinzipiell einsetzbarer Synthesegasverfahren können demnach folgende Schlussfolgerungen gezogen werden:

- Für Anlagen mit kleineren Leistungen, wie sie für eine Biomassevergasung zu erwarten sind, kommen lediglich Niedertemperaturverfahren zur Dieselherstellung in Frage.
- Die Vor- und Nachteile der Betriebsoptionen zur Restgasverwendung (Full-Conversion oder Once-Through) sind in Abhängigkeit vom Gesamtsystems zu analysieren und nicht allgemein gültig bewertbar.
- Je nach Wahl des einsetzbaren Katalysators ergeben sich unterschiedliche Vor- und Nachteile. Aus derzeitiger Sicht scheint wegen der höheren Aktivität und geringeren Oxidierbarkeit der Einsatz von Kobalt-Katalysatoren geeignet zu sein.
- Hinsichtlich der Haupteinflussfaktoren Temperatur und Katalysator ist die FT-Synthese als sehr empfindlich einzuschätzen. Daraus ergeben sich sehr hohe Anforderungen an die Reinheit und Zusammensetzung des bereitzustellenden Synthesegases.

Vergasungsverfahren für biogene Festbrennstoffe

Bild 1 zeigt den Aufbau eines Gesamtsystems zur Kraftstofferzeugung durch Vergasung biogener Festbrennstoffe. Der biogene Brennstoff wird im Prozess der Bereitstellung nach den Anforderungen des Vergasungsprozesses aufbereitet. Im Vergasungsreaktor wird das so genannte Rohgas produziert. Die Gasaufbereitung reinigt und konditioniert das Rohgas auf Synthesegas-Qualität, bevor in der FT-Synthese der Kraftstoff produziert wird.

Bild 1

Systemaufbau einer Kraftstoffbereitstellung durch Vergasung und FT-Synthese.

Theoretische, maximale Produktausbeute

Aus der theoretisch maximal möglichen Produktausbeute lässt sich je nach Art des Vergasungsmittels beurteilen, welche Vergasungstechniken aus ökonomischer Sicht zu bevorzugen sind. Ausgangspunkt dieser Betrachtung kann zum Beispiel die Umwandlung von Holz zu CH_2–Molekülsequenzen (Näherung für Diesel) sein. Dabei ist von folgenden H/C-Verhältnissen auszugehen:

Holz	$C_{4,2}O_{2,8}H_6$	$\rightarrow H/C = 1,5$
FT-Produkt (Diesel)	$-CH_2-$	$\rightarrow H/C = 2$

Folglich ist beim Ausgangsstoff Holz der Wasserstoff als limitierendes Element der Kraftstofferzeugung zu betrachten. Aus der FT-Reaktion folgt, dass für einen vollständigen Kohlenstoffumsatz vier Wasserstoffatome pro Kohlenstoffatom erforderlich sind. Unter dieser Maßgabe ergeben sich für 1 kg trockenes Holz aus der Sauerstoff- und der Wasserdampfvergasung unterschiedliche Wasserstoffmengen:

- Bei der *Sauerstoffvergasung* kann nur der Wasserstoff aus dem Holz (trocken) genutzt werden, um daraus gasförmigen Wasserstoff bilden und damit Kohlenstoff umsetzen zu können. Zu dem Brennstoff wird im Idealfall gerade so viel Sauerstoff zugegeben, dass theoretisch eine vollständige Umsetzung zu CO und H_2 erfolgt. Unter diesen idealen Bedingungen gilt:

$$C_{4,2}O_{2,8}H_6 + 0{,}7\,O_2 \rightarrow 4{,}2\,CO + 3H_2$$

Für diese ideale Umsetzung folgt:

- Aus 1 kg trockenem Holz erhält man 60 mol H.
- Damit können 15 mol C zu FT-Produkten umgesetzt werden.
- Daraus bilden sich wiederum 15 mol CH_2-Molekülsequenzen.
- Bei einer Molmasse von 14 g/mol entspricht dies **210 g Diesel.**

- Bei der *Wasserdampfvergasung* wird auch aus dem Vergasungsmittel Wasser Wasserstoff gebildet. Dadurch steht nach der Vergasung mehr Wasserstoff für die FT-Reaktion zur Verfügung als im Holz gebunden ist. Daraus resultiert die folgende Reaktionsgleichung, bei der im Vergleich zur Sauerstoffvergasung eine um den Faktor 4,4/3 = 1,47 höhere Wasserstoffmenge zur Verfügung steht:

$$C_{4,2}O_{2,8}H_6 + 1{,}4\,H_2O \rightarrow 4{,}2\,CO + 4{,}4\,H_2$$

Für diese ideale Umsetzung folgt:

- Aus 1 kg trockenem Holz erhält man 60 mol H
- und durch Vergasung maximal 88 mol H im Synthesegas.
- Damit können 22 mol C zu FT-Produkten umgesetzt werden.
- Daraus bilden sich wiederum 22 mol CH_2-Molekülsequenzen.
- Bei einer Molmasse von 14 g/mol entspricht dies 308 g Diesel.

Bedingt durch das höhere H_2-Angebot für die FT-Synthese sind Synthesegase aus der Wasserdampfvergasung somit besser geeignet als Synthesegase aus der reinen Sauerstoffvergasung. Folglich kommen für die Produktion eines hochqualitativen Synthesegases nur die allotherme Wasserdampf- oder die autotherme Sauerstoff-Wasserdampfvergasung in Frage.

Praxiserfahrungen

Die Entwicklung der Vergasung biogener Festbrennstoffe hat eine Vielzahl an Verfahrenslösungen hervorgebracht. Dennoch wurden bislang nur wenige Anlagen in Betrieb genommen und Kopplungen mit Synthesegasprozessen kaum realisiert. Die Praxiserfahrungen der zurzeit laufenden Demonstrations- und Pilotanlagen für die Vergasung von biogenen Festbrennstoffen lassen sich wie folgt zusammenfassen:

- Die Zielrichtung der Entwicklung lag und liegt eindeutig bei der Stromerzeugung. Deshalb sind die Anforderungen der FT-Synthese bisher kaum in die Entwicklungen eingeflossen.
- Die meisten der vorhandenen Anlagen haben die Vorgabe eines störungsfreien Betriebes selbst für die Stromerzeugung noch nicht vollständig erreicht.

Ein Hauptgrund dafür sind die hohen Reinheitsanforderungen von Synthesegasprozessen und die teilweise deutlich höheren Schadstoffgehalte der bislang in Vergasungsprozessen erzeugten Gase. In der **Tabelle 3** sind die Eigenschaften typischer Gase aus unterschiedlichen Vergasungsprozessen und die Anforderungen der in FT-Prozessen eingesetzten Rohgase gegenübergestellt [19 bis 22]. Daraus wird deutlich, dass die meisten Gaseigenschaften – wie zum Beispiel der Gehalt an organischen Kohlenwasserstoffen – um Größenordnungen von den Anforderungen an das Rohgas für die FT-Synthese abweichen. Damit ist eine Gasaufbereitung zur Einstellung der notwendigen Synthesegaseigenschaften unabhängig vom eingesetzten Vergasungsverfahren immer erforderlich. Der notwendige technische Aufwand wird allerdings durch die eingesetzte Vergasungstechnologie (mit-)bestimmt.

Tabelle 3

Erreichbare Rohgasqualitäten ausgewählter Vergasungsverfahren [19 bis 22].

Gasbestandteil		Festbettvergasung		Wirbelschicht-vergasung	Mehrstufige Vergasung	Anforderungen an FT-Synthese
		Gleichstrom	Gegenstrom			
H_2/CO	[-]	0,88	0,66	1,52 1)	1,0 2) 2,0 3)	größer als 1,35
Inertgase 4)	[Vol.-%]	64	53	25	69 2) 19 3)	kleiner als 10
Partikel	[mg/m³]	weniger als 20	200	5 000 bis 10 000	kleiner als 50	0
Organische Kohlenwasserstoffe	[mg/m³]	100 bis 150	12 000	2 000	kleiner als 50	0
Alkalien	[mg/m³]	?	?	?	?	kleiner als 0,010
Schwefelverbindungen	[mg/m³]	?	?	76 bis 152	?	kleiner als 0,150
Stickstoffverbindungen	[mg/m³]	20 bis 140	?	1 200 bis 1 500	?	kleiner als 0,015

1) Vergasungsmittel: Wasserdampf (allotherm); 2) Vergasungsmittel: Luft;
3) Vergasungsmittel: Sauerstoff-Wasserdampf-Gemisch; 4) N_2 und CO_2 in Vol.-% (trocken).

Tabelle 4

Energiegehalte möglicher Vergasungsstoffe in Abhängigkeit vom Ausgangsstoff.

Vergasungsstoffe	Energiegehalt des Ausgangsbrennstoffes 1)	
Biogener Festbrennstoff (Holz)		≙ 100 %
Flüchtige Bestandteile	12,5 MJ/kg(Gas) · 0,8 kg(Gas)/kg(Brennstoff) = 10 MJ/kg(Brennstoff)	≈ 67 %
Kohlenstoff (Koks)	25 MJ/kg(Koks) · 0,2 kg(Koks)/kg(Brennstoff) = 5 MJ/kg(Brennstoff)	≈ 33 %

1) berechnet aus dem durchschnittlichen Heizwert und Massenanteil der Pyrolyseprodukte von Holz

Fazit

Auf der Grundlage dieser Erkenntnisse lassen sich für die Auswahl geeigneter Vergasungssysteme die folgenden Schlüsse ziehen:

- *Festbett-Gleichstromsysteme* sind unter bestimmten Bedingungen, zum Beispiel bei dampfhaltigem Vergasungsmittel, prinzipiell einsetzbar. Sie sind bislang für Leistungsbereiche von 1 bis 3 MW verfügbar, lassen sich jedoch nur sehr begrenzt auf eine für die FT-Synthese wirtschaftlich vertretbare Größenordnung übertragen.
- *Festbett-Gegenstromsysteme* mit Luft als Vergasungsmittel sind zwar für eine gekoppelte Strom- und Wärmeerzeugung bei geringer Stromkennzahl einsetzbar. Ohne sichere Abtrennung der langkettigen Kohlenwasserstoffe (Teere) aus dem Rohgas sind sie jedoch zur Synthesegasproduktion nicht einsetzbar.
- *Wirbelschicht- und mehrstufige Systeme* sind bei einer Vergasung von Pyrolysegas mit Wasserdampf (Dampfreformierung) trotz der gegenüber der Flugstromvergasung etwas höheren Teergehalte ebenfalls für die Bereitstellung von Synthesegas geeignet. Mehrstufige Systeme mit Flugstromvergasung haben wegen sehr geringer Teergehalte zwar Vorteile für die Produktion von Synthesegas, benötigen dafür jedoch Sauerstoff (Sauerstoffvergasung).
- Alle Vergasersysteme, die mit Luft als Vergasungsmittel arbeiten, sind unter anderem wegen des hohen Inertgasanteils als wenig vielversprechend einzuschätzen.

Grundlegende Systemaspekte

Bei der Konzeption und Auslegung von Gesamtsystemen, in denen biogene Festbrennstoffe vergast werden und das entstehende Rohgas einen FT-Prozess durchläuft, sind folgende grundlegende Systemaspekte zu berücksichtigen:

- die Art des einsetzbaren Ausgangsbrennstoffes,
- die eingesetzten Verfahren für die thermochemische Brennstoffveredlung,
- der Standort, an dem der Brennstoff thermochemisch veredelt wird.

Ausgangsbrennstoff

Neben dem technischen Potenzial [23] holz- und halmgutartiger Brennstoffe sind die brennstofftechnischen Eigenschaften der Ausgangsstoffe relevant. Für zeitnahe Technologieentwicklungen erscheint der Einsatz von holzartigen Brennstoffen, die im Vergleich zu Halmgütern beispielsweise geringere Gehalte an Alkalien- oder Chlorverbindungen aufweisen, aus heutiger Sicht vorteilhaft zu sein. Erst in einem zweiten Schritt sollten daher die vergleichsweise schwierig zu handhabenden Halmgüter erschlossen werden.

Thermochemische Veredlung

Die Eigenschaften biogener Festbrennstoffe lassen sich mit unterschiedlichen Verfahren der Brennstoffaufbereitung und -konditionierung mechanisch (z.B. Zerkleinern), thermisch (z.B. Trocknen) und/oder thermochemisch (z.B. durch pyrolytische Zersetzung) beeinflussen. Wird lediglich eine mechanische oder thermische Aufbereitung realisiert, kann der Energiegehalt des Ausgangsstoffes durch den Vergasungsprozess weitgehend genutzt werden. Bei einer thermochemischen Veredlung des Ausgangsbrennstoffes in einem mehrstufigen Prozess wird die ursprüngliche Ausgangsenergie im Zuge des Vergasungsprozesses in den flüchtigen Komponenten und im Koks gebunden (**Tabelle 4**). Die von der Pyrolysetemperatur und -geschwindigkeit abhängigen Ausbeuten an flüchtigen Bestandteilen und Koks [24] werden dabei nicht betrachtet.

Im Sinne einer optimalen Ausnutzung der eingesetzten Brennstoffenergie zur Synthesegasproduktion ist demnach nur eine direkte Vergasung der biogenen Festbrennstoffe – zum Beispiel über ein Wirbelschichtverfahren – oder bei mehrstufigen Prozessen eine gemeinsame Vergasung von flüchtigen Bestandteilen und Koks zielführend. Dies gilt jedoch nur, wenn keine Wärmebereitstellung betrachtet wird. Andernfalls ist unter bestimmten Umständen auch die Dampfreformierung flüchtiger Pyrolysebestandteile als gleichwertig anzusehen, bei der der Koksanteil zur Erzeugung des Vergasungsmittels (Dampf) und der benötigten Prozesswärme verbrannt wird.

Standort der Brennstoffveredlung

Bei der mehrstufigen Vergasung lässt sich die zentrale und die lokale Brennstoffveredlung unterscheiden (**Bild 2**). Für die lokale Variante sprechen eine Erweiterung des Brennstoffeinzugsgebietes sowie die Erzeugung von Strom oder Prozesswärme am Veredlungsstandort. Der letztere Aspekt ist allerdings vor dem Hintergrund möglichst hoher Umwandlungswirkungsgrade der Kraftstofferzeugung nicht zielführend. Für ein erweitertes Einzugsgebiet müssen die Transportkosten zum Beispiel durch eine Steigerung des Energiegehaltes der Veredlungsprodukte reduziert werden. In der **Tabelle 5** sind die Energieinhalte verschiedener Brennstoffe und ihrer Veredlungsprodukte zusammengestellt.

Eine Veredlung zu Koks ist aus der

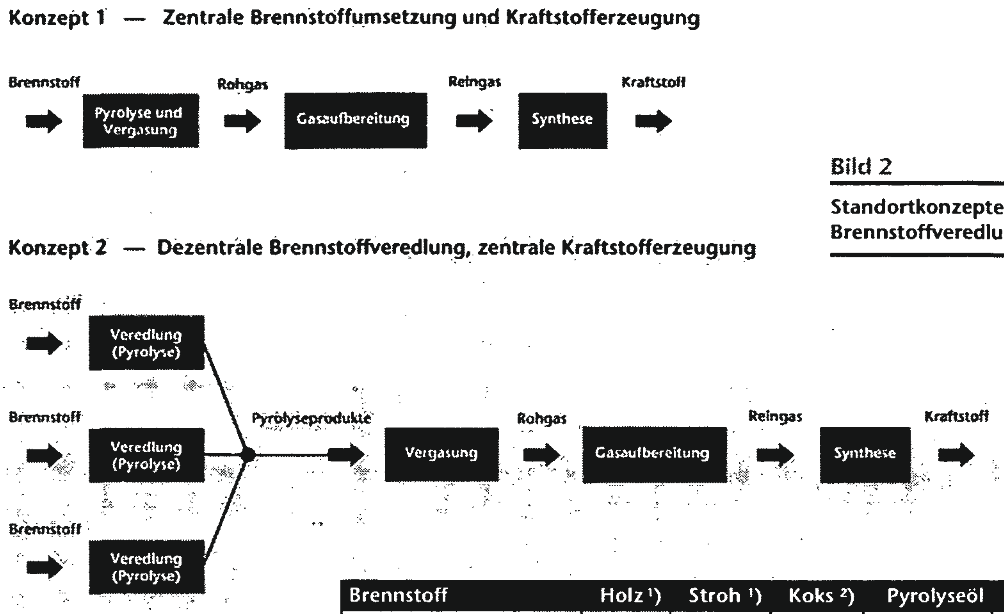


Bild 2

Standortkonzepte für die Brennstoffveredlung.

Brennstoff	Holz 1)	Stroh 1)	Koks 2)	Pyrolyseöl	Slurry 3)
Energiedichte [MJ/m^3]	3 600	1 488	4 650	22 496	26 875

1) Basis: trocken und Lagerdichte; 2) Schüttdichte: 150 kg/m^3; 3) 23 bis 26 % Koks im Öl.

Tabelle 5

Energiedichten fester und flüssiger biogener Brennstoffe und ihrer Veredlungsprodukte [25 bis 28].

Sicht der Transportkosten nicht sinnvoll, da vergleichbar geringe Energiedichten erzielt werden wie bei nicht veredelter Biomasse. Darüber hinaus kann bei dieser Variante nur ein geringer Teil der Brennstoffenergie genutzt werden. Eine Erhöhung der Energiedichte bei gleichzeitiger vollständiger Ausnutzung der Brennstoffenergie ist aus heutiger Sicht nur durch die Veredlung zu einem Öl-Koks-Schlamm (Slurry) möglich. Nur bei diesem Prozess sind lokale Veredlungsanlagen zur Erschließung größerer Brennstoffpotenziale aus Kostengründen sinnvoll. Dafür wären allerdings Anlagen zur Flash-Pyrolyse erforderlich, die derzeit noch im Technikumsmaßstab erforscht werden. Ferner sind die bei einer Slurry-Produktion anfallenden Verluste von rund 20 % der eingesetzten Energie zu berücksichtigen.

Lösungen für das Gesamtsystem

Ausgehend von diesen Betrachtungen können mit der *allothermen Vergasung* im kleineren Leistungsbereich von etwa 20 bis 100 MW(th.) und mit der *autothermen Vergasung* im größeren Leistungsbereich oberhalb von 500 MW(th.) zwei vielversprechende Gesamtsystemlösungen für eine Kraftstoffbereitstellung durch Vergasung biogener Festbrennstoffe definiert werden. Diese Leistungsbereiche ergeben sich vor allem aus ökonomischen Überlegungen (Economy of Scale), die nachfolgend skizziert werden.

Allotherme Vergasung

Für kommerzielle FT-Syntheseanlagen dürfte eine Leistung von 20 MW(th.) eine untere realisierbare Leistungsgrenze darstellen, da die spezifischen Investitionskosten bei geringeren Leistungen deutlich ansteigen. Die obere Leistungsgrenze ist bei 100 MW(th.) anzusetzen, da die Kosten für die Brennstoffbereitstellung bei noch höheren Leistungen deutlich ansteigen würden. In diesem Leistungsbereich von 20 bis 100 MW(th.) ist lediglich eine allotherme Vergasung sinnvoll, da diese die Produktion eines Synthesegases ohne Stickstoffanteil und damit niedrigere Kompressionsdrücke bei der FT-Synthese ermöglicht.

Eine Sauerstoffvergasung ist wegen der Notwendigkeit einer Luftzerlegungsanlage oder einer anderweitigen Form der Sauerstoffbereitstellung und der in diesem Leistungsbereich kaum darstellbaren Wirtschaftlichkeit abzulehnen. Damit lässt sich für das Gesamtsystem festhalten:

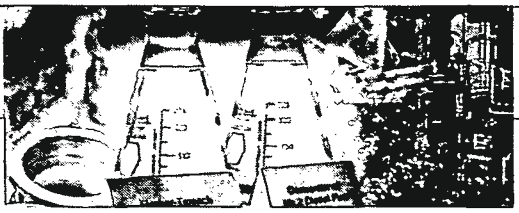
- Holz als Einsatzstoff,
- allotherme Vergasung über einen Zweizonen-Wirbelschichtreaktor,
- Verzicht auf Sauerstoff als Vergasungsmittel aus Kostengründen,
- Verzicht auf CO_2-Abtrennung in der Gasaufbereitung aus Kostengründen,
- Niedertemperatur-FT-Synthese im Once-Through-Betrieb, da hierbei keine CO_2-Abtrennung erforderlich ist,
- Einsatz eines Kobalt-Katalysators,
- Einsatz einer Gasturbine bzw. eines GuD-Prozesses zur Restgasnutzung.

Autotherme Vergasung

Alternativ könnte eine Vergasung im großen Leistungsbereich oberhalb von 500 MW(th.) sinnvoll sein. In diesem Fall relativieren sich die Kosten für den Einsatz von Sauerstoff als Vergasungsmittel und den Aufwand der CO_2-Abrennung. Als Standort für den Vergaser müssten beispielsweise Hafenanlagen in Betracht gezogen werden, die große Stoffströme biogener Festbrennstoffe von 100 t Holz pro Stunde kostengünstig ermöglichen. Für die Produktion des Rohgases würden Wirbelschichtreaktoren mit einem Wasserdampf-Sauerstoff-Gemisch als Vergasungsmittel eingesetzt. Allotherme Vergasungsprozesse, die ausschließlich mit Wasserdampf als Vergasungsmittel arbeiten, sind aus derzeitiger Sicht nur auf Leistungen bis etwa 100 MW(th.) übertragbar. Unter diesen Bedingungen gilt für ein Gesamtsystem:

- Holz als Einsatzstoff,
- autotherme Vergasung über einen Wirbelschichtreaktor,
- Sauerstoff-Wasserdampf-Gemisch als Vergasungsmittel,
- CO_2-Abtrennung,
- Niedertemperatur-FT-Synthese im Rezirkulations-Betrieb,
- Einsatz eines Kobalt-Katalysators,
- Einsatz einer Dampfturbine zur Restwärmenutzung.

Im Leistungsbereich oberhalb von 500 MW(th.) ist die Vergasung veredelter biogener Brennstoffe und ein Einsatz von mehrstufiger Anlagentechnik eine Alternative, die im Vergleich zur Wirbelschichttechnik den Vorteil aufweist, dass nahezu alle biogenen Festbrennstoffe einsetzbar sind. Bei entsprechenden Standortbedingungen kommt eine Pyrolyse zur lokalen Herstellung eines Öl-Koks-Schlammes mit anschließender



Flugstromvergasung in Frage. Für den Aufbau eines Gesamtsystems gelten die gleichen Aussagen wie oben.

Zusätzlich oder alternativ könnte die Anbindung an eine Raffinerie für die Produktaufbereitung sinnvoll sein. Dieser Lösungsansatz würde allerdings eine entsprechende Veränderung der administrativen Vorgaben erfordern.

Schlussbetrachtung

Ausgehend von einer Analyse unterschiedlicher Verfahren zur Vergasung biogener Brennstoffe, die sich für eine Ankopplung an FT-Syntheseprozesse eignen, wurden Gesamtsystemlösungen für die Bereitstellung flüssiger Bioenergieträger identifiziert. Dabei wurden die folgenden Erkenntnisse erzielt:

- Anlagen zur FT-Synthese auf der Basis fossiler Energieträger können erfolgreich großtechnisch betrieben werden, sind allerdings nicht problemlos auf die Leistungen und Anforderungen einer Biomassevergasung übertragbar.
- Die für den Einsatz in FT-Prozessen notwendigen Anforderungen an die Reinheit des Rohgases sind sehr hoch und werden von den bisher verfügbaren Vergasungsreaktoren nicht erreicht, so dass eine aufwändige und damit teure Gasreinigung zwingend erforderlich ist.
- Der im Synthesegas benötigte Wasserstoff sollte möglichst durch Wasserdampfvergasung und/oder Vergasung mit Wasserdampf-Sauerstoff-Gemisch sicher gestellt werden.
- Die Vergasung biogener Festbrennstoffe sollte mit Wirbelschichtvergasern oder mehrstufigen Verfahren realisiert werden, da zu diesen Verfahren die meisten Erfahrungen vorliegen und die erforderlichen thermischen Leistungen sicher erreichbar sind.

Auf der Grundlage dieser Erkenntnisse lassen sich technisch und wirtschaftlich darstellbare Gesamtsysteme für die Bereitstellung von FT-Diesel aus biogenen Festbrennstoffen ableiten:

- Allotherme Vergasung von biogenen Festbrennstoffen im Leistungsbereich von 20 bis 100 MW(th.), Wasserdampf als Vergasungsmittel, Verzicht auf eine CO_2-Abtrennung, Restgasnutzung der FT-Synthese mittels Gasturbine.
- Autotherme Vergasung von biogenen Festbrennstoffen (eventuell nach Veredlung) im Leistungsbereich oberhalb von 500 MW(th.), Wasserdampf-Sauerstoff-Gemisch als Vergasungsmittel, CO_2-Abtrennung und Rezirkulationsbetrieb.

Für eine erfolgreiche Umsetzung derartiger Konzepte müssen die Vergasung, die Gasreinigung und die FT-Synthese hinsichtlich der chemischen, physikalischen und technischen Grundlagen ebenso wie die verfahrenstechnische Umsetzung – vor allem die Kopplung der Einzelsysteme – im Detail untersucht werden.

Ausgehend davon sollten Pilot- und Demonstrationsvorhaben mit unterschiedlichen technischen Ansätzen unter wissenschaftlicher Begleitung realisiert und bewertet werden. Unter diesen Prämissen könnte die FT-Synthese zukünftig einen energiewirtschaftlich relevanten, umwelt- und klimaverträglichen Beitrag zur Deckung der Kraftstoffnachfrage in Deutschland und Europa leisten, um die Vorgaben der European Biofuel Directive zu erfüllen.

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X. PAPER

Vogel, A.; Kaltschmitt, M.; Bolhàr-Nordenkampf, M. Hofbauer, H.

„Vergasung zur Kraftstoffbereitstellung- Grundsätzliche konzeptionelle Überlegungen“

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Biomasse-Vergasung – Internationale Tagung Leipzig, Oktober 2003

Vergasung zur Kraftstoffbereitstellung – Grundsätzliche konzeptionelle Überlegungen

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1 Kurzfassung

Das Interesse an erneuerbaren Energien hat vor allem durch die Zielsetzung einer Klimagasreduktion und Erhöhung der Unabhängigkeit von Brennstoffimporten in den letzten Jahren verstärkt an Bedeutung gewonnen. Von den unterschiedlichen Möglichkeiten der Endenergiebereitstellung hat – u. a. durch administrative Vorgaben wie z. B. European Biofuel Directive – auch die Kraftstoffbereitstellung besonders große Relevanz erlangt.

Unter den dazu verfügbaren regenerativen Pfaden bietet aus derzeitiger Sicht insbesondere die Vergasung biogener Festbrennstoffe und anschließende Synthese zu flüssigen Kraftstoffen ausreichend technisches Potenzial, diese gesetzten Zielvorgaben zu erfüllen.

Dabei zeigt sich, dass – durch die seitens der Automobilindustrie forcierten Anforderungen an die Kraftstoffe – besonders mit der Synthese zu Fischer-Tropsch-Diesel eine Kombination günstiger Eigenschaften erreicht werden kann. Die Anforderungen, die an das dazu erforderliche Synthesegas gestellt werden, sind – und das gilt z. B. auch für Methanol- oder DME-Synthese – um ein Vielfaches höher als bei der Strom- und Wärmeproduktion. Um den Aufwand einer – in jedem Fall erforderlichen – Gasaufbereitung jedoch möglichst gering zu halten, ist die Entwicklung fortschrittlicher Vergasungsverfahren eine der Hauptaufgaben der zukünftigen Kraftstoffbereitstellung.

Betrachtet man ausgehend von diesen Anforderungen an das Synthesegas sowohl die wissenschaftlichen Grundlagenerkenntnisse, als auch die in der Vergangenheit realisierten Entwicklungen im Bereich der Vergasungstechnik, so ist festzustellen, dass nur

- Bewegtbett- oder mehrstufige Reaktoren unter dem Einsatz von
- Wasserdampf oder Wasserdampf-Sauerstoff-Gemischen als Vergasungsmittel

zielführend sind. Sowohl die Entwicklung geeigneter Vergasungsverfahren als auch die Zusammenführung zu funktionierenden Gesamtkonzepten ist jedoch noch nicht abgeschlossen. Eine Fragestellung dabei ist, die – für die Vergasung erforderliche – Bereitstellung der entsprechenden Brennstoffmengen zur Reduktion der Transportkosten; dazu bedarf es entweder sehr günstiger Standortbedingungen der Gesamtkonzepte oder einer thermochemischen Wandlung der dezentral anfallenden Brennstoffe.

Aus diesen Überlegungen heraus werden in diesem Vortrag zwei Gesamtkonzepte vorgestellt, welche zwar weiterer Untersuchungen bedürfen, jedoch die Kommerzialisierung synthetischer Bio-Krafstoffe als sehr wahrscheinlich erscheinen lassen.

Zusammenfassend gesehen zeigen die angestellten Betrachtungen, dass die Kopplung von Biomassevergasung und Synthese noch einer deutlichen Weiterentwicklung und Optimierung bedarf; sie bietet aber eine sehr vielversprechende Möglichkeit der Erfüllung der – mit der European Biofuel Directive – für die Zukunft gestellten CO_2-Minderungsmaßnahmen im Kraftstoffsektor.

2 Einleitung

Der Einsatz biogener Festbrennstoffe zur Energieerzeugung stellt heute sowohl national als auch international eine wichtige Möglichkeit zur Substitution fossiler Brennstoffe und somit zur Schonung fossiler Energieressourcen dar. Gleichzeitig kann damit wesentlich zur geforderten Minderung des anthropogenen CO_2-Ausstoßes beigetragen werden.

Im Bereich der Stromerzeugung konnte die Vergasung biogener Festbrennstoffe als eine technisch machbare Option nachgewiesen werden und soll in den nächsten Jahren – im Rahmen nationaler und internationaler F&E-Projekte – eine deutliche Weiterentwicklung bis zur Marktreife erfahren. Für die Technik der Kraftstoffbereitstellung aus biogenen Festbrennstoffen mittels Vergasung und anschließender Synthese steht ein Nachweis der (groß)technischen Machbarkeit vom biogenen Festbrennstoff einschließlich eines Langzeiteinsatzes derartiger synthetisierter Kraftstoffe in Kraftfahrzeugen allerdings noch aus.

Ein Grund dafür ist u. a. die auf dem Gebiet der Vergasung biogener Festbrennstoffe in der Vergangenheit vorgeschlagene und z. T. auch entwickelte enorme Vielzahl an Konzepten und Verfahren, wie es kaum bei eine anderen Technologieentwicklungen der Fall war. Trotz der sich z. T. abzeichnenden ersten Erfolge fehlen für eine Kommerzialisierung zur Vergasung biogener Festbrennstoffe mit anschließender Synthese zu flüssigen Kraftstoffen sowohl wesentliche Grundlagenerkenntnisse als auch deren (erfolgreiche und betriebssichere) technische Umsetzung.

Vor diesem Hintergrund wird – nach einem einleitenden Überblick über die verfügbaren Konversionspfade und ihre Potenziale – analysiert, welche Synthesepfade sich für die Erzeugung von Kraftstoffen anbieten; dabei steht v. a. der Bezug zur zukünftige Entwicklung der Motorentechnik im Vordergrund. Ausgehend davon erfolgt dann – exemplarisch für alle weiteren Synthesen – die Betrachtung der Fischer-Tropsch(FT)-Synthese; dazu werden die unterschiedlichen Verfahren analysiert und die sich daraus ableitenden Synthesegasanforderungen aufgezeigt. Diese Untersuchung der Synthesetechnik stellt wiederum die Grundlagen für die Analyse der Synthesegaserzeugung (Techniken der Vergasung) dar; in diesem Zusammenhang werden die Grundlagen der Vergasung – soweit es für diese Analyse notwendig ist – diskutiert und anschließend geeignete Verfahren für die Erzeugung von gut geeignetem Synthesegas abgeleitet. Beide Problemfelder – d. h. Synthese und Synthesegaserzeugung – werden danach zusammengeführt und entsprechende (Gesamt-)Lösungsansätze aufgezeigt und diskutiert.

3 Konversionspfade und technische Potenziale

Um die Erzeugung von Kraftstoffen mittels Vergasung in die insgesamt verfügbaren Möglichkeiten der Kraftstoffbereitstellung einordnen zu können, werden zunächst die verschiedenen Konversionspfade betrachtet. Darüber hinaus erfolgt für diese Pfade die Analyse der technischen Potenziale. Somit lässt sich ableiten, welche Konversionspfade aus Sicht der erreichbaren Kraftstoffmengen als besonders aussichtsreich einzustufen sind.

3.1 Konversionspfade

Das Zielprodukt Kraftstoff kann über verschiedene Konversionspfade erzeugt werden, deren prinzipielle Einteilung in Abb. 1 dargestellt ist; dabei wird zwischen thermo-chemischer, bio-chemischer und physikalisch–chemischer Umwandlung unterschieden. Diese Optionen – das gilt für die Energieerzeugung i. Allg. und die Kraftstofferzeugung im Speziellen – unterscheiden sich wiederum in Abhängigkeit der Biomasse-Eigenschaften (Waldrestholz, Rapssaat, Weizen etc.); daneben sind für eine praktische Umsetzung dieser Pfade der Stand der Technik und die erreichbaren technischen Potenziale entscheidend.

Thermo-chemische Umwandlung. Bei der thermo-chemische Umwandlung – dies beinhaltet prinzipiell die Vergasung sowie die Verkohlung und die Pyrolyse – werden aus organischen Stoffen in erster Linie unter dem Einfluss von Wärme feste, flüssige und/oder gasförmige Energieträger gewonnen. Das Hauptunterscheidungsmerkmal der benannten Verfahren liegt somit in den jeweiligen Zielprodukten:

Bei der Verkohlung wird eine möglichst hohe Ausbeute an Festbrennstoff angestrebt, welcher lediglich zur Wärmebereitstellung oder alternativ stofflich genutzt werden kann; ein Anwendungsfeld als Kraftstoff ist nicht erkennbar.

Bei der Pyrolyse soll hingegen eine möglichst hohe Ausbeute an flüssigen Komponenten erzielt werden, welche – wenn die dafür benötigte

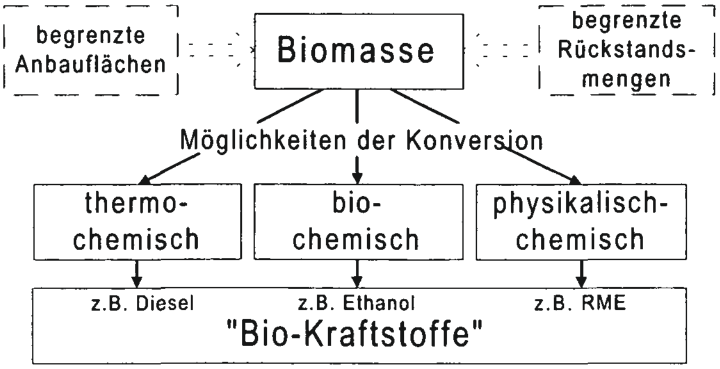

Abbildung 1: Vereinfachte Darstellung der Konversionspfade

Technik verfügbar wäre – beispielsweise als Treibstoff für Motoren genutzt werden könnte.

Die Vergasung biogener Festbrennstoffe hat eine möglichst vollständige Umwandlung in gasförmige Energieträger (d. h. ein Synthesegas) zum Ziel. Das so produzierte Gas kann in Gasmotoren oder -turbinen direkt genutzt werden; muss jedoch für den Einsatz als Kraftstoff im Verkehrssektor – v. a. aus Gründen der praktischen Anwendbarkeit – durch eine anschließende Synthese des Gases zu flüssigen Kraftstoffen (DME, Diesel, etc.) umgewandelt werden.

Physikalisch-chemische Umwandlung. Öle und Fette, welche mit Hilfe von physikalisch-chemischen Verfahren (Pressung/Extraktion) gewonnen werden, lassen sich energetisch sehr vorteilhaft nutzen. Die dazu notwendigen Verfahren sind Stand der Technik; jedoch ist die Produktion der Ölsaat technisch sehr aufwändig.

Durch eine zusätzliche Umesterung kann das Endprodukt (z. B. Pflanzenöl) weitgehend den Eigenschaften konventionellen Dieselkraftstoffs angenähert und dadurch ein Einsatz in vorhandenen Dieselmotoren ermöglicht werden. Diese Technologie ist – wenn auch verbesserungswürdig – ebenfalls als Stand der Technik zu betrachten; der Einsatz von RME in entsprechenden Motoren wird bereits seit Jahren realisiert.

Bio-chemische Umwandlung. Bei den bio-chemischen Veredlungsverfahren erfolgt die Umwandlung in flüssige oder gasförmige Sekundärenergieträger bzw. in End- oder Nutzenergie mit Hilfe von Mikroorganismen. Dabei kann zwischen alkoholischer Gärung, anaerobem Abbau und aerobem Abbau unterschieden werden:

Der aerobe Abbau führt letztlich nur zur Freisetzung von Wärme und kann nicht zur Kraftstofferzeugung genutzt werden. Dagegen lässt die Wandlung über die alkoholische Gärung zu Bio-Ethanol den Einsatz im Verkehrsektor zu; derzeit werden rund 66 % des weltweit erzeugten Ethanols im Kraftstoffsektor – als Reinkraftstoff oder als Mischkomponente – umgesetzt. Demgegenüber bietet die Vergärung – wie bei der thermo-chemischen Umwandlung die Vergasung – die Möglichkeit eines Produktgaseinsatzes in einem Gasmotor oder einer Gasturbine. Prinzipiell möglich – wenn auch noch nicht realisiert – ist somit auch ein Einsatz von verdichtetem Biogas im Kraftstoffsektor /1/.

Fazit. Für die Erzeugung regenerativer Kraftstoffe durch eine Umwandlung von Biomasse bieten sich zunächst verschiedenste Konversionspfade an. Da es sich bei Biomasse um einen Energieträger handelt, der nur in begrenzten Mengen zur Verfügung steht, sind für die Auswahl der Konversionspfade nicht nur die erreichbaren Zielprodukte oder der Stand der Technik relevant. Auch die über die Konversionspfade erreichbaren technischen Potenziale sind zu berücksichtigen. Letztere sind – v. a. durch administrative Vorgaben in bezug auf zukünftige Entwicklungsstrategien (z. B. European Biofuel Directive) – von entscheidender Bedeutung und sollen nachfolgend (exemplarisch) betrachtet werden.

3.2 Technische Potenziale

Bei Potenzialabschätzungen kann zwischen theoretischen, technischen, wirtschaftlichen und erschließbaren Potenzialen unterschieden werden. Nachfolgend wird ausschließlich das technische Potenzial betrachtet, d. h. der Anteil des unter gegebenen technischen Restriktionen nutzbaren theoretischen Potenzials.

In Abb. 2 sind dazu die technischen Potenziale ausgewählter Kraftstoffe für Deutschland den Forderungen der European Biofuel Directive gegenübergestellt. Aus dieser vergleichenden Darstellung wird deutlich, dass über die verfügbaren Techniken der Pflanzenöl- oder PME(Pflanzenöl-Methyl-Ester)-Produktion die Forderungen bereits in Bezug auf die angestrebten 5,75 % regenerativer Kraftstoffe nicht erfüllt werden können. Lediglich die Pfade der synthetischen Kraftstoffe sowie von Synthese- und Biogas bieten ausreichend hohe Potenziale.

3.3 Schlussfolgerungen

Die Betrachtung der verfügbaren Techniken zur Kraftstofferzeugung aus Biomasse hat deutlich die Unterschiede der einzelnen Konversionspfade aufgezeigt. Zusammenfassend ist folgendes festzustellen:

- Biokraftstoffe aus physikalisch-chemischen (Pflanzenöle, PME etc.) und bio-chemischen Verfahren (Ethanol etc.) sind heute weitgehend technisch verfügbar.
- Die damit erreichbaren Mengen sind zur Erfüllung der EU-Vorgaben nicht ausreichend (2010: 5,75 % Anteil).

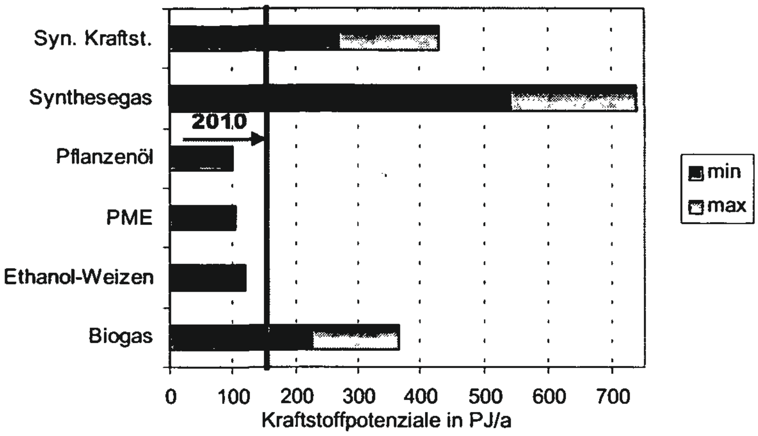

Abbildung 2: Technische Potenziale biogener Kraftstoffe in Deutschland vs. den Forderungen der European Biofuel Directive (5,75 % regenerative Kraftstoffe am Gesamt-Kraftstoffverbrauch)

- „Bio-Kraftstoffe" aus der thermo-chemischen Vergasung und der bio-chemischen Vergärung bieten ausreichende technische Potenziale.
- Nur synthetische „Bio-Kraftstoffe" können in Bezug auf ihre Einsatzmöglichkeiten deutlich leichter adaptiert werden und lassen somit einen entscheidenden Beitrag im Kraftstoffsektor erwarten.

4 Synthetische Kraftstoffe

Für zukunftsorientierte Strategien im Kraftstoffsektor ist die Entwicklung geeigneter synthetischer Kraftstoffe weitergehend zu analysieren. Im Folgenden wird ein Überblick über die synthetischen Kraftstoffe für den Verkehrssektor gegeben.

Die katalytische Kohlenstoffmonoxidhydrierung stellt ein klassisches Beispiel dar, wie aus Synthesegas – welches die Ausgangsstoffe CO und H_2 enthält – durch die Änderung von Reaktionsbedingungen (Temperatur, Druck, Katalysator) verschiedene Roh-Produkte erzeugt werden können. Somit unterscheiden sich die – für die Kraftstofferzeugung einsetz-

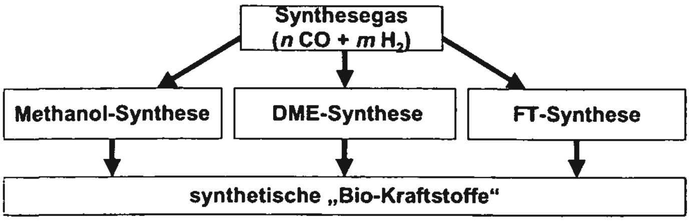

Abbildung 3: Übersicht der Synthesetechniken

baren – Synthesen v. a. in den o. g. Parametern und führen zu den in Abb. 3 dargestellten Zielprodukten DME, FT-Kraftstoff oder Methanol.

Entscheidend für die Auswahl des Syntheseverfahrens sind – neben ökonomischen und ökologischen Kriterien der Wandlungskette von der Biomasse bis zum Kraftstoff – die chemischen Eigenschaften der Syntheseproduktes. Daher werden nachfolgend die Eigenschaften der o. g. Syntheseprodukte den Anforderungen an (zukünftige) Kraftstoffe gegenübergestellt.

Kraftstoffeigenschaften. Für eine Einführung synthetischer Kraftstoffe über einen mittelfristigen Zeithorizont (z. B. in den nächsten 5 bis 7 Jahren) sind die verbrennungstechnischen Eigenschaften sowie die Transport- und Lagermöglichkeiten im Vergleich zu den derzeit existierenden Infrastrukturen und der im Verkehrssektor eingesetzten Motorentechnik relevant. Daher werden im Folgenden die jeweiligen Kraftstoffeigenschaften in bezug auf einen Praxiseinsatz (Tankstellen, KfZ-Motoren etc.) dargestellt werden.

Methanol. Ähnlich wie Ethanol kam Methanol – vor allem in den USA – vor geraumer Zeit als Kraftstoff zum Einsatz. Methanol kann ausgehend vom Verbrennungsverhalten unverdünnt oder mit fossilen Kohlenwasserstoffen gemischt eingesetzt werden. Dabei bereitet die geringe Cetanzahl von Methanol für einen Einsatz in Dieselmotoren Schwierigkeiten, wogegen Otto-Motoren – durch die hohe Oktanzahl von Methanol – prinzipiell geeignet sind. In der praktischen Anwendung ergeben sich allerdings bei Temperaturen unter 10 °C Startprobleme, welche die genannten Vorteile von Methanol mindern. Daher ist – ohne Motorenanpassung – technisch nur eine Zumischung von bis zu 15 % Methanol zum konventionellen Otto-Kraftstoff praktikabel und nach DIN 228 sogar nur maximal 3 % Zumischung gestattet. Methanol ist –

ungeachtet seiner günstigen Eigenschaften in Bezug auf biologische Abbaubarkeit und kanzerogene Wirkung – neben den o. g. Restriktionen durch zusätzlich erforderliche Sicherheitsmaßnahmen (da keine sichtbare Flamme und giftig) derzeitig für einen Einsatz im Verkehrssektor – entgegen landläufigen Meinungen – als nicht unproblematisch einzustufen.

DME. Gegenüber Methanol kann DME zwar nicht mit Diesel-Kraftstoff gemischt werden; eine Verbrennung in umgerüsteten Dieselmotoren ist jedoch möglich und verursacht als Rein-Kraftstoff nicht die beim Methanoleinsatz auftretenden Zündprobleme. Das Hauptproblem eines DME-Einsatzes liegt – durch seinen Aggregatzustand – vielmehr in den erforderlichen Speicher- und Lagerungssysteme (Tankstellen, Zapfsäulen, Kfz-Tanks etc.), die für DME 5 bis 10 bar Überdruck sicherstellen müssten. Es gibt jedoch schon Entwicklungen (z. B. von Volvo), die eine DME-Nutzung auch im KfZ-Bereich ermöglichen; insgesamt ist jedoch noch keine ausreichende Infrastruktur für den Einsatz von DME geschaffen. Somit wäre für den kommerziellen Einsatz von DME – der erhebliche Vorteile in Bezug auf Emissionssenkungen verspricht – die Entwicklung von Speicher- und Transportsystemen sowie entsprechende Motoren-Anpassungen notwendig.

FT-Diesel. Gegenüber den beiden o. g. Kraftstoffen besitzt FT-Diesel die annähernd gleichen Eigenschaften wie Diesel aus fossilen Brennstoffen. Folglich lässt sich FT-Diesel in allen Verhältnissen mit konventionellem Diesel mischen und kann modifikationslos in die derzeit vorhandenen Systeme des Verkehrssektors (Motoren, Tankstellen) integriert werden. Darüber hinaus bietet FT-Diesel gegenüber konventionellen Diesel-Kraftstoffen in einigen Details günstigere Eigenschaften, wie geringeren Schwefelgehalt, höhere Cetan-Zahl und geringeren Gehalt an Aromaten /2,3,4/.

Anforderungen an zukünftige Kraftstoffe. Neben der Darstellung in bezug auf die für derzeitige Technik relevanten Eigenschaften ist es – für eine Analyse zukünftiger Kraftstoffpfade – auch entscheidend, welche Anforderungen zukünftige Kraftstoffe erfüllen müssen.

Eine wichtige Anforderung lässt sich aus den in Abb. 4 dargestellten Zusammenhängen ableiten. Zur Senkung der Abgasemissionen bieten sich – ausgehend vom derzeitigen Stand der Motorenentwicklung – unterschiedliche Möglichkeiten, welche über die Optimierung der Verbrennung, die Optimierung der Einspritzung etc. letztlich zu besseren

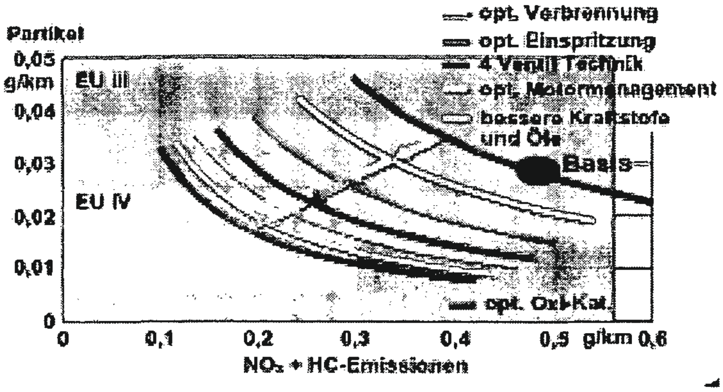

Abbildung 4: Technologische Möglichkeiten zur Verminderung von Abgasemissionen /5/

Kraftstoffen führen müssen; nur so lassen sich die aktuell definierten Grenzwerte (z. B. EU-Abgasvorgabe IV) erfüllen. Gleichzeitig gehen die Entwicklungen der Automobilindustrie zu sog. „combined combustion systems", welche Vorteile von klassischen Otto- und Dieselverfahren verbinden sollen. Dazu sind jedoch Kraftstoffe mit „scharfen Produkteigenschaften" (z. B. Siedepunkt) notwendig.

Folglich müssen zukünftige Kraftstoffe sowohl deutlich bessere Eingenschaften in Bezug auf Emissionen (z. B. geringere Schwefelgehalte) bieten und gleichzeitig – durch ihre verbrennungstechnischen Eigenschaften – neuen Motorenentwicklungen gerecht werden. Darüber hinaus ist müssen sie auch in der derzeit vorhandenen Verkehrsflotte einsetzbar sein.

Schlussfolgerungen. Synthetische Kraftstoffe bieten – neben den hohen technischen Potenzialen – die Möglichkeit einer Anpassung ihrer Eigenschaften auf die jeweiligen Anforderungen. Die Fragestellung, welcher der drei potenziell verfügbaren synthetischen Kraftstoffe sich im Verkehrssystem durchsetzen wird, ist derzeit jedoch noch nicht vollständig beantwortet und bedarf umfassenderer Analysen und Untersuchungen.

Geht man jedoch von den o. g. Kriterien und Randbedingungen zur Auswahl der Synthesetechnik aus, bieten FT-Kraftstoffe gegenüber

Methanol und DME zahlreiche Vorteile. Dies gilt sowohl für die betrachteten Produkteigenschaften als auch für die Erfüllung der Anforderungen an zukünftige Kraftstoffe.

Daher soll im Folgenden die FT-Synthese – exemplarisch für Methanol- und DME-Synthese – in ihren Techniken und Anforderungen untersucht werden.

5 FT-Synthese

Die FT-Synthese wurde 1925 am Kaiser-Wilhelm Institut (KWI) für Kohleforschung in Mühlheim (Ruhr) als Verfahren zur Gewinnung von flüssigen Kohlenwasserstoffen aus Kohle entwickelt. Ab 1938 begann die industrielle Verwertung, deren anschließende Entwicklung und Anwendung Hand in Hand mit der Entwicklung des Ölpreises ging /6/.

Derzeit ist die FT-Synthese u. a. infolge der politischen Klimaschutz-Vorgaben in Bezug auf Biotreibstoffe – insbesondere in Deutschland – wieder von besonderem Interesse, da das Synthesegas, das als Ausgangsmaterial für synthetische Kraftstoffe dient, auch durch eine Vergasung biogener Festbrennstoffe gewonnen werden kann.

5.1 FT-Reaktion

Die FT-Synthese kann durch die Reaktion (1)

$$n\,CO + (n + \frac{m}{2})\,H_2 \longrightarrow C_nH_m + n\,H_2O \qquad (1)$$

beschrieben werden. Dabei werden verschiedene Teilreaktionen unterschieden. Die Basisreaktion (2)

$$CO + 2\,H_2 \longrightarrow -CH_2- + H_2O \qquad (2)$$

durch die CH_2-Stücke aufgebaut werden, ist sehr exotherm (ca. -165 kJ/mol) /7/; deshalb kommt der Wärmeabfuhr aus dem Prozess eine sehr große Bedeutung zu. Aus den entstandenen CH_2-Stücken wachsen dann Kohlenwasserstoffketten heran, die – bedingt durch die Kettenwachstumswahrscheinlichkeit – ein Produkt-Spektrum bilden /8,9/.

5.2 Verfahren und Einflussfaktoren

Verfahren. Bei der technischen Umsetzung der FT-Synthese wird zwischen Hoch- und Niedertemperaturverfahren unterschieden.

Hochtemperaturverfahren. Hochtemperaturverfahren im Temperaturbereich von 300 bis 350 °C sind speziell für die Benzinproduktion geeignet, wobei die Benzinselektivität mit 36 % /10/ nicht sonderlich hoch liegt und eine nachträgliche intensive Produktaufarbeitung erforderlich wird. Deshalb sind diese Verfahren für Anlagen kleinerer Leistung – wie sie bei der Biomassevergasung im Unterschied zu FT-Verfahren auf der Basis fossiler Gase zu erwarten sind – eher nachteilig. Sie werden daher im Folgenden nicht weiter betrachtet.

Niedertemperaturverfahren. Bei Niedertemperaturverfahren (200 bis 240 °C) entstehen aus Synthesegas langkettige Kohlenwasserstoffe (Wachse), die – nach einem angeschlossenen Hydrocracking – Diesel hoher Qualität liefern /11/. Aufgrund des geringeren Aufwandes zur Produktaufarbeitung sind derartige Verfahren auch im kleineren Leistungsbereich leichter einsetzbar. Es kommen im wesentlichen zwei Reaktortypen (Abb. 5) zur Anwendung:

- Rohrbündelreaktoren (Tubular fixed bed reactor (TFBR)) und
- Slurry- Reaktoren (Slurry bubble column reactor (SBCR)).

TFBR-Reaktoren dienen zur Produktion von Wachs, wobei dieses flüssig anfällt. Die Reaktoren werden von oben beschickt, wobei das Synthesegas durch eine Katalysatorschüttung strömt, die sich in den Rohren eines

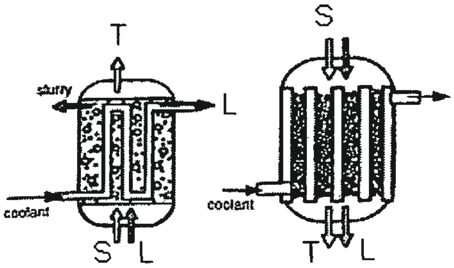

Abbildung 5: Reaktorarten : a. SBCR; b. TFBR; S... Synthesegas, T...Restgas, L... Flüssiges FT-Produkt /12/

Wärmeübertragers befindet. Das Wachs tropft abwärts und verlässt unten den Reaktionsraum /6/. SBCR-Reaktoren bestehen dagegen aus einem Reaktormantel, in den eine Kühlschlange eingebaut ist, welche die Wärme mittels Dampferzeugung abführt. Das Synthesegas wird von unten eingeblasen und steigt in der Suspension (die aus den flüssigen Reaktionsprodukten und dispergierten Katalysatorteilchen besteht) auf. Dabei entsteht das gewünschte Reaktionsprodukt /11/.

Weiterhin können FT-Anlagen in Abhängigkeit von der Restgasverwendung nach zwei Betriebsarten unterteilt werden /9/:

- „full conversion" Betrieb – FT-Synthese unter Rückführung des nicht umgesetzten Synthesegases in den FT-Prozess zur Maximierung der Flüssigfraktion,
- „once through" Betrieb – FT-Synthese, bei der die Restgase zur Erzeugung elektrischer Energie in einer Gasturbine bzw. zur Wärmeerzeugung genutzt werden.

Einflussfaktoren. Der Ablauf der FT-Synthese wird im Wesentlichen durch die Art des Katalysators und die Betriebsparameter (dabei v. a. durch die Temperatur) maßgeblich beeinflusst (Tabelle 1).

Temperatur. Höhere Reaktionstemperaturen begünstigen insgesamt

- die Bildung von Methan (in der Regel unerwünscht),
- die Aromatenbildung und damit Koksablagerungen am Katalysator, speziell bei Eisenkatalysatoren /6,13/ und
- kürzere Kettenlängen und damit eine geringere Treibstoffausbeute (v. a. Diesel) /13/.

Daher ist die Steigerung der Reaktionsgeschwindigkeit mittels einer Temperaturerhöhung nur begrenzt möglich.

Tabelle 1: Einflussfaktoren auf die FT-Synthese im Zusammenhang mit dem FT-Katalysator und den Betriebsparametern /11/

FT-Katalysator	**Betriebsparameter**
- Metall	- Reaktortyp
- Trägermaterial	- Temperatur
- Herstellung (Promotoren, etc.)	- Druck
- Vorkonditionierung, Aktivierung	- Raum-Zeit-Geschwindigkeit
- Alter	- Rückführrate

Katalysatoren. Zur Katalyse der FT-Reaktion kommen im Wesentlichen Eisen- (Fe) und Kobalt- (Co) -Katalysatoren in Frage /14,6,13/.

- Eisen-Katalysatoren sind vielfältiger verwendbar als Kobalt-Katalysatoren. Sie katalysieren die Hydrogenierung weniger stark und produzieren daher weniger Methan /15/. Weiterhin katalysiert Eisen die Wassergas-Shiftreaktion (WGS-Reaktion). Jedoch ist Wasser hinsichtlich der FT-Reaktion ein starker Inhibitor der Katalysatoraktivität /13,16,17/.
- Kobalt ist im Vergleich zu Eisen der aktivere Katalysator; er kann aber nur bei niederen Temperaturen verwendet werden /15/, da bei hohen Temperaturen die (unerwünschte) Methanproduktion steigt. Wasser wirkt auf Kobalt-Katalysatoren – im Gegensatz zu Eisen – nur sehr leicht inhibierend. Daher ist dieser vor allem bei der Once-through-FT-Synthese, wo möglichst hohe Umsätze beim einmaligen Durchlauf im Reaktor erzielt werden sollen und viel Wasser im Gleichgewicht vorliegt, zu bevorzugen.

Allen FT-Katalysatoren ist jedoch die Empfindlichkeit gegenüber ungenügender Gasreinheit, insbesondere gegenüber Schwefelverbindungen (dauerhafte Vergiftung) /18/, und Sinterprobleme durch Hitzeentwicklung und Bildung von Koksablagerungen /6/ gemein.

5.3 Synthesegasanforderungen

Je nach eingesetztem FT-Verfahren unterscheiden sich die Anforderungen, die an ein Synthesegas zu stellen sind. Entscheidend dabei ist aber die notwendige Gasreinheit und das H_2/CO-Verhältnis.

Gasreinheit. Über die Wirkungen der meisten im Synthesegas vorkommenden Verunreinigungen auf die FT-Synthese ist – außer beim Schwefel – nur sehr wenig bekannt. Typische Literaturwerte für die einzelnen Komponenten sind in Tabelle 2 Werten eines 750 h Versuchs mit einem Kobalt-Festbettkatalysator gegenübergestellt. Demnach konnten im Versuch die in der Literatur angegebenen Werte deutlich überschritten werden, obwohl kein Aktivitätsverlust am Katalysator festgestellt wurde. Insgesamt sind jedoch generell sehr geringe Gehalte an Schadkomponenten (u. a. Chlor- und Stickstoff-Verbindungen) sicherzustellen /18,19/.

Tabelle 2: Synthesegasanforderungen für die FT-Synthese (Reinheitsangaben aus Literaturwerten und Betriebserfahrungen von ECN) /9,20,21/

	Literaturwerte	**ECN: LTFT, Festbett, Co**
CO_2	< 5 Vol %	< 5 Vol %
Asche, Partikel	k.A.	< 0,1 mg/Nm³
N (HCN, NH_3)	< 20 ppb_V	< 1 ppm_V
S (H_2S, COS)	< 10 ppb_V	< 1 ppm_V
Alkalien	< 10 ppb_V	< 10 ppb_V
Cl (HCl)	< 10 ppb_V	< 10 ppb_V
Br, F	k.A.	< 10 ppb_V
Teer	unter Taupunkt	unter Taupunkt

H_2/CO-Verhältnis. Auch beim H_2/CO-Verhältnis bestehen je nach Verfahren und Katalysator, unterschiedlichste Anforderungen /6,9,17,22/. Demnach verlangt der Einsatz von Kobalt-Katalysatoren ein hohes H_2/CO-Verhältnis (>2, optimal 2,15); Grund dafür ist die FT-Reaktion als die bestimmende Reaktion. Bei Einsatz von Eisen-Katalysatoren sind dagegen keine hohen H_2/CO-Verhältnisse erforderlich, da zusätzlich das Wassergasgleichgewicht (3)

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{3}$$

berücksichtigt werden muss. Setzt man nun Gleichung (3) in Gleichung (2) ein, ergibt sich

$$2CO + H_2 \longrightarrow -CH_2- + CO_2 \tag{4}$$

Demnach wird statt des ursprünglichen stöchiometrischen H_2/CO-Verhältnisses von 2 (FT-Reaktion) lediglich ein Verhältnis von 0,5 notwendig; dies entspricht auch praktisch dem mehrfach gefundenen minimalen Verhältnis für Eisen-Katalysatoren von ~0,6.

5.4 Schlussfolgerungen

In der Analyse der FT-Synthese wurde sowohl die für „vergaste Biomasse" einsetzbaren Verfahren als auch die zugehörigen Anforderungen, die an ein Synthesegas zu stellen sind untersucht. Es zeigte sich folgendes:

- Bedingt durch die zu erwartende Leistungsgröße sind für die Kopplung mit einer Vergasung – bei Einsatz von Biomasse – nur bestimmte FT-Verfahren als geeignet einzustufen.
- Die FT-Synthese ist in bezug auf die Haupteinflussfaktoren Temperatur und Katalysator als sehr empfindlich einzuschätzen.
- Folglich ist eine entsprechend hohe Reinheit des Synthesegases in bezug auf die o. g. Schadkomponenten erforderlich.
- Neben den Reinheitsanforderungen stellt die FT-Synthese bestimmte Anforderungen an den maximalen Inergasanteil und das H_2/CO-Verhältnis.

6 Problemfeld: Synthesegaserzeugung

Aufbauend auf den Untersuchungen der FT-Synthese werden nachfolgend geeignete Verfahren zur Synthesegaserzeugung abgeleitet.

Der Systemaufbau zur Bereitstellung eines Synthesegases unterscheidet sich im Aufbau nur unwesentlich von der Vergasung zur Stromerzeugung. Der Brennstoff wird über den Prozess der Bereitstellung auf die Anforderungen des Vergasungsprozesses aufbereitet und im Vergasungsreaktor zu Rohgas umgesetzt. Die Gasaufbereitung reinigt und konditioniert das Rohgas auf Synthesegas-Qualität, um die anschließende Synthese zu Kraftstoff zu ermöglichen (Abb. 6). Bedingt durch die hohen Anforderungen der Synthesetechnologien differieren Rohgas- und Synthesegaseigenschaften jedoch teilweise erheblich und müssen über entsprechend aufwändige – und damit teure – Gasaufbereitungssysteme kompensiert werden. Daher werden nachfolgend die Eigenschaften von Roh- und Synthesegasen gegenübergestellt.

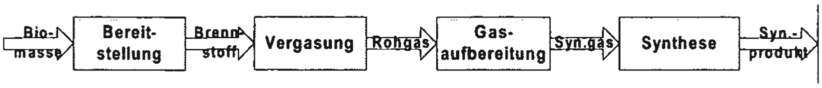

Abbildung 6: Systemaufbau zur Synthesegaserzeugung aus Biomasse

6.1 Vergleich von Roh- und Synthesegaseigenschaften

Die Entwicklung der Vergasung biogener Festbrennstoffe hat eine Vielzahl an Verfahrenslösungen hervorgebracht. Trotzdem befinden sich derzeit nur wenige Anlagen zur Vergasung biogener Festbrennstoffe im (Demonstrations-)Betrieb und die Kopplung mit Syntheseprozessen ist kaum realisiert. Ein Hauptgrund dafür sind die hohen Reinheitsanforderungen der Syntheseprozesse und die z. T. deutlich höheren Schadgehalte der heute verfügbaren Vergasungsgase. Tabelle 3 zeigt die Gaseigenschaften typischer Vertreter von Vergasungsverfahren den Synthesegasanforderungen.

Tabelle 3: Erreichbare Gasqualitäten ausgewählter Vergasungsverfahren /23,24,25,26/

	Gleichstromvergasung	Gegenstromvergasung	Wirbelschichtvergasung	Mehrstufige Vergasung	Anforderungen FT-Synthese
H_2/CO	0,88	0,66	1,52[a]	1[b], 2[c]	>1,35
Inerte %[d]	64	53	25	69[b], 19[c]	< 10 %
Partikel mg/m^3	< 20	200	5.000-10.000	< 50	0
org. KWST mg/m^3	100-150	12.000	2.000	< 50	0
Alkalien mg/m^3	?	?	?	?	< 0,010
S-Verbind. mg/m^3	?	?	76-152	?	< 0,150
N-Verbind. mg/m^3	20-140	?	1.200-1.500	?	< 0,015

a. Vergasungsmittel Wasserdampf (allotherm)
b. Vergasungsmittel Luft
c. Vergasungsmittel Sauerstoff-Wasserdampf-Gemisch
d. Inerte = $N_2 + CO_2$ in Vol.-% $_{trocken}$

Ausgehend von dieser Gegenüberstellung lassen sich folgende Schlussfolgerungen ziehen:

- Einige Vergasungsverfahren bieten deutliche Vorteile (z. B. erhöhter Produktgas-H-Anteil durch Dampfvergasung) in Bezug auf eine Kopplung mit der FT-Synthese.

- Kein Vergasersystem erfüllt direkt die notwendigen Anforderungen der FT-Synthese.
- Der Einsatz einer entsprechenden Gasaufbereitung ist somit in jedem Fall zwingend erforderlich.
- Durch den Einsatz einer Gasreinigung ist kein Vergasungsverfahren a priori für die Synthesegaserzeugung prädestiniert.
- Zur Minimierung des Gasaufbereitungs-Aufwandes sind geeignete Vergasungsverfahren zu identifizieren.
- Daher müssen geeignete Vergasungsverfahren – dies betrifft die Wahl von Vergasungsmittel und Vergasungsreaktor – für die Kopplung mit einer FT-Synthese abgeleitet werden.

6.2 Ableitung geeigneter Vergasungsverfahren

Vergasungsmittel. Die Wahl des passenden Vergasungsmittels soll aus der theoretisch maximal möglichen Produktausbeute abgeleitet werden. Ausgangspunkt einer solchen Betrachtung kann die Wandlung von Holz zu -CH_2-Stücken (Näherung für Diesel) sein. Dabei ist von folgenden H:C-Verhältnissen auszugehen.

- Holz:	$C_{4,2}O_{2,8}H_6$	→ **H:C 1,5**
- FT-Produkt (Diesel):	-CH_2-	→ **H:C 2**

Folglich ist Wasserstoff beim Ausgangsstoff Holz als das limitierende Element der Kraftstofferzeugung zu betrachten. Um nun im Vorfeld der Synthese den Produktgas-Wasserstoff-Anteils zu erhöhen, stehen grundsätzlich drei Möglichkeiten zur Verfügung:

- Einsatz eines wasserreichen Vergasungsstoffes
- Einsatz eines CO-Shift-Reaktors
- Wasserstoffeintrag über das Vergasungsmittel

Die erstgenannte Möglichkeit würde jedoch mit einer Minderung des Kaltgaswirkungsgrades im Vergasungsreaktor einhergehen, während die homogene Wassergasreaktion im sog. Shift-Reaktor zur Wandlung von CO zu CO_2 und damit verbunden zur Inertisierung des Synthesegases führt. Folglich ist nur die Möglichkeit des Wasserstoffeintrages über das Vergasungsmittel vorteilhaft.

Aus der FT-Reaktion ergibt sich, dass für einen vollständigen Kohlenstoffumsatz 4 Wasserstoff-Atome pro Kohlenstoff-Atom erforderlich sind. Unter dieser Maßgabe ergibt sich für eine Sauerstoff- und eine

Wasserdampfvergasung die folgende Betrachtung für 1 kg trockenes Holz:

Sauerstoffvergasung. Hier kann nur der Wasserstoff aus dem Holz (trocken) genutzt werden, um daraus gasförmigen Wasserstoff zu bilden und den Kohlenstoff umsetzen zu können. Zum Brennstoff wird dabei so viel Sauerstoff zugegeben, dass theoretisch eine vollständige Umsetzung zu CO und H_2 erfolgen kann:

$$C_{4,2}O_{2,8}H_6 + 0{,}7\,O_2 \longrightarrow 4{,}2\,CO + 3\,H_2 \qquad (5)$$

Für diese ideale Umsetzung erhält man:

- aus 1 kg trockenes Holz 60 mol H
- damit können ¼, also 15 mol C zu FT-Produkt umgesetzt werden,
- woraus wiederum 15 mol CH_2-Stücke entstehen,
- was mit einem Formelgewicht von 14 g/mol 210 g Diesel/kg trockenes Holz liefert.

Dampfvergasung. Hier wird auch aus dem Vergasungsmittel (Wasserdampf) Wasserstoff gebildet, wodurch nach der Vergasung mehr Wasserstoff für die FT-Reaktion zur Verfügung steht, als im Holz gebunden ist. Damit ergibt sich folgende Reaktionsgleichung

$$C_{4,2}O_{2,8}H_6 + 1{,}4\,H_2O \longrightarrow 4{,}2\,CO + 4{,}4\,H_2 \qquad (6)$$

d. h. es steht im Vergleich zur Sauerstoffvergasung eine um den Faktor 4,4/3 = 1,47 höhere Wasserstoffmenge zur Verfügung.

- Aus 1 kg trockenes Holz 60 mol H
- und durch die Vergasung max. das 1,47-fache 88 mol H im Synthesegas,
- damit können wieder ¼, also 22 mol C umgesetzt werden,
- woraus wiederum 22 mol CH_2-Stücke entstehen,
- was mit einem Formelgewicht von 14 g/mol 308 g Diesel/kg trockenes Holz liefert.

Damit haben Synthesegase aus der Dampfvergasung gegenüber einer ausschließlichen Sauerstoffvergasung aufgrund des höheren H_2-Angebotes für die FT-Synthese Vorteile.

Fazit. Folglich kommen für die Produktion eines hochqualitativen Synthesegases nur die allotherme Wasserdampf- oder die autotherme Sauerstoff-Wasserdampfvergasung in Frage.

Vergasungsreaktoren. Neben der Betrachtung des Vergasungsmittels ist die Art der Prozessführung für die erfolgreiche Kombination mit einer Synthese entscheidend. Dazu bieten sich zunächst – unabhängig vom Vergasungsmittel – folgende Reaktoren an:

- Festbett-Gleichstromsysteme,
- Festbett-Gegenstromsysteme,
- Wirbelschichtreaktoren,
- Flugstromreaktoren.

Je nach Produktgaseinsatz und v. a. je nach Leistungsklasse ergeben sich unterschiedliche Vor- und Nachteile dieser Reaktoren. Festbett-Gegenstromsysteme sind – das haben auch die Erfahrungen der Vergangenheit bestätigt – für eine Kraft-Wärme-Kopplung einsetzbar; für die Kopplung mit einer Synthese sind diese Reaktoren jedoch v. a. durch die hohen Teerbildungsraten ungeeignet.

Mittels Festbett-Gleichstromsystemen können dagegen deutlich geringere Teergehalte erreicht werden. Somit sind diese für die Kopplung mit einer Synthese theoretisch nutzbar; jedoch ist – aus den bisherigen Erfahrungen – ein upscale auf kommerzielle Leistungen von Synthesen nur begrenzt möglich. Es existieren zwar Bemühungen, die eine Kopplung von Gleichstromverfahren mit einer Synthese anstreben; Erfahrungen für den Bereich der Biomasse sind derzeit jedoch kaum verfügbar.

Wirbelschicht- und Flugstromreaktoren bieten bezüglich der erreichbaren Gaseigenschaften bessere Voraussetzungen. Für Wirbelschichtreaktoren bestehen ausreichend Erfahrungen (auch für den Einsatz „schwieriger“ Brennstoffe), um eine Kopplung mit der Synthese gewährleisten zu können. Reaktorbedingt sind dabei höhere Teerbildungen als bei einer Flugstromvergasung zu berücksichtigen.

Die Flugstromvergasung – ursprünglich für die Synthesegaserzeugung entwickelt – bietet dagegen den Vorteil eines nahezu teerfreien Gases. Allerdings ist – für den Einsatzstoff Biomasse – die Brennstoffaufbereitung sowohl ökonomisch als auch technisch sehr umstritten.

6.3 Schlussfolgerungen

Ausgehend von der Betrachtung der Technik der FT-Synthese, der Identifikation der theoretisch günstigen Vergasungsverfahren und des Entwicklungsstandes bestehender Vergasersysteme für biogene Festbrennstoffe sind in Bezug auf eine Reaktorwahl insgesamt folgende Schlussfolgerungen zu ziehen:

- Festbett-Gleichstromsysteme sind unter bestimmten Bedingungen (z. B. dampfhaltiges Vergasungsmittel) prinzipiell einsetzbar, jedoch – das haben die Erfahrungen der Vergangenheit gezeigt – in einem möglichen upscale von den derzeitigen Leistungsbereichen (zumeist 1 bis 3 MW) auf eine wirtschaftlich vertretbare Größenordnung sehr begrenzt.
- Festbett-Gegenstromsysteme (mit Luft als Vergasungsmittel) sind zwar zur gekoppelten Strom- und Wärmeerzeugung (bei geringer Stromkennzahl) einsetzbar; ohne Aggregate zur Konversion der langkettiger Kohlenwasserstoffe (Teere) im Rohgas sind sie jedoch zur Synthesegasproduktion nicht einsetzbar.
- Schlackebadvergaser (Vergasung unter Sauerstoffzufuhr) könnten ggf. einsetzbar sein; sie sind aber für biogene Brennstoffe noch nicht hinreichend untersucht.
- Bewegtbett- und mehrstufige Systeme sind in Bezug auf die Anlagentechnik deutlich aufwändiger; sie bieten aber in den Gaseigenschaften gute Voraussetzungen zur Synthesegasproduktion.
- Dabei bieten mehrstufige Systeme in Kombination mit einer Flugstromvergasung durch die sehr geringen Teergehalte Vorteile für die Synthesegasbereitstellung, bedürfen aber der Bereitstellung von Sauerstoff.
- Wirbelschichtvergaser sowie mehrstufige Verfahren in Kombination mit einem Dampfreforming (Vergasung von Pyrolysegas mit Wasserdampf) sind trotz der – gegenüber der Flugstromvergasung – etwas höheren Teergehalte für die Synthesegasbereitstellung geeignet.
- Alle Vergasersysteme, die Luft als Vergasungsmittel einsetzen, sind u. a. aufgrund des hohen Inertgasanteils als wenig vielversprechend einzuschätzen.
- Gute H_2/CO-Verhältnisse werden nur durch einen Wasserdampf- oder Mischgasprozess (Wasserdampf + Sauerstoff) erreicht.

Auf dieser Basis sollen nachfolgend Gesamtkonzepte, d. h. Möglichkeiten für eine Zusammenführung von Vergasung und Synthese betrachtet werden.

7 Lösungsansätze: Gesamtkonzepte

Aufbauend auf dem für die Komponenten der Vergasung und Synthese erarbeiteten Wissen werden im Folgenden Lösungsansätze für der Kopplung; d. h. für Gesamtkonzepte der Wandlung von „Holz zu Diesel" erarbeitet.

7.1 Problemfeld Brennstoffversorgung

Durch den dezentralen Anfall von Biomasse ist für die Darstellung von Gesamtlösungskonzepten die Wahl der Leistungsklasse einer Konversionsanlage von besonderer Bedeutung. Im Vergleich zur Strom- und/oder Wärmeerzeugung (z. T. im „kW-Bereich") ist für ausgeführte Anlagen zur Kraftstofferzeugung – u. a. durch die Komplexität der Anlagentechnik – eine deutlich gesteigerte Leistungsgröße zu erwarten. Dazu sind in Tabelle 4 beispielhaft zwei mögliche Szenarien einer solchen Konversion dargestellt; ausgehend von einem stündlichen Brennstoffdurchsatz von z. B. 100 Tonnen ergeben sich über die entsprechende Synthesegasausbeute etwa 130.000 Tonnen Flüssigprodukt pro Jahr. Stellt man diese Menge der in Sasol/Südafrika erzeugten Flüssigproduktmenge (6.000.000 Tonnen) gegenüber, so wird deutlich, welche Größenordnungen kommerzielle Anlagen zur Kraftstofferzeugung einnehmen. Auch wird ersichtlich, dass für die Substitution eines geringen Anteils des Kraftstoffverbrauches im Verkehrssystem (ca. 55 Mio. Tonnen jährlicher Kraftstoffverbrauch in Deutschland) relativ große Brennstoffmengen umgesetzt werden müssten.

Die in Tabelle 4 dargestellten Verhältnisse zwischen Brennstoff- und Flüssigproduktmenge zeigen die Schwierigkeit, für die dezentral anfallende Biomasse geeignete Lösungskonzepte der Brennstoffversorgung zu integrieren.

Ungeachtet, in welcher Form der Brennstoff an der Konversionsanlage angeliefert wird, kann im Vergasungsprozess der ursprüngliche Brennstoff (z. B. Holz) oder seine – mittels Pyrolysereaktor erzeugten –

Tabelle 4: Szenarien der Wandlung vom „Holz zum Diesel“

Holz-Durchsatz	t/h	10	100
Vergaserleistung	$MW_{thermisch}$	50	500
Synthesegas	m^3/h	11.400	114.000
Flüssigprodukt	t/h	1,75	17,5
Jahresproduktion	t	13.100	131.000
Jahresproduktion Sasol in t			6.000.000

Rahmenannahme Sauerstoffvergasung: 1,75 Nm^3 Rohgas/kg Holz;
65 % $CO+H_2$ im Rohgas, 6500 m^3 Synthesegas/ t Flüssigprodukt

Zersetzungsprodukte (z. B. Pyrolyseöl) genutzt werden. Unterstellt man das Ziel einer möglichst vollständigen Ausnutzung des Energiegehalts des Brennstoffs, so ist nur

- eine direkte Vergasung der biogenen Festbrennstoffe (d. h. mittels Wirbelschicht) oder
- bei mehrstufigen Prozessen die gemeinsame Vergasung der Flüchtigen und des Kokses

als zielführend zu erachten. Würde beispielweise lediglich das Pyrolyseprodukt Koks der Vergasung zugeführt und die Flüchtigen zur Wärmeerzeugung genutzt, würde – wie aus Tabelle 5 ersichtlich – ein erheblicher Anteil des Ausgangs-Energiegehaltes (etwa 2/3) für die Kraftstoffproduktion verloren gehen.

Tabelle 5: Energiegehalte möglicher Vergasungsstoffe in Abhängigkeit des Ausgangsstoffes

Vergasungsstoffe	**Energiegehalt des Ausgangsbrennstoffs**[a]	**%**
Biogener Festbrennstoff (Holz)		100
Flüchtige Bestandteile	$12{,}5\ MJ/kg_{Gas} \cdot 0{,}8\ kg_{Gas}/kg_{Brennstoff} = 10\ MJ/kg_{Brennstoff}$	67
Kohlenstoff (Koks)	$25\ MJ/kg_{Koks} \cdot 0{,}2\ kg_{Koks}/kg_{Brennstoff} = 5\ MJ/kg_{Brennstoff}$	33

a. berechnet aus durchschnittlichem Heizwert und Masseanteil der Pyrolyseprodukte von Holz

Unter Beachtung des aufgezeigten Problemfeldes der Brennstoffversorgung und den vorangegangen Betrachtungen sollen daher im Folgenden für die einstufige und die mehrstufige Vergasung Gesamtlösungskonzepte dargestellt werden.

7.2 Ableitung von Gesamtlösungskonzepten

Einstufige Vergasung. Für eine einstufige Vergasung bieten sich zwei vielversprechende Gesamtsystemlösungen an:

- allotherme Vergasung im kleinen Leistungsbereich (20 bis 100 MW Brennstoffwärmeleistung (BWL)) und
- autotherme Vergasung im großen Leistungsbereich (größer 500 MW BWL).

Diese Leistungsgrößen ergeben sich primär aufgrund ökonomischer Überlegungen (Economy of Scale) und werden nachfolgend skizziert.

Allotherme Vergasung. Für kommerzielle Anlagen zur FT-Synthese dürfte eine Leistung von 20 MW_{BWL} eine untere realisierbare Leistungsgrenze darstellen, da bei geringeren Anlagenleistungen die spezifischen Investitionen deutlich ansteigen. Als mögliche obere Leistungsgrenze sind etwa 100 MW_{BWL} anzusetzen, da bei höheren Leistungen die Kosten der Brennstoffbereitstellung deutlich ansteigen.

In diesem Leistungsbereich ist nur eine allotherme Vergasung zielführend. Diese ermöglicht die Produktion eines Synthesegases ohne Stickstoffanteil und damit niedrigere Kompressionsdrücke bei der FT-Synthese. Die Sauerstoffvergasung ist, durch die benötigte Luftzerlegungsanlage (oder anderweitiger Sauerstoffbereitstellung) und der in diesem Leistungsbereich kaum darstellbaren Wirtschaftlichkeit, wenig vorteilhaft. Damit könnte ein entsprechendes Gesamtsystem wie folgt realisiert werden:

- Holz als Einsatzstoff (relativ „sauberer" Brennstoff),
- allotherme Vergasung mittels Zweizonen-Wirbelschichtreaktor,
- Verzicht auf Sauerstoff als Vergasungsmittel aus Kostengründen,
- Verzicht auf CO_2-Abtrennung innerhalb der Gasaufbereitung aus Kostengründen,
- Niedertemperatur-FT-Synthese im Once-Through-Betrieb (da keine CO_2-Abtrennung),
- Kobalt-Katalysator,
- Gasturbine bzw. GuD-Prozess zur Restgasnutzung.

Autotherme Vergasung. Alternativ dazu könnte eine Vergasung im großen Leistungsbereich (größer 500 MW_{BWL}) sinnvoll sein. In dieser Leistungsgröße relativieren sich die Kosten für den Einsatz von Sauerstoff (als Vergasungsmittel) und einer der CO_2-Entfernung. Dafür müssten allerdings Standortbedingungen (z. B. Hafenanlage als Vergaserstandort) gegeben sein, die ein Handling derart großer Stoffströme an biogenen Festbrennstoffen (100 t Holz/h) kostengünstig erlauben.

Zur Rohgaserzeugung eignet sich ein oder mehrere parallel geschaltete Wirbelschichtreaktor(en) mit einem Wasserdampf-Sauerstoff-Gemisch als Vergasungsmittel. Eine allotherme Dampfvergasung, ist aus derzeitiger Sicht nur bis ca. 100 MW_{BWL} upscalebar. Damit könnte ein entsprechendes Gesamtsystem wie folgt realisiert werden:

- Holz als Einsatzstoff (relativ „sauberer“ Brennstoff),
- Vergasung mittels Wirbelschichtreaktor,
- Sauerstoff-Wasserdampf-Gemisch als Vergasungsmittel,
- CO_2-Abtrennung,
- Niedertemperatur-FT-Synthese im Rezirkulations-Betrieb,
- Kobalt-Katalysator,
- Dampfturbine zur Restwärmenutzung.

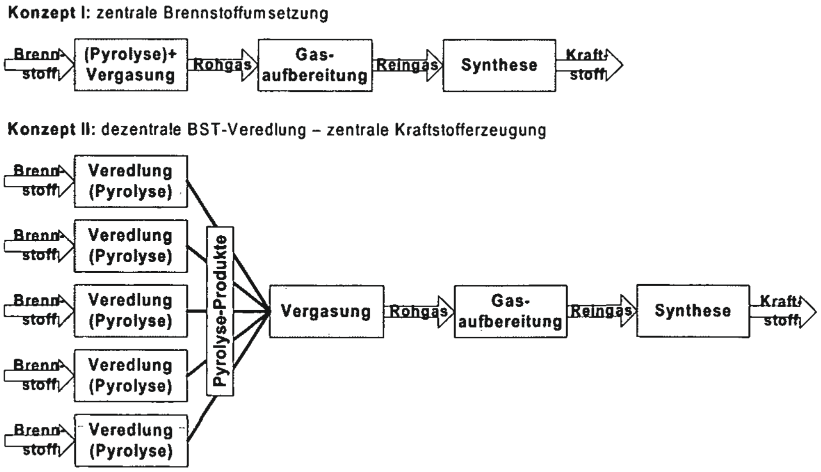

Abbildung 7: Mögliche Standortkonzepte der Brennstoffveredlung

Konzept mehrstufige Vergasung. Für den Fall der o. g. mehrstufigen Vergasung lassen sich ebenfalls zwei potenzielle Konzepte (Abb. 7) identifizieren, welche sich in der Brennstoffaufbereitung unterscheiden:

- zentrale Brennstoffumsetzung (Konzept I) und
- lokale Brennstoffveredlung und zentrale Vergasung (Konzept II).

Für letztere Variante (Konzept II) sprechen

- eine Erweiterung des Brennstoff-Einzugsgebietes und
- die Erzeugung von Strom oder Prozesswärme am lokalen Veredlungsstandort.

Letzteres ist aber – mit dem Ziel möglichst hoher Wandlungswirkungsgrade der Kraftstofferzeugung – nicht zielführend. Für den ersten Punkt, eine Erweiterung des Einzugsgebietes, müssen die Transportkosten z. B. durch eine Steigerung des Energiegehaltes der Veredlungsprodukte minimiert werden. Deshalb zeigt Tabelle 6 die Energieinhalte verschiedener Brennstoffe und deren Veredlungsprodukte.

Tabelle 6: Energiedichte fester und flüssiger biogener Brennstoffe und deren Veredlungsprodukte /27,28,29,30/

Brennstoff	Holz	Stroh	Koks	Pyrolyseöl	Slurry
Energiedichte in MJ/m³	3 600	1 488	4 650	22 496	26 875

Basis Holz, Stroh: trocken und Lagerdichte, Basis Gas: Heizwert in MJ/Nm³,
Basis Slurry: Angaben Forschungszentrum Karlsruhe (23-26 % Koks im Öl),
Basis Koks: Schüttdichte 150 kg/m³

Die Veredlung zu Koks ist aus Sicht der Transportkosten wenig sinnvoll, da ähnlich geringe Energiedichten wie die der unveredelten Biomasse erzielt werden. Auch kann bei dieser Variante nur ein (geringer) Teil der Brennstoffenergie genutzt werden. Eine Erhöhung der Energiedichte bei gleichzeitiger vollständiger Ausnutzung der Brennstoffenergie ist letztlich nur durch die Veredlung zu einer Öl-Koks-Slurry möglich. Nur dann macht die Errichtung lokaler Veredlungsanlagen zur Erschließung größerer Brennstoffpotenziale aus Kostengründen Sinn. Dafür wären allerdings Anlagen zur Flash-Pyrolyse erforderlich, die derzeit noch im Technikumsmaßstab erforscht werden. Zusätzlich sind die bei einer derartigen Slurry-Produktion anfallenden Verluste von ca. 20 % zu berücksichtigen.

Unter Weiterentwicklung der Pyrolyse bis hin zur Möglichkeit einer Kommerzialisierung ist die Vergasung veredelter biogener Brennstoffe (Slurry) und damit verbunden der Einsatz einer mehrstufigen Anlagentechnik (Pyrolyse + Flugstromreaktor) ein mögliches Gesamtlösungskonzept. Neben der technischen Fragestellung ist die ökonomische Vertretbarkeit dieses Konzeptes zu berücksichtigen. Derzeit ist der Aufwand der Brennstoff-Aufbereitung auf „Flugstromtauglichkeit" umstritten; belastbare Bewertungen liegen noch nicht vor. Ungeachtet dessen gelten für die Gaskonditionierung und Synthese die gleichen Aussagen wie für das 500 MW-Konzept.

Additiv oder alternativ könnte auch die Anbindung an eine bestehende Raffinerie zur Produktaufbereitung sinnvoll sein. Dieser Lösungsansatz würde allerdings eine entsprechende Veränderung der administrativen Vorgaben erfordern.

8 Schlussbetrachtung

Ziel der Untersuchung ist es, die Vergasung biogener Festbrennstoffe in Bezug auf die Erzeugung von Synthesegasen zur FT-Synthese zu analysieren. Ausgehend davon können Konzepte zur Bereitstellung flüssiger Bioenergieträger identifiziert werden. Diese Analyse zeigt, dass

- Anlagen zur FT-Synthese auf der Basis fossiler Energieträger zwar erfolgreich großtechnisch betrieben werden, diese technischen Lösungen aber nicht problemlos auf die bei einer Biomassevergasung erreichbaren Leistungen und Anforderungen übertragbar sind,
- die Anforderungen, die von der FT-Synthese an die Synthesegaseigenschaften gestellt werden, in Bezug auf die Gasreinheit sehr hoch sind und von den bisher vorhandenen Vergasungsreaktoren nicht ohne weiteres erreicht werden; eine aufwändige (und damit teure) Gasreinigung ist somit zwingend notwendig,
- der benötigte Wasserstoff im Synthesegas sinnvollerweise durch eine Wasserdampfvergasung oder eine Vergasung mit Dampf-Sauerstoff sichergestellt werden sollte,
- die Biomassevergasung sinnvollerweise mit Bewegtbettvergasern oder mehrstufigen Verfahren realisiert werden sollte; hier liegen die meisten Erfahrungen vor und die benötigten thermischen Leistungen sind erreichbar.

- Ausgehend davon lassen sich Gesamtkonzepte einer Bereitstellung von FT-Diesel aus biogenen Festbrennstoffen ableiten, die einen technisch sinnvollen und ggf. wirtschaftlich darstellbaren Anlagenbetrieb ermöglichen könnten:
- Allotherme Vergasung biogener Festbrennstoffe im Leistungsbereich 20 bis 100 MW_{BWL} mit Wasserdampf als Vergasungsmittel, Verzicht einer CO_2-Abtrennung und Restgasnutzung der FT-Synthese mittels Gasturbine.
- Autotherme Vergasung biogener Festbrennstoffe (ggf. nach Veredlung) mit Leistungen über 500 MW_{BWL} mit einem Wasserdampf-Sauerstoff-Gemisch als Vergasungsmittel, CO_2-Abtrennung und Rezirkulationsbetrieb.

Zur erfolgreichen technischen Umsetzung derartiger Konzepte ist es zwingend notwendig, sowohl die Vergasung als auch die Gasreinigung und die anschließende FT-Synthese in Bezug auf die chemischen, physikalischen und technischen Grundlagen als auch im Hinblick auf deren verfahrenstechnische Umsetzung – und insbesondere die Kopplung der einzelnen Systemelemente – vertieft zu untersuchen. Ausgehend davon müssen entsprechende Pilot- und Demonstrationsvorhaben, die von unabhängiger Seite wissenschaftlich zu begleiten sind, realisiert werden, bei denen verschiedene technische Ansätze untersucht werden sollten. Nur dann besteht die begründete Hoffnung, dass die FT-Synthese zukünftig einen energiewirtschaftlich relevanten sowie umwelt- und klimaverträglichen Beitrag zur Deckung der Kraftstoffnachfrage in Deutschland und Europa wird leisten können und die Vorgaben der European Biofuel Directive erfüllt werden können.

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