Rapport SGC 240

Gasification

- Status and technology

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Cover picture: The gasification plant in Oberwart, Austria.

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SAMMANFATTNING

Rapporten behandlar förgasnings- och gasreningstekniker för biobränslen. Syftet med förgasning är att förädla bränslet så att det kan användas för effektiv el- och värmeproduktion, som drivmedel eller som insatsråvara i industriella processer. Fokus ligger på framställning av syntesgas som kan användas för produktion av drivmedel samt gas som kan användas för kraftvärmeproduktion. Beroende på användningsområde är olika förgasartyper, förgasningstekniker och process-betingelser aktuella.

Vid framställning av syntesgas från biobränslen har två förgasningstekniker identifierats som lämpliga, i huvudsak beroende på att de ger en gas ut från förgasaren som är fri från kväve; **Indirekt förgasning** och **Trycksatt syrgasblåst förgasning**

Vid framställning av gas för kraftvärmeproduktion finns det inget krav på att gasen ska vara fri från kväve och för sådana tillämpningar är även **Luftblåst förgasning** aktuell.

När det gäller gasrening är det, i första hand, hantering av tjäror och svavel som utgör utmaningen. Här finns det olika koncept och alternativ. Några bygger på konventionell teknik med färdigutvecklade komponenter som finns kommersiellt tillgängliga, medan andra, mer fördelaktiga lösningar, kräver fortsatt utveckling.

Rapporten tar även i viss mån upp omvandling (syntetisering) av syntesgas till syntetiska bränslen/drivmedel.

Det pågår omfattande forskning och utveckling av förgasningsteknik på såväl nationell som internationell nivå. Även om många processkoncept och del-komponenter har demonstrerats så finns det fortfarande ingen fullskalig anläggning för framställning av syntetiska bränslen/drivmedel baserad på biobränslen. De projekt som kommit längst är:

- EU-projektet *Bio-SNG*. Framställning av metan som drivmedel via förgasning av träflis har demonstrerats i Güssing, Österrike. Anläggningen är baserad på indirekt förgasningsteknik. Förgasaren är på 8 MW_{th} medan metaniseringsenheten har en kapacitet på 1 MW. I direkt anslutning till anläggningen har en tankstation för metan byggts. Den invigdes den 24 juni 2009.
- Inom GoBiGas-projektet planeras det för en anläggning i industriell skala i Göteborg. I en första etapp byggs en anläggning på 20 MW, baserad på indirekt förgasning. Förgasningstekniken kommer från Repotec medan tekniken för gasrening och metanisering kommer från Haldor Topsøe. I en andra etapp planeras ytterligare en anläggning på 80-100 MW. Projekt-ägare är Göteborg Energi AB.

- Choren med sin patenterade Carbo-V®-process har byggt en 45 MW_{th} anläggning (Beta-anläggning) för framställning av syntetisk diesel via Fischer-Tropsch-syntes. Dessvärre kom Choren Group på obestånd och advokatfirman Kübler utsågs till konkursförvaltare. Intentionen var att antingen omstrukturera företaget eller att sälja det till en investerare. Februari 2012 köpte Linde Engineering Dresden GmbH Carbo-V® teknologin från konkursförvaltaren Dr. Bruno M. Kübler.
- I Piteå har svartlut förgasats i en pilotanläggning på 3 MW_{th} vid Energitekniskt Centrum (ETC). Tekniken har utvecklats av Chemrec. Testerna från pilotanläggningen har fallit väl ut och en produktions-anläggning där syntesgas syntetiseras till DME har byggts. Kapaciteten är 4-5 ton DME/dygn. Syntetiseringen görs med teknik från Haldor Topsøe. Volvo har 10 lastbilar som går på bio-DME i fältprov och Preem har byggt fyra tankstationer för DME. Det planerades även för en anläggning i industriell skala vid bioraffinaderiet Domsjö Fabriker i Örnsköldsvik. Anläggningen beräknades få en kapacitet på 100 000 ton/år men ägaren till Domsjö Fabriker, Aditya Birla Group har bestämt sig för att lägga ner projektet på grund av osäkerhet kring de långsiktigt politiska förut-sättningarna för gröna drivmedel.

Vidare finns det anläggningar som via förgasning av biobränslen producerar el och värme med gasmotorer eller förser industriella processer med ett rent bränsle. Kravet på bränslet är inte lika stort vid stationär drift som vid framställning av drivmedel för fordon och därför är även luftblåsta förgasare aktuella:

- Harboøre, Danmark. Luftblåst uppströmsförgasare (updraft) med tjär-avskiljning tillverkad av Babcock & Wilcox Vølund. Anläggningen är på 3,5 MW_{th}. Produktgasen används för elproduktion i två gasmotorer från Jenbacher.
  Elverkningsgraden, η_{el} uppmättes till 27-29 % vid prestandaprov.
- Lahti, Finland. Luftblåst CFB-förgasare, med en kapacitet på 40-70 MW_{th}, där den producerade gasen förbränns tillsammans med pulveriserat kol i en panna. El och värme produceras via konventionell ångteknik (ångdata 540 °C och 170 bar).
- Skive, Danmark. Luftblåst BFB-förgasare med tjärkracker och elproduktion via tre gasmotorer (Jenbacher). Carbona (Finland) står för förgasningsteknologin.
  Anläggningen är på 20 MW_{th} och 6 MW_{el} (η_{el} = 32 %).
- Oberwart, Österrike. Indirekt förgasning och elproduktion via två gasmotorer (Jenbacher) och en ORC (Organic Rankine Cycle). Anläggningen är på 8,5 MW_{th} och 2,8 MW_{el} (η_{el} = 32 %).
- Värö Bruk, Sverige. CFB-förgasare på 28 MW_{th} levererad av Götaverken (numera Metso Power). Har varit i drift sedan 1987. Råvaran utgörs av bark och den producerade gasen används för att ersätta olja i mesaugnen.

Byggandet av anläggningar i kommersiell skala, för produktion av syntetiska bränslen/ drivmedel eller för el- och värmeproduktion från biobränsle, är behäftat med både tekniska och ekonomiska risker.

Faktorer som påverkar är val av teknik, anläggningens storlek, driftbetingelser, möjlighet till processintegrering, tillgång till råvara, avsättningsmöjligheter, styrmedel etc.

Ökad konkurrens om biobränslen leder ofrånkomligen till en högre råvarukostnad. Detta i sin tur innebär att drivmedelskedjor med hög verkningsgrad, såsom biometan via förgasning och metanisering, gynnas. Ju lägre investeringskostnad, desto lägre ekonomisk risk. Detta talar för att tekniker som är relativt kostnadseffektiva i den mindre skalan, initialt kan komma att gynnas. I takt med teknikutveckling och erfarenhetsuppbyggnad lär anläggningarnas storlek öka.

SUMMARY

In this report gasification and gas cleaning techniques for biomass are treated. The main reason for gasifying biomass is to refine the fuel to make it suitable for efficient CHP production, as vehicle fuel or in industrial processes. The focus is on production of synthesis gas that can be used for production of vehicle fuel and for CHP production. Depending on application different types of gasifiers, gasification techniques and process parameters are of interest.

Two gasification techniques have been identified as suitable for syngas generation, mainly due to the fact that they allow the production of a nitrogen free gas out of the gasifier; **Indirect gasification** and **Pressurized oxygen-blown gasification**

For CHP production there are no restrictions on the gas composition in terms of nitrogen and here air-blown gasification is of interest as well.

The main challenge when it comes to gas cleaning is related to sulphur and tars. There are different concepts and alternatives to handle sulphur and tars. Some of them are based on conventional techniques with well-proven components that are commercially available while others, more advantageous solutions, still need further development.

The report deals to a minor extent with the conversion of syngas to synthetic fuels.

The ongoing research and development of gasification techniques is extensive, both on national and international level. Although many process concepts and components have been demonstrated, there is still no full-scale plant for the production of synthetic fuels based on biomass. The projects that have reached furthest are:

- The EU-project *Bio-SNG*. Production of biomethane as vehicle fuel through gasification of wood chips has been demonstrated in Güssing, Austria. The plant is based on indirect gasification. The gasifier has a capacity of 8 MW_{th} while the methanation unit has a capacity of 1 MW. A filling station for biomethane, inaugurated 24 June 2009, has been built in direct vicinity of the plant.
- In the GoBiGas-project an industrial scale plant, 20 MW in a first stage, is under construction, in Gothenburg. The gasification technology is provided by Repotec and the gas cleaning and methanation technology by Haldor Topsøe. In a second stage an 80-100 MW plant is planned. Gothenburg Energy is the stakeholder.
- Choren with its patented Carbo-V® process has built a 45 MW_{th} plant (the Beta plant) for production of synthetic diesel through Fischer-Tropsch

synthesis, in Freiberg, Germany. Unfortunately the company encountered insolvency problems. The law firm Kübler was appointed insolvency administrator. The intention was to restructure the Choren Group through an insolvency plan or through a sale of the group to an investor. In February 2012 Linde Engineering Dresden GmbH acquired the Carbo-V® technology of the insolvency administrator Dr. Bruno M. Kübler.

- In Piteå black liquor has been gasified in a pilot plant, 3 MW_{th}, at Energy Technology Centre (ETC). The technology is developed by Chemrec. The tests in the pilot plant have been successful and a plant where the syngas is synthesised to DME has been built. The capacity is 4-5 tonnes DME/day. The synthetisation technology is provided by Haldor Topsøe. Volvo has 10 bio-DME trucks in field tests and Preem has built four filling stations for DME. An industrial scale plant, with a capacity of 100,000 tonnes/year, was planned to be built at the biorefinery Domsjö Fabriker in Örnsköldsvik. However, the owner of Domsjö Fabriker, Aditya Birla Group, has decided not to continue with the project. The main reason is the insecurity related to long term political conditions for green transport fuels.

Furthermore, there are plants that, through gasification of biomass, produce electricity and heat or provide industrial processes with a clean fuel. The gas composition is normally not as critical in stationary applications as in the production process of synthetic fuels for the transportation sector and therefore airblown gasification is of interest as well:

- Harboøre, Denmark. Airblown updraft gasifier with tar separation supplied by Babcock & Wilcox Vølund. The plant has a capacity of 3.5 MW_{th}. The product gas is used for electricity production in two gas engines supplied by Jenbacher.
  The measured electric efficiency, η_{el} was 27-29 % in the performance test.
- Lahti, Finland. Airblown CFB-gasifier, with a capacity of 40-70 MW_{th}, where the produced gas is combusted together with pulverized coal in a boiler. Electricity and heat are produced through the conventional steam cycle (admission data 540 ˚C and 170 bar).
- Skive, Denmark. Airblown BFB-gasifier with a tar cracker and electricity production through three gas engines (Jenbacher). Carbona (Finland) has provided the gasification technology.
  The plant is designed for a capacity of 20 MW_{th} and 6 MW_{el} (η_{el} = 32 %).
- Oberwart, Austria. Indirect gasification and electricity production through two gas engines (Jenbacher) and an ORC (Organic Rankine Cycle). The plant has a capacity of 8.5 MW_{th} and 2.8 MW_{el} (η_{el} = 32 %).
- Värö Bruk, Sweden. The CFB-gasifier with a capacity of 28 MWth was delivered by Götaverken (now Metso Power). The plant has been in operation since 1987. Bark is used as feedstock and the produced gas is used as oil replacer in the lime kiln.

The building of commercial scale plants for production of synthetic fuels or CHP through gasification of biomass is associated with technical and economical risks

Factors affecting the choice of technology are plant size, operating conditions, the possibility for process integration, access to feedstock, market aspects, incentives and economic instruments etcetera.

Increased competition for biofuels will inevitably lead to higher raw material costs. This in turn means that the fuel chains with high efficiency, such as biomethane through gasification and methanation, are favored. The lower the investment cost, the lower the financial risk. This implies that techniques that are relatively cost-effective in the smaller scale may benefit initially. As the technology develops and experience is built up the plant size will increase.

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1. INTRODUCTION

This report is done by the Swedish Gas Centre (SGC).

The report is a result of the technology surveillance SGC conducts in terms of visits at pilot, demonstration and reference plants, literature studies, participation in different expert and reference groups, scientific committees, editorial boards, reviews, seminar and conference activities as well as information gathered through the network that SGC systematically has built up within the field of gasification.

The report is by no means comprehensive and should more be regarded as a documentation of the technology development that SGC has come in contact with in recent years.

1.1 TERMINOLOGY

There are a large number of specific terms and abbreviations within the field of gasification. Sometimes there is no clear definition and the expressions and terms are used with different meaning. Below a number of expressions and abbreviations are listed including which meaning put in to them in this report.

Biofuel	A fuel that originates from biomass. The material the fuel is made up of may has been altered chemically or biologically and originally had another use.
Biomass	Material of biological origin that hasn't, or only to a minor extent, went through chemical or biological conversion.
Biomethane	A gas or a gas mixture that mainly consists of methane and is produced from biomass/biofuel.
Bio-SNG	A gas with a quality that can substitute natural gas. The prefix ”bio”, indicates that the gas has been produced from renewable resources (biomass).
BFB	Bubbling fluidized bed. The bed, consisting of fuel and bed material (normally sand), is fluidised by means of air or steam moving up through the bed with a velocity high enough to hold the bed in suspension.

CFB	Circulating fluidized bed. Due to the high fluidization velocity fuel particles and bed material are entrained and leave the gasifier together with the product gas. The entrained fuel particles and bed material are separated in a cyclone and returned to the bed.
CHP	Combined heat and power. By taking advantage of the heat generated within the thermo-chemical process a high total efficiency is achieved.
DME	Dimethyl ether. Chemical composition CH_3OCH_3.
FT (Fischer-Tropsch)	The FT-process was invented by Franz Fischer and Hans Tropsch in the 1920-ies. Through catalytic reactions the synthesis gas is converted to alkanes (paraffins) and alkenes (olefines).
Gasification	Thermochemical conversion of the bio-mass/biofuel into a gas in the presence of an external oxidizing agent (gasification medium).
IGCC	Integrated gasification combined cycle. The gas produced in the integrated gasifier is combusted in the combustion chamber of the gas turbine. The heat in the hot exhaust gas leaving the gas turbine is then used in a steam cycle.
Pyrolysis	Thermochemical conversion of the bio-mass/biofuel in the absence of oxidizing agents.
RME	Rapeseed methyl ester.
SNG	Substitute Natural Gas (sometimes referred to as Synthetic Natural Gas or Sustainable Natural Gas). A produced gas of natural gas quality. May be produced through gasification and methanation of lignite coal. Bio-SNG indicates that biomass/biofuel has been used as feedstock.
Synthesis gas (syngas)	A gas consisting of hydrogen, H_2, and carbon monoxide, CO.

1.2 ADVANTAGES WITH GASIFICATION

Gasification is a way to increase the quality and value of the feedstock. Biomass with a low or even negative heating value can through gasification be converted into a high quality fuel that can be used in the transportation sector, for efficient heat and power production or as a raw material in chemical processes.
The conversion of solid biofuels and waste to gaseous fuels is associated with several advantages

- Gaseous fuels admit grid distribution and access to the markets that have been built up by natural gas.
- The control and regulation of the combustion process is simpler with fuels in the gas phase.
- Clean combustion of the gas. It is advantageous to purify the product gas from the gasifier compared to the flue gas from a solid biofuel plant because of the smaller volume of gas (the flue gas contains a high proportion of nitrogen).
- Gaseous fuels take advantage of the high electric efficiency of gas engines and gas turbines compared to the conventional steam cycle.
- The gas, in particular syngas, can be used for production of transportation fuels or in chemical products like ammonia, fertilizers, plastics, paints etc.

1.3 CHOICE OF GASIFICATION TECHNOLOGY

In this report different types of product gas out of the gasifier are treated. The choice of gasification technology and process parameters is dependent on the desired final product.

- For synthetisation of the syngas to other hydrocarbons than methane, e.g. methanol, DME and FT-diesel a syngas free of nitrogen and methane is desired. Nitrogen may be avoided through oxygen-blown gasification. High gasification temperature, > 1000 ˚C, implies that both tars and methane are cracked resulting in high levels of H and CO in the gas. It is H and CO that takes part in the synthetisation. The lower heating value of the syngas is normally approx. 20 MJ/ Nm^3.
- For synthetisation to methane a syngas free of nitrogen but with as high as possible level of methane is desired. Synthetisation to methane is an exothermic process and the less amount of syngas that has to be synthesised the more efficient is the process. Low gasification temperature, < 850-900 ˚C, contributes to high levels of methane in the gas formed in the gasifier.
- For heat and power generation there are no requirements of a gas free of nitrogen and normally air-blown gasifiers are used. The lower heating value of the gas leaving the gasifier is then normally approx. 5 MJ/Nm^3 due to the dilution of nitrogen[1].

2. DESCRIPTION OF DIFFERENT GASIFIERS AND GASIFICATION TECHNOLOGIES

There are many different types of gasifiers and gasification technologies and they can be categorized and named in different ways. In this chapter various gasifiers and gasification technologies are treated on a fairly general level.

2.1 FIXED BED GASIFIER

Fixed bed gasifiers where the fuel bed rests on a grate can be subdivided into different categories of which two are treated here; downdraft and updraft reactor.
In both cases the fuel is fed into the top of the reactor while the product gas leaves the reactor at the bottom in a downdraft reactor and at the top in an updraft reactor. The fuel in the bed moves down due to gravity at the same rate as the fuel is ”consumed”. The retention time for the fuel is long and the gas velocity low. The fuel should have a certain coarseness to ensure a homogeneous gas distribution in the reactor. An uneven gas distribution may result in lower carbon conversion in certain zones of the reactor and overheating in others.

Producer gas units used during World War II were often downdraft reactors. Swedish inventors[2] like Källe and Hedlund contributed to the development of wood based producer gas units. Although the technology was refined and further developed, almost all units were taken out of operation as soon as the war ended and gasoline became available again.

2.1.1 Downdraft gasifier

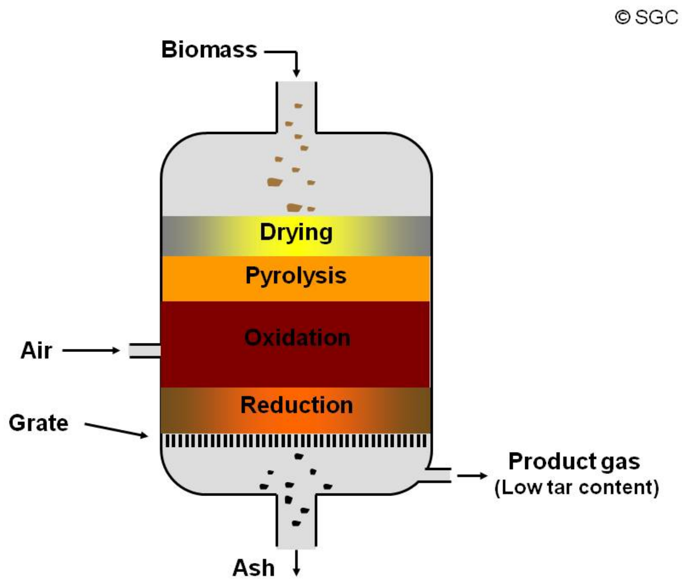

Figure 1. Schematic picture a fixed bed gasifier of downdraft type.

In a downdraft gasifier also referred to as co-flow gasifier the fuel is fed into the top of the gasifier and the product gas leaves the reactor in the bottom.

The advantage of a downdraft gasifier is the relatively low level of tars in the product gas leaving the gasifier. Since the gas formed in the gasifier has to pass through the hot zone the tars are cracked. At part load the temperature in the gasifier decreases and the levels of tars in the product gas increases. At high load the tar levels are low but the amount of ash particles entrained by the product gas increases due to the higher gas velocity. The product gas leaving the gasifier has a relatively high temperature (approx 700 ˚C), resulting in a low efficiency.

2.1.2 Updraft gasifier

In an updraft gasifier also referred to as counter-flow gasifier the fuel is fed into the top and air into the bottom of the gasifier. The product gas leaves the reactor in top.

In an updraft gasifier it's inevitable that high levels of tars are formed. VTT and BIONEER in Finland performed extensive tests in the middle of the 80-ies regarding tar levels for different types of feedstock[3]. For woodchips tar levels of 50 – 100 g/Nm^3, were obtained which may be compared to the tar levels in a downdraft gasifier which is in the order of 500 – 1000 times lower. An advantage of the updraft gasifier is that it's not so sensitive to high levels of moisture in the feedstock since the fuel fed into the gasifier is dried by the outgoing product gas. As a result updraft gasifiers have in general a high efficiency.

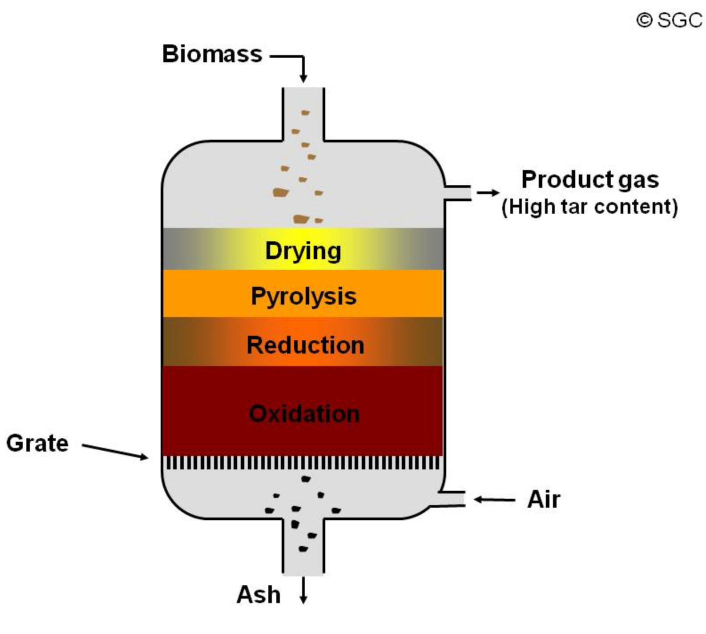

Figure 2. Schematic picture over a fixed bed gasifier of updraft type.

Independent of type, e.g updraft or downdraft gasifier, fixed bed gasifiers are not suited for upscaling due to the risk for uneven gas distribution and streak formation in the bed. Frontline Bioenergy mentions 1 – 1.5 MW as a practical upper size for downdraft gasifiers. When it comes to updraft gasifiers there are plants of a size of 4 – 6 MW_{th}. BIONEER delivered 8 plants with a thermal capacity of 4 – 5 MW to Sweden and Finland in the middle of the 80-ies. FosterWheeler built a 6.4 MW plant in Ilomantsi, Finland in 1996.

Table 1. Characteristics of fixed bed gasifiers[4]

	Downdraft gasifier	Updraft gasifier
Fuel		
- Moisture content (% wet fuel)	12 (max 25)	43 (max 60)
- Ash content (% wet fuel)	0,5 (max 6)	1,4 (max 25)
- size (mm)	20-100	5-100
Product gas exit temperature (˚C)	700	200-400
Tar level (g/Nm^3)	0,015-0,5	30-150
Turn down ratio[*]	3-4	5-10

2.2 ENTRAINED-FLOW GASIFIER

In an entrained-flow gasifier solid particles, atomised liquid fuel or a fuel-slurry are gasified in a co-flow arrangement. The gasification reactions take place in a thick cloud of very fine particles/droplets. High temperature and high pressure admits a high reactor load. The gasifier is referred to as a slagging or non-slagging reactor dependent on if it operates above respectively below the ash melting temperature of the feedstock.

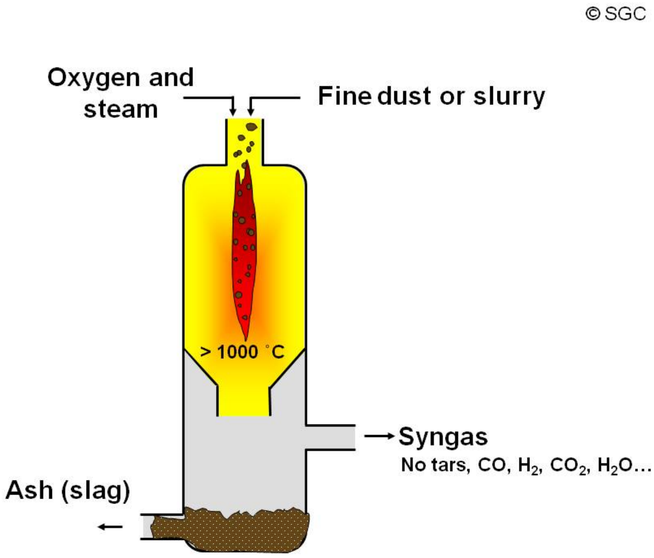

Figure 3. Schematic picture of an entrained-flow gasifier

If the temperature exceeds the ash melting temperature the ash leaves the gasifier in form of molten slag. High gasification temperature is required when coal is used as fuel, due to the low reactivity of coal. Biofuels have a high reactivity which is beneficial for gasification at lower temperatures. The energy needed to generate a powder fine enough to be suited for suspension gasification with biomass as feedstock is significant. Biofuels have a high porosity and water

[*] Turn down ratio: The ratio of the maximum output of a gasifier to its minimum output.

holding capacity which makes them unsuitable for slurry feeding, which is common in commercial pressurized suspension gasification of coal.

Black liquor gasification is a special case since "the fuel" is already dissolved in the spent cooking liquor. High reactor temperature and presence of alkali metals in black liquor gasification is beneficial for formation of hydrogen and carbon monoxide while the formation of methane is suppressed, se table 2.

Table 2. Gas composition[5] (recalculated to volume nitrogen free gas) in black liquor gasification, pressure 29 bar, fuel feeding 650 kg/h.

Gas composition	Vol-%
H_2 (hydrogen)	43 %
CO (carbon monoxide)	30 %
CO_2 (carbon dioxide)	27 %
CH_4 (methane)	1 %
H_2S (hydrogen sulfide)	1,4 %

A low level of methane is beneficial if the desired final product is any hydrocarbon other than methane. If the desired final product is methane a low level of methane in the gas leaving the gasifier is disadvantageous since it implies that more hydrogen and carbon monoxide has to be synthesised to methane in the subsequent methanation unit. Since methane formation is an exothermic process heat is produced. If the heat can't be utilized it results in a low overall efficiency.

2.3 FLUIDIZED BED GASIFIER

In a fluidized bed gasifier the fuel and the bed material is fluidised by an oxidizing agent. By introducing the oxidizing agent (e.g. air, oxygen, steam or any combination of these) from below the bed expands in the vertical direction. Dependent on the velocity of the oxidizing agent a bubbling fluidized bed (BFB) or circulating fluidized bed (CFB) is obtained.

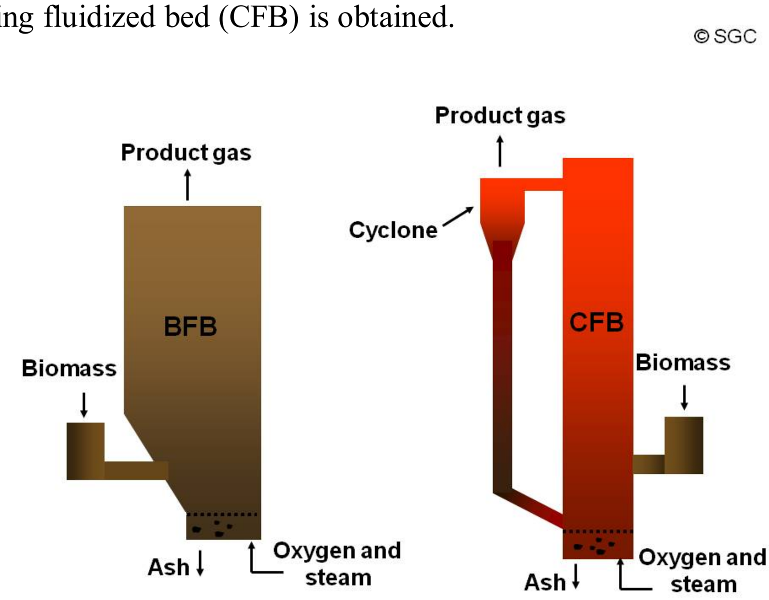

*Figure 4. Schematic picture of a bubbling fluidized bed gasifier (**BFB**) to the left and a circulating fluidized bed gasifier (**CFB**) to the right.*

In a circulating fluidized bed the velocity of the oxidizing agent is so high that fuel particles and bed material are entrained and leave the reactor together with the product gas. The particles are separated in a cyclone and returned to the gasifier. The bed material contributes to a more even temperature distribution and stable operation. The bed material may be inert (e.g. quartz sand) or to some extent have a catalytic behaviour (e.g. olivine[6]). Fluidized beds are relatively insensitive to ash content and fuel specifications[7].

Fluidized bed gasifiers exist in a large number of types, oxygen-blown, air-blown, atmospheric and pressurized. In Integrated Gasification Combine Cycle (IGCC) plants where the product gas is feed into the combustion chamber of the gas turbine at elevated pressure (10-25 bar) it's beneficial with pressurized gasification since in atmospheric gasification the product gas has to be cooled down and then compressed which results in a high internal energy consumption. On the other side pressurized gasification is associated with an increased complexity in terms of fuel feed-in and gas cleaning at high temperatures.

Fluidized beds are well suited for up-scaling.

2.4 INDIRECT GASIFICATION

In double or twin bed gasifiers the combustion takes place in a separate reactor and heat is transferred to the gasifier through circulation of hot bed material, so called indirect gasification. Gasifiers for indirect gasification exist in different versions and of different design. The biofuel is fed into the gasifier where it, in contact with the hot bed material from the combustion reactor, undergoes thermo-chemical decomposition. Bed material and char are transferred from the gasifier to the combustion reactor. The char is combusted in air in the combustion reactor and the bed material is heated up again.

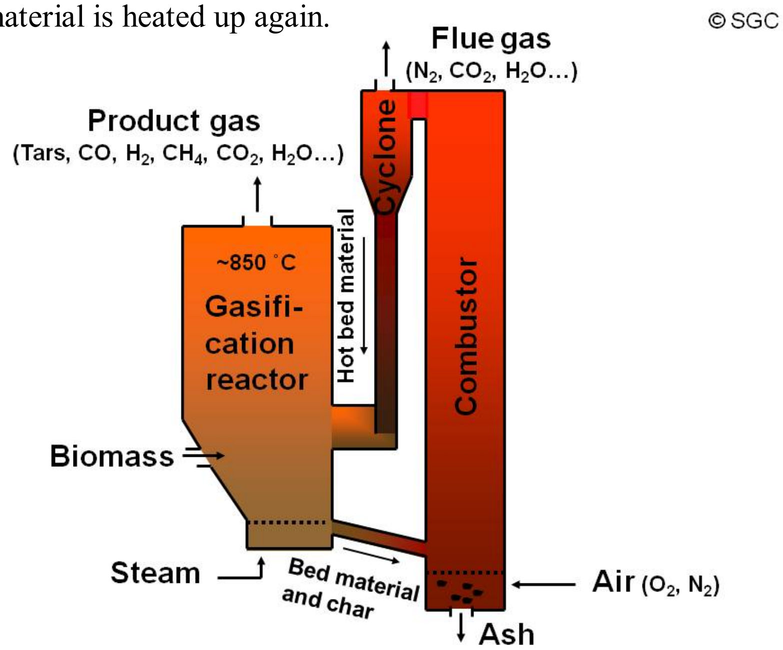

Figure 5. Schematic picture of a double bed gasifier (indirect gasification) corresponding to the gasifier in Güssing, Austria.

One of the advantages with this type of gasifier is that a gas free of nitrogen and with a relatively high heating value is obtained.

The temperature in the gasifier is limited to levels that are below the temperature of the combustor and this may cause problems regarding tar destruction. To achieve sufficient conditions for tar cracking in the gasification reactor a surplus of steam or oxygen may be added. The tars may also be cracked catalytically.

In the Güssing plant the gas is cooled down after the gasifier and the tars are separated by means of an Rapeseed Methyl Ester (RME) scrubber. The separated tars are transferred to the combustion reactor where they are combusted and the energy content recovered.

There are different types of indirect gasifiers. In Güssing the combustion reactor is of CFB-type and the gasification reactor of BFB-type. The gasification technology is commercialized for heat and power production and demonstrated for SNG production.

The Future Energy Resources (FERCO) markets another type, named Silvagas™, developed at Batelle Columbus Laboratories, consisting of two CFB-reactors. The gasification technology has been demonstrated in a 40 MW plant in Burlington, Vermont, USA. The gas is co-combusted with coal in an existing furnace.

Energy Research Centre of the Netherlands (ECN) has developed another type, MILENA, with a combustion reactor of BFB-type and a gasification reactor (riser) of CFB-type. The gasification technology has been tested in both lab-scale, 25 kW, and pilot-scale, 800 kW, at ECN.

A fourth type is the Blue Tower-concept with three moving beds, one for pyrolysis of biomass, one for steam reforming of the pyrolysis gas and one for the combustion of char remaining after the pyrolysis. The flue gases from the combustion reactor heat up ceramic heat carriers which in turn supply heat to the reforming and pyrolysis reactors. The Blue Tower-concept distinguish itself through the separation of pyrolysis and steam reforming in two separate reactors while these processes take place in the same reactor in the other variants. The Blue Tower-concept is also referred to as a staged reforming process. The technology has been tested in a 1 MW pilot plant. A 13 MW plant is under construction in Herten, Germany.

In Gothenburg, Sweden the Chalmers 8 MW_{th} CFB-boiler has been supplemented with a 2 MW_{th} gasification reactor. The gasifier was supplied by Metso Power and financed by Göteborg Energi AB. It's beneficial to take advantage of an existing CFB-boiler to keep the investment cost down and limit the economical risk. The rebuilding went very quick. From the start of construction in July 2007 it took only six months until the first measuring campaign could be conducted[8].

The plant is equipped with extensive measuring devices related to gas analysis and measurements of pressure and temperature. Generally speaking the thermal capacity of the gasifier may be as high as the one of the CFB-boiler (which then has to be fed with the corresponding amount of additional fuel) under the conditions that there are no practical limitations regarding increased fuel feeding capacity, load on heat transferring surfaces, placing of superheaters etcetera.

2.5 MULTISTAGE GASIFICATION

From an efficiency point of view it is desirable with as low temperature as possible of the product gas leaving the gasifier at the same time as tar destruction requires high temperatures. By separating the gasification process in different stages in a clever way there is a possibility to combine these two apparently contradictory conditions.

There are different types of multistage gasifiers out of which the DTU two-stage gasifier (the Viking gasifier) and the Choren CarboV®-process are presented here.

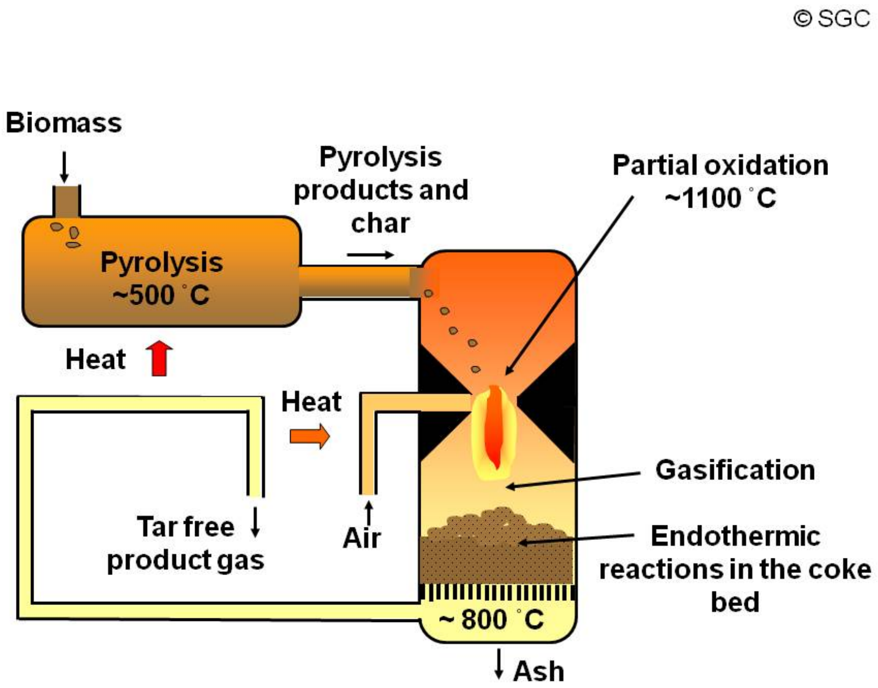

Figure 6. Schematic picture of a two-stage gasifier corresponding to the Viking gasifier developed at DTU in Denmark.

The principle of the Viking gasifier is illustrated in Figure 6. The biofuel is dried and undergoes pyrolysis through external heat supply. The heat is taken partly from the hot product gas, partly from the exhaust gas of the gas engine (not shown in the picture) in which the product gas is used.
The pyrolysis products and the remains (mainly char) are fed into the gasifier together with a certain amount of preheated air. Through partial oxidation the temperature is increased from approx 500 ˚C to approx 1 100 ˚C and the tar levels decreases from approx 50 000 mg/Nm^3 to 500 mg/Nm^3. When the gas has passed through the hot char bed where endothermic reactions take place the tar levels are lower than 5 mg/Nm^3. Particles are removed by baghouse filters and the water by condensation (not shown in the picture).

Table 3. Data for the Viking gasifier (Source prof. Ulrik Henriksen, DTU, 2008).

Thermal capacity	70 kW_{th}
Gasification efficiency	93%
Electric efficiency gas engine	27%
Electric efficiency for the system	25%
Accumulated hours of operation	3 600 h
Commissioned	August 2002

The Viking gasifier is fully automated and is run without any operator. Since the gasifier is air-blown the product gas contains nitrogen and is not suited for synthetisation.

The DTU two-stage gasification concept has been scaled up in cooperation with COWI and Weiss A/S[9]. The plant capacity is 600 kW_{th}/200kW_{el}. With further development and up-scaling an electric efficiency of 38% and an overall efficiency of 98% for the system is expected. The high overall efficiency is based on the lower heating value and heat recovery of the water vapor in the exhaust gas out from the gas engine.

Choren Industries in Germany has developed and patented a three-stage gasification process, Carbo-V®[10].

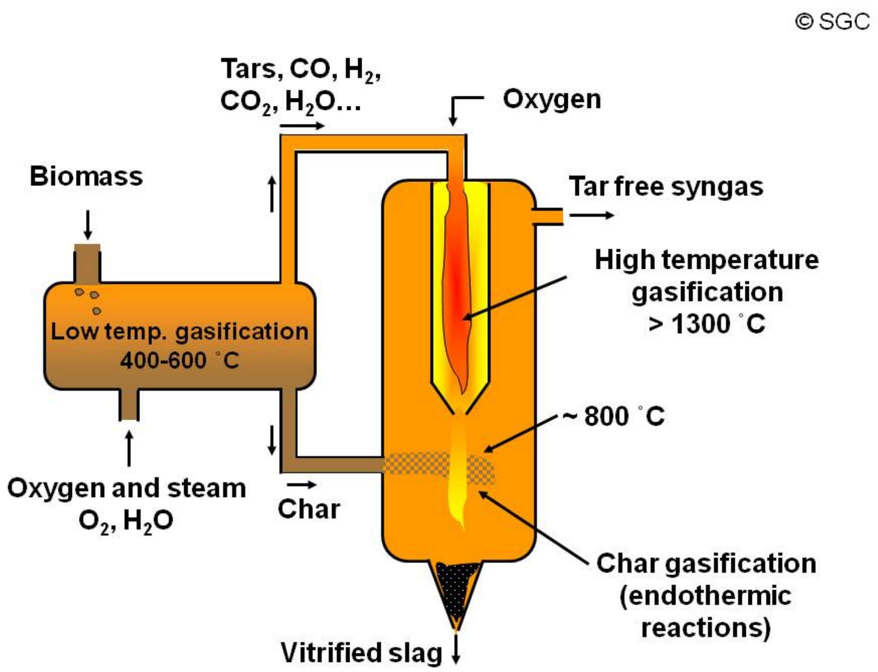

Figure 7. Simplified schematic picture of the Choren three-stage gasification process.

The biomass is gasified at low temperature and the volatile components are separated from the char. A mixture of oxygen and steam is used as oxidizing agent in the low temperature gasifier. The volatile constituents are oxidized in the high temperature gasifier. Due to the high temperature, approx. 1 300 ˚C, the tars are thermally cracked. The hot gas products are cooled through the endothermic reactions that take place in contact with the char bed. Since none of the three gasification steps (low temperature, high temperature and char gasification) are air-blown nitrogen is avoided in the raw synthesis gas coming out of the gasifier.

The raw synthesis gas is cleaned and synthesised through the FT-process to Diesel. The produced fuel is trademarked as SunDiesel® by Choren and a 45 MW_{th} plant (Beta plant) has been built.

3. DESCRIPTION OF DIFFERENT GAS CLEANING CONCEPTS

There are a number of different gas cleaning concepts and techniques but common for them all is the removal of substances that may compromise the function (e.g. catalyst deactivation or poisoning) and the life time of the components used downstream of the gasifier and to ensure the required quality of the final product.

Many concepts are based on advanced and extensive gas cleaning while others are based on development of components that are more durable and robust.

3.1 HIGH TEMPERATURE FILTER

In cyclones the gas is forced to rotate and particles are separated due to centrifugal forces. In this way more than 90% of particles with a size larger than 5 µm (micrometer) are separated[4,11]. Some particles with a size in the interval 1-5 µm are most likely separated as well.

Cyclones are often placed in a series where the first cyclone separates the largest particles and subsequent cyclones separate smaller and smaller particles. As mentioned before, cyclones are not able to separate small particles (< 1 µm), which implies that tar droplets of a size smaller than 1 µm passes through as well. Tars in gaseous phase will pass through the cyclones together with the product gas. One alternative would be to cool down the gas but the stickyness of the condensed tars in combination with particle separation implies an imminent risk for clogging.

Barrier filters made of porous material permit gases to pass but prevents particles. In principle, the barrier filter can be designed to remove any particle size, including submicron particles but the pressure difference across the filter increases with decreasing pore size. Technical and economic considerations provide a limit at about 0.5 microns in systems that handle high gas flows, such as gasifiers[12]. The technology that looks most promising for separation of particles at high temperature[13] involves ceramic filters, known as ceramic candle filters, where the candle refers to the filter's geometric shape (cylindrical and elongated like a candle).

In an extensive large study[14] conducted by Siemens Westinghouse Power Corporation, funded by the Department of Energy och National Energy Technology Laboratory, a large number of ceramic filters in a PCBC-plant (Pressurized Fluidised Bed Combustion) were tested. In that application gas cleaning at a temperature above 800 ˚C was demonstrated. Participating filter suppliers were among others

Coors Tek Inc. (USA) http://www.coorstek.com/
Pall Corporation (USA) http://www.pall.com/
McDermott International Inc. (USA) http://www.mcdermott.com/
Albany International Techniweave (USA)
http://www.albint.com/web/techweav/techw.nsf
Schumacher (Germany) http://www.schumacher-filters.de/ (In 2002 Schumacher was acquired by Pall Corporation and is now a part of Pall Filtersystems GmbH).

3.2 TAR SEPARATION/CRACKING

Tars can be removed from the gas in two fundamentally different ways

- physical separation, where condensed tars in the form of droplets and aerosols are removed in a similar manner to particles, and tars in the gas phase are absorbed by a solvent.
- Catalytic of thermal cracking of tars.

The use of a wet scrubber to remove tars requires that the gas temperature is 35-60 ˚C in case of a water scrubber. The tars are hydrophobic and have a low solubility in water which implies that only the aerosols are separated. By using solvents which are lipophilic, the tars in gaseous phase dissolve in the liquid and the scrubber efficiency increases. In the Güssing gasification plant RME is used as scrubbing liquid. The used, and with tars and condensate saturated, scrubbing liquid is then combusted in the combustion reactor of the plant.

Energy Research Centre of the Netherlands (ECN) has developed and patented OLGA (an acronym for oil based gas cleaning in Dutch). The OLGA-process[15] is divided in two scrubbing stages, a stage in which liquid tars are separated and another in which gaseous tars are absorbed. The liquid tars are separated from the scrubbing liquid and recycled to the gasifier. The gaseous tars that have been absorbed by the scrubbing liquid are removed in a stripper. In case of air-blown gasification air is used for the stripping. The air, containing tars, is then used as an oxidizing agent in the gasifier. Advantages with OLGA are:

- Tar dewpoint of clean product gas is below temperature of application, therefore there is no condensation of tars in the system downstream of the OLGA unit.
- Tars are removed prior to water condensation to prevent pollution of process water.
- Tars are recycled to gasifier and destructed avoiding the handling of problematic tar waste streams.

Thermal cracking is another way to reduce the levels of tars. The large hydrocarbon molecules are broken up into smaller bits. Thermal cracking takes place in gasifiers operating at high temperatures, e.g. entrained flow gasifiers operating at 1 000 ˚C or higher and in multistage gasifiers where the tar rich gas undergoes partial oxidation and is subject to high temperature > 1 000 ˚C.

Tar cracking may be obtained at significantly lower temperatures if a catalyst is present. In a literature survey[16] conducted 2002 at the National Renewable Laboratory different catalysts and their ability to crack tars are examined. The report shows that tar conversion of > 90% is obtained at temperatures in the interval of 450-900 ˚C depending on which catalyst that has been used.

Paul Scherrer Institute (PSI) and Clean Technology Universe AG (CTU) have shown in lab scale tests that a total tar conversion in the PSI combined shift and methanation reactor (bubbling bed) was obtained at temperatures around 350 ˚C. The problem was that some of the tars, thiophenes, contained sulphur and the nickel based catalyst died after approx. 200 hours due to sulphur poisoning. The problem is solved by removing the tars through an RME scrubber upstream of the shift and methanation reactor.

Nickel based catalysts are not poisoned at higher temperatures and therefore there are ideas to crack the tars directly after the gasifier or even inside the gasifier.

Bed materials containing nickel have been tested and even if the results are promising the environmental hazard with nickel in the ash and in the filters is worrying. A French research group has shown that olivine impregnated with 10 % and 20 % iron respectively give the corresponding tar destruction as olivine impregnated with nickel[17].

Another option is to build in the catalysts in ceramic candle filters integrated with the gasifier. The porous ceramic material prevents particles to be in contact with the catalyst and hence the mechanical wear of the catalyst is reduced. The risk of catalyst deactivation due to fouling and clogging is also reduced. However, the candle filter itself may experience filter blinding if a filter cake is build up on the surface of the candle filter.

3.3 SULPHUR REMOVAL

Whereas tar formation is mainly caused by the operating conditions of the gasifier and less by the composition of the biomass feedstock, for non-tar components such as sulphur and chlorine the situation is reversed. The elemental composition of the feedstock therefore determines the basic requirements for gas cleaning downstream the gasifier.

Table 4. Excerpt of from ECN[18].

Biomass	Sulphur (weight% of dry and ash free feedstock)	Chlorine (weight% of dry and ash free feedstock)
Wood, untreated	0,03	0,02
Wood, impregnated	0,17	0,11
Straw	0,15	0,48
Cow manure	0,95	1,66
RDF (Refuse derived fuel)	0,40	0,39
Municipal waste	0,50	1,13

The sulphur in the biomass is mainly released as H_2S and COS, and only in small amounts as organic sulphur (mercaptanes and thiophenes)[18]. Some gas treatment systems, like Rectisol, are able to remove COS together with H_2S, while others, in particular amine washes, require that COS is converted to H_2S for sufficient sulphur removal[19].

The capacity of processes based on physical absorption (e.g. Rectisol) is a strong function of partial pressure. At low partial pressure the physical absorption processes are not economically competitive. The boundary line between physical and chemical solvents is approximately 7 bar[18]. Processes based on physical or chemical absorption are suitable for treating high-volume gas streams containing H_2S and/or COS to below 1 ppmv. The standard technology for recovery of concentrated H_2S to elemental sulphur is the Claus process. Normally this process is operated parallel to physical or chemical absorption/desorption process like the Rectisol or alkanol amine process. In general the Claus process will be too expensive on the small scale associated with biomass applications. Even for large scale biomass gasification facilities the amounts of sulphur are limited, unless typical feedstocks like MSW, RFD, manure or sludge are applied. Alternatively to the Claus process, H_2S can easily and economically be converted to elemental sulphur by biological processes, using microorganisms. The THIOPAQ process by Paques is an example of such a biological process[18].

Sulphur can be removed by adsorption on solids. Suitable adsorbents are oxides of Fe, Mn, Zn, Cu och Ca. Solid sorption is applicable to low quantities of H_2S. Most sorbents cannot be regenerated and must be disposed after being used. Adsorption with molecular sieves is a viable option when the amount of sulphur is very low and the gas contains heavier S compounds (such as mercaptane and COS) that must also be removed. The effect on thiophenes, however is limited[18].

In Güssing activated carbon is used to remove the major part of the sulphur while a bed of ZnO takes care of the final removal.

3.4 SHIFT AND SYNTHETISATION

The ratio between hydrogen and carbon monoxide can be adjusted in a shift reactor by adding steam. The process that takes place in the shift reactor is:

$$CO + H_2O \rightarrow H_2 + CO_2$$

Depending on the final product different rations between hydrogen and carbon monoxide are desired in the synthesis step, see table 5 below.

Table 5. Synthesis reactions (excerpt from Gas Production for Polygeneration Plants by H. Hofbauer)

Synthesis	Stökiometriskt H_2/CO-ratio	Synthesis reaction
Fischer-Tropsch	2	$CO+2H_2 \rightarrow -[CH_2]- + H_2O$
Methanol	2	$CO+2H_2 \rightarrow CH_3OH$
Methanation	3	$CO+3H_2 \rightarrow CH_4+H_2O$

The synthesis reactions are governed by the choice of catalysts and process conditions. In table 6 an overview of suitable process conditions is given.

Table 6. Ranges of suitable conditions for synthesis reactions (excerpt from Gas Production for Polygeneration Plants by H. Hofbauer)

Synthesis	Catalysts	Pressure [bar]	Temperature [ºC]
Fischer-Tropsch	$Fe/Co/ZrO_2/SiO_2$	20-40	220-300
Methanol	Zn/Cr/Cu	50-300	220-380
Methanation	Ni/Mg	1-10	200-400

Fischer-Tropsch processes can be used to produce either a light synthetic crude oil (syncrude) and light olefins or heavy waxy hydrocarbons. The syncrude can be refined to environmentally friendly gasoline and diesel and the heavy hydrocarbons to specialty waxes or, if hydrocracked and/or isomerised, to produce excellent diesel fuel, lube oils and naphtha[4].

Methanol can be produced by means of catalytic reaction of carbon monoxide and some carbon dioxide with hydrogen. The presence of a certain amount of carbon dioxide in the percentage range is necessary to optimize the reaction. Both reactions are exothermic and proceed with volume contraction; a low temperature and high pressure consequently favor them[4].

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + 2H_2O$$

In the methanation unit hydrogen, carbon monoxide and carbon dioxide in the syngas are converted to methane and water according to following reactions:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Methanation normally takes place over a nickel based catalyst at a temperature of approx. 250 – 450 ˚C. The methanation process is strongly exothermic and the methanation reactor is usually cooled by internally recycled gas and heat exchangers. The strong heat release is an important reason to chose a gasification technique and process conditions that favor methane formation already in the gasification step. Then there are less amounts of hydrogen, carbon monoxide and carbon dioxide that have to be converted to methane.

The combined shift and methanation reactor developed at PSI is based on fluidized bed technology. The combined shift and methanation reactor has according to Dr. Serge Biollaz, head of the Thermal Process Engineering group at PSI shown to work at hydrogen/carbon monoxide-ratios within as broad interval as 1 to 5. The carbon management on the methanation catalyst has been studied in detail[20].

There is an ongoing development of catalysts that are more robust and less sensitive to impurities in the gas, primarily sulphur.

3.5 CONDITIONING

In the PSI methanation process the carbon dioxide is separated after the methanation using conventional technology. In Haldor Topsøe´s TREMP (Topsøe Recycle Energy-efficient Methanation Process) the carbon dioxide is removed after the shift conversion where the H_2/CO-ratio is adjusted to 3:1 but before the methanation.

A part of the separated carbon dioxide may be used as inert gas for the biomass feeding. The wet gas is dried and depending on the specifications of the final product excess hydrogen is separated. The heating value of hydrogen is three times lower than that of methane and the less hydrogen the higher heating value and Wobbe index.

4. STATUS

An increased focus on climate change issues, security of supply and the need to reduce the strong oil dependency, especially in the transport sector, has led to a renaissance of biomass gasification. Gasification plants are planned or being built around Europe targeted for electricity and heat generation as well as fuel production. While there are commercial plants for electricity and heat production based on biomass gasification, we still await the first industrial plant for production of transport fuel.

4.1 HEAT AND POWER PRODUCTION

Gasification plants for heat and power compete with conventional CHP plants based on combustion of solid biomass and the Rankine cycle. The Swedish Electrical Utilities R&D Company (Elforsk) has made a compilation[21] of the electrical efficiency of different plants. It specifies the electrical efficiency of biofuel cogeneration based on a steam cycle to 27% for a plant size of 10 MW_{el} corresponding to more than 35 MW of fuel supplied. The efficiency drops rapidly in response to reduced plant size. This should be compared with, for example the gasification plant in Oberwart, which has an electrical efficiency of over 32%, 2.8 MW_{el} and 8.5 MW of fuel supplied.

4.2 FUEL PRODUCTION

At the plant in Güssing the entire chain from wood chips to the production of bio-SNG via gasification and methanation, and refuelling of gas vehicles has been demonstrated[22]. Commissioning of the gas cleaning and the methanation step was completed in November 2008; in December 2008, the producer gas was converted to methane-rich gas in the process development unit (PDU). In March 2009, commissioning of the gas purification was completed; in April 2009, the first operation of the full process chain was achieved. In June 2009, the PDU was operated during 250 h at up to 1 MW SNG, producing 100 m^3/h of SNG in H-gas quality (Wobbe index = 14.0, HHV = 10.67 kWh/Nm^3).

Table 7. Gas composition[23] after conditioning in the Güssing plant.

Gas component	Vol-%
CH_4	>94,5%
H_2	< 2%
CO_2	<0,5%
CO	<1%
N_2	<2%

Within the Gothenburg Biomass Gasification project (GoBiGas) the goal is to build a plant on an industrial scale, in Gothenburg, for the production of bio-SNG via gasification and methanation of wood chips. The facility will be the first in the world that produces bio-SNG from a commercial perspective. The project has received support from the Energy Agency with 222 million SEK (approx. 25 million euro). The total cost is ~1,400 million SEK (approx. 155 million euro). The gasification technology is supplied by Repotec while the gas cleaning and methanation technology comes from Haldor Topsøe.

German Choren, in partnership with Daimler and Volkswagen, has built a 45 MW_{th} gasification plant in Freiberg for the production of Fischer-Tropsch- Diesel. The commissioning of the plant has been delayed several times. The security and safety of the facility has been been reviewed and updated. Systems for logistics and fuel feed are in place. Hot tests of the gasifier have been conducted at the end of 2009. Cold tests of the systems for gas conditioning and synthetisation were planned for 2010 and production of FT-Diesel was expected during the second quarter of 2010[24]. However, both Daimler and Volkswagen have left the project and Choren has encountered insolvency problems. The law firm Kübler was appointed insolvency administrator. The intention was to restructure the Choren Group through an insolvency plan or through a sale of the group to an investor. In February 2012 Linde Engineering Dresden GmbH acquired the Carbo-V® biomass gasification technology of the insolvent Choren Industries GmbH from the insolvency administrator Dr. Bruno M. Kübler. According to Jörg Linsenmaier, managing director of the Linde Engineering Dresden GmbH, the plan is to offer the Carbo-V® technology as licensor and participate as an engineering and contracting company on a strongly growing market[25].

Chemrec's technology for black liquor gasification and Haldor Topsøe's technology for DME synthesis are vital parts of the development activities at the Energy Technology Center (ETC) in Piteå. The gasification technology has been tested in a 3 MW pilot plant located at the pulp mill Smurfit Kappa Kraftliner. A facility for the synthesis of the syngas to DME has been built. This was done in a joint venture between Volvo (coordinator), Chemrec, Haldor Topsøe, Preem, Total, Delphi and ETC within the EU project, Bio-DME. 10 Volvo Trucks will drive 100 000 km/year, on average, in real operation during the period 2010-2013. Furthermore, there were plans to build a plant on an industrial scale, 75 MW, at Domsjö in Örnsköldsvik. The project has received support from the Energy Agency of 500 million SEK (approx. 56 million euro). However, the owner of Domsjö Fabriker, Aditya Birla Group, has decided to cancel the project.

4.3 COMMERCIAL PLANTS

Below are some examples of plants that have been built for commercial purposes alternatively for production of a final product intended for a commercial market listed.

<u>Indirect gasification</u>
The 15 MW_{th} plant in Oberwart (Austria), based on the technology with indirect gasification of wood chips, include two gas engines from Jenbacher and an ORC (Organic Rankine Cycle) for power generation. The plant produces already today

a nitrogen-free syngas and there is no real hindrance for future SNG production if the facility is supplemented with shift and methanation units. The plant has been in operation since 2008/2009.

Air-blown pressurized bubbling fluidized bed gasification

The plant in Skive[26] (Denmark), based on Carbona's gasification technology, includes catalytic tar cracking before the product gas is cooled down and filtered and 3 Jenbacher gas engines for electricity production. The tar cracker is outsourced to Haldor Topsøe. The gasifier is fed with wood pellets.

The facility is designed to operate at 30-140% load. 140% load is equivalent to 28 MW_{th}. The gasifier is operated at a maximum pressure of 2 bar and at a temperature of 850 °C. Cold tests were conducted in autumn 2007. Warm test was conducted with the gasifier, gas cooling, filters and gas boiler as an independent system. When this system was able to supply heat to the district heating system work started on the gas cleaning. Based on extensive measurements of the gas quality in the hot samples of the gas boiler it was decided to engage one of the three gas engines. A few days later, in May 2008, the plant reached full operation of the generator connected to the power grid. The project has suffered numerous delays, but after adjustments and operational optimization the plant is in continuous operation.

Air-blown atmospheric circulating fluidized bed gasification

Götaverken (nowadays a part of Metso Power), delivered a gasification plant with a capacity of 28 MW_{th} to Värö Bruk where the produced gas is used in a lime kiln. Lime kilns can be found in the chemical pulp industry based on the sulphate process. The lime sludge consists mainly of calcium carbonate, $CaCO_3$, and is formed at the causticising of green liquor. By heating the lime sludge carbon dioxide leaves the sludge and $CaCO_3$ is converted to CaO (burnt lime). The lime is in turn a part of the pulp mill chemical recovery. The gasifier using bark as a raw material has been in operation since 1987[27].

The gasification plant in Lahti (Finland), based on Foster Wheeler's CFB technology is used to produce a gas that is co-fired with pulverized coal in a furnace. The plant produces electricity and heat via a conventional steam cycle. Through the gasification low grade fuel such as paper, paperboard, separated waste and plastic can be used in an efficient coal boiler with steam data of 540 °C and 170 bar. The gasification capacity of 40-70 MW_{th} constitutes about 15% of the capacity of the pulverized coal furnace.

Foster Wheeler has in the mid 80's, delivered CFB gasifiers for production of gas to lime kilns in Sweden (Karlsborg and Norrsundet Mill), Finland and Portugal.

Air-blown updraft gasification

The plant in Harboøre (Denmark), based on the Babcock & Wilcox Vølund technology, include a 3.5 MW_{th} air-blown updraft gasifier, gas cleaning, two Jenbacher gas engines for electricity and a boiler for combustion of separated tars.

The Harboøre plant has accumulated more than 100,000 operating hours. In January 2007 a 7.5 MW_{th} updraft gasifier, based on the Babcock & Wilcox

Vølund technology, was taken into operation in Yamagata, Japan. Electrical output is given to 2 MW.

Air-blown downdraft gasification

The Belgian company Xylowatt SA has delivered 5 air-blown downdraft gasifiers[28] for combined heat and power production during the period 2003-2006. The electric capacity is 300 kW. The plants are fully automatic with remote control and intended for 24 hour a day operation.

In 2007 Xylowatt delivered a NOTAR® gasification reactor to the municipality of Gedinne in Belgium. The plant, fuelled with wood from local forestry, produces heat and power for the municipality. Xylowatt has also delivered a plant to Saint-Gobain in France. The feedstock is wood by-products of pruning and vines and the produced gas is used for substitution of fossil fuels in a glass furnace.

5. MARKET POSITION AND ECONOMY[4]

In many cases, it is small entrepreneurial companies that are engaged in the development of gasification technology. They rarely have the financial strength to take total responsibility for the construction and meet the investors' demands for financial guarantees. At the same time the investor can't justify higher costs than for other available technologies that can deliver the same end product. As the major engineering and construction firms prefer to limit their risk exposure to conventional components, by necessity, more actors are often involved. This creates more interfaces, which in turn often prolongs the duration of the project and requires a variety of contractual arrangements.

5.1 EXAMPLES OF SUPPLIERS

Repotec, Austria, is a small company with 8 employees, who does basic engineering and to some extent takes responsibility for the construction work. Normally Repotec works with local suppliers. Repotec have built the plant in Güssing and made the "basic engineering" for the plant in Oberwart. Repotec is involved in two new plants in Germany. The plant in Senden, 14.3 MW_{th} and 5 MW_{el}, is expected to enter commercial operation in 2011. The plant in Türkheim (near Geislingen) has a capacity of 10 MW_{th} and 3.3 MW_{el}. The facility is designed to run with Absorption Enhanced Reforming (AER) to produce a gas with a high proportion of hydrogen and no carbon dioxide.

Ortner GmbH, Austria, built the plant in Oberwart and is involved in the plants in Villach and Klagenfurt. It was a surprise that it was Ortner GmbH and not Repotec who was awarded the contract for the plant in Oberwart since Ortner GmbH previously had no experience of building gasification plants. On the other hand, Ortner GmbH has completely different financial resources compared to Repotec.

German M+W Zander was commissioned by H2Herten GmbH to be responsible for planning, procurement and supervision in connection with the construction of the Blue Tower facility, 13 MW_{th} and 5 MW_{el}, based on indirect gasification in Herten, Germany[29]. It is Blue Tower GmbH, part of the Solar Millennium Group, which owns the rights to the Blue Tower technology and has the right to issue licenses.

Babcock & Wilcox Vølund has further developed the concept of updraft-gasifier and gas engine to include a steam cycle. In Agust 2008 Babcock & Wilcox Vølund signed an agreement with Advanced Renewable Energy Ltd regarding development, construction and implementation of up to 25 decentralised CHP plants in Italy. The plants were designed to deliver 4 MW electricity and 5 MW heat. However, as a direct consequence of the global financial crises the contract was later cancelled.

Carbona is a Finnish company with roots in the developments taking place at the Gas Technology Institute in the USA. In 2006, Andritz Oy, a leading supplier of pulp and paper industry, became a minority shareholder in Carbona. During 2006-2008 Andritz gradually acquired ownership in Carbona. The focus is on gasification based on large-scale fluidized bed technology.

Xylowatt is a spin-off company of the Catholic University of Louvain in Belgium. Through collaboration with Electrabel customers can be offered complete solutions. The focus is on small downdraft gasifiers in combination with a gas engine.

5.2 ECONOMY

In a comparative study[30] conducted in 2008 the production cost for bio-SNG is in the interval 380-410 SEK/MWh (approx. 43-46 euro/MWh) which clearly exceeds the, in the report, assumed natural gas cost of 250 SEK/MWh (approx. 28 euro/MWh) excluding taxes. In a subsequent study[31] the authors point out that, on basis of ongoing work in Sweden, there are indications that the production cost of bio-SNG probably is higher.

Different instruments and taxes such as electricity certificate trading systems, energy and environmental taxes together with political ambitions to increase the share of renewables in the energy system are factors that favor biomass gasification. The gasification technology facilitates a large scale introduction of renewable fuels in the transportation sector and the possibility to produce electricity with a high efficiency in areas with low heat demand. When it comes to political ambitions or binding directives to increase the share of renewables it's important to remember that the production cost for the renewable fuel shouldn't be compared to the cost of fossil fuels but to the cost of other competing renewable alternatives. This implies that technologies with high conversion efficiency from feedstock to final product are desirable, especially since the feedstock cost is expected to increase in the same rate as the competition of biomass increases. Those technologies that are less capital intensive and technical complex compared to the alternatives will probably be commercialized first.

6. LIST WITH LINKS FOR MORE INFORMATION

BioEnergy List: Gasifiers & Gasification
http://gasifiers.bioenergylists.org is a website administered by T. R., Miles Technical Consultants, USA. The website contains among other links to manufacturer and suppliers of gasification equipment and a discussion forum. There is also an option to join an email list and take part of the active discussion forum.

Bio-SNG
http://www.bio-sng.com is a terminated European project where production of methane from woodchips has been demonstrated in the MW scale during 2008/2009. SGC participated in the advisory board.

BioSNG
http://www.biosng.com is a website maintained by the Energy Research Centre of the Netherlands, ECN. Here, the concept with ”Green Natural Gas”, that is renewable gas of natural gas quality, produced through microbial or thermo-chemical decomposition of organic material followed by subsequent gas cleaning/upgrading/conditioning is described. The website contains links to relevant ECN-reports and a short description of ongoing development activities.

BTG Biomass Technology Group
BTG is an indendent, private group of companies, which has specialised in the process of conversion of biomass into useful fuels and energy. At the website www.btgworld.com there are quite a lot about technology status. Click on ”RTD” and thereafter ”Technologies”. BTG initiated and took part in the European network GasNet. Here, one may also order ”Handbook on Biomass Gasification” which is described in more detail under literature, further back in this report. Click on ”References” and thereafter ”Books”.

ERA-NET Bioenergy
At the ERA-NET Bioenergy website http://www.eranetbioenergy.net there are bagground information and project descriptions of European bioenergy research. There is a so called Joint Work Programme directed towards Synthetic natural gas from biomass that is coordinated by Tekes, Finland. The objective is to make a survey on R&D needs and recommendations as well as industrial demonstration needs. Decisions about action are still to be made (28-02-2012).

Gasification Guide
Gasification guide www.gasification-guide.eu is a project within the framework of Intelligent Energy for Europe regarding health, safety and environmental aspects in biomass gasification. Within the project a software tool called Risk Analyzer has been generated. One can download the Risk Analyzer and a manual from the website.

Gasifier Inventory

Gasifier Inventory gives an overview of existing biofuel based gasification plants and suppliers of equipment around the world. The database contains gasifiers based on different gasification technology, capacity and supplier. Lab and bench-scale gasifiers are excluded from the database. For more information visit www.gasifiers.org. June 2011 the database was down. According to Harrie Knoef, BTG World, who is responsible for the website, it's only temporary (due to change of internet supplier) and the intention is that the database will work as before.

GasNet (the project is terminated and the website closed)

GasNet was a European network within the field of biomass gasification coordinated by prof. Hermann Hofbauer, TU Vienna, and supported by Intelligent Energy for Europe. On the website there were information about applications and gasification technologies etcetera. The GasNet newsletter could be downloaded through the website www.gasnet.uk.net. The report could be ordered free of charge through the GasNet website.

GoBiGas

The Gothenburg Biomass Gasification project (GoBiGas) has its own website www.gobigas.se where one can follow the construction of the world's first industrial scale biomethane plant through a webcam.

IEA Bioenergy. Task 33 Thermal Gasification of Biomass

The objectives of Task 33 are to exchange information globally, stimulate industrial involvement and coordinate research, development and demonstration within the member group. More information is available at the website, www.ieabioenergy.com/Task.aspx?id=33. There are many gasification related reports under "Media Centre", e.g.

ExCo66 workshop "Thermal Pre-treatment of Biomass for Large-scale Applications – summary and conclusions", October 2011.
From 1st- to 2nd-Generation Biofuel Technologies: An overview of current industry and RD&D activities, November 2008.
Biomass pyrolysis, February 2007.
Observations on the Current Status of Biomass Gasification, May 2005.
Biomass Gasification Success Stories, December 2004
Thermal Gasification of Biomass, June 2002

SGC

Gasification database

The gasification database, gdf.sgc.se has been built up within an SGC project, see SGC report 242 for more details. The database contains information about biomass based gasification plants in the world. The aim of the project was to benchmark current and past gasifier systems in order to create a comprehensive database for computer simulation purposes. The result of the investigation is presented in a Microsoft Excel sheet, so that the user easily can implement the data in their specific model. In addition to provide simulation data, the technology is described briefly for every studied gasifier system. The primary pieces of information that are sought for are temperatures, pressures, stream compositions and energy consumption.

Gasification Seminars
International seminar on gasification 2012 www.sgc.se/gasification2012
International seminar on gasification 2011 www.sgc.se/gasification2011
International seminar on gasification 2010 www.sgc.se/gasification2010
International seminar on gasification 2009 www.sgc.se/gasification2009
International seminar on gasification 2008 www.sgc.se/gasification2008
International seminar on gasification 2007 www.sgc.se/gasification2007

Reports
SGC-rapport 234 Biomass Gasifier Database – for computer Simulation Purposes. Christian Hulteberg, 2011.
SGC-rapport 232 Förgasning – teknik och status. Jörgen Held, 2011 (in Swedish).
SGC-rapport 213 *International Seminar on Gasification 2009 – Biomass Gasification, Gas Clean-up and Gas Treatment*. Jörgen Held (editor), 2009.
SGC-rapport 212. *Marknadsförutsättningar för SNG i Sverige och i Europa*. Linda Colmsjö och Ronny Nilsson, 2009 (in Swedish).
SGC-rapport 193 *International Seminar on Gasification 2008*. Jörgen Held (editor), 2008.
SGC-rapport 187 *Substitute natural gas from biomass gasification*. Per Tunå, 2008.
SGC-rapport 185 *System- och marknadsstudie för biometan (SNG) från biobränslen*. Martin Valleskog, Åsa Marbe och Linda Colmsjö, 2008 (in Swedish).
SGC-rapport 168 *The potentials for integration of black liquor gasification with gas fired paper drying processes – A study from the energy cost perspective*. Kristian Lindell och Stig Stenström, LTH, 2006.
SGC-rapport 156 *Förnybar Naturgas – Förgasning av biobränslen för framställning av metan eller vätgas*. David Malm och Staffan Karlsson 2005 (in Swedish).

The reports can be downloaded as PDFs free of charge at the SGC website, www.sgc.se, click on ”Publications” in the horizontal menu and then “Reports” in the left column.

TarWebNet
The website is designed and constructed for all end-users, suppliers and developers of biomass gasification technologies to present the development and to stimulate the use of a standard method for the measurement of organic contaminants (tars) in biomass producer, www.tarweb.net. ECN from the Netherlands coordinates the project.

ThermalNet (the project is terminated)
ThermalNet treated three technolgies, pyrolysis (PyNe), gasification (GasNet) and combustion (CombNet) and was financed through Altener, Intelligent Energy for Europe within DG TREN. The website address is www.thermalnet.co.uk. There are also links to PyNe, GasNet and CombNet. The only website still active is PyNe.

Unique
The EU-project Unique is aiming at integration of the biomass gasification process, the gas cleaning and the conditioning in one and the same fluidized bed reactor. www.uniqueproject.eu.

Woodgas
Tom Reed, former professor at MIT och Colorado Scholes of Mine has developed a website related to gasification of biomass, www.woodgas.com. The homepage is pedagogic and contains among others an animation of the gasification process. There is also a bookstore with relevant literature.

LITERATURE

Jean-Pierre Badeau and Albrecht Levi (Eds). *Biomass Gasification – Chemistry, Processes and Applications*. ISBN 978-1-60741-461-2. Nova Science Publishers, Inc. 2009.
474 pages covering both auto- and allothermal gasification as well as gas cleaningand synthetization. Contains many tables and diagrams.
The book may be ordered at http://www.bokus.com for 1090 SEK, approx. 123 euro.

Basu, Prabir. *Biomass Gasification and Pyrolysis – Practical Design and Theory*. ISBN 978-0-12-374988-8. Elsevier Inc. 2010.
365 pages on biomass gasification including guidelines for the design and selection of biomass handling equipment.
The book may be ordered at http://www.bokus.com for 666 SEK, approx. 75 euro.

Basu, Prabir. *Combustion and Gasification in Fluidized Beds*. ISBN 0849333962. Taylor & Francis 2006.
473 pages with combustion and gasification in fluidized beds. Contains some pictures, equations and diagrams (all in black and white). Reminds of a textbook with sample problems.
The book may be ordered at http://www.adlibris.se for 1122 SEK, approx. 127 euro.

A V Bridgwater, H Hofbauer and S van Loo (Eds.). Thermal Biomass Conversion. ISBN 978-1-872691-53-4, 2009.
429 pages about combustion, pyrolysis and gasification of biomass. Contains some pictures full colour. Three chapters treat gas cleaning, synthetization and conditioning. None-technical barriers and HSE (Health, Saftey and Environment) are treated in one chapter each.
The book may be ordered at http://www.cplbookshop.com/contents/C3568.htm for £125, about 1300 SEK.

Highman, C. and van der Burgt, M. *Gasification*. ISBN 978-0-7506-7707-3. Elsevier, 2003.
391 pages about coal and biomass gasification. The book treats gasification from a rather theoretical perspective.
The book may be ordered from http://www.bokus.com for 452 SEK, approx. 51 euro.

Knoef, H.A.M. *Handbook Biomass Gasification*. ISBN 90-810068-1-9. Biomass technology group, the Netherlands, 2005.
378 pages about biomass gasification. Tretas gasification from a practical point of view with many references to real plants. The book is relatively lavish with a

large number of colour pictures of plants, components, process schemes etcetera. The book may be ordered at http://www.btgworld.com for approx. 90 €.

Prins, Mark Jan. *Thermodynamic analysis of biomass gasification*. ISBN 978-3-639-10006-8, 2008.
148 pages about biomass gasification. Deals with gasification from a thermo dynamic perspective but treats also torrefaction, a thermal treatment of wood for increased energy density. The book contains many equations and diagrams but is written in a way that is easy to understand.
The book may be ordered at http://www.adlibris.se for 415 SEK, approx. 47 euro.

Rezaiyan, John och Cheremisinoff, Nicholas, P. *Gasification Technologies – A Primer for Engineers and Scientists*. ISBN 0824722477, 2005.
336 pages with coal and biomass gasification. Contains relatively few pictures and diagrams compared to the other books. Has an extensive chapter (approx. 100 pages) about gas cleaning.
The book may be ordered at http://www.adlibris.se for1025 SEK, approx. 116 euro.

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