

## Syngas Production from Coal

### HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS** – Coal gasification – and virtually all gasification of other carbon-based resources such as biomass or refinery residues - is a versatile conversion technology which adds flexibility to the energy systems. In the gasification reactors, the feedstock is converted into a synthesis gas (syngas), a mixture of H<sub>2</sub>, CO and CO<sub>2</sub>, which enables the production a variety of downstream energy carriers. A lot of knowledge has been gained from coal gasification worldwide as this so-called town-gas was produced from coal as early as 1792, a high-temperature fluidized-bed gasifier was patented in 1921 by Winkler, and synfuels production from coal was common practice in Germany during World War II. According to the Gasification Technologies Council, in 2007, some 144 gasification plants and 427 gasifiers were in operation worldwide, adding up to an equivalent thermal capacity of 56 GW<sub>th</sub>, of which coal gasification accounted for approximately 31 GW<sub>th</sub>.

■ **PERFORMANCE AND COSTS** – Performance and costs of coal gasification plants depend largely on the plant design and the final production objectives. A gasification system that is part of an integrated chemical plant producing methanol, ammonia and electricity differs substantially from a system that only feeds an IGCC plant with carbon capture and storage (CCS). Coal quality is also very important for coal gasification output. The overnight capital cost of coal gasification plants is given per GJ of syngas output and ranges from \$13/GJ for bituminous coal to \$17.2/GJ for sub-bituminous coal (US\$ 2005). Similarly, the syngas production cost decreases with the increase of coal quality and ranges from \$15.6/GJ to \$19.3/GJ. The production cost is dominated by the investment cost. However, costs may vary significantly depending on the location. Chinese plants may cost 60-65% of the US and European installations. Syngas may be further upgraded to meet specific demands. Co-production of 20% of H<sub>2</sub> using a H<sub>2</sub> separation unit is only slightly more costly than the basic process, resulting in 5% higher capital and 4% higher product costs. The conversion into synthetic natural gas (SNG), i.e. pipeline quality gas, requires additional processes and costs. If the syngas is converted into SNG, the capital cost increases by approximately 25% and the cost of the final product increases by 40%, while the conversion efficiency of the process decreases by some 14 percentage points, reaching about 60%.

■ **POTENTIAL AND BARRIERS** – There is huge potential for coal gasification worldwide, as the technology allows fuel production for many applications such as transport, chemicals, heat and power production. High natural gas prices and limited availability at a regional level are driving factors for investments in coal gasification. Based upon planned projects, the Gasification Technologies Council, a non-profit organization promoting technological advances and surveying the market, expects further market growth to reach a global equivalent thermal capacity of 73 GW<sub>th</sub> by 2010. Other projections indicate up to 155 GW<sub>th</sub> by 2014. Most of the growth will materialize in Africa and the Middle East (64%), Asia and Australia (27%), compared with only 9% in Europe and almost no investment in America. Marketable products from new gasification plants include Fischer-Tropsch (F-T) liquids (69%), chemicals (22%) and power (9%). However, because of the need to mitigate GHG emissions and climate change, these market projections appear to be realistic only if CCS technology is made available.

### PROCESS AND TECHNOLOGY STATUS –

Gasification of coal - and other carbon-based resources such as biomass or oil residues - is a versatile conversion technology that adds flexibility to energy systems. In a gasification reactor the feedstock is transformed into a synthesis gas (syngas), basically a mixture of H<sub>2</sub>, CO and CO<sub>2</sub>, which opens up to make a variety of downstream energy carriers. The syngas may be used as a fuel in integrated gasification combined cycles (IGCC, see ETSAP TB E01) or as a feedstock for producing H<sub>2</sub> or a synthetic natural gas (SNG). Depending on the CO to H<sub>2</sub> ratio, which can be adjusted using catalysts, the gas can also be used as a feedstock for a number of chemical processes, including Fischer-Tropsch synthesis (see ETSAP TB P06), conversion into CH<sub>4</sub> (methanation), or methanol and ammonia production. The multiple productions of fuels, chemicals and electricity from coal gasification is defined as poly-

generation. Coal gasification in IGCC plants holds the potential for easy capture of CO<sub>2</sub> from the syngas and for CO<sub>2</sub> storage in geological formations (CCS).

Gasification takes place under oxygen shortage. Coal is first heated in a closed reaction chamber where it undergoes a pyrolysis process at temperatures above 400°C.

During pyrolysis, hydrogen-rich volatile matter is released, along with tar, phenols, and gaseous hydrocarbons. Char is then gasified, with the release of gases, tar vapours and solid residues. The dominant reaction consists of partial oxidation of char, which produces a syngas with high fractions of H<sub>2</sub> and CO. The process takes place at temperatures between 800°C and 1800°C. Specific operating conditions depend on coal type, properties of the resulting ash, and the gasification technology. The most important variable in a gasification process is the oxidant. It can be either air (with its nitrogen component) or pure

oxygen if the process includes an air separation unit (ASU) for oxygen production. The use of oxygen instead of air facilitates the partial combustion of coal, but involves higher investment costs due to expensive additional equipment. As gasification takes place under stoichiometric shortage of oxygen, the reaction mechanism in the gasification chamber has to be adjusted with appropriate energy balance. The direct partial oxidation of carbon to CO, for instance, is strongly exothermic, leading to a high release of energy in the form of sensible heat. However, steam gasification of coal, (forming both CO and H<sub>2</sub>) is strongly endothermic. As a result, a steam/oxygen mixture is commonly used. In the gasification practice, the basic equipment can be grouped into three main categories: moving-bed gasifiers, fluidized-bed gasifiers, and entrained-flow gasifiers.<sup>1</sup>

■ **Moving-Bed Gasifier** (Figure 1) – Sometimes called fixed-bed gasifier, this is the oldest gasification device in use. Lurgi developed an atmospheric reactor in 1927 and a pressurized version in 1931. It is characterized by a reaction bed where coal moves slowly downward under gravity and is gasified by a blast (in general) in counter-flow to coal. An important feature of the Lurgi dry bottom gasifier is the low consumption of oxygen and the high steam demand. Moving-bed gasifiers need graded coal in the range 6–50 mm. Highly caking coals cannot be processed in moving-bed gasifiers. Mildly caking coals require the assistance of a stirrer in order to avoid the pasting-up of the bed. Tars and other oxygenated compounds are produced as by-products. An advanced variant of the original Lurgi pressure gasifier was developed jointly by British Gas and Lurgi during the 1950s and 1960s. The British Gas/Lurgi (BGL) **slagging gasifier** incorporates a molten slag bath. The much lower steam and somewhat lower oxygen consumption of the slagging gasifier results in much higher syngas production per unit of coal intake and a much lower yield of pyrolysis products compared with the dry bottom unit. Furthermore, the CO<sub>2</sub> content of the gas is lower and the methane content is halved.

■ **Fluidized Bed Gasifier** (Figure 2) – This device offers the advantage of promoting excellent mass and heat transfer due to the intensive mixing. On the other hand, individual particles have widely varying residence time in the bed volume. Therefore, unreacted carbon particles are inevitably removed from the bed along with fully reacted particles (ash). The best existing fluidized bed devices offer a carbon conversion of 97%. In comparison, both moving-beds and entrained-flow processes offer carbon conversions of 99%.

<sup>1</sup> Gasification reactors and manufacturers: a) Moving-bed reactor: Lurgi and Sasol-Lurgi (dry bottom), British Gas Lurgi (BGL) (slagging); b) Fluidized-bed reactor: High Temperature Winkler (HTW) process (earlier Rheinbraun, now RWE), HRL Ltd. Australia, Bharat Heavy Electricals Limited (BHEL); c) Entrained reactor: Koppers-Totzek, Shell Coal Gasification Process (SCGP), Prenflo, Siemens, GE Energy, E-Gas, Mitsubishi Heavy Industries (MHI), Eagle.

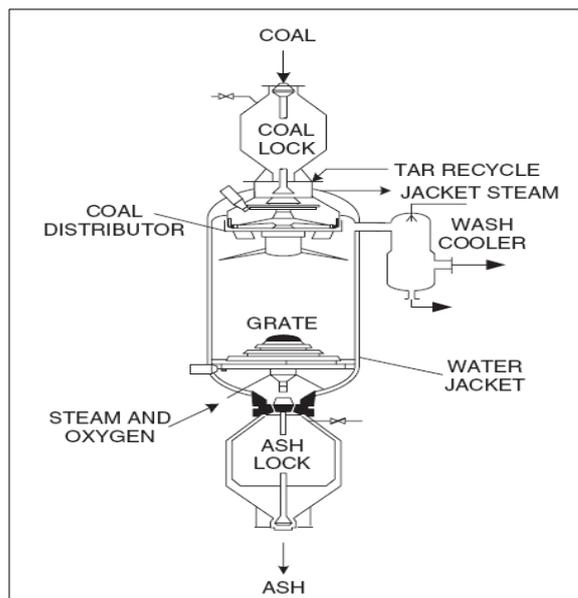


Fig. 1 – Moving Bed Gasifier concept

■ **Entrained Flow Gasifier** (Figure 3) – The advantage of entrained flow gasifiers is the ability to handle any coal feedstock and produce a clean, tar-free gas. In addition, the ash is produced in the form of inert slag or frit. This is achieved by making an additional effort in the coal preparation and high oxygen consumption, especially in the case of coal-water slurries or coals with high moisture or ash content. The majority of the coal gasification processes that have been developed after 1950 are based on entrained-flow, slagging gasifiers operating at pressures of 20 to 70 bar and high temperatures (≥1400°C).

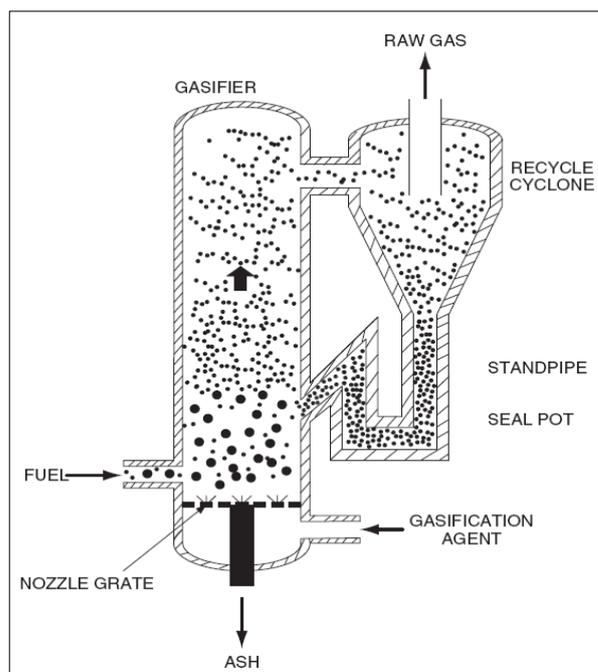


Figure 2 – Fluidized Bed Gasifier concept

Entrained-flow gasifiers have become the technology of choice for hard coals, and have been selected for the majority of commercial-sized IGCC plants. A lot of knowledge has been gained from coal gasification over several decades: town gas was manufactured from coal as early as 1792; the first process to produce methanol from syngas was installed in 1913 (BASF); an improved high temperature fluidized bed gasifier was patented in 1921 by Winkler; and during World War II, Germany produced large amounts of synthetic fuels from coal. According to the Gasification Technologies Council, in 2007 there were 144 gasification plants and 427 gasifiers in operation worldwide, adding up to an equivalent thermal capacity of some 56 GW<sub>th</sub>. Coal gasification accounted for approximately 31 GW<sub>th</sub>, with the remaining gasification plants running on petroleum, gas, petcoke, biomass and waste feedstock (NETL, 2007). A large part of the world's coal-based syngas is produced in 97 gasifiers in Sasol's plants in South Africa: in 2008, an estimated conversion capacity of 14 GW<sub>th</sub> enabled the conversion of some 43 Mt/y of coal into 7,4 Mt/y of transport fuels and chemicals (Sasol, 2008). Most of the remaining coal-based syngas produced in other regions of the world is used for ammonia or methanol production, and in China, for the production of town-gas. China has become the global test case for large-scale coal conversion activities. In 2008, China held licenses from Shell for the installation of 18 coal gasification plants. Among these, 11 commercial-size coal gasification plants were already in operation, most of them for the industrial production of methanol or ammonia. Plans for the installation of further large-scale coal conversion plants include one direct liquefaction and five Fischer-Tropsch (FT) plants for liquid fuel production. While syngas is the primary product of the gasification plants, marketable products obtained from syngas include chemicals (45%), FT liquid fuels (28%), gaseous fuels (8%), and electric power (19%). In other products, gaseous fuels include synthetic natural gas (SNG). In the IGCC power plant of the Great Plains in the US, the syngas is used to produce SNG (NETL, 2007).

While coal gasification is a commercial technology, further research aims to increase product yields, reduce consumption of catalysts and energy, and lower capital and operation costs. In IGCC plants with CCS, reducing the energy input to produce oxygen represents an essential research area.

**PERFORMANCE AND COSTS** – Performance and costs of coal gasifiers depend largely on the plant design and on final production objectives. A gasifier that is part of an integrated chemical plant for methanol & ammonia production, with cogeneration of electricity, has completely different characteristics from a gasifier producing feedstock for an IGCC plant with CCS.

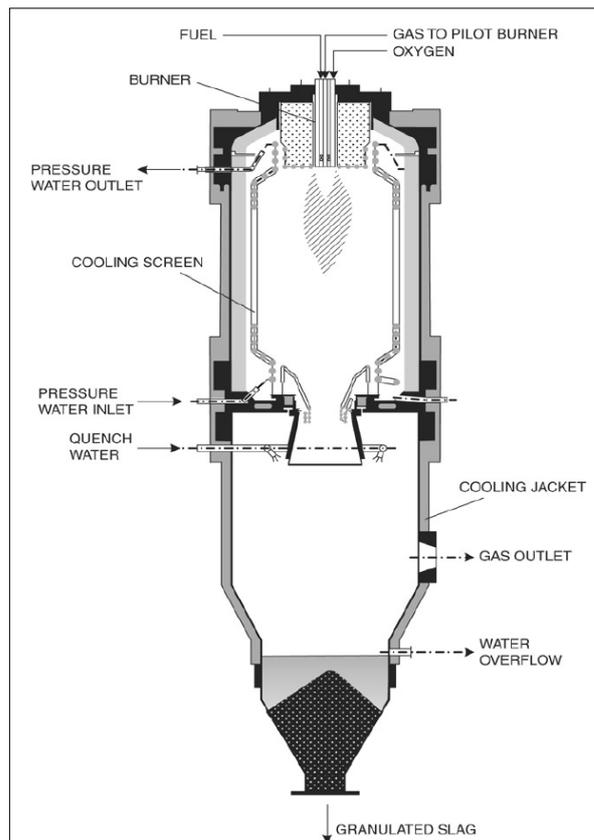


Fig. 3 – Entrained Flow Gasifier concept

Depending on the type of gasifier and on desired syngas composition, the energy conversion efficiency of the gasification process may range from 70-80%. As far as cost is concerned, overnight investment costs of the gasification plants depend on the geographical location as a number of components can be manufactured locally. A study regarding IGCC costs indicates a 0.65 China "location" factor vs. the US overnight investment cost. Similarly, Shell China typically applies a location factor of 0.60 to the European costs of gasification projects, on the basis of its own detailed evaluations of local Chinese manufacturing and construction costs (Larson, 2003).

Coal gasification performance and costs have been explored in various studies. Table 1 draws on detailed engineering and cost studies of coal gasification plants for two locations in the US (NETL 401, 2007). These plants with oxygen blown BGL slagging moving-bed gasifiers have basically an identical design, but use different coal qualities as feedstock: Illinois No.6 bituminous and Wyodak Powder River Basin sub-bituminous. Both plants are commercial-size installations that produce syngas from a feed of some 930-1.030 t/d coal (802-1180 GJ/h), with no CO<sub>2</sub> capture. The two examples demonstrate that the influence of coal quality on the output is very significant. The overnight capital cost is \$13.5/GJa for bituminous coal, compared to \$17.2/GJa for sub-bituminous coal.

Likewise, the syngas production cost is lower for the higher quality coal, i.e. \$15.6/GJ vs. \$19.3/GJ.

Syngas may be further upgraded to meet specific demands. Co-production of a 20% H<sub>2</sub> using H<sub>2</sub> separation devices is only slightly more costly, resulting in 5% higher capital and 4% higher product costs. The conversion into SNG, i.e. pipeline quality gas, requires additional processes and considerable costs: the capital cost increases by approximately 25% and the production cost by 40%, while the conversion efficiency decreases by over 14% percentage points (NETL 401, 2007). The application of CCS technologies increases the capital cost. For example, in a coal gasification plant for H<sub>2</sub> production, the devices for CO<sub>2</sub> drying and compression account for 5% of the total investment cost. At the same time, the overall efficiency decreases by around 3% points (IEA, 2005).

**Table 1 – Performance and Costs of Syngas Production from Different Coal Quality**

Performance		Illinois #6bitum.	Wyodak sub-bitum.
Gasif. capacity, output	MW <sub>th</sub>	310	207
Syngas production (HHV)	GJ/h	1005	671
Coal feed	GJ/h	1180	802
Net efficiency	%	74.7	72.8
<b>Costs (US \$2005)</b>			
Tot. plant cost		118.7	101.3
Specific capital cost	\$/GJ	13.5	17.2
O&M cost			
Fixed O&M cost	Mill.\$/y	6.0	5.8
Var. O&M cost, output	\$/GJ	1.4	1.6
Coal cost, input	\$/GJ	1.3	0.9
Production cost	\$/GJ	15.6	19.3

**POTENTIAL AND BARRIERS** – There is huge potential for coal gasification worldwide, as the technology enables production of fuels and feedstock for many applications such as transport, chemical production, heat and power generation. As coal is the most abundant fossil resource available on earth and even low-grade coal can be used for gasification, the technology is of primary interest in many regions. Increasing gas prices and limited availability of natural gas in regional consumer markets are driving factors for investments in coal gasification technology. The Gasification Technologies Council, a non-profit organization promoting technological advances and surveying the market, expects a further growth in gasification to reach a global equivalent capacity of 73 GW<sub>th</sub> by 2010 based upon planned projects. Experts forecast 155 GW<sub>th</sub> by 2014 (Higman, 2008). Most of the growth will materialize in Africa and the Middle East (64%), in Asia and Australia (27%), with 9% in Europe and no investments in America. Marketable products from new gasification plants include Fischer-Tropsch liquids (69%), chemicals (22%) and power (9%) (NETL, 2007). However, these market projections only appear to be realistic if the CCS technology is used in gasification plants to mitigate the CO<sub>2</sub> and other GHG emissions. As a matter of fact, coal gasification technology enables easy CO<sub>2</sub> capture and separation, with limited additional components and costs. A typical cost of CCS in power plants today may range from \$ 30 to 90/tCO<sub>2</sub>. This cost includes capture \$ 20-80/t; transport \$ 1-10/t per 100 km; and storage and monitoring \$ 2-10/t. Coal gasification in IGCC plants allows a significant reduction in the capture cost, the most important component of the CCS cost. (IEA, 2006)

**Table 2 – Summary Table: Key Data and Figures for Coal Gasification Technology**

Technical Performance		Typical current international values and ranges								
Ranges refer to different coal qualities: 20.700 - 27.300 kJ/kg HHV										
Coal Gasification System: ASU, oxygen blown fixed-bed BGL 1000 gasifier, acid gas removal (Rectisol), sulphuric acid plant										
System Output		Syngas			Syngas/H <sub>2</sub>			SNG		
H <sub>2</sub> production system					Pressure swing adsorption (Rectisol)					
SNG production system								Water gas shift reactor, methanation reactor		
Gasification capacity, output, MWth		210 - 310			210 - 310			170 - 260		
Coal input, GJ/h		800 - 1.200			800 - 1.200			800 - 1.200		
Output	main product, GJ/h HHV	Syngas: 670 – 1.000			Syngas: 560 - 810, H <sub>2</sub> : 110 - 190			SNG: 560 - 840		
	By-product H <sub>2</sub> SO <sub>4</sub> , kg/h	120 - 1.350			120 - 1.350			120 - 1.350		
Efficiency, thermal %		73 - 75			73 - 75			60		
Construction time, yr		4			4			4		
Technical lifetime, yr		20			20			20		
Load factor and availability, %		90			90			90		
<b>Environmental data</b>										
CO <sub>2</sub> emissions, kt/PJ <sub>total output</sub>		55			55			78		
CH <sub>4</sub> emissions, kt/PJ <sub>total output</sub>		0.0061			0.0061			0.0061		
N <sub>2</sub> O emissions, kt/PJ <sub>total output</sub>		0 (only marginal emissions depending on the nitrogen content of the coal)			0 (only marginal emissions depending on the nitrogen content of the coal)			0 (only marginal emissions depending on the nitrogen content of the coal)		
Reduction of CO <sub>2</sub> emissions if CCS is applied, %		up to 99%			up to 99%			up to 99%		
<b>Costs (US \$<sub>2005</sub>)</b>										
Capital cost, \$/GJ output		17,2 - 13,5			18,3 - 14,1			27,2 - 20,1		
Fixed O&M, \$/GJ output		1,0 - 0,7			0,7 - 1,0			1,6 - 0,8		
Variable O&M cost, \$/GJ output		1,6 - 1,4			1,6 - 1,4			2,1 - 1,9		
Coal cost, \$/GJ input		1,3 - 0,9			1,3 - 0,9			1,3 - 0,9		
CO <sub>2</sub> capture & compression, \$/t CO <sub>2</sub>		20 - 80			20 - 80			20 - 80		
Transport & storage of CO <sub>2</sub> , \$/t CO <sub>2</sub>		6 - 20			6 - 20			6 - 20		
<b>Data Projections</b>										
		<b>2020</b>	<b>2030</b>	<b>2050</b>	<b>2020</b>	<b>2030</b>	<b>2050</b>	<b>2020</b>	<b>2030</b>	<b>2050</b>
Efficiency, thermal %		76 - 78	78 - 80	80 - 82	76 - 78	78 - 80	80 - 82	63 - 64	65 - 66	67 - 68
Capital cost, \$/GJ output		16,2 - 12,5	15,7 - 12,0	15,2 - 11,5	17,3 - 13,1	16,8 - 12,6	16,3 - 12,1	25,2 - 18,1	24,2 - 17,1	23,7 - 16,6
<b>References and Further Information</b>										
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