THE STATUS AND DEVELOPMENT TRENDS OF IGCC SYSTEMS WITH CAPTURE OF CO_2

Pablo A. Silva[1], Osvaldo J. Venturini, Electo E. Silva

ABSTRACT

The scarcity of world oil reserves and the constant growing in consumption of these natural resources has lead to an increase in the development of alternative uses of heavy oils. Among these alternatives is the coking process, which by-product is petroleum coke. This process can be used in residual fractions of heavy oils to produce lighter and more valuable products.

Considering the increasing petroleum coke (pet coke) production and the concentration and size of reserves of coal around the world it is important to carefully study to the pet coke and coal efficient utilization in order to address the use of this energy resource. This article presents the technological trends of IGCC (Integrated Gasification Combined Cycle) systems, which is one of the most efficient way to produce energy using coal and pet coke as fuel. Finally, various schemes for CO_2 capture and sequestration are evaluated.

Keywords: Coal, Petroleum Coke, capture and sequestration of CO_2, Gasification, Combined Cycle, IGCC.

NOMENCLATURE

ASU, air separation unit; NGCC, natural gas combined cycle; CCU, combined cycle units; CCS, carbon capture and storage; COS, carbonyl sulphide; GHG, greenhouse gases; MDEA, methyldiethanolamine; HRSG, heat recovery steam generator; IGCC, integrated gasification combined cycle; TG, gas turbine; LHV, lower heating value, HHV, higher heating value; OECD, Organization for Economic Co-operation and Development; PC, pulverized coal.

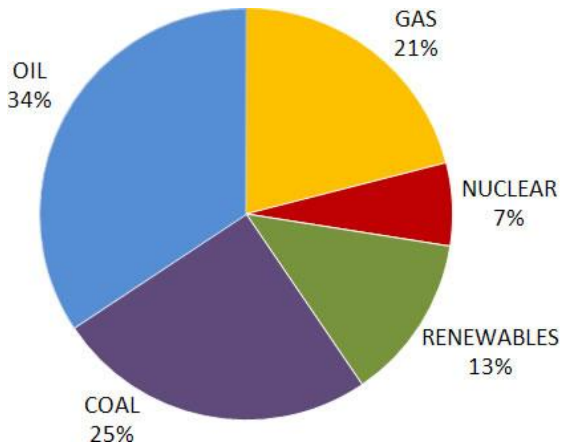
INTRODUCTION

This paper analyses the combination of two different technologies that are incorporated on IGCC plants, the gasification process which is used to produce a clean fuel gas (syngas) and secondly, combined cycle itself, which is one of the most efficient methods for generating electricity. Furthermore, the major schemes and types of gasifiers, performance, possibilities and options for the schematic capture of CO_2 are also analyzed.

Nowadays, the use of new sources of energy like natural gas and renewable power systems is increasing. Based on the annual report 2008 of the Energy Information Administration, Figure 1 provides the world primary energy and marketed energy use by fuel (EIA, 2008).

Much of the electricity production is still based on fossil fuels, specifically oil and coal. According to the Brazilian National Agency of Petroleum, Natural Gas and Biofuels, it can be estimated that 39% of the electricity consumed is generated with these fuels and that this proportion will continue until almost 2030 (ANP, 2007).

[1] Federal University of Itajubá - UNIFEI, Excellence Group in Thermal Power and Distributed Generation - NEST, Av. BPS 1303, CEP 37500-903, Itajubá, Minas Gerais (Brazil).
Corresponding author. Tel.: +55 35 36291321; fax: +55 35 36291355.
E-mail address: pablo.silvaortiz@gmail.com (P.A. Silva).



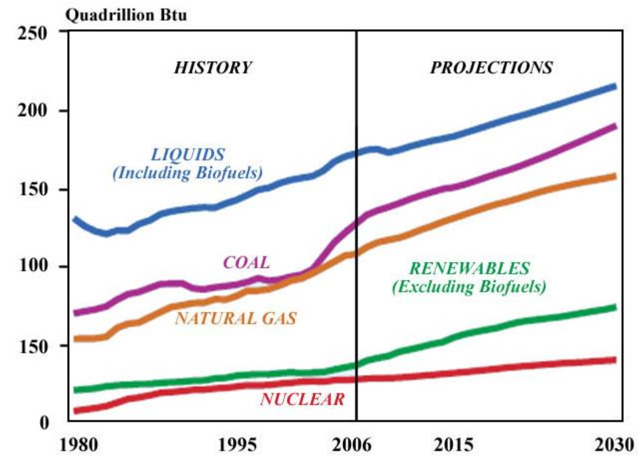


Figure 1. World primary energy and marketed energy use by fuel

Fuel shared of world primary energy supply 2007

World marketed energy use by fuel type 1980 – 2030

Based on World Energy Council (2007), coals are characterized by their high content of ash, a component that influences the performance of a generation system, based on it combustion. For this reason, in many applications it is recommended to mix coal with petroleum coke (with a maximum content of 20% of coke) to improve fuel properties. (WEC Statement, 2007).

According to Speight (2004), petroleum coke is a by-product of petroleum refining industry, with a high calorific value, low cost and a sulfur content depending on the type of oil which originates it. Due to increasing quantities of processed heavy oil, the production of coke has increased. The high availability of pet coke makes it attractive to the some industries, mainly for the generation of electricity (Wang et al. 2004).

The worldwide production of petroleum coke in 2007 was 91 Mt (million tonnes) based on the annual energy outlook 2008 of the EIA. The price of the petroleum derivatives is related to the international price of coal. It appears that the price of petroleum coke was always less than the price of coal. From July 2004 the pet coke prices increased close to the price coal. However, between July 2006 and January 2007 petroleum coke price exceeded the price of coal. For this reason, the use of coal or petroleum coke must now be more technical than economical (Santos et al. 2003).

After the description of the main characteristics of pet coke and coal, used as fuel in IGCC, plants the most representative aspects of this technology are shown. Figure 2 provides the main components of an installation and the different levels of integration possibilities in IGCC plants.

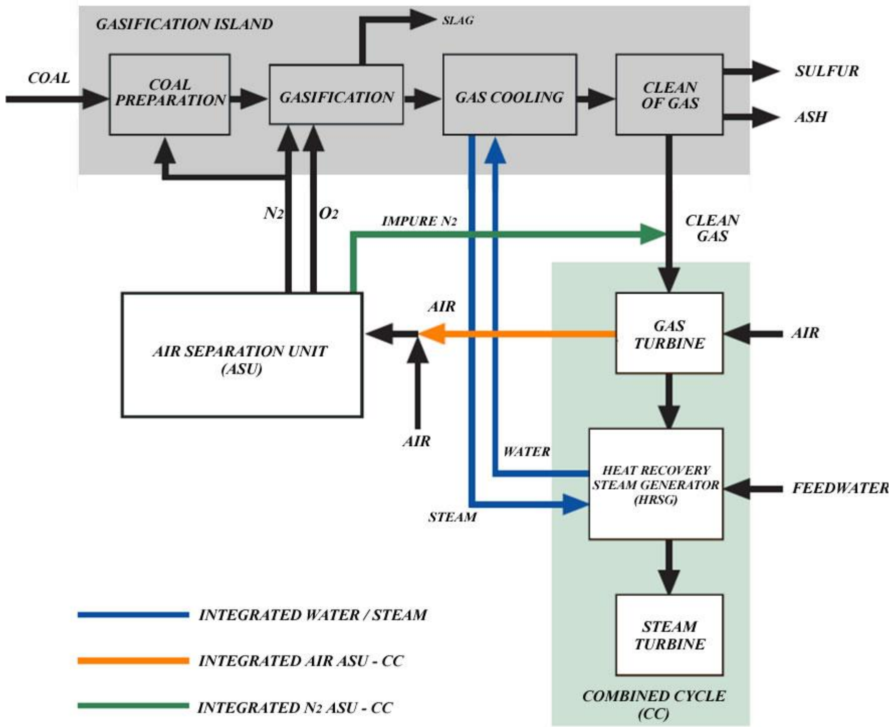


Figure 2. Diagram of IGCC power plant (Treviño et al. 2003)

According to Treviño (2003), the integration of the water/steam systems is common in all IGCC power plants in operation. By contrast, the integration between ASU and CC is a much more controversial. The highly integrated designs can increase the plant efficiency, since they reduce the consumption of auxiliary air compressors. However, involve longer boot times, which consumed fuel support (natural gas in most cases).

IGCC plants, using coal as fuel operating in Europe have an highly integrated design aiming a high efficiency while in the U.S., with lower fuel prices, are proposed the high availability and flexibility offered by the non-integrated design. In the current design tendency part of the air needed by the ASU comes from the compressor of the gas turbine and part of a separate compressor.

EVOLUTION AND PROSPECTIVE OF IGCC TECHNOLOGY

In planning future electricity supply the most important factors are the security of energy supply, the environmental impacts and the final energy price. In this context it should consider the IGCC technology from the perspective of each one of these factors.

The future development of IGCC plants is focused on improved efficiency and reduced investment costs. In addition, reduced emissions are expected, especially CO_2. According to NETL (2008), Table 1 shows the decrease in the cost of investment and the increase is thermal efficiency from the experience of the IGCC plants since 1997. It is also presented in Figure 3, a projection from 1997 to 2015, based on the consolidation of commercial power.

Table 1. Decrements of investment cost and thermal efficiency increase for 1990 to 2015 period (NETL, 2008)

Year	Cost Investment (USD/kW)	Efficiency (HHV,%)
1997	1450	39.6
2000	1250	42
2010	1000	52
2015	850	> 60

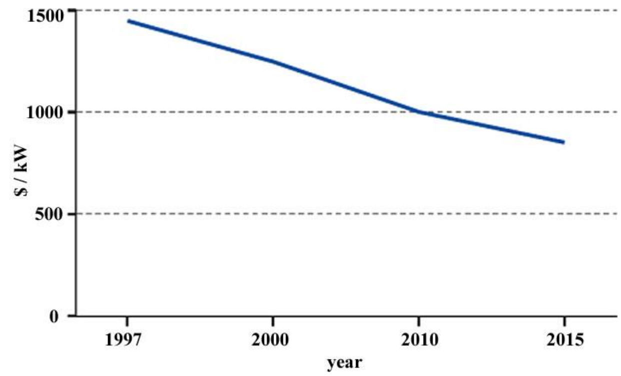


Figure 3. Expected cost of IGCC plants (Treviño et al. 2003)

According to Franco et al. (2009), currently are being built or upgraded a large amount of combined cycle plants throughout the world, especially in developed countries. Regarding existing IGCC plants, Table 2 illustrates the main projects implemented worldwide (Treviño et al. 2003).

Table 2. Some of the IGCC plants installed around the world.

Project - Location	Start-Up	Net Power	Feedstock	Gasification Cycle	Gasification Technology
Cool Water, USA	1984	120 MW	Coal	GE 107E	Texaco
Nuon, Buggenum, The Netherlands	1994	253 MW	Coal / Waste and Biomass	Siemens V94.2	Shell
Wabash River, Indiana, USA	1995	262 MW	Coal / Petroleum Coke	GE 7FA	E-GASTM
Tampa Electric, Florida, USA	1996	250 MW	Coal / Petroleum Coke	GE 7F	Texaco
ELCOGAS, Puertollano, Spain	1997	282,7 MW	Coal / Petroleum Coke	Siemens V94.3	Entrained Flow
SUV, Vresova, Czech Republic	1996	350 MW	Lignite	2 x GE 9E	Fixed Bed, Lurgi
SVZ, Schwarze Pumpe, Germany	1996	40 MW	Lignite /Residues	GE 6B	Noell
Fife Energy, Scotland	2003	109 MW	Coal /Residues	GE 6FA	BGL
Sulcis, Cerdeña, Italy	2006	450 MW	Coal	–	Shell
Clean Coal Power, Nakoso, Japan	2006	250 MW	Coal	–	Mitsubishi
Piñon Pine, Nevada, USA	–	100 MW	Coal	GE 6FA	KRW
Global Energy, Kentucky, USA	–	500 MW	Coal /Residues	–	BGL
Texaco El Dorado, Kansas, USA	1996	40 MW	Petroleum Coke	GE 6B	Texaco
Motiva, Delaware, USA	2000	240 MW	Petroleum Coke	2 x GE 6FA	Texaco
CITGO, LA, USA	2006	570 MW	Petroleum Coke	3 x GE 7FA	Texaco
IOC, Orissa, India	2006	180 MW	Petroleum Coke	GE 306B	Shell
API, Falconara, Italy	2000	260 MW	Visbreaker tar	ABB 13E2	Texaco
SARLUX, Cerdeña, Italy	2000	550 MW	Visbreaker tar	3 x GE 9E	Texaco
Exxon Mobil, Singapore	2000	180 MW	Visbreaker tar	2 x GE 6FA	Exxon
NPRC, Sekiyu, Japan	2003	342 MW	Residual Oil	MHI 701F	Texaco

Regarding the impact and environmental legislation it is important to emphasize that whatever the fuel (petroleum coke or coal) the IGCC technology should be implemented in compliance with the emission standards for contaminants, especially in relation to SO_2. Despite that an IGCC power plant presents a good behavior on the issue of regulated air pollutants (SO_2, NO_X, particulates). It is possible to establish that the overall impact is a limited contaminant, waste products are commercial and emit less CO_2, mercury and heavy metals that other processes based on coal.

ENERGY BALANCE OF GASIFICATION

Gasification is a thermo-chemical process that transforms carbonaceous materials, such as coal or coke, into a fuel gas (synthesis gas - syngas) through it partial oxidation with air, oxygen or steam.

Coal gasification is a process that allows removing certain contaminants before burning the gas. The produced gas is burned in combined cycles with high efficiencies, allowing further increase, what reduces CO_2 emissions per unit of energy produced and will, even more, in future installations. According to Fernández (2006a), one factor that should be considered around the gasification process and gas cleaning is the cost associated with the production of energy.

The synthesis gas, i.e., the gas produced from gasification, contains most of the chemical energy of the fuel fed (coal / coke). For the modern gasifiers with high fuel conversion, we can establish roughly the distribution of the energy supplied with the initial fuel:

- Energy content in synthesis gas (calorific value): 75% of the calorific value of coal.
- Sensible heat of synthesis gas: 15%. This energy is recovered by cooling the gas in steam generation process.
- Energy content in solid waste (molten slag and ash weight), and heat losses to the environment: 10%.

Figure 4 shows the possibilities in a gasification plant. The combination of the different production units in a modular way allows schemes to adapt the basic design of an IGCC plant to a configuration of multiple plants, fitting optimally the market demands at any time to obtain different products (Treviño et al. 2003).

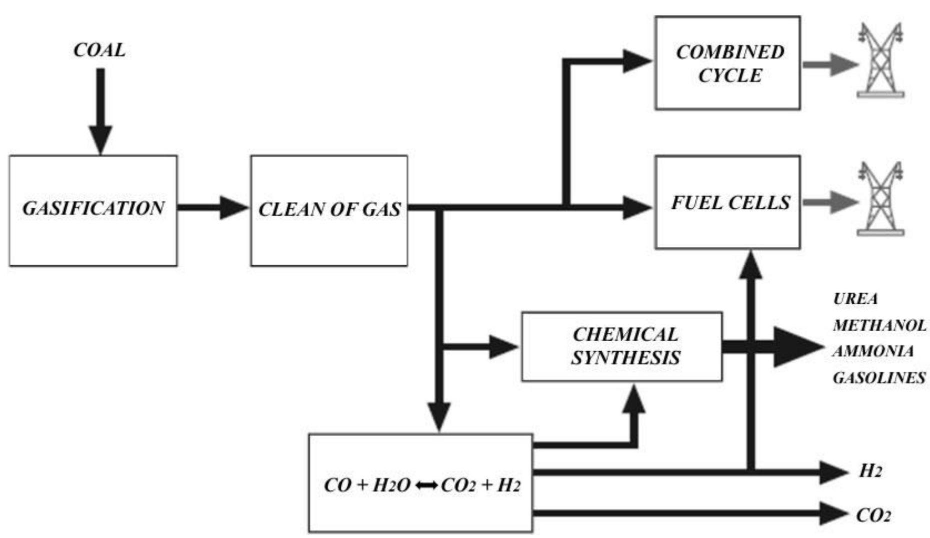


Figure 4. Applications gasification (Fernández al. 2006a)

THE CHEMISTRY OF THE GASIFICATION PROCESS

Coal and other fuels can be converted into gas by a processes in which oxygen and steam are provided at high temperatures at sub-stoichiometric conditions conversion (lower oxygen content than the required for complete combustion). Conversion reactions are both exothermic and endothermic. In the exothermic reactions energy is released in the form of heat that is consumed in the process or in the flue gas, while in the endothermic reactions energy is absorb to release volatile elements or compounds (Martínez al. 2008).

The possible responses are numerous, but the most significant are shown in Figure 5, where are indicate reactions of sulfur in the fuel mix with hydrogen to form H_2S and COS in low proportion, it means that the atmosphere is avoided reducing SO_2 combination. The H_2S is soluble in organic compounds, amines, do it can be removed from some process. The COS is hydrolyzed and reduced to H_2S in a reactor for treatment and almost completely remotion, producing a sulfur fuel gas.

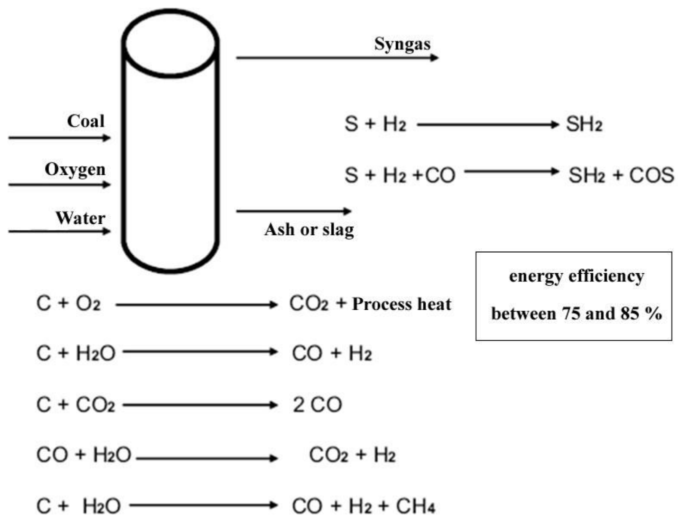


Figure 5. Gasification Process (Martínez al. 2008).

TYPES OF GASIFIERS

There are several types of gasifiers that can be used for the development of gasification, and different factors are used in their classification: heat power produced, type of oxidizing agent, pressure and relative movement of the fuel, the gasification agent and others. According to García-Bacaicoa et al. (1994), the selections the type of gasifier depends on the characteristics of the fuel to be gasified and the final use of gas energy produced.

Currently, the gasification process takes places in high pressure, between 10 and 100 bar, thereby reducing the volume of the reactors, both gasification and gas cleaning. There are different types of reactors and technologies, all working with oxygen or a mixture of steam and oxygen as gasifying agent, the entrained flow, fluidized bed and fixed bed gasifier are from previous designs that have already been used for decades (Martínez al. 2008).

Entrained flow gasifier

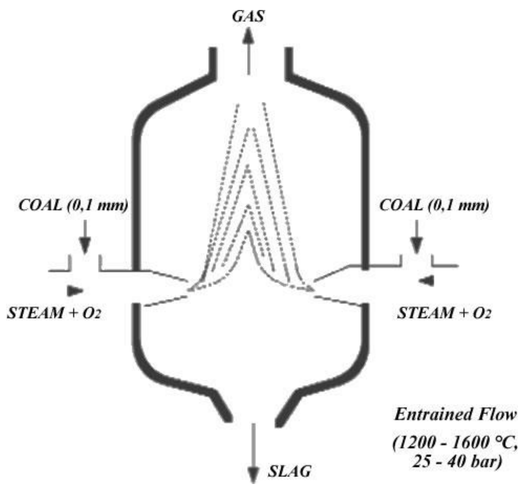


Figure 6. Entrained flow gasifier

Figure 6 shows the entrained flow gasifier. This reactor is preferred in the electricity generation plants, looking for an easier process to obtain clean gas without tar and ashes, as all the mineral matter is transformed into molten slag that is not leachable when deposited in the landfill of sterile.

Fluidized bed gasifier

The design is similar to the fluidized bed boilers coal with particle sizes smaller than 6 mm is fed from the bottom, sometimes mixed with lime if some retention of sulfur in coal is desired, oxygen and water vapor is injected into the bottom. Figure 7 shows a scheme of a Fluidized bed gasifier.

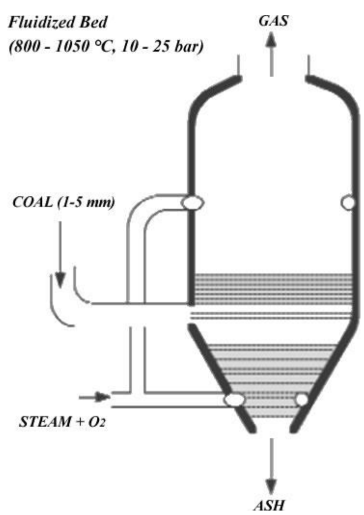


Figure 7. Fluidized bed gasifier

The temperature of the hottest area of the reactor is between 800 and 1050°C according to the type of operation, the operation pressure is between 10 and 25 bar. The mineral matter comes out the bottom as ash. The process is very suitable for highly reactive coals, coals of high volatile content. Sub-bituminous coal allows the treatment of fuels with high ash content.

Fixed bed gasifier

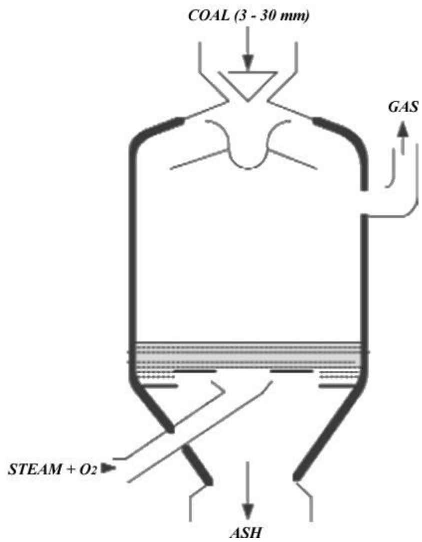


Figure 8. Fixed bed gasifier

Figure 8 shows a scheme of a fixed bed gasifier. The dry coal is fed from the top of the reactor, and descends slowly reacting with the gases flowing counter currently through the bed. On its way down, coal successively experienced the drying, heating, pyrolysis, gasification and combustion stages. The ashes can be removed or dried. The product has a low gas temperature (400-500 ºC) and contains significant amounts of tars and oils.

Considering the previous classification, Figure 9 provides a list of the leading gasification technologies indicating also the developer/supplier in each case (Rezaiyan et al. 2008).

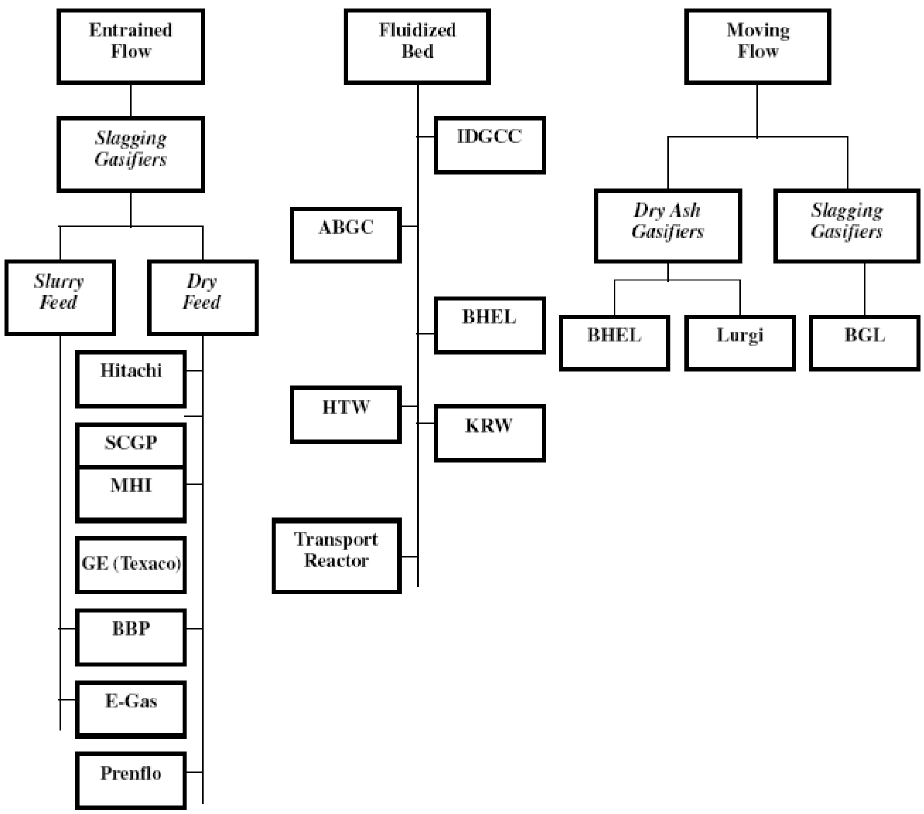


Figure 9. Coal gasification technology suppliers by flow characteristics (Rezaiyan et al. 2008)

CO_2 CAPTURE AND SEQUESTRATIONAPTURE AND SEQUESTRATION

Currently in the energy and industrial sectors there exist several viable methods of CO_2capturing, with the possibility of absorption by chemical or physical methods. Both can be carried out by pre-combustion, post-combustion and oxy-combustion technologies. The chemical absorption technology is well developed, it has been in used for several years in power generation (coal, gas), chemical plants, fertilizer production, etc. It reaches an absorption efficient of 99% (Fernández al. 2006b).

The physical absorption technology is innovative and is used preferentially in high pressure. In the IGCC plants both methods can be used, pre-combustion and post-combustion. The CO_2 capture systems for pre-combustion are commercially available, but not yet implemented in any IGCC plant incorporating CO_2 capture. According to Booras et al. (2000), the cost of energy produced would be significantly lower than IGCC coal power plant and ultra-supercritical to improve competitiveness in relation to a Natural Gas Combined Cycle (CCGN) at current prices for both fuels existing technologies in Spain.

Figure 10 provides the thermal efficiency of coal-fired power generation. Note that the multi-coloured line shows efficiencies for state-of-art plants on a net electrical output, lower heating value basis.

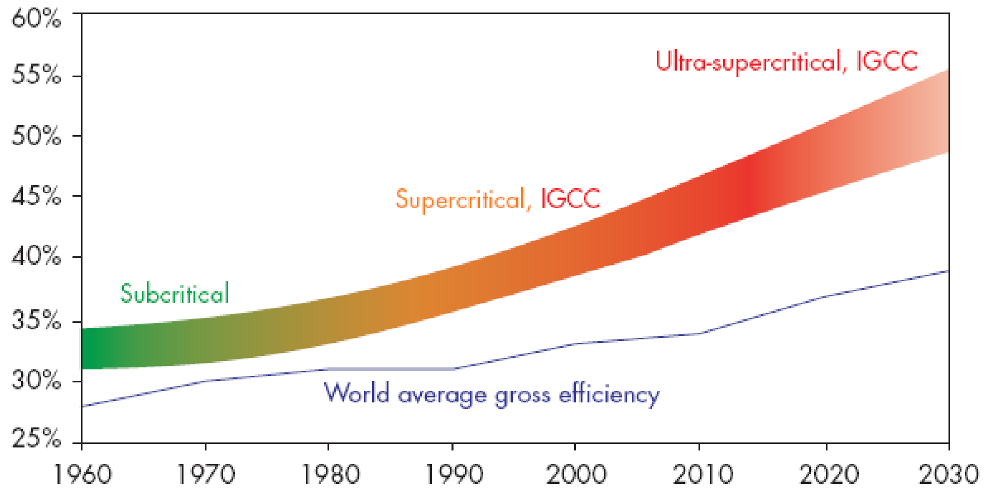


Figure 10. Thermal efficiency of coal-fired power generation

Only four successful IGCC plants have so far been built: two in Europe and two in the United States. At high temperatures, efficiency can be as high as 41%, or even higher with the latest gas-turbine models. Based on the Reference scenario supply projections of the world energy outlook 2007, for IGCC to establish itself in the market, further development to bring down costs and improve operational flexibility are necessary.

A number of plants are being built in China and Japan, and several others are being considered elsewhere. IGCC has inherent advantages for emission control, as gas clean-up takes place before combustion of the fuel gas, using relatively small equipment, and solid waste is released in the form of a vitrified slag. If carbon capture and storage (CCS) becomes an established mitigation measure, then CO_2 capture from an IGCC plant is technically easier than post-combustion capture from a conventional steam plant (IEA - WEO, 2007).

Moreover, a number of other technologies and hybrid systems are at the research and development stage, notably in the United States and Japan. Integrated gasification-fuel cell combined cycle involves combining a fuel cell and the combined cycle component of IGCC to generate power. Efficiency could reach 60%. For example, there is a demonstration project in China, Yantai IGCC Plant (with the option of future CCS and hydrogen production) (Shisen, 2006).

A demonstration power plant of 300-400 MW, burning high-sulphur (2-3%) bituminous coal, is planned for 2010 in China. It will closely follow the China Huaneng (CHNG) Greengen first stage plan for a 250 MW IGCC plant. The second phase of the Greengen will have a 400 MW IGCC and CO_2 separation / H_2 power and is planned for operation in 2015 (IEA - WEO, 2007).

COSTS OF CO_2 CAPTURE

Based on US Department of Energy (2006), the cost of electricity increases are in the range of 20 to 55% for IGCC plants, from 35 to 70% for combined cycle power plants with natural gas and from 40 to 85% for pulverized coal plants when using CO_2 capture. For existing plants, the options for CO_2 capture and their associated costs are highly dependent on location. According to Gibbins (2006), For each thermal power plant factors affecting the cost of capture is characterized by the definition of technology and its maturity, and the system boundary of which consider the cost.

There are several indicators being used to consider the cost of capturing CO_2 (investment cost, cost of electricity, cost of CO_2 avoided or cost of the CO_2 captured or eliminated). Within the emerging technologies for capturing CO_2 for both coal gasification and for the reform of natural gas, are incorporated into innovative systems that combine reaction and separation, such as reform with improved desorption reaction, the shift reaction with water and enhanced desorption reaction, the reform membrane and shift reaction with water and membranes.

According to IEA and EPRI databases (2007), for emerging technologies, especially CCS, the main challenge is to lower costs and to demonstrate reliable operation. Figure 11 shows different scenarios indicators for the OECD coal-fired power plant investment cost. The addition of CCS equipment increases significantly the capital cost of capacity for all coal technologies, not least thermal efficiency is lower.

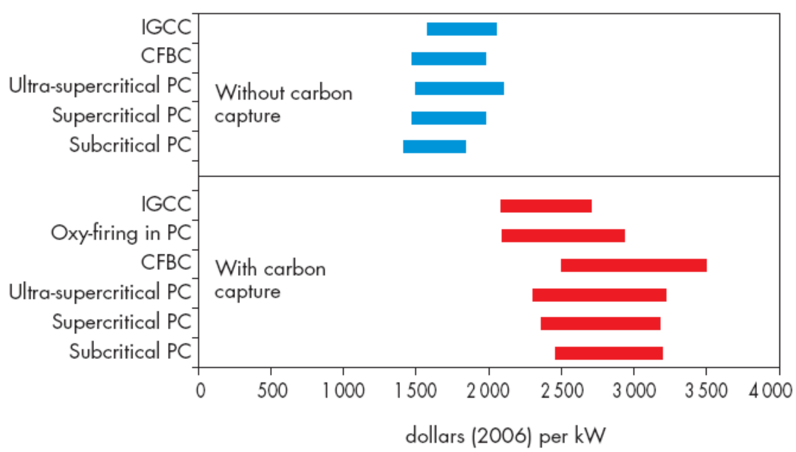


Figure 11. OECD Coal-fired power plant investment cost

While clean coal technologies have made significant progress in the last decade or so, there are still considerable challenges in exploiting the remaining potential, particularly for low-grade coals. For high-moisture coals, a cheaper and more efficient drying system is needed together with a reliable system for feeding these coals into a pressurised gasifier. For high ash coals, the main challenge is to overcome fouling problems in gasification and combustion. For all types of coals, gas clean-up at higher temperature is needed to obtain higher efficiency in IGCC units.

CONCLUSIONS

The technology of Integrated Gasification Combined Cycle is presently applicable. It results particularly attractive for cogeneration in oil refineries. The IGCC should be included already in the projects for expansion of energy infrastructure around the world, even in the development plans in the short, medium and long term. From the review of the state of the art it is possible to establish that in the world to the research and development in this area are taking place mostly in EE. UU and Japan.

One of the most important factors of IGCC generation costs plants are variable costs of fuel used, coal, petroleum coke or other fuel of low quality. IGCC technology competes directly with the central combined cycle natural gas and competition is reduced costs of fuel.

On the other hand, the economic and financial variables involved in investment projects in energy sector, requires a detailed study that will assess, together with the environmental and social benefits.

Regarding the type of fuel used in IGCC plants, it must be taken into account the possibility of blending coals with low sulfur content, striving to achieve the important consumer markets of the plants. So it can be a balance between production and consumption of waste from processing oil.

The reduction of CO_2 emissions in all systems does not have a clearly defined route. The major problems are: the reduction of conversion efficiency of the cycle with the incorporation of procedures for the separation of CO_2, the difficulty of implementing these processes to the required volumes and the uncertain prospects of disposing the sequestered CO_2.

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REFERENCES

BOORAS, G., HOLT, N., WOLK, R. (2000). *"Analysis of innovative fossil fuel cycles incorporating CO2 removal"*. Gasification Technologies Conference. San Francisco - US.

Brazilian National Agency of Petroleum, Natural Gas and Biofuels. ANP (2007), [Online]. Available: http://www.anp.gov.br/

World Energy Council (2007), *"WEC Statement"*. [Online]. Available: http://www.worldenergy.org/

ENERGY INFORMATION ADMINISTRATION - EIA (2008). *"Annual Energy Outlook Annual Report"*. [Online]. Available: http://www.iea.org/

INTERNATIONAL ENERGY AGENCY – IEA WEO (2007). *"World Energy Outlook 2007 – China and India Insights".* Reference Scenario Supply Projections.

ELECTRIC POWER RESEARCH INSTITUTE – EPRI / MIT. (2007), *"Database IEA and EPRI".*

FERNÁNDEZ, I. P. (2006a), *"Generación termoeléctrica: Gasificación Integrada en Ciclo Combinado"*, E.P.S. de Ingeniería. Universidad de Oviedo, Gijón, pp. 14–20.

FERNÁNDEZ, I. P. (2006b), *"Captura y almacenamiento de CO_2 procedente de instalaciones de combustión para la generación de energía eléctrica"*, Grupo de investigación de Ingeniería Térmica. Universidad de Oviedo. pp. 35–42.

FRANCO A.; DIAZ A. (2009), *"The future challenges for clean coal technologies: Joining efficiency increase and pollutant emission control*". Energy, vol. 34, pp. 348–354.

GARCÍA-BACAICOA, P., BILBAO, R., ARAUZO, J., SALVADOR, M. L. (1994), *"Scale-Up of Downdraft Moving Bed Gasifiers (25-300 kg/h) – Design, Experimental Aspects and Results"*, Bioresource Technology, vol. 48, pp. 229-235.

GIBBINS, A. (2006), *"Capture ready fossil fuel plants: definitions, technology options and economics"*. 8th International Conference on Greenhouse Gas Control Technologies.

MARTÍNEZ, J. (2008), *"Electricity generation technologies report"* El futuro del carbón en la política energética española. Fundación para Estudios sobre la Energía.

NATIONAL ENERGY TECHNOLOGY LABORATORY - NETL, U. S. DOE. (2008), [Online]. Available: http://www.netl.doe.gov/

TREVIÑO, C. M. (2003), *"Tecnología de gasificación integrada al ciclo combinado: GICC. Aplicación real en España: ELCOGAS. Puertollano"*. EnerClub - Club de la energía de España.

US Department of Energy (2006). *"CO_2 Capture: Comparison of cost & performance of gasification and combustion-based plants"*.

REZAIYAN, J., CHEREMISINOFF, N. P. (2005), *"Gasification Technologies: A Primer for Engineers and Scientists"*, CRC; 1 edition.

SANTOS, A. R., SILVA, R. J. (2008), *"Análisis del consumo de coque de petróleo en algunos sectores industriales"*, vol. 19, n.2, pp. 93 - 101.

SHISEN, X. (2006), *"The status and development trends of IGCC",* International Conference on Thermal Power Research Institute.

SPEIGHT, J.G. (2004); *"New Approaches to Hydroprocessing"*, Catalysis Today, vol. 98, pp. 55 – 60.

WANG, J., ANTHONY E.J., ABANADES J.C. (2004); *"Clean and efficient use of petroleum coke for combustion and power generation"*, Fuel, vol. 83, pp. 1341 – 1348.