

COMBINED PRODUCTION OF HYDROGEN AND ELECTRIC POWER FROM HEAVY RESIDUES: THE IGCC ANSWER TO THE REFINERY NEEDS

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Refineries, in all parts of the world, are facing growing difficulties in finding market outlets for the heavy, high sulphur, residues. The reasons for this are:

- crude oils are getting heavier and richer in sulphur, thus increasing the yield of residual oil;
- increasingly stringent environmental legislation obliges Refiners to meet higher product qualities and restrict the market for residual product slates utilization. The lower and lower sulphur limits of gasoline and gas oil products are met with increasing consumption of hydrogen.

Integrated Gasification Combined Cycle (IGCC) is a promising answer to these refinery needs: it is a commercially proven technology available for the combined production of hydrogen and electric power from fossil fuels, heavy residue oils as well as from coal and coke. In this paper asphalt will be assumed as a feedstock with the intent to represent the most exhausted and unvalued refinery product of European refineries.

The design of the IGCC plant can easily comply with several needs of the current market:

- Environmental: emission well below the limits of the European Directive, without penalizing plant efficiency and investment cost.
- Production capacity: flexible design to meet different requests of hydrogen or electric energy.
- Productions costs: competitive Cost of Electricity (C.O.E.) and Cost of Hydrogen (C.O.H.) for selling in the market.

IGCC plants can also be associated with CO₂ capture and sequestration facilities to give an effective answer to the most sever, future, environmental constraints.

This paper describes some IGCC plant alternatives, sized to produce different amounts of hydrogen and electric energy. Overall performances and investment costs are evaluated and discussed by means of a sensitivity analysis on Cost of Electricity (C.O.E.) and Cost of Hydrogen (C.O.H.).

Preliminary remark

This work is the prosecution of the study that the same authors presented at the previous Hydrogen Conference (Pisa, Italy, May 16-19, 2004): *"IGCC plant: a practical pathway for combined production of hydrogen and power from fossil fuels"*.

The work performed in this study takes reference from the results of case A, which processed asphalt from a deasphalting unit to produce 150,000 Nm³/h of hydrogen, and investigates five additional IGCC plant configurations, to make a sensitivity analysis on C.O.E. and C.O.H. and to evaluate the loss of performances due to the CO₂ sequestration. As a consequence, general information on the plant configuration are also contained in the paper presented at the Hydrogen Conference of year 2004.

IGCC in the chemical industry

Gasification is the conversion of either a solid (coal, coke, biomass, solid waste) or a liquid fuel (oil, tar, pitch) into a gas, often identified as syngas, in which the major components are hydrogen (H₂) and carbon monoxide (CO).

During the last century, gasification was mainly used to convert coal into fuel gas for domestic heating and lighting. In the last few decades of the past century, gasification was used in the petrochemical industry for the manufacture of chemical products.

Today gasification is also integrated with power production, acting as a bridge between coal or heavy fuel oils and the gas turbines. Gasification of such fuels generates a fuel gas that, after cleaning, can be used in a gas turbine combined cycle power plant. The resulting process configuration (Integrated Gasification Combined Cycle – IGCC) is the only power technology that, even burning coal or high sulphur residues, can approach the environmental performance of natural gas fired systems. In fact the syngas, before firing in the gas turbine, can be cleaned to reduce to very low levels contaminants such as sulphur compounds and particulates. Furthermore, the syngas can be mixed with nitrogen and/or saturated with water to reduce similarly the nitrogen compounds originated in the combustion.

In addition, IGCC represents the most promising technology for the CO₂ capture, based on the only utilization of the state-of-art technologies.

This paper describes six alternative IGCC plant configurations for the combined production of hydrogen and power, with and without the CO₂ capture, starting from a fossil fuel, i.e. asphalt from a refinery solvent deasphalting unit.

Bases of design

The IGCC is designed considering different power generation plants to produce alternatively 150,000, 100,000 or 50,000 Nm³/h (99.8 % purity) of hydrogen at 30 barg, and approx 350 MWe of electric power. Both the alternatives with and without capture of the produced CO₂ are considered. Plants are designed to process, in an environmentally acceptable manner, asphalt, which is produced by a deasphalting unit fed with Visbroken Vacuum Residue (LHV equal to 38,124 kJ/kg and 7.58 % wt sulphur content).

The site conditions assumed for the IGCC plant are a green field on a seacoast with an average air temperature of 9°C and an average sea water temperature of 12°C. Table 1 summarizes the six cases that have been evaluated.

Table 1 – Description of the process alternatives.

CASE	CO ₂ capture	Hydrogen production, Nm ³ /h
A.1	No	150,000
A.2	Yes (1)	150,000
B.1	No	100,000
B.2	Yes (1)	100,000
C.1	No	50,000
C.2	Yes (1)	50,000

Note (1): 85% of asphalt carbon content.

The gasification is based on oxygen-blown entrained bed gasification, operating at a pressure at least suitable to feed the gas turbine (42 barg). For each alternative the IGCC plant design capacity is fixed to fulfil both the required production of hydrogen and the appetite of one gas turbine General Electric Frame 9FA. This gas turbine is representative of the current state-of-the-art of large commercial gas turbines suitable for syngas operation.

The IGCC Complex main products are hydrogen and electric energy; by-products are: sulphur (liquid or solid), solid by-products (metal cake) and carbon dioxide (alternatives recovering CO₂).

The overall gaseous emissions from the IGCC Complex, referred to dry flue gas with 15% volume O₂, shall not exceed the following limits:

- ◆ NO_x (as NO₂): ≤ 50 mg/Nm³
- ◆ SO_x (as SO₂): ≤ 10 mg/Nm³
- ◆ CO: ≤ 30 mg/Nm³
- ◆ Particulate: ≤ 10 mg/Nm³

These limits are lower than those defined by the applicable European Directive and are set in order to reduce the emissions without penalizing the plant efficiency and investment cost.

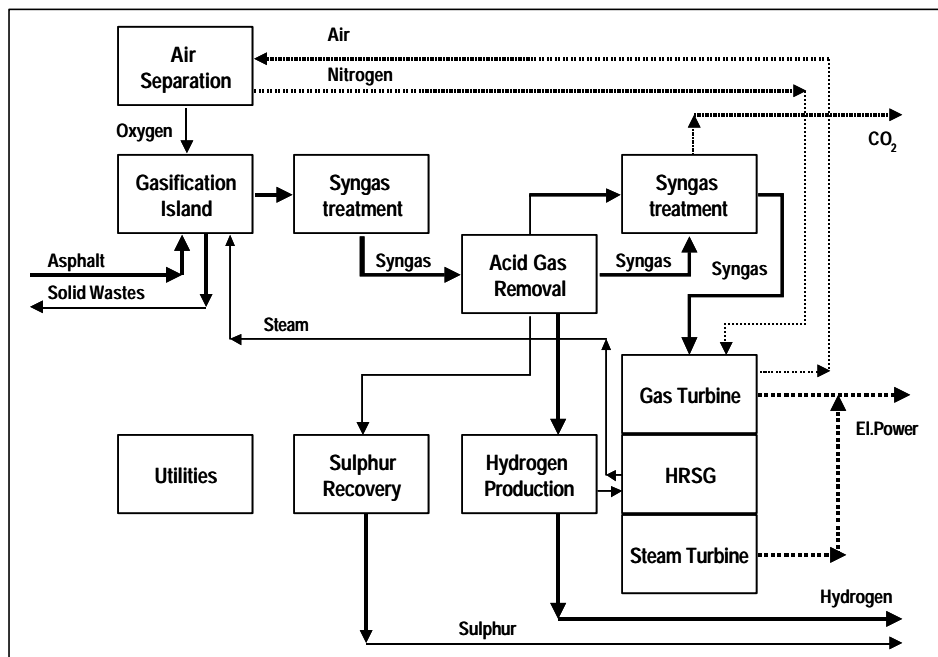
Description of the IGCC complex

The IGCC Plant is a multi unit complex (process and utility units), which is called to operate simultaneously in an integrated way. Its design can be easily optimised to meet the desired hydrogen and electric power production.

The following description makes reference to Figure 1, showing the IGCC block flow diagram and the main process streams. The main process blocks of the complex are:

- Feedstock storage and preparation;
- Air separation (cryogenic technology);
- Gasification, including black water/grey water treatment;
- Syngas treatment and conditioning, including acid gas removal (AGR);
- Hydrogen production.
- Combined cycle power generation.

Fig. 1 – IGCC Block flow diagram.



These basic blocks are supported by other ancillary units, such as sulphur recovery, tail gas treatment, and a number of utility and offsite units, such as cooling water, flare, plant/instrument air, machinery cooling water, demineralized water, auxiliary fuels, etc.

Each process unit of the complex may be a single train for the total capacity or split in two or more parallel trains, depending on the maximum capacity of the equipment involved or on the necessity to assure, through the use of multiple parallel trains, a superior degree of reliability.

The key and first process step is the entrained flow gasification, which is suitable both for solid and liquid feed. In this type of gasifier the feed, atomized oil, flows concurrently with the gasification agents (O₂ and steam). Residence time is very short, between 0.5 and 5 seconds; the temperature inside the gasifier is uniform and very high, from 1,300° to over 1,500°C, well above the ash fusion temperature.

Recovery of gasifier sensible heat is made through a water quench inside the gasifier and subsequent recovery of the degraded heat in external waste heat boilers, producing medium and low-pressure steam. The quench system permits to remove efficiently solids from the raw gas, before entering the downstream facilities. In addition, water quench is attractive for the downstream CO shift reaction, which increases the H_2/CO ratio. In fact CO shift requires large amounts of water in the gas, which can be conveniently added in the quench.

Syngas main components are H_2 , CO, CO_2 , H_2O and, additionally, H_2S and COS that need to be removed, and inerts. Downstream gasification, the shift reaction occurs on a catalyst suitable to process H_2S containing syngas (sour shift) to convert CO and water to H_2 and CO_2 . The shift catalyst promotes also the COS hydrolysis with its conversion to H_2S and CO_2 . Raw syngas is then treated in the syngas treatment and conditioning unit to remove all the contaminants and prepare the syngas to produce both hydrogen and electric energy.

A physical solvent washing makes the removal of acid gases (H_2S and CO_2). For alternatives without the CO_2 capture, in the acid gas removal (AGR) two clean syngas streams are produced: the first one taken from the H_2S absorber outlet is ready to be fed to the power island. The second one is further washed to remove CO_2 and then sent to a pressure swing adsorption unit for hydrogen purification. The hydrogen produced with a purity of 99.8% is sent to the plant battery limits at 30 barg, to be delivered to users by means of a dedicated pipeline. The CO_2 rich stream is compressed and mixed to the clean syngas upstream of the gas turbine.

For alternatives with the CO_2 capture, CO_2 is removed by the entire syngas stream entering AGR, and then dried/compressed to 110 bar in order to be delivered to geological storage reservoirs. The cost of CO_2 storage depends on local factors, such as transport distance, pipeline diameter and type of reservoir. At some locations CO_2 could have a positive value for enhanced oil recovery but at other locations transport and storage results in additional substantial costs.

In the sulfur recovery unit, the H_2S rich stream coming from the AGR regenerator is burned in the presence of oxygen in a muffle furnace, followed by two reactors in series where the Claus reaction takes place to produce liquid sulfur.

The oxygen required both for the gasification reaction and the Claus reaction is produced in the air separation unit (ASU), where air is fractionated by cryogenic distillation. The ASU is partially integrated with the power island as a portion of the compressed air required by the oxygen plant is delivered from the gas turbine compressor. For alternatives with the CO_2 capture, the absence of CO_2 as medium for NOx control and power augmentation is compensated with compressed nitrogen from the ASU, added to the syngas before feeding the gas turbine.

Performance data

The performance data of the six alternatives are summarised in Table 2.

Table 2 – Performance data.

Case	Fuel t/h	Gross Power Output MWe	Hydrogen production		Aux. Cons. MWe	Net Power Output MWe	Thermal Efficiency %	Net Electrical Efficiency %	Total Efficiency %
			Nm ³ /h	MWth					
A.1	165.9	466.0	150,000	449.1	124.9	341.1	25.6	19.4	45.0
A.2	168.0	461.2	150,000	449.1	188.1	273.1	25.2	15.3	40.5
B.1	142.4	451.0	100,000	300.1	104.4	346.6	19.9	23.0	42.9
B.2	144.2	446.1	100,000	300.1	159.3	286.8	19.6	18.7	38.3
C.1	118.7	436.0	50,000	150.0	84.7	351.3	11.9	28.0	39.9
C.2	120.1	430.9	50,000	150.0	131.2	299.7	11.8	23.5	35.3

Both electrical and thermal efficiency of the plant are referred to the feedstock Low Heating Value. The IGCC thermal efficiency is related to the hydrogen production.

The total efficiency is the sum of thermal and net electrical efficiency.

The feedstock flow rate shown in Table 2 is different for each alternative whose target is to produce sufficient syngas to fulfil both the required hydrogen production and the appetite of one GE 9FA gas turbine.

Investment cost data

The investment cost data of the six IGCC plants are reported in Table 3, showing the total investment cost split into the main sections of the IGCC Complex. Figures represent the total investment cost including the EPC and the Owner's cost.

Table 3 – Total Investment cost data.

CASE	MAIN IGCC SECTIONS INVESTMENT					Total Investment 10 ⁶ Euro
	Air Separation	Process Units	CO ₂ Compression	Power Island	Utilities & Offsites	
	10 ⁶ €	10 ⁶ €	10 ⁶ €	10 ⁶ €	10 ⁶ €	
A.1	95	269	0	167	112	643
A.2	99	274	22	166	112	673
B.1	86	245	0	164	105	600
B.2	93	250	20	163	105	631
C.1	69	207	0	162	98	536
C.2	78	211	18	161	98	566

Production costs

The following Table 4 provides the cost of electricity (C.O.E.) of the six alternatives. The cost of electricity has been evaluated on the basis of the following assumptions:

- Cost of Asphalt: 20 Euro/t (Asphalt value could be below 0)
- Price of hydrogen: 0.095 Euro/Nm³
- No selling price is attributed to the sequestered CO₂.
- 7,446 equivalent syngas operating hours of the (100% capacity).
- Total investment cost as given in Table 3.
- 10% discount rate on the investment cost over 25 operating years.
- Maintenance cost equivalent to approx 3.5% of the total capital costs.

Table 4 – Cost of electric power production.

CASE	Hydrogen prod., Nm ³ /h	Cost of H ₂ cent/Nm ³	C.O.E. cent/kWh
A.1	150,000	9.5	1.96
A.2	150,000	9.5	2.74
B.1	100,000	9.5	2.85
B.2	100,000	9.5	3.71
C.1	50,000	9.5	3.55
C.2	50,000	9.5	4.40

Sensitivity Analysis

To complete the evaluation, three diagrams are attached to the end of the paper:

- Fig. 2 - Cost of Electricity versus hydrogen production;
- Fig. 3 - Cost of Electricity versus Cost of Hydrogen (C.O.H.);
- Fig. 4 - Cost of Electricity versus Carbon tax, expressed in €/t of CO₂ emitted, for a cost of H₂ equal to 9.5 c €/Nm³.

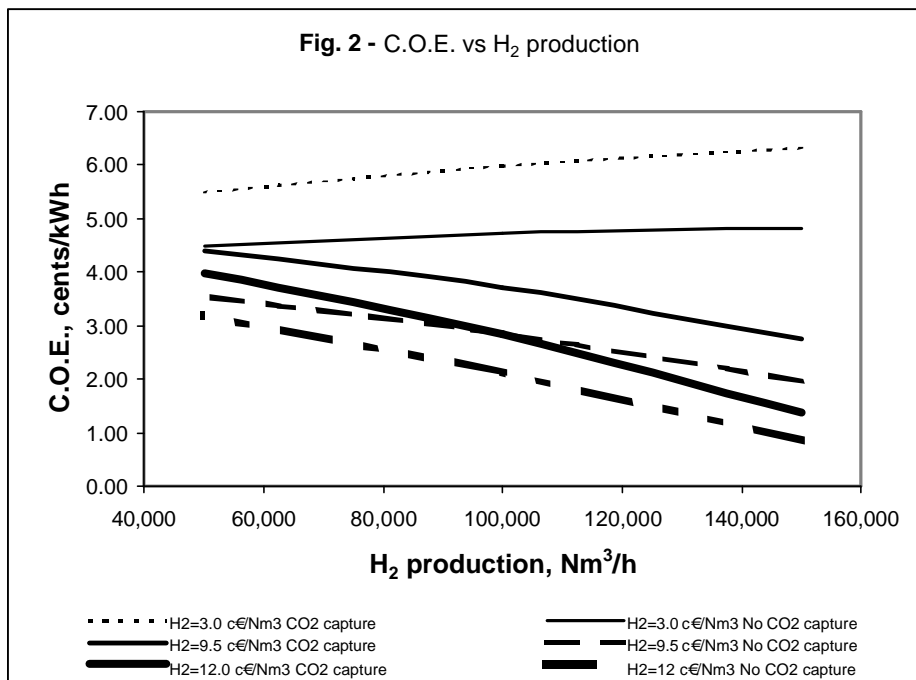
Analysis and conclusions

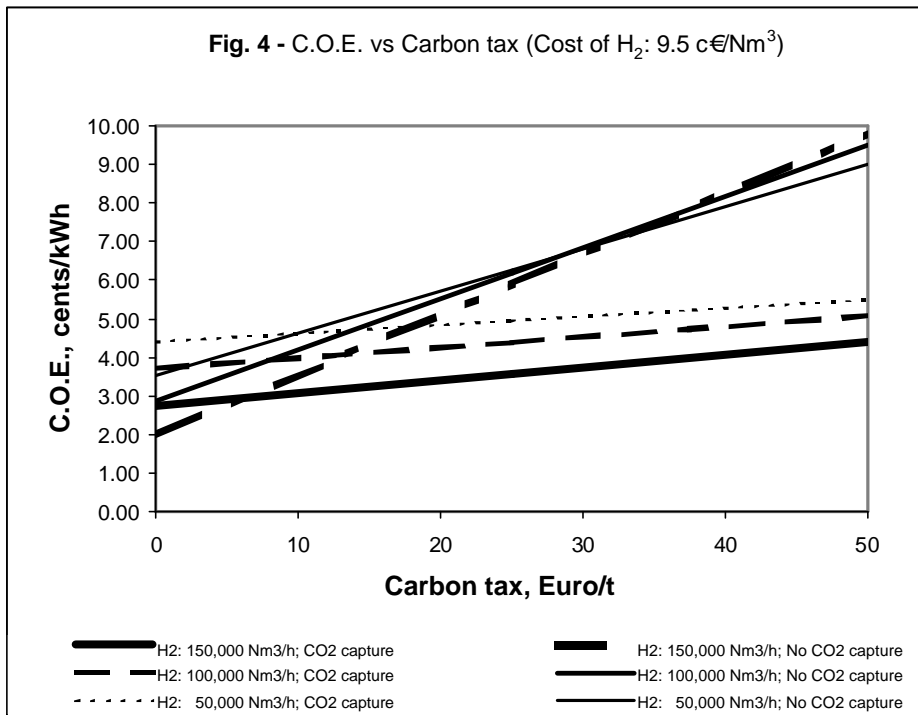
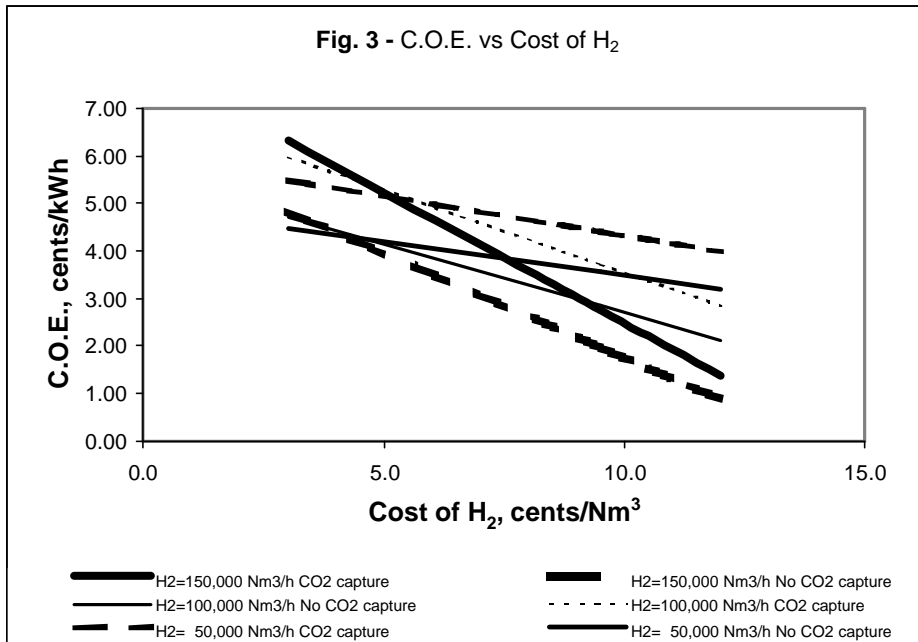
The analysis performed in this study lead to the following conclusions:

- Hydrogen and electric power are produced with an acceptable efficiency, taking into account the feedstock quality and the environmental performances, which are far superior to that of any other power producing technology known today, based on solid or liquid fossil fuels.
- The IGCC plant configuration and size can be easily adjusted to fulfil different requirements of electric power and hydrogen production. The CO₂ capture can also be made by using state-of-art technologies.
- The cost of electricity, obtained assuming a hydrogen price of 9.5 cents/Nm³, is attractive for all alternatives, including cases with the CO₂ capture, demonstrating the advantage of their combined production. This demonstrates that, in a competitive electric power market, the IGCC will always be able to dispatch power still maintaining hydrogen cost compatible with the market value.
- The convenience is demonstrated through a wide range of both the hydrogen production flow rate and the cost of hydrogen, values as can be deducted from the

sensitivity analysis diagrams reported; it should be considered that asphalt has been priced as a valuable feedstock, while it is recognized that it is really a burden.

- The penalties on the C.O.E., due to the CO₂ capture, depends both on the cost of hydrogen and the hydrogen production, ranging from additional 20% to 40%, with respect to the alternative without the CO₂ sequestration.
- For alternatives without the CO₂ capture, hydrogen and electric energy are equally produced, independently from the hydrogen flow rate, for a C.O.E. and a C.O.H. respectively equal to 4.1 cents/kWh or cents/Nm³. For alternatives with the CO₂ sequestration, the same considerations are made for a C.O.E. and a C.O.H. of 5.4.
- The capture of the CO₂ leads to a higher investment cost and to a loss of efficiency with respect to the alternatives without the CO₂ capture. However, the plant with CO₂ capture is economically convenient even at low level of carbon tax (less than 12€/t), depending on the hydrogen production and hydrogen cost.
- Improvements in the main areas like the gas turbines, gasifiers and Air Separation Unit are expected in the next years, thus making the IGCC alternative more and more attractive.





References

- Arienti S., 2002, Review of ISAB IGCC Plant Operation, PowerGen 2002, Milan – Italy.
- Davison J., L. Bressan and R.M. Domenichini, 2003, Coal Power Plants with CO₂ capture: the IGCC option, Gasification Technologies Conference 2003, San Francisco – USA.
- Domenichini, R.M. and Mancuso L., 2004, IGCC plants: a practical pathway for combined production of hydrogen and power from fossil fuels, H₂ age: when, where, why, Pisa – Italy.
- Farina G.L., L. Bressan and D. Todd, 1998, Oil Refining and Zero Fuel Oil Production with Integrated Gasification Combined Cycle, Heavy Oil Conference, USA.
- Farina G.L., L. Bressan and S. Darling , 1999, Utilization of refinery residues with cogeneration, The 1999 European Oil Refining Conference & Exhibition, Taormina – Italy.
- Pisacane F., R. Domenichini and L. Fadabini, 1998, Dynamic Modeling of the ISAB Energy IGCC Complex, 1998 Gasification Technologies Conference, San Francisco – USA.
- Ubis T., L. Bressan and L. O'Keefe, 2000, The 800 MWe Piemsa IGCC Project, Texaco Gasification Technologies Conference 2000, San Francisco – USA.