

# COAL POWER PLANTS WITH CO<sub>2</sub> CAPTURE: THE IGCC OPTION

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## ABSTRACT

One of the most promising technologies for capture of CO<sub>2</sub> from power generation plants based on fossil fuels, is Integrated Gasification Combined Cycle (IGCC).

This paper summarizes the results of a study carried out by Foster Wheeler for the IEA Greenhouse Gas R&D Programme (IEA GHG).

The study is aimed at assessing the current state of the art of coal based 750 MWe nominal IGCC, with and without CO<sub>2</sub> capture, and the potential for improvements, between now and 2020. Several alternatives are evaluated to analyze the performance and investment cost sensitivities to some important technology options:

- gasifier selection: due to the large plant size and to the specific application oxygen blown entrained bed gasifiers are adopted by studying two possible designs:
  - Slurry Feed Gasifier, with product gas cooling by Water Quench (SFG-WQ);
  - Dry Feed Gasifier, with product gas cooling in a Waste Heat recovery Boiler (DFG-WHB).These two types of gasifier cover the broad range of entrained gasifiers currently available.
- H<sub>2</sub>S removal and CO<sub>2</sub> capture: washing options with physical (PhS) and chemical solvents (ChS) are investigated;
- Shift of syngas containing sulphur compounds (Sour Shift) versus shift of clean syngas (Clean Shift).

All the plant configurations are based on two 9FA frame gas turbines selected as representative of the current state-of-the-art of large commercial gas turbines suitable for operation with IGCC syngas.

The Air Separation Unit is cryogenic, integrated with gas turbines (i.e. a portion of compressed air for the plant is extracted from the gas turbine, while the remaining part is provided by air compressor). Nitrogen produced by the ASU and exceeding the process consumption is injected into the gas turbine for NO<sub>x</sub> reduction and power augmentation.

Sensitivities to a variety of potentially significant parameters are assessed to help to determine the way forward for IGCC with CO<sub>2</sub> capture, i.e.:

- gasification pressure;
- separate removal of CO<sub>2</sub> and H<sub>2</sub>S vs production of a combined CO<sub>2</sub>/H<sub>2</sub>S stream.

For each alternative plant configuration, overall performances and investment cost are estimated and used to evaluate the electric power production cost. From the comparison of economic data for plant configurations with and without CO<sub>2</sub> capture, the cost of CO<sub>2</sub> avoidance is also determined.

## SCOPE OF THE STUDY

The study investigate alternative power generation plant designs, based on coal gasification, with and without capture of the produced CO<sub>2</sub> in order to determine the increase of the cost of the electricity due to the capture of CO<sub>2</sub>. The primary purpose of the study is, therefore, the evaluation of the technologies that can be used in these complex power generation schemes to optimize efficiency and capital cost and reduce, at the same time, emissions to the atmosphere.

The study is based on commercially available technologies and developing technologies close to commercialization, evaluating costs and performances of plants which can be presently engineered and built. The study have, however, considered possible improvements to current technologies and also potential future technologies in order to assess the likely performance of a plant in the year 2020.

The study investigated 13 alternative designs of power generation plant, which differ for the gasification technology, the gasification pressure, the presence or not of a shift step and, the acid gas removal process. For each alternative sufficient basic design data have been developed in order to evaluate performance and capital cost. For some alternatives specific optimization studies have been made in order to select the most convenient acid gas removal process and the best arrangement of the shift reactors.

The study concluded with a comparison of the cost and and performance data of the various alternative designs.

## BASES OF DESIGN

The IGCC plants are designed to process, in an environmentally acceptable manner, an open-cut coal from eastern Australia and produce electric energy to be delivered to the local grid. The coal has a low heating value (LHV) equal to 25870 kJ/kg and a sulphur content equal to 1.1% wt (dry ash free). The plant site is a green field located on the NE coast of The Netherlands; with an average air temperature of 9°C and an average sea water temperature of 12°C.

For each of the alternatives considered, the IGCC design capacity has been fixed to match the appetite of the selected gas turbines which are two General Electric Frame 9FA. These gas turbines are representative of the current state-of-the-art of large commercial gas turbines suitable for use with IGCC fuel gas. The resulting overall net power output is nominally 750 MWe.

The IGCC Complex main product is electric energy. By-products are:

- Sulphur (liquid or solid)
- Carbon Dioxide for the alternatives recovering CO<sub>2</sub>
- Solid by-products: slag, fly ash and filter cake, depending on the gasification technology.

The overall gaseous emissions from the IGCC Complex referred to dry flue gas with 15% volume O<sub>2</sub> shall not exceed the following limits:

NO <sub>x</sub> (as NO <sub>2</sub> )	:	≤	80 mg/Nm <sup>3</sup>
SO <sub>x</sub> (as SO <sub>2</sub> )	:	≤	10 mg/Nm <sup>3</sup>
Particulate	:	≤	10 mg/Nm <sup>3</sup>
CO	:	≤	50 mg/Nm <sup>3</sup>

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

#### ALTERNATIVE IGCC PROCESSING SCHEMES

Several design alternatives of the IGCC Complex have been developed to compare the following key process aspects:

- Two gasification technologies:
  - Slurry Feed Gasifier, with product gas cooling by Water Quench (SFG-WQ); ChevronTexaco gasification technology is considered.
  - Dry Feed Gasifier, with product gas cooling in a Heat Recovery Boiler (DFG-WHB); Shell gasification technology is considered.

These two types of gasifier cover the broad range of entrained gasifier types currently available.
- Performance penalties for the capture of CO<sub>2</sub> to reduce environmental impact; 85 % C capture has been considered.
- Performance penalties for the simultaneous capture of CO<sub>2</sub> and H<sub>2</sub>S;
- Two levels of gasification pressure;
- Syngas utilization in the gas turbine without and with prior conversion of CO to H<sub>2</sub>;
- Different arrangements of the CO conversion reactors: number of reactors and dirty shift vs. clean shift.

The following Table 1 provides a summary of the 13 cases which have been evaluated. It is necessary to remark that only two Acid Gas Removal (AGR) processes have been considered: MDEA (Dow Technology) and Selexol (UOP technology). This is a limitation that has been tried to be removed, proposing other processes, such as Rectisol and Purisol, which could be interesting, specially for the cases with CO<sub>2</sub> removal. Design information were not made available by technology owners.

The state-of-the-art plants are based on cryogenic air separation. In most of the cases, 50% of the compressed air for the air separation unit (ASU) is extracted from the gas turbine during normal full load operation and the remaining 50% is provided by a separate electrically driven compressor. Pressurised nitrogen from the ASU is fed through booster compressors to the gas turbine, to maximise the loading on the turbine and reduce NO<sub>x</sub> emissions. Various ASU configurations can be used in the state-of-the-art.

IGCCs range from complete integration, in which all of the air for the ASU is provided by the gas turbine, to zero integration in which the ASU is a completely stand-alone unit providing only oxygen. The optimum choice depends on various parameters, particularly the type of gas turbine, and whether the ASU is an off-site unit for commercial reasons, providing oxygen "over the fence". For each alternative evaluated the integration degree has been optimized.

Cases with CO<sub>2</sub> capture assume CO<sub>2</sub> compression to 110 bar but do not include transport and storage of CO<sub>2</sub>. Costs of CO<sub>2</sub> storage depend greatly on local factors, such as transport distance, the pipeline diameter and the type of storage reservoir. At some locations CO<sub>2</sub> could have a positive value for enhanced oil recovery but at other locations it may have to be transported a long distance to a storage reservoir, resulting in substantial costs.

**Table 1 - Description of the process alternatives**

CASE	Gasification Process	Gasification Pressure	Shift	CO <sub>2</sub> Capture	AGR Process (3)
<b>A.1</b>	<b>DFG-WHB</b>	<b>Low</b>	<b>NO</b>	<b>NO</b>	<b>MDEA</b>
A.2	DFG-WHB	High	NO	NO	MDEA
<b>B.1</b>	<b>DFG-WHB</b>	<b>Low</b>	<b>Sour</b>	<b>YES</b>	<b>Selexol</b>
<b>B.2</b>	<b>DFG-WHB</b>	<b>Low</b>	<b>Clean</b>	<b>YES</b>	<b>Selexol</b>
<b>B.3</b>	<b>DFG-WHB</b>	<b>Low</b>	<b>Sour</b>	<b>YES (1)</b>	<b>MDEA</b>
<b>B.4</b>	<b>DFG-WHB</b>	<b>High</b>	<b>Sour</b>	<b>YES</b>	<b>Selexol</b>
<b>C.1</b>	<b>SFG-WQ</b>	<b>High</b>	<b>NO</b>	<b>NO</b>	<b>Selexol</b>
C.2	SFG-WQ	High	Sour	NO	Selexol
C.3	SFG-WQ	Low	NO	NO	MDEA+AGE
<b>D.1</b>	<b>SFG-WQ</b>	<b>High</b>	<b>Sour</b>	<b>YES</b>	<b>Selexol</b>
<b>D.2</b>	<b>SFG-WQ</b>	<b>High</b>	<b>Sour</b>	<b>YES (1)</b>	<b>Selexol</b>
<b>D.3</b>	<b>SFG-WQ</b>	<b>High</b>	<b>Sour</b>	<b>YES (2)</b>	<b>Selexol</b>
<b>D.4</b>	<b>SFG-WQ</b>	<b>Low</b>	<b>Sour</b>	<b>YES</b>	<b>Selexol</b>

Note (1): Combined removal of CO<sub>2</sub> and H<sub>2</sub>S

(2): Lower capture rate

(3): MDEA is MethylDiEthanolAmine (chemical solvent); Selexol is polyethylene glycol dimethylether (physical solvent), AGE is Acid Gas Enrichment (installation downstream AGR of another MDEA washing)

## PERFORMANCE DATA

The most important performance data of the 13 IGCC process schemes studied, are summarized in the following Table 2.

The cold gas efficiency, which is an indication of the efficiency of the gasification process, being the ratio of combustion energy of the raw syngas and the combustion energy of the coal feed, shows a distinct advantage for the DFG-WHB process. The efficiency difference between the two processes is due to the type of coal feed system.

SFG-WQ uses a slurry of pulverized coal in water; this implies that a fraction of the coal energy is used in the gasifier to vaporize the water of the slurry. In the DFG-WHB process pulverized coal is fed dry to the gasifier, pneumatically transported by pressurized nitrogen, so without energy waste. SFG-WQ feed system is however less costly and the gasification pressure can be much higher because the slurry is pumped by volumetric pumps. DFG-WHB feed system is more expensive and is currently limited to a maximum pressure of 40 bar.

The superior cold gas efficiency of DFG-WHB is reflected in the net electrical efficiency, which is also distinctly better for the DFG-WHB process.

The coal feed rates shown in Table 2, vary for each case because in each IGCC scheme the optimum target is to produce sufficient syngas to saturate the appetite of the two GE 9FA gas turbines. Since the efficiency of conversion of coal to syngas changes from case to case, the coal feed rate of the 13 cases is different.

## INVESTMENT COST DATA

The investment cost data of the 13 IGCC cases are reported in the attached Table 3. A ratio 1:1 between Euro and US Dollar has been considered.

The IGCC cases, based on SFG-WQ technology, show a distinct advantage with respect to the analogous IGCC cases based on DFG-WHB. This trend goes in the usual direction of a lower investment associated with a lower efficiency and viceversa.

Since the coal processing capacity is not the same for all cases it is more important to make the comparison on the base of the specific investment rather than the total investment.

**Table 2 – Performance data**

Case	Gasification Process	Pressure Bar g	Coal t/h	Cold Gas Efficiency %	Gross Power Output MW	Aux. Consumptions MW	Net Power Output MW	Net Electrical Efficiency %
A.1	DFG-WHB	36	250.6	83.5	909.8	133.9	775.9	43.1
A.2	DFG-WHB	61	252.1	83.0	895.0	146.7	748.3	41.3
B.1	DFG-WHB	39	273.1	83.5	896.2	220.0	676.2	34.5
B.2	DFG-WHB	39	274.6	83.5	875.0	223.7	651.3	33.0
B.3	DFG-WHB	39	271.4	83.5	883.3	200.0	683.3	35.0
B.4	DFG-WHB	61	271.9	83.5	879.2	240.3	638.9	32.7
C.1	SFG-WQ	65	303.0	70.5	988.7	162.2	826.5	38.0
C.2	SFG-WQ	65	327.6	70.5	1012.8	152.2	860.6	36.6
C.3	SFG-WQ	38	300.9	71.0	954.3	154.4	799.9	37.0
D.1	SFG-WQ	65	323.1	70.5	972.8	242.5	730.3	31.5
D.2	SFG-WQ	65	323.2	70.5	979.9	237.6	742.3	32.0
D.3	SFG-WQ	65	323.1	70.5	978.7	234.4	744.3	32.1
D.4	SFG-WQ	38	320.4	71.0	942.1	237.1	705.0	30.6

**Table 3 – Investment cost data**

CASE	Gasification Process	MAIN IGCC SECTIONS INVESTMENT					Total Investment 10 <sup>6</sup> Euro	Specific Investment Euro/kW
		Air Separation	Process Units	CO <sub>2</sub> Compr.	Power Island	Utilities Offsites		
		10 <sup>6</sup> €	10 <sup>6</sup> €	10 <sup>6</sup> €	10 <sup>6</sup> €	10 <sup>6</sup> €		
A.1	DFG-WHB	106	480	0	365	113	1064	1372
A.2	DFG-WHB	112	557	0	361	113	1143	1528
B.1	DFG-WHB	112	636	23	363	124	1258	1860
B.2	DFG-WHB	113	642	25	359	124	1262	1937
B.3	DFG-WHB	112	561	26	361	121	1180	1726
B.4	DFG-WHB	118	695	25	358	122	1317	2061
C.1	SFG-WQ	128	360	0	363	130	981	1187
C.2	SFG-WQ	131	3 400	0	366	135	1032	1199
C.3	SFG-WQ	125	3 335	0	360	140	960	1200
D.1	SFG-WQ	131	2 424	27	362	147	1092	1495
D.2	SFG-WQ	131	3 382	27	362	147	1050	1414
D.3	SFG-WQ	131	2 429	25	362	148	1095	1471
D.4	SFG-WQ	129	2 455	27	359	147	1117	1585

## PRODUCTION COSTS

The following Table 4 provides the cost of electricity (C.O.E.) and the cost of the CO<sub>2</sub> recovery for the cases designed for the capture of CO<sub>2</sub>.

The cost of electricity has been calculated on the following assumptions:

1. cost of coal: 1.5 Euro/GJ (38.8 Euro/t);
2. 7446 equivalent operating hours of IGCC fed by syngas at 100% capacity;
3. total investment cost as given above in table 3;
4. 10% discount rate on the investment cost over 25 operating years;

The cost of avoiding CO<sub>2</sub> emissions is calculated as follows:

$$\frac{\Delta \text{Electric Power Cost}}{\Delta \text{Specific CO}_2 \text{ emission}} \left[ \frac{\text{Euro}}{\text{t of CO}_2 \text{ avoided}} \right]$$

where:

- Δ Electric Power Cost = Electric Power Cost of the alternative with CO<sub>2</sub> capture – Electric Power Cost of corresponding alternative w/o CO<sub>2</sub> capture. The unit of measurement is Euro/kWh.
- Δ Specific CO<sub>2</sub> Emission = Ratio of (CO<sub>2</sub> emission/Power production) of alternative with CO<sub>2</sub> capture – ratio of (CO<sub>2</sub> emission/Power production) of the corresponding alternative w/o CO<sub>2</sub> capture. The unit of measurement is t CO<sub>2</sub>/kWh.

For DFG-WHB and SFG-WQ alternatives, the reference cases for the evaluation of the CO<sub>2</sub> removal cost are respectively case A.1 and C.1.

The cost of electricity of the IGCC based on SFG-WQ gasification is marginally lower than the cost of electricity from DFG-WHB based IGCC. This result is a consequence of the advantage of SFG-WQ in the specific investment cost which more than compensates the advantage of SFG-WHB in efficiency.

**Table 4 - Cost of electric power production**

Case	Gasification Process	C.O.E. (DCF= 10%) Cent/kWh	Cost of CO <sub>2</sub> (DCF = 10%) Euro/t
<b>A.1</b>	<b>DFG-WHB</b>	<b>4.8</b>	<b>-</b>
<b>B.1</b>	<b>DFG-WHB</b>	<b>6.3</b>	<b>24.2</b>
<b>B.3</b>	<b>DFG-WHB</b>	<b>6.0</b>	<b>19.0</b>
<b>C.1</b>	<b>SFG-WQ</b>	<b>4.5</b>	<b>-</b>
<b>D.1</b>	<b>SFG-WQ</b>	<b>5.6</b>	<b>16.5</b>
<b>D.2</b>	<b>SFG-WQ</b>	<b>5.4</b>	<b>13.5</b>
<b>D.3</b>	<b>SFG-WQ</b>	<b>5.3</b>	<b>15.2</b>

Note: Some cases (A.2, B.2, C.2, C.3, D.4) developed during the study to select the main process parameters (i.e gasification pressure) and resulted losers from the techno-economic point of view are not included in this Table.

## ANALYSIS AND CONCLUSIONS

IGCC is a complex combination of different technologies. The primary purpose of this study is the evaluation of the technologies that can be used in an IGCC in order to optimize capital cost and efficiency and reduce, at the same time, emissions to the atmosphere.

The most important conclusions of the study are described:

### Efficiency and investment cost

DFG-WHB based IGCC displays a superior coal to power efficiency (Table 2: A.1 vs C.1 or B.1 vs. D.1). The main reasons for the higher efficiencies of the DFG-WHB gasifier plants are the higher efficiency of conversion of coal-to-fuel gas in the gasifier and the method of cooling the product gas. Coal is fed to the DFG-WHB gasifier through dry lock hoppers; a water slurry is used in the SFG-WQ gasifier. More oxidation of carbon with O<sub>2</sub> producing CO<sub>2</sub> and heat has to take place in the Texaco gasifier to evaporate and heat the water contained in the slurry, resulting in a lower coal-to-fuel gas efficiency. The extra oxidation in the gasifier requires more oxygen, which increases the ancillary power consumption. Another reason for the lower coal-to-fuel gas efficiency is that, according to the data provided by the vendors for the IEA GHG standard coal, the SFG-WQ gasifier produces a larger amount of ungasified carbon. The product gas from the DFG-WHB gasifier is cooled in a heat recovery boiler which generates high pressure steam for the steam cycle. In the quench version of the SFG-WQ gasifier the fuel gas is quenched with water, resulting in lower temperature heat recovery.

To enable CO<sub>2</sub> to be captured, the fuel gas has to be fed to a catalytic shift reactor, where most of the CO is reacted with steam to give H<sub>2</sub> and CO<sub>2</sub>. In DFG-WHB gasifier plants a large amount of steam has to be taken from the steam cycle and added to the fuel gas feed to the shift converter but in the SFG-WQ gasifier plants sufficient steam is already present in the fuel gas, from evaporation of the coal slurry water and from the quench cooling of the gasifier product gas. This is the main reason why the efficiency penalty for CO<sub>2</sub> capture is lower in the SFG-WQ gasifier plant.

SFG-WQ based IGCC requires a lower investment, given in Euro per unit of installed power production (Table 3: see same cases listed above for power efficiency). The reasons for the higher efficiency of the DFG-WHB

gasifier plant are also the main reasons for the higher capital cost. Lock hopper feed systems and fuel gas heat recovery boilers are relatively expensive.

In the calculation of cost of production of electricity, the SFG-WQ advantage in investment more than compensates the DFG-WHB advantage in efficiency; resulting, at the conditions established for the study (cost of coal and discounted cash flow rate of return), in a cost of electricity and a cost of CO<sub>2</sub> recovery marginally inferior for the SFG-WQ based IGCC (Table 4).

However, it should be noted that the DFG-WHB technology plant emits and captures less CO<sub>2</sub> per kWh of electricity. If the SFG-WQ technology plant had to emit the same amount of CO<sub>2</sub> as the DFG-WHB technology plant, it would have to capture a slightly higher percentage of the CO<sub>2</sub> which would increase its costs. The costs of transporting and storing captured CO<sub>2</sub> would also be higher for the SFG-WQ case but, even taking this into account, the SFG-WQ technology is still likely to be the lower cost option. However, if the quantity of CO<sub>2</sub> that has to be stored is a major environmental concern, higher thermal efficiency processes such as the DFG-WHB gasifier may be favoured.

#### **Gasification pressure**

The pressure at which gasification is operated is an important design parameter for IGCC optimization. Increasing the gasifier operating pressure, the heat recovery on the syngas stream is enhanced, the driving force for physical solvent scrubbing of CO<sub>2</sub> is increased and the equipment size is reduced, allowing to limit the number of parallel trains. It can also have other benefits for example it enables power to be generated by a fuel gas expander prior to the gas turbine but it increases the power consumption and cost of coal and oxygen pressurization. The trade-off between the various factors is complex.

DFG-WHB technology shows superior efficiency and lower investment at medium pressure, 30-40 bar. The maximum pressure limit is set by the type of coal feed system chosen by DFG-WHB, which is based on lock hoppers. These devices are currently proven for pressures not exceeding 40 bar. The study has, however, also investigated the DFG-WHB gasification at 61 bar, to compare with the medium pressure cases at 36-39 bar, but the higher pressure 61 bar penalizes both efficiency and specific investment (Tables 2 and 3: A.1 vs A.2). High pressure (61 bar) DFG-WHB technology is not commercial but there is confidence to be able to develop it, if required.

SFG-WQ technology based IGCCs, on the contrary, are more competitive when gasification pressure is increased, 65 bar or even higher. This conclusion is valid for both options, without and with CO<sub>2</sub> removal (see Tables 2 and 3: C.1 vs. C.3 or D.4 vs D.1).

#### **Shift conversion without capture**

In most locations at present there would be little incentive to include CO<sub>2</sub> capture in an IGCC plant. However, it may be necessary to retrofit capture to meet future emission regulations. IGCCs built in the near future could be designed in a way which minimises the extent of changes required to retrofit CO<sub>2</sub> capture. One such option would be to install a shift converter when the plant is built. Installing a shift converter can have some advantages. For example, when gasifier product gas is cooled, a large amount of steam is condensed but, if some of the steam is reacted with CO to give CO<sub>2</sub> and H<sub>2</sub>, the mass of the fuel gas remains higher, which increases the amount of power generated in the gas turbine. A SFG-WQ technology based IGCC with a shift converter but no CO<sub>2</sub> capture was assessed as a sensitivity case (Tables 2 and 3, C.2 vs. C.1). The thermal efficiency was 1.4 percentage points lower than that of the base case SFG-WQ gasifier plant without capture and the capital cost per kW increased but only by \$12/kW.

#### **Production of combined CO<sub>2</sub>/H<sub>2</sub>S steam**

The base case plants produce separate streams of CO<sub>2</sub> for storage and H<sub>2</sub>S rich gas, which is fed to a sulphur recovery unit. Producing a single stream containing all of the CO<sub>2</sub> and sulphur compounds would simplify the acid gas removal process and eliminate the need for the sulphur recovery unit. To quantify these benefits, DFG-WHB and SFG-WQ plants producing a combined CO<sub>2</sub>/H<sub>2</sub>S output stream were assessed. Both performance efficiency and investment cost become more attractive, compared to the capture of CO<sub>2</sub> alone for both technology cases. (Table 2 and 3: B.3 vs B.1 and D.2 vs D.1).

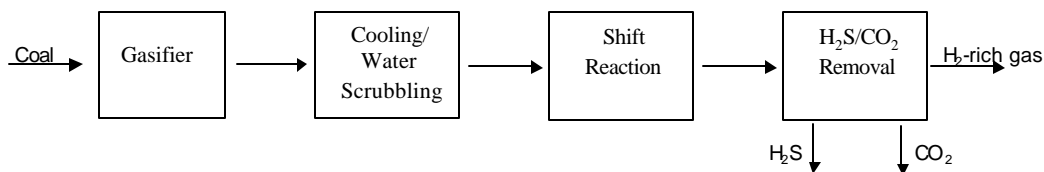
Whether or not it would be acceptable and advantageous to transport and store H<sub>2</sub>S along with CO<sub>2</sub> would depend on local circumstances. It may be more expensive to transport and inject CO<sub>2</sub> containing significant concentrations of H<sub>2</sub>S and if the CO<sub>2</sub> had to be transported long distances, these extra costs may be greater than the reductions in capture costs. It may be also be more difficult to obtain permits to transport CO<sub>2</sub>, containing H<sub>2</sub>S. On the other hand, H<sub>2</sub>S can be advantageous for CO<sub>2</sub> enhanced oil production (EOR), as it enhances the miscibility of CO<sub>2</sub>. Some of the H<sub>2</sub>S injected with the CO<sub>2</sub> would pass through the oil output; if the oil field is already sour, the additional oil processing costs and environmental impacts may not be significant but if the oil field is not sour, the H<sub>2</sub>S could be a problem. Underground injection of mixtures of CO<sub>2</sub> and H<sub>2</sub>S is an established practise.

About 1 million tonnes/year of such gases, separated from natural gas, are injected in western Canada, as described in IEA GHG report PH4/15. In addition, CO<sub>2</sub> containing about 2% H<sub>2</sub>S and other sulphur compounds such as mercaptans is used for EOR at the Weyburn oil field in Canada. This gas is transported by pipeline from the Great Plains gasification plant in the USA.

If the CO<sub>2</sub> was to be fed into a transmission grid supplying many different users and storage reservoirs, it may be required to have a low impurity concentrations, to meet the most stringent requirements of any of the users of CO<sub>2</sub>. In this circumstance, combined capture would not be acceptable.

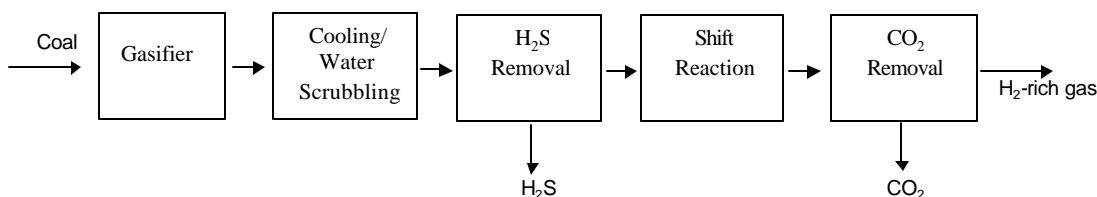
### Type of shift converter

There are two possible arrangements for shift conversion, sour shift and clean shift, as shown in figures 1 and 2.



**Figure 1: Sour shift conversion**

In the "sour shift" arrangement the fuel gas from gasification, after water scrubbing, is reheated and fed to a shift conversion reactor which uses sulphur-tolerant catalyst. This catalyst also hydrolyses COS to H<sub>2</sub>S. The fuel gas is then cooled, water is condensed and the gas is fed to a solvent scrubber which removes sulphur compounds and CO<sub>2</sub>.



**Figure 2: Clean shift conversion**

In the "clean shift" arrangement, the fuel gas from water scrubbing is reheated and fed to a COS hydrolysis reactor. It is then cooled and fed to a solvent scrubber which removes sulphur compounds. The sulphur free gas is reheated, fed a shift reactor, cooled and fed to a second solvent scrubber for removal of CO<sub>2</sub>.

The clean shift arrangement is more complex, involving more heating and cooling of the fuel gas but it may have some advantages for Shell type gasifiers justifying the evaluation of an alternative case (Case B.2). Clean shift catalyst is much less expensive than sour shift catalyst, even allowing for the need for a separate COS hydrolysis catalyst. The ratio of CO<sub>2</sub>: H<sub>2</sub>S is lower in the gasstream prior to shift conversion, which makes it easier to produce the concentrated H<sub>2</sub>S stream needed for a Claus sulphur recovery unit.

However the result of this evaluation (Tables 2 and 3, Case B.1 vs B.2) shows that the use of sour shift catalyst, compared to clean shift catalyst, gives better performance efficiency and lower specific investment in a Shell based IGCC.

In a SFG -WQ technology based the clean shift catalyst option does not exist because sour shift catalyst is perfect for processing the syngas from a quench gasifier, with only a small temperature trim. On the contrary the use of a clean shift would require upstream the expenditure of substantial amount of energy and investment.

### Environmental performances

The environmental performance of IGCC technology is far superior to that of any other power producing technology known today based on solid or liquid fossil fuels. Further the impact on the environment of IGCC is independent of the quality of feedstock, which makes it possible to process in IGCC the worst coals or residue and still meet the most severe emission limits.

### TECHNOLOGY STRETCH 2020

Potential improvements that could be made to the key components of IGCC by 2020 were identified and the performance and costs of a 2020 IGCC plant were predicted.

The most significant area of efficiency improvement is expected to be the gas turbine. There is a high probability of a significant improvement because of the large development effort being devoted to natural gas combined cycles. The first "H" class gas turbine with a higher inlet temperature than the current "F" turbines and steam cooled blades is currently being tested on natural gas and is expected to become available for use in IGCC later. The impact that the "H" turbine would have on IGCC efficiency is uncertain. Published studies have shown improvements between 1.3 and 1.4 percentage points. By 2020 the features included in the "H" turbine could be combined with other efficiency improvements such as two stage firing (already used in some Alstom turbines), improved thermal barrier and oxidation coatings, use of ceramic components and air compressor staging, resulting in IGCC efficiency improvements of 36 percentage points. The costs per kW of advanced gas turbines may not be lower than current turbines but the higher efficiency would significantly reduce the overall IGCC plant cost by reducing the required size of the gasifier, gas processing and ancillary equipment.

More radically different large gas turbines, such as humid air turbines, may become commercially available over the next 20 years but this is uncertain because of their high development costs and high water consumption. Fuel cells, particularly solid oxide cells, have the potential to provide large efficiency improvements in IGCC but their costs are currently very high and major technical development would be needed.

The exhaust temperatures of advanced gas turbine are expected to be higher than those of current turbines, which will make higher efficiency supercritical once-through heat recovery steam generators and steam cycle feasible.

Various improvements could be made to gasifiers to improve reliability and reduce maintenance costs.

Feeding coal as a slurry with liquid CO<sub>2</sub> could provide large efficiency increases for lignite and other low rank coals but significant improvements are not expected for bituminous coals. Other advanced dry coal feeding systems may be developed by 2020.

2 stage gasifiers, in which part of the coal feed is injected into the product from the first gasification stage, have higher coal-to-fuel-gas efficiencies than single stage gasifiers. The E-Gas gasifier, which is used in a commercial scale IGCC plant in the USA, is a 2 stage slurry feed gasifier and 2 stage dry feed gasifiers are being developed in Japan. Current 2 stage gasifiers include heat recovery boilers but a product gas water quench may be a more economic option for a plant with CO<sub>2</sub> capture. If there is a market demand, such as a gasifier could be developed.

Cryogenic air separation is a mature technology but novel high temperature ceramic ion transport membrane are being developed. These membrane are particularly well suited for integration with IGCC. The overall IGCC efficiency improvement may be around 1 percentage point. There is considered to be a medium probability of this technology being state-of-the-art by 2020.

Physical solvent scrubbing to separate CO<sub>2</sub> and H<sub>2</sub>S is a well established technology but improvements could probably be made compared to the Selexol process used in the state-of-the-art plants in this study, for example by using different solvents and optimisation for integration in IGCC with CO<sub>2</sub> capture.

Marginal improvements may also be made in shift conversion, which is another established technology.

#### 2020 plant performance and costs

The predicted performance and cost of a 2020 IGCC plant with CO<sub>2</sub> capture, and the improvements compared to the current state-of-the-art plants are shown in table 5. The 2020 plant has the following features:

1. Dryfeed, 2 stage entrained flow gasification
2. Product gas quench
3. Sour shift conversion
4. Physical solvent scrubbing acid gas removal
5. 2020 gas turbine (see above)
6. Once-through supercritical HRSG
7. Ion transfer membrane air separation

**Table 5 - 2020 IGCC performance improvements (plants with CO<sub>2</sub> capture)**

	2020 plant performance	2020 plant compared to current IGCC plants	
		DFG-WHB	SFG-WQ
Efficiency, % (LHV)	43.2	+ 8.7	+ 11.7
Capital Cost, \$/kW	1250	- 610	- 250
Cost of Electricity, c/kWh	4.5	- 1.8	- 1.1

The overall capital cost reduction is mainly a result of the increase in the overall plant efficiency, which reduces the size of the gasifier, gas processing and ancillary equipment per kW of electricity. The proposed 2020 gasifier is more expensive per tonne of coal feed than the current SFG-WQ gasifier but is cheaper than the DFG-WHB gasifier. The cost of electricity from the 2020 plant is about 20% lower than from the current technology SFG-WQ plant with capture and about 30% lower than from the current DFG-WHB plant.

Research is currently being carried out on various radically different CO<sub>2</sub> separation technologies such as high temperature membranes and electric swing adsorption. If these developments are successful and the technologies become commercially proven by 2020, the costs of IGCC with CO<sub>2</sub> capture would be even lower than those projected in this study.

Further cost reductions may result from widespread application of IGCC. Relatively small numbers of IGCC plants are in existence or under construction at present, most of which use oil residues. As a result, each plant and its equipment are built as one-offs. If IGCCs were built in large numbers, more standard designs would be used, which would reduce the engineering and design costs and a larger number of equipment manufacturers would enter the market, which may help to drive costs down. Great operating experience would enable design margins to be reduced on individual components and the overall plant.

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