



## **Co-production of hydrogen and electricity with CO<sub>2</sub> capture**

**John Davison - IEA Greenhouse Gas R&D Programme**  
**Rosa Maria Domenichini - Foster Wheeler Italiana**  
**Silvio Arienti - Foster Wheeler Italiana**

## ABSTRACT

Nowadays hydrogen is largely used in refineries and ammonia plants. In future, hydrogen could be used for vehicles, power generation and distributed heat instead of natural gas. The cheapest way to produce hydrogen with CO<sub>2</sub> capture is expected to be by fossil fuels. This paper focuses on possible advantages of hydrogen and electricity co-production from coal that is likely to be the main fuel in the long term, although in the near term natural gas and petroleum residues are also used. The expected advantage of co-production will be the ability to vary hydrogen and electricity production to meet market demands. A market analysis on natural gas, diesel and gasoline demand seasonal variations has been performed for the Netherlands and USA to determine the future hydrogen demand trend. In a near term, the Integrated Gasification Combined Cycle (IGCC) is the best answer to this co-production from coal with CO<sub>2</sub> capture. The paper considers different IGCC plant configurations:

- Production of Hydrogen, with minimum amount of electricity for a stand-alone plant production;
- Co-production of optimum hydrogen/electricity ratio;
- Co-production of hydrogen and electricity in a flexible plant that varies the hydrogen/electricity ratio.

The paper reviews some of the available gasification technologies and performs the study based on the selected one. Plant performance and costs are estimated and used to evaluate the electric power production cost. Electricity and hydrogen co-production plants are compared to plants that produce electricity only; alternatives, without hydrogen production, with and without CO<sub>2</sub> capture are also analyzed to evaluate the cost of CO<sub>2</sub> avoidance.

## SCOPE OF THE STUDY

The paper summarizes the preliminary results of a study carried out by Foster Wheeler Italiana for the IEA Greenhouse Gas R&D Programme (IEA GHG). The study investigates alternative power and hydrogen generation plant designs, based on high rank coal gasification, in order to assess the potential advantage of flexible co-production of hydrogen and electricity with capture of CO<sub>2</sub>.

The primary purpose of this study is, therefore, the evaluation of the technologies and the process alternatives that can be used in these complex power and hydrogen generation schemes to optimize efficiency and capital cost and reduce, at the same time, emissions to the atmosphere.

Use of hydrogen storage is considered to meet periodical demand variations. Different hydrogen storage options are considered.

The study is based on the hydrogen and electricity demands of The Netherlands and of the USA, in a hypothetical scenario with the standard fossil fuel systems replaced as much as possible by hydrogen systems. These two areas have been chosen because The Netherlands and the USA represent, on a regional scale, two significantly different consumption scenarios.

The study is based on the current state-of-the-art technologies, evaluating costs and performances of plants, which can be presently engineered and built.

The study reviews and compares three available gasification technologies and two available solvents for acid gas removal from the syngas.

After the selection of the technologies (Shell gasification and Selexol washing), the study develops five possible production plant schemes.

Finally five co-production scenarios, obtained as combinations of different types of production plants and different hydrogen storage volumes, are evaluated and compared to find the most promising combination of plants and storages.

A spreadsheet has been prepared to automatically provide the relevant data to each scenario on the basis of different energy consumption values.

## **BASES OF DESIGN**

### **Process design basis**

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, as well as hydrogen. The coal has a lower heating value (LHV) equal to 25,870 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 seawater temperature of 12°C.

For each of the alternatives considered, the IGCC design capacity in terms of syngas production has been fixed to match the appetite of two gas turbines, 250 MWe frame, F Technology. The resulting nominal overall net power output is 750 MWe.

The IGCC Complex main products are electric energy and hydrogen. By-products are sulphur (liquid or solid), carbon dioxide (for the alternatives recovering CO<sub>2</sub>) and solid by-products (slag, fly ash and filter cake, depending on the gasification technology).

The IGCC is designed to remove 85% of carbon contained in the feedstock.

The application of the IGCC scheme allows to obtain emissions (NO<sub>x</sub>, SO<sub>x</sub>, particulate and CO) much lower than those defined by the applicable European directive, without significantly penalizing the plant efficiency and investment cost.

### **Consumption of hydrogen and electrical power**

In order to fully take advantage of co-production, the entire system has to be designed to completely fulfill the hydrogen and electricity demands. To define these demands two steps have been followed.

First, at all energy consumption data such as electricity, natural gas, gasoline and diesel oil consumptions have been collected for The Netherlands and USA (Figures 1 and 2). These two regions have been chosen because they represent, at a regional scale, two possible different world consumption scenarios; in fact The Netherlands presents for electricity a moderate demand increase in winter while in the United States the electricity peak is during summertime, mainly due the massive use of electrical air conditioners.

Then assumptions have been stated to estimate the quantity of hydrogen that can provide for the fossil fuel consumption based on the state-of-the-art technology. In this way the quantity of electricity and hydrogen that would be required if the conventional fossil fuel systems were replaced with hydrogen systems, have been computed.

These assumptions are based on efficiency and market considerations and can be summarized as follows.

- The hypothetical system will keep producing the same percentage of electric energy from nuclear and renewable energy as at present.
- The natural gas used for power generation and industrial use is not converted into hydrogen consumption.
- One natural gas actualization factor reflects the quantity of natural gas that is converted into hydrogen consumption. This value has been set to 0.6 following realistic forecast considerations on the current days relevant to the consumption for commercial and residential use.
- Gasoline and diesel consumptions are entirely converted into hydrogen consumption taking into account the gasoline motors, diesel motors and fuel cells efficiency.

A summary of the above assumptions is shown in Table 1.

Thus, starting from the actual energy consumption shown in Figure 1 and 2 and applying the factors summarized in Table 1, the calculated expected energy consumptions (hydrogen and electricity) for The Netherlands and USA have been evaluated and are shown in Figure 3 and 4 respectively.

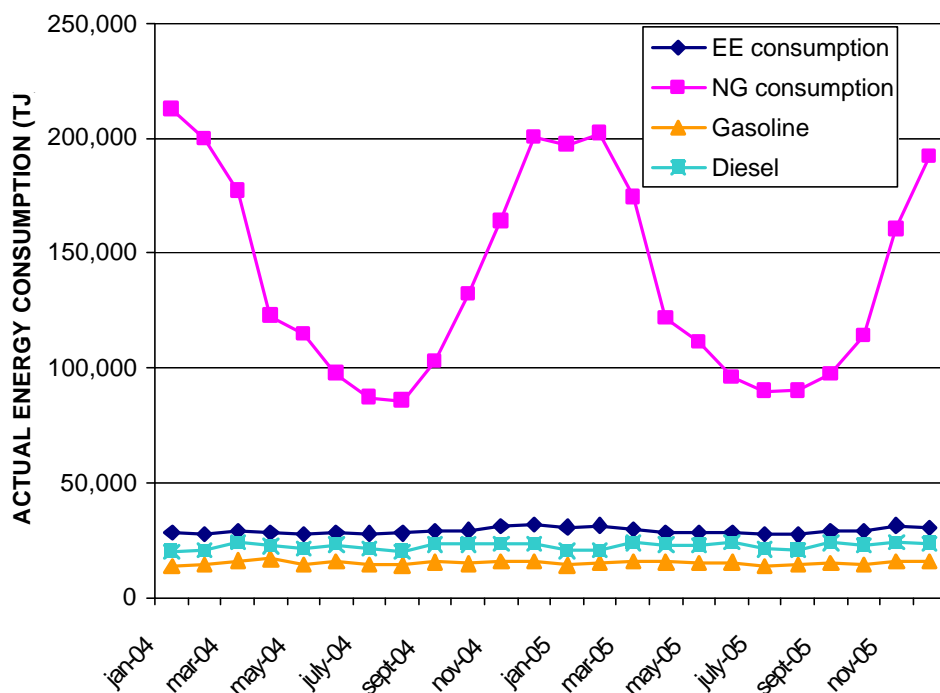


Figure 1: Electricity, natural gas, gasoline and diesel oil consumption for The Netherlands

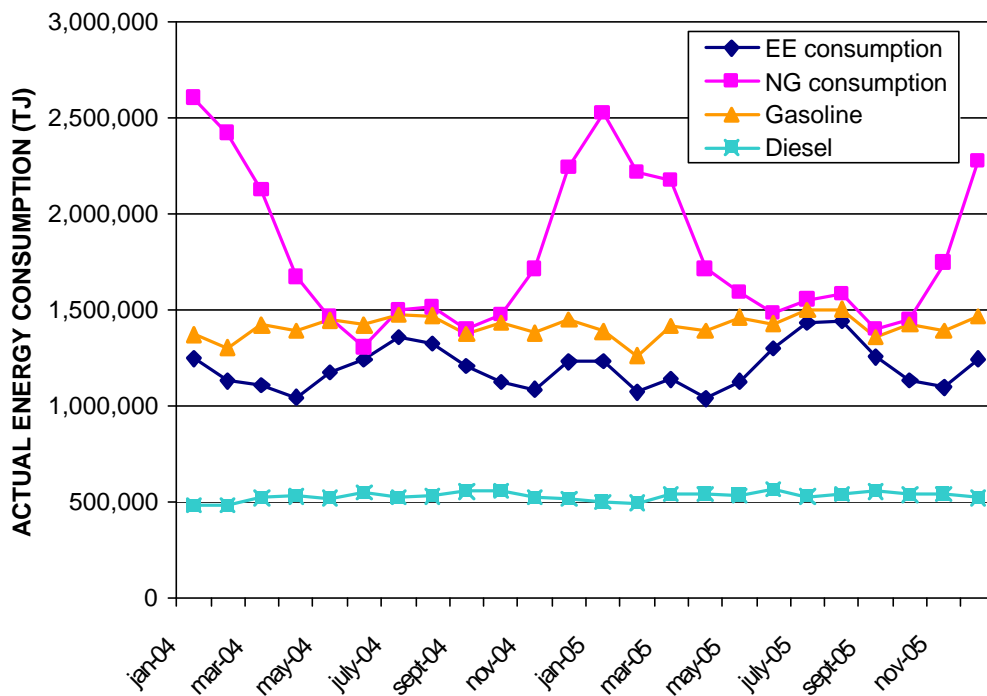


Figure 2: Electricity, natural gas, gasoline and diesel oil consumption for USA

	NL	USA
Nuclear and Renewable Energy % of Total Electric Power Production	7.1%	12.7%
Power Generation and Industrial Natural Gas % of Total consumed Gas	58%	61%
Natural Gas actualization factor	0.60	0.60
Gasoline Motor Efficiency	25%	25%
Diesel Motor Efficiency	40%	40%
Fuel Cell Efficiency	70%	70%

Table 1: Assumptions for hydrogen equivalent consumption for The Netherlands and USA

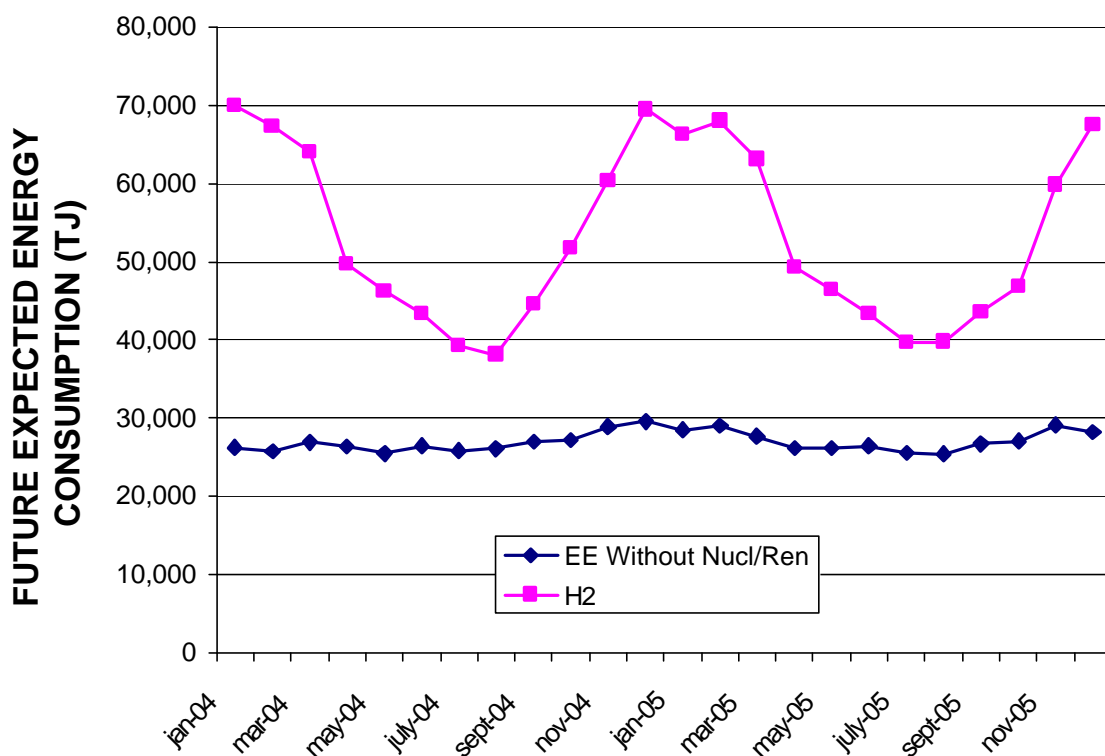


Figure 3: Equivalent hydrogen and electricity consumption for The Netherlands

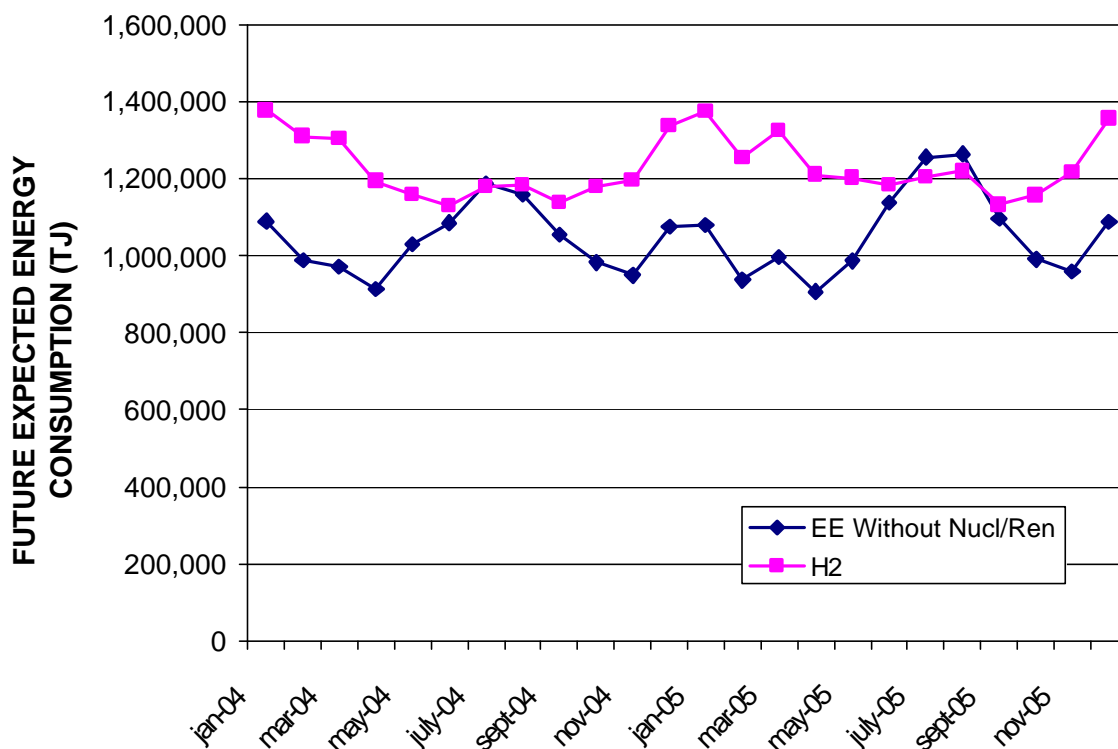


Figure 4: Equivalent hydrogen and electricity consumption for USA

### Storage of hydrogen

In order to constantly meet the hydrogen periodical demand variations with different plant configurations and to keep the number of plant as low as possible, hydrogen storage is considered.

The main options for storing hydrogen are as a compressed gas (above ground or underground), as a liquid or in metal hydrides.

The following general considerations can be made:

- Metal hydride option is not suitable for large quantities of hydrogen;
- Geological underground gaseous storage is convenient for large quantities of gas for long periods;
- Aboveground compressed gas storage is suitable only for small quantities of gas and short periods due to its very high costs;
- Liquid hydrogen has specific applications related to its high degree of safety and low storage density but requires very expensive cryogenic facilities.

For the scope of this study the geological underground storage is the best solution in relation to the very large volumes of hydrogen involved for a long period storage.

Some underground storages of hydrogen are in operation, providing a certain experience on this technology (City of Kiel in Germany, GAZ de France, Praxair). One of the most significant worldwide experience is the storage operated by ConocoPhillips at Clemens Terminal, Texas. Detailed

description of hydrogen cavern operation is present in reference [3], while information on costs and technologies of underground hydrogen storage have been collected from reference [4]. One concern of the gaseous underground storage is the possible contamination of hydrogen with other gases present such as H<sub>2</sub>S and CH<sub>4</sub>; for this reason a cost allowance for a hydrogen purification unit has been considered in the scenarios including storage. Another concern is the possibility of hydrogen leakages through the storage walls, strongly dependent on the type of storage environment (for example the leaks in earth caves are evaluated in 1-3% of the total volume per year). This last issue has not been considered in the economics of this study.

## COMPARISON OF TECHNOLOGIES

### Gasification technologies

Three technologies for gasification are investigated and compared:

General Electric Energy (GEE)  
Shell  
Siemens

The most important performance and economical data of the co-production plant based on the three gasification technologies are summarized in the following Table 2 where, for the COE calculation, the following parameters have been used according to IEA GHG standards:

- Discount rate: 10%
- Plant life: 25 years
- Coal price: 1.5 \$/GJ

		GEE Gasifier	Shell Gasifier	Siemens Gasifier
<b>Acid gas removal technology</b>		Selexol	Selexol	Selexol
<b>CO<sub>2</sub> Capture Efficiency</b>	%	84.8	85.1	84.7
<b>CO<sub>2</sub> Capture Flowrate</b>	t/h	623	548	631
<b>Coal Flow Rate A.R.</b>	t/h	323.1	273.1	316.6
<b>Thermal Energy of Feedstock</b>	MWth	2321.8	1962.5	2275.1
<b>Gross Equivalent Electric Power Output</b>	MWe	960	853.5	871.3
<b>H<sub>2</sub> produced</b>	MWth	598	599	593.4
<b>H<sub>2</sub> produced</b>	Nm <sup>3</sup> /h	200,510	200,858	199,022
<b>H<sub>2</sub> equivalent electric power</b>	MWe	334.9	335.4	332.3
<b>Auxiliary Consumption</b>	MWe	234.3	201	216.1
<b>Net Equivalent Electric Power Output</b>	MWe	725.7	652.5	655.2
<b>Gross Equivalent Electrical Efficiency</b>	%	41.3	43.5	38.3
<b>Net Equivalent Electrical Efficiency</b>	%	31.3	33.3	28.8
<b>(H<sub>2</sub>/effective EE) ratio</b>	MWt/MWe	1.5	1.9	1.8
<b>Total Investment</b>	10 <sup>6</sup> €	1476.8	1336.9	1317.5
<b>O&amp;M Costs</b>	MM€	136.2	116.5	129.4
<b>C.O.E (DCF=10%)</b>	€/kWh	<b>0.071</b>	<b>0.071</b>	<b>0.073</b>

Table 2: Gasification technology performance data.

Shell gasification allows the best efficiency of the plant, but requires the highest investment cost. These parameters concur to the evaluation of the cost of electricity (COE), significant value calculated to compare the three alternatives, at fixed H<sub>2</sub> selling price (9.5 €/Nm<sup>3</sup>).

The calculated COE for Shell and GEE are the same (0.071€/kWh), while for Siemens it is slightly higher, demonstrating that all the technologies may be selected depending on commercial and technical considerations which may slightly modify the analysis for each specific project.

For the prosecution of the study Shell technology is used due to the following reasons:

- syngas composition more suitable for the hydrogen/electric energy needs of The Netherlands
- better efficiency, consequent lower production of CO<sub>2</sub> and lower cost for transportation and storage.

### Acid Gas Removal solvent

Two Acid Gas Removal solvents are evaluated:

- Option 1 - Selexol
- Option 2 - Rectisol

For both solvents, the comparison has been performed on the following gasification technologies:

- GEE HP gasification with separate H<sub>2</sub>S and CO<sub>2</sub> capture;
- Shell LP gasification with separate H<sub>2</sub>S and CO<sub>2</sub> capture;

For both gasification technologies, the CAPEX comparison is in favour of Option 1 – Selexol (saving respectively 58.0 MM€ and 92.8 MM€ in GEE and Shell case).

For both gasification technologies, the OPEX comparison is in favour of Option 2 – Rectisol (saving respectively 9.5 MM€/y and 3.6 MM€/y in GEE and Shell case).

From the comparison of OPEX and CAPEX, the pay back time for Rectisol in GEE case is approx 6 years, while for Shell case is more than 20 years.

The Selexol based AGR is therefore preferred for Shell gasification technology and thus has been chosen for this study.

## CO-PRODUCTION ALTERNATIVES

### Plant alternative review

The general block flow diagram of the IGCC is given in Figure 5.

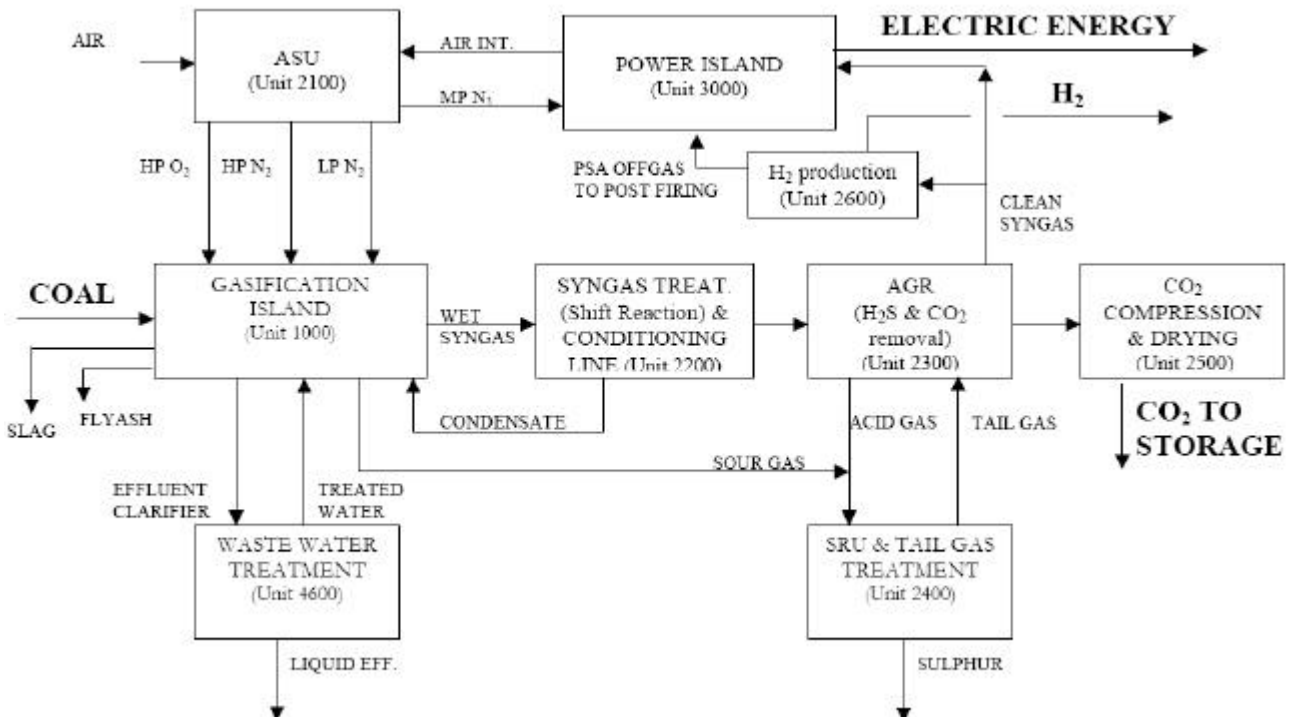


Figure 5: IGCC Block Flow Diagram

The following five design alternatives of the IGCC complex are developed in the study:

Case 1: production of electric energy only, without CO<sub>2</sub> capture, case taken as reference

Case 2: production of electric energy only, with CO<sub>2</sub> capture

Case 3: co-production of the maximum quantity of hydrogen and of the minimum electric energy to satisfy the internal electrical consumption, with CO<sub>2</sub> capture

Case 4: co-production of hydrogen and electric energy at fixed specific ratio and with CO<sub>2</sub> capture; the ratio corresponds to the future H<sub>2</sub>/electric energy consumption ratio evaluated for the Netherlands.

Case 5: co-production of hydrogen and electric energy at flexible ratio and with CO<sub>2</sub> capture.

Table 3 summarizes the performances, O&M costs and investment costs of the IGCC complex for the five alternatives. For case 5 the performances are given at the minimum and at the maximum required H<sub>2</sub>/electric energy ratio for the Netherlands. The data contained in this table are used for the evaluation of the different co-production scenarios presented.

			<b>Case #1 plant</b>	<b>Case #2 plant</b>	<b>Case #3 plant</b>	<b>Case #4 plant</b>	<b>Case #5 plant- R low</b>	<b>Case #5 plant- R high</b>
			w/o CO <sub>2</sub> capture, w/o H <sub>2</sub> production	CO <sub>2</sub> capture; w/o H <sub>2</sub> production	CO <sub>2</sub> capture; maximum H <sub>2</sub> production	CO <sub>2</sub> capture; H <sub>2</sub> production; optimum fixed H <sub>2</sub> /EE ratio	CO <sub>2</sub> capture; H <sub>2</sub> production; flexible H <sub>2</sub> /EE ratio	CO <sub>2</sub> capture; H <sub>2</sub> production; flexible H <sub>2</sub> /EE ratio
<b>Gasification</b>	Coal consumption	t/h	<b>250.6</b>	<b>273.1</b>	<b>273.1</b>	<b>273.1</b>	<b>273.1</b>	<b>273.1</b>
	Hydrogen production (99.5% purity)	Nm <sup>3</sup> /h	<b>n/a</b>	<b>n/a</b>	<b>372,400.0</b>	<b>200,858.0</b>	<b>162,240.0</b>	<b>246,160.0</b>
<b>Power Island</b>	Gas turbines total power output	MWe	<b>553.6</b>	<b>572</b>	<b>87.6</b>	<b>286</b>	<b>286</b>	<b>286</b>
	Steam turbine power output	MWe	<b>338.3</b>	<b>303</b>	<b>121</b>	<b>232.1</b>	<b>279</b>	<b>157.4</b>
	Net electric power output (B)	MWe	<b>762.3</b>	<b>654.7</b>	<b>0.10</b>	<b>317.1</b>	<b>363.1</b>	<b>236.6</b>
<b>CO<sub>2</sub> capture</b>	CO <sub>2</sub> to Storage	kmol/h	<b>n/a</b>	<b>12458</b>	<b>12458</b>	<b>12458</b>	<b>12458</b>	<b>12458</b>
	CO <sub>2</sub> Emissions	kmol/h	<b>n/a</b>	<b>2183</b>	<b>2183</b>	<b>2183</b>	<b>2183</b>	<b>2183</b>
<b>Cost</b>	Capital cost	EUR	<b>1,041,278,700</b>	<b>1,560,120,000</b>	<b>1,196,050,000</b>	<b>1,336,860,000</b>	<b>1,350,140,000</b>	<b>1,350,140,000</b>
	O&M fixed cost	EUR/y	<b>39,560,000</b>	<b>54,930,000</b>	<b>40,670,000</b>	<b>46,290,000</b>	<b>46,780,000</b>	<b>46,780,000</b>
	O&M variable cost	EUR/y	<b>62,455,000</b>	<b>70,270,000</b>	<b>70,250,000</b>	<b>70,260,000</b>	<b>70,270,000</b>	<b>70,270,000</b>

Table 3: Plant alternatives performance data

## CO-PRODUCTION SCENARIOS COMPARISON

To satisfy the future H<sub>2</sub> and electric energy needs of the two regions considered, five scenarios have been evaluated, obtained as a configuration of different types of IGCC plants and H<sub>2</sub> storage.

The five scenarios are:

- Scenario 1: electricity-only and H<sub>2</sub>-only production plants, without H<sub>2</sub> storage
- Scenario 2: non-flexible co-production plants, without H<sub>2</sub> storage
- Scenario 3: non-flexible co-production plants, with H<sub>2</sub> storage
- Scenario 4: flexible co-production plants, without H<sub>2</sub> storage
- Scenario 5: flexible co-production plants, with hydrogen storage

Relevant data and economics of the five scenarios are summarized in Table 4 for The Netherlands and Table 5 for USA. Those tables show: the number of plants of each type, the average percentage of time of the year the plants are running by type, the maximum necessary hydrogen storage volumes, the carbon dioxide capture and emissions, the costs and the environmental impact.

The scenarios are compared on the basis of the electricity production cost, at a fixed hydrogen price (9.5 €cent/Nm<sup>3</sup>), and considering an underground hydrogen storage cost of 1.5 €/kg.

The most convenient case is by far scenario 5, consisting in the configuration of 40 flexible co-production plants and 4,564 million Nm<sup>3</sup> of hydrogen storage for The Netherlands and of 1216 flexible co-production plants and 41,967 million Nm<sup>3</sup> of hydrogen storage for the USA. The electricity production cost of scenario 5 is 0.072 €/kWh for The Netherlands and 0.068 €/kWh for the USA.

The results are based on the monthly energy consumptions for years 2004-2005. A more detailed analysis on hourly basis for The Netherlands for the same years has been performed and it shows that the electricity production cost for the same scenario is even lower (0.065 €/kWh). In fact the detailed hourly analysis of the consumptions allows to optimize hourly, instead of monthly, the relative amounts of hydrogen and electric power produced. In this way the hourly analysis can take advantage of a more efficient utilization of the hydrogen storage volume and therefore a lower number of plants is required.

In both cases, the Netherlands and USA, the economics of flexible co-production and fixed-ratio co-production would be similar in the case hydrogen storage was not used (see scenarios 2 and 4).

## UNDERGROUND STORAGE SENSITIVITY STUDY

Because the cost of underground storage, in dependence with the geological configuration of the area, varies within a wide range (from 1 to 40 €/Kg), it could strongly affect the results. Thus a sensitivity study has been also performed for The Netherlands.

Figure 6 shows the Electricity production cost based on monthly consumption in dependence of the hydrogen storage cost.

For hydrogen storage costs lower than approximately 35 €/kg, scenario 5 remains the winning choice. For higher storage costs the impact on overall investment costs becomes higher and both alternatives with hydrogen storage appear underprivileged. It is to be noted that the cost of 35 €/kg for underground storage is on the extreme higher side of the cost range.

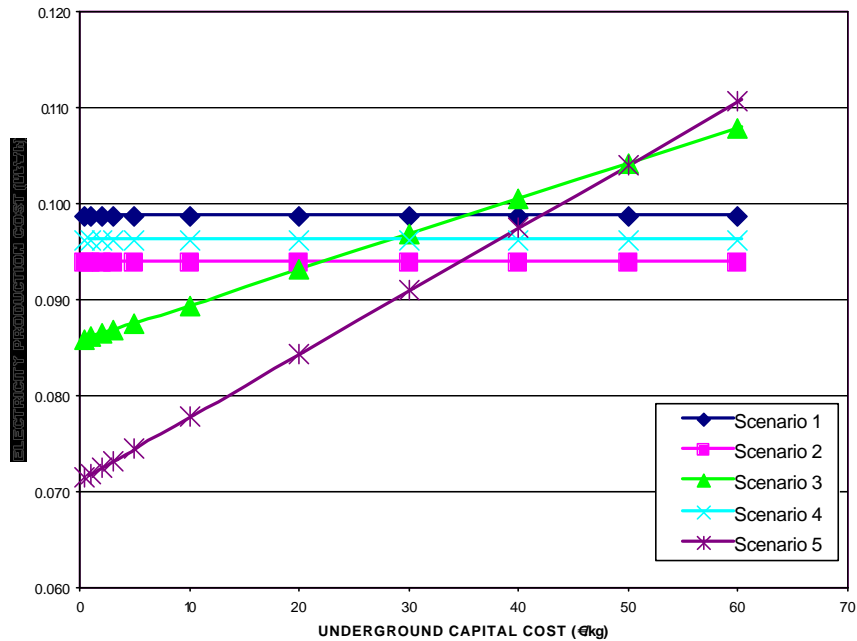


Figure 6: Underground capital cost sensitivity study

## CONCLUSIONS

The primary scope of the study is the evaluation of the plant scenarios to satisfy the future demands of hydrogen and electricity for the Netherlands and for the USA, based on the monthly 2004-2005 energy consumptions.

The scenarios are compared on the basis of the electricity production cost, at fixed hydrogen price (9.5 ¢/Nm<sup>3</sup>) and considering the underground hydrogen storage capital cost of 1.5 €/kg.

The most important conclusions of the study are:

- the most convenient scenario is by far scenario 5 (flexible co-production plants with gaseous hydrogen underground storages); in this scenario the electricity production cost for the Netherlands is 0.072 €/kWh vs. 0.086 €/kWh of the scenario including non-flexible co-production plants and hydrogen storages, and even higher costs for the other scenarios without storage; same conclusion applies also to the USA case;
- making reference to more detailed data of energy consumption on hourly basis, the number of required co-production plants decreases and the electricity production cost for the Netherlands in scenario 5 becomes 0.065 €/kWh;
- the cost of the gaseous underground storage, in dependence of the geological configuration of the area, widely varies between 1 €/kg and 40 €/kg based on available studies on the subject; the comparison among different plant scenarios depends on this cost: scenario 5 (flexible co-production plants with hydrogen storages) remains the winning choice for hydrogen storage cost lower than approximately 35 €/kg; for higher cost the impact of the storage on investment cost becomes too high and both alternatives with hydrogen storage appear unprivileged.
- the use of underground storage requires compressor facilities and purification facilities of the stored hydrogen, whose cost is very limited in comparison with the plant cost.
- The compressed underground storage of hydrogen is technically proved and some plants are in operation; despite this, the technology related to this type of storage is still under development to improve some aspects such as hydrogen contamination with other gases and leakages of hydrogen.

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
Quantity Plants #1	0	0	0	0	0
Quantity Plants #2	21	7	4	7	0
Quantity Plants #3	29	13	5	9	0
Quantity Plants #4	0	29	36	0	0
Quantity Plants #5	0	0	0	33	40
Total quantity of plant	50	49	45	49	40
Monthly average installed plants #1 load factor					
Monthly average installed plants #2 load factor	89.1%	66.5%	35.1%	45.9%	
Monthly average installed plants #3 load factor	75.0%	47.1%	32.5%	45.6%	
Monthly average installed plants #4 load factor		100.0%	100.0%		
Monthly average installed plants #5 load factor				100.0%	98.4%
Max quantity hydrogen in storage (million Nm <sup>3</sup> )	n/a	n/a	2,389	n/a	4,564
Max quantity hydrogen in storage per plant with storage (million Nm <sup>3</sup> )	n/a	n/a	66	n/a	114
Overall coal consumption (t/h)	9392	9234	9060	9358	9135
CO <sub>2</sub> capture (kg/h)	18,855,935	18,537,750	18,189,524	18,787,583	18,338,737
CO <sub>2</sub> emission (kg/h)	3,304,102	3,248,347	3,187,328	3,292,125	3,213,474
Overall CO <sub>2</sub> removal efficiency (net carbon/liquid capture)	85.1%	85.1%	85.1%	85.1%	85.1%
Plants Capital Cost (excluding storage)					
(millions EUR)	67,448	65,238	60,348	66,240	54,006
Underground Storage Capital Cost (including extra purification unit) (millions EUR)	n/a	n/a	390	n/a	670
Total Capital Cost (millions EUR)	67,448	65,238	60,738	66,240	54,675
Total O&M Cost million EUR/y (monthly average)	4,749	4,631	4,432	4,702	4,212
Electricity Prod Cost (€/kWh)	0.099	0.094	0.086	0.096	0.072
NO <sub>x</sub> EMISSION (kg/h) (month average)	7,447	7,663	7,707	7,568	7,469
SO <sub>x</sub> EMISSION (kg/h) (month average)	172	169	166	171	167
CO EMISSION (kg/h) (month average)	3,138	3,243	3,265	3,206	3,168
PART EMISSION (kg/h) (month average)	516	563	528	480	465

Table 4: Relevant Data and Economics for each scenario for The Netherlands

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
Quantity Plants #1	0	0	0	0	0
Quantity Plants #2	876	462	426	170	0
Quantity Plants #3	563	101	0	97	0
Quantity Plants #4	0	856	932	0	0
Quantity Plants #5	0	0	0	1132	1216
<b>Total quantity of plant</b>	<b>1439</b>	<b>1419</b>	<b>1358</b>	<b>1399</b>	<b>1216</b>
Monthly average installed plants #1 load factor					
Monthly average installed plants #2 load factor	83.0%	67.6%	65.2%	40.1%	
Monthly average installed plants #3 load factor	89.2%	40.3%	0.0%	46.7%	
Monthly average installed plants #4 load factor		100.0%	100.0%		
Monthly average installed plants #5 load factor				100.0%	100.0%
Max quantity hydrogen in storage (million Nm <sup>3</sup> )	n/a	n/a	37,830	n/a	41,968
Max quantity hydrogen in storage per plant with storage (million Nm <sup>3</sup> )	n/a	n/a	41	n/a	35
Overall coal consumption (t/h)	285375	280681	280838	289100	282218
CO <sub>2</sub> capture (kg/h)	572,918,979	563,495,711	563,811,042	580,398,901	566,581,706
CO <sub>2</sub> emission (kg/h)	100,391,887	98,740,660	98,795,915	101,702,585	99,281,415
Overall CO <sub>2</sub> removal efficiency (net carbon/liquid capture)	85.1%	85.1%	85.1%	85.1%	85.1%
Plants Capital Cost (excluding storage) (millions EUR)	2,040,041	1,985,929	1,910,565	1,909,596	1,641,770
Underground Storage Capital Cost (including extra purification unit) (millions EUR)	n/a	n/a	5,717	n/a	7,779
<b>Total Capital Cost (millions EUR)</b>	<b>2,040,041</b>	<b>1,985,929</b>	<b>1,916,281</b>	<b>1,909,596</b>	<b>1,649,549</b>
Total O&M Cost million EUR/y (monthly average)	144,436	141,322	138,978	140,624	129,737
Electricity Prod Cost (€/kWh)	0.089	0.085	0.083	0.082	0.068
NO <sub>x</sub> EMISSION (kg/h) (month average)	265,091	271,442	272,711	265,429	258,526
SO <sub>x</sub> EMISSION (kg/h) (month average)	5,225	5,139	5,142	5,293	5,167
CO EMISSION (kg/h) (month average)	111,468	114,575	115,147	112,591	109,762
PART EMISSION (kg/h) (month average)	18,201	18,849	18,602	17,575	17,054

Table 5: Relevant Data and Economics for each scenario for USA

## ACKNOWLEDGEMENTS

The paper is based on preliminary results from a study carried out by FWI for IEA GHG. The final report will be published by IEA GHG in mid-2007.

For the preparation of the study, FWI based part of the work on the two following studies performed by FWI for IEA GHG:

Gasification Power Generation Study – March 2003 [1],  
CO<sub>2</sub> Capture in Low-Rank Coal Power Plants – November 2005 [2].

These previous studies were supported by several companies (Dow, General Electric, Shell, Syntex, Sud-Chemie, Texaco, UOP, Future Energy, Siemens, Johnson Matthey Catalysts).

For the present study FWI would like to acknowledge the following companies for their fruitful support: General Electric, Shell and Siemens for the review of the sections concerning gasification; Linde for the data provided in the past on the Rectisol solvent; UOP for the data provided on the hydrogen production system.

## REFERENCES

1. GHG IEA, "Gasification power generation study – Final Report" by Foster Wheeler Italiana, March 2003
2. GHG IEA, "CO<sub>2</sub> capture in low rank coal power plants – Final Report" by Foster Wheeler Italiana, November 2005
3. George D. Parker, "Hydrogen Cavern operation", Presentation at IPCE 2006, Conoco Phillips, Bartlesville, OK, USA
4. Wade A. Amos, "Cost of storing and transporting hydrogen"; National Renewable Energy Laboratories, November 1998

## CONTACTS

To receive further information and the electronic file of the paper please contact:

John Davison – IEA Greenhouse Gas R&D Programme  
john@ieaghg.org

Rosa Maria Domenichini - Foster Wheeler Italiana  
rosa\_maria\_domenichini@fwceu.com

Silvio Arienti - Foster Wheeler Italiana  
silvio\_arienti@fwceu.com