CHEMICAL ENGINEERING TRANSACTIONS

VOL. 37, 2014

Guest Editors: Eliseo Ranzi, Katharina Kohse- Höinghaus

ISBN 978-88-95608-28-0; **ISSN** 2283-9216

A publication of

AIDIC

The Italian Association
of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1437024

Techno-economic and Environmental Analysis of Hydrogen and Power Co-generation based on Co-gasification of Coal and Biomass / Solid Wastes with Carbon Capture

Calin-Cristian Cormos*

Babes – Bolyai University, Faculty of Chemistry and Chemical Engineering
11 Arany Janos, RO-400028, Cluj – Napoca, Romania
cormos@chem.ubbcluj.ro

Development of energy efficient ways to convert biomass and wastes to energy is of paramount importance in modern society. The development and large scale deployment of energy and cost effective carbon capture and storage (CCS) technologies are equally important for transition to low carbon economy. This paper investigates the potential use of biomass (sawdust and agricultural wastes) and solid wastes (e.g. municipal wastes, meat and bone meal etc.) in a co-gasification process with coal to co-generate hydrogen and electricity with carbon capture. The paper underlines one of the main advantages of gasification technology, namely the possibility to process lower grade fuels (lower grade coals, biomass, solid wastes etc.), which are more widely available and cheaper than the high grade coals normally used in combustion-based power plants, this fact contributing to the improvement of energy security supply.

Based on a proposed plant concept that generates 400 – 425 MW net electricity with a flexible output of 0 – 200 MW_{th} hydrogen and a carbon capture rate of at least 90 %, the paper presents in details coal and biomass / solid waste blending for optimizing plant performance, mass and energy integration aspects, hydrogen and power co-generation and overall energy efficiency. Energy vectors poly-generation capability of gasification plants and a critical comparison of coal and biomass co-gasification with correspondent co-combustion are also discussed. The key technical performance indicators are calculated for a number of case studies through process flow simulations. The mass and energy balances resulted from simulation are then used to assess the main techno-economic and environmental indicators of the evaluated cases, like plant energy efficiency, ancillary power consumption, carbon capture energy and cost penalty, specific CO_2 emissions, capital costs, specific capital investment per kW, operation and maintenance (O&M) costs, cost of electricity, CO_2 removal and avoidance costs, cash flow analysis.

1. Introduction

The importance of the energy issue is underlined by the double significance of the problem: enhancing the security of primary energy supply and climate change prevention by reducing the greenhouse gas emissions resulted from fossil fuels utilisation. Solid fossil fuels (e.g. coal and lignite) ensure much bigger energy independence compared with liquid and gaseous fossil fuels (BP, 2013) but their utilisation is regarded with concern because of bigger fossil greenhouse gas emissions. Subsequently, solid fossil fuels can be used in the future only in conjunction with Carbon Capture and Storage (CCS) technologies.

In addition, utilization of biomass (e.g. sawdust, agricultural wastes) and other different solid wastes (e.g. municipal waste, organic wastes) in energy conversion processes is become more and more significant and its use is predicted to increase sharply. In this context, European Commission has set as a target for the whole community block that until 2020, 20 % from the energy mix should be covered by renewable energy sources (EC, 2008). Since the carbon footprints of these fuels are much lower than in case of coal, co-processing represents a viable way to reduce fossil CO_2 emissions.

Gasification is one flexible energy conversion technology being able to process a large variety of fuels, fossil and renewable / solid wastes (Higman and Burgt, 2007). By gasification, the solid fuels are

Please cite this article as: Cormos C.C., 2014, Techno-economic and environmental analysis of hydrogen and power co-generation based on co-gasification of coal and biomass / solid wastes with carbon capture, Chemical Engineering Transactions, 37, 139-144
DOI: 10.3303/CET1437024

converted into syngas which can be then used for power generation and / or via chemical conversion into valuable compounds (e.g. hydrogen, methanol, ammonia etc.). This multi-fuel multi-product operation of the Integrated Gasification Combined Cycle (IGCC) power plants is a distinctive feature which is extremely important for plant flexibility. Considering the growing integration of highly time-irregular renewable energy sources (wind and solar), the capability of fossil fuel power plants to adjust the generated load is particular important. Another advantage of gasification technology relies in the fact that pre-combustion carbon capture configurations can be applied for decarbonisation with lower energy and cost penalties than post-combustion cases (Cormos, 2012). Based on coal and biomass / solid wastes co-gasification to generate about 425 MW net electricity with a flexible output of 0 - 200 MW_{th} hydrogen and a carbon capture rate of at least 90 %, the paper presents in details the techno-economic and environmental evaluations. The concepts are modelled and simulated using process flow modelling software (ChemCAD) then the mass and energy balances are used to assess the main techno-economic and environmental indicators e.g. energy efficiency, ancillary consumption, CO_2 capture energy and cost penalties, specific CO_2 emissions, capital costs, operation and maintenance (O&M) costs, cost of electricity, cash flow analysis etc.

2. Plant configuration and main design assumptions

An IGCC power plant uses the syngas resulted from gasification for power production by burning in a gas turbine. The flue gases coming from the gas turbine are then used to raise steam in Heat Recovery Steam Generator (HRSG) which by expansion generates extra electricity in addition to the one generate by the gas turbine. Various gasifier types were developed (moving bed, fluidised bed and entrained-flow). Presently, oxygen-blown entrained-flow gasifiers are considered the state of the art for IGCC plants.
The modification of IGCC design to introduce the pre-combustion carbon capture step involves several changes in the plant configuration as follow: a catalytically water gas shift stage to convert carbon monoxide to carbon dioxide, a bigger Acid Gas Removal (AGR) unit which captures H_2S and CO_2, a hydrogen purification stage based on Pressure Swing Adsorption (PSA) and a combined cycle gas turbine running on hydrogen-rich gas. Captured CO_2 stream has to comply with quality specifications imposed by transport and storage (De Visser et al., 2008). In this paper, the following capture CO_2 quality specification was used (expressed in % vol.): >95 % CO_2; <2,000 ppm CO; <500 ppm H_2O; <100 ppm H_2S and <4 % all non-condensable gases (H_2, N_2, Ar etc.). The purified hydrogen stream has a purity higher than 99.95 % to be compatible with chemical, petro-chemical and other energy-related applications (e.g. PEM fuel cells).

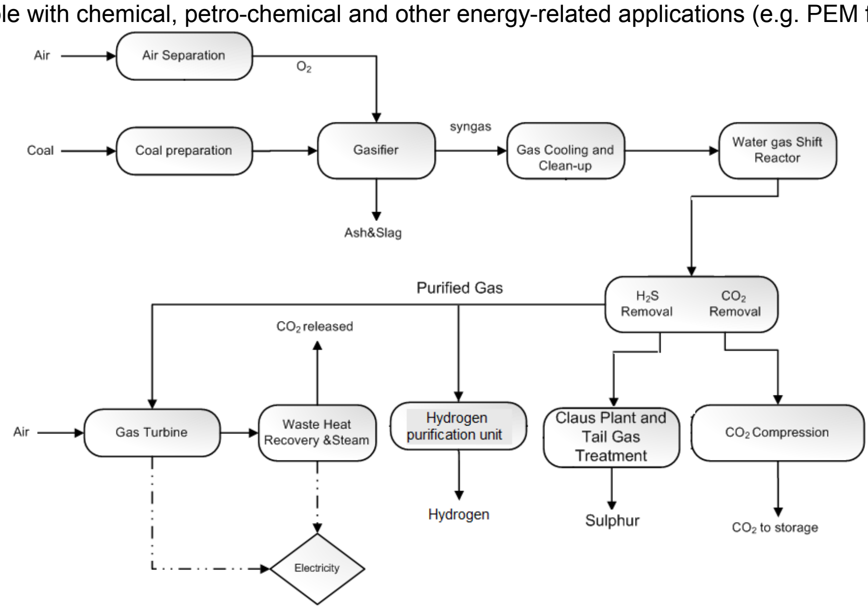


Figure 1: IGCC scheme for hydrogen and power co-generation with pre-combustion CO_2 capture

The conceptual layout of IGCC scheme for hydrogen and power co-generation based on coal and various alternative fuels co-processing with pre-combustion CO_2 capture is presented in Figure 1.
The following IGCC cases for hydrogen and power co-generation with CCS were evaluated in this paper:
Case 1 – Coal only as feedstock;
Case 2 – Coal in addition with sawdust (75 / 25 % wt. blending ratio);
Case 3 – Coal in addition with wheat straw (75 / 25 % wt. blending ratio);

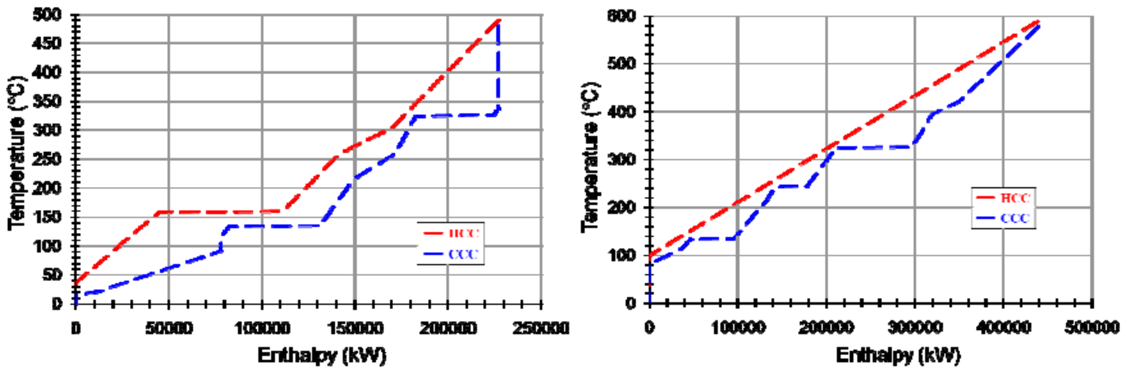
Case 4 – Coal in addition with corn stalks (75 / 25 % wt. blending ratio);
Case 5 – Coal in addition with municipal solid waste - MSW (75 / 25 % wt. blending ratio);
Case 6 – Coal in addition with meat and bone meal - MBM (75 / 25 % wt. blending ratio).
The cases have the same plant configuration, the main difference being the used fuel. Unlike previous investigations (Cormos, 2013), this work considers a higher ratio of alternative fuels (biomass, solid wastes) mixed with coal. The reason for choosing 75 : 25 (% wt.) blending ratio, is the fact that coal gasifiers are tolerating up to 20 - 30 % biomass without any major design modification. Within these limited ratios, the coal and alternative fuels mixtures are behaved like coal during gasification process. In addition, the alternative fuels being more reactive in comparison to coal, this fact has a positive influence on fuel conversion. The main design assumption of all evaluated plant concepts are presented in Table 1.

Table 1: Main design assumptions

Plant unit	Parameter
Gasifier	Dry fed & full water quench gasifier
Air separation unit (ASU)	Oxygen purity: 95 % O_2; Power consumption: 225 kWh/t O_2
Water gas shift (WGS)	Sour shift; 3 catalytic beds; Steam/CO ratio: 2.5; CO conversion: >95 %
Acid Gas Removal (AGR)	Selexol®-based gas-liquid absorption - desorption cycle
CO_2 drying and compression	Delivery pressure: 120 bar; Drying solvent: TEG
Gas turbine	Type: M701G2 (MHI); Net power output: 334 MW; 39.5 % efficiency
Steam cycle	Steam pressure: 120 bar / 34 bar / 3 bar
Condenser pressure	50 mbar
Cooling water temperature	15 ^oC
Heat exchanger $\Delta T_{min.}$	10 ^oC
HX pressure drop (ΔP)	2 - 5 %

3. Results and discussions

Evaluated IGCC power plant cases with CCS were modelled and simulated using ChemCAD. Developed mathematical models were validated against available industrial and experimental data, e.g. International Energy Agency – Greenhouse Gas R&D Programme reports (IEA-GHG, 2003; IEA-GHG, 2007). No significant differences between simulation results and experimental data were reported. After simulation, the energy balances were subject of process integration analysis using pinch technique for quantification of energy efficiency as presented by Cormos (2010) and Anantharaman and Berstad (2012). As illustrative example, Figure 2 presents hot and cold composite curves for Case 1 (coal gasification) for the two main plant sub-systems (the gasification island including syngas conditioning and shift conversion stage - Figure 2.a and the combined cycle gas turbine - Figure 2.b).



(a): Composite curves for gasifier island *(b): Composite curves for power block (CCGT)*

Figure 2: Composite curves for calcium looping cycle (Case 1)

The next step after mathematical modelling, simulation and thermal integration analysis of evaluated concepts was to use the results to assess the key techno-economic and environmental plant performances. First, the evaluated case studies were simulated only in a power generation scenario with carbon capture. Table 2 presents the main technical and environmental indicators for evaluated cases.

Table 2: Key plant performance indicators (power generation only)

Main plant parameter	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Fuel flowrate (as received)	t/h	167.48	184.47	191.58	187.53	193.36	169.92
Fuel thermal energy (A)	MW_{th}	1,170.12	1,180.05	1,187.58	1,179.86	1,181.95	1,131.25
Gross power output (B)	MW_e	533.50	536.02	538.95	538.65	537.01	532.05
Ancillary power consumption (C)	MW_e	112.15	113.45	115.73	113.91	114.72	111.43
Net power output (D = B - C)	MW_e	421.35	422.57	423.23	424.74	422.29	420.63
Gross power efficiency (B/A * 100)	%	45.56	45.42	45.38	45.63	45.43	47.03
Net power efficiency (D/A * 100)	%	36.00	35.80	35.63	35.99	35.73	37.18
Carbon capture rate	%	91.85	92.25	92.85	93.12	92.88	92.34
CO_2 specific emissions	Kg/MWh	78.15	73.41	69.82	69.85	71.92	72.05

As can be noticed from Table 2, in terms of power generation, all case studies generate about 420 – 425 MW net power with an electrical efficiency in the range of 35.6 – 37.2 % and specific CO_2 emissions in the range of 70 – 78 kg/MWh (IGCC plants without CCS have specific CO_2 emission in the range of 700 – 800 kg/MWh). It is observed that the overall efficiency is not influenced significantly by the addition of alternative fuels. In most of the cases the energy efficiency is decreasing up to 0.4 net percentage points and in some cases the plant efficiency is even increasing up to 1.2 % (MBM). This is due to a complex of factors: a positive influence on gasification step of lowering slag viscosity (MBM contains high proportion of modifier oxides like CaO which decrease the slag viscosity improving gasification performance), low ash content of MBM combined with high calorific value. These results are underlining the good potential of IGCC technology to process various low grade fuels in condition of high energy efficiencies.

The second evaluated scenario is considering a combined production of hydrogen and power based on IGCC scheme with CCS. Plant flexibility in the context of this article means the capability of the plant to change the produced energy vectors and to vary the plant output, whilst maintaining acceptable level of energy efficiency. For flexible co-production in range of 0 to 200 MW_{th} hydrogen as evaluated in this paper, the gas turbine is gradually turned down to about 80 % from the nominal load in order to displace an energy stream of hydrogen-rich gas which can be then purified by PSA unit. Figure 3 presents the variation of plant performance indicators with hydrogen output for Case 6 (coal and MBM co-gasification).

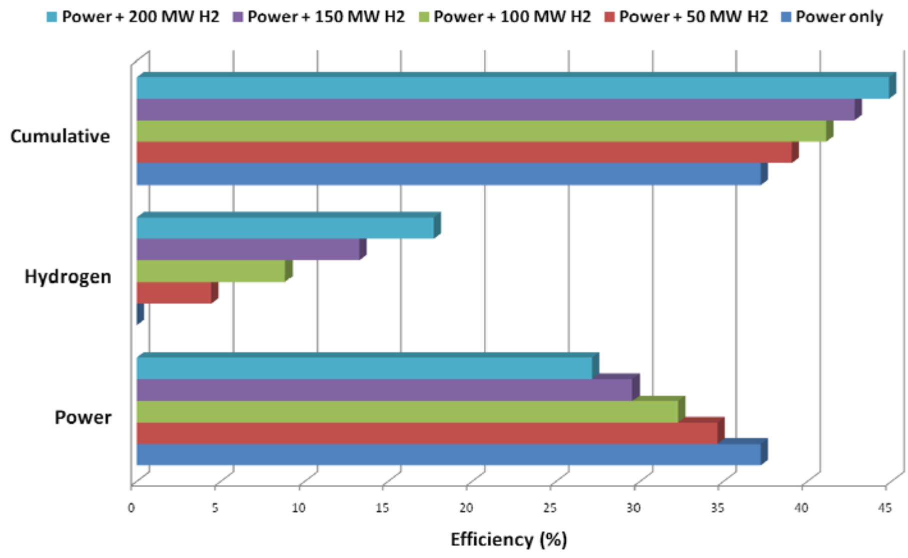


Figure 3: Key plant performance indicators vs. hydrogen output (Case 6)

It is observed that for co-production mode, the cumulative plant energy efficiency (sum of power and hydrogen efficiencies) is increasing in the situation in which the ancillary power consumption is remaining virtually constant. This fact is very important and attractive for plant cycling considering that for low electricity demand the plant can produce mostly hydrogen which can be stored to be used during the peak loads or for other energy and chemical applications (transport sector, petro-chemical sector etc.).

The next evaluated aspects were the economic indicators for assessed cases: capital costs, specific capital investments, operational and maintenance (O&M) costs, cost of electricity, CO_2 removal and avoidance costs, cash flow analysis etc. Firstly, capital cost was estimated using the cost correlations; the whole methodology was presented in details in another paper (Cormos, 2012). Equipment capital costs were estimated as a power law of capacity (see Eq.1) which were expressed based on the material / energy flows that the equipment has to handle within the process.

$$C_E = C_B * (\frac{Q}{Q_B})^M \quad (1)$$

where:
C_E – equipment cost with capacity Q;
C_B – known base cost for equipment with capacity Q_B;
M – constant depending on equipment type.
Once the total capital (investment) cost is estimated for each power plant concept, the specific capital investment per gross or net power generation (€/kW) was calculated using Eq.2.

$$Specific\ capital\ investment\ per\ kW(gross/net) = \frac{Total\ investment\ cost}{Gross/Net\ power\ output} \quad (2)$$

For estimation of operational and maintenance (O&M) costs, the mass and energy balances were used. O&M costs are generally allocated as variable and fixed costs. Variable operating costs are directly proportional to amount of generated power (raw materials, chemicals, solvents, waste disposal etc.). Fixed operating costs are essentially independent of the amount of generated power (maintenance, direct labour cost, administrative etc.). The procedure and main economic assumptions used in the analysis are presented in Cormos (2013). Table 3 presents the plant capital costs, specific capital investments as well as fixed and variable operating and maintenance (O&M) costs for the investigated cases.

Table 3: Capital costs, specific investments and operation & maintenance (O&M) costs

Main plant parameter	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Total investment cost	MM €	1,105.42	1,133.25	1,150.76	1,142.12	1,149.55	1,094.05
Capital investment per kW gross	€ / kW	2,072.01	2,114.19	2,135.18	2,120.33	2,140.64	2,056.29
Capital investment per kW net	€ / kW	2,623.51	2,681.80	2,718.99	2,688.98	2,722.18	2,600.97
Total fixed O&M costs (year)	M€ / y	38.45	39.12	39.62	39.45	39.92	38.32
Total fixed O&M costs (MWh)	€ / MWh	12.35	12.34	12.48	12.38	12.60	12.14
Total variable O&M costs (year)	M€ / y	79.22	74.25	75.12	73.01	75.12	136.81
Total variable O&M costs (MWh)	€ / MWh	25.06	23.42	23.66	22.91	23.71	43.36
Total fixed and variable costs (year)	M€ / y	117.67	113.37	114.74	112.46	115.04	175.13
Total fixed and variable costs (MWh)	€ / MWh	37.41	35.76	36.14	35.30	35.32	55.51

As investment cost indicators, all six cases have similar capital costs in the range of 1,094 to 1,150 MM €. The specific capital investments are in the range of 2,600 to 2,720 €/kW net. One can noticed a positive situation for MBM co-processing (Case 6) compared to other cases due to higher energy efficiency. For operation & maintenance (O&M) costs, considering Case 1 (coal only) as base case, there are positive differences for most of the cases (Cases 2 to 5) and negative difference for Case 6. For MBM case, the increase of O&M costs is due to higher fuel price (compared to coal).
CO_2 removal and avoidance costs are important parameters when evaluating various carbon capture technologies (e.g. pre- and post-combustion capture). These indicators are considering the levelised cost of electricity (LCOE) in a power plant with CCS compared with cost of electricity without CCS as well as specific CO_2 emissions in both cases. These costs are calculated using Eq.3 and Eq.4.

$$CO_2\ removal\ cost = \frac{LCOE_{with\ CCS} - LCOE_{without\ CCS}}{CO_2\ removed} \quad (3)$$

$$CO_2\ avoided\ cost = \frac{LCOE_{with\ CCS} - LCOE_{without\ CCS}}{CO_2\ emissions_{without\ CCS} - CO_2\ emissions_{with\ CCS}} \quad (4)$$

The cumulative cash flow analysis for one illustrative case (Case 6: coal and MBM co-gasification) is presented in Figure 4. The levelised cost of electricity was 7.36 ¢/kWh for CCS case and 5.90 ¢/kWh for non-CCS case. The CO_2 removal and avoidance costs were 30.58 €/t and respectively 38.29 €/t.

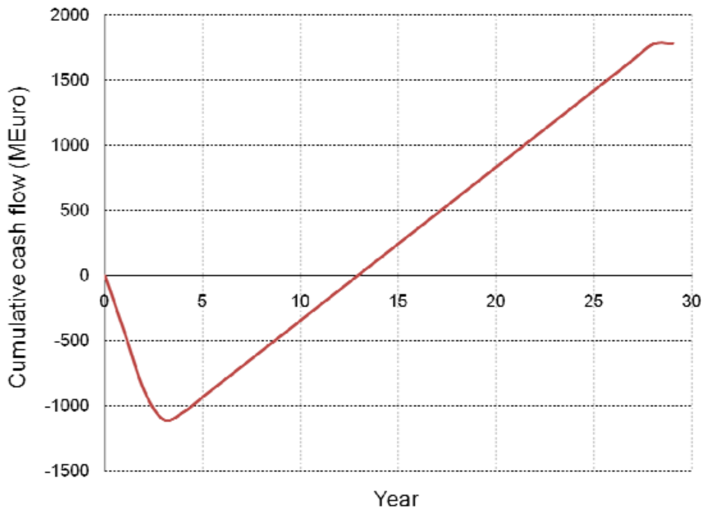


Figure 4: Cumulative cash flow analysis for Case 6

4. Conclusions

This paper investigates hydrogen and power co-generation based on coal and alternative fuels co-gasification with pre-combustion CO_2 capture. The assessment is using an integrated methodology based on mass and energy balances resulted from process simulation. As the in-depth techno-economic and environmental evaluations show, co-gasification of coal with alternative fuels (either biomass of various sorts or solid wastes) is a promising option to produce efficiently power and hydrogen and at the same time to significantly reduce the greenhouse gas emissions.

Acknowledgements

This work was supported by two grants of the Romanian National Authority for Scientific Research, CNCS – UEFISCDI: project ID PN-II-PT-PCCA-2011-3.2-0162: "*Technical-economic and environmental optimization of CCS technologies integration in power plants based on solid fossil fuel and renewable energy sources (biomass)*" and project ID PNII-CT-ERC-2012-1 / 2ERC: "*Innovative systems for carbon dioxide capture applied to energy conversion processes*".

References

Anantharaman R., Berstad D., 2012, Energy integration in an NGCC plant with post-combustion CO_2 capture – Systematic methodology for evaluating process alternatives, Chemical Engineering Transactions, 29, 451-456, DOI: 10.3303/CET1229076.

BP Statistical Review of World Energy, 2013, <www.bp.com> accessed 12.11.2013.

Cormos C.C., 2010, Evaluation of energy integration aspects for IGCC-based hydrogen and electricity co-production with carbon capture and storage, Int. J. Hydrogen Energy, 35, 7485-7497.

Cormos C.C., 2012, Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS), Energy, 42, 434-445.

Cormos C.C., 2013, Assessment of flexible energy vectors poly-generation based on coal and biomass/solid wastes co-gasification with carbon capture, Int. J. Hydrogen Energy, 38, 7855-7866.

De Visser E., Hendriks C., Barrio M., Mølnvik M.J., de Koeijer G., Liljemark S., le Gallo Y., 2008, Dynamis CO_2 quality recommendations, Int. J. Greenhouse Gas Control, 2, 478-484.

European Commission (EC), 2008, Communication from the Commission: 20 20 20 by 2020: Europe's climate change opportunity, COM(2008) 30 final, Brussels, Belgium.

Higman C., Van Der Burgt M., 2007, Gasification, Elsevier Science, Massachusetts, USA.

International Energy Agency - Greenhouse Gas R&D Programme (IEA-GHG), 2003, Potential for improvement in gasification combined cycle power generation with CO_2 capture, Report PH4/19, Cheltenham, UK.

International Energy Agency - Greenhouse Gas R&D Programme (IEA-GHG), 2007, Co-production of hydrogen and electricity by coal gasification with CO_2 capture, Report 13/2007, Cheltenham, UK.