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Techno-Economic Assessment of Co-gasification of Coal-Petcoke and Biomass in IGCC Power Plants

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A process simulation model of the Integrated Gasification Combined Cycle (IGCC) plant of Elcogas was developed and validated with industrial data. The model was used to assess the technical and economic feasibility of the process co-fired with up to 20% by weight of two local biomass samples (olive husk and grape seed meal). Results indicate promising features of the process in the forthcoming scenario of more severe limitations to CO_2 emissions.

1. Introduction

Integrated Gasification Combined Cyle plants (IGCC) are efficient power generation systems with low pollutants emissions when compared to other thermal coal technologies. Moreover, the entrained flow gasifier of IGCC plants allows the combined use of other lower cost fuels (waste, biomass) together with coal and provides with fuel flexibility to the plant. Despite a number of demonstration installations were setup all around the world since the 1990s, IGCC plants are not yet a widespread commercial technology due to their high investment cost and due to the need to decrease the greenhouse gas emissions. Possible options to address the GHG reduction are the use of renewable fuels like biomass in addition to the fossil coal (Pérez-Fortes et al., 2009) and the introduction of a CO_2 capture section in the process before the gas turbine combustion (Kishimoto et al., 2011). Some previous studies have also assessed the combination of co-gasification with biomass and CO_2 capture (Perez-Fortez et al., 2011) in the IGCC plant. Different process concepts have been proposed considering the CO_2 capture before or after the syngas combustion and assessing several emerging technologies (Kunze and Spliethoff, 2012). In general, the results of these analyses suggest that the improved process require significant additional capital costs for the new CO_2 capture units and, therefore, imply high marginal cost of energy per ton of avoided CO_2 (i.e. mitigation cost). A more profitable scenario could be drawn if the IGCC plant produces hydrogen in addition to electricity (Pérez-Fortes et al., 2009, 2011). This work is part of the FECUNDUS project aiming at demonstrating the technical and economic feasibility of co-gasification with biomass and precombustion CO_2 capture process schemes for the IGCC with innovative technologies based on the use of water gas shift reactors, solid sorbents for CO_2 capture and hydrogen selective membranes. The present paper reports the first step consisting in the development of the process simulation model of the IGCC plant and the techno-economic assessment of the co-gasification of coal and petroleum coke mixtures with biomass available in the Mediterranean area.

2. Model description

The IGCC plant of ELCOGAS in Puertollano was modeled using the steady-state process simulator Aspen Plus version 7.2. The process flowsheet of the base case IGCC plant includes a feed preparation section, an air separation unit (ASU), an entrained flow gasifier, a sequence of syngas cleaning section and a combined cycle power generation. The different sections of the IGCC plant were modelled as hierarchy blocks (sub-flowsheets) of the simulation flowsheet reported in the Figure 1. The modelling approach and

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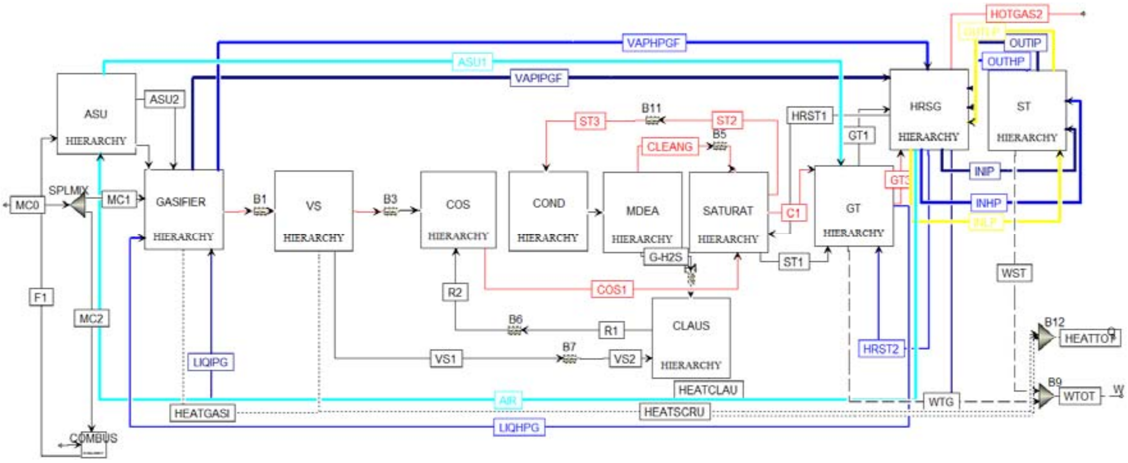

Figure 1: Simulation flow sheet of the IGCC power plant of Elcogas.

main assumptions for each process section are reported in the following subsections. Further details are reported by Giuliano (2012).

2.1 Gasifier

The Prenflo gasification reactor was simulated using a a modular-sequential approach by a sequence of a yield reactor model (Ryield), a stoichiometric reactor (RStoic) and an equilibrium reactor (Rgibbs) (Bhattacharyya et al., 2011). In the yield reactor the non-conventional components of the feed (coal, petcoke, biomass) are decomposed into basic conventional species according to atomic balances (C, O_2, H_2, S, N_2, Cl_2, H_2O, ash). The stoichiometric reactor simulates the oxidation of carbon to CO_2 and sulphur conversion into H_2S assuming conversion degree values of 98.8% and 90%, respectively, on the base of experimental values of the industrial gasifier of Puertollano plant (Elcogas, 2000). The stream leaving this reactor is fed to an equilibrium reactor together with other streams: 85% pure oxygen and 99.9% pure nitrogen coming from the ASU, medium pressure steam coming from the heat recovery section and limestone (95% $CaCO_3$, 5% ash). These stream flow rates were chosen on the basis of the Equivalence Ratio, ER, and the Steam Ratio, SR, reported for real cases. The equilibrium reactor evaluates at constant temperature and pressure the final raw syngas (RSG) composition by using the Gibbs free energy minimization method. The reactions considered are listed in Table 1. Reactions R4 and R6 were not considered at equilibrium, while restricted equilibrium was assumed introducing two “temperature approach to equilibrium” ΔT as model parameters (Bhattacharyya et al., 2011). Optimal ΔT values for these reactions were found by searching the best fitting between the simulation results and the experimental data of raw syngas composition for different coal-petcoke mixtures available in the Elcogas report (Elcogas, 2000). The thermodynamic model used in this section is the Peng and Robinson equation of state. Heat recovery from the gasifier is accounted for and is coupled with the Heat Recovery Steam

Table 1: Reactions modeled in the gasifier

N° of reaction	Type	Reactions
R 1	equilibrium	$C + H_2O \leftrightarrow CO + H_2$
R 2	equilibrium	$C + 0.5\ O_2 \leftrightarrow CO$
R 3	equilibrium	$H_2 + S \leftrightarrow H_2S$
R 4	temperature approach	$CO + H_2O \leftrightarrow CO_2 + H_2$
R 5	equilibrium	$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$
R 6	temperature approach	$N_2 + 3\ H_2 \leftrightarrow 2\ NH_3$
R 7	equilibrium	$COS + H_2O \leftrightarrow CO_2 + H_2S$
R 8	equilibrium	$H_2 + Cl_2 \leftrightarrow 2\ HCl$
R 9	equilibrium	$CaCO_3 \leftrightarrow CaO + CO_2$
R 10	equilibrium	$CO + NH_3 \leftrightarrow HCN + H_2O$

Table 2: Properties of the fuels and operating conditions of the gasifier

	Units	Mix1	Mix2	Mix3	Mix4	Mix5	Olive husk	Grape seed meal
Coal/pet-coke	%	39-61	45-55	54-46	58-42	50-50	/	/
Proximate analysis								
Moisture	%	7.91	8.80	9.37	7.59	9.84	18.6	12.3
Fixed Carbon	%	63.00	58.87	55.80	53.37	64.00	26.3	18.9
Volatiles	%	16.33	17.44	18.25	18.42	15.10	69.4	72.4
Ash	%	20.67	23.69	25.95	28.21	20.90	4.3	8.7
Ultimate analysis								
Carbon	%	68.80	65.61	62.76	60.66	65.35	54.7	53.7
Hydrogen	%	3.36	3.68	3.15	3.24	3.09	5.86	6.48
Nitrogen	%	1.39	0.80	1.46	1.16	1.50	1.88	1.84
Chlorine	%	0.07	0.06	0.04	0.05	0.02	0.02	0.88
Sulphur	%	3.82	3.47	3.28	3.00	3.66	0.16	0.15
Oxygen	%	1.89	2.69	3.36	3.68	3.54	37.41	36.91
HHV	MJ/kg	27.92	26.84	25.22	24.49	25.52	18.29	19.76
Dry feed rate	kg/s	24.06	26.53	25.98	24.22	28.49	28.49	28.49
Gasifier temperature	ºC	1706	1735	1746	1797	1700	1700	1700
Gasifier pressure	bar	25.10	23.87	24.87	23.54	25	25	25
ER	-	0.39	0.395	0.409	0.412	0.40	/	/
SR	-	0.145	0.15	0.123	0.111	0.143	/	/

Generator of the Combined Cycle.
The raw syngas is first separated from the solids (ash, $CaCO_3$, unconverted sulfur, slag) by simulating the withdrawal from the gasifier bottom and the ceramic filtration of the fly ashes by a single ideal separator.

2.2 *Cleaning* section

The syngas cleaning section consists in a sequence of a Venturi scrubber, VS, a Carbonyl Sulphide, COS, hydrolysis reactor, a Sour Water Steam stripper, SWS, a N-Methyl Diethanol Amine, MDEA, absorber, a sulphur recovery Claus plant.

Venturi scrubber

The absorption of hydrogen sulfide, ammonia pollutants and carbon dioxide from the syngas in a water-NaOH solution in the Venturi scrubber was modeled by a rigorous multistage vapor-liquid model addressing also mass transfer phenomena. Electrolytic reactions in the liquid phase were accounted for and consequently the thermodynamic model used in this section was the electrolyte NRTL. The model parameter was the ratio between the water-NaOH solution flow rate and the raw syngas flow rate (H_2O-NaOH/raw syngas). The polluted water regeneration and recycle was also addressed by modeling the acid and basic water treatment columns.

COS hydrolysis reactor

The COS hydrolysis reactor converting COS into H_2S was modeled as a stoichiometric reactor with an assigned conversion degree of 0.9. The thermodynamic model used in this section was the Peng and Robinson EOS.

MDEA absorber

The MDEA absorption column to remove H_2S and CO_2 was modeled with a rigorous multistage vapor-liquid equilibrium model including the electrolytic reactions in the liquid. Solvent recovery was modeled by a stripper column with the same modeling approach. The thermodynamic model used in this section was the electrolyte NRTL

Claus process

The gas stream leaving the basic water treatment column and the gas stream leaving the MDEA desorber are fed to the Claus process. The Claus process was simply modeled by a sequence of a stoichiometric reactor converting H_2S contained in the gas stream into elementary sulphur and of an equilibrium reactor

Table 3: Comparison between experimental and simulated data

Raw gas	Mix1		Mix2		Mix3		Mix4		Mix5	
% Vol	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**
H_2	20.8	19.4	20.8	21.3	20.8	19.9	19.4	18.6	21.4	18.9
CO	61.1	58.5	60.1	57.4	59.4	58.7	59.6	57.2	59.3	58.4
CO_2	1.8	1.6	2.7	2.2	2.8	2.1	3.8	2.9	2.8	2.9
N2+Ar	15.1	15.4	15.2	14.5	15.9	16.4	16.1	17.5	15.2	15.8
H2S+COS	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.2
NH_3	-	1.3	-	1.3	-	0.67	-	1.2	-	1.2
HCN	-	2.6	-	2.1	-	1.1	-	1.6	-	1.6
Clean gas	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**
H_2	21.1	20.3	21.2	22.2	21.1	20.4	19.8	22.6	22.0	19.5
CO	62.1	59.5	61.1	58.42	60.4	58.9	60.7	59.8	59.3	59.0
CO_2	1.4	1.4	2.2	2.1	2.3	2.2	3.0	2.5	2.4	2.4
N_2+Ar	15.3	18.0	15.5	17.0	16.1	18.8	16.4	21.6	15.9	18.1
Power, MW	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**	**Model**	**Exper.**
Gas turbine	165.6	168.7	174.7	173.0	159.8	163.0	144.2	137.8	183.3	182.3
Steam turbine	119.4	121.5	126.6	130.0	128.5	124.8	111.8	109.7	136.8	135.4
Total power	285.0	290.2	301.3	303.0	288.3	287.8	256	247.5	320.1	317.7

to evaluate the distribution of sulphur between the elementary form and the oxidized compounds. These units generate also the recycle gas stream to the COS reactor.

2.3 Combined cycle and ASU

The integrated combined cycle was modelled in detail by including block models for the gas turbine, GT, the gasifier heat recovery unit, GHRU, the heat recovery steam generator, HRSG, and the steam turbines, ST. Heat integration according to the pinch analysis was addressed (Madzivhandila et al., 2009). The combustor was modelled as an equilibrium reactor. The clean gas enters into the combustor after water saturation. The total power was calculated as the sum of the power produced by the GT and the STs, while the net power was evaluated by subtracting the power used by the ASU and the fuel preparation section from the total power. The ASU was not modelled in detail, but its power consumption was calculated by an empirical function of the air feed to the cryogenic section based on industrial data.

3. Results

3.1 Base case process

Experimental data of the Puertollano plant previously published by Elcogas (2000) were used to determine the few fitting parameters of the process simulation model. In particular, process simulations were performed by using four different fuel feed mixes of coal and petcoke (Mixes 1-4), whose characteristics are reported in Table 2 The two ΔT of the gasifier model were found by searching the best fitting between the simulation results and the experimental data of raw syngas composition. The H_2O-NaOH/RSG ratio was found by comparing simulation results and experimental data for the clean syngas. Once all the model parameters were set up, model validation was successfully carried out by simulating the process fed by the base case Mix5, a 50% coal and 50% petcoke mix by weight. Comparison between experimental and model data regarding the raw gas composition on dry basis for all five mixes, reported in Table 3, reveals a mean squared relative error, MSRE, lower than 6%. Higher error values are observed for the gas species with low concentration. This is the case for CO_2 concentration depending on the degree of oxidation occurring in the gasifier that is very sensitive to the ER value. Moreover, the MSRE for the clean syngas compositions and the produced power does not exceed 7% and 2%, respectively. As a result, it can be concluded that the process simulation model predicts the IGCC plant performances with good accuracy.

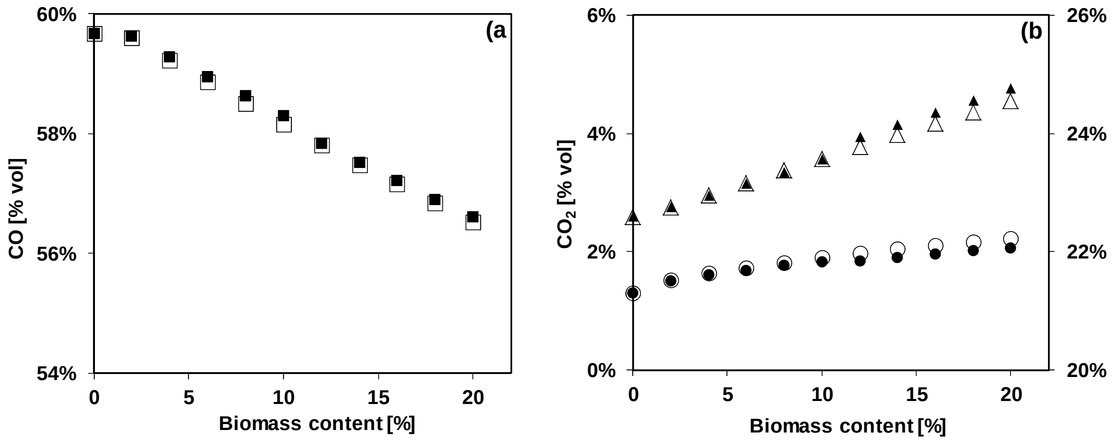

Figure 2: volumetric fractions of chemical species in the clean syngas as a function of the biomass content in the fuel feed. a) CO: □, olive husk; ■, grape seed meal, b) CO_2: △, olive husk; ▲, grape seed meal; H_2: ○, olive husk; ●, grape seed meal.

3.1 Co-gasification with biomass

The validated model was used to simulate the IGCC performance when co-fired with olive husk and grape seed meal biomass whose characteristics are reported in Table 2. Simulations regarded feeds of ternary mixes formed by the coal-petcoke 50% by weight (Mix5) and increasing amounts of one biomass up to 20% by weight. This value was chosen to avoid significant decreases of the fuel HHV and due to uncertainties in the operating performance of the fuel mill. The total feed rate was kept constant, while the ER and the SR of the gasifier were changed according to an empirical function of the fuel HHV. In particular, ER increases and SR decreases with decreasing HHV to keep constant the gasifier temperature. The operating parameters of the cleaning section units were also kept unchanged with respect to the base case.

Results of simulations in terms of clean syngas volumetric compositions are reported in Figure 2. The concentration of CO decreases, while those of CO_2 and H_2 increase with increasing biomass content in the feed. This result might be caused by the higher oxygen concentration in the feed due to the higher values of ER and of content of oxygen in the biomass with respect to the coal-petcoke mixture. As expected, the emissions of fossil CO_2 per MWh decreases with increasing biomass content in the feed. In particular, the CO_2 goes down by 16% for a 20% biomass mixture (Figure 3a). Correspondingly, an energy penalty is recorded for both biomass types (Figure 3b). In fact, the net power decreases up to 4.3% and 5.8% for a 20% olive husk and grape seed meal content, respectively. Differently, the net efficiency of the power plant does not change significantly (Figure 3b) since the decrease of the net power is mainly due to the lower heating value of the mixtures with biomass. Finally, a simple economic analysis was performed. Assuming

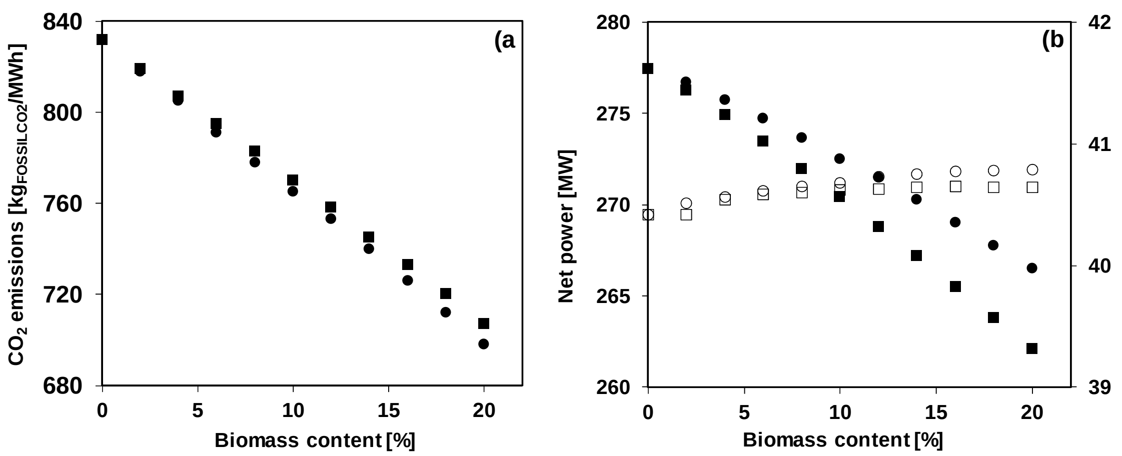

Figure 3: a) CO_2 emissions: ■, olive husk; ●, grape seed meal. b) Net power: ■, olive husk; ●, grape seed meal; Net efficiency: □ olive husk; ○ grape seed meal.

a cost of 60 €/t for the coal-petcoke mix, 63 €/t for the olive husk and 70 €/t for the grape seed meal, the cost per MWh increases with increasing biomass percentage in the feed because of the higher cost of the raw material. However, it ought to be considered that the biomass price is very variable over the time due to the lack of a stable market. The additional cost of energy can be related to the avoided CO_2 emissions by the so called mitigation cost:

$$\text{mitigation cost} = \frac{\left.\frac{Cost}{MWh}\right|_{\text{with biomass}} - \left.\frac{Cost}{MWh}\right|_{\text{basecase}}}{\left.\frac{tCO_2}{MWh}\right|_{\text{basecase}} - \left.\frac{tCO_2}{MWh}\right|_{\text{with biomass}}} = \left[\frac{\text{EUR}}{tCO_2}\right] \tag{1}$$

The mitigation cost increases with increasing biomass content up to 14 EUR/$t$$CO_2$ for a 20% biomass mix. This cost is higher than the current EU allowance price (less than 10 EUR/$t$$CO_2$), but seems comparable with the price forecasted for the forthcoming years according to the “cap and trade” approach of the EU Emissions Trading Systems which will be constrained by the EU commitment to reduce CO_2 emissions by 20% by the year 2020.

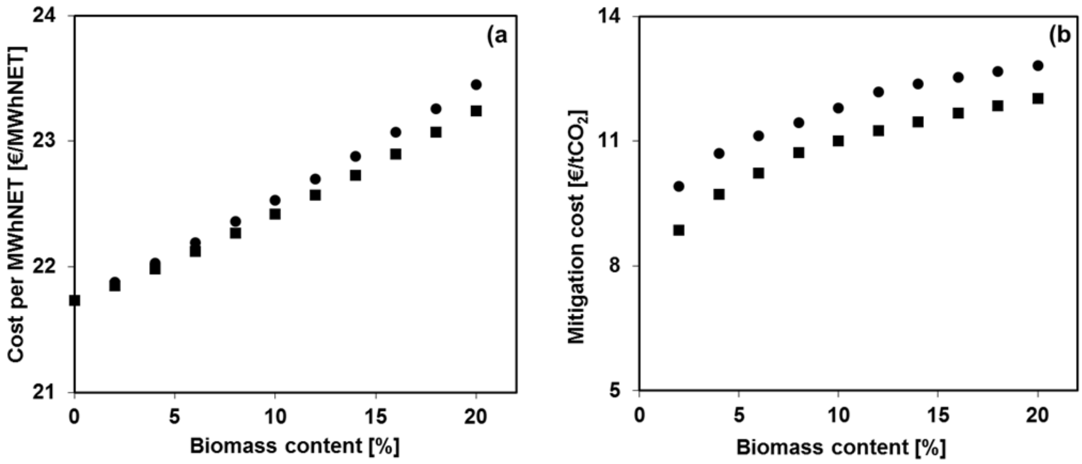

Figure 4: a) Cost per MWh, b) Mitigation cost. ■, olive husk; ●, grape seed meal.

4. Conclusions

A process simulation model of an IGCC plant was validated with experimental industrial data of the ELCOGAS plant. This model was used to assess the performance of the plant co-fired with biomass. A 16% decrease of fossil CO_2 emissions implies a loss of net power lower than 6% and does not cause significant change of the net efficiency. The mitigation cost seems to be consistent with the forthcoming scenario of the EU Emissions Trading Systems.

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