

USE OF ALTERNATIVE FUELS OBTAINED FROM RENEWABLE SOURCES IN BRAYTON CYCLES

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ABSTRACT

Analysis and simulation of the behaviour of gas turbines for power generation using different non-conventional fuels obtained from different renewable sources are presented. Three biomass-to-biofuel processes are considered: anaerobic digestion of biomass (biogas), biomass gasification (synthesis gas) and alcoholic fermentation of biomass and dehydration (bioethanol), each of them with two different biomass substrates (energy crops and municipal solid waste) as input.

The gas turbine behaviour in a Brayton cycle is simulated both in an isolated operation and in combined cycle. The differences in gas turbine performance when fired with the considered biofuels compared to natural gas are studied from different points of view related with the current complex energetic context: energetic and exergetic efficiency of the simple/combined cycle and CO₂ emissions. Two different tools have been used for the simulations, each one with a different approach: while PATITUG (own software) analyses the behaviour of a generic gas turbine allowing a total variability of parameters, GT-PRO (commercial software) is more rigid, albeit more precise in the prediction of real gas turbine behaviour. Different potentially interesting configurations and its thermodynamic parameters have been simulated in order to obtain the optimal range for all of them and its variation for each fuel.

KEYWORDS: renewable energy sources, bioenergy, biofuels for power generation, gas turbine systems, Brayton combined cycle, emissions reduction

1. OBJETIVE AND INTRODUCTION

The goal of this work is to simulate and analyse the behaviour of gas turbines for power generation using different non-conventional fuels (biogas, synthesis gas and bioethanol) obtained from different biomass renewable resources energy crops (EC) and municipal solid waste (MSW).

Gas turbine power generation is being pushed to the utilisation of alternative fuels that can be used with reliability and efficiency (Basu *et al.*, 2001; Gökalp and Lebas, 2004; Gadde *et al.*, 2006; Shortt, 2005; Nieto *et al.*, 2011). Different reasons arise behind this new tendency, e.g. price evolution of natural gas and availability of renewable sources (McMillan *et al.*, 2006), environmental strategies (Board, 2005) and pollutant emissions (Anheden, 2000; Rising *et al.*, 2004) among others. In the last years, the energy policies of the industrialized countries have been encouraging to find more sustainable ways of power generation. Nevertheless, many of the signatories of the Kyoto protocol are not reaching the greenhouse gas emission objective for 2012. Anyway, more ambitious limits should be set in the future, and therefore, further research on the use of CO₂-free alternative fuels is highly needed and will be promoted.

In this context, combustion of biomass and biofuels as an alternative to conventional fuels is becoming an active area of research in the recent years: Elmegaard *et al.*, 2003; IDAE, 2007; Hilkiah-Igoni, 2008; Dong, 2010; San Miguel *et al.*, 2010; Al-attab and Zainal, 2010, as an example. In this works, external combustion of biomass or co-combustion with coal, external combustion of

biofuels, and the use of biofuels in internal combustion engines technologies are examined. Gas turbines allow the operation in higher ranges of power and obtain significantly higher energetic and exergetic efficiencies if they are configured in combination with a steam cycle (combined cycle, CC). With the same goal, the Integrated Gasification Combined Cycle (IGCC) power plants represent a mature technology for high efficient power generation from coal.

In this paper, the behaviour of gas turbines working with different biofuels, namely biogas, synthesis gas (syngas) and bioethanol will be analysed. Natural gas is taken as the reference fuel since it is the most commonly used fuel in gas turbine power generation installations. For the set of considered biofuels, the differences in performance with the reference case are studied from different points of view in relation with the complex current energetic context, mainly:

- energetic and exergetic efficiency of the simple/combined cycle
- CO₂ emissions.

Different potentially interesting configurations and its thermodynamic parameters have been simulated in order to obtain its optimal values for all of them and its variation for each fuel. This optimisation has been performed with a very precise and rigorous thermodynamic modelling, regarding thermal state equations, mixing models, properties calculation, etc., through the use of PATITUG, a modular and flexible software tool for design, analysis and optimisation of thermodynamic cycles developed by the *Applied Thermodynamics Group* of the Universidad Politécnica de Madrid. It allows a total and completely free variability of the main design parameters, and full control of the physical models applied. PATITUG provides a series of different modules that calculate thermodynamic properties of the streams that take part in the cycle and the behaviour of the components involved from a thermodynamic point of view. Modules have been implemented for filters, mixing chambers, adiabatic humidifiers, pumps, compressors, adiabatic turbines, refrigerated turbines, combustion chambers, heat recovering boilers and heat exchangers, among others. Models for handling substances, mixtures and chemical reactions are included. A variety of state equations, like ideal gas, virial gas, Lee-Kesler state equation and the IAPWS-IF97 equation for water, as well as different expressions for the heat capacity at null pressure limit, can be selected. For mixtures, the models of ideal gas mixture and Lewis-Randall mixture are available. Other recent studies have been carried with this software (Nieto *et al.*, 2011).

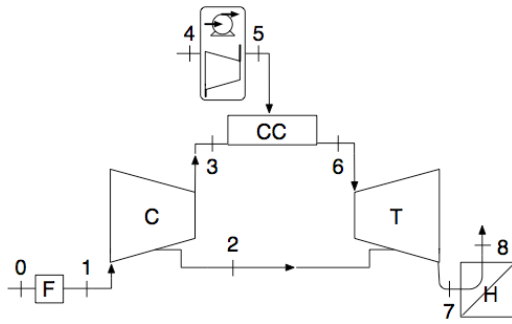
Once the optimal configurations and cycle parameters have been defined, calculations for the power plant have been carried out, considering the commercial turbines and devices that are more adequate for the optimised conditions obtained in the previous phase. For this purpose, GT-PRO (Thermoflow Inc., 2001) has been used. GT-PRO is a commercial application software that includes data about a huge set of industrial gas turbines; it is more rigid, albeit more precise in the prediction of the particular gas turbines behaviour.

2. METHODS

A thorough bibliographical research was carried out to collect the data needed for the study, mostly concerning typical chemical composition values for biogas (Rao and Singh, 2003), (Deublein and Steinhauser, 2008); syngas (Mueller-Langer *et al.*, 2007; Wang *et al.*, 2009) and bioethanol (Kim and Dale, 2004; Pimentel and Patzek, 2005; Kwiatkowski *et al.*, 2006; Sassner *et al.*, 2008).

2.1. PATITUG simulations

A standard gas turbine has been programmed with PATITUG as shown in Figure 1. Thermodynamic properties in PATITUG have been calculated using the two-term virial equation of state for air components and the Lee-Kesler generalised equation (Lee and Kessler, 1975) for the fuels. All gas mixtures have been treated as ideal (Lewis-Randall). For all components, the correlation of exponential type given in (Daubert and Danner, 1989) is used for the specific heat at null pressure.



$$\begin{aligned}
 T_0 &= 15^\circ\text{C}, P_0 = 1 \text{ bar} \\
 \Delta P_F &= P_0 - P_1 = 996.3 \text{ Pa} \\
 \eta_{s,C} &= 0.845 \\
 m_2 &= 0.062m_1 \\
 T_4 &= 15^\circ\text{C}, P_4 = 10.34 \text{ bar} \\
 P_5 &= 1.41P_3 \quad (\eta_{s,4-5} = 0.84) \\
 \Delta P_{CC} &= P_3 - P_6 = 0.0399P_3, Q_{CC} = 0.0034e_4 \\
 \eta_{s,T} &= 0.845 \\
 P_7 &= 1.2499 \text{ bar} \\
 T_8 &= 120^\circ\text{C}
 \end{aligned}$$

Figure 1. Schematic view of the programmed Combined Cycle and its parameters

The programme calculates the *exergetic* efficiencies in simple and combined cycle:

$$\begin{aligned}
 \xi_{SC} &= \frac{\eta_{em}(W_T + W_C + W_{4-5})}{m_4 e_4} \\
 \xi_{CC} &= \frac{\eta_{em}(W_T + W_C + W_F) + \zeta m_7(e_7 - e_8)}{m_4 e_4}
 \end{aligned} \quad (1)$$

with W_T the turbine gross power output, W_C and W_{4-5} the turbine compressor and the fuel compressor/pump gross power consumptions. e_i is the chemical flow exergy of stream i . A global electromechanical conversion efficiency η_{em} is introduced and assumed equal to 0.98. The fraction of the combustion gases exergy recovered in the HRSG and converted into work by the steam cycle ζ have been assumed equal to 0.7.

The maximum efficiency conditions were found for each of the studied fuels, in both simple and combined cycle. Furthermore, the variation of efficiency related to turbine inlet temperature (TIT) and compressor pressure ratio (PR) was analysed and exergy balances were performed. TIT was limited between 1273.15-1723.15 K while limits for PR were 10 and 40. The lower limits were chosen considering that the efficiency at lower inlet temperatures or pressure ratios would be uninteresting, while the upper limits were set considering that gas turbines will not usually be capable to work above them.

Natural gas was considered as pure methane. Biogas was considered as a mixture of mainly methane and carbon dioxide, with small constant quantities of oxygen and nitrogen ($x_{N_2} = 0.04$ and $x_{O_2} = 0.01$), typical in biogas (Deublein and Steinhauser, 2008). x_{CH_4} was varied from 0.45 to 0.75 (and hence x_{CO_2} from 0.5 to 0.2), covering the whole range of typical biogas compositions, as calculated using data from different energy crops biomass compositions (Duke, 1983) and empirically confirmed for some of them (Amon *et al.*, 2003). Syngas was studied as a binary H_2 -CO mixture and then the influence of adding CO_2 up to 30% was studied in a $x_{H_2} / x_{CO} = 1$ case.

2.2. GT-PRO simulations

After completing the analysis of the results yielded by the previous of simulations, a further study with GT-PRO was started. Now a real natural gas (containing impurities) was considered as reference. The composition of this fuel is: 97.65% CH_4 , 0.97% C_2H_6 , 0.3% C_3H_8 , 0.11% C_4H_{10} , 0.02% C_5H_{12} , 0.01% C_6H_{14} 0.86% N_2 , 0.08% CO_2 .

Regarding biogas from energy crops, a composition of 53% CH_4 , a methane generation of $180 \text{ Nm}^3 \text{ t}^{-1}$ of substrate (maize) and a 24 kWh t^{-1} electric and 240 kWh t^{-1} heat consumption have been considered (Deublein and Steinhauser, 2008). If the substrate is MSW, the biogas methane content is 65% and the yield is $200 \text{ Nm}^3 \text{ CH}_4 \text{ t}^{-1}$, with a power and heat consumption of 18.7 and 2.25 kWh t^{-1} (Rao and Singh, 2003). This has been taken into account in the GT-PRO simulations.

GT-PRO allows the simulation of a gasification plant obtaining syngas fuel from biomass, with the possibility of adding a pre-combustion CO_2 capture module. It calculates the final syngas composition and the energy consumption in these processes. A Texaco gasifier with radiant and

convective coolers has been chosen for the simulation. Ambient air (288.15 K, 1 bar) is compressed to the air separation unit (ASU) working conditions (288.15 K, 5.171 bar).

For ethanol an energy consumption of 20% has been considered, based on an average value of the results of previous studies (Pimentel and Patzek, 2005; Sassner *et al.*, 2008). It should be pointed out that some of the found data on energy consumption for ethanol production do not always agree.

Using data from the GT-PRO simulation, CO₂ emission intensities were calculated. However, some problems were encountered when evaluating net emissions for biofuels, as the complete carbon cycle must be considered, i.e. the carbon that is fixed from the atmosphere by biomass during its growth as well as the power plant emission. No clear data about how to calculate CO₂ net emission using biofuels were found, and, as a matter of fact, European Environment Agency (EEA) studies reveal that there is a high variability in net emission values (and these can be either positive or negative) and depend on the substrate and the technology used to obtain the biofuel (EEA, 2008).

example of the kind of problems encountered when trying to find a single indicator to quantify the net emission of a power plant which uses biofuels, if the emission intensity F is calculated as $F = (E_+ - E_-)/P$, being E_+ the power plant emission, E_- the carbon which is fixed by the biomass and P the net power output, it would be concluded that:

- a less efficient biomass-to-fuel conversion process (i.e. which needs more biomass to produce the same amount of fuel) would be environmentally more advantageous (F becomes smaller).
- if $F < 0$ a less efficient power plant would be environmentally better ($|F|$ would increase).

These conclusions would be misleading so the previous approach was rejected.

Furthermore, not all of the carbon in the biomass ends up in the fuel, and the fraction of carbon that does so is different for each fuel and substrate, e.g. while in gasification approximately 98% of the initial carbon gets to the fuel, in anaerobic digestion this value is around 36% using energy crops as a substrate. Therefore, the net emission will depend on the final destination of the residual carbon (solid or as CO₂ in alcoholic fermentation).

Taking into account the aforementioned issues, net CO₂ emissions for all biofuels were considered equal to zero, as is advised by the Spanish Ministry of Industry in its Renewable Energy Plan for 2005-2010 (MITC and IDAE, 2005). For MSW, the value set in the same document will be used: 60.5 tCO₂ per GW_{th}h. If there is pre-combustion CO₂ capture, then the net emission would be the result of subtracting the gross power plant emission with capture to that obtained with gasification without capture. The efficiency of CO shift reaction and CO₂ capture were assumed equal to 98% and 90% respectively.

3. RESULTS AND DISCUSSION

3.1. Analysis using PATITUG

Tables 1 to 4 show the conditions (TIT and PR) for which the exergetic efficiency of the modelled gas turbine is maximum for simple and combined cycle when working with methane, biogas (with constant $x_{N_2} = 0.04$ and $x_{N_2} = 0.01$), syngas (binary H₂-CO) and ethanol, respectively.

Table 1. Maximum exergetic efficiency conditions for pure methane

$\xi_{SC,max}$	TIT (K)	PR	$\xi_{CC,max}$	TIT (K)	PR
0.3506	1723.15	40	0.5411	1723.15	29.5

The dependence of the exergetic efficiency with the fuel composition is presented in Figures 2 and 3. Figure 2 shows the curves of the exergetic efficiency in simple and combined cycle respectively, as a function of pressure ratio, for a binary biogas (CH₄-CO₂) in the case of TIT = 1723.15 K, when varying the CH₄ fraction. Figure 3 shows analogous results for a $x_{H_2} / x_{CO} = 1$ syngas with varying CO₂ fractions.

Table 2. Maximum exergetic efficiency conditions for biogas

X_{CH_4}	$\xi_{SC,max}$	TIT (K)	PR	$\xi_{CC,max}$	TIT (K)	PR
0.45	0.3476	1723.15	40	0.5316	1723.15	32.7
0.55	0.3491	1723.15	40	0.5353	1723.15	31.5
0.65	0.3501	1723.15	40	0.5378	1723.15	30.8
0.75	0.3507	1723.15	40	0.5396	1723.15	30.2

Table 3. Maximum exergetic efficiency conditions for syngas

X_{H_2}	$\xi_{SC,max}$	TIT (K)	PR	$\xi_{CC,max}$	TIT (K)	PR
0.40	0.3608	1723.15	38.5	0.5670	1723.15	21.5
0.50	0.3602	1723.15	38.0	0.5654	1723.15	21.5
0.60	0.3594	1723.15	37.5	0.5634	1723.15	21.5
0.70	0.3585	1723.15	37.5	0.5612	1723.15	21.5
0.80	0.3573	1723.15	37.5	0.5586	1723.15	22.0
0.90	0.3558	1723.15	37.0	0.5555	1723.15	22.0
1.00	0.3537	1723.15	37.0	0.5514	1723.15	22.0

Table 4. Maximum exergetic efficiency conditions for pure ethanol

$\xi_{SC,max}$	TIT (K)	PR	$\xi_{CC,max}$	TIT (K)	PR
0.3399	1723.15	40	0.5177	1723.15	35.75

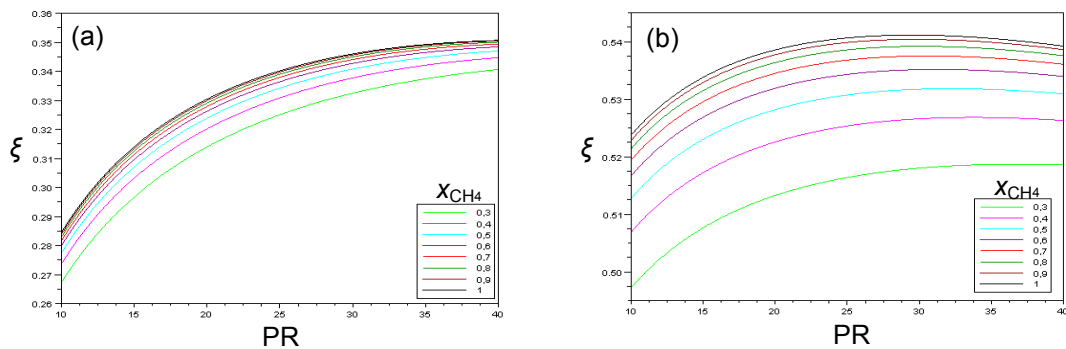


Figure 2. Dependence of exergetic efficiency as a function of PR on biogas composition (a) simple cycle; (b) combined cycle

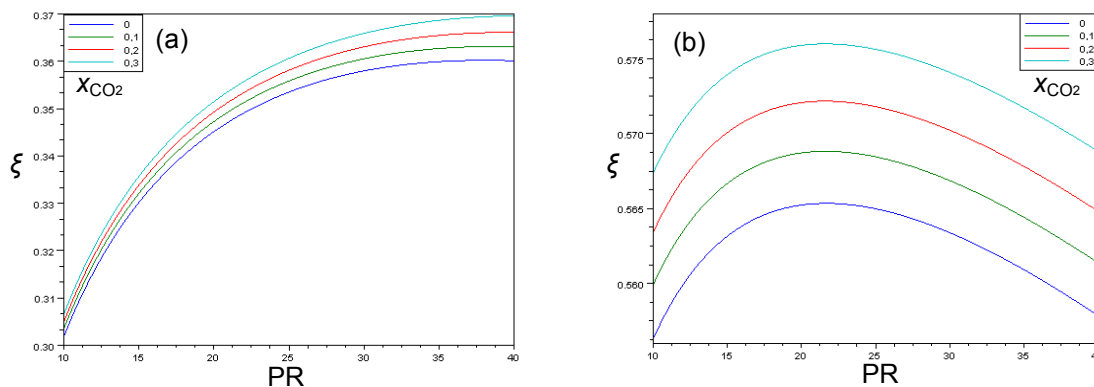


Figure 3. Dependence of exergetic efficiency as a function of PR on syngas composition. (a) simple cycle; (b) combined cycle

The exergy balances in the gas turbine also provide interesting information. Figure 4 shows these balances, for the maximum TIT and for the whole range of PR considered, for pure methane, biogas (53 % CH₄, 42 % CO₂, 4 % N₂, 1 % O₂), syngas (50 % H₂, 50 % CO) and pure ethanol, respectively.

It can be noticed that the exergy destruction obtained with syngas is the lowest, and the exergy carried by the combustion gases is higher for this fuel than for natural gas, what opens the door to a better heat recovery efficiency in the HRSG if a combined cycle were planned. Ethanol presents the highest exergy destruction.

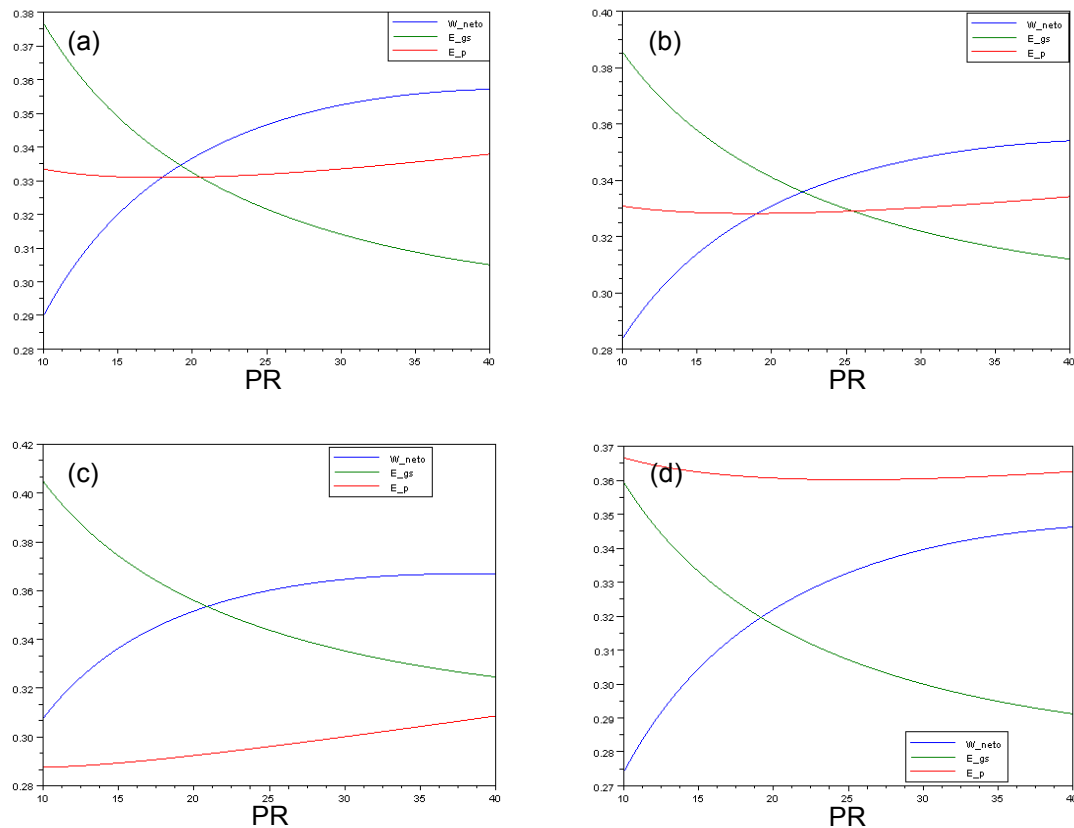


Figure 4. Exergy balances in the gas turbine as a function of PR for TIT = 1723.15 K. Net turbine power output in blue; exhaust gases exergy in green; exergy destruction in red. All values are expressed as a fraction of the inlet exergy (m_4e_4). (a) methane; (b) biogas; (c) syngas; (d) ethanol

3.2. Analysis using GT-PRO

Gas turbine maximum gross LHV efficiencies found in the simulations with GT-PRO using two different commercial gas turbines for the fuels under study are shown in Table 5. Two different size turbines have been chosen in order to highlight the possible scale effects.

Table 5. Efficiency of simple Brayton cycle for large and small size commercial gas turbines and its optima working conditions

Fuel	Mitsubishi 701-G (334 MWe)			Siemens SGT-200-1S (6.7 MWe)		
	$\xi_{SC,max}$	TIT (K)	PR	$\xi_{SC,max}$	TIT (K)	PR
Natural gas	0.3929	1700	21.0	0.3142	1297	11.8
Biogas from EC (53 % CH ₄)	0.3994	1674	21.9	0.3182	1287	12.1
Biogas from MSW (65 % CH ₄)	0.3978	1684	21.6	0.3152	1291	12.0
Syngas (31% H ₂ , 37 % CO) ^a	0.4172	1653	21.9	0.3314	1278	11.9
Syngas (87% H ₂ , 1 % CO) ^{a,b}	0.4203	1704	20.5	0.3319	1297	11.4
Ethanol	0.3919	1690	21.3	0.3152	1295	11.9

^a Resulting composition after gasification of MSW. Gasification of maize would lead to almost the same results

^b Resulting syngas composition after addition of CO₂ pre-combustion capture module

Now the optima conditions are slightly different than the predicted by PATITUG for each of the fuels, due to effects other than those purely thermodynamical (mainly related to the specific turbine design)

which were not taken into account with PATITUG, and to the different definition of the efficiency (LHV and e are very close for all fuels, but they are not exactly the same). The smaller turbine has lower efficiencies because both its turbine inlet temperature and pressure ratio are lower. Results for differences in exergy loss between fuels found with PATITUG are confirmed by GT-PRO.

Considering the complete biomass-to-power process through a gas turbine system, two main steps occur: the biomass-to-biofuel process (here anaerobic digestion, gasification and fermentation-dehydration have been considered) and the power production by the gas turbine fired by that biofuel (biogas, syngas and bioethanol, respectively). The results of simulation of the second step have been showed in Table 5. For the overall biomass-to-power cycle, taking into account the auxiliary power consumption in the first step, gasification yields a higher efficiency than biogas and bioethanol production, especially in combined cycle. This is due to a higher biomass-to-fuel conversion efficiency and to the recirculation of the water vapour produced in the gasification process to the HRSG in combined cycle, which allows an extra power production in the Rankine cycle. The greatest auxiliary power consumption takes place in the case of gasification. In a biomass IGCC with pre-combustion CO₂ capture, 60-65 % of the auxiliary power consumption would be due to the gasifier (85% of it to the ASU), and 31-36 % to CO₂ capture. The actual values depend on the substrate. The decrease of efficiency when adding pre-combustion CO₂ capture is around 6 % in combined cycle and 4-6% in simple cycle. Net feedstock (biomass or natural gas) LHV efficiencies are shown for simple and combined cycles in Table 6 for the Mitsubishi 701-G turbine. Calculated gas turbine optimum conditions are the same for both simple and combined cycles.

Table 6. Overall biomass-to-power efficiency of the simple and combined cycle

Fuel	Simple	Combined
Natural gas	0.3833	0.5410
Biogas from EC biomass (53% CH ₄)	0.1383	0.1804
Biogas from MSW (65% CH ₄)	0.2210	0.3124
Syngas from EC biomass	0.2050	0.4152
Syngas from EC biomass with CO ₂ capture	0.1575	0.3398
Syngas from MSW	0.1834	0.3779
Syngas from MSW with CO ₂ capture	0.1357	0.3294
Ethanol	0.1348	0.2036

3.3. Carbon dioxide emissions

Simulations were carried out on three large-size gas turbines in combined cycle to calculate the emission using natural gas and those saved with CO₂ capture: Ansaldo AE

94.3A (284.8 MW), Siemens SGT5-4000F (263.6 MW) and Mitsubishi 701 G (334 MW). The mean value of emission intensity in natural gas combined cycle (NGCC) for the three turbines that were simulated is 369.5 tCO₂ GWh⁻¹. This would equal the emissions saved when using an energy-crops-biofuel power plant without capture. Thus, the hypothetical substitution of a 400 MW NGCC working with capacity factor of 80%, i.e. 2805 GWh year⁻¹ by an analogous CC power plant fired with that biofuel would save 1.04 MtCO₂/year. If a precombustion CO₂ capture module is added, the net carbon emission would be reduced further, reaching negative values (globally CO₂ would be removed from the atmosphere). Assuming the CO oxidation efficiency of 98% and the capture module efficiency of 90%, as stated previously, a total of 3.36 MtCO₂/year would be avoided.

Table 7. Average CO₂ emission intensities of CC fed by EC biomass and MSW and CO₂ emissions saved when substituting a 400MW NGCC by a biomass CC of the same power output and capacity factor of 80%

	MSW		EC
	tCO ₂ GWh ⁻¹	MtCO ₂ saved	MtCO ₂ saved
Anaerobic digestion (Biogas)	194	0.46	1.04
Gasification (Syngas)	158	0.56	1.04
Gasification (Syngas) + CO ₂ Capture	-654	2.83	3.36
Fermentation + dehydration (Ethanol)	-	-	1.04

For the case of MSW, a net emission of $60.5 \text{ t CO}_2 \text{ GW}_{\text{th}}^{-1}$ is considered. Hence, the global emission is related to the overall efficiency of the power plant. Table 7 shows the mean emission intensities for MSW Combined Cycles, and the CO_2 emissions saved if a 400MW NGCC were substituted by an equivalent MSWCC with a capacity factor of 80%:

4. CONCLUSIONS

The thermodynamical cycle efficiency is high enough for all biofuels so that they can be thought of as an alternative to natural gas, being ethanol the worst from this point of view (1% lower exergetic efficiency in simple Brayton cycle and 2.3% in combined cycle than natural gas). Syngas is the fuel which provides the highest efficiency (including methane) and it is reached at lower pressure ratios (21.5-22 for a combined cycle), more easily achievable by real gas turbines. Exergy destruction is also lower for syngas than for natural gas, so more exergy can be recovered from the exhaust gases, whereas the fuel with the highest exergy destruction is ethanol.

Considering the global conversion process of feedstock to electricity, gasification yields the highest efficiency, due to a higher efficiency in both the power generation and biomass-to-fuel processes. This is even more noticeable in combined cycle because the water vapour produced in the gasification process can be recirculated to the HRSG, so that a bigger fraction of the energy contained in the substrate is used in the power plant. Thus, an efficiency of around 40% in a biomass IGCC can be attained, much higher than that of biogas and ethanol plants ($\approx 20\%$), albeit around 14% lower than the obtained in NGCC. Pre-combustion CO_2 capture in gasification plants requires an additional power consumption that means a 6% efficiency loss in combined cycle.

The CO_2 emission reduction when using biofuels is important but difficult to measure. Around $370 \text{ tCO}_2 \text{ GWh}^{-1}$ can be saved by substituting a natural gas combined cycle for a power plant fired with biofuels produced from energy crops, with an additional $850\text{-}900 \text{ tCO}_2 \text{ GWh}^{-1}$ if pre-combustion CO_2 capture is used. This results in a 1 MtCO_2 reduction for a 400 MW plant (3.36 MtCO_2 with capture). These values are lower for MSW derived biofuels, as less carbon is fixed by the substrate. However, these figures should be revised via a thorough study of the carbon cycle for each case.

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