Analysis of the behaviour of biofuel-fired gas turbine power plants

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ABSTRACT

The utilisation of biofuels in gas turbines is a promising alternative to fossil fuels for power generation. It would lead to significant reduction of CO_2 emissions using an existing combustion technology, although significant changes seem to be needed and further technological development is necessary. The goal of this work is to perform energy and exergy analyses of the behaviour of gas turbines fired with *biogas*, *ethanol* and synthesis gas (*bio-syngas*), compared with natural gas. The global energy transformation process (i.e. from biomass to electricity) has also been studied. Furthermore, the potential reduction of CO_2 emissions attained by the use of biofuels has been determined, considering the restrictions regarding biomass availability. Two different simulation tools have been used to accomplish the aims of this work. The results suggest a high interest and the technical viability of the use of Biomass Integrated Gasification Combined Cycle (BIGCC) systems for large scale power generation.

INTRODUCTION

As in other combustion technologies, an effort is being done to stimulate the use of alternative fuels in gas turbines that can be used reliably and efficiently [1]. Several recent works analyse the use of different non-convetional fuels, such as synthesis gas [2], dimethil ether [3,4], alkane hydrocarbons [5] and biomass [6] for power generation. This new trend is pushed by different reasons, as environmental strategies [7], reduction of pollutant emissions [8,9] and the availability of both natural gas (which directly affects its price evolution) and renewable resources [10].

The energy policies of many governments striving to reduce greenhouse gas (GHG) emissions resulted in 1997 in the Kyoto Protocol, signed by many of the world's countries. However, some of them, like Spain, are not reaching its objective for 2012. In any case, more ambitious limits should be set, and therefore, further research in technologies which contribute to significant GHG emission reduction is highly needed and promoted. In 2009, the electrical power generated from biomass in Spain represented 1.35% of the total power, with an increase of 4.9% over 2008 [11]. This is a relatively low penetration in comparison with wind and solar power. The Spanish PANER 2011-2020 (National Plan for Action on Renewable

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Energy) admits the great energetic potential of biomass for power generation, and that this renewable energy source has been underused in the last years [12]. In the context of the European Union, Finland and Sweden are the countries which have encouraged the most the use of biomass for heat and power generation (the biomass consumption was 1.34 and 0.904 tep/inhabitant respectively in 2008, compared to Germany's 0.125, France's 0.141, Spain's 0.0905, Italy's 0.0319 or UK's 0.0180). The average biomass consumption per inhabitant in the EU-27 was 0.138 tep [11,13].

In this global scenario, combustion of biomass or biofuels as an alternartive to fossil fuels is becoming an active area of research in recent years. Currently most of the electrical power generation from biomass is produced through a) external combustion systems in co-combustion with coal, or b) the combustion of biogas, obtained from a previous methanisation of biomass, in internal combustion engines (ICE) with a typical power output in the range of 30 kW-6 MW [14]. A common alternative to methanisation is gasification with air, which produces a bio-syngas with a high nitrogen content, followed by combustion in an ICE [14]. Another suggested possibility is the use of external combustion of biomass combined with internal firing in a gas turbine [6].

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). There also exist gas turbines in the same range of typical ICEs, so small gas turbines could be used as a substitute for these if biomass availability were not so quantitative. Nevertheless, gasification for use of syngas as fuel in gas turbines is mainly interesting for large scale power generation, due to the high investment cost and energy consumption of the gasifier. Integrated Gasification Combined Cycle (IGCC) is already a mature technology for efficient power generation from cheap fossil fuels, such as coal, refinery residues and residual oil [7]. In IGCC power plants gasification with oxygen instead of air is used in order to reduce the fuel volume. Although biomass gasification is not currently available on a large scale, it is technically viable and a very promising technology, considering the environmental advantages of a renewable CO_2-free source of energy. Thus, extra efforts on research in this area would be fully justifiable. Furthermore, gasification allows the possibility of including a pre-combustion CO_2 capture module reducing GHG emissions even more. In the case of a BIGCC with pre-combustion CO_2 capture, the net emissions would be negative.

The present study analyses the behaviour of gas turbines working with different biofuels, namely biogas, synthesis gas (or syngas) and ethanol. Natural gas is taken as the reference fuel, since it is the fuel usually used in gas turbines for power generation. For each biofuel, the differences in performance with the reference case are studied from different aspects related to the current complex energetic context, mainly:

- Energetic and exegetic efficiency of the simple and combined cycle.
- CO_2 emissions.
- Use and availability of renewable resources.

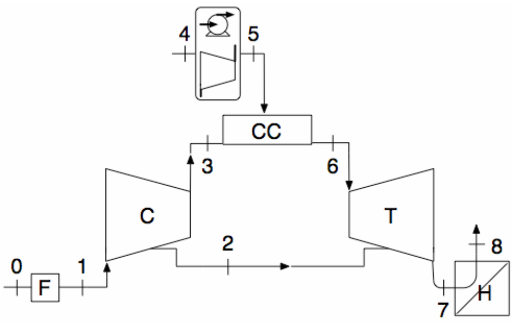
Different configurations which were judged as potentially interesting have been simulated in order to obtain the optimal values of their thermodynamical parameters for each fuel and its variations. This optimisation has been performed using PATITUG, a modular and flexible software application for analysis of thermodynamical cycles developed by the Applied Thermodynamics Group of the Universidad Politécnica de Madrid. This software uses a very precise and rigorous thermodynamic modelling, regarding thermal state equations, mixing models, properties calculation, etc. It allows a total and completely free variation of the main design parameters, and full control of the models applied.

After analysing the results yielded by this first stage of the work, finding the optimal configurations and cycle parameters and the differences between the biofuels studied, a further stage of the study has been carried out for the most interesting biofuel, considering not only energetic and exegetic efficiency but also other important aspects as CO_2 emissions. This second part of the analysis was performed using GT-PRO [15], a commercial program which includes data about several real gas turbines. GT-PRO is more rigid than PATITUG, albeit more precise in the prediction of real gas turbine behaviour. Furthermore, the global biomass-to-electricity energy transformation process was studied.

GENERAL STUDY WITH PATITUG

Methodology

Description of the cycle and operating conditions A standard gas turbine has been programmed with PATITUG as shown in Figure 1.



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

Figure 1: Diagram and main cycle parameters of the standard gas turbine programmed with PATITUG.

The cycle parameters given above have been adjusted to make them representative of a generic configuration. These are reasonable values within their range in real power plants. They have been previously used with PATITUG giving accurate results, as shown in [16]. In particular, the predictions for General Electric's F6 gas turbine given by GT-PRO are reproduced almost exactly using this set of operating parameters. Several other commercial devices given by GT-PRO have been compared with similar results.

The program calculates the exergetic efficiencies in simple and combined cycle using equations 1 and 2:

$$\eta_{\text{ex}} = \frac{\eta_{\text{em}}(\dot{W}_{\text{T}} + \dot{W}_{\text{C}} + \dot{W}_{\text{F}})}{\dot{m}_4 e_4} \tag{1}$$

$$\xi_{\text{ex}} = \frac{\eta_{\text{em}}(\dot{W}_{\text{T}} + \dot{W}_{\text{C}} + \dot{W}_{\text{F}}) + \zeta \dot{m}_7 (e_7 - e_8)}{\dot{m}_4 e_4} \tag{2}$$

where $\dot{W}_\mathrm{T}$, $\dot{W}_\mathrm{C}$ and $\dot{W}_\mathrm{F}$ are the turbine, turbine compressor and fuel compressor gross power outputs, respectively, computed as the product of the mass flow rate and the enthalpic jump in each of them. η_em represents an overall electromechanical efficiency of the ensemble which has been assumed equal to 0.98. ζ is the exergetic efficiency of the coupled steam cycle, i.e. the fraction of the exergy released by the combustion gases in the Heat Recovery Steam Generator (HRSG) converted into work in the steam cycle, for which the value 0.7 has been assumed. The variable e denotes the thermodynamic function flow exergy.

Thermodynamic modelling In this study, air flow and combustion gases have been treated as a Lewis-Randall mixture:

$$h^\mathrm{M} = 0 \quad ; \quad v^\mathrm{M} = 0 \quad ; \quad s^\mathrm{M} = -R\sum_i x_i \ln x_i \tag{3}$$

where the superindex M indicates the corresponding mixing function.

Pure gases have been modelled with virial equations of state truncated after the second term:

$$Pv = RT + \mathbf{B}(T) \tag{4}$$

Function $\mathbf{B}$(T) and the ideal gas heat capacity $c_p{}^*(T)$ (heat capcity at null pressure limit) for all gases have been taken from [17]

$$\mathbf{B}(T) = \alpha + \frac{\beta}{T} + \frac{\gamma}{T^3} + \frac{\delta}{T^8} + \frac{\varepsilon}{T^9} \tag{5}$$

$$c_p{}^*(T) = \mathbf{a} + \mathbf{b}\left(\frac{\frac{\mathbf{c}}{T}}{\sinh\frac{\mathbf{c}}{T}}\right)^2 + \mathbf{d}\left(\frac{\frac{\mathbf{e}}{T}}{\cosh\frac{\mathbf{e}}{T}}\right)^2 \tag{6}$$

with the set of constants α, β, γ, δ, ε, $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, $\mathbf{d}$ and $\mathbf{e}$ given for every compound. It must be remarked that the temperature-exponential model for $c_p{}^*$ given by (6) is needed in this analysis, because polynomial expressions would lead to losing accuracy, due to the very wide temperature range involved in the combustion.

Ethanol, which is a liquid compound in conditions of state 4 and 5, is treated by the Lee-Kesler equation of state:

$$\frac{Pv}{RT} = z^{(0)} + \omega z^{(1)} \tag{7}$$

where ω is the acentric factor of the substance, and $z^{(0)}$ and $z^{(1)}$ are well known functions of the reduced pressure $P_\mathrm{r} = P/P_\mathrm{c}$ and temperature $T_\mathrm{r} = T/T_\mathrm{c}$ [18]. Pressure and temperature at critical point P_c, T_c and ω for ethanol have been read from [17].

The thermochemical properties (standard heat of formation $\Delta_\mathrm{f}H^\mathrm{o}$ and standard absolute specific entropy s^o) of fuels and gases, given in a compatible reference frame, are also taken from [17]. Chemical flow exergy of fuels has been calculated as described in [19].

Combustion The chemical combustion reaction of methane, hydrogen, carbon monoxide and ethanol has been assumed to be a total combustion. No formation of NO_x has been considered. Quantifying NO_x in combustion gases is very important from the point of view of environmental effects, but it is irrelevant for the calculation of thermodynamic properties of the combustion gases, since very small quantities are formed so they do not have any influence on the energetic and exegetic performance of the cycle.

Combustion has been assumed to take place in presence of moist air. Dry air has been modelled as a mixture of N_2 (78.045 %), O_2 (20.990 %), Ar (0.935 %) y CO_2 (0.030 %)[*]. Minor components of air have been ignored. The quantity of water added has been adjusted for the target 60% RH, leading to a computed value for the water molar fraction close to 1%.

Biofuels considered and cases under study Simulations with three different biofuels (biogas, syngas and ethanol) as well as with the reference fuel (i.e. natural gas considered as pure methane) were performed using PATITUG in order to find for each of them the maximum efficiency conditions and to study the effect of the variation of turbine inlet temperature (TIT) and compressor pressure ratio (PR) in the exergetic efficiency. Furthermore, exergy balances were performed. Operation limits were 1000 ºC and 1450 ºC for TIT and 10 and 40 for PR. The lower limits were set because it was considered that the study of the operation of gas turbines below them would be uninteresting, while the upper limits were chosen considering that gas turbines will usually not be capable of working above them. The composition of the combustion gases is different for every case (defined by a pair of values of compression ratio and turbine inlet temperature, TIT) and for every fuel, not only because different relative quantities of CO_2 and H_2O are formed, but mainly because the air mass flow $\dot{m}_0$ is specifically computed iteratively for each case in order to reach the desired TIT.

A thorough bibliographical research was carried out to collect the data needed, mostly concerning typical chemical composition values for the biofuels considered. 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 [20]. 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 [20], as calculated using data from different energy crops biomass compositions [21] and empirically confirmed for some of them [22]. 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 $x_{H_2}/x_{CO} = 1$ mixture [23,24]. Bioethanol was considered as pure ethanol.

Results

Tables 1 to 4 show the conditions (TIT and PR) for which the exergetic efficiency of a gas turbine is maximum for simple and combined cycle when working with methane, biogas (with constant $x_{N_2} = 0.04$ and $x_{O_2} = 0.01$), syngas (H_2-CO) and ethanol, respectively.

Table 1. Maximum exegetic efficiency conditions for pure methane

$\eta_{ex,max}$	TIT (ºC)	PR	$\xi_{ex,max}$	TIT (ºC)	PR
0.3506	1450	40	0.5411	1450	29.5

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[*] Molar fractions

Table 2. Maximum exegetic efficiency conditions for biogas

x_{CH_4}	$\eta_{ex,max}$	TIT (ºC)	PR	$\xi_{ex,max}$	TIT (ºC)	PR
0.45	0.3476	1450	40	0.5316	1450	32.7
0.50	0.3485	1450	40	0.5337	1450	32.1
0.55	0.3491	1450	40	0.5353	1450	31.5
0.60	0.3496	1450	40	0.5367	1450	31.1
0.65	0.3501	1450	40	0.5378	1450	30.8
0.70	0.3504	1450	40	0.5388	1450	30.5
0.75	0.3507	1450	40	0.5396	1450	30.2

Table 3. Maximum exegetic efficiency conditions for syngas (binary H_2-CO mixture)

x_{H_2}	$\eta_{ex,max}$	TIT (ºC)	PR	$\xi_{ex,max}$	TIT (ºC)	PR
0.35	0.3610	1450	38.5	0.5676	1450	21.5
0.40	0.3608	1450	38.5	0.5670	1450	21.5
0.45	0.3605	1450	38.0	0.5662	1450	21.5
0.50	0.3602	1450	38.0	0.5654	1450	21.5
0.55	0.3598	1450	38.0	0.5644	1450	21.5
0.60	0.3594	1450	38.0	0.5634	1450	21.5
0.65	0.3590	1450	37.5	0.5624	1450	21.5
0.70	0.3585	1450	37.5	0.5612	1450	21.5
0.75	0.3579	1450	37.5	0.5599	1450	22.0
0.80	0.3579	1450	37.5	0.5586	1450	22.0
0.85	0.3566	1450	37.5	0.5571	1450	22.0
0.90	0.3558	1450	37.0	0.5555	1450	22.0
0.95	0.3549	1450	37.0	0.5537	1450	22.0
1.00	0.3537	1450	37.0	0.5514	1450	22.0

Table 4. Maximum exegetic efficiency conditions for pure ethanol

$\eta_{ex,max}$	TIT (ºC)	PR	$\xi_{ex,max}$	TIT (ºC)	PR
0.3399	1450	40	0.5177	1450	35.75

The exergetic efficiencies for a $x_{H_2}/x_{CO}=1$ syngas when varying the CO_2 fraction in simple and combined cycle are shown in figure 2.

Figure 3 shows the Brayton cycle exergetic efficiency as a function of PR (horizontal axes) and TIT (data series) for pure methane, biogas (53% CH_4, 42% CO_2, 4% N_2, 1% O_2), syngas (50% H_2, 50% CO) and pure ethanol. Exergy balances for the same fuels are shown in fig. 4.

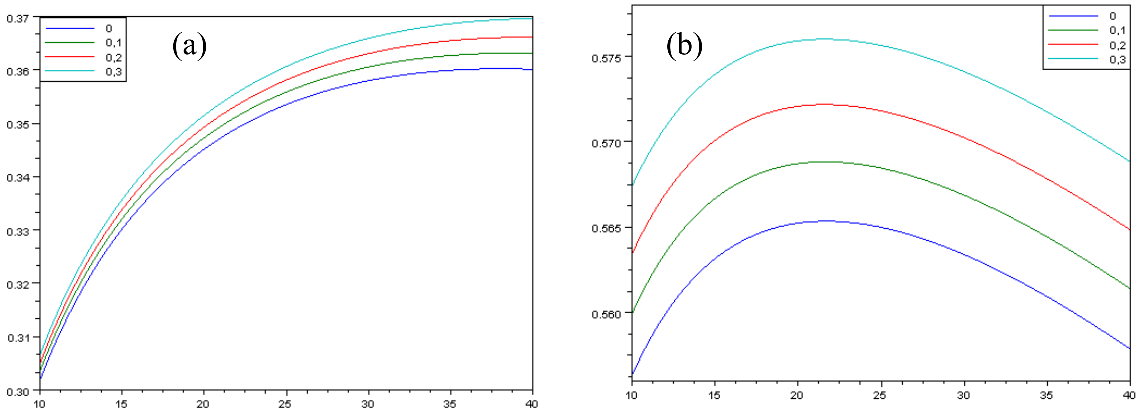

Figure 2: exergetic efficiency for $x_{H_2}/x_{CO} = 1$ syngas at TIT=1450 ºC as a function of PR (horizontal axes) and CO_2 fraction (data series) in Brayton cycle (a) and combined cycle (b).

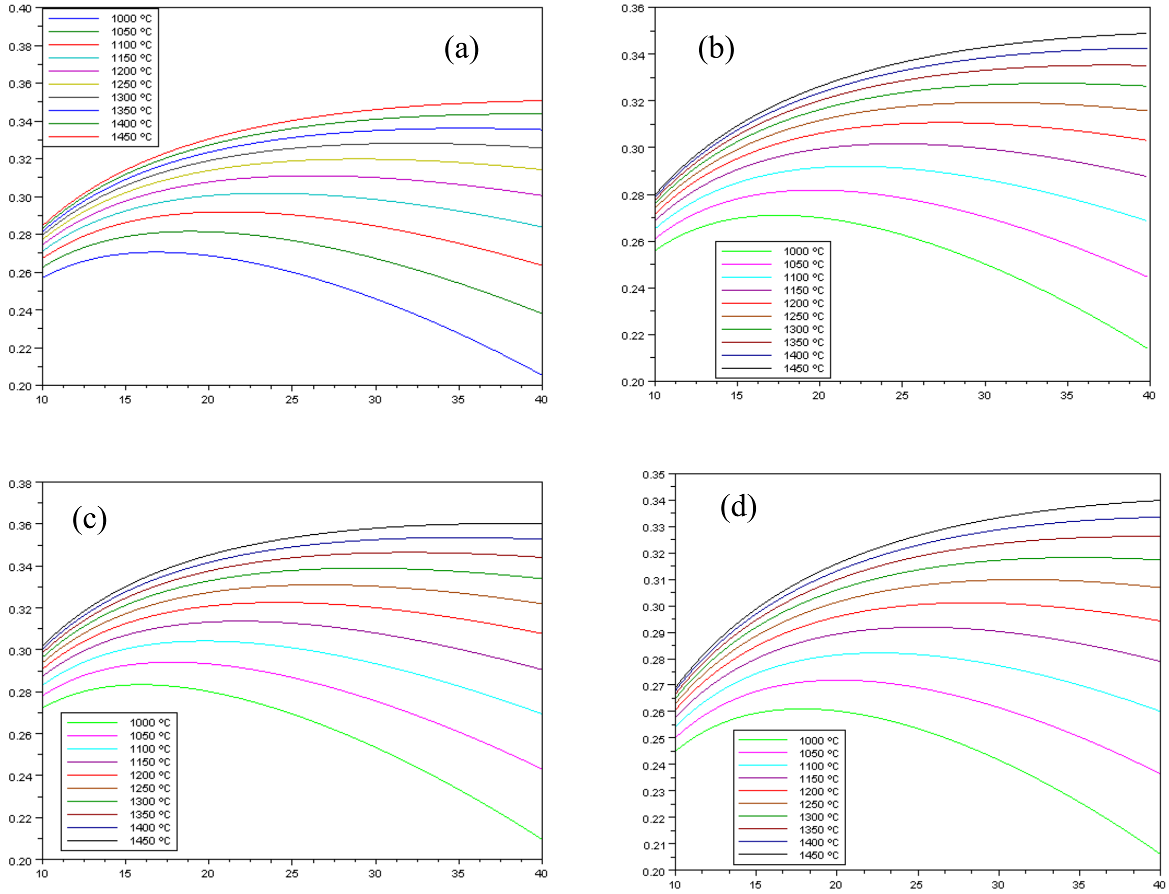

Figure 3: Brayton cycle exergetic efficiency as a function of PR (horizontal axes) and TIT (data series) for: (a) pure methane, (b) biogas (53% CH_4, 42% CO_2, 4% N_2, 1% O_2), (c) syngas (50% H_2, 50% CO) and (d) pure ethanol.

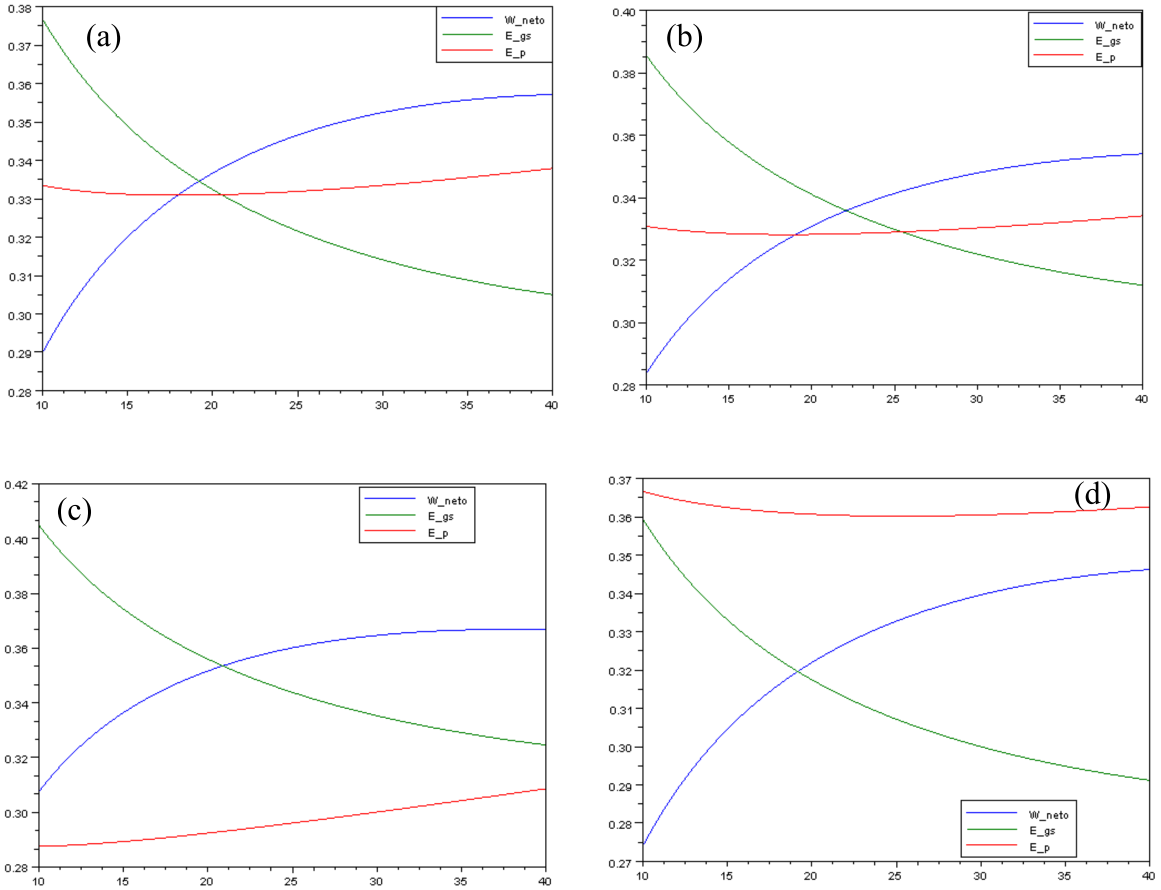

Figure 4: Exergy balances (TIT=1450 ºC) as a function of the pressure ratio for (a) pure methane, (b) biogas (53% CH_4, 42% CO_2, 4% N_2, 1% O_2), (c) syngas (50% H_2, 50% CO) and (d) pure ethanol, respectively. Blue: Turbine net power output. Green: exhaust gases exergy. Red: exergy loss. All values are expressed as a fraction of the inlet exergy (e_0+e_4).

Partial conclusions

The study with PATITUG shows that, for every fuel, the exergetic efficiency as a function of pressure ratio has a maximum, which happens at higher PRs as the turbine inlet temperature increases (obviously the efficiency always increases with the TIT). The optimum PR is different for each of the fuels considered, and it should be noted that it is lower for syngas than for any other fuel considered. This is an advantage of working with this synthesis gas, because it means that the optimum conditions are more easily achievable by a real gas turbine when working with this fuel than with any other of the fuels studied, including methane.

Furthermore, this general analysis of different biofuels reveals that the exergetic efficiency of a gas turbine working with synthesis gas is higher than with any other fuel, including methane, both in simple and combined cycle. The exergy analysis explains that this happens because the exergy loss is smaller for the case with syngas, than for any other (while the highest exergy loss occurs for ethanol). Moreover, the exhaust gases exergy is highest for syngas, which means that more exergy can be potentially recovered in a HRSG.

Apart from purely thermodynamical considerations, there are other reasons to think of the use of synthesis gas in gas turbines for power generation as especially interesting compared to other biofuels. First of all, syngas has a great potential for reduction of CO_2 emission with, due to the possibility of introducing a CO_2 pre-combustion capture module, which decreases the global efficiency in a much lesser extent than post-combustion capture. Furthermore, the global efficiency is higher for syngas than for the other biofuels considered, because the efficiency of the biomass-to-fuel conversion process is higher [20,22,23,25] and water vapour is generated in the gasification process [26], which can be added to the HRSG in a BIGCC (as is usual in coal IGCC plants), or used as process steam, considerably increasing the global efficiency.

Therefore, synthesis gas will be the fuel selected for the next stage of this work, the in-depth analysis of gas turbines fired with it, including the study of the global energy transformation process (from biomass to electricity) in terms of energetic efficiency, reductions in CO_2 emissions and availability of biomass. This second part of the present study will be carried out using GT-PRO a commercial program which allows a precise thermodynamic simulation of a huge set of real gas turbines, as well as the gasification and pre-combustion CO_2 capture processes.

IN-DEPTH STUDY OF BIGCC USING GT-PRO

Methodology

Once the simulations with PATITUG and the analysis of its results were completed, a further study with GT-PRO was commenced. Now, only the most advantageous biofuel was considered and an in-depth analysis not only of the Brayton cycle but also of the global energy conversion process (i.e. considering the biomass rather than the obtained biofuel as the entrance to the system) was carried out.

GT-PRO enables the simulation of a gasification plant which produces syngas from biomass and allows the possibility of introducing a pre-combustion CO_2 capture module. The program calculates the final syngas composition and the energy consumption in these processes. The simulations have been carried out considering a Texaco gasifier with radiant and convective coolers. Ambient air (15 ºC, 1 bar) is compressed to the air separation unit (ASU) working conditions (15 ºC, 5.171 bar). Pre-combustion CO_2 capture has two main steps: oxidation of CO in the syngas to CO_2 (for which a 98% conversion efficiency has been assumed) and CO_2 capture (for which an efficiency equal to 90% has been considered).

This work is centred on energy crops (barley straw, alfalfa stems, rice straw and switchgrass) and municipal solid waste (MSW) as substrates, although most conclusions also apply to other biomass substrates, such as other crops, agricultural residues and woody biomass.

It should be reminded that water vapour and acid gases (H_2S and COS) are always removed, regardless of the implementation of pre-combustion capture. The ultimate analysis of these substrates is shown in Table 5, while the compositions of the resulting synthesis gases with and without pre-combustion CO_2 capture are shown in Tables 6 and 7. As it has already been mentioned, the steam removed from gasifier is recirculated to the HRSG in IGCC plants, increasing the power output of the steam cycle, thus enhancing the global efficiency.

Table 5. Chemical characteristics of the substrates studied

Substrate	Ultimate analysis (weight %)								LHV (kJ/kg)[†]
	C	H	N	Cl	S	O	Moisture	Ash	
Barley straw	40.93	5	0.53	0.24	0.07	36.53	11.5	5.2	15154
Alfalfa stems	42.56	5.41	2.42	0.45	0.18	34.91	9.29	4.78	15525
Rice straw	35.2	4.79	0.8	0	0.17	33.92	7.93	17.19	15809
Switchgrass	42	5.24	0.69	0.17	0.17	33.8	9.84	8.09	14902
MSW	33.75	4.7	0.5	0.6	0.33	24.62	21.5	14	12399

Table 6. Resulting synthesis gas compositions (vol%) and LHV at 25ºC (kJ/kg) for different substrates after moisture and acid gas removal.

Substrate	H_2	CO	CO_2	H_2O	CH_4	H_2S	N_2	Ar	LHV
Barley straw	31.55	39.41	26.92	0.0225	0.0006	0.0004	1.584	0.5183	7775
Alfalfa stems	30	38.03	28.35	0.0225	0.0005	0.0011	3.016	0.5876	7266
Rice straw	40.15	39.13	19.01	0.0219	0.0015	0.0011	1.355	0.3339	10072
Switchgrass	29.11	37.85	30.44	0.0225	0.0004	0.0011	1.952	0.6271	6998
MSW	31.13	36.84	29.37	0.0226	0.0004	0.0025	1.973	0.6618	7277

Table 7. Resulting synthesis gas compositions (vol%) and LHV at 25ºC (kJ/kg) for different substrates after pre-combustion CO_2 capture and moisture and acid gas removal.

Substrate	H_2	CO	CO_2	H_2O	CH_4	H_2S	N_2	Ar	LHV
Barley straw	88.15	0.9901	8.183	0.0355	0.0009	0.0005	1.989	0.6509	33364
Alfalfa stems	86.1	0.9734	8.274	0.0383	0.0007	0.0014	3.86	0.7518	30045
Rice straw	90.6	0.9033	6.509	0.0346	0.002	0.0012	1.564	0.3852	40083
Switchgrass	86.85	0.993	8.734	0.0393	0.0006	0.0014	2.56	0.8224	30803
MSW	87.36	0.9574	8.218	0.0362	0.0006	0.0032	2.562	0.8595	31899

For the reference case, a real natural gas (i.e. containing impurities) was considered. Its molar composition is as follows: 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.

The simulations in simple cycle were carried out in four turbines of different power ranges (turbines 1 to 4), while only turbines 1 and 2 and two additional turbines of the two highest power ranges (5 and 6) were considered for the simulation in combined cycle. The manufacturer, model and nameplate characteristics of these turbines are shown in Table 8:

[†] at 25ºC, moisture and ash included

Table 8. Turbines considered in the simulations with GT-PRO

Turbine No.	Model	Power (kWe)	TIT (ºC)	PR
1	Mitsubishi 701G	334000	1427	21.0
2	Siemens W401	85900	1349	18.6
3	Hitachi H25	31820	1193	14.7
4	GE 5	5500	1232	14.8
5	Siemens SGT5-4000F	263600	1343	16.9
6	GE 6111FA	78300	1327	15.5

Using data from the GT-PRO simulations, CO_2 emission intensities were calculated, in order to know the reduction in emissions achieved by using syngas, considering energy crops and MSW as substrates.

Finally, fuel consumptions were calculated for syngas (both without capture and with pre-combustion capture) to study the amount of biomass needed for each case. The importance of biomass availability must be highlighted, as it is a limited resource and, in the case of energy crops, it needs the use of land which could otherwise be employed for other purposes, mainly for food crops. This could eventually lead to food shortage problems [27]. Therefore it would be of utmost importance to know the availability of land compared to the land use needed in each case (which would vary from country to country) if building power stations using biomass from energy crops were decided.

Results

Analysis of the thermodynamical cycle. Table 9 shows the maximum gas turbine efficiency (based on the lower heating value, LHV) for natural gas and two different compositions of synthesis gas for the four turbines considered, and the maximum efficiency conditions. Table 10 shows the net power output ($\dot{W}_n$), the exergy loss (E_l) and the exergy of the exhaust gases (E_g) as a fraction of the inlet exergy. Syngas compositions are after moisture and acid gas removal. MSW was chosen as an example, as results are similar for other substrates (Tables 6 and 7).

Table 9. Maximum gas turbine LHV efficiency calculated by GT-PRO

Fuel	Turbine No.			
	1	2	3	4
Natural gas	0.3929	0.3621	0.3460	0.3041
Syngas (MSW)	0.4172	0.3835	0.3602	0.3206
Syngas (MSW+capture)	0.4203	0.3812	0.3657	0.3243

The GT-PRO simulations validate the results yielded by PATITUG. The exergy losses are lower for syngas than for natural gas (and lower for a syngas with less H_2), while the exhaust gases exergy is higher. The LHV efficiency of the gas turbine is also higher with syngas than with natural gas. GT-PRO also provides that between 70% and 80% of the exergy loss is due to the combustion process while the remaining loss is mainly due to the compression and expansion processes. This value depends on the turbine used and is slightly higher for natural gas than for syngas when using the same turbine.

Table 10. Exergy balances calculated by GT-PRO for the optimum conditions

Fuel		Turbine No.			
		1	2	3	4
Natural gas	$\dot{W}_n$	0.375	0.345	0.331	0.290
	E_l	0.352	0.378	0.394	0.414
	E_g	0.259	0.269	0.275	0.295
Syngas from MSW	$\dot{W}_n$	0.399	0.367	0.346	0.308
	E_l	0.295	0.324	0.340	0.361
	E_g	0.293	0.302	0.314	0.331
Syngas from MSW with capture	$\dot{W}_n$	0.409	0.371	0.358	0.317
	E_l	0.312	0.343	0.357	0.379
	E_g	0.265	0.279	0.286	0.305

Analysis of the global energy conversion process. It is of high interest to study the complete energy conversion process of a BIGCC power plant, i.e. from biomass to electrical power. The gasification and CO_2 capture processes demand a considerable amount of energy and the recirculation of the water vapour produced in the gasification process can only be considered if the substrate, and not the fuel, is considered as the entrance to the system. Moreover, when working with biofuels, the raw material is the biomass, rather than the fuel, unlike what happens with fossil fuels. Thus, only by analysing the global process can CO_2 emissions and biomass and land use, as well as the economic viability of the plant, be studied.

Figure 5 depicts a diagram of the global energy conversion process of a BIGCC power plant. Syngas fuel can follow either of two alternative paths after gasification.

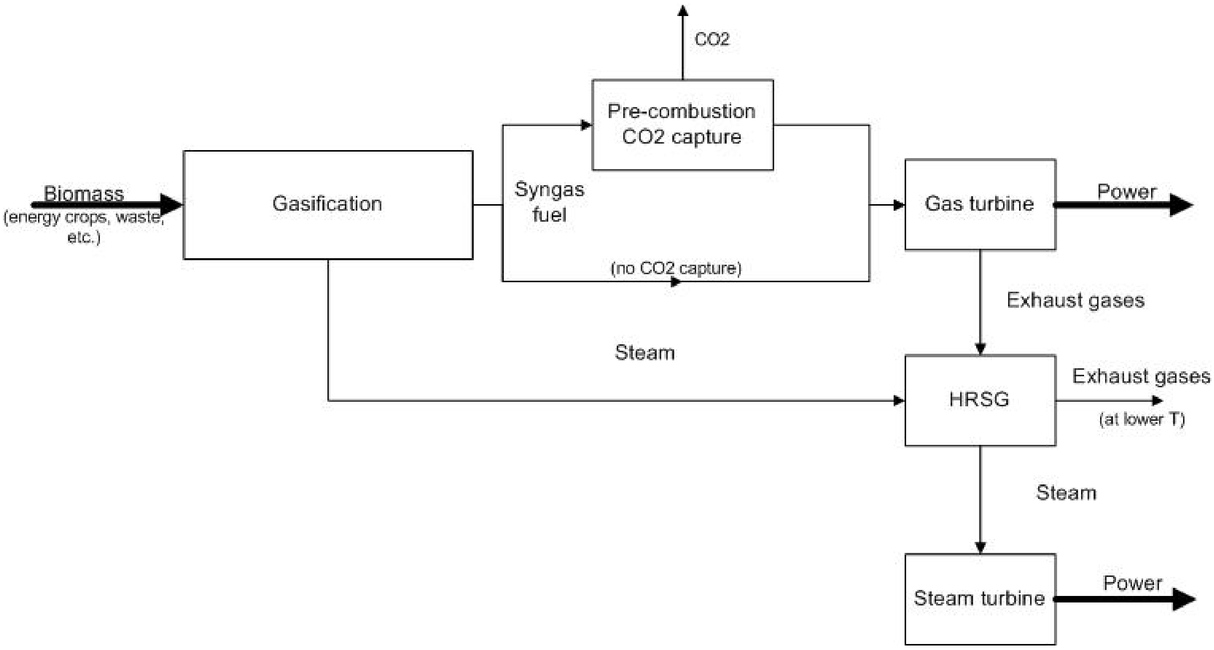

Figure 5: Block diagram of a gasification power plant (in Brayton cycle or BIGCC)

The auxiliary losses (including gasification plant and pre-combustion CO_2 capture module) have been calculated by GT-PRO, in order to obtain the maximum net LHV efficiencies of the global process (thus considering the biomass LHV for syngas and the fuel LHV for natural gas), which are shown in Table 11. Two substrates have been analysed: MSW and barley straw, which has been chosen as a typical energy crop for this part of the study.

While the auxiliary losses are about 2% of the gross power in NGCC plants, they increase to 12-17% in BIGCC plants without CO_2 capture and 20-26% with pre-combustion CO_2 capture. The variations depend on the substrate (the losses are higher when the substrate LHV is smaller) and the plant size (the losses account for a higher fraction of the gross power in smaller plants). The breakdown of these losses is shown in fig.6 for syngas from energy crops (figures are similar with other substrates)

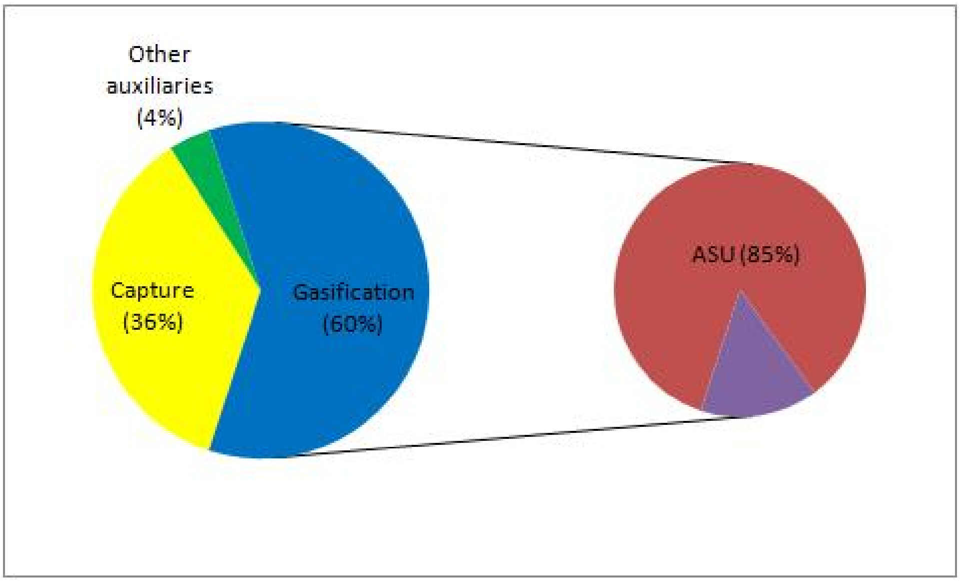

Figure 6: Breakdown of auxiliary losses for an energy crops BIGCC power plant

In a BIGCC, the steam generated in the gasification process is recirculated to the HRSG, which enhances very considerably the global efficiency, attaining values around 40% without capture and 30-35% with pre-combustion CO_2 capture. The results show that the introduction of pre-combustion capture decreases the global plant efficiency in 6%.

Table 11. Maximum global LHV efficiencies for the simulated plants in combined cycle

Fuel	Turbine No.			
	1	2	5	6
Natural gas	0.5410	0.5030	0.5404	0.5078
BIGCC / MSW	0.3779	0.3759	0.3855	0.3795
BIGCC / MSW with capture	0.3294	0.2967	0.3297	0.3012
BIGCC / energy crops	0.4152	0.3885	0.4140	0.3931
BIGCC / energy crops with capture	0.3398	0.3137	0.3603	0.3187

The high auxiliary power demands makes biomass gasification suitable for medium and large-sized power plants (even more if pre-combustion CO_2 capture is introduced), working in combined cycle or cogeneration of heat and electricity, so that the water vapour produced in the gasification process is used, thus obtaining a high global efficiency (especially provided this is a renewable energy), which cannot be reached with other biofuel production processes, e.g. methanisation.

Environmental analysis. Gross CO_2 emissions (i.e. that of the power plant exhaust gases) were calculated by GT-PRO for each case.

Nevertheless, some problems were encountered when evaluating the net CO_2 emissions for syngas, 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 accurately CO_2 net emission using biofuels were found, and, in fact, European Environment Agency (EEA) studies reveal that net emissions present a high variability (and can be either positive or negative) and depend on the substrate and the biofuel obtention technology used [28]. In a first attempt, equation 8 was used to calculate emission intensities (tCO_2/GWh):

$$I = \frac{E_+ - E_-}{P_\mathrm{n}} \tag{8}$$

where I is the emission intensity, E_+ the power plant gross emission, E_- the carbon fixed by the biomass and P_n the net electric power output. This formula seems suitable to compare emission intensities with fossil fuels. However, this approach was rejected as its use would lead to two unacceptable conclusions:

- a biomass-to-fuel process with a lower efficiency (one which would need more biomass to produce the same amount of biofuel) would be environmentally better (I would decrease as E_- increases).
- if I is negative, a decrease of the power plant efficiency would be environmentally positive ($|I|$ would increase).

According to the GT-PRO simulations, 87-90% of the carbon contained in the biomass ends up in the fuel (depending on the substrate). The remaining carbon goes to a slag. Depending on the use of this slag, this carbon can be emitted to the atmosphere or not. Therefore, the actual net emission when using biofuels depends on how the residues are utilised (other technologies, such as methanisation produce larger amounts of residues). As this would require a further life cycle analysis of carbon, a net emission equal to zero will be assumed when using energy crops. This value is widely used as it is usually realistic and, furthermore, it is set by the Directive 2003/87/EC of the European Parliament [29]. Along with this value, the Spanish Renewable Energy Plan 2005-2010 also sets the net emissions for plants using MSW as 243 tCO_2/GWh if the thermoelectric efficiency is equal to 24.88% [30], i.e. 60.5 $tCO_2/GW_{th}h$. The CO_2 emissions avoided by using a BIGCC instead of a natural gas combined cycle (NGCC) will be calculated, assuming an emission intensity of 358 tCO_2/GWh for the latter, equal to the average intensity in the Spanish NGCC power plants in 2009 [11]. If pre-combustion capture is introduced, the amount of CO_2 captured will be added to compute the total CO_2 emission avoided.

As it has been discussed previously, the study of the biomass consumption is also of great importance and is intertwined with the CO_2 emission analysis as part of an integral environmental evaluation. Hence, the quotient $E_{\mathrm{avoided}}/m_{\mathrm{bm}}$, $E_{\mathrm{avoided}} = E_{\mathrm{ng}} + E_{\mathrm{captured}}$ where E_{ng} is the CO_2 emission of a NGCC with the same power output as the BIGCC studied, E_{captured} is the CO_2 captured and m_{bm} the BIGCC biomass consumption, has been calculated. This allows the analysis of both CO_2 emissions avoided in relation with efficiency in biomass use.

Only turbines number 1 and 2 working in BIGCC have been considered for the environmental analysis, and five substrates have been studied: barley straw, alfalfa stems, rice straw, switchgrass and MSW (see substrate and syngas compositions in Tables 5 to 7).

Table 12. Environmental parameters calculated for each BIGCC case studied.

Substrate	Turbine No.	CO_2 Capture	$\dot{m}_{\mathrm{bm}}$ (kg/s)	P_{n} (kW)	c_{bm} (kg/kWh)	I_{avoided} (tCO_2/GWh)	$E_{\mathrm{avoided}}/m_{\mathrm{bm}}$ (tCO_2/t_{bm})
Barley straw	1	No	95.27	599444	0.5722	358	0.626
	1	Yes	101.0	519604	0.6998	1274	1.821
	2	No	26.09	154168	0.6092	358	0.588
	2	Yes	27.72	131792	0.7572	1350	1.783
Alfalfa stems	1	No	96.12	592575	0.5838	358	0.613
	1	Yes	101.5	537552	0.6797	1327	1.952
	2	No	26.42	155342	0.6123	358	0.585
	2	Yes	27.86	130389	0.7692	1409	1.832
Rice straw	1	No	86.67	593980	0.5253	358	0.682
	1	Yes	92.15	582679	0.5693	997	1.751
	2	No	23.88	152105	0.5652	358	0.633
	2	Yes	25.31	136211	0.6689	1109	1.658
Switchgrass	1	No	102.3	587939	0.6264	358	0.572
	1	Yes	107.6	527246	0.7347	1346	1.832
	2	No	28.12	156529	0.6467	358	0.554
	2	Yes	29.57	129520	0.8219	1463	1.780
MSW	1	No	121.3	568233	0.7685	198	0.258
	1	Yes	127.3	520154	0.8810	1166	1.323
	2	No	33.34	155401	0.7724	197	0.255
	2	Yes	35.02	128836	0.9785	1217	1.244

The results shown in Table 12 prove that the use of BIGCC plants has a significant impact in avoiding CO_2 emissions, especially if CO_2 capture is introduced (in this case, the net emission would result negative, effectively reducing the concentration of atmospheric CO_2). The emission avoidance is lower when using MSW, although the difference with energy crops is smaller if CO_2 is captured. Anyway, gasification of MSW can also be very interesting from the point of view of waste management.

Nonetheless, over $2{\cdot}10^6$ t/yr of MSW would be needed to supply a 400 MW MSW BIGCC working with an 80% capacity factor (7000 h), and over $2.5{\cdot}10^6$ t/yr if CO_2 capture is introduced. This amounts to approximately 20% and 25% of the organic fraction of MSW produced each year in Spain. It is clear, then, that this biomass consumption is too high to enable the viability of a large scale power plant using MSW, except perhaps very areas with both high population and population density (e.g. London or Paris metropolitan areas, the Ruhr region, or, outside the EU, the Moscow, Tokyo or New York City metropolitan areas). Nevertheless, MSW can be mixed with other substrates (other waste, energy crops) so that these plants are viable in other contexts. Of course, smaller plants (50-100 MW) can also be used in not so high densely populated areas.

Comparing the different energy crops, rice straw provides the lowest biomass consumption (i.e. the highest efficiency) of the four substrates studied, due to a higher gasifier efficiency ($\frac{\text{Energy contained in syngas}}{\text{Energy contained in biomass}} = \frac{m_{\text{syngas}} \cdot \text{LHV}_{\text{syngas}}}{m_{\text{bm}} \cdot \text{LHV}_{\text{bm}}}$). On the other hand, the biomass consumption is the highest when using switchgrass. From the point of view of CO_2 emissions, less CO_2 is captured when using rice straw because this substrate (and, consequently, the syngas produced with it) has a lower carbon concentration than the others under study. This also improves the global thermal efficiency as auxiliary power decreases. The substrate with a highest CO_2 capture potential per tonne is alfalfa stems.

It would be very interesting to perform analogous calculations using land areas needed for cultivation instead of substrate mass. This could determine which substrate is the most advantageous environmentally in a global way. However, crop yields (and also grain/straw ratios) depend on the climate and soil, that is, they are different in each region. Therefore, an individual study would be required in each case when the construction of a certain BIGCC power plant in a specific location were considered. Of course, different substrates can be mixed and crop rotation to optimise yields should also be studied, but this is out of the scope of this work.

The results also show that calculating the avoided emissions divided by the electrical output yields a parameter which is incomplete and could suggest misleading conclusions, especially when CO_2 is captured, because the CO_2 emissions avoided seem higher when the plant efficiency decreases (see Table 12: turbine 2, which presents a lower global energetic efficiency, predicts a slightly higher value of I_{avoided}). This can be corrected by using the parameter $E_{\text{avoided}} / m_{\text{bm}}$, which considers more properly the global environmental efficiency of biomass use. Of course, the emission avoidance would be higher if compared to coal-fired thermal power plants.

CONCLUSIONS

The use of biofuels in gas turbines for power generation is very promising, although significant technological development is needed. When fired with biofuels, the efficiency of a gas turbine is similar to that obtained when working with natural gas. It is even higher for synthesis gas than for methane (up to 1 %) if both thermodynamical optima are considered. However, syngas is the only fuel of the ones studied whose maximum efficiency PR can be achieved by a real gas turbine. This efficiency improvement is even more noticeable in combined cycle, because the exergy loss for syngas in the Brayton cycle is lower than that for natural gas. Exergy destruction is higher for ethanol than for any other biofuel and natural gas, and consequently its LHV efficiency is the lowest.

Gasification allows the implementation of pre-combustion CO_2 capture, which can decrease CO_2 emissions very significantly, obtaining negative net emissions, and with a lower energy consumption than post-combustion capture (which could be used for any fuel). This fact, along with a higher global efficiency than that attainable using any other biofuel, due to a higher biomass-to-fuel process efficiency and the recirculation of the steam produced in this process to the HRSG in combined cycle, makes biomass gasification the most promising among biomass power generation technologies. Nonetheless, due to the high power demand of the gasification process (12-17% of the turbine power output in combined cycle, but up to 35% in a Brayton cycle) and the high investment cost of the plant, it is only suitable for medium and large-sized plants (with a power output higher than 50 MW), and its potential is only fully developed in BIGCC plants.

Pre-combustion CO_2 capture decreases the global efficiency of a BIGCC power plant in around 6%, but it is very advantageous from an environmental point of view, as CO_2 emission avoidance is increased in a factor of more than 3 compared to a BIGCC without capture, effectively obtaining net negative emissions. It should remain clear that the quantification of CO_2 reduction when using biofuels is difficult, and depends on the residues generated and its use. As an example, under the assumptions made in this work (which are in most cases very close to real values, and underestimations in any case), a 400 MW BIGCC without capture working with a capacity factor of 80% would avoid 1 $MtCO_2$/yr compared to a NGCC, while an analogous BIGCC with pre-combustion CO_2 capture would increase this value up to 3.36 $MtCO_2$/yr (adding not emitted and captured CO_2). These figures account for 1.4% and 4.5% of the total CO_2 emissions due to power generation activities in Spain in 2009 [11]. These values are lower for MSW, as less carbon is fixed by the substrate (the average reductions are 0.56 $MtCO_2$/yr without capture and 2.83 $MtCO_2$/yr with capture under the same conditions). These figures should be revised with the aid of a thorough study of the carbon cycle in each case. It should be reminded that, unlike most renewable energy technologies, BIGCC power plants are in principle capable of working with high capacity factors (if there is a regular biomass supply in the quantities needed), as any other thermal power plant.

There is a wide variety of substrates that can be used in biofuel production technologies, and gasification in particular. In this work, some annual growth energy crops and MSW have been studied. Although many of the conclusions obtained are valid for other substrates, further studies should be carried out in each case. MSW consumption is too high for BIGCC to be viable under most circumstances (only in smaller plants, up to 100 MW, which is on the lower range of this technology optimum size, or in large and very densely populated areas), although it can be mixed with other substrates. The use of MSW would be very interesting from a waste management point of view, along with other types of waste (e.g. agricultural). The viability of energy crops for large scale power generation in BIGCCs is less compromised. The most suitable energy crop will vary from case to case, depending on availability and suitability depending on the climate, as well as on crop yields. A substrate with a higher carbon concentration will allow more CO_2 to be captured, although the power demand of the gasification and the pre-combustion capture module will increase, decreasing the global efficiency.

NOMENCLATURE

ASU: air separation unit
BIGCC: Biomass integrated gasification combined cycle
c_{bm}: biomass consumption
c_p^*: specific heat at null pressure
CC: combined cycle / combustion chamber
e_i: flow exergy at cycle point i
E_{avoided}: CO_2 emission avoided when using a BIGCC instead of a NGCC with equal power output and capacity
E_{g}: exhaust gases exergy
E_{ng}: CO_2 emission of a NGCC with equal power output and capacity
E_{l}: exergy loss
HRSG: heat recovery steam generator
I: CO_2 emission intensity

I_{avoided}: CO_2 emission intensity avoided when using a BIGCC instead of a NGCC with equal power output and capacity
ICE: internal combustion engine
IGCC: Integrated gasification combined cycle
LHV: lower heating value
$\dot{m}_{\mathrm{bm}}$: biomass flow
$\dot{m}_i$: mass flow at point i
MSW: municipal solid waste
NGCC: natural gas combined cycle
P_{c}: critical pressure
P_0: ambient pressure
P_{n}: net plant power output
P_{r}: reduced pressure
PR: compressor pressure ratio
s^{o}: standard absolute specific entropy
T_{c}: critical temperature
T_0: ambient temperature
T_{r}: reduced temperature
TIT: turbine inlet temperature
$\dot{W}_{\mathrm{C}}$: compressor gross power
$\dot{W}_{\mathrm{F}}$: fuel compressor/pump gross power
$\dot{W}_{\mathrm{n}}$: net Brayton cycle power output
$\dot{W}_{\mathrm{T}}$: turbine gross power output
$\Delta_{\mathrm{f}}H^{\mathrm{o}}$: standard heat of formation
η_{ex}: exergetic efficiency of the simple Brayton cycle
η_{em}: electromechanical conversion efficiency
η_s: isentropic efficiency
ξ_{ex}: exergetic efficiency of the combined cycle
ζ: exergetic efficiency of ther steam cycle
ω: acentric factor
ΔP_{CC}: pressure loss in the combustion chamber
Q_{CC}: heat loss in the combustion chamber

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