ANALYSIS OF THE BEHAVIOUR OF BIOFUEL-FIRED GAS TURBINE POWER PLANTS

by

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The utilisation of biofuels in gas turbines is a promising alternative to fossil fuels for power generation. It would lead to a significant reduction of CO_2 emissions using an existing combustion technology, although considerable changes appear to be required and further technological development is necessary. The goal of this work is to conduct 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) also has been studied. Furthermore, the potential reduction of CO_2 emissions attained by the use of biofuels has been determined, after considering the restrictions regarding biomass availability. Two different simulation tools have been used to accomplish this work. The results suggest a high interest in, and the technical viability of, the use of biomass integrated gasification combined cycle systems for large scale power generation

Key words: *bioenergy, biomass gasification, integrated gasification combined cycle, biofuel-fired gas turbine, CO_2 emission reduction, biomass availability analysis*

Introduction

As in other combustion technologies, an effort is being made 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 unconventional fuels, such as synthesis gas [2], dimethyl ether [3], and alkane hydrocarbons [4], among others. This new trend is supported by various factors, such as environmental strategies [5], the reduction of pollutant emissions [6] and the availability of both natural gas (which directly affects its price) and renewable resources [7].

The energy policies of many governments that strive to reduce greenhouse gas (GHG) emissions resulted in 1997 in the Kyoto Protocol, which was signed by representatives of many of the industrialised world's countries. However, some of these countries, like Spain, are not reaching their target for 2012. In any case, more ambitious limits should be set. Therefore, further research in technologies that contribute significantly to GHG emission reduction is needed and should be promoted. In 2009, the electrical power generated from

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biomass in Spain represented 1.35% of the total power generated, an increase of 4.9% over 2008 [8]. However, this is a relatively low share of electrical power generation in comparison to wind and solar power. The Spanish PANER 2011-2020 (National Plan for Action on Renewable Energy) recognizes the great energetic potential of biomass for power generation, and believes that this renewable energy source has been underused in recent years [8]. Within the European Union, Finland, and Sweden are the countries that have most encouraged the use of biomass for heat and power generation[1]. The average biomass consumption per inhabitant in the EU-27 was 0.138 tep [9].

In this global scenario, the combustion of biomass or biofuels as an alternative to fossil fuels for electrical power generation has become an active area of research in recent years [10]. Currently, most of the power produced from biomass is generated by (a) external combustion systems (the combustion of biomass or the co-combustion of biomass and coal [11, 12]), or (b) the combustion of biogas obtained from anaerobic digestion of biomass in internal combustion engines (ICE) that have a typical power output in the range of 30 kW-6 MW [13]. A common alternative to anaerobic digestion is gasification with air. This produces a bio-syngas with a high nitrogen content, which is subsequently fired in an ICE [13]. Another possibility is the combined use of external biomass combustion and internal firing in a gas turbine [5].

Gas turbines permit 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 are also gas turbines in the same range as typical ICE, so that small gas turbines could be used as substitutes for these if biomass availability is insufficient or problematic. Nevertheless, gasification for the use of syngas as a fuel in gas turbines is interesting mainly for large scale power generation, due to the high investment required 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 [2]. In IGCC power plants, gasification with oxygen instead of air is used in order to reduce the fuel's volume. Although biomass gasification is not currently available on a large scale, it is technically viable and constitutes a very promising technology, considering the environmental advantages of a CO_2-neutral renewable energy source (RES). Furthermore, gasification enables a pre-combustion CO_2 capture module to be included, reducing GHG emissions even more. A biomass integrated gasificiation combined cycle (BioIGCC) with pre-combustion CO_2 capture would provide *negative* net emissions.

The present study analyses the behaviour of gas turbines working with different biofuels, namely biogas, synthesis gas (or syngas) and bioethanol. Natural gas is used as the reference fuel, since it is the fuel that normally is used in gas turbines for power generation. The differences in performance between the reference case and each biofuel are studied from different perspectives:

– energetic and exegetic efficiency of the simple and combined cycle,
– CO_2 emissions, and
– use and availability of biomass resources.

Different configurations that were judged to be potentially interesting have been simulated in order to obtain the optimal values of the cycle's thermodynamic parameters and

[1] Their biomass consumption was 1.34 and 0.904 toe/inhabitant, respectively, in 2008, compared to Germany's 0.125, France's 0.141, Spain's 0.0905, Italy's 0.0319 or the UK's 0.0180.

the variations for each biofuel. This optimisation has been undertaken using PATITUG, a modular and flexible software application for the analysis of thermodynamic cycles that was developed by the Applied Thermodynamics Group of the Universidad Politecnica de Madrid. PATITUG provides a series of different modules that calculate the 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 pure substances, mixtures and chemical reactions are included. A variety of state equations can be selected 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 nil pressure limit. For mixtures, the models of ideal gas mixture and Lewis-Randall mixture are available. Other studies have been carried out with this software recently [4, 14].

After analysing the results of this first stage of the work, a further stage of the study has been carried out for the most efficient biomass-to-power process, considering energetic and exegetic performance and CO_2 emission reduction. This second part of the analysis was undertaken using GT-PRO [15], a commercial program that includes data from several real gas turbines. GT-PRO is more rigid than PATITUG, albeit more precise in the prediction of real gas turbine behaviour. In addition, 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 fig. 1.

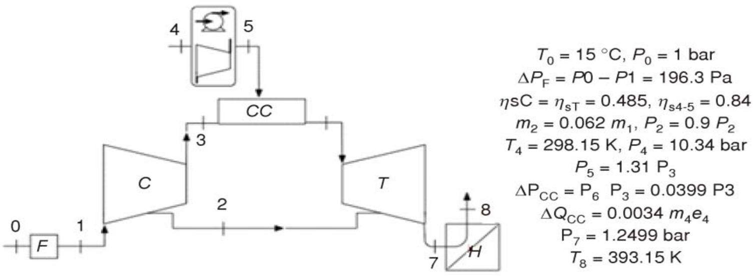

Figure 1. Diagram and main cycle parameters of the standard gas turbine programmed with PATITUG
C – air compressor, CC – combustion chamber, F – air filter, H – flue gases exergy recovery system, T – gas turbine, 1-8 – flow streams

The cycle's parameters given above have been adjusted to make them representative of a generic configuration. They are reasonable values within their range in real power plants. They have been used previously with PATITUG and given accurate results [14]. 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 are also modelled with similar values.

The program calculates the exergetic efficiencies in both a simple and a combined cycle using eqs. (1) and (2):

$$\eta_{\mathrm{ex}} = \frac{W_{\mathrm{n}}}{m_4 e_4} \tag{1}$$

$$\xi_{\mathrm{ex}} = \frac{W_{\mathrm{n}} + \zeta\, m_4 (e_7 - e_8)}{m_4 e_4} \tag{2}$$

In these equations W_{n} is the net power output of the Brayton cycle. It is calculated as $W_{\mathrm{n}} = \eta_{\mathrm{em}}(W_{\mathrm{T}} + W_{\mathrm{C}} + W_{\mathrm{F}})$, where W_{T}, W_{C}, and W_{F} are the turbine, air compressor, and fuel pump/compressor gross power outputs, respectively, η_{em} represents an overall electromechanical efficiency of the ensemble, which is assumed to be equal to 0.98, and ζ is the fraction of the exergy released by the combustion gases in the heat recovery steam generator (HRSG) that results converted into work in the steam cycle, for which a value of 0.7 has been assumed. According to the First Law, the gross power outputs are calculated as the product of the mass flow rates and the enthalpic drops in each component:

$$\begin{aligned} W_{\mathrm{T}} &= (m_0 - m_2 + m_4)(h_6 - h_7) + m_2(h_2 - h_7) \\ W_{\mathrm{C}} &= m_0(h_1 - h_2) + (m_0 - m_2)(h_2 - h_3) \\ W_{\mathrm{F}} &= m_4(h_4 - h_5) \end{aligned} \tag{3}$$

The variable e in eqs. (1) and (2) denotes the thermodynamic function flow exergy. In particular, e_4 is the fuel's flow exergy, which is mostly of chemical nature (hardly any physical exergy is carried by the fuel). The chemical exergy of a fuel is close to its LHV and HHV, but differs somewhat from both [16] and is normally between them. Some authors (*e. g.*, [17]) use LHV instead of exergy in the denominators of eqs. (1) and (2). By adopting the exergy approach, we are attempting to keep a totally "exergetic point of view" throughout the analysis. This may lead to somewhat different results.

Thermodynamic modeling

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

$$v^{\mathrm{M}} = 0; \quad h^{\mathrm{M}} = 0; \quad s^{\mathrm{M}} = -\mathrm{R}\sum_j x_j \ln x_j \tag{4}$$

where the superindex M indicates the corresponding mixing function.

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

$$Pv = \mathrm{R}T + \mathrm{B}(T) \tag{5}$$

Function B(T) and heat capacity at nil pressure limit $c_p^*(T)$ of gases have been taken from [18]:

$$\mathrm{B}(T) = \alpha + \frac{\beta}{T} + \frac{\gamma}{T^3} + \frac{\delta}{T^8} + \frac{\varepsilon}{T^9} \tag{6}$$

$$c_p^*(T) = a + b\left[\frac{(c/T)}{\sinh(c/T)}\right]^2 + \mathrm{d}\left[\frac{(e/T)}{\cosh(e/T)}\right]^2 \tag{7}$$

with the set of constants α, β, γ, δ, ε, a, b, c, d, and e given for every compound. It must be mentioned that the temperature-exponential model for c_p^* given by (7) is required in this analysis, because polynomial expressions would lead to a loss of 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:

$$\frac{Pv}{\mathrm{R}T} = z^{(0)} + \omega z^{(1)} \tag{8}$$

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 $T_\mathrm{r} = T/T_\mathrm{c}$ [19]. The pressure and temperature at critical point P_c, T_c and ω for ethanol have been read from [16].

The thermochemical properties (standard heat of formation $\Delta_\mathrm{f} H^\mathrm{o}$ and standard absolute specific entropy s^o) of fuels and gases, which are given in a compatible reference frame, are also taken from [18]. The chemical flow exergy of fuels has been calculated as described in [16].

Combustion

The combustion chemical 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 formation is very important from the point of view of environmental effects, but is irrelevant for the calculation of the thermodynamic properties of the combustion gases, since very small quantities are formed. Any influence on the energetic and exegetic performance of the cycle is negligible.

Combustion has been assumed to take place in the presence of moist air. Dry air has been modelled as a mixture of N_2, O_2, Ar, and CO_2 ignoring minor components of air. The quantity of water added has been adjusted for the target of 60% RH.

Biofuels considered and cases under study

Simulations with three different biofuels (biogas, syngas and bioethanol) and the reference fuel (*i. e.*, natural gas considered as pure methane) were performed using PATITUG in order to find the conditions of maximum efficiency for each of them and to study the effect of the variations of turbine inlet temperature (*TIT*) and compressor pressure ratio (*PR*) on the exergetic efficiency. Exergy balances are also performed. The operation limits are 1273.15 K $\leq$ $\leq$ *TIT* $\leq$ 1723.15 K and 10 $\leq$ *PR* $\leq$ 40. The lower limits were selected because it was believed that a study of the operation of gas turbines below these values would be of no interest, while the upper limits were chosen in recognition of the fact that gas turbines are not usually capable of working above these values. The composition of the combustion gases differs for every case (defined by a fuel and a pair of values of *PR* and *TIT*), not only because different relative quantities of CO_2 and H_2O are formed for each, but also because the fuel-air ratio (*FAR*) m_4/m_0 is specifically computed iteratively for each case in order to reach the desired *TIT*.

Thorough bibliographical research was carried out to collect the data needed, primarily concerning typical chemical compositions of biofuels. Biogas is considered to be a mixture mainly of methane and carbon dioxide, with small constant quantities of air (x_{N2} = = 0.04 and x_{O2} = 0.01), typical in biogas [20]. x_{CH4} is varied from 0.45 to 0.75, and hence x_{CO2} from 0.50 to 0.20. This covers the entire range of typical biogas compositions [20], as calculated from data of different agricultural biomass compositions [21] and experimentally confirmed in some cases [22]. Syngas is first studied as a binary H_2-CO mixture. Then, the influence of adding CO_2 up to a level of 30% was studied in a mixture with $x_{H2} = x_{CO}$ [23, 24]. Bioethanol is considered to be pure ethanol.

Results

Figure 2 shows the simple Brayton cycle exergetic efficiency as a function of *PR* (horizontal axis) 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. 3.

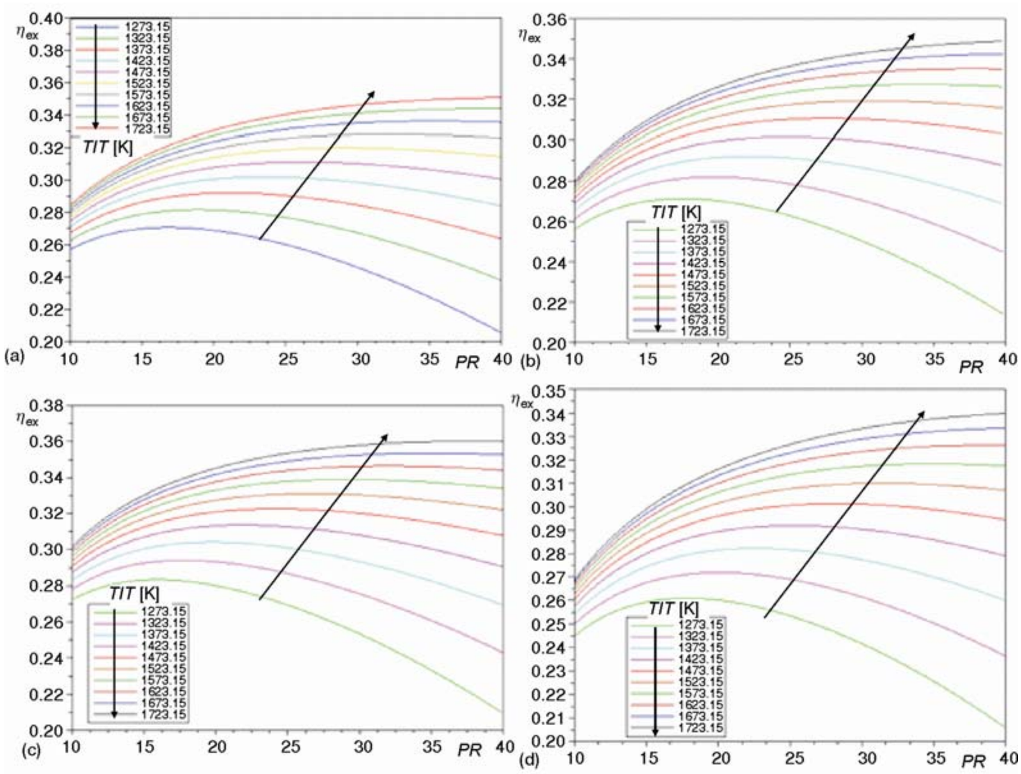

Figure 2. Brayton cycle exergetic efficiency as a function of *PR* (horizontal axis) and *TIT* (data series) for: (a) pure methane, (b) biogas (53% CH_4, 42% CO_2, 4% N_2, 1% O_2), (c) syngas (50% H_2, 50% CO) and (d) pure ethanol (color image see on our web site)

Tables 1 to 4 show the conditions (*TIT* and *PR*) for which the exergetic efficiency of a gas turbine is maximum for both a simple and a combined cycle when working with methane, biogas (with constant (x_{N2} = 0.04 and x_{O2} = 0.01), syngas (binary H_2-CO) and ethanol, respectively.

Table 1. Maximum exegetic efficiency conditions for pure methane

$\eta_{ex,max}$	*TIT* [K]	*PR*	$\xi_{ex,max}$	*TIT* [K]	*PR*
0.3506	1723.15	40	0.5411	1723.15	29.5

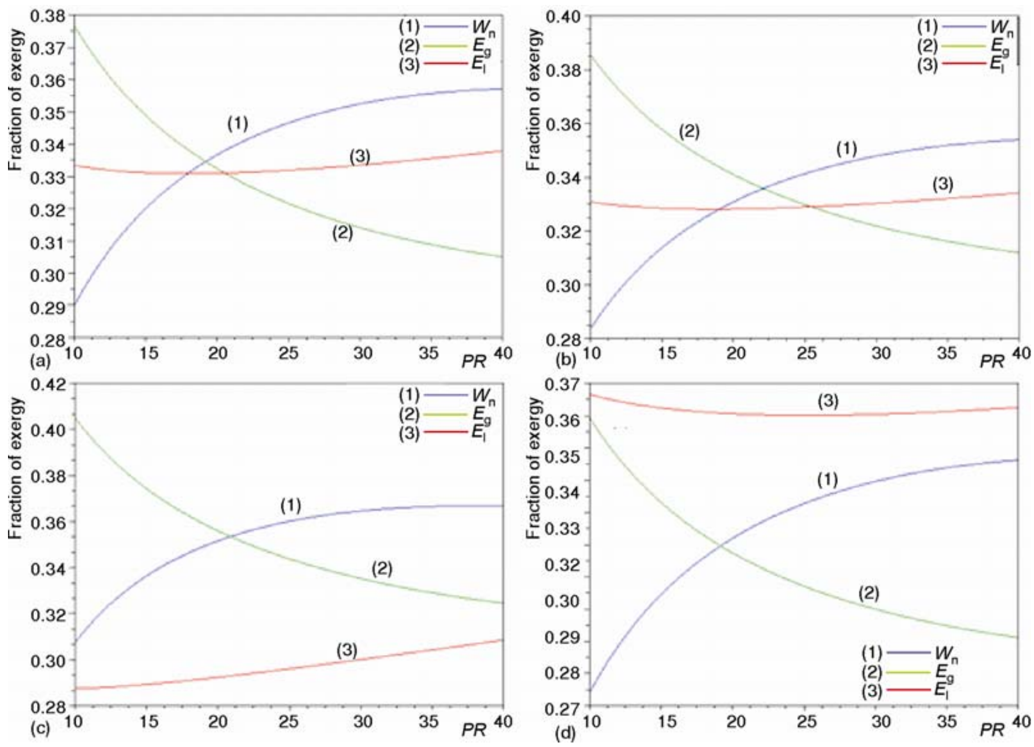

Figure 3. Exergy balances (*TIT*=1723.15 K) for (a) pure methane, (b) biogas (53% CH_4, 42% CO_2, 4% N_2, 1% O_2), (c) syngas (50% H_2, 50% CO), and (d) pure ethanol, respectively. Values are expressed as fractions of the inlet exergy, m_4e_4

Table 2. Maximum exegetic efficiency conditions for biogas

x_{CH4}	$\eta_{ex,max}$	*TIT* [K]	*PR*	$\xi_{ex,max}$	*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 exegetic efficiency conditions for syngas (binary H_2-CO mixture)

x_{H2}	$\eta_{ex,max}$	*TIT* [K]	*PR*	$\xi_{ex,max}$	*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	38.0	0.5634	1723.15	21.5
0.70	0.3585	1723.15	37.5	0.5612	1723.15	21.5
0.80	0.3579	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 exegetic efficiency conditions for pure ethanol

$\eta_{ex,max}$	*TIT* [K]	*PR*	$\xi_{ex,max}$	*TIT* [K]	*PR*
0.3399	1723.15	40	0.5177	1723.15	35.75

Partial conclusions

This general analysis of different biofuels reveals that the optimum *PR* is different for each of the fuels considered and, it should be noted, is lowest for the synthesis gas. This is interesting as these *PR* values can be more easily achieved by the gas turbine or, from a complementary point of view, the working conditions of a given commercial gas turbine will be closer to the optimum. In addition, the exergy analysis shows that the exergy loss is the smallest in the case of syngas, while the highest exergy loss occurs for ethanol. As a consequence, the exergetic efficiency of the simple cycle fueled by syngas is higher than by any other fuel, including methane. Moreover, the exergy of the exhaust gas is highest for syngas, which means that more exergy can be potentially recovered in a HRSG, leading to a further increase of the exergetic efficiency in the combined.

Apart from the previous considerations, there are other thermodynamic reasons to consider the use of synthesis gas as an especially interesting biofuel to be used in gas turbines for power generation. First, syngas offers great potential for the reduction of CO_2 emissions due to the possibility of introducing a CO_2 pre-combustion capture module, which decreases the global efficiency to a much lesser extent than post-combustion capture [25]. Furthermore, the overall biomass-to-power efficiency is considerably greater in the case of biomass gasification because:(a) the efficiency of the biomass-to-fuel conversion process is higher [20, 22, 23, 26] and (b) additional steam is generated during gasification (since it is an exothermic chemical transformation), which can be added to what is produced in the HRSG for extra power generation, or used as process steam.

Therefore, gasification is selected for the next stage of this work, the in-depth analysis of a BioIGCC power plant. This involves the study of the overall biomass-to-electricity energy transformation process in terms of energetic efficiency, reductions in CO_2 emissions and availability of biomass resources.

In-depth study of a BioIGCC power plant using GT-PRO

Methodology

A further study with GT-PRO was undertaken in order to obtain accurate data of the power production and potential environmental benefits of a combined cycle power plant with biomass integrated gasification. GT-PRO enables the complete characterisation of a BioIGCC, including calculations related to the gasifier, as its energy consumption and the final syngas composition (with and without CO_2 pre-combustion capture), together with the gas turbine and steam cycle simulation.

Regarding the biomass substrates, this work focuses on agricultural residues (barley straw, alfalfa stems, rice straw), herbaceous energy crops (switchgrass) and municipal solid waste (MSW). The ultimate analysis of these substrates is shown in tab. 5, while the compositions of the resulting synthesis gases with and without pre-combustion CO_2 capture are shown in tab. 6. As has been mentioned already, the steam generated at the gasifier coolers in IGCC plants is redirected to the steam turbine enhancing the power output and the overall biomass-to-power efficiency. Most conclusions would apply also to other biomass substrates (other crops, other agricultural residues, wood …).

The simulations have been carried out assumed a gasifier with radiant and convective coolers (Texaco). Ambient air (288.15 K, 1 bar) is compressed to the air separation unit's (ASU) working conditions (288.15 K, 5.171 bar). Pre-combustion CO_2 capture, if applicable, has two main steps: oxidation of CO to CO_2 (a conversion efficiency of 98% is assumed) and CO_2 capture (an assumed efficiency of 90%). Water vapour and acid gases (H_2S and COS) are always removed, regardless of the implementation of pre-combustion capture.

Table 5. Chemical characteristics of the substrates studied

Substrate	Ultimate analysis [wt %]								LHV[a] [kJkg^{-1}]
	C	H	N	Cl	S	O	Moisture	Ash	
Barley straw	40.93	5.00	0.53	0.24	0.07	36.53	11.50	5.20	15154
Alfalfa stems	42.56	5.41	2.42	0.45	0.18	34.91	9.29	4.78	15525
Rice straw	35.20	4.79	0.80	0.00	0.17	33.92	7.93	17.19	15809
Switchgrass	42.00	5.24	0.69	0.17	0.17	33.80	9.84	8.09	14902
MSW	33.75	4.70	0.5	0.60	0.33	24.62	21.50	14.00	12399

[a] At 298.15 K, moisture and ash included

Table 6. Resulting synthesis gas composition [vol.%] and LHV at 298.15 K for different substrates after moisture and acid gas removal with and without CO_2 pre-combustion capture

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
+ CO_2 capture	88.15	0.990	8.183	0.0355	0.0009	0.0005	1.989	0.6509	33364
Alfalfa stems	30	38.03	28.35	0.0225	0.0005	0.0011	3.016	0.5876	7266
+ CO_2 capture	86.1	0.973	8.274	0.0383	0.0007	0.0014	3.86	0.7518	30045
Rice straw	40.15	39.13	19.01	0.0219	0.0015	0.0011	1.355	0.3339	10072
+ CO_2 capture	90.6	0.903	6.509	0.0346	0.002	0.0012	1.564	0.3852	40083
Switchgrass	29.11	37.85	30.44	0.0225	0.0004	0.0011	1.952	0.6271	6998
+ CO_2 capture	86.85	0.993	8.734	0.0393	0.0006	0.0014	2.56	0.8224	30803
MSW	31.13	36.84	29.37	0.0226	0.0004	0.0025	1.973	0.6618	7277
+ CO_2 capture	87.36	0.957	8.218	0.0362	0.0006	0.0032	2.562	0.8595	31899

Four turbines of different power ranges (turbines 1 to 4) have been selected for the simulations. Only the first two, together with a couple of turbines of the two highest power ranges (5 and 6) have been considered for the simulation in a combined cycle. The manufacturer, model and nameplate characteristics of these turbines are shown in tab. 7:

Table 7. Turbines considered in the simulations with GT-PRO

Turbine No.	Model	Power [kWe]	*TIT* [K]	*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

The gas turbine's LHV efficiency and the overall efficiency of the biomass-to-power process have been calculated. In addition, the power plant's CO_2 gross emissions have been obtained in order to determine the reduction of emissions achieved by a BioIGCC based on the gasification of the previously mentioned substrates. For that purpose, a natural gas containing impurities has been taken as reference fossil fuel. Finally, the power plant's consumption is calculated in both cases, with and without pre-combustion capture. The importance of biomass availability must be highlighted, as it is a limited resource and, in the case of energy crops, it would require the use of land that could otherwise be used for other purposes, particularly food crops. The use of land for biomass availability instead of food crops could eventually lead to food shortages [27].

Results

Analysis of the thermodynamical cycle

Table 8 shows the maximum LHV gas turbine efficiency for natural gas and MSW syngas and the four turbines considered, and the maximum efficiency conditions. Table 9 shows the net power output W_n, the exergy loss E_l and the exergy of the exhaust gas E_g as a fraction of the inlet exergy. Syngas compositions are similar for other substrates (tab. 7).

Table 8. The maximum gas turbine LHV efficiency calculated by GT-PRO

Fuel	Turbine			
	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

Table 9. Exergy balances calculated by GT-PRO for the optimum conditions.

Fuel		Turbine No.			
		1	2	3	4
Natural gas	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	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	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

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

Analysis of the global energy conversion process

Figure 4 depicts the global energy conversion process of a BioIGCC power plant. It is particularly interesting to study the complete energy conversion process of a BioIGCC power plant, from biomass to electrical power. The gasification and CO_2 capture processes demand a considerable amount of energy and the recirculation of the steam produced in the gasification process can be considered only if the biomass substrate, and not the syngas, is considered as the input to the system. Moreover, 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. Two substrates have been analysed for this part of the study: MSW and barley straw (which has been chosen as a typical agricultural waste).

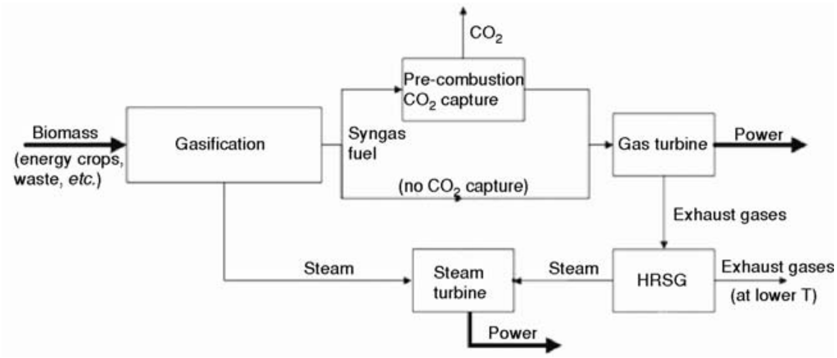

Figure 4. Block diagram of a BioIGCC power plant

The auxiliaries' consumption has been calculated by GT-PRO in order to obtain the net LHV efficiencies of the overall process, which is the ratio $P_n/(m_{bm}LHV_{bm})$, where P_n is the BioIGCC plant's net electric power output, m_{bm} is the biomass consumption and LHV_{bm} is the biomass' lower heating value (see tab. 10). While the auxiliary losses are about 2% of the gross power in NGCC plants, they increase to 12-17% in BioIGCC plants without CO_2 capture and to 20-26% with pre-combustion CO_2 capture. The variations depend on the substrate (higher losses for smaller LHV) and the plant size (scale effects severely penalise smaller plants). The main causes of these losses are the gasifier, with 60% of auxiliary consumption (85% of it is due to the ASU), and the CO_2 pre-combustion capture module, with 36%.

Table 10. 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
BioIGCC / MSW	0.3779	0.3759	0.3855	0.3795
BioIGCC / MSW with capture	0.3294	0.2967	0.3297	0.3012
BioIGCC / barley straw	0.4152	0.3885	0.4140	0.3931
BioIGCC / barley straw with capture	0.3398	0.3137	0.3603	0.3187

The overall BioIGCC energetic efficiency attains a very interesting value of about 40% without capture, reduced by 5-7% if pre-combustion CO_2 capture is carried out. The high auxiliary power demands makes biomass gasification suitable for medium and large-sized power plants when integrated in a combined cycle or heat/electricity cogeneration, so that the steam produced in the gasification process is valorised. This would permit the system to achieve that high global efficiency, which cannot be reached by other biofuel production processes or by an external combustion of biomass.

Environmental analysis

Gross CO_2 emissions of the power plant have been 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 should be considered. The European Environment Agency (EEA) studies reveal that net emissions are highly variable during the entire biomass cycle and depend on the substrate and the biofuel production technology used [28]. 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 ends up in a slag. Depending on the use of this slag, this carbon may or may not be emitted to the atmosphere. Therefore, the actual net emission when using biofuels depends on how the residues are utilised. As this would require a further life cycle analysis of carbon, a net emission equal to zero will be assumed when using biomass of agricultural origin. This value is widely used as it is usually realistic and, furthermore, is established by Directive 2003/87/EC of the European Parliament [29]. Along with this value, the Spanish PANER 2011-2020 also establishes the maximum net emissions for plants using MSW as 243 tCO_2/GW_eh if the thermoelectric efficiency is equal to 24.88% [8], *i. e.*, 60.5 tCO_2/GW_th. The CO_2 emissions that are avoided by using a BioIGCC instead of a natural gas combined cycle (NGCC) will be calculated, assuming an emission intensity of 358 tCO_2/GWh for the latter, to be equal to the average intensity in Spanish NGCC power plants in 2009 [8]. If pre-combustion capture is introduced, the amount of CO_2 captured will be added to compute the total CO_2 emission avoided.

In a first attempt, eq. 9 was used to calculate emission intensities (tCO_2/GWh):

$$I = (E^+ - E^-) / P_n \tag{9}$$

where I is the emission intensity, E^+ the power plant gross emission and E^- the carbon fixed by the biomass. We would then introduce the emission intensity avoidance $I_{av} = I - I_{ng}$ where I_{ng} is the emission intensity of a NGCC with equal power outputs and capacity. This formula might seem to be suitable for use in comparing emission intensities with fossil fuels. However, this approach was rejected as its use would lead to two unacceptable implications:

- a biomass-to-fuel process with a lower efficiency would cause a decrease in I since E^- increases, and
- if I is negative (the case with CO_2 capture), a decrease in the power plant's efficiency would give an increment of $|I|$ (a lower value of I).

The study of biomass consumption intertwined with the CO_2 emission analysis is also of great importance as a part of an integral environmental evaluation. Hence, to quantify the environmental performance of the BioIGCC, we use the quotient E_{av}/m_{bm}, where E_{av} is the addition of two terms that account for emission avoidance: E_{ng}, the CO_2 emission saved by the use of biomass instead of a NGCC with the same power output as the BioIGCC studied, and $E_{captured}$, the CO_2 removed by capture. The BioIGCC biomass consumption m_{bm}, has been calculated to complete the analysis.

Only gas turbines number 1 and 2 (see tab. 7) working in BioIGCC 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 tabs. 5 and 6).

The results shown in tab. 11 prove that the use of BioIGCC plants has a significant potential for emissions reduction, especially if CO_2 capture is introduced. In the last case, a negative net emission would result, effectively reducing the concentration of atmospheric

CO_2. The emission avoidance is lower when using MSW, although the difference with agricultural residues and herbaceous biomass is smaller if CO_2 is captured.

Table 11. Environmental parameters calculated for each BioIGCC case studied

Substrate	Turbine No.	CO_2 Capture	m_{bm} [kgs^{-1}]	P_n [kW]	m_{bm}/P_n [kgkWh^{-1}]	$I_{avoided}$ [tCO$_2$GWh^{-1}]	$E_{avoided}/m_{bm}$ [tCO$_2$t$_{bm}$$^{-1}$]
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

Nonetheless, over $2 \cdot 10^6$ t per year of MSW would be needed to supply a 400 MW MSW BioIGCC working with an 80% capacity factor, and 25% more if CO_2 capture is introduced. This amounts to approximately 20% and 25% of the organic fraction of MSW produced each year in Spain. Thus, it is clear that this biomass consumption is too high to ensure the viability of a large scale power plant using MSW, except perhaps in areas with both a very 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 (agricultural and other waste, energy crops) so that these plants are viable in other contexts. Smaller plants (50-100 MW) can also be used in less densely populated areas. In any event, gasification of MSW also can be very interesting from the point of view of waste management.

A comparison of the different agricultural substrates shows that rice straw provides the lowest biomass consumption of the four substrates studied, mainly due to a higher gasification efficiency $(m_{bm}LHV_{bm})/(m_{sg}LHV_{sg})$. The biomass consumption is greatest when using switchgrass. From the point of view of CO_2 emissions, less CO_2 is captured when using rice straw because this substrate has a lower carbon concentration than the others under study. This also improves the global thermal efficiency, since the power consumption of the gasifier decreases. The substrate that has the highest CO_2 capture potential per tonne is alfalfa stems.

Calculating the avoided emissions divided by the electrical output yields a parameter that is incomplete and could cause misleading conclusions, especially when CO_2 is captured. See tab. 11 for illustration: 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_{av}/m_{bm}, which considers more properly the global environmental efficiency of biomass use.

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 around 1% higher for synthesis gas than for methane, due to the fact that syngas's optimum efficiency *PR* is closest to that achieved by the commercial gas turbines for industrial use. This efficiency improvement is even more noticeable in a combined cycle, because the exhaust gas' exergy in the Brayton cycle is higher for syngas than for natural gas. Ethanol has the lowest exergetic efficiency among the fuels analysed.

Gasification permits the implementation of pre-combustion CO_2 capture, with lower energy consumption than post-combustion capture, obtaining an effective negative net emission. Furthermore, the overall biomass-to-power efficiency of gasification is the highest among the alternatives considered, due to a higher biomass-to-fuel process efficiency and the recirculation of the steam produced in the gasifier when integration is introduced to the power plant. This makes BioIGCC the most promising among large-scale biomass power generation technologies. Nonetheless, due to the high power demand of the gasification process (12--17%) of the turbine power output in a combined cycle), and the high investment required in the plant, it is only suitable for medium and large-sized plants.

Pre-combustion CO_2 capture decreases the global efficiency of a BioIGCC power plant by around 5-7%, but is very advantageous from an environmental point of view, as CO_2 emission avoidance is more than triple that of the same plant without capture, giving place to a negative net emission. However, the quantification of CO_2 reduction when using biofuels is not straightforward and depends on the quantity and kind of residues generated and their use. For example, under the assumptions made in this work, a 400 MW BioIGCC without capture and working with a capacity factor of 80% would avoid 1 $MtCO_2$ per year compared to a NGCC, whereas an analogous BioIGCC with pre-combustion CO_2 capture would increase this value up to 3.36 $MtCO_2$ per year, adding the "not emitted" and the "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 [8]. These values are lower for MSW, as less carbon is fixed by the substrate (0.56 $MtCO_2$ per year without capture and 2.83 $MtCO_2$ per year with capture, under the same conditions). These data could be revised with the aid of a thorough study of the carbon cycle in each case. It should be remembered that, unlike most RES technologies, BioIGCC power plants are, in principle, capable of working with capacity factors as high as any other thermal power plant, provided there is a regular biomass supply in the quantities needed.

There is a wide variety of substrates that can be used in biofuel production technologies and gasification in particular. Biomass substrates from such different origins as agricultural residues, herbaceous energy crops and MSW have been studied in this work. Although many of the conclusions drawn would be the same for other substrates, further study should be carried out for each case.

MSW consumption is too high for BioIGCC to be viable, except perhaps in large and very densely populated areas. Nevertheless, the use of MSW along with other types of waste (*e. g.*, agricultural or cattle) would be very interesting from a waste management point of view as well as from an energetic and environmental perspective. The viability of agricultural bioenergy for large scale power generation in BioIGCC fed by agricultural waste is less compromised. The most suitable energy crop will vary from case to case, depending on its availability, the climate, suitability, yields, *etc.* 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, thereby decreasing global efficiency.

Nomenclature

c_p* – specific heat at nil pressure, [$kJkg^{-1}K^{-1}$]
e_i – flow exergy at cycle point *i,* [$kJkg^{-1}$]
$E_{avoided}$ – CO_2 emissions avoided when using BioIGCC instead of a NGCC with equal power outputs and capacity, [$tCO_2t_{bm}^{-1}$]
E_l – exergy loss, [kW]
E_g – exhaust gas exergy, [kW]
FAR – fuel-air ratio, [–]
h_i – specific enthalpy at point *I,* [$kJkg^{-1}$].
HHV – higher heating value, [$kJkg^{-1}$]
I – CO_2 emission intensity, [tCO_2GWh^{-1}]
I_{av} – CO_2 emission intensity avoided when using a BioIGCC instead of a NGCC with equal power outputs and capacity, [tCO_2GWh^{-1}]
LHV – lower heating value, [$kJkg^{-1}$]
m_i – mass flow at point *i,* [kgs^{-1}]
ΔP_{CC} – pressure loss in the combustion chamber, [bar]
P_c – critical pressure, [bar]
P_i – pressure at point *i,* [bar]
P_r – reduced pressure, [–].
PR – compressor pressure ratio, [–].
ΔQ_{CC} – heat loss in the combustion chamber, [kW]
s_i – specific entropy at point *i,* [$kJkg^{-1}K^{-1}$]
s^o – standard absolute specific entropy, [$Jkg^{-1}K^{-1}$]
T_c – critical temperature, [K]
T_i – temperature at point *i,* [K]
T_r – reduced temperature, [–]
TIT – turbine inlet temperature, [K]
v_i – specific volume at point *i,* [m^3kg^{-1}]
W_C – compressor gross power, [kW]
W_F – fuel compressor/pump gross power [kW]
W_n – Brayton cycle net power output, [kW]
W_T – gas turbine gross power output, [kW]
x_j – molar fraction of compound *j* in a mixture, [–]

Greek symbols

$\Delta_f H^o$ – standard heat of formation, [$kJkg^{-1}$]
ζ – exergetic efficiency of the steam cycle, [–]
ξ_{ex} – exergetic efficiency of the combined cycle, [–]
η_{ex} – exergetic efficiency of the simple Brayton cycle, [–]
η_{em} – electromechanical conversion efficiency, [–]
η_s – isentropic efficiency, [–]
ω – acentric factor, [–]

Subscripts

C – air compressor
F – air filter
H – flue gases exergy recovery system
i – state
bm – biomass
sg – synthesis gas (syngas)
T – gas turbine

Superscripts

M – mixing function

Acronyms

ASU – air separation unit.
BioIGCC – biomass integrated gasification combined cycle.
CC – combined cycle/combustion chamber
HRSG – heat recovery steam generator
ICE – internal combustion engine
IGCC – integrated gasification combined cycle
MSW – municipal solid waste
NGCC – natural gas combined cycle

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