USE OF ALTERNATIVE FUELS OBTAINED FROM RENEWABLE SOURCES IN BRAYTON CYCLES

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EXTENDED ABSTRACT

The goal of this work is to simulate and analyse the behaviour of gas turbines for power generation using different non-conventional fuels obtained from different renewable sources (biogas: anaerobic digestion of biomass, synthesis gas: biomass gasification, bioethanol: alcoholic fermentation of biomass and dehydration) and with different origins (energy crops, municipal solid waste). The gas turbine behaviour in a Brayton cycle is simulated both in an isolated operation and in combined cycle.
Two different softwares 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.
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
- CO_2 emissions.

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.
Some of the conclusions are:

- The global energetic efficiency of a gas turbine is high enough to be able to consider biofuels as an alternative to the conventional natural gas, from a technical point of view.
- The behaviour of a gas turbine fired with biogas is quite similar to when it uses pure methane fuel, and it can lead to an important CO_2 emissions reduction with a relatively low increase of investment cost. Methanisation arises as a very interesting technology for a low or medium-sized gas turbine power plant.
- Regarding synthesis gas, the efficiency in power production of a gas turbine is even higher than that obtained using natural gas. This efficiency improvement is more noticeable in a combined cycle for several reasons. From the point of view of CO2 emissions, syngas offers a better result due to the possibility of introducing pre-combustion capture, which, on the other hand, causes a decrease of the global energetic efficiency. Furthermore, syngas still improves the global energetic efficiency in the case of a combined cycle, even considering the power consumption of gasification.
- The analysis of bioethanol reveals that exergetic destruction is higher than for any other biofuel (and for natural gas).

Keywords: gas turbine, power generation, biofuels, renewable energy sources, Brayton cycle, biogas, syngas, bioethanol, biomass, gasification, anaerobic digestion

1. INTRODUCTION

Gas turbine power generation is being pushed to the utilisation of alternative fuels that can be used with reliability and efficiency (Gökalp and Lebas, 2004). 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 this context, combustion of different biofuels as totally alternative fuels is becoming and active area of research in recent years (Elmegaard et al., 2003), (Gadde et al., 2006), (Basu et al., 2001), (Shortt, 2005), (Jiménez et al. 2009).

One of the consequences of the current energy policies of most of the industrial countries is the Kyoto Protocol, signed in 1997 by many of them. However, some of the signatories, like Spain, 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 CO_2-free alternative fuels is highly needed and promoted by the energy policy of several countries.

In this paper, the behaviour of gas turbines working with different biofuels, namely biogas, syngas and ethanol 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
- CO_2 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 for design, analysis and optimisation of thermodynamic cycles developed by 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.

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 has been used. GT-PRO is a commercial software that includes data about a huge set of real gas turbines; it is more rigid, albeit more precise in the prediction of real gas turbine behaviour.

2. METHODOLOGY

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

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 for the fuels. All mixtures have been treated as ideal (Lewis-Randall). For all components, a correlation of exponential type is used for the specific heat at null pressure:

$$c_p^* = \alpha + \beta\left(\frac{(\gamma/T)}{\sinh(\gamma/T)}\right)^2 + \delta\left(\frac{(\varepsilon/T)}{\cosh(\varepsilon/T)}\right)^2$$

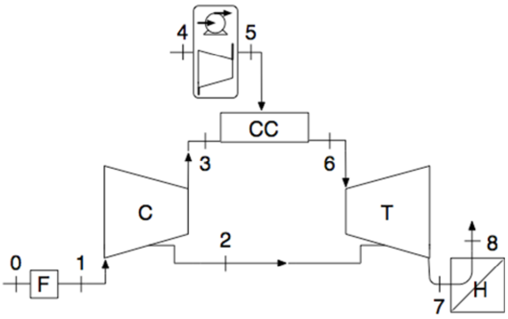

Figure 1

$T_0 = 15$ ºC, $P_0 = 1$ bar

$\Delta P_F = P_0 - P_1 = 996.3$ Pa

$\eta_{s,C} = 0.845$

$m_2 = 0.062 m_1$

$T_4 = 15$ ºC, $P_4 = 10.34$ bar

$P_5 = 1.41 P_3$ ($\eta_{s,4\text{-}5} = 0.84$)

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

$$\eta = \frac{\eta_{em}(W_T + W_C + W_{4-5})}{m_4 e_4} \quad ; \quad \xi = \frac{\eta_{em}(W_T + W_C + W_{4-5}) + \varsigma m_7 (e_7 - e_8)}{m_4 e_4}$$

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. Electromechanical conversion efficiency η_{em} and fraction of the combustion gases exergy recovered in the HRSG to the steam cycle ζ have been assumed equal to 0.98 and 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 1000-1450 ºC 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 H_2/CO = 1.
After completing the analysis of the results yielded by this set 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.
When working with biofuels, the global process of energy conversion from biomass to electricity should be studied, i.e. considering the biomass rather than the obtained biofuel as the entrance to the system. 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 (15 ºC, 1 bar) is compressed to the air separation unit (ASU) working conditions (15 ºC, 5.171 bar).
Regarding biogas from energy crops, a composition of 53% CH_4, a methane generation of 180 Nm^3/t of substrate (maize) and a 24 kWh/t electric and 240 kWh/t heat consumption have been considered. If the substrate is municipal solid waste (MSW), the biogas methane content is 65% and the yield is 200 Nm^3 CH_4/t, with a power and heat

consumption of 18.7 and 2.25 kWh/t. This has been taken into account in the GT-PRO simulations.

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 noted that some of the data found on energy consumption for ethanol production are contradictory.

Using data from the GT-PRO simulation, CO_2 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 CO_2 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.

As an 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 methanisation 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 CO_2 in alcoholic fermentation).

Taking into account the aforementioned issues, net CO_2 emissions for all biofuels were considered equal to 0, as is advised by the Spanish Ministry of Industry in its Renewable Energy Plan for 2005-2010. For MSW, the value set in the same document will be used: 60.5 $tCO_2/GW_{th}h$. If there is pre-combustion CO_2 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 CO_2 capture were assumed equal to 98% and 90% respectively.

Simulations were carried out on three gas turbines in combined cycle to calculate the emission using natural gas and those saved with CO_2 capture: Ansaldo AE 94.3A (284.8 MW), Siemens SGT5-4000F (263.6 MW) and Mitsubishi 701 G (334 MW).

3. RESULTS

3.1 Analysis using PATITUG

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 2 (with constant $x_{N_2} = 0.04$ and $x_{N_2} = 0.01$), syngas (H_2-CO) and ethanol, respectively.

Table 1. Maximum exergetic efficiency conditions for pure methane

η_{max}	TIT (ºC)	PR	ξ_{max}	TIT (ºC)	PR
0.3506	1450	40	0.5411	1450	29.5

Table 2. Maximum exergetic efficiency conditions for biogas

x_{CH4}	η_{max}	TIT (ºC)	PR	ξ_{max}	TIT (ºC)	PR
0.45	0.3476	1450	40	0.5316	1450	32.7
0.55	0.3491	1450	40	0.5353	1450	31.5
0.65	0.3501	1450	40	0.5378	1450	30.8
0.75	0.3507	1450	40	0.5396	1450	30.2

Table 3. Maximum exergetic efficiency conditions for syngas

x_{CH4}	η_{max}	TIT (ºC)	PR	ξ_{max}	TIT (ºC)	PR
0.45	0.3476	1450	40	0.5316	1450	32.7
0.55	0.3491	1450	40	0.5353	1450	31.5
0.65	0.3501	1450	40	0.5378	1450	30.8
0.75	0.3507	1450	40	0.5396	1450	30.2
x_{H2}	η_{max}	TIT (ºC)	PR	ξ_{max}	TIT (ºC)	PR
0.40	0.3608	1450	38.5	0.5670	1450	21.5
0.50	0.3602	1450	38.0	0.5654	1450	21.5
0.60	0.3594	1450	37.5	0.5634	1450	21.5
0.70	0.3585	1450	37.5	0.5612	1450	21.5
0.80	0.3573	1450	37.5	0.5586	1450	22.0
0.90	0.3558	1450	37.0	0.5555	1450	22.0
1.00	0.3537	1450	37.0	0.5514	1450	22.0

Table 4. Maximum exergetic efficiency conditions for pure ethanol

η_{max}	TIT (ºC)	PR	ξ_{max}	TIT (ºC)	PR
0.3399	1450	40	0.5177	1450	35.75

Figures 2 and 3 show the exergetic efficiency in simple and combined cycle, respectively, for a binary biogas (CH_4-CO_2) as a function of pressure ratio (TIT = 1450 ºC) when varying the CH_4 fraction. Figures 4 and 5 show analogous results for a H_2/CO=1 syngas with varying CO_2 fractions.

Figures 6, 7, 8 and 9 show the exergy balances (TIT=1450 ºC) as a function of the pressure ratio 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, respectively. The net power output of the turbine is shown in blue, the exhaust gases exergy in green and the exergy loss in red. All values are expressed as a fraction of the inlet exergy (e_{fuel}+$e_{inlet\ air}$).

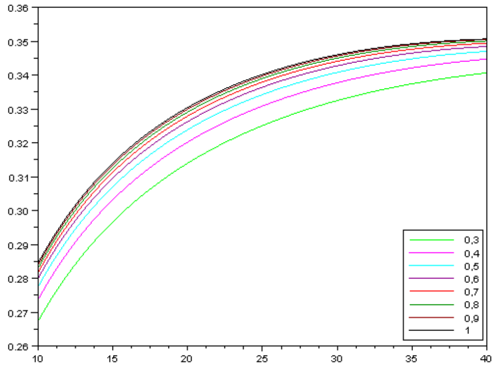

Figure 2.

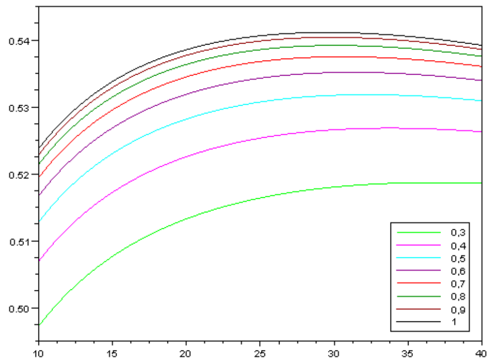

Figure 3.

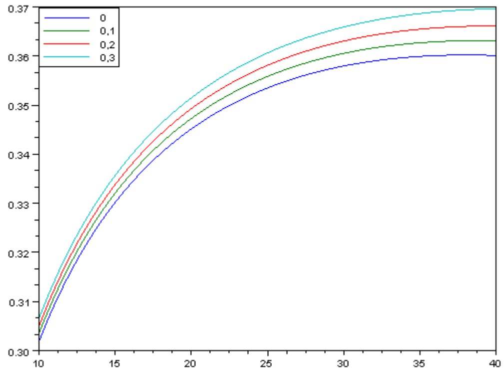

Figure 4.

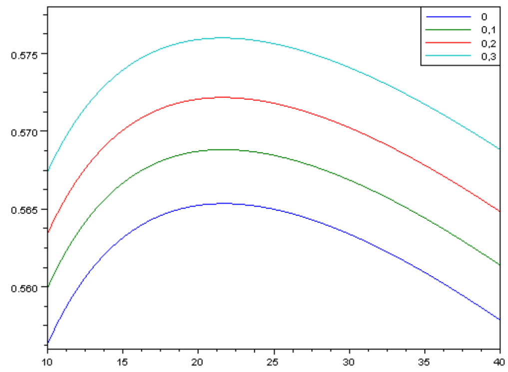

Figure 5.

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:

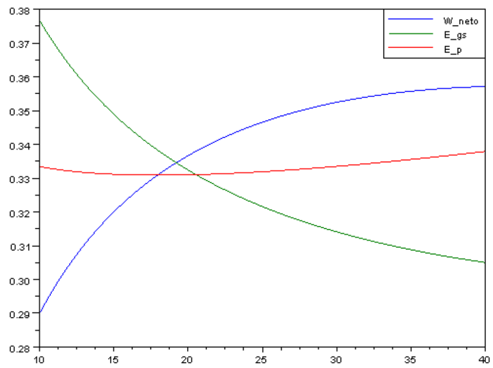

Figure 6

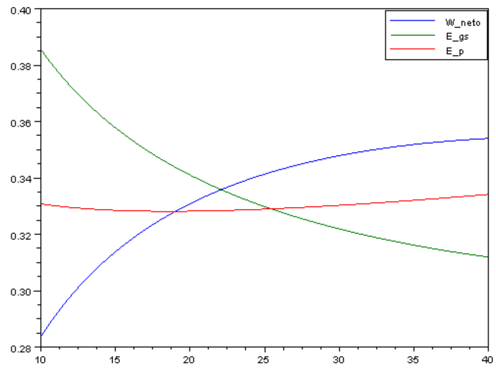

Figure 7

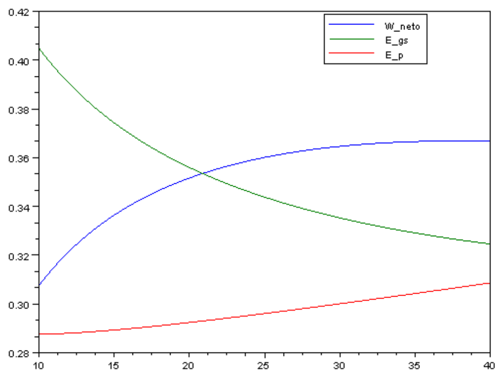

Figure 8.

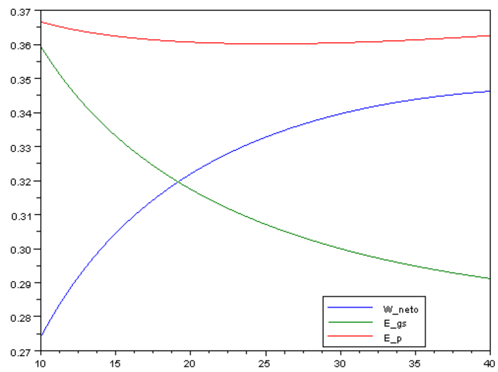

Figure 9.

Now the optimum 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. 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.

Table 5.

	Mitsubishi 701 G (334 MWe)			Siemens SGT-200-1S (6.7 MWe)		
Fuel	η_{max}	TIT (ºC)	PR	η_{max}	TIT (ºC)	PR
Natural gas	0.3929	1427	21.0	0.3142	1024	11.8
Biogas (53% CH_4)	0.3994	1401	21.9	0.3182	1014	12.1
Biogas (65% CH_4)	0.3978	1411	21.6	0.3152	1018	12.0
Syngas (31% H_2, 37% CO)	0.4172	1380	21.9	0.3314	1005	11.9
Syngas (87% H_2, 1% CO)	0.4203	1431	20.5	0.3319	1024	11.4
Ethanol	0.3919	1417	21.3	0.3152	1022	11.9

Considering the complete process, gasification yields a higher efficiency than methanisation 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 decrease of efficiency when adding pre-combustion CO_2 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.

Fuel	Simple	Combined
Natural gas	0.3833	0.5410
Biogas from energy crops (53% CH_4)	0.1383	0.1804
Biogas from MSW (65% CH_4)	0.2210	0.3124
Syngas from energy crops	0.2050	0.4152
Syngas from energy crops 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

In a biomass IGCC with pre-combustion CO_2 capture, 60-65% of the auxiliary power consumption would be due to the gasifier (85% of it to the ASU), and 31-36% to CO_2 capture. The actual values depend on the susbstrate.

3.3 Carbon dioxide emissions

The mean value of emission intensity in natural gas combined cycle (NGCC) for the three turbines that were simulated is 369.5 tCO_2/GWh. This is equal to the emissions saved when using an energy crops biofuel power plant without capture. Thus, the hypothetical substitution of a 400 MW NGCC working 7000 h per year (capacity factor of 80%) for an analogous biofuel CC would save 1 $MtCO_2$/yr (2800 GWh/yr). If a pre-combustion CO_2 capture module is added (with an efficiency of 90%) 3.36 $MtCO_2$/yr would be avoided.
Table 7 shows the mean emission intensities for MSW CC, and the CO_2 emissions saved if a 400MW NGCC (7000 h/yr) were substituted for an equivalent MSW CC:

Table 7. Average CO_2 emission intensities of MSW CC and CO_2 emissions saved when substituting a 400MW NGCC working 7000 h/yr (2800 GWh/yr) for a CC using biogas and syngas from MSW.

	tCO_2/GWh	$MtCO_2$ saved
Methanisation (Biogas)	194	0.46
Gasification (Syngas)	158	0.56
Gasification (Syngas) + CO_2 Capture	-654	2.83

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, syngas 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 (≈20%), albeit around 14% lower than the obtained in natural gas combined cycles. 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 tCO_2/GWh can be saved by substituting a natural gas combined cycle for a power plant fired with biofuels produced from energy crops, with an additional 850-900 tCO_2/GWh 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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