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GAS TURBINES CHP FOR BIOETHANOL AND BIODIESEL PRODUCTION WITHOUT WASTE STREAMS

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ABSTRACT

In the context of the recent decision of the European Commission to incorporate a minimum of 10% biofuel by 2020 in total transport fuel use, the production of bioethanol and biodiesel will be boosted. When compared to fossil fuels this two biofuels have numerous advantages i.e. they are renewable, they run in conventional vehicles, they are not toxic, they are biodegradable, they show low particulate emissions and they are CO2 neutral. However they show some disadvantages such as the high energy demand of their production and the high yield of byproducts (i.e. glycerin for biodiesel and distiller's waste for bioethanol), that require a dedicated marketing effort and supply chain. The energy demand required for the production of both biodiesel, through transesterification of vegetal oils, and bioethanol, through fermentation followed by distillation, is thermal and mechanical and can be satisfied by means of a CHP plant integrated in the production line fueled by its own byproducts. The paper analyzes the energy balances of two CHP plants fed with the above mentioned wastes (glycerin and wheat straw residues) and integrated in the biofuels (respectively biodiesel and bioethanol) production plants. The CHP plant considered are based on the IPRP (Integrated Pyrolysis Regenerated Plant) technology, meaning a gas turbine fed with syngas obtained from slow pyrolysis of the residues. Results show that in the case of biodiesel the production of glycerine is sufficient to satisfy the electricity demand of the plant that is lower than the heat demand, while the last cannot be completely covered because glycerine production is reduced respect to the input mass of vegetable oil and equal to 10 % w/w. Concerning bioethanol, wheat straw residues are enough to cover heat demand that is the most important energy input of the process but they are not able to cover electricity input that is linked with the milling of the raw material. This is because of the reduced syngas yields and its lower energy content if compared with that obtained using glycerine.

[*Keywords*: IPRP, Pyrolysis, CHP, Gas Turbine, bioethanol, biodiesel]

NOMENCLATURE

CC	Combustion Chamber
CHP	Combined Heat and Power
Cp	Specific heat at constant pressure
IPRP	Integrated Pyrolysis Regenerated Plant
LHV	Low Heating Value (kJ/kg)
	Mass flow (kg/s)
P	Pressure (Pa)
QPyr	Heat required to sustain pyrolysis (MJ/kg $_{SF}$)
REC	Recuperator
REG	Regenerator
RR	Regeneration Ratio (%)
SF	Solid Fuel
SYN	Syngas
sim	simple
T	Temperature (K)
TIT	Turbine Inlet Temperature (K)
TP	Pyrolysis Temperature
W	Work
β	Compressor Pressure Ratio
Q	Heat (MJ/kg $_{RF}$)
v/v	Volume fraction

w/w	Weight fraction
Subscripts	
av	Average
Eg	Exhaust gases
el	electric
Ext	External
g	global
HT	High Temperature
LT	Low Temperature
NG	Natural Gas
P	Pyrolysis
REG	Regenerator

1 INTRODUCTION

2009 EU biodiesel production increased 16,6% with respect to the previous year with an overall output around 9 million tons. Although this stands well below the increase in production of 35% registered in 2008 and in previous years (54% in 2006 and 65% in 2005), it testifies the strong vitality of the EU biodiesel sector, which mantains its market positions regardless of economic crisis, as it already happened in 2007 when the industry growth rate was around 16% [1-2].

In 2003 in Europe there were: 6 biodiesel plants in Austria, 14 biodiesel plants in the Czech Republic, 4 plants in France, 23 in Germany, 7 companies producing biodiesel in Italy, about 6 in Spain [3]. While in 2006 there were 40 biodiesel plants under construction in USA and 4 plants in expansion and 24 plants in pre-construction [4].

EU Bioethanol production in 2009 was 4.14 times higher than that of biodiesel however, while almost 50% percent of biodiesel is produced in Europe, only 4% of bioethanol world production is realized in Europe. Brazil produces 34% of the total amount and USA produces 54% [5].

By the end of 2005, there were 95 operating plants in the United States with total capacity of 16.4 billion lt per year. In mid-2006, 35 additional plants were under construction with further capacity of 8 billion lt per year. Brazil has over 300 plants in operation, of which 80 licensed in 2005, and is expected to increase sugar cane production by 40% by 2009 as a part of a new national plan. Potential market for bioethanol is estimated around 45 EJ by 2050 [6].

With the recent development of biomass conversion technologies a much wider range of crops and crop types are now available for bioethanol production (poplar, triticale, miscanthus etc.), and winter wheat could be included as a feedstock in the short term. The use of other biomass feedstocks (lignocellulosic feedstocks) will markedly increase energy input/output ratio as well as multiply the production potential.

Bioethanol production requires large amount of energy during the methanol recovery process and the distillation phase. In particular the energy demand in sugarcane processing to bioethanol is about 500-580 kg of steam (saturated at 1.5 bar) per ton of sugar cane (tc) [7-8] and 28 kWh/tc of mechanical energy for sugar cane preparation, milling and motopumps. If ethanol is produced from straw, it requires about 19 MJ/kg (of biofuel produced) of thermal energy and 1.1 kWh/kg of electricity. For each kilogram of straw as an input about 0.22 kg of ethanol are produced and 0.44 kg of residues, with 10% moisture and 18 MJ/kg of LHV.

For biodiesel production the energy demand is about: 30 kWh electricity and 2200 MJ of steam per ton of biodiesel produced [9]. The main byproduct of biodiesel production residue is glycerin, that is obtained in proportion of 10% of the vegetable oil used [10]. The average LHV of glycerol is about 24 MJ/kg [11].

Given the energy intensive production process of these biofuels and the availability of energy rich by-products (glycerin and straw/bagasse) it is interesting to evaluate the possibiity of reusing the byproducts as fuels to a CHP plant which provides part (or all) of the heat required to the process.

The aim of the paper is to analyze the thermal performances and energy balances of two CHP plants fed with the above mentioned wastes (glycerin and wheat straw residues) and integrated in the biofuels (respectively biodiesel and bioethanol) production plants. When coming to bioethanol waste wheat straw was preferred to bagasse because the study is focused on a EU centered supply chain.

As a CHP technology different solution are technically available such as direct combustion and a Rankine-HIRN cycle or an intermediate conversion to a low LHV syngas via gasification or pyrolysis coupled to an internal combustion engine or gas turbine.

This work focuses on slow pyrolysis coupled to a gas turbine via the IPRP technology while other studies are ongoing to evaluate CHP performance through combustion and gasification process.

2 IPRP TECHNOLOGY

The IPRP (Integrated Pyrolysis Regenerated Plant) is mainly composed (Figure 1) by a rotary kiln pyrolyzer coupled to a Gas Turbine (GT) fuelled by a medium LHV pyrolysis syngas previously cleaned. Char and tars post-combustion on the GT exhaust gases line provides the heat required to sustain the process and eventually to regenerate the Joule cycle in the GT. At the end of the process there is still heat available for cogeneration purposes and, for this is the case, to provide heat to the biofuel production plant.

The thermodynamic optimization of the IPRP technology for some feedstock was carried out in previous works [12-16] through a sensitivity analysis on main design parameters such as GT manometric compression ratio (β), regeneration ratio (RR), turbine inlet temperature (TIT) and pyrolysis temperature (Tp). Typical results show that IPRP technology is a scalable concept, because best efficiency points are always obtainable for a combination of operational parameters which are coherent with existing and operating microturbines (mGT), aero-derivative (AD GT) and heavy duty GTs (HD GT).

Previous works [10-11] showed also that for plants fuelled with biomass residues like coconut shell, straw and wood the electric efficiency is higher than 30% and HD GT gives the highest plant efficiency. Plant fuelled with corncob, groundnut shell, rice husk, olive husk and rapeseed show electric efficiencies around 20% for mGT and efficiency decreases increasing the GT size; for mGT electric efficiency is quite low while produced heat is quite high, therefore it could be used in small CHP plant.

From these premises the authors have carried out extensive experimental and simulation activity on a laboratory scale rotary kiln pyrolyzer as a preliminary activity to the design and construction of an 80 kW electric IPRP pilot plant in the regenerated arrangement (REG, no REC), which is running for tests at the Terni facility of the University of Perugia, Italy [16]. Figure 2 shows the pilot plant as built, with the pyrolyzer on the left, the gas cleaning section in the middle and the micro GT on the right.

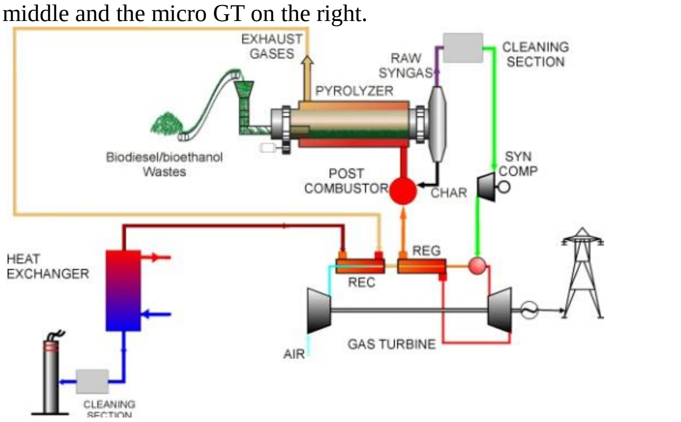

Figure 1. IPRP technology scheme

Figure 2. Photo of the pilot plant

3 BIOETHANOL PLANT DESCRIPTION

IBUS process (Integrated Biomass Utilization System) [17], is considered for bioethanol production from wheat straw through second generation technology. This is a pilot process mainly diffuse on a small scale. The reason of the choice is that on Literature several studies are available dealing with CHP integration with first generation bioethanol produced from sugar cane and corn, while second generation bioethanol is less studied and the only application found is to integrate it with biogas production but not with solid biofuel based CHP plants, such as gasification or pyrolysis plants.

IBUS process consists of different phases: pretreatment, hydrolysis, fermentation, distillation and separation (see figure 3).

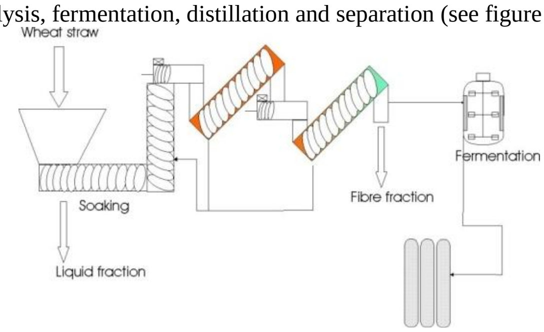

Figure 3. Bioethanol plant layout

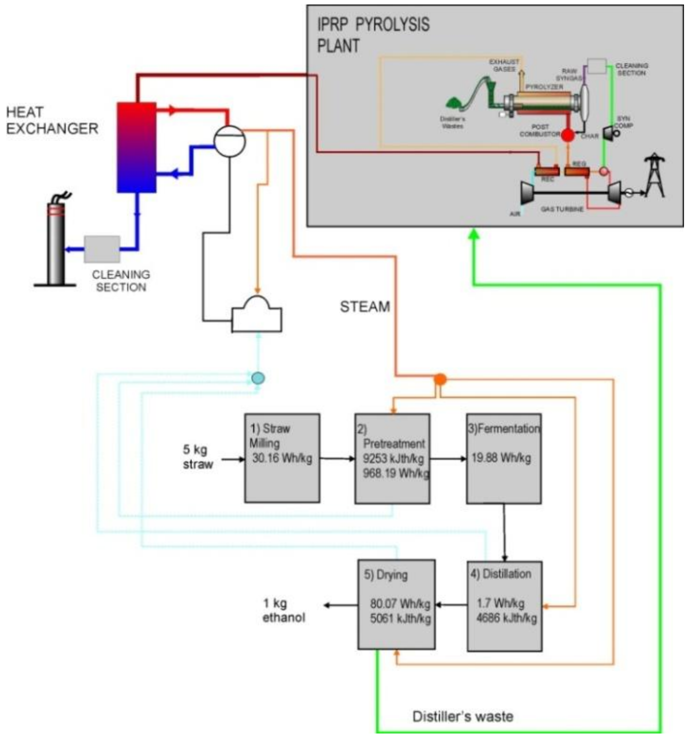

Figure 4. Bioethanol plant mass and energy balance

Pretreatment is required to make cellulose more accessible for subsequent enzymatic hydrolysis. This is done through a continuous hydrothermal solution where the biomass at high dry matter content is preheated by steam and afterwards washed.

BIOETHANOL PLANT ENERGY DEMANDS		
Section	**Heat (kJ/kg)**	**Electricity (kJ/kg)**
Straw milling	/	108
Pretreatment	9253	3485
Fermentation	/	71
Drying	4686	6
Distillation	5061	288
TOTAL	19000	3960
MASS BALANCE		
Mass	**Input**	**Output**
Wheat straw	1 kg	/
Bioethanol	/	0.22 kg
Solid biofuel (5% water)	/	0.44 kg

Table 1. Bioethanol plant energy demands and mass balance

The hydrolysis or liquefaction phase is performed through a free fall mixing system, that is an efficient way of performing enzymatic hydrolysis at high dry matters.

The preheated fiber fraction is loaded continuously into a liquefaction reactor with insoluble dry matter to water ratio of 25-30%. Even at low enzyme dose, the fiber fraction consisting of about 50% cellulose will liquefy within 6 hour and convert the fibers into a pumpable viscous liquid where 30-40% of the cellulose is hydrolyzed into glucose.

Dealing with fermentation, the optimum temperature for enzymatic hydrolysis of cellulose is around 50 °C. This temperature is chosen for the 6 initial hours of hydrolysis. After pre-hydrolysis, the temperature is decreased to the optimum temperature for yeast, typically around 33 °C and yeast is added.

To distillate the second generation bioethanol directly from the fermentation broth, a conventional vacuum distillation plant has to be employed for its high separation efficiency and low energy consumption.

The energy balance referred to 1 kg of ethanol produced from wheat straw is indicated in figure 4 and table 1.

3 BIODIESEL PLANT DESCRIPTION

The chemistry of transesterification should yield almost exactly 1 kg of biodiesel per kg of crude vegetable oil. In this paper, the lay-out (Figure 5) presented in [18] and the model of the plant was run using the software Superpro Designer to obtain the necessary data on energy and mass balances.

The facility contains four processing sections:

(1) a transesterification unit where the vegetable oil is subjected to chemical transesterification to produce fatty acid methyl esters (biodiesel) and glycerol as a coproduct;

(2) a biodiesel purification section (through centrifugation);

(3) a methanol recovery section;

(4) a glycerol recovery section.

Transesterification of soybean oil triacylglycerols with methanol, catalyzed by sodium methoxide, is realized as a continuous reaction conducted in steam jacketed, stirred tank reactors at 60 °C.

Transesterification is realized in two sequential reactors.

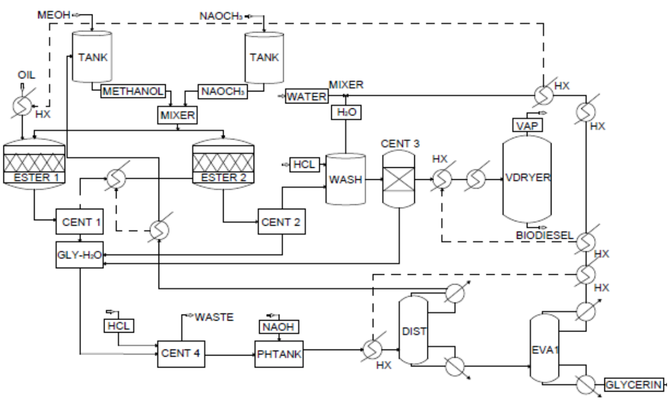

Figure 5. Biodiesel plant layout [18]

Glycerol, a coproduct of acylglycerol transesterification, separates from the oil phase as the reaction proceeds. A transesterification efficiency of 90%, is reported [19-20] and if two reactors are used, then the overall efficiency is of 99%.

The mixture of methyl esters, glycerol, unreacted substrates and catalyst exiting the second reactor is fed to a continuous centrifuge. Typical municipal quality water is used for this, and all subsequent, washes. The glycerol-rich aqueous stream from this operation is sent to the glycerol recovery section while the impure methyl ester product goes to the biodiesel refining section for purification and dehydration.

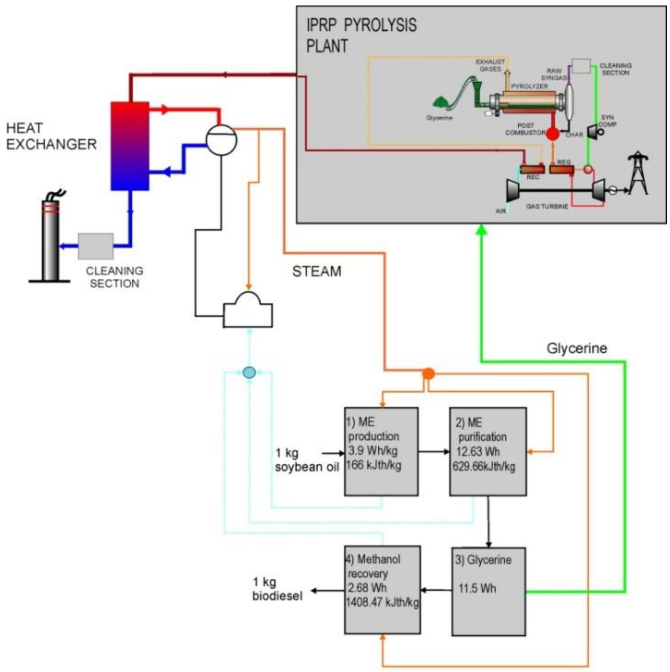

Figure 6. Biodiesel plant mass and energy balances

BIODIESEL PLANT ENERGY DEMANDS		
Section	**Heat (kJ/kg)**	**Electricity (kJ/kg)**
ME production	166	14
ME purification	630	45
Glycerine section	/	41
Methanol recovery	1408.47	10
TOTAL	2204	110
MASS BALANCE		
Mass	**Input**	**Output**
Soybean oil	1 kg	/
Biodiesel	/	1 kg
Glycerin (20% water)	/	0.1 kg

Table 2. Biodiesel plant energy demands and mass balance

The crude methyl ester stream is washed with water at pH 4.5 to neutralize the catalyst and convert any soaps to free fatty acids, reducing their emulsifying tendencies. Centrifugation is then employed to separate biodiesel from the aqueous phase. The latter is cycled to the glycerol recovery section. The crude, washed methyl ester product may contain several percent of water. This must be lowered to a maximum of 0.050% (v/v). Water is removed in a vacuum dryer from an initial value of 2.4% to a final content of 0.045%.

Finally, the diluted glycerol stream is distilled to reduce its water content. At this point the glycerol concentration is 80% (w/w), suitable for sale into the crude glycerol market. The energy balance referred to 1 kg of biodiesel produced form soybean oil is presented in figure 6 and table 2.

The production of biodiesel, compared with that of bioethanol gains a very limited quantity of residue: 10% in w/w, instead of 200% w/w. Glycerin has also an important content in moisture: 20 % instead of 10% of the wheat straw residues, these two sub products have respectively 24 MJ/kg and 18 MJ/kg as LHV. So glycerin has a higher energy content.

4 CHP PLANT DESCRIPTION

IPRP technology was considered for CHP production. Figure 1 shows the scheme of the IPRP technology, mainly composed by a rotary kiln pyrolyzer coupled to a Gas Turbine (GT).

Solid fuel is fed in the rotary kiln pyrolyzer and is transformed into char and raw syngas that is cooled to condense tar and water vapour in the syngas cleaning section. The energy required by the pyrolysis reaction is provided by the GT exhaust gases that are conveyed to the postcombustor where tar and char combustion increases their temperature and their thermal energy. The air coming out from the GT compressor may be preheated recovering thermal energy of GT exhaust gases in the regenerator (REG) or recovering thermal energy of exhaust gases out of the pyrolyzer in the recuperator (REC) before they are conveyed to the heat exchanger for cogeneration, to the filtering section and eventually to the stack.

5 OBJECTIVES AND METHODOLOGY

5.1 OBJECTIVES

As above mentioned the paper aims to analyze the feasibility of the integration of the biofuel production plant with a IPRP plant fuelled with biofuel residues producing the energy required by the biofuel production process.

5.2 METHODOLOGY: IPRP TECHNOLOGY

IPRP Plant modelling was carried out with a home-made software that utilizes thermodynamic relations, energy balances and data available from the Literature. The overall IPRP performances were determined as a function of four design variables that were varied in an adequate range and with an adequate step as described in Table 3. Results are then grouped for different parameters representative of different GT size namely:

- **microturbines**, (mGT), (β=4; TIT = 1000-1200 K); electric power less than 1 MWe
- **medium size aeroderivative GT** (ADGT) (β=12 TIT = 1200-1400 K); electric power in the range 1-10 Mwe;
- **big size heavy duty GT** (HDGT) (β=20 TIT = 1400-1600 K) electric power higher than 10 MWe.

Parameter	Range	Step
Pyrolysis temperature (T_p)	Depending on available data on glycerol and wheat straw pyrlysis	
GT Compression ratio (β)	2 – 30	1
GT Regeneration Ratio	75 %	
Turbine Inlet Temperature (TIT)	1000 K –1600K	100K

Table 3. Parameterization of the simulations

The pyrolysis reactor was simulated in the steady state and no transient or kinetic behavior was considered both for heat transfer and pyrolysis reactions. Storage of part of the produced char to be used during the transient period is not taken into account. The equilibrium temperature, to which, pyrolysis products and exhaust gases out of the pyrolyzer are referred, is the pyrolysis temperature (Tp). Pyrolysis products percentages and LHV as a function of pyrolysis temperature, were obtained from data available in Literature [21-22]. Syngas yield is shown in figure 7 that indicates that data for wheat straw residues from bioethanol production are available only for TP=550°C, while for Glycerin data are available for four Tp, all higher than TP for wheat straw.

When the percentage or the LHV of one of the three pyrolysis products was not given, the mass balances or the energy balances in the reactor were used to calculate it.

Char and tar produced from pyrolysis are considered to be burnt in the post combustion chamber providing heat to the pyrolyzer, recuperator (when present) and eventually to the heat exchanger for cogenerative purposes.

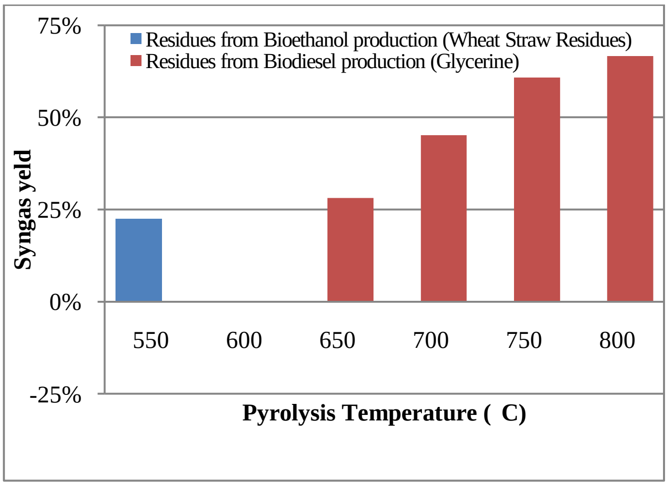

Figure 7. Syngas production from bioethanol production residues (Wheat straw residues) and from biodiesel production residues (Glycerine) for different T_P

As it can be seen from figure 7 glycerin syngas yields are very high. This is because of the very low char content of glycerin that besides, produces an hydrogen rich gas that has an interestin heating value. On the other hand difficulties can be encountered during pyrolysis of glyecerin due to its fluid behaviour that makes its transport difficult especially with conventional means such as screw conveyors. For this reason glycerin can be fed into the pyrolysis reactor also mixed with other solid biofuels (like wood chips). Straw residues are supposed to be more solid and less moist nevertheless their pyrolysis yields are not so good as those of glycerin.

The energy required for pyrolysis was assumed as the sum of different contributions:

a) Heat capacity of the feedstock at the reaction temperature considered;

b) Vaporization energy of pyrolysis reactants;

c) Heat of reaction;

d) Heat capacity of pyrolysis products at the Tp.

Where the only item that is sensibly dependent from Tp is the last one (d).

Gas turbine, syngas compressor and heat exchangers were simulated according to ideal conditions while irreversibilities were introduced through efficiencies as described in Table 4 that also shows other technical assumptions of the simulation. Different values were considered for the efficiency of air compressor, syngas compressor and turbine and for pressure losses for the different GT size considered. These data were derived numerically from operational data provided by manufacturers.

	Parameter	Value		
		micro GT	Aero derivative	Heavy Duty
Air	$P_{air,in}$	101325 Pa		
	$T_{air,in}$	288 K		
Syngas	$P_{syn,in}$	101325Pa		
	$T_{syn,in}$	323 K		
Efficiencies	Air Compressor	71%	74%	78%
	Syngas Compressor	71%	74%	78%
	Turbine	83%	86%	89%
	Syngas Combustion	98%	98%	98%
	Char/Tar combustion	90%	90%	90%
	Pyrolyzer heat exchange	90%		
	REG & REC heat exchange	90%		
Pressure losses	Combustion Chamber	5%	3%	3%
	Fuel injection nozzle	3%		

Table 4. Technical assumption used in the simulation

The GT regenerator (REG), in particular, was modelled considering the Regeneration Ratio (RR) defined as the ratio between the recovered energy on primary air, and the theoretical recoverable energy from GT exhaust gases assuming that they were cooled to the compressor outlet air temperature. With regard to the recuperator (REC) it was assumed that it was always in priority respect to the regenerator (REG) because the enthalpy of exhaust gases from Pyrolyzer would else be lost. No regeneration ratio was considered when discussing the recuperator, which will always preheat primary air to a temperature which is 50 K lower than the considered T_p.

Finally the gas treatment section analysis will be neglected assuming that syngas is cooled to 50°C in the humid scrubber and that the entire fraction of water vapour is condensed. Also no consideration is made on acid vapours treatment and other aggressive compounds production and abatement also related to the different concentration of trace elements in the different fuels.

The GT combustion chamber, usually designed for conventional fuels, will require some adaptation, especially in the fuel injection nozzles due to low LHV fuel gas, but they are not analysed in the present work.

6 RESULTS AND DISCUSSION

This section shows best performance points for the technology in terms of global efficiency (electric + thermal from char/tar + thermal from exhaust gases).

Results are grouped for each biofuel considered: bioethanol from wheat straw and biodiesel from soybean oil. For each biofuel, as previously described, results are grouped for three different GT sizes (mGT, AD GT, HD GT).

Only best efficiency points are shown for each case:

- **Case 1**, SIM C. - simple cycle (no REG, no REC)
- **Case 2**, REG C. - regenerated GT (REG)
- **Case 3**, REC C. - recuperated cycle (REC)

Each case yields different efficiencies therefore different straw/glycerin consumption to produce the same power ouput; to compare results the same amount of residue (which means also the same biofuel production) was considered for the three cases. A table shows biofuel production and straw/glycerin available for IPRP for three different plant size together with power (electric and thermal) consumption and IPRP electric power output range (depending on the case). Results are grouped in bas graphs showing the CHP performance of the IPRP in terms of power and efficiencies; nine different bars are presented for the three different plant sizes (mGT; AD GT and HD GT) considered and for the three heat recovery system (Simple cycle, regenerated cycle, recuperated cycle). Each bar sums the electric power (blue), and the thermal power available for cogeneration from the combustion of char/tar not used in the plant to sustain the pyrolysis process (red), from exhaust gases at high temperature (>180 °C, green) and low temperature (180 °C > T > 150 °C, violet).

Four graphs for each biofuel (bioethanol and biodiesel) are presented, representing:

A) the IPRP power output;

B) the IPRP specific power ouput (ie. with reference to 1 kg of biofuel produced);

C) the IPRP overall efficiency (with reference to the energy content of the byproduct used i.e. glycerin or straw);

D) the combined IPRP and biofuel net power output (with reference to 1 kg of produced biofuel; negative values show external requirements from the grid or from an auxiliary fuel).

Bio-ethanol from Wheat Straw

Table 5 shows data used for the simulation of the integrated IPRP-bio-ethanol production from wheat straw, that is mass and energy exchanges between bio-ethanol production plant and IPRP plant. If compared with the data reported in table 1 the EE/Heat required for biofuel production expressed in kJ/kg bioethanol seem not to be completely similar, this has to be explained taking into account that the second generation bioethanol plant considered in the study it is still on a pilot scale and so it may give imperfect results if scaled up.

	mGT	AD GT	HD GT
Residue out biofuel plant (t/h)	4.20	3.64	61.90
Bioethanol produced (t/h)	2.10	1.82	30.95
EE required for biofuel production (MW)	2	15.4	25.5
EE required for biofuel production (kJ/kg bioethanol)	3400	3050	2980
Heat required for biofuel production (MW)	9.5	74	122.6
Heat required for biofuel production (kJ/kg bioethanol)	16320	14650	14260

Table 5. Wheat Straw bio-ethanol and IPRP plant size

Figure 8 shows the power of the IPRP plant for each case considered. Figure 9 shows the energy output of the IPRP plant referred to 1 kg of bioethanol produced and figure 10 shows the efficiency of the IPRP plant.

For the three plant sizes considered, electric efficiency (blue bar) is always very low and increases with plant size; for mGT the recuperator gives the highest efficiency while for bigger plants the regenerator gives the highest efficiency. Char energy is always higher than 65%.

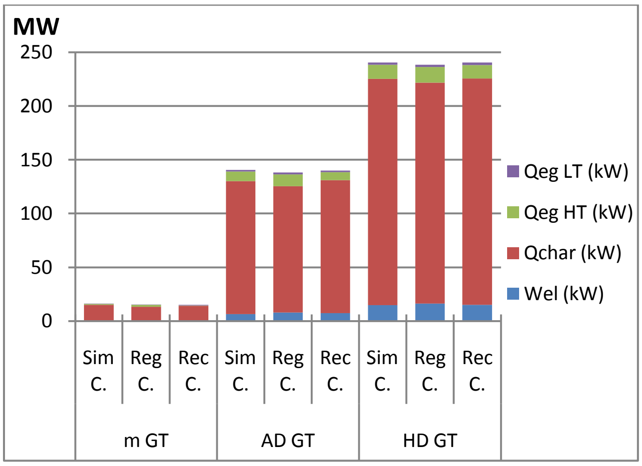

FIGURE 8. (A) IPRP CHP performance on wheat straw residues from bioethanol production

Figure 11 shows the output of the IPRP plant coupled to the bioethanol production plant, data are referred to 1 kg of produced bioethanol. For each GT size considered the electrical energy produced by the IPRP is less than electricity required by bioethanol plant, therefore part of electricity required to run the plant should come from the grid. Low temperature heat from exhaust gases (violet) is not used in the plant because it was considered not necessary to dry the wheat straw, due to the low moisture content; this heat can be used for cogeneration purposes. Heat available from exhaust gases at high temperature (green) is always used to provide heat to the plant. Char/tar (red) is enough to sustain the bioethanol plant heat demand, therefore the amount shown in the graph may be sold.

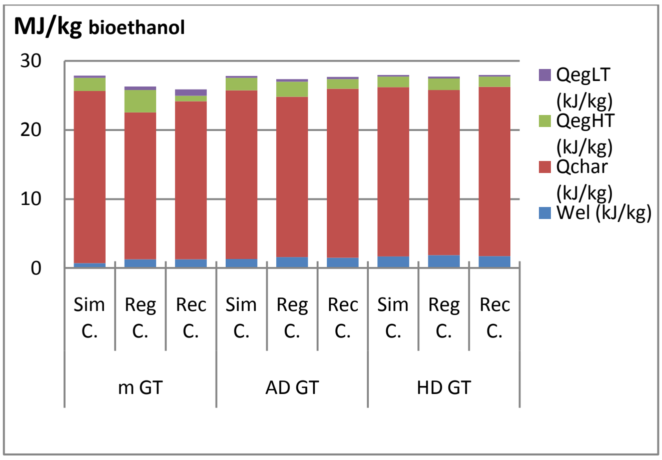

Figure 9. (B) IPRP CHP performance on wheat straw residues from bioethanol normalised to 1 kg of bioethanol

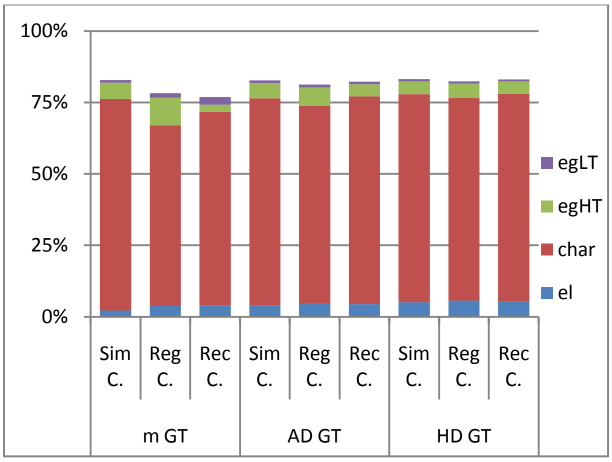

Figure 10. (C) IPRP CHP efficiency on wheat straw residues from bioethanol

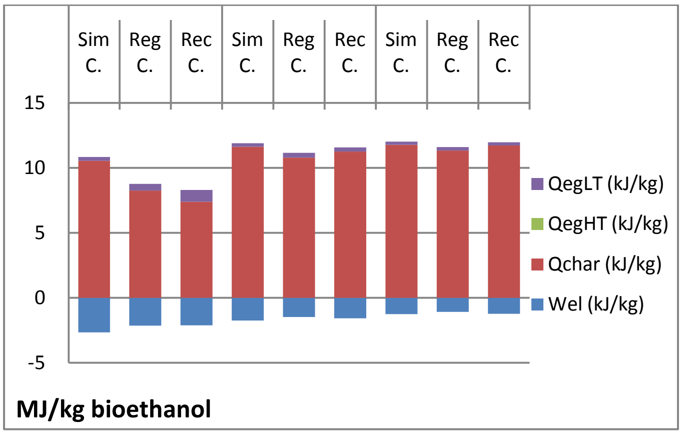

Figure 11. (D) Overall IPRP + Wheat Straw Bioethanol energy output normalised to 1 kg of bioethanol

Bio-diesel from soybean oil

Table 6 shows data used for the simulation of the integrated IPRP-biodiesel production from soybean oil, that is mass and energy exchanges between biodiesel production plant and IPRP plant.

	mGT	AD GT	HD GT
Residue out biofuel plant (t/h)	0.63	4.90	9.14
Biodiesel produced (t/h)	6.15	47.50	89.00
EE required for biofuel production (MW)	0.18	1.3	2.4
EE required for biofuel production (kJ/kg biodiesel)	108	97	94
Heat required for biofuel production (MW)	3.2	22.6	41
Heat required for biofuel production (kJ/kg biodiesel)	1900	1700	1660

Table 6. Soy biodiesel and IPRP plant size

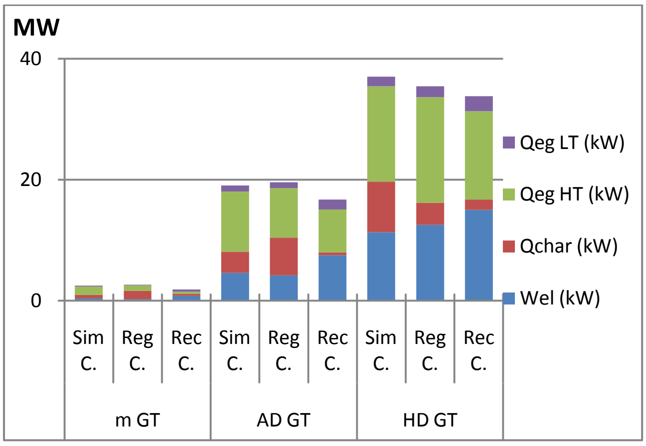

Figure 12. (A) IPRP CHP performance on glycerin from soybean oil biodiesel production

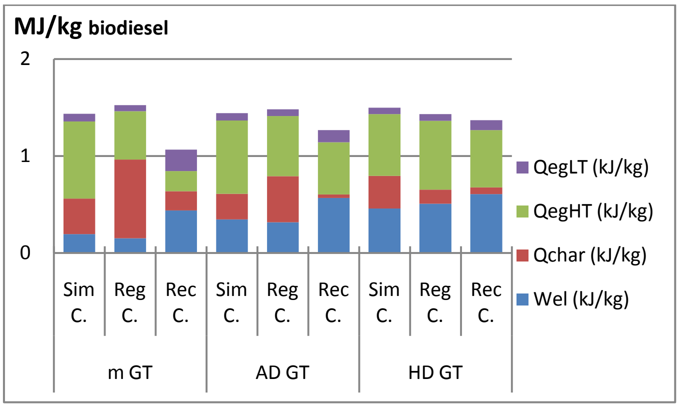

Figure 13. (B) IPRP CHP performance on glycerin from soybean oil biodiesel normalised to 1 kg of biodiesel

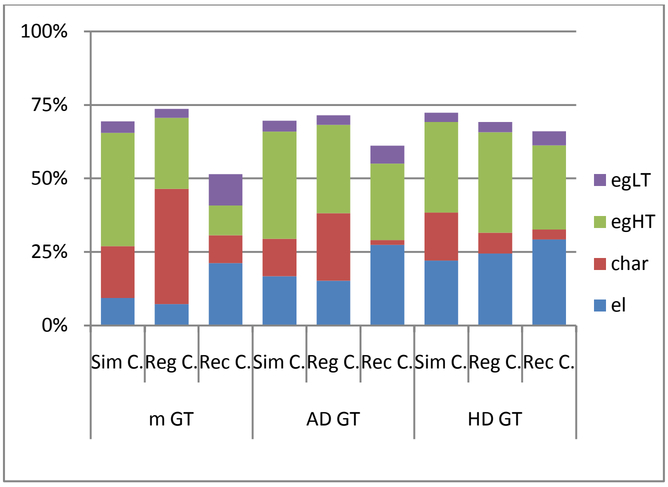

Figure 14. (C) IPRP CHP efficiency on glycerin from soybean oil biodiesel

Figure 12 shows the power output of the IPRP plant for each case considered. Figure 13 shows the energy output of the IPRP plant, referred to 1 kg of biodiesel produced and figure 14 shows the efficiency of the IPRP plant. For the three plant sizes considered, the electric efficiency (blue bar) is almost the same for simple and regenerated cycle while is a little bit higher for the recuperated cycle, because the recuperator increases the temperature of the air in the GT combustion chamber reducing fuel requirements. For recuperated cycle electric efficiency is higher than 20% for small plant size, lower than 30% for medium plant size and about 30% for big plant size.

Figure 15 shows the output of the IPRP plant coupled to the biodiesel production plant, data are referred to 1 kg of produced biodiesel. Electric energy produced by the IPRP is more than electricity required by the biodiesel plant, therefore part of the produced electricity may be sold to the grid. Low temperature heat from exhaust gases (violet) always exceeds the requirements to dry the glycerin therefore it can be used for cogenerative purposes. Heat available from char/tar (red) is not enough to sustain the biodiesel plant, therefore the amount shown in the graph should be increased with an auxiliary fuel. For the big plant size and for the smaller plant size the electricity produced is increased with the use of the recuperator. When the recuperator is used, electric efficiency is high but also the required amount of auxiliary fuel.

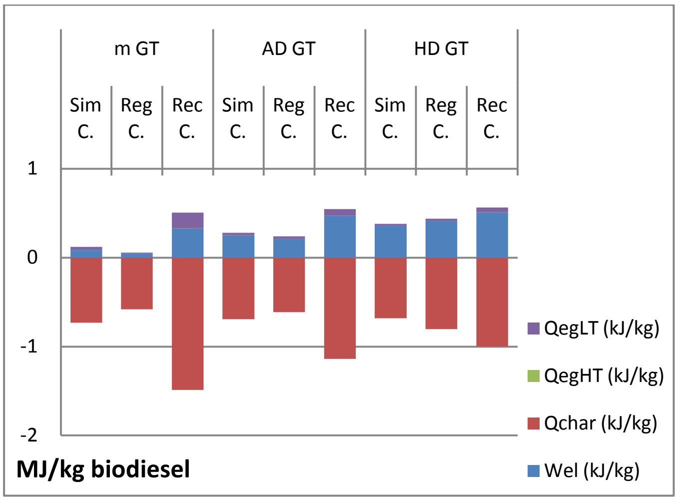

Figure 15. (D) Overall IPRP + Soybean oil biodiesel plant energy output normalised to 1 kg of biodiesel

Discussion

The analysis performed in this paper shows how the production of biofuels (biodiesel and bioethanol) can be integrated with a CHP plant fed with the residues obtained (glycerine and wheat straw residues) and based on IPRP technology. In the case of biodiesel the production of glycerine is sufficient to satisfy the electricity demand of the plant that is lower than the heat demand, while the last cannot be completely covered because glycerine production is reduced respect to the input mass of vegetable oil and equal to 10 % w/w. Concerning bioethanol, wheat straw residues are enough to cover heat demand that is the most important energy input of the process but they are not able to cover electricity input that is linked with the milling of the raw material. This is because of the reduced syngas yields and its lower energy content, if compared with that obtained using glycerine.

Dealing with the technical feasibility of the two CHP plants also considerations about how the fuels are fed into the IPRP have to be taken into account being glycerine at a liquid state.

9 SUMMARY AND CONCLUSIONS

This paper analyzes the integration of the IPRP technology in a biofuel production plant. The IPRP plant is fed with biofuel production wastes (wheat straw residues from bioethanol production or glycerine from biodiesel production) and will produce heat and electricity used in the biofuel production plant. IPRP technology combines a rotary kiln pyrolyzer and a gas turbine fuelled by the pyrolysis gas produced from the thermal degradation of residual fuels. Exhaust gases from the Gas Turbine provide the heat required to maintain pyrolysis, while additional energy may be supplied by post-combustion of tars and chars produced by the pyrolysis. The mass and energy balances of two biofuel plants were analyzed: bioethanol from wheat straw and biodiesel from soybean oil. Heat and electricity demand were determined. The pyrolysis products yields and characteristics were found in literature for the two residues. Three plant configurations were analyzed, with different heat recovery solutions, and for each one of them, performance was evaluated by varying main thermodynamic parameters. Results were then collected for the typical parameters of three GT size, namely micro GT (β=4; TIT=1000-1200K), medium size aeroderivative GT (β=12; TIT=1200-1400K) and big scale heavy duty GT (β=20; TIT=1400-1600K). Pyrolysis data on wheat straw residues were available only for low pyrolysis temperature, therefore syngas production is quite low and also its LHV, resulting in very low IPRP efficiencies. Char production is quite high, therefore coupling IPRP plant to bioethanol plant EE produced by the IPRP is not enough to sustain biofuel plant. Char is enough to sustain biofuel plant and may be even sold on the market. Pyrolysis data on glycerine were available for different pyrolysis temperatures; IPRP efficiencies are quite high. For small plant size electric efficiency is 21%, for medium size plant electric efficiency is 27% and for big plant size electric efficiency is 29%. On the other hand the heat and electricity demand of the two biofuel plants (bioethanol and biodiesel) are respectively of 19 MJ/kg, 3960 kJ/kg for bioethanol and 2.2 MJ/kg, 110 kJ/kg. for biodiesel. The whole integrated biofuel and IPRP plant efficiency were also analyzed, and the results show that coupling an IPRP plant to a bioethanol plant, the electricity produced by the IPRP is not enough to sustain the biofuel plant while char production is high therefore thermal energy produced by the IPRP is higher than the energy required by bioethanol plant. The IPRP fuelled with glycerine produces more electricity and less heat with respect to the energy demands of the biodiesel production plant. For both biofuels the IPRP provides part of the overall energy demand of the biofuel production plant but an auxiliary fuel or electricity is still required. Critical points of the proposed technology may be found in variable yields and energy content of pyrolysis products, that may produce combustion irregularities in the GT combustion chamber, and problems in syngas cleaning, that are linked with the performance of the syngas compressor and of the GT. In order to evaluate critical points of the IPRP technology, a microscale IPRP prototype (80 kWel) was built at the Terni facility of the University of Perugia and is now operating. Tests on glycerin and biomass co-pyrolysis are planned for 2011-2012.

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REFERENCES

1 PRESS RELEASE 2009-2010: EU biodiesel industry restrained growth in challenging times, July 22nd, 2010, European Biodiesel Board;

2 **Hajek, M. Skopal F.,** Treatment of glycerol phase formed by biodiesel production, Bioresource Technology 101 (2010) 3242–3245;

3 S. Butzen, Biodiesel Production in the US, CROP INSIGHTS, • VOL. 16 • NO. 5 • PAGE 1-4;

4 W. Körbitza, St. Friedricha, E. Wagingerb, M. Wörgetterc, Worldwide review on biodiesel production, Prepared for IEA Bioenergy Task 39, Subtask „Biodiesel“,Wieselburg, August 11, 2003;

5 Production of biofuels in the world in 2009 Geographic distribution of bioethanol and biodiesel production in the world, ENERS energy concept, http://www.biofuels-platform.ch/en/infos/production.php?id=bioethanol

6 IEA Energy Technology Essentials, ETE02, January. 2007;

7 Sugarcane-based bioethanol : energy for sustainable development / coordination BNDES and CGEE – Rio de Janeiro : BNDES, 2008. 304 p. ISBN: 978-85-87545-27-5;

8 Ethanol benchmarking and best practices (march 2008), Minnesota technical assistance program;

9 **Sheehan J., Camobreco V., Duffield J., Graboski M., Shapouri H.**, Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus *Final Report* May 1998, NREL/SR-580-24089;

10 **Dasari M.A., Kiatsimkul P.P., Sutterlin W.R., and Suppes G.J.,** 2005. Low-pressure hydrogenolysis of glycerol to propylene glycol. *Applied Catalysis A: General* 281(1-2): 225-231;

11 **Doradoa M.P., Cruza F., Palomara J.M., Lopez F.J.**, An approach to the economics of two vegetable oil-based biofuels in Spain, Renewable Energy 31 (2006) 1231–1237;

12 **Fantozzi F., D'Alessandro B., Bartocci P., Desideri U., Bidini G.**, Assessment of the energy conversion of whole oil fruits with a pyrolysis and gas turbine process, Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air, GT2010, June 14-18, 2010, Glasgow, UK;

13 **Fantozzi F., D'alessandro B., Bartocci P., Desideri U., Bidini G.**, Performance evaluation of the IPRP technology when fuelled with biomass residuals and waste feedstocks. ASME Turbo Expo 2009 Power for Land, Sea, and Air. Orlando FL USA, 8-12 giugno 2009;

14 **Fantozzi, F., Dalessandro, B., Bidini, G.**.. IPRP – Integrated Pyrolysis Regenerated Plant – Gas Turbine and externally heated Rotary Kiln as a biomass and waste to energy conversion system. Influence of thermodynamic parameters. Proceedings of the institution of mechanical engineers. Part a, Journal of Power and Energy. vol. 217, (2003) pp. 519-527 ISSN: 0957- 6509;

15 **Fantozzi, F., D'Alessandro, B., and Desideri., U.,** IPRP – Integrated Pyrolysis Recuperated Plant – An efficient and scalable concept for gas turbine based energy conversion from biomass and waste. TRANSACTION OF THE ASME. Journal of Engineering for Gas Turbines & Power vol. 127, (2005). pp. 348-357;

16 **Fantozzi, F., D'Alessandro, B., and Desideri, U.,** (2007) "An IPRP (Integrated Pyrolysis Regenerated Plant) Microscale Demonstrative Unit In Central Italy" ASME PAPER GT-2007-28000;

17 **Larsen J., Petersen M. Ø., Thirup L., Li H. W., Iversen F. K.,** The IBUS Process – Lignocellulosic Bioethanol Close to a Commercial Reality, *Chem. Eng. Technol.* **2008**, *31*, No. 5, 765–772

18 **Haas M. J., McAloon A. J., Yee W. C., Foglia T. A.**, A process model to estimate biodiesel production costs, Bioresource Technology 97 (2006) 671–678;

19 **Freedman B., Pryde, E.H., Mounts, T.L.**, 1984. Variables affecting the yields of fatty esters from transesterified vegetable oils. J. Am. Oil Chem. Soc. 61 (10), 1638-1643;

20 **Noureddini, H., Zhu D.**, 1997. Kinetics of trasesterification of soybean oil. J. Am. Oil Chem. Soc. 74 (11), 1475-1463;

21 Y**ang Z., Zhang B., Chen X., Bai Z., Zhang H.**, Studies on pyrolysis of wheat straw residues from ethanol production by solid-state fermentation, J. Anal. Appl. Pyrolysis 81 (2008) 243–246;

22 **Valliyappan T., Bakhshi N.N., Dalai A.K**., Pyrolysis of glycerol for the production of hydrogen or syn gas, Bioresource Technology 99 (2008) 4476–4483