International Scientific Journal
Environmental Science
http://environment.scientific-journal.com

Comparison of Biomass Energy Conversion Systems

Mario Amelio, Pietropaolo Morrone*, Emanuele Piraino

Department of Mechanical, Energy and Management Engineering (DIMEG)
University of Calabria, Arcavacata di Rende (CS), Italy
* e-mail: pietropaolo.morrone@unical.it

***Abstract* —This paper aims to analyze the performances and the economic feasibility of different arrangements of combined cycle (CCGT) power plants able to utilize biomass. In particular, the first CCGT arrangement includes a recovery boiler that is conveniently converted to a biomass post-combustion system. A second way is based on the co-firing of the syngas produced in a biomass gasifier. A third, hybrid configuration, includes a two output gasifier: a first gas stream is co-fired with the main fuel, while the second stream, characterized by low quality syngas, feeds a post combustor at the gas turbine outlet. Different hybrid configurations have been taken into account, depending on the high quality syngas proportion: 10%, 20% and 50%. Finally, a techno-economic analysis has been carried and the three plant arrangements analyzed have been compared with two reference plants: a standard CCGT and a typical direct biomass power plant. The plants have been modeled by using the commercial software Thermoflex®. The analysis has been conducted with the objective of determining the conversion rate of energy added by the biomass and the investment required for plant modifications. To this purpose, a new efficiency parameter has been introduced, defined as the ratio between additional electrical power output and heat power from biomass input. Then the kWh generation cost has been calculated taking into account both incremental capital and maintenance costs. Results show a reduction in energy production cost with the biomass conversion efficiency, except for the hybrid configuration, when it has a gasifier output less than 20% in high quality syngas. Although the thermodynamic result and the economic profitability are strongly related, as is evident in the co-fired system, an economic advantage can also be achieved in hybrid systems, despite their lower efficiency, as they can manage also a poor quality, less expensive biomass.**

Keywords—biomass, combined cycle

I. INTRODUCTION

In the last years the energy market has developed, as in a new industrial revolution, under the influence of three main factors: security of supply, sustainability and the level of commercial competition. In front of this setting, that is in constantly changing and which proposes new challenges to the men of government, Europe has thought to set more green for the environment. In particular, the European institutions, by the so-called Europe 20 20 20 plan [1], expect to reduce greenhouse gas emissions by 20%, raise to 20% the share of energy produced from renewable sources and to 20% energy saving. The economic evaluations now days include, with an increasing weight, the environmental costs coming from the traditional conversion systems and from the usage of conventional energy sources, which are more polluting than renewable ones.

The present work looks at the biomass energy conversion. In fact, biomass, in addition to curb the depletion of fossil fuel sources, contributes to reduce the emissions of CO2, the main greenhouse gas[2]. The biomass of vegetable origin is also characterized by a modest content of sulfur and nitrogen and can have a say in containing the emissions of SO2 and NOx. Therefore, among the alternative sources of energy, the biomasses arouse more interest in energy policy and technical-scientific research[3]. Also, if thermal energy is the first type of energy recovered from biomass, from an industrial and scientific point of view, today it's certainly the electricity production the most attractive goal [4].This study examines the possibility of a more convenient employment of biomass, through its use as supplementary fuel in a combined cycle plants powered by natural gas, currently the technology with the highest efficiency. Indeed, a critical issues in the use of biomass comes, as in almost all renewable sources, by the highest production costs and lower efficiencies, compared to plants powered by fossil fuels[5].

The use of biomass in the same plant powered by fossil fuels is a possible solution because, if the conventional thermodynamic cycle is not altered by the share of biomass energy, the conversion of the latter into electrical energy takes place with a efficiency equal to that of fossil fuel to which it is accompanied in feeding the plant. Moreover, the excess costs of renewables are decreasing with the share of renewable energy in the baseline [6].

The work has been carried out by analyzing in detail some possible system applications. In particular, one of the possible strategies is adding the syngas, produced by a biomass gasifier, to the natural gas entering the combustor of the gas turbine ("co-firing" application). Direct co-firing is the most common technical solution, both in the industrial practice and in the research literature [7]. This solution enables a reduction of natural gas consumption and guarantee the most efficient thermodynamic energy conversion in natural gas Combined Cycle Systems [8][9][10][11] or in coal-based CC plants[12][13]. As the gasification process offers higher efficiencies, especially in CHP operation, it is anyway interesting and will be, in the future, the best choice for either small or big size power plants.Another solution provide the use of biomass as a fuel for making the post-combustion at atmospheric pressure of the gases leaving the turbine, option that fits well with existing systems and with low output gas temperatures (750 K) [3].

The aim of this work is to present and compare concepts for improved efficiency of biomass-based power production, by integration with existing natural gas plants (CCGTs). The investigated plants have small size, suitable to the usage of many gasifiers. For the direct biomass combustion reference plant, the size was set at 10 MWe [4].

II. DESCRIPTION OF THE REFERENCE PLANT

The comparison between the performances of the plant configurations have been investigated by means of Thermoflex®, a software product by American company Thermoflow. This software is widely used in the analysis of various kinds of industrial plants[14].A generic combined cycle plant has been modeled by Thermoflex® accordingly with the scheme depicted in Figure 1. The net electric power output is of 58 MW, while the efficiency is about 53% on LHV basis. That plant has played, in the present work, the role of reference plant.

A. Gas Turbine

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations. The first part of the plant contains a gas turbine engine. Itsmodel, in Thermoflex® environment, considers separately the combustor and the turbine, in order to have more freedom degree in the analysis. The selected turbine is aero-derivative, like the General Electric LM6000-PD. Because of its high compression ratio (30) and low exhaust temperature(slightly lower than 500 °C), that turbine is more suitable to a post-combustion system[3]. In particular, the LM6000-PD produces electric power in the range of 42÷47 MW, with an industry-leading efficiency up to 41%.The LM6000-PD is equipped with a second generation DLE1.0,that doesn't need water to abate emissions (NO_x emissions are below 25 ppm)[15].

Table 1 shows the operating parameters, under nominal conditions, of the gas turbine block assembled with the software.

B. Heat Recovery Steam Generator (HRSG)

The modeled system includes a recovery boiler that produces steam at three different pressure levels. The flue gases through the heat recovery steam generator, against the current of the water-steam circuit. The HRSG, at pinch points, has a nominal temperature difference of 10 °C, for all the evaporators; subcooling temperature in economizers is set at 10 °C below the evaporation temperature; finally, the difference between the maximum temperature of the steam and the temperature of the hot gases exiting the post-combustion is at least 25 °C (approach point temperature difference). In all heat exchangers, loss of heat has been imposed equal to 0.75% while the deaerator works at 120 °C / 2 bar. The flow rates of the water/steam in the different circuits (high, intermediate and low pressure level) are calculated by Thermoflex.

TABLE 1. *PARAMETERS OF OPERATION OF THE GAS TURBINE,UNDER NOMINAL CONDITIONS*

Parameter	Value
Compression ratio	30
Speed [rpm]	3600
Exhaust gas Temp. [°C]	498,7
Air flow [kg/s]	120
Power output [kWe]	42944
LHV Eff. [%]	41
Price [MM$]	17

C. 2.3 Steam Turbine

The first two stages of the turbine (high and intermediate pressure) both work at the maximum temperature imposed by the superheaters in heat recovery steam generator. The inlet temperature of steam at low pressure level is equal to approximately half of maximum allowable temperature for the higher pressure levels. The condensation is performed at a rated pressure of 0.1 bar, by a dry cooled system (air-cooled condenser, with a drop in temperature between inlet and outlet of the cooling fluid of 15° C).The bottoming cycle is completely defined by a high pressure 110 bar, an intermediate pressure of 27 bar and a low pressure of 3.5 bar (this last steam flow is split towards two turbine bodies).The isoentropic and mechanical turbine efficiencies are assumed to be 85% and 99.8% respectively.

III. PLANT CONFIGURATIONS

In the integration options studied, the reference CCGT has been modified with a biomass-firing unit or coupled with a biomass gasifier. The biomass usage will decrease CO_2 emissions by decreasing the investment needs in new fossil capacity, or by decreasing consumption of other fossil fuel plants. The biomass availability depends on the characteristics of the site that include the richness of plant species and the ease of transport. From an economic point of view, one can derive a radius which identifies the area for a convenient collection [16][17] and, simultaneously, the annual quantity to be used. To perform a comparison on equal terms, the same annual availability of biomass (40,000 tons/year) was supposed for all combined cycle plants, while an availability of 55,000 tons/year was taken for the standard arrangement (the biomass direct combustion - steam power plant), that otherwise would be penalized by the size scale effect. Also, the generated power has been changed, hypothetically, between two levels, with the seasons and the time of the day. In particular, in summer, it is established a maximum power of approximately 55 kW, during the daytime, then reduced to 45 kW in the rest of the day. With the change of the season, the lower level of power was set at 35 kW. The different plant arrangements analyzed are the following:

Ref: Reference CCGT option, above illustrated.
BioSt: Reference stand-alone biomass steam power plant.
BIPCC (Biomass Integrated Post-Combustion Combined Cycle): the post-combustion of biomass is used to increase the temperature of gases entering into the heat recovery steam generator.
Cof: Co-firing concept, by adjoining a biomass gasifier to the combined cycle. The produced syngas is cleaned, cooled, compressed, and burnt simultaneously with the natural gas in CCGT plant.
Hyb: the plant is made by integrating a two-output gasifier with the combined cycle plant, in order to have two streams of syngas and obtain operation of both the systems "BIPCC" and "Cof".

A. *BioSt*

The most common way to obtain energy from biomasses is to burn them and to obtain first the thermal energy contained inside. Depending on the needs, such energy could be directly transferred to the users, for example in districts-heating, or transformed in electricity with a steam-water Rankine Cycle. Such plants are well proven and reliable but, because of their overall efficiency and cost, they are suitable only for medium or large size systems, generally bigger than 10 MWe [4]. The Reference plant has therefore a size of 10 MWe, it works according to a Hirn cycle and is fed, for hypotesis, by wood chips, whose composition is summarized in Table 3.1, with a lower heating value of 18.5 MJ/kg and a higher heating value of 19.5 MJ/kg. It burns 55000 tons/year of biomass, in a time of operation of 8000 hours. The plant reaches an electrical efficiency of 26% [16].

B. *BIPCC*

The model of the modified combined cycle plant is shown in Figure 2. Depending on load, the temperature at HRSG inlet, after the biomass combustion varies between 623 and 700 °C. The temperature at turbine outlet, around 500°C, allows a biomass contribution ranging between 11 and 22 % of the whole generated power. The bottoming cycle takes advantage from the increased heat input and, in the conditions of rated load for the gas turbine, reaches the theoretical efficiency of 30.1%, against 25.9% calculated without post-combustion.The quantity of biomass that feeds the post-combustion is about 40000 tons/year, with a composition summarized in Table 2.

C. *Hybrid*

The hybrid configuration joins a combined cycle gas turbine and a hypothetical biomass gasifier that has a double output: a high quality syngas, that is co-fired with natural gas in the combustion chamber of the GT, and a low quality syngas, which is used in a post-combustion with the flue gas of the gas turbine. The gasifier, which operates at a pressure slightly lower than atmospheric one, utilizes oxygen as oxidizing agent. The properties of exiting syngas are summarized in Table 2.

TABLE 2. *COMPOSITION OF THE BIOMASS USED FOR BIOST AND BIPCC MODELS*

Biomass (demolition wood)	Composition
C [%]	42.1
H[%]	4.9
O[%]	31.37
N[%]	0.05
S[%]	0.11
ash [%]	11.94
moisture [%]	9.01
LHV [MJ/kg]	18.5

D. *Co-firing*

The last case is similar to the hybrid case but with a single syngas output. The gasifier is called the "Blu tower", it is a multistage type and it works at atmospheric pressure, with a temperature of 1000 °C, air like gasification agent and 78.5% efficiency. With reference to an input of 40,000 tons / year of biomass, it has an installed power of 3 MWe (traditional combustion), 5 MWe (gasification with engines) and 7.5 MWe (gasification with fuel cells) with their respective energy conversion rate of 20%, 33% and 55% [17]. Unlike ordinary combustion systems, this energy conversion system based on biomass gasification, has efficiency less sensitive to the size of the plant. The syngas characteristics are summarized in Table 3 [17][8]. Moreover, in this case it is assumed that the gas turbine can easily use the flow of the syngas generated, therefore, the Blue Tower is integrated in the reference power plant, to co-fire the syngas with natural gas, in the combustion chamber of the gas turbine. The gasification of biomass contributes to the power with 9,65MWe, 16.8% of the nominal power. High quality comes from excellent particle size of the biomass. For hypothesis, the gas turbine (LM6000-PD) can employ such a flow of syngas. The low quality syngas used for the post-combustion, does not require any purification. The biomass used for this two-stream gasification system, is the same reported in the previous section and in the same amount.

Figure 3 shows the model reproduced with the software Thermoflex®; there are two gasifiers, because in the archive of the software, gasifiers with a double output are not available. The system includes an air separation unit, since the oxygen gasification agent and all the necessary ancillary. The hypothesis of cold gas gasifier efficiency is 81%. The whole conversion efficiency depends on the percentage of syngas used for co-firing (with a conversion rate equal to the combined cycle one). For this reason three different quantities of high quality gas used to co-fire are investigated; they are equal to10% of the total syngas product from the gasifier (Hyb 90-10), 20% (Hyb 80-20) and 50% (Hyb 50-50).

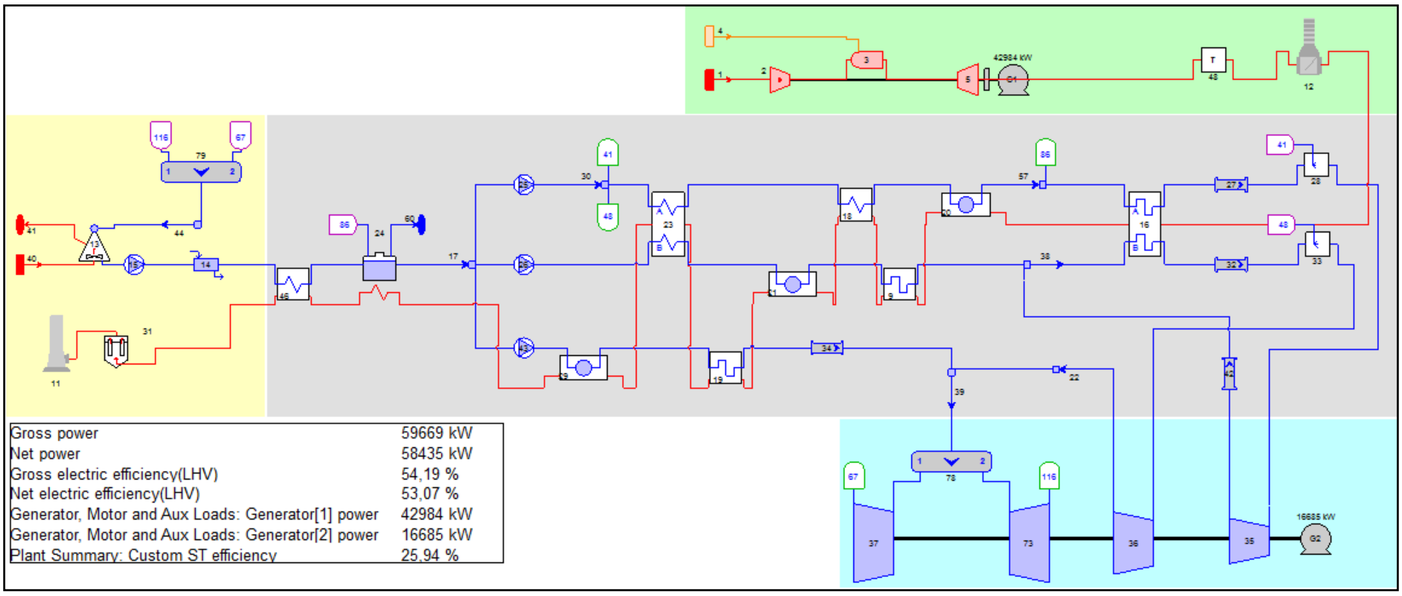

Figure 1. Combined cycle model reproduced in Thermoflex as reference plant. Different parts of the system are highlighted with different colors: gas turbine (green), heat recovery steam generator (gray), steam turbine(blue),section of condensation and discharge (yellow) [14]

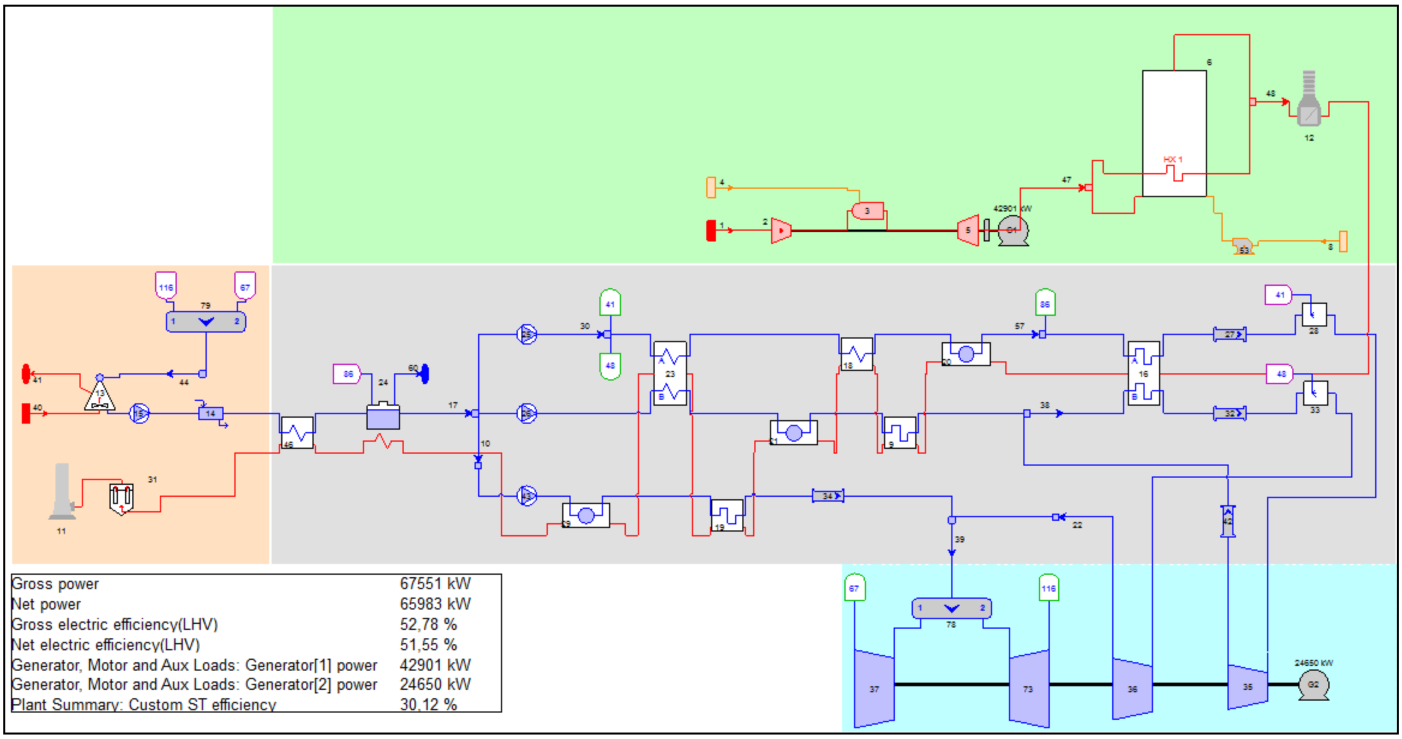

Figure 2. BIPCC model reproduced in Thermoflex. Different parts of the system are highlighted with different colors: gas turbine and post-combustion (green), heat recovery steam generator (gray), steam turbine (blue), section of condensation and discharge (yellow)

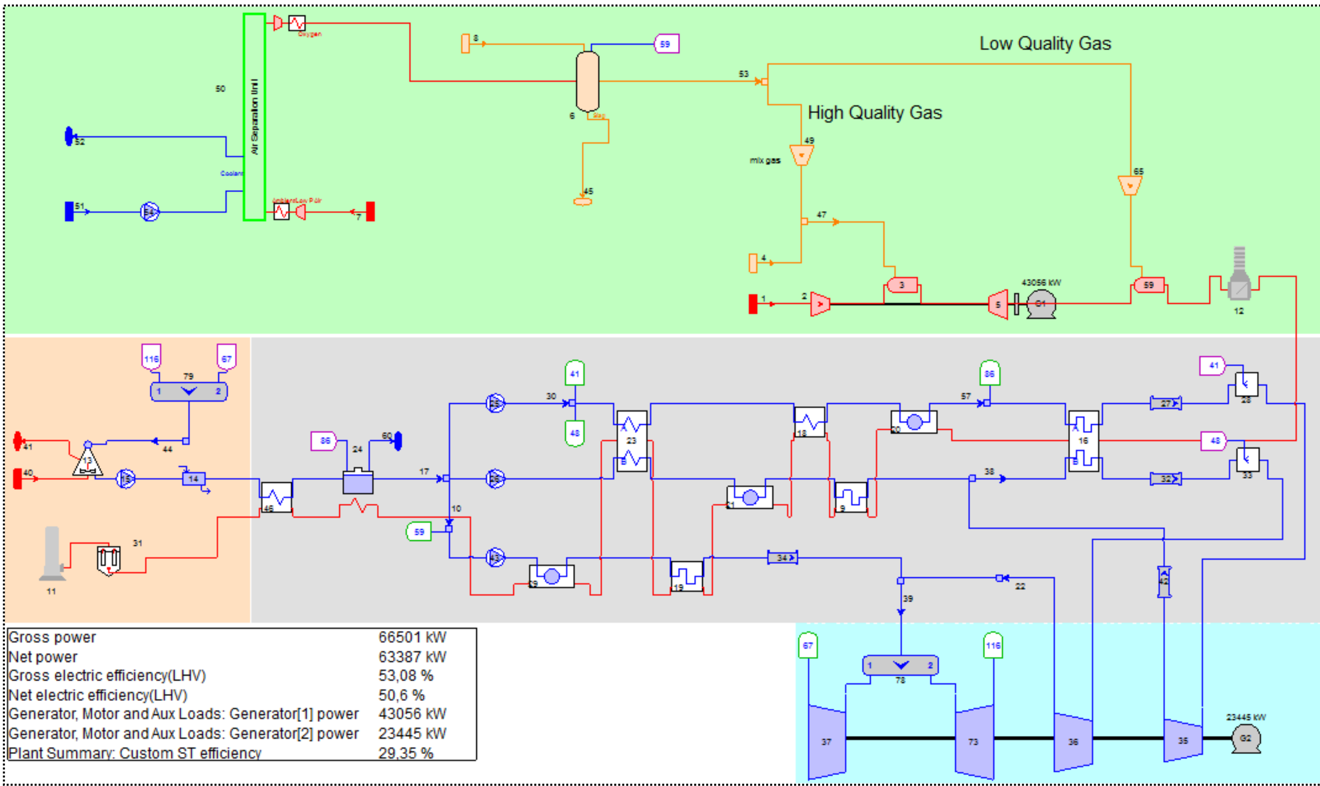

Figure 3. Hybrid model reproduced in Thermoflex. Different parts of the system are highlighted with different colors:: gas turbine and gasifier with co-firing and post-combustion (green), heat recovery steam generator (gray), steam turbine (blue), section of condensation and discharge (yellow)

TABLE 3. COMPOSITION AND PROPERTIES OF THE SYNGAS

Syngas Type / Composition	High quality gas	Low quality gas	Blu Tower
	molar fraction	**molar fraction**	**molar fraction**
[%]	[-]	[-]	[-]
CO	0.415	0.287	0.18
CO_2	0.065	0.101	0.23
CH_4	0.042	-	0.015
H_2	0.422	0.285	0.55
N_2	-	0.32	0.025
H_2O(g)	0.056	0.007	-
T [°C]	827	614	1000
LHV [MJ/Nm^3]	11.3	6.7	9

IV. RESULTS

The simulation results are expressed in terms of plant efficiency, energy production cost and cash flows for each plant configuration analyzed.

A. *Efficiency*

The overall plant efficiency is calculated as the ratio of produced power P to input fuel, Q_{tot}:

$$\eta_{tot} = \frac{P}{\dot{Q}_{in}} \tag{1}$$

The difference between the biomass-fired plants and the CCGT system is taken into account by the biomass efficiency, η_{bio} (or marginal electric efficiency) that is defined as the ratio between the power due to the biomass provision to the plant heat power input. In order to compute the marginal electric efficiency, the efficiency related to the natural gas power production was assumed to be equal to the reference CCGT plant efficiency [18][9]:

$$\eta_{bio} = \frac{P - \eta_{ref}\dot{Q}_{NG}}{\dot{Q}_{bio}} \tag{2}$$

where η_{ref} is the rated efficiency of ~~a~~ the reference CCGT plant, Q_{NG} is the thermal input from natural gas and Q_{bio} is the heat input due to biomass.

B. Costs

The economic analysis has been carried out in terms of incremental variables (power, capital costs and operating costs). This makes the study independent from the particular system. The cost of the energy produced was evaluated for the repowered scheme proposed, as well as for the initial combined cycle [19][10]. The main assumptions for the economic analysis are summarized on Table 4. The cost of kWh is a sum of four different terms:

- amortization of the invested capital;
- operating and maintenance costs which include costs for personnel, materials (spare parts, reagents, lubricants, etc..), external resources (contractors to work on the outside companies), insurance, taxes and fees;
- fuel cost;
- external cost (costs derived from environmental impact)

TABLE 4. *PARAMETERS USED TO CALCULATE THE ENERGY PRODUCTION COST FOR THE REFERENCE COMBINED CYCLE*

C_{cap}	600	€/kW
Useful life	20	anni
ammort. C_{cap}	5%	
$C_{O\&M,fix}$	6,2	€/kW
h_{eq}	7385[12] [16]	
$C_{O\&M,var}$	1,2	€/MWh
$C_{gasnaturale}$	18	€/MWh
η	53,1%	
η *penalization*	2,5%	
$\eta_{pen.}$	51,8%	
C_{ind}	0,0401	€/kWh
$C_{emission}$ *(external)*	0,01	€/kWh
C,kWh	0,0501	€/kWh

The comparisons are based on the discounted cash flows and the net present value.
As far as the operating and management costs are concerned, it should be noticed that the fixed fee includes the independent cost of the effective plant output (staff costs, insurance, etc.), while the variable share refers to charges dependent on the size of the production (lubricants, chemicals, waste disposal, etc..).
Finally, the industrial total cost is calculated as follows [20] [11]:

$$C_{IND} = \frac{C_{cap} + C_{OM,fix}}{h_{eq}} + C_{OM,var} + \frac{p_{fuel}}{\eta} \quad (4)$$

where C_{cap} is the share regarding the annual amortization of the invested capital [€/kW]; $C_{OM,fix}$ are the fixed costs about O&M [€/kW]; h_{eq} are the equivalent hours of operation per year; $C_{OM,var}$ are the variable cost about O&M [€/kWh]; p_{fuel} is the cost of the fuel [€/kWh]; η_{is} the annual average efficiency of the power plant.
The combined cycle power plant described is characterized by an investment cost of about 600 €/kW [11][12] and an estimated useful life of 20 years [12]. The total installed cost is equal to 35.000.000 €.
On the other hand, the fixed and variable O&M costs are assumed to be equal to 6.2 €/kW and 1.2 €/MWh, respectively [21][22]; so the annual total O&M cost amounts to 880,000 €, of which 362,000 fixed costs and 518,000 variable costs. The nominal power plant's efficiency is 53.1% with a penalization of 2,5% it is therefore about to 51.8% [21][22]. In the case of combined cycle power plants, most of the cost of the kWh is due to the cost of natural gas. Currently, the price of the natural gas fluctuates between 15 and 25€/MWh, depending on the type of supply. Therefore, the estimated total cost of the kWh is around 0.04 €/kWh, without the external costs. The portion of the costs relate to the emission of pollutants produced directly from the generation of electricity affects approximately 0.01 €/kWh [12] of the unit cost of energy. All data for the calculation of the kWh cost are summarized in Table 4. The cash flows have been evaluated through this equation:

$$F_k = F_c \cdot \left(\frac{1+i}{1+d}\right)^k \quad (5)$$

where d is the investment factor (equal to 5%), i is the inflation rate (equal to 2,5%) and k is the year.
The economic feasibility of the different configurations has been carried out. The parameters that remain constant in all the system arrangements are the capital cost of the gasification power plant, which amounts to 1270 €/kW [23] (with an amortization of the 5%), the capital cost of the combustion power plant, which amounts to 1000 €/kW [24] and the useful life, equal to 20 years. The annual operation hours are set to 8760 hours for all plant versions, except for the standard system BioSt, where they were set to 7271 hours, due to the higher consumption of biomass (55000 tons per year instead of 40000) and the unavailability, for that plant, of natural gas as an alternative fuel. The unit prize of the biomass equal to 55 €/ton [25][26] for BioSt case, 85 €/ton [27] for BIPCC case, 87.5 €/ton for Hyb 90-10 case, 90 €/ton for Hyb 80-20 case, 97.5 €/ton for Hyb 50-50 case and 110 €/ton [27] for Cof case.

Table 5 summarizes the parameters used in the economic analysis. The different costs of the kWh produced are reported for the different cases.

Table 6 summarizes the results for each plant arrangement regarding the installed capacity, the produced electricity, the efficiency and cost of the kWh for the different systems. Also, annual costs and annual revenues have been analyzed together with the difference between revenues and costs that generates the cash flows.

TABLE 5. *COST PARAMETERS USED FOR THE EVALUATION OF THE PRODUCTION ENERGY COST FOR THE DIFFERENT PLANTS*

	BioSt	BIPCC	Hyb 90-10	Hyb 80-20	Hyb 50-50	Cof
P_{inst} [MW]	10,00	7,77	7,29	7,57	8,30	9,65
$C_{O\&M,fix}$ [€/kW]	-	18,0	18,5	18,5	18,5	18,5
h_{eq}	7271	8760	8700	8700	8700	8700
$C_{O\&M,var}$ [€/kWh]	0,006	0,007	0,007	0,007	0,007	0,007
biomass [t/year]	55000	40000	40000	40000	40000	40000
$C_{biomass}$ [€/kWh]	0,042	0,050	0,055	0,055	0,054	0,052
η[%]	*26,00*	*32,17*	*31,06*	*32,28*	*35,01*	*40,83*
C_{kWh} *[€/kWh]*	*0,173*	*0,170*	*0,194*	*0,185*	*0,171*	*0,145*

For the cases BioSt, BIPCC, Hyb 90-10, Hyb 80-20, Hyb 50-50 and Cof, the cash flows are respectively 1.427.000 €/year, 10,290,000 €/year, 8.100.000 €/year, 8.100.000 €/year, 9.300.000 €/year and 12.477.000 €/year. To complete the analysis of costs and revenues, it is worth noting that the biomass input changes in the different system configurations and this determines dissimilar quantity of natural gas consumption, depending on the type of use of biomass (post-combustion or direct combustion). The saved amounts of NG, with respect to the original CC power plant, result 13,697,000 smc/year (15.9 %) for BIPCC, 13,580,000 smc/year (15.7 %) for Hyb90-10, 14,722,000 smc/year (17.1 %) for Hyb80-20, 15,580,000 smc/year (18,1 %) for Hyb50-50 and 16,972,000 smc/year (19.7 %) for Cof.
For the purposes of economic calculations, it was assumed the gas price of € 0.385 / smc (all taxes included). The unit sale price of electricity was taken equal to 70 €/MWh, while grants were estimated to be 122 €/MWh [30].

C. *Parametric plots*

In calculating the cost of kWh, equation 4.3, the highest weight falls on the cost of biomass and conversion efficiency. Parametric plots for all four cases of exploitation of biomass are shown below, in the Figures 4 (a – d), where the cost per kWh generated is expressed as a function of the biomass cost and efficiency.
Obviously, the cost per kWh produced increases with the price of biomass and decrease with efficiency. Also, for the cash flows is made an argument analogue to the previous one. The independent variables are the cost of the biomass and the sale price of electricity [30]. As expected, cash flows increase with the selling price of the electricity and with the reduction of the cost of biomass, as Figures 5 (a – d) show.

It is worthwhile to notice from figures that the range of variation of biomass cost is different for the four plant configurations because the quality of biomass, mostly related to the humidity, that can be treated by the different arrangements is different. Particularly, the dashed curve represents the average cost of biomass, assumed as reference in the calculations, for each plant configuration; the other curves reflect the possible variation of this cost, because of the actual market conditions. From the thermodynamic and economic point of view, the exploitation of the biomass in combined cycles is more rational than the direct use.
BioSt plant converts into electricity 26% of the biomass thermal input, whereas BIPCC, Hyb 90-10, Hyb80-20, Hyb50-50 and Cof have efficiency respectively of 32%, 31%, 32%, 35% and 41%.

TABLE 6. *EFFICIENCY AND COSTS RESULTS*

	BioSt	BIPCC	Hyb 90-10	Hyb 80-20	Hyb 50-50	Cof
$\mathbf{\Delta P_{bio}}$ [MW]	10.0	7,77	7.2	7.5	8.3	9.6
$\mathbf{EE_{tot}}$ [GWh]	73.2	431.3	431.3	431.3	431.3	430.6
$\mathbf{EE_{NG}}$ [GWh]	-	363.2	367.9	365.2	359.1	346.7
$\mathbf{EE_{bio}}$ [GWh]	73.2	68,08	63.4	66.1	72.1	83.9
$\mathbf{EE_{bio}}$ [%]	100.0	15.7	14.7	15.3	16.7	19.4
$\boldsymbol{\eta_{bio}}$ [%]	*26.0*	*32.1*	*31.0*	*32.2*	*35.1*	*40.8*
η_{tot} [%]	26,00	51,55	51,65	51,89	52,34	53,01
$C_{kWh,to}$ [€/kWh]	0,173	0,061	0,063	0,063	0,063	0,061
$C_{kWh,natural\ gas}$ [€/kWh]	-	0,040	0,040	0,040	0,040	0,040
$C_{kWh,bio}$ [€/kWh]	*0,173*	*0,170*	*0,194*	*0,185*	*0,171*	*0,145*

It is possible to notice that the curve trends strongly depend on the plant size. While for BioSt the kWh cost varies from 0.10 to 0.29 € / kWh, for BIPCC it varies from 0.11 to 0.26 € / kWh, for Hyb 50-50 it varies from 0.11 to 0.24 € / kWh and, for Cof, from 0.10 to 0.21 € / kWh; on the other hand, the cash flows reach the value of 9.200.000 €/year for the Biomass standard plant, 14.500.000 €/year for the BIPCC, 13,800,000 €/year for the hybrid configuration and 17,500,000€/year for the cofiring arrangement. All this occurs not only for the different cost of the kWh, but also for the large natural gas savings, that adds to the revenue item. Here it should be recalled that, in the Hyb case and in the Cof case, the gasifier is required with different performance and different quality of output syngas (Table 3).

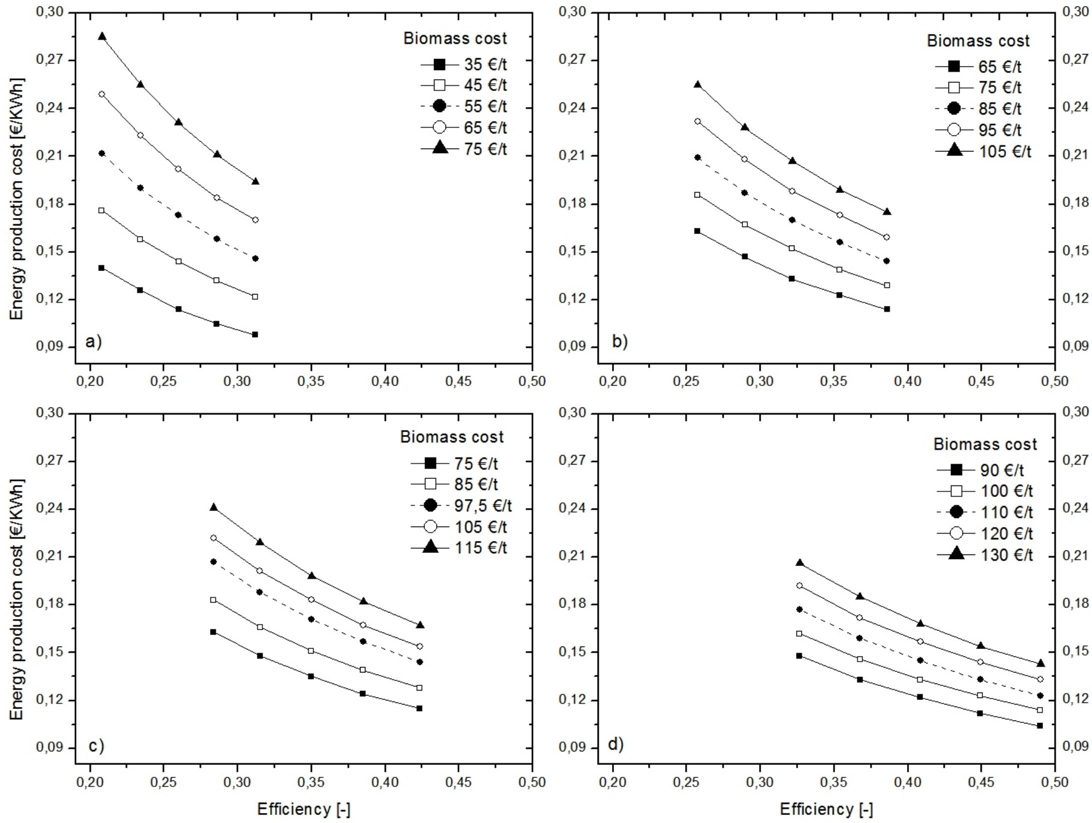

Figure 4. Cost of kWh generated, function of the cost of the biomass and efficiency for for *BioSt (a), BIPCC(b), Hyb 50-50 (c), Cof (d)*

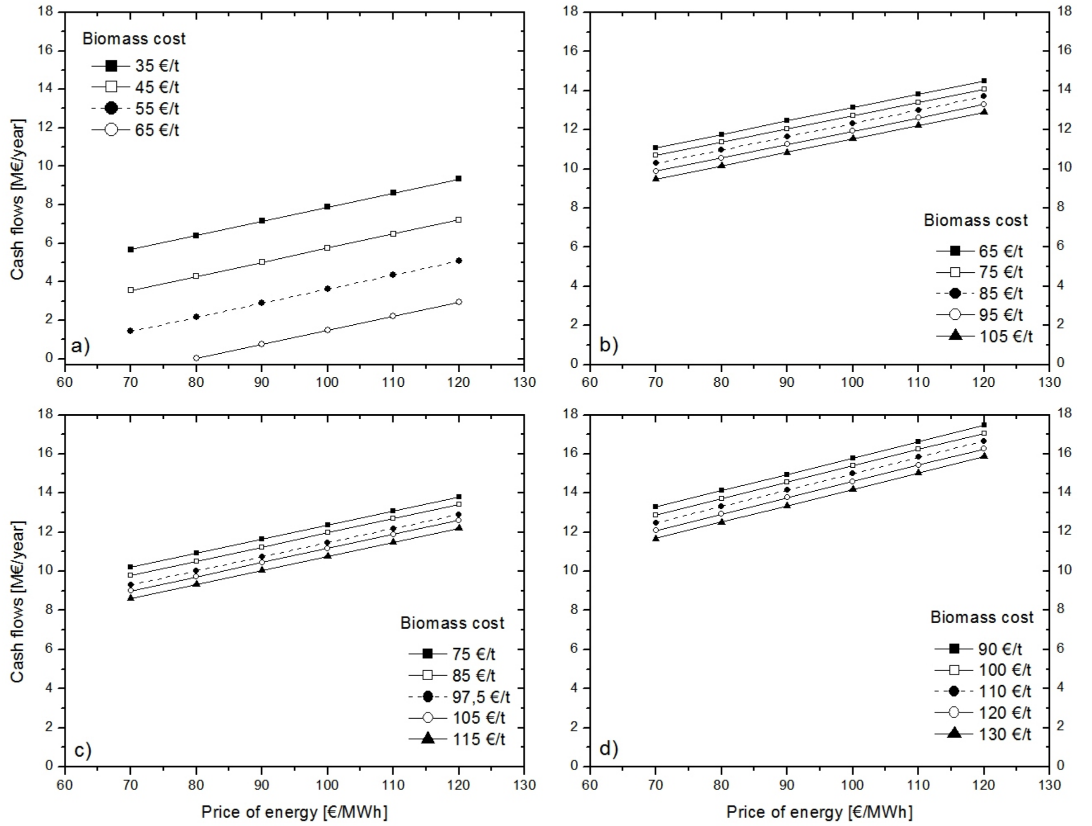

Figure 5. Cash flows versus biomass cost [€/ton]for several sale prices of electricity [€/MWh] for *BioSt (a), BIPCC(b), Hyb 50-50 (c), Cof (d)*

CONCLUSIONS

The paper aims to analyze different biomass thermoelectric conversion systems, integrated with existing CCGT power plants. The studied configurations include combustion and gasification technologies. The study shows that the integrated solution guarantees a significant benefit in terms of overall efficiency with respect to the usual steam plant.

For the systems characterized by an electric power higher than 10 MWe, according to the literature, the combustion based plant represents the more appropriate alternative from the industrial point of view. On the other hand, the gasification process offers higher efficiency, particularly in CHP operation, and appears to be better for small size plants. The development of gasifiers looks promising so we expect, in the future, the extension of their use in the conversion plants of all sizes.

Furthermore, for electric power values less than 10 MW_{el}, three hybrid configurations, characterized by the combined use of biomass with natural gas in a combined cycle plant, have been analysed. Particularly, the hybrid configuration requires the use of an hypothetical gasifier with a 40000 tons/year rate of biomass and with double output: a high quality syngas (10, 20 and 50% used for co-firing) and a low quality syngas (90, 80 and 50% used for the post-combustion) with a conversion efficiency in the range 31-35% and cost per kWh variable between 0,145 and 0,194 €/kWh, depending on the cost of the biomass.

The Hybrid configuration has been compared with the BIPCC, which provides the only direct post-combustion of biomass (always in the same amounts 40000 tons per year). If the syngas used for co-firing is equal to only 10% of the total syngas produced, the biomass conversion efficiency in the Hyb plant is almost equal to the efficiency of the BIPCC configuration (31-32%). If the percentage of the syngas used for the co-firing increases, the conversion efficiency increases.

The last configuration (Cof) uses a gasifier called Blue Tower of size equal to the previous one (40000 tons per year) with an installed capacity approximately equal to BioSt case, so to compare the two limit cases. The efficiency of conversion of biomass with only co-firing appears to be high, 41%, and also the cash flows are elevated thanks to the great saving of natural gas (19.7%) and the reduction of costs compared to BioSt configuration (from 0.173 to 0.145 €/kWh). For the reference traditional biomass steam power plant, efficiency rarely exceeds 26-28%.The best solution is the co-firing of the high quality gas, to exploit the high efficiency of the CCGT in which a gas turbine with higher exhaust temperature can be adopted, since the afterburning is not applied.

REFERENCES

[1] europarlamento, «le direttive che faranno raggiungere gli obiettivi di europa 20/0,1254,106_ART_634,00.html,» 2010. [Online]. Available on the link: http://www.europarlamento24.eu.

[2] D. Fiaschi e R. Carta, «CO2 abatement by co-firing of natural gas and biomass-derived gas in a gas turbine,» *Energy,* vol. 32, p. 549–567, 2007.

[3] A. Franco e T. Parabita, «Biomasse per la generazione termoelettrica,» *La termotecnica,* 2004.

[4] C. Aichernig e R. Fabbri, «Renewable Energy from Biomass: Traditional plants versus Gasification Process. Operating Experience,» in *3° Congresso Internazionale "Energy and Environment 2004"*, Sorrento, 2004.

[5] S. Proenca e M. St. Aubyn, «Hybrid modeling to support energy-climate policy: Effects of feed in tariffs to promote renewable energy in Portugal,» *Energy Economics,* n. 38, pp. 176-185, 2013.

[6] S. Boeters e J. Koornneef, «Supply of renewable energy sorces and the cost of EU climate policy,» *Energy and Economics,* n. 33, pp. 1024-1034, 2011.

[7] F. Al-Mansour e . J. Zuwala, «An evaluation of biomass co-firing in Europe,» *Biomass and bioenergy,* vol. 34, pp. 620-629, 2010.

[8] F. Delattin, . D. R. J. e B. S., «Detailed study of the impact of co-utilization of biomass in a natural gas combined cycle power plant through perturbation analysis,» *Applied Energy,* vol. 86, p. 622–629, 2009.

[9] A. Franco e N. Giannini, «Perspectives for the use of biomass as fuel in combined cycle power plants,» *International Journal of Thermal Sciences,* vol. 44, p. 163–177, 2005.

[10] F. Jurado, A. Cano e J. Carpio, «Modelling of combined cycle power plants using biomass,» *Renewable Energy,* vol. 28, p. 743–753, 2003.

[11] M. Rodrigues, A. Walter e F. André, «Co-firing of natural gas and Biomass gas in biomass integrated gasification/combined cycle systems,» *Energy,* vol. 28, p. 1115–1131, 2003.

[12] M. Berggren, E. Ljunggren e F. Johnsson, «Biomass co-firing potentials for electricity generation in Poland—Matching supply and co-firing opportunities,» *Biomass and bioenergy,* vol. 32, p. 865 – 879, 2008.

[13] Y. Huang, McIlveen-Wright, D, Rezvani, S., Wang, Y.D., N. Hewitt e B. C. Williams, «Huang, Y., McIlveen-Wright, D., Rezvani, S., Wang, Y.D., Biomass co-firing in a pressurized fluidized bed combustion (PFBC) combined cycle power plant: A techno-environmental assessment based on computational simulations,» *Fuel Processing Technology,* vol. 87, n. 10, pp. 927-934, 2006.

[14] «Thermoflow Inc.,» [Online]. Available: http://www.thermoflow.com. [Consultato il giorno Giugno 2014].

[15] «General Electric,» [Online]. Available: https://www.ge-distributedpower.com/products/power-generation/35-to 65mw/lm6000-pd. [Consultato il giorno giugno 2014].

[16] B. S. Hoffmann, A. Szklo e R. Shaeffer, «An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil,» *Biomass and bioenergy,* vol. 45, pp. 295-302, 2012.

[17] E. Mupondwa, X. Li, L. Tabil, A. Phani, S. Sokhansanj, M. Stumborg, M. Gruber e S. Laberge, «Technoeconomic analysis of wheat straw densification in the Canadian Prairie Province of Manitoba,» *Bioresource Technology ,* vol. 110, pp. 355-363, 2012.

[18] «Relazione Rabitt-Casson Centrale del Mercure,» [Online]. Available: http://www.asklepios.it/cgi-bin/ssp.cgi?page=852&lang=en. [Consultato il giorno giugno 2014].

[19] «blue tower?,» [Online]. Available: http://www.rdb-ev.de/zeitung09/09-04-164-166.pdf. [Consultato il giorno giugno 2014].

[20] E. Pihl, T. Heyne, H. Thunman e F. Johnsson, *Highly efficient electricity generation from biomass by integration and hybridation with combined cycle gas turbine (CCGT) plants for naturaal gas,* 2010.

[21] R. Carapellucci e A. Milazzo, «Potenziamento di impianti combinati,» *La Termotecnica,* n. 9, pp. 66-73, 2006.

[22] [Online]. Available: http://www.iea.org. [Consultato il giorno giugno 2014].

[23] L. Gregori, C. Rinaldi, G. Crippa e F. Bregni, «Valutazione dei costi associati in termini di ripartizioni/soatituzioni/fermo impianto,» CESI, 2004.

[24] «L'affidabilità della fornitura di energia elettrica in un sistema economico aperto alla competizione,» RESCOM, 2007.

[25] D. L. Granatstein, *Gasification vs combustion of waste/biomass in fluidized bed reactors.*

[26] G. Lozza, Turbine a gas e cicli combinati, II a cura di, Bologna: Esculapio, 2006.

[27] S. Palmieri e F. Fabrizi, «Studio di fattibiità relativo all'installazione di un modulo CSP a sali fusi integrato con sistema di gassificazione di biomasse nel Comune di Loiano,» ENEA, 2010.

[28] E. Antonini e V. Francescato, «Aspetti e valutazioni economiche - Impianti termici a cippato,» 2009.

[29] V. Francescato, E. Antonini e L. Z. Bergomi, «Legna e cippato, produzione/requisiti qualitativi/compravendita,» 2009.

[30] *Schede informative sugli strumenti di sostegno economico,* CNA Energia, 2012.

[31] «Ridefinizione dei prezzi minimi garantiti per impianti di produzione di energia elettrica fino a 1 MW alimentati da fonti rinnovabili,» 2013. [Online]. Available: www.autorita.energia.it.