Integration of biomass in combined cycle plants. A possible solution to obtain both thermodynamic and economic convenience

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Abstract

For a combined cycle power plant it is well known that, from a thermodynamic point of view, it is convenient to introduce thermal power in the topping cycle. Heat introduction in the bottoming cycle could be interesting, mainly if a low enthalpy fuel is used for refiring. The study involves the analysis of biomass integration in combined cycle power plants, showing the possibility of obtaining efficiency up to 60%. After an analysis of the available technical solution, a thermoeconomic method is proposed to perform an optimization of this particular technological solution, concerning the integration of biomass in high efficiency power plants.

1 Introduction

Energy policy is promoting many researches in order to find the most effective ways to use low enthalpy fuels. Today the most currently low enthalpy fuel in vogue for power generation is biomass. Biomass is a “fuel” with a calorific value between 8-25 MJ/kg, with respect to the 25-30 MJ/kg of coal, 40-45 MJ/kg of fuel oil and to the 50-55 MJ/kg of the natural gas [1]. The term biomass refers to a large kind of organic matter that can be converted into energy joined by the common features about renewability in the field of energy production. Actually it represents a diversified survey varying from residuals, manufacturing scraps and solid waste to dedicated agricultural products [2]. This renewable energy source presents several benefits, both socioeconomics and environmental, when compared to conventional energy sources but, although these benefits are well
known, it seems that bio-fuels cannot compete effectively in the current energy market without tax, credits, subsidies or other artificial measures [3].

The conversion of biomass into energy encompasses a wide range of options, end-use applications and infrastructure requirements. In recent years various solutions have been proposed in order to use biomass for energy production, but notwithstanding the large interest these integrations cannot be yet considered an industrially assessed technology and require further investigations in the fields of thermodynamic analysis, components optimization and economics. One of the most important barriers for biomass widespread implementation is represented by high operating cost joined to the low thermal efficiency of the expensive charging energy conversion systems. In this perspective, the paper analyses a particular method for the integration of biomass into natural gas fired combined cycle power plant, in order to evaluate both the thermodynamic performances and the investment profitability. The attention is focused on the external combustion before the bottoming cycle, that nowadays seems to be the most promising solution. The use of this particular biomass postcombustion permits to assess thermodynamic efficiencies of the whole plant up to 60%, resorting to the currently available gas turbine (GT) technology, only by an optimization of the overall heat recovery steam generator (HRSG). After a thermodynamic analysis of the available technical solution, a thermoeconomic method of analysis is proposed to evaluate this particular technological solution concerning the integration of a generically low enthalpy fuel like biomass in a high efficiency energy conversion system.

2 The load of operating cost in bio-fuel conversion

Like other renewable energy sources, biomass fuels are gaining increasing acceptance worldwide, making possible the perspective of reducing both fossil fuel depletion, greenhouse gas and NOx emissions [4], particularly limited, mainly in fluidized-bed systems, because of the low combustion temperatures. The majority of biomass is represented by wood and wood wastes, followed by MSW, agricultural wastes and landfill gases (Table 1) [5]. The principal selection criteria for biomass species are: growth rate, ease of management, harvesting and intrinsic material properties, such as moisture/ash/alkali content. The latter properties influence particularly the operational characteristics of thermal-conversion plant, as drying processes, that are always necessary. Again, about the material properties, it is important to underline that biomass is mainly made up of carbon. That makes it looked at with great attention among the alternative fuels, in fact it can be either directly used as fuel indeed in order to produce energy, or turned into gaseous fuels after appropriated treatments.

Three processes are mainly used for the thermo-chemical conversion of biomass: combustion, gasification and pyrolysis [6]. The first two are the most efficient, requiring a less costly drying process and their products are more easy to use.
Table 1: Calorific value for different biomass used as fuels.

<table>
<thead>
<tr>
<th>Material used as fuel</th>
<th>CV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical waste</td>
<td>18.5 - 23.0</td>
</tr>
<tr>
<td>Wood</td>
<td>17.0 - 20.0</td>
</tr>
<tr>
<td>Hospital and clinical waste</td>
<td>17.5 - 22.5</td>
</tr>
<tr>
<td>Municipal Solid Waste</td>
<td>8.5 - 11.0</td>
</tr>
<tr>
<td>Agricultural biomass fuels (sugar cane, bagasse, rice husk, rice straw, coffee husk, tobacco dust, cotton stalk, etc.)</td>
<td>7.5 - 20</td>
</tr>
</tbody>
</table>

**Combustion** is the way to turn directly biomass chemical power into thermal energy. Many different types of biomass are available as these ones reported in Table 1, with their respective calorific value (CV). Combustion of biomass produces hot gases at temperatures of about 800-1000 °C. It is generally possible to burn any type of biomass, but in practice combustion is feasible only for biomass with a moisture content lower than 35%. The most interesting biomass fuels result agricultural and industrial residues not chemically processed. Even if today municipal waste turning is well developed too.

**Gasification** is the conversion of biomass into a gas mixture by the partial oxidation of biomass at high temperatures, typically in the range between 800 and 900 °C. The product in inert gas atmosphere is a gas (syngas) with low calorific value, about 4 - 6 MJ/Nm³. The syngas can be used to generate clean conventional fuels like methanol or for direct thermochemical conversion. In this case the required moisture content is under 15 % and before burning, the syngas needs to be cooled to 500 °C, for removing alkali content.

There are often political and economical constraints to biomass use, that doesn’t encourage their use instead of fossil fuels. Energy prices do not generally reflect the environmental benefits of biomass and of the other renewable energy resources. Biomass is a fuel abundant in many countries, especially in developing countries, where it can be considered a relatively cheap fuel. But it is not always possible to consider it as a low cost fuel, even when it is available as a waste or by-product of a higher-value activity. Biomass is not in ideal form for fuel use and to execute a correct integration it is necessary to start up a sequence of operations with their related cost. These consecutive operations can be summarized in: transportation, storage, palletizing, handling, drying process, mincing and stockpiling, if any indirect thermochemical process is carried out. At the end of all treatments the cost of biomass derived fuel is raised so that, in a lot of cases, it becomes comparable to traditional fossil fuel cost, even if it doesn’t appear because a great part of the above mentioned costs is not generally paid by the final users. So, on an economical point of view, it appears to be convenient converting these bio-resources in old and inefficient steam cycles as usually done in practice. But in order to evaluate more correctly the use of biomass and biomass derived fuels it is necessary, to contemplate all the process costs. Moreover, accepting a general thermoeconomic formulation, that attributes a value to the exergy losses, the convenience of a conversion plant that use biomass as input fuel, corresponds to satisfy the following inequality:
The terms inside square parentheses have to be correctly defined: $c_l I$ is the cost of exergy loss and it’s added with respect to a classical economic analysis, in the second one $c_{bio}$ consider the whole biomass life cycle before its use in the plant.

If the exergetic loss of the plant is defined, with reference to the efficiency, as $I = \left[\frac{(1-\eta)}{\eta}\right] W_{out}$, the gain factor defined by eqn. (1) becomes positive if:

\[
\left\{ p_{el} \cdot W_{out} - \left[ c_l \left( \frac{1-\eta}{\eta} \right) W_{out} + c_{bio} \frac{W_{out}}{\eta} \right] \right\} \cdot \tau > \sum C_{comp} \tag{2}
\]

\[
1 - \left( \frac{1-\eta}{\eta} \right) \frac{c_l}{p_{el}} = \frac{1}{\eta} \frac{c_{bio}}{p_{el} \cdot W_{out} \cdot \tau} \sum C_{comp} \tag{3}
\]

About eqn. (1-3), $C_{comp}$ is the rate of depreciation of the plant referred to a reference temporal base (e.g. annual). The cost of the components and the selling price of electricity, $p_{el}$, can be simply extrapolated by market analysis, while biomass cost needs an evaluation about the expenses of the aforesaid sequence of treatments. The cost of the exergy losses, $c_l$, is the key element of this approach; on the basis of reasonable considerations, it can range between the real cost of biomass and the cost of a conventional fuel, like natural gas. On this point of view the use of biomass can be considered as a saving of fossil fuels, so a correct choice seems to evaluate the cost of exergy losses from biomass as the cost of a conventional fuel. The second member of eqn. (3) depends on the cost of the components and on the economic life of the plant. In the case in which its value is 0.25, the sensitivity analysis shows the presence of a minimum of global plant efficiency (Fig.1). In our hypothesis, even if the bio-fuel could be available at null cost ($c_{bio} = 0$), the plant efficiency must be definitely higher than 30%, but this limit raise up to 50%, when bio-fuel cost is similar to the one of natural gas. Those data leads to reject a lot of low efficient plants today used to convert energy from biomass and propose to reconsider the use of biomass as integrative fuel in highly efficient conversion system, like the combined plants. The solutions can be various depending on a lot of variables and boundaries.

3 Strategies for integrating biomass in combined cycle plants

Due to the above exposed considerations, the most profitable possibility to use biomass for energy conversion is to introduce the derived thermal energy in a combined cycle plant, which today is the most efficient energy conversion technology. We try to reconsider the problem of biomass integration in combined plants, with particular reference to a new installation. In other cases the introduction of biomass can be carried out in existing plants configurations and
similar solution could be proposed. The various possibilities to integrate biomass in a combined cycle plant structure are concisely summarized in Fig. 2. In the literature there are three strategies particularly investigated for biomass integration in combined cycle power plants [7].

1. co-combustion of natural gas and biomass derived gas from gasification;
2. post-combustion with an additional firing of biomass derived gas in the HRSG (post-combustion or biomass cofiring in the HRSG);
3. external combustion of biomass or biogas to preheat the low temperature air before entering the gas turbine.

In the first solution “biomass derived fuel” is mixed with natural gas to be burned in the combustion chamber. This solution is surely the one that promises the most interesting performances, because biomass thermal power is introduced in the topping cycle. It is largely investigated in the literature and also in some experimental plants, like those, that contemplate the presence of pressurized fluid bed combustion system for the gasification process of both coal and biomass. Although this one is probably the best solution in a long period perspective, its applications requires modification in the gas turbine technology, because the GT has to be adapted to receive 4–5 times the volume flow of natural gas [8]. About the second option, the post-combustion of biogas, the biomass is used to obtain an exhaust gas aftertreatment before going to the HRSG.

![Figure 1: Gain curves for different value of the ratio $c_{bio}/p_{el}$.](image)

The increase of temperature at the inlet of the HRSG, by mixing biomass exhaust gas and the exhaust from the GT, permits to obtain a higher amount of power from the steam cycle optimizing the HRSG by the reduction of the exergy losses. This solution is the less efficient one, since energy from biomass is used at low thermal level [9]. In a previous study the possibility to obtain power plants with high thermodynamic efficiency has been shown, associating HRSG optimization, regeneration, postcombustion and reconsidering the GT operating parameters. The gross efficiency increase can vary from the 2%, by resorting
only to HRSG optimization to the 6-7%, with the joined use of postcombustion, regeneration and HRSG optimization [10]. The use of postcombustion, gas to gas recuperation and HRSG optimization, described in Fig. 3 can be opportunely adapted to the use of biomass as fuel for the postcombustion, giving an externally fired biomass integrated recuperated combined cycle (EFBIRCC) plant. A scheme of a EFBIRCC plant is in Fig. 4. The combustion gas, coming out from biomass-firing-unit determines an increase of the exhaust gas temperature.

Figure 2: Bioenergy integrated conversion opportunities in combined plants.

Figure 3: Brayton cycle with biomass post-combustion regeneration and HRSG.
The exhaust gas reach a temperature sufficiently high to preheat air entering the GT combustion chamber in a gas to gas heat exchanger, before going through the HRSG to heat steam-water. This solution allows the most efficient integration because permits an increase of the gas cycle performances, maintaining a current technology, in addition to the possibility of increasing the steam cycle efficiency.

4 Thermodynamic optimization of an EFBIRCC configuration

A thermodynamic optimization of the plant configuration described in Figs. 3-4 has been carried out, considering the global plant efficiency as the objective function to maximize. In this case a usual gas turbine model is considered. After the discharge of the gas from the gas turbine at a temperature of about 800 K, the mass flow is reheated to increase its temperature. The exhaust gas at higher temperature is used to preheat air mass flow in the regenerator and then to obtain steam in the HRSG, as it is previously described. The analysis has been carried out according to the next reference basic cycle data:

- Turbine inlet temperature: 1509 K
- Maximum pressure: 26 bar
- Isoentropic efficiency of GT compressor: 87%
- GT turbine: 88%
- Pressure loss of the gas in the recuperator: 5%
- Minimum temperature drop in the recuperator: 40K
- Isoentropic efficiency of the steam turbines: 90%
- Reference mass gas flow: 386.7 kg/s
- Maximum temperature of the gas after the biomass postcombustion: 1100 K

The real critical element of the plant is the gas to gas heat exchanger, where the working fluid receives the heat from the biomass exhaust gas. An upper limit of 1100 K is imposed to the temperature of the gas coming from biomass conversion burner, so that it is possible to use a stainless steel structure. The
constraint on the mass flow is necessary to obtain a solution with the power output in the surroundings of 250 MW, like the current combined power plant.

Using biomass integration the gross efficiency of the plant can be higher than the one of the simple plant mainly due to the presence of the gas to gas regeneration.

The application of the aforesaid concepts does not require further particular advancement in the gas turbine technology and in the gasification technology, but is already available today. These data show an interesting result, finding an optimal solution with a quite low compression ratio (Table 2 and Fig. 5).

Table 2: Thermodynamic optimized configurations [GT+P+R+3PRSH HRSG].

<table>
<thead>
<tr>
<th>$\lambda_0$</th>
<th>$T_{g,in\text{HRSG}}$ [K]</th>
<th>$\eta$</th>
<th>$W$ [MW]</th>
<th>$T_2$ [K]</th>
<th>$T_3^*$ [K]</th>
<th>RW</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>950</td>
<td>0.5930</td>
<td>261</td>
<td>580</td>
<td>734</td>
<td>1.30</td>
</tr>
<tr>
<td>9.2</td>
<td>950</td>
<td>0.5965</td>
<td>264</td>
<td>607</td>
<td>662</td>
<td>1.32</td>
</tr>
<tr>
<td>10.2</td>
<td>823</td>
<td>0.5990</td>
<td>231</td>
<td>628</td>
<td>911</td>
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</tr>
<tr>
<td>11.7</td>
<td>823</td>
<td>0.6025</td>
<td>232</td>
<td>657</td>
<td>938</td>
<td>1.95</td>
</tr>
<tr>
<td>13.2</td>
<td>823</td>
<td>0.6028</td>
<td>231</td>
<td>684</td>
<td>951</td>
<td>1.95</td>
</tr>
<tr>
<td>17.5</td>
<td>823</td>
<td>0.6018</td>
<td>227</td>
<td>750</td>
<td>1009</td>
<td>1.90</td>
</tr>
<tr>
<td>20</td>
<td>950</td>
<td>0.5998</td>
<td>260</td>
<td>784</td>
<td>939</td>
<td>1.29</td>
</tr>
<tr>
<td>22</td>
<td>950</td>
<td>0.5982</td>
<td>257</td>
<td>809</td>
<td>964</td>
<td>1.26</td>
</tr>
<tr>
<td>25</td>
<td>950</td>
<td>0.5950</td>
<td>252</td>
<td>842</td>
<td>998</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Figure 5: Efficiency for the plant configuration of Fig. 4, varying $T_{g,in\text{HRSG}}$.

5 A thermoeconomic analysis method

The ideas carried out in the previous paragraph are only based on a thermodynamic analysis of the several solutions; a definitive response to the problem of increasing efficiency in the integrated combined cycle plants raises in economic or thermo-economic evaluations of the proposed EFBIRCC plant configuration.
In the actual economic analysis, the gain factor takes into account only the cost of the fuel, the cost of the components and the gain in selling energy. Considering the point of view exposed by eqns. (1-3), a different way to evaluate the optimal plant configuration is an analysis that combine thermodynamic and economic aspects, taking into account also the cost of exergy losses. In this case, another possible strategy is represented by the minimization of the global plant cost per unit power, that results as the sum of the components cost, plus the fuels cost, plus the cost of the exergy losses, giving a well defined plant size obtained for example assigning a well defined gas mass flow. So the optimum plant configurations is the one that minimize the objective function:

$$\frac{C_{TOT}}{W_{out}} = \sum C_{comp} + \sum \frac{C_{in}}{W_{out}} + \sum C_{I}$$  \hspace{1cm} (4)

A different point of view is to perform the maximization of a gain factor of the plant, similar to that of eqn. (1), defined taking into account separately both of gas and biomass thermal power input and gas and biomass exergy loss as:

$$f_g = \left[ p_{el} W_{out} - \left( \frac{c_g W_{in,g} + c_{bio} W_{in,bio}}{W_{in}} \right) \frac{W_{out}}{\eta} - \left( c_{g} I_{g} + c_{bio} I_{bio} \right) \right] - \sum C_{comp}$$  \hspace{1cm} (5)

Considering the plant represented in Fig. 4, the cost of the components is given by the cost of the five main constitutive elements of the plant: gas turbine, steam turbine, biomass burner, regenerator and heat recovery steam generator so that:

$$\sum C_{comp} = C_{GT} + C_{REG} + C_{HRSG} + C_{ST} + C_{B}$$  \hspace{1cm} (6)

The nature of the exposed method permits one to evaluate, as a monetary cost, all the effects coming from thermodynamic improvement on the combined cycle. This kind of analysis lead us to consider as profitable an efficient use of the renewable sources, individuating a maximum value of the plant efficiency. A future development and the application of this method probably may permit to confirm the convenience of configuration of the optimized plants similar to those resulting from thermodynamic analysis, with pressure ratio in the range between 15 and 20 and efficiency of about 60%.

6 Conclusions

Biomass can be converted into useful forms of energy using a number of different processes. Factors that influence the choice of conversion process are: the type and quantity of biomass feedstock, the desired form of the energy, i.e. end-use requirements, environmental standards, economic conditions and project specific factors. In order to improve biomass conversion in a more profitable
way, an interesting strategy seems to be the use of biomass in high efficient energy conversion. The paper undertakes a possible perspective for an efficient use of biomass for electric power generation, using them as integrative fuel inside high efficient thermal plant. Today the most promising solution in order to integrate the use of a biomass derived fuel into a combined cycle power plant is represented by the external post-combustion. The perspective of using biomass or biomass derived fuel in combined cycle power plant, resorting to optimized components, perfect in a short period, the feasibility of biomass-integrated power plants with efficiency level of the order of 60%. A thermoeconomic method for the analysis has been also proposed in this paper. This method shows how the conversion efficiency of renewable sources as biomass, has a lower limit that is considerably high in a lot of cases.

Nomenclature

c specific cost (€/kWh)
C cost referred to a specified temporal basis (€)
f_g gain factor (€)
I exergy losses (W)
p_el selling price of electricity (€/kWh)
RW ratio between gas turbine power and steam turbine power
T temperature (K)
W power (W)

Greek symbols

\( \lambda_c \) total pressure ratio
\( \eta \) combined cycle plant efficiency
\( \tau \) temporal basis (year)

Subscripts, acronyms and abbreviations

B biomass conversion system
bio of the biomass
c.c. combustion chamber
COND condenser
g of the natural gas
GT gas turbine
HRSG heat recovery steam generator
in of the inputs
I of the exergy losses
out of the outputs
REG regenerator
ST steam turbine
3PRSH three pressure levels with reheat
References


