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The case study of an innovative small scale biomass waste gasification heat and power plant contextualized in a farm

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Abstract

The use of biomass waste in high efficient low pollutants emissions micro-cogeneration plants overpasses the main biomass barriers: competition with the food and material uses, dispersion of a low energy density fuel and high emissions. Evaluations of present technical aspects, economic benefits and their future projections are very important to bring into focus the needs of the technological development of this energy application.

This paper is focused on a small (250 kWth) steam gasification fluidized bed and hot gas conditioning system, contextualized in the case study of a farm situated near Rome. Since most of usable biomass waste comes from agriculture, appraisal of applicability to real rural contexts deserves closer examination, considering the necessity of a small size solution as well. A feasibility study of an actual employment of this energy system has included: biomass availability and energy consumption analysis, biomass and gasification tests, power plant sizing, using experimental data and chemcad simulation. Finally an economic analysis has been carried out by varying the main economic parameters. Olive pruning are confirmed as very suitable, and in this case, able to satisfy the farm energy consumption. Global electrical efficiency of 25% can be achieved without any auxiliary fuel consumption. Consumption of 60% of the heat generated are required, meanwhile investment and biomass costs up to 8000 €/kW and 100 €/t can be sustained, especially if the farm electricity cost are higher than 0.15 €/kWh.

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Keywords: biomass, gasification, hot gas conditioning, power plant, economic analysis

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1. Introduction

Recently, a shift in the biomass energy uses is occurring,from traditional (e.g. combustion to produce heat[1]) to modern's one (e.g. processes to produce electricity and bio-fuels integrated in farms and

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industries[2,3]) [4]. Distributed generation emerged as a different approach to traditional power generation, aiming to reduce distribution losses and favour the use of renewable energy resources locally available such as biomass [4,5], solar [4,6], wind, etc..Biomass technical and economic potentials are higher than actual world energy consumption[4,7]. Nevertheless, competition with the food and material demand, dispersion of a low energy density fuel and high emissions limit the bioenergy use (e.g. the Italian territory amounted to about 30 million metric tons/year [8]). Furthermore, at small scale, the technology development issues still remain. Actually, a small biomass power plant can reach annual operating hours lower than 6000, efficiency lower than 25%, high local and environmental meaningful impacts [2]. Therefore, technical and economic aspects of high efficient low pollutant emissions micro-cogeneration plants applied in agricultural farm have to be analysed in order to overcome the main biomass barriers. Gasification-ICE based cogeneration of lignocellulosic residues/waste, as the one of the present case, is the most direct and accessible way to power generation[9–13]. After the biomass waste analysis and the relative gasification tests, starting from the farm energy consumption, a power plant has been sized and the efficiencies calculated, using experimental data and chemcad simulation. Finally an economic analysis has been carried out, by varying the main economic parameters.

2. Description of the farm studied and the activity

The case study is an olive/house farm (“Il Bagolaro”) located in the area so-called *Sabina*, north of Rome that consists of 150 olive-growing hectares (14080 trees);0.64 viticulture hectares (2000 trees);2 wooded and pasture hectares;0.13 fit for seed hectares.

Pruning and olive residues total 330 tonnes per year plus 66 tonnes of leaves. Pruning residues from viticulture amount to 2 tonnes per year and, from wood, 6 tonnes. The residues from seed hectares total 1 ton per year. These values have been assessed and determined considering mean values of residual products of the last five years. The farm is already equipped with a chipper to process the biomass to a uniform size necessary to feed a biomass boiler which can be used for the gasifier. Owing to the fact that the biomass analysis is a very important step [14],the residues have been sampled and analysed and in the following paragraph the results of the most important of them are shown.

3. Biomass analysis and gasification tests

The gasification test rig is shown in Figure 1.

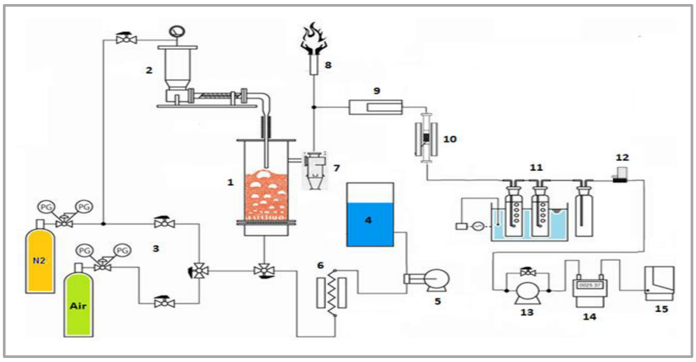


Fig. 1.Test rig: (1) bubbling fluidized bed gasifier; (2) biomass feed system; (3) agents inlet; (4) water storage; (5) pump; (6) electric steam generator; (7) cyclone; (8) torch; (9) ceramic candle filter; (10) secondary reactor; (11) TAR condensation system; (12) mass flow controller (13) vacuum pump; (14) cumulative gas flow meter; (15) gas-chromatograph (TCD).

In the gasifier concept considered in this work, the fuel is fed into the gasification zone and gasified by using only steam. The bed material, together with residual charcoal, circulates to the combustion zone. This zone is fluidized with air and the charcoal is burned, heating the bed material that is circulated back to the gasifier supplying the thermal power needed for the gasification reactions. With this concept, the two reaction chambers (air combustor and steam gasifier) are physically separated and it is possible to get a high-quality gas, with a reduced N2 content even if air (instead of pure oxygen) is used for the combustion [18]. By the way, steam is generated recovering heat by the exhaust gases.

The gas yield of the process, and in particular hydrogen, increases at the increasing temperature and steam to biomass ratio[15–17]. Nevertheless, increasing temperature and S/B above a certain value, the advantages (better gas composition and yield) start to become lower than the disadvantages (higher energy required). Bench-scale tests were carried out fixing steam/biomass ratio (S/B=1.0) and operating temperature (T=800°C) and the composition of the produced gas was continuously monitored in terms of H_2, CO, CO_2 and CH_4. The gas yield obtained for T=800°C and S/B=1.0 is 1.2 Nm^3/kg [19].

Tests were carried out on olive-growing, vine-growing wood and on other most abundant and usable types of biomass of the farm. The preliminary and ultimate analysis of the biomass samples is reported in Table 1. The main difference among the various types of biomass is the moisture content that varies between 21% to 40%. The different moisture content can influence the internal energy balance of a real gasification process. Moreover, particular biomass, as vine and pine wood, generated problems in the feeding systems and in the reactor, that required to decrease the humidity content below 10% and the size below 10 mm, before carrying out the gasification tests.The results of the gasification tests, shown in Table 2, include producer gas composition and characteristics (regarding the tar, benzene included, pine have generated about 40 g/Nm^3 respect to the less than 30 g/Nm^3 of the olive). The volume concentration of gas mixture, represented in Table 2, influences the LHV, making it vary between 9.9 MJ/Nm^3 and 11.3 MJ/Nm^3[20]. Cold gas efficiency, as defined in eq. (1),varies between 0.56 and 0.68.

$$\eta_{cold} = \frac{LHV_{gas} \times \dot{Q}_{gas}}{LHV_{biomass}} \qquad (1)$$

. Table 1. Preliminary and ultimate analysis of biomass samples

	Preliminary analysis (Raw)					Ultimate analysis[wt%]			
	Moisture [wt%]	Ash [wt%]	Volatile matter [wt%]	Fixed Carbon [wt%]	LHV[MJ/ kg_{dry}]	C	H	N	O
Olive pruning	21.4	3.2	64.0	11.3	19.2	48.0	6.1	0.6	45.3
Vine pruning	34.9	3.6	52.3	9.2	18.6	56.8	6.8	0.7	35.8
Chipped oak wood	30.2	2.6	57.1	10.1	22.6	50.9	6.1	0.5	42.5
Chipped beech wood	40.0	3.4	48.1	8.5	18.9	48.5	6.1	0.3	45.0
Chipped pine wood	35.0	3.0	52.7	9.3	20.0	48.9	8.0	1.2	42.0

Table 2. Volume concentration of syngas components resulted by gasification process test at 800°C and S/B=1

Biomass	H_2	CO	CO_2	CH_4	LHV MJ/Nm^3	η_{cold}
Olive pruning	44.4	23.5	24.8	7.2	9.9	0.62
Vine pruning	47.2	24.2	23.5	7.8	10.4	0.67
Chipped oak wood	39.2	26.1	21.3	9.9	10.5	0.56
Chipped beech wood	38.0	21.9	24.8	10.0	10.0	0.64

Chipped pine wood	49.0	23.0	25.0	10.0	11.3	0.68

4. Energy consumptions, production and economical evaluation

Farm energy annual consumptions have been determined considering the energy meters data and are:

1. 80 MWh_{el}: main electric consumption of farm, holiday farm restaurant and owner house;
2. 100 MWh_t: main thermal consumption of holiday farm restaurant and owner house;
3. 100 MWh_{el} : electric consumption of the accommodation facilities;
4. 100 MWh_t: main thermal consumption of the accommodation facilities requested for domestic hot water production and heating;
5. 300 MWh_t : main thermal consumption of the heated outdoor swimming pool.

The farm holiday restaurant and the owner apartment are situated in the same building and the accommodation facilities include 10 floor apartments. The annual energy consumption results are 180 MWh electric energy and almost 500 MWh thermal energy. Owing to the fact that the olive pruning are the major resource able to satisfy the energy consumption and that no problems occurred during the gasification tests, for sizing the power plant, we considered only this biomass. Hypothesizing 5500 equivalent hours for the gasifier, consistent with the operating thermal hour needed by the thermal load, the biomass feeding rate will be 60 kg/h (see paragraph 2). Considering the calorific value and the moisture content (see paragraph 3), the CV of the dry biomass is 15 MJ/kg, corresponding to an input thermal power of 250 kW.

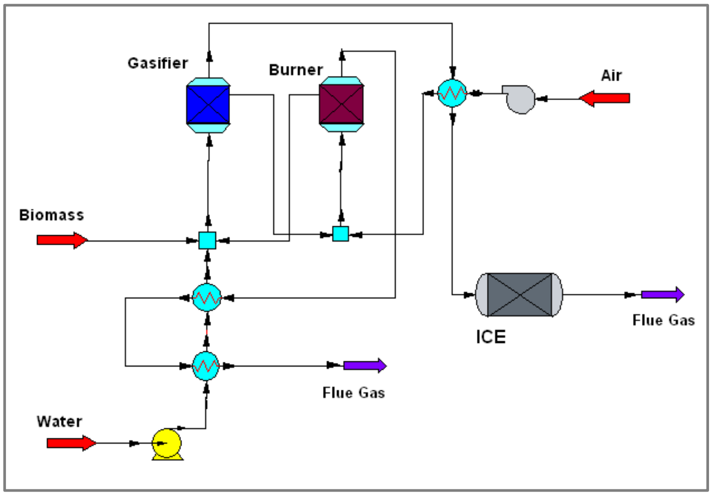


Fig. 2. Simplified sketch of the plant

Facing the 60 kg/h of wet biomass feeding rate and the gas yield, 56.6 Nm^3/h and thus 155 kW of syngas can been obtained (see paragraph 3), corresponding to95kW of gases enthalpy and thermal losses. Using a Chemcad simulation showed in Fig. 2, has been calculated the energy spent for the production of the necessary steam (up to 400 °C) with a S/B = 1.0, equal to42.8 kW, exchanged with the flue gas from the air combustor, and the energy spent for the pre-heating of the air (up to 400 °C) equal to 18.2 kW, exchanged with the residual heat coming from the cooling down of the syngas for the feeding of the cogenerator. Finally,29 kW thermal are used inside the gasifier to heat the air and steam flows up to the process temperature and 5 kW are the thermal losses of the reactor, corresponding to a 2% of reactor thermal losses.The syngas flow of 56.6 Nm^3/h (155 kW) is sent to the Internal Combustion Engine (ICE) for electricity and heat production. Obviously a conditioning system have to be used, e.g. [2], notaffecting the energy balance, thus it was not taken into account. The cogeneration device considered is a GM RMG engine produced by General Motors and modified by the company Ma-Tech for the feeding with syngas. With the syngas feeding, the ratio between the electrical and thermal power produced by the cogenerator is 0.55/50 kWe and 91 kWth[21]. Considering these values and the annual equivalent operative hours, the ICE produces 275.3 MWh$_{el}$ and 500.5 MWh$_{th}$(gasifier plus ICE electric efficiency of 25.3% ; in line with the literature plant [22]). These values allow the system to cover the thermal and electrical farm's consumptions, producing also an excess of electric energy (95.3 MWh$_{el}$) that covers the plant auxiliary systems (about 15 MWh$_{el}$) and that can be sell to the electrical grid (80.3 MWh$_{el}$).

Technical and economic feasibility of energy generation systems from biomass sizes have often been investigated in the last 20 years [23], [24] while many economical and management aspects of the small scale power generation need to be studied more in detail [25]. The system sizing choices have been made tracking the farm thermal loads and considering a suitable cogenerator size available on the market. Thermal load tracking is one of the most efficient solutions to maximize the system yield because if heat produced could be wholly exploited, electricity always finds a way to get a return: energy saving or sale by injection to the electric grid if exceeds. The case evaluation baseline considers a low cost woody biomass and no Italian government incentives. The following figures show the sensitivity of investment indicators varying some important parameters as cost of electricity, cost of biomass, cost of investment and thermal energy exploited.

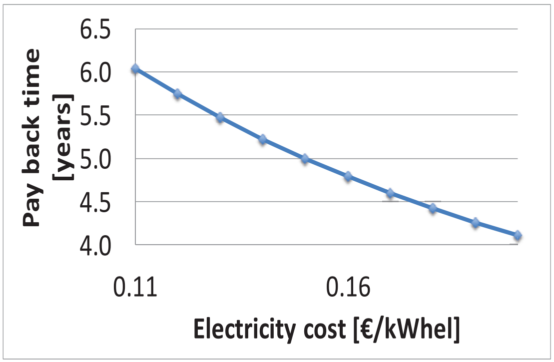


Fig. 3. PBT(years) at different electricity costs (€/kWh)

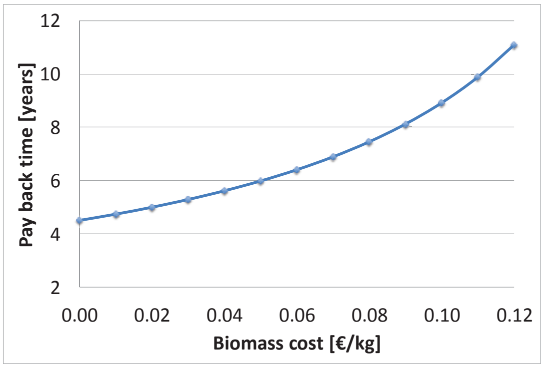
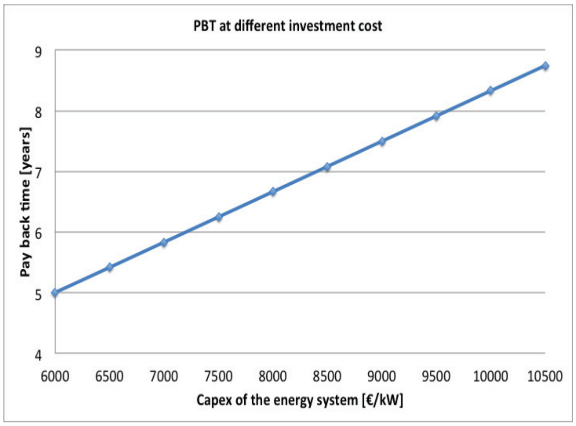


Fig. 3. PBT(years) at different biomass costs (€/kg)



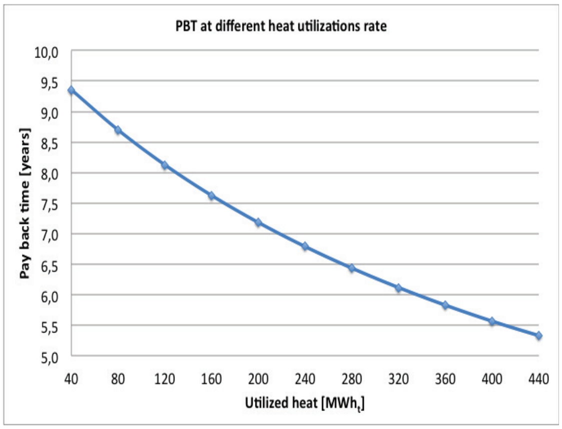


Fig. 5. PBT(years) at different investment costs (€)

Fig. 6. PBT (years) at different heat utilization rates (kWh_{th})

For instance, ranging the electricity cost, a pay back time of the investment at a specific cost of 6000 €/kWe varies from 6.0 to 4.1 years making the electricity cost range from 0.11 to 0.20 €/kWh (Figure 3). At the same investment conditions, PBT varies from 4.5 to 12.1 years making the biomass cost range from 0 to 0.12 €/kg (Figure 4), while making the investment cost vary from 6,000 €/kWe to 10,500 €/kWe, the PBT ranges between 5.0 and 8.7 years (Figure 5). The thermal energy exploitable is a further parameter considered in the sensitivity analysis: the results are the variation of PBT between 5.3 and 9.3 years ranging the heat between 440 and 40 MWh.

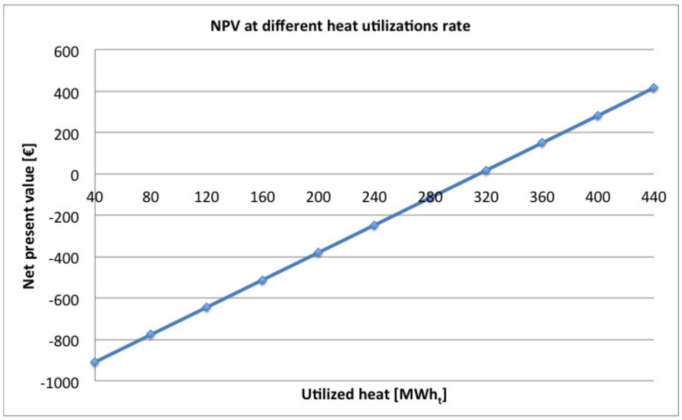


Fig. 7.NPV(€) at different heat utilization rates (kWh_{th})

5. Analysis of the results and Conclusions

Results of the case study lead to the preliminary conclusion that the virtuous nature of the biomass cogeneration can be accompanied by a good profitability, especially in the context of the agriculture sector where biomass waste can become an asset. The case studied maximizes the benefits because of both electric and thermal energy consumption, while many farmsdo not present relevant thermal consumption. If the power generated fits to the electric load of the farm the business plan gives sufficient return but the most exciting energy and economical performances are achieved if, besides electricity, the company needs heat and thermal generation from the cogenerator fits to the loads. Figure 6 seemingly shows that as the heat utilization decreases, the trend of PBT do not produce unacceptable results unless in case of heat utilization nearly almost null, but the NPV in Figure 7 shows that zero NPV is obtained under condition of 300 MWh heat consumed in the farm. Then, it would be necessary to consume at least 60% of the heat generated.

Nevertheless, the maturity of the biomass application do not seem to be very far. Until now, renewable energies have benefitted from several different incentive systems. Nowadays, since Italian G.S.E. incentives are seemingly reaching the end and nobody knows if they will be renewed, the data obtained show that in case of biomass the roadmap towards maturity, reliability and decreasing technology cost faces a positive feedback making it potentially become the first virtuous case able to generate profitability without any external dopant support.

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6. Copyright

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Biography

Mauro Villarini, was born in Rome, Italy, in 1979. He received M.S. degree in mechanical engineering, in 2003 and the Ph.D. degree in Energy Systems, in 2007 at the University of Sapienza, Rome. From 2007 to 2012, he has been a Research Assistant at the Sapienza University at CIRPS. Since 2012, he has been an Assistant Professor at Tuscia University of Viterbo of Fluid Dynamics and Energy Systems. He is Author or co-Author of 4 books and more than 20 articles. His research interests include thermal processes of energy systems (solar thermal, biomass, gasification and photovoltaic).