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Thermo-Economic Assessment of a olive pomace Gasifier for Cogeneration Applications

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Abstract

A thermo-economic analysis of a combined heat and power (CHP) plant fed by syngas produced through the gasification of dry olive pomace is presented. The plant is composed by a 800 kW_t downdraft gasifier, a gas clean-up system, a 200 kW_e microturbine (MGT) and a heat recovery system to cogenerate hot water. Surplus heat is used to dry olive pomace from 50% to 17% wb moisture content.
The plant is modeled in ASPEN Plus. Real data from experimental tests are used to calibrate the gasifier model, while the technical specification and performance of the CHP plant are collected from commercial plants in operation and data from manufacturers. Mass and energy balances are reported throughout the paper. The thermodynamic simulation of the biomass gasifier coupled to the MGT, the thermal and electrical conversion efficiency and temperature of cogenerated heat available are also presented.
A thermo-economic assessment is then proposed, to investigate the economic profitability of this small scale CHP plant in the Italian energy policy scenario and considering the subsidies available for renewable electricity in the form of feed-in tariffs. For this purpose, the case study of base load CHP plant operation and heat supplied to different typologies of energy end user is assumed. The results allow quantifying the most influencing economic and technical factors that affect the performance and profitability of such investment and the bottlenecks that should be faced to facilitate a broader implementation of such CHP schemes for on site generation.

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Keywords: Olive pomace gasification; Combined heat and power; Experimental tests; Thermo-economic analysis; ASPEN Plus model

1. Introduction

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Gasification of olive pomace represents a valuable solution for energy conversion of olive oil by-products and in turn to increase the economic profitability of this food sector, limiting the discharge issues. Olive oil production has considerable relevance for the economy of Mediterranean Countries, which are responsible for the largest part of the worldwide production of olive oil. The main by-products of the olive oil mills are the olive mill wastewater (OMW) and the crude olive pomace (COP) that can be further processed in pomace oil extraction plants to obtain the dry olive pomace (DOP), which is hereby considered as input fuel. An overview of olive oil extraction technologies and related typologies of by-products is provided in [1-2]. The most common olive oil extraction technology in Italy is the three-phase centrifugation system, which produces olive oil (20% of input olives), COP with a moisture content of 46–54% w.b. (50% of olives) [3], and a large amount of OMW (120% of olives) [4], since water is added in different steps to facilitate oil extraction. Currently, most of COH is processed in pomace-extraction plants in order to extract the low percentage of contained residual oil (pomace oil) and obtain, as a by-product, the DOP, which has a low moisture content (8-12% w.b.) and is widely used as biofuel for heat and power production. However, the declining market demand for pomace oil, the diffusion of two-phase extraction systems that have olive sludge (a pomace with 65-75% moisture content w.b.) as by-product, other than the COH storage and transport issues are causing a reduction in the number of pomace-extraction plants in operation, thus raising the problem of COH disposal [5]. In some cases, COH is discharged on the soil as an organic fertilizer; however, the fatty acid, phenol and tannin content (highly phytotoxic compounds) of COH is the main obstacle to this technique [3,6]. For these reasons, there is recently a marked tendency towards the energy valorisation of COH, after drying processes [7]. Despite of the environmental benefits of using this biomass as a fuel, some problems remain such as air pollution (CO and particulates such as soot and ash produced by combustion), ashes melting point, logistics of supply and storage [8].

The Italian energy policy and subsidies available for biomass CHP generation, in particular in the small scale size and using agricultural and food processing by-products such as olive pomace, increased in the last decade the development of both biomass heating plants for rural-industrial applications and district heating, and cogeneration by means of a number of turbines or engine based technologies. In [9], an overview of Italian biomass policy framework is proposed, comparing the thermal vs CHP routes and addressing the main barriers towards a wider implementation of biomass ESCO business models. In [10-13], a thermo-economic approach is proposed to evaluate the energy balances, operation strategies, part load efficiencies and profitability of small scale gas turbines with natural gas/biomass dual fuelling, while in [14] the same topping microturbines are coupled to bottoming ORC to evaluate in which market segment and operating conditions these options best fit.

As regards downdraft biomass gasification, a simulation of the process requires the assessment of the different phases of pyrolysis, partial oxidation and gasification. The modelling of the chemical reactions is very complex and all the kinetics are far from the equilibrium conditions. For this reason, simplified models are usually assumed, such as mono-dimensional ones [15,16].

The options currently available for energy conversion of produced syngas are internal combustion engines (ICE) and Micro gas turbines (MGT). Sometimes, also high temperature fuel cells (SOFC, MCFC) are considered as possible power plant to be fed with syngas from biomass gasification [17].

To proper simulate the real behaviour of the plant, numerical codes can be successfully used, provided that a credible description of the processes is implemented. In [18], the anaerobic digestion of organic fraction of municipal solid wastes and the successive combustion of the biogas in a SOFC based power plant was proposed. Furthermore, in [19] a ChemCad model of a biomass gasification plant coupled to a (MGT) was validated against experimental data. In [20], syngas from lignocellulosic biomass gasification was delivered to a SOFC/ORC power plant. The influence of air enrichment and biomass moisture content were also addressed in [19] and [20].

In this paper, we investigated the use of MGT because of the lower emissions and the reduced O&M costs. In the next section, the CHP plant modelling approach is presented. The energy balance of the system and the thermo-economic analysis in light of the Italian legislative scenario is then presented, and results are discussed in the last part.

2. Plant modelling

The gasifier was modelled by Aspen Plus and the model was then validated by means of a laboratory scale olive pomace gasifier available at the Department of Chemical engineering of University of Rome. Such class of reactor is a downdraft fixed bed gasifier (see Fig.1). Pomace is dried at 10% w.b. moisture content and fed into an oblique reactor, whose walls are heated at 750 °C. Here pyrolysis occurs. The biomass is fluidized by a nitrogen flux. After pyrolysis, the gas moves up towards gasifier (T-3 in Fig.1). The char falls into the fixed bed (at 800 °C at the freeboard) where air in ambient condition is flowing. Part of the char burns (partial oxidation - PO). The heat released by PO sustains char gasification reaction.

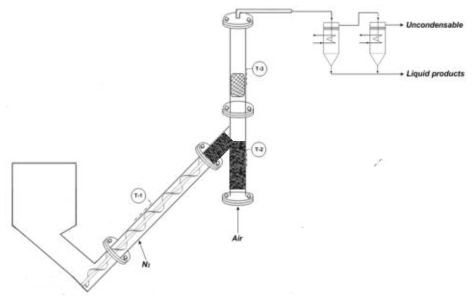

Figure 1 Pomace gasifier: experimental setup

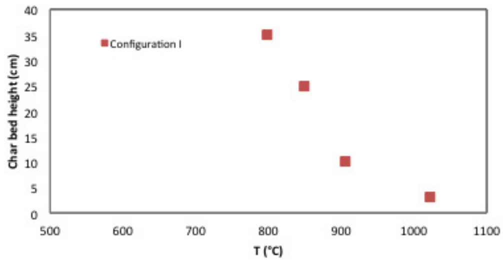

Figure 2 Temperature in the fixed bed

The temperature distribution in the fixed bed is reported in Figure 2. The pomace mass flow rate is equal to 400 g/h, while the air flow is equal to 300 l/h. Pomace composition is reported in Table 1.

Table 1: Olive pomace composition

Humidity	Volatiles (% dry)	Solid (% dry)	Ashes (%dry)	C (% wt)	H(% wt)	N (% wt)	O (% wt)
10%	65	29.6	5.4	44.2	5.8	1.8	48.2

The biomass has 50% humidity when delivered to the plant and it is dried using waste heat from the micro-turbine before the storage. Biomass gasification requires modelling separately pyrolysis, combustion and gasification [15-16]. However, the process is very complex and we are mostly interested in the evaluation of the overall energy and mass balance. For such reason, here we use a simplified model.

Due to the characteristics of the gasifier, we considered equilibrium reactions and absence of tars in the syngas. In ASPEN Plus, the gasifier is modelled using the Gibbs Reactor model. However, ASPEN Plus demonstrated to be very stiff in modelling the reaction of solids and then a CHEMCAD® version of the gasifier is currently under development.

Biomass composition is obtained by elemental analysis reported in Table 1. The dry olive pomace LHV is equal to 16.7 MJ/kg.

The products of the gasification are syngas (0.68 l per g of biomass at 600°C and 1.013 bar) and tars 2.1% in weight. The syngas composition obtained in the experiments is shown in Table 2.

Table 2: Syngas composition - experimental test:

Syngas	CO	CH4	CO2	H2	N2
% vol	19.26	1.2	8.9	12.6	58.4

For the time being, such composition is used for modelling the plant. As regards the energy balance, 145.8 W are needed to pre-heat 400 g/h of biomass up to 650°C, while 132.5 W are required for pyrolysis and water evaporation. The LHV of the syngas (dry basis) is equal to 5.4 MJ/kg.

2.2. Syngas clean-up

The biogas clean-up is carried out by cooling syngas up to 70°C, separating water and trapping tars into a cooling bath at ambient temperature and at -20°C in order to sample tars in 2-propanol filled impingement bottle [19]. After the clean-up the biogas is then compressed, reheated (using the same heat-exchanger used for cooling) and sent to the combustor.

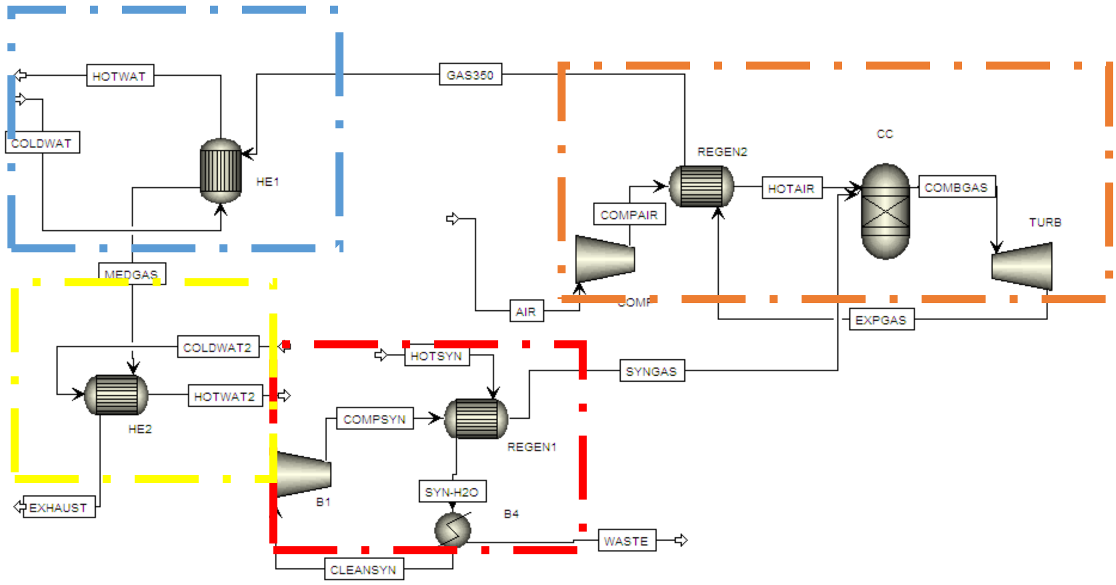

Figure 3 MGT Cogeneration Plant: Aspen Plus model

2.3. CHP plant

The whole plant is described in Figure 3. Downstream from the gasifier, the cogeneration plant consists on: a section for separation of water and TARs (red box); a MTG with internal heating of compressed air by using turbine exhausts (orange box); the thermal generation section (blue box); the biomass drier (yellow box).

3. Results

3.1. Mass and energy balance of the whole plant

The syngas exits from the gasifier with the composition described in Table 2 at temperature of 873.15 K and moisture content of 46% in volume. In the heat exchanger, the syngas is cooled up to 343.15 K to separate water while tars are trapped after a gurgling in a propanol bottle. The clean syngas is then compressed up to 5.5 bar (and heated up to 643.88 K) and finally heated up to 833.15 K in the heat exchanger. The mass flow of syngas from the gasifier is equal to 0.2 kg/s. The clean syngas flowing through the combustor is equal to 0.13 kg/s. This means that about 715 kW_{th} are delivered in the syngas burner during the combustion. The air (1.4 kg/s) enters the compressor at 298.15 K and 1 bar to be compressed up to 5 bars. Assuming a compressor efficiency of 0.78 the air exit temperature is about 500 K. The energy consumption of the compressor is equal to 287 kW. A regenerator is placed after the compressor, increasing air temperature to 873.15 K before entering the combustion chamber. The exhausts exiting from the combustion chamber have a temperature equal to 1245 K. No unburnt syngas is present in the exhausts. The turbine produces a mechanical power of 498 kW. After passing in the regenerator, the exhausts feed the cogeneration heat exchanger producing 10 m3/h of hot water at 90°C (entering at 70°C), resulting in a useful thermal power of 240 kW. Finally, the waste heat is sent to a heat exchanger aiming at feeding the biomass drier reducing biomass humidity from 55% to about 10%. The total electric power is obtained from the turbogas electric production (turbine minus compressor power is equal to 211 kW). The syngas compressor power (31 kW) must be also deducted. The power delivered to the grid is 188 kW.

The electric efficiency of the whole plant (based on syngas LHV) is equal to 25%.

3.2. Thermo-economic balance

The assessment of global energy efficiency and the financial appraisal of the proposed CHP investment is carried out considering the case studies of only electricity sale (case A) and the combined sales of heat and electricity (case B and C). In particular, case B is referred to residential heat demand (1,500 hours/year) and case C to industrial heat demand (4,000 hours/year equivalent heat demand) with the assumption of low temperature (90°C) heat demand. The operating hours of the plant (baseload operation mode) is assumed 6,600 (in agreement with data from reference manufacturer). In order to carry out the profitability assessment, the main cost items and biomass consumption figures of Table 3 are assumed. The turn key investment and operational costs are personal estimates from manufacturers data and data collected from case studies. The annual O&M costs are assumed 5% of upfront costs, while biomass char discharge costs are accounted for assuming unitary cost of 70 Eur/t of biochar. The following further input data are assumed: LHV of wet basis biomass (55% moisture content olive cake) equal to 1.97 kWh/kg; cost of wet olive cake at the biomass CHP plant (included transport) equal to 40 Eur/t; electric autoconsumption of CHP plant = 12%; biomass electricity feed-in tariff equal to 287 Eur/MWh (case A) and 297 Eur/MWh (cases B and C), on the basis of Italian legislation for subsidies on biomass electricity; heat selling price for residential and industrial end users equal to 75 and 45 Eur/MWh respectively, on the basis of estimates from Italian Energy Authority data for 2014. The financial appraisal of the investment is carried out assuming the following hypotheses: (i) 20 years of operating life; no 're-powering' throughout the 20 years; zero decommissioning costs; (ii) maintenance costs, fuel supply costs, electricity and heat selling prices held constant (in real 2014 values); (iii) duration of feed-in tariff for biomass electricity of 20 years (iv) capital assets depreciated using a straight line depreciation over 20 years; (v) cost of capital (net of inflation) equal to 5%, corporation tax neglected, capital investments and income do not benefit from any support.

Data in Table 4 report the main economic indices of the investment, and the NPV results positive for all the considered configurations. Of course the best results are obtained in Case C where the thermal power is massively used (4000 hours/year). In this case the Discounted pay back time is about 9 years and very interesting values for Internal Rate of Return and Profitability Index are obtained.

Table 3 Main capex and opex cost figures and biomass fuel consumption for the selected case studies

Description	Unit	Value
Wet olive pomace consumption	t/year	2,344
Dry olive cake consumption	t/year	1,172
Heat demand for biomass drying	MWh/yr	1,199
Total upfront cost [21]	kEur	930 (case A) – 1,130 (case B and C)
- gasifier	kEur	438
- turbine	kEur	293
- syngas cleaning	kEur	69
- civil works	kEur	50
- heat distribution	kEur	200 (for case B and C)
- Engin, develop, insur, grid connection	kEur	80
Specific upfront cost	kEur/kWe	4.65 – 5.65
Operational cost, of which:	kEur/yr	208-218
- Fuel cost	kEur/yr	94
- Personnel cost	kEur/yr	67
- O&M cost	kEur/yr	47 - 57

Table 4 Results of the thermo-economic assessment

Economic indices	Unit	Case A	Case B	Case C
Net present value	kEur	285	777	860
Discounted pay back time	years	14	10	9
Internal rate of return	%	8.4	11.6	13.3
Profitability index	pu	1.31	1.59	1.76

4. Conclusions

The coupling of a 800 kW downdraft pomace gasifier with a MGT for CHP was modeled using ASPEN Plus. The thermodynamic analysis demonstrated that 190 kW can be obtained by the power plant, while the cogeneration section is able to provide 240 kW for heating water up to 90°C.

Thermodynamic analysis was complemented with a thermo-economic balance to study the profitability of the proposed configuration. Three different Cases were analyzed to exploit the importance to sale the thermal power. By considering the present regime of Feed-in Tariff in Italy, all the cases returned interesting values of the profitability and other economic indices (also when only electricity sale is considered. However, massive sale of thermal power to an industrial user, strongly increase the economic performance of the investment. This demonstrates that, in presence of cogeneration, also the quite low conversion efficiency of the plant gives an interesting economic performance when adopting a low quality fuel (wet olive pomace).

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