TECHNO-ECONOMIC ANALYSIS OF OLIVE POMACE GASIFICATION FOR COGENERATION APPLICATIONS IN SMALL FACILITIES

by

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A mathematical model approach was employed to simulate olive pomace gasification in a bubbling fluidized bed reactor. To validate the model a set of gasification experiments were performed in a 250 kW_{th} quasi-industrial gasifier. The cold gas efficiency of the gasifier and tar production were evaluated to assess the energy potential of olive pomace while determining its most suitable end-use applications. A techno-economic analysis addressing the comparison of two different commercially manufactured gasifying unit sizes (100 kW and 1000 kW) and a Monte-Carlo sensitivity analysis were employed to assess both the feasibility of each application size and also foresee the main investment risks in conducting olive pomace gasification in small rural facilities. Olive pomace gasification showed to be more suitable for personal household purposes. The low cold gas efficiency (around 20%) makes this producer gas more appropriate for small cogeneration facilities applications. The use of olive pomace residues in gasification showed viable economic performance in small cogeneration solutions at a scale of 1000 kW for agriculture waste-to-energy recovery in olive oil agriculture cooperatives, while 100 kW showed to be unable to reach an economically sustainable scenario. Final remarks point out that despite the feasibility of the venture at a scale of 1000 kW special concerns must be considered regarding the study attractiveness to potential investors.

Key words*: gasification, CFD, small-scale power production, techno-economic analysis, Monte-Carlo sensitivity analysis*

Introduction

The olive oil industry is massively concentrated in the Mediterranean region granting 95% of the world's olive oil production [1]. Most of this industry is settled in EU member countries namely Spain, Italy, Greece, and Portugal, which together lead the production with an astonishing 75% of the total share, while the remaining 25% belongs to countries such as Tunisia, Morocco, Algeria, Syria, and Turkey [1]. Currently, Portugal stands as the 4th world's largest olive oil producer [2]. The olive growing area in Portugal is of 336 000 ha [3]. The largest olive tree domains are in the Alentejo region, which accounts for 50% of the total olive growing area in Portugal [4]. During the olive oil extraction process, a by-product known as olive pomace (containing pulp, pieces of olive pits, olive husk, and some remaining oil and water) derives. The estimated quantities, of olive oil industry residues (pruning material, leaves) and by-products, in

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the EU are 6.8 million tons per year [5]. Among these, olive pomace is a promising energy source with lower heating value of around 19.5 MJ/kg (dry basis) [6]. The estimated quantities in Portugal are about 23754 tons per year, with an energy potential of 0.463 PJ per year. Regarding the huge amount produced every year and its elevated heating value, olive pomace has the potential to contribute as a renewable energy source in Portugal [7-9] .

As an energy conversion process, biomass gasification delivers high-efficient power production with enhanced environmental performance helping to fulfill the current energy demands and ever more stringent environmental regulations [10, 11]. While combustion of biomass is the most direct and technically easiest process, the overall efficiency of generating heat from biomass energy is low [12]. Gasification has many advantages over combustion: Gasification process can use low-value feedstocks and convert them into gas (mixture of CO, CO_2, H_2, CH_4, *etc.*), which can be further processed into chemicals (*e.g.* ammonia), liquid fuels (*e.g.* CH_3OH, C_2H_5OH), gaseous fuels (*e.g.* hydrogen) and heat and electrical power by direct utilization of the producer gas in boilers (hot water and steam production), combustion engines (heat and electricity), gas turbines (heat and electricity) as well as solid fuel cells (heat and electricity) [13]; During gasification process, due to lower amount of oxygen and lower temperatures, compared with combustion, emissions of sulphur and nitrogen compounds (mainly their oxides), particles and other noxious compounds are significantly reduced [12]. During combined cycles for combined heat and power generation, contaminants in the producer gas such as sulfur and nitrogen species (*e.g.* NH_3, HCN, COS, H_2S) and other trace elements (*e.g.* KCl, HCl) are removed efficiently resulting in much lower emissions [12, 14].

Almeida *et al* [1] carried out an experimental analysis of olive pomace gasification in a fluidized bed reactor. Results of the experiments showed that higher bed temperatures favored gas production as well as carbon conversion efficiency and cold gas efficiency (CGE). Puig-Gamero *et al*. [15], carried out a TGA-MS experimental analysis of the gasification process of three raw materials (olive pomace/coal/petcoke) and the comparison of co-gasification process of their binary and ternary blends. Experimental results showed that olive pomace had the highest reactivity (followed by petcoke and coal), and highest yield of evolved gases (H_2, CO, CO_2, CH_4 and NO) comparing to other samples. Moreover, the binary and ternary blends reactivities increased when olive pomace ratio in the blend was also increased. In binary and ternary blends, the presence of olive pomace led to both an increase of the H_2 release and the H_2/CO ratio and a decrease of the CO yield. Castro *et al*. [16] analyzed the potential of olive pomace for gasification purposes and determined the optimal gasification parameters. The investigation comprised a full physico-chemical characterization of the olive pomace and gasification process energy characterization. Results show that at gasification operating condition of 750-850 °C and equivalence ratio of 0.21-0.33, producer gas contains 23.90% of H_2, 34.10% of CO, 0.10% of CO_2, 1.12% of CH_4, and 40.52% of N_2 (low heating value of 7.35 MJ/m^3). Addressing to the Portuguese biomass power generation policy, Cardoso *et al*. [17] performed a techno-economic analysis of an 11 MW biomass gasification power plant for electricity production in Portugal. Results showed that the venture was feasible yet the economic performance strongly relied on revenues from electricity sales regulated by uncertain tariffs and reimbursements. Thus, special concerns must be considered regarding the project attractiveness to potential investors.

The purpose of this paper is to present a techno-economic analysis of the possible application of the olive pomace gasification, coupled with cogeneration, for small-scale commercial facilities in the Alentejo region. Olive pomace gasification runs gathered from a quasi-industrial 250 kWth bubbling fluidized bed reactor were employed to validate the numerical model [18]. The CGE of the gasifier and tar production of the process were evaluated to assess the energy potential of olive pomace and to determine the most suitable end-use applications. The obtained results served as a starting point to assess the technical capabilities of olive pomace and for techno-economic analysis on different gasifier sizes. A techno-economic analysis coupled with Monte-Carlo sensitivity analysis is performed for two different gasifier sizes (100 kW and 1000 kW), in order to assess both the feasibility of each application size and also foresee the main investment risks in conducting olive pomace gasification in small rural facilities.

Experimental set-up

The gasification process was conducted in a quasi-industrial gasification plant installed in the Alentejo region at the Polytechnic Institute of Portalegre, Portugal. The proximate and ultimate analyses of the olive pomace feedstock are shown in tab. 1 [7]. The main components of the gasification unit are depicted in fig. 1.

Table 1. Olive pomace proximate and ultimate analysis, as received.

Biomass properties	Olive pomace
Density [kgm^{-3}]	410.68
Proximate analysis (wt.%)	
Moisture	8.90
Ash	0.65
Volatile matter	70.96
Fixed carbon	19.48
Ultimate analysis (%, db)	
C	53.87
H	8.83
N	2.03
O	26.51

The 250 kWth fluidized bed reactor is 0.5 m wide and 4.15 m height, with a static bed height of 0.15 m composed of 70 kg of dolomite $CaMg(CO_3)_2$. Dolomite is used as bed material in fluidized bed gasification processes, due to its favorable properties in catalytic tar cracking and anti-sintering properties [19]. Olive pomace enters the reactor at a height of 0.4 m from the distributor plate, while preheated air enters the reactor from the base through a set of diffusers. Gas sampling bags are used to collect the producer gas samples at the condenser outlet once the gasification process reaches a stationary state. Producer gas samples are then inserted into the gas chromatograph for further analysis. Detailed descriptions of the gasification plant (*e.g.* gas cooling and cleaning, chromatograph analysis characteristics) are provided in [18, 20].

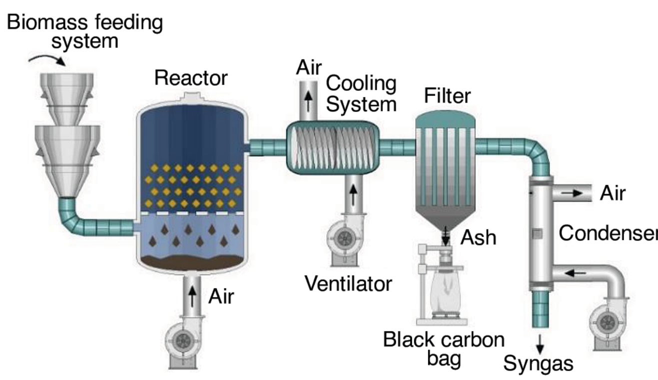

Figure 1. Schematic of the biomass gasification plant located in Portalegre, Portugal.

Mathematical model

The 2-D Eulerian-Eulerian mathematical model used in this study was developed by Silva *et al.* [18]. The gasification process in the fluidized bed reactor was simulated by a multiphase (gas/solid) model within the ANSYS Fluent database. The solid phase was treated as a Eulerian granular model, while the gas phase was set as a continuum. Interactions between phases were modeled, exchanging heat by convection, momentum (due to drag between phases), and mass (given the heterogeneous chemical reactions). Table 2 summarizes the main governing equations for both solid and gas phases and the hydrodynamic model. Table 3 provides the devolatilization, main chemical reactions and reaction rates coefficients (based on the Arrhenius law) in the chemical model. Since the present model has already been broadly presented in recent literature published by the research group, only key points will be featured [19, 21, 22].

Table 2. Main governing equations and hydrodynamic model for both gas and solid phases.

Conservation equations
Energy (gas phase):
$\frac{\partial(\alpha_q \rho_q h_q)}{\partial t} + \nabla(\alpha_q \rho_q \vec{v}_q h_q) = -\alpha_q \frac{\partial(\rho_q)}{\partial t} + \vec{\tau}_q : \Delta\vec{v}_q - \nabla\vec{q}_q + S_q + \sum_{p=1}^{n}(\vec{Q}_{pq} + \dot{m}_{pq}h_{pq})$
Mass (gas phase):
$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla\cdot(\alpha_g \rho_g v_g) = S_{gs}$
Momentum (gas phase):
$\frac{\partial(\alpha_g \rho_g v_g)}{\partial t} + \nabla(\alpha_g \rho_g v_g v_g) = -\alpha_g \nabla\rho_g + \alpha \rho_g g + \beta(v_g - v_s) + \nabla \alpha_g \tau_g + S_{gs}U_s$
Energy (solid phase):
$\frac{\partial(\alpha_p \rho_p h_p)}{\partial t} + \nabla(\alpha_p \rho_p \vec{v}_p h_p) = -\alpha_p \frac{\partial(\rho_p)}{\partial t} + \vec{\tau}_g : \nabla\vec{v}_p - \nabla\vec{q}_p + S_p + \sum_{p=1}^{n}(\vec{Q}_{pq} + \dot{m}_{pq}h_{pq})$
Mass (solid phase):
$\frac{\partial(\alpha_s \rho_s)}{\partial t} + \nabla(\alpha_s \rho_s v_s) = S_{sg}$
Momentum (solid phase):
$\frac{\partial(\alpha_s \rho_s v_s)}{\partial t} + \nabla(\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla p_s + \alpha \rho_s g + \beta(v_g - v_s) + \nabla \alpha_s \tau_s + S_{sg}U_s$
Hydrodynamic model
Kinetic energy:
$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}\cdot(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$
Dissipation rate:
$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial_\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + G_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$
Granular Eulerian model:
$\frac{3}{2}\left[\left(\frac{\partial(\rho_s \alpha_s \theta_s)}{\partial t} + \nabla(\rho_s \alpha_s \vec{v}_s \theta_s)\right)\right] = (-P_s\vec{I} + \vec{\tau}_s):\nabla(\vec{v}_s) + \nabla(k_{\theta\alpha}\nabla(\Theta_s) - \gamma_{\theta\alpha} + \varphi_{1s}$

Results and discussion

Model validation

Table 4 shows the experimental operating conditions and producer gas analysis for five different gasification runs. These data are used to validate the mathematical model. The mathematical model has already been thoroughly validated strengthening its accurate predictability in a broad range of applications [23-25]. Figure 2 presents the relative deviations between the experimental and numerical results for producer gas composition. It can be seen that

Table 3. Chemical reaction model

Biomass devolatization $\rightarrow$ char + volatiles + + water steam + ach	Reaction rate: $r_1 = A_i \exp\left(\frac{-E_i}{T_s}\right)(1-a_i)^n$
Volatiles $\rightarrow \alpha_1 CO + \alpha_2 CO_2 + \alpha_3 CH_4 + \alpha_4 H_2$	Reaction rate: $r_2 = A_i \exp\left(\frac{-E_i}{T_s}\right)(1-a_i)^n$
Homogeneous reactions:	Arrhenius reaction rate:
$CO + 0.5O_2 \rightarrow CO_2$	$r_3 = 1.0 \cdot 10^{15} \exp\left(\frac{-16000}{T}\right) C_{co} C_{O_2}^{0.5}$
$CO + H_2O \rightarrow CO_2 + H_2$	$r_4 = 5.159 \cdot 10^{15} \exp\left(\frac{-3430}{T}\right) T^{-1.5} C_{O_2} C_{H_2}^{1.5}$
$CO + 3H_2 \rightarrow CH_4 + H_2O$	$r_5 = 3.552 \cdot 10^{14} \exp\left(\frac{-15700}{T}\right) T^{-1} C_{O_2} C_{CH_4}$
$H_2 + 0.5O_2 \rightarrow H_2O$	$r_6 = 2780 \exp\left(\frac{-1510}{T}\right)\left[C_{CO} C_{H_2O} - \frac{C_{CO} C_{H_2}}{0.0265 \exp\left(\frac{3968}{T}\right)}\right]$
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	$r_7 = 3.0 \cdot 10^{5} \exp\left(\frac{-15042}{T}\right) C_{H_2O} C_{CH_4}$
Heterogeneous reactions:	Arrhenius reaction rate:
$C + 0.5O_2 \rightarrow CO$	$r_8 = 596 T_p \exp - \left(\frac{-1800}{T}\right)$
$C + CO_2 \rightarrow 2CO$	$r_9 = 2082.7 \exp - \left(\frac{-18036}{T}\right)$
$C + H_2O \rightarrow CO + H_2$	$r_{10} = 63.3 \exp - \left(\frac{-14051}{T}\right)$

the mathematical model results show a good agreement with those obtained from five experimental runs. A maximum error of 20% was delimited within the dashed lines, which is a reasonable margin for such a complex process as biomass gasification in a quasi-industrial fluidized bed reactor [18]. The largest deviations were measured for CH_4, around 17%, as its yield in the producer gas is the smallest, which favors higher relative errors.

Table 4. Experimental operating conditions and producer gas analysis.

Gasification run	1	2	3	4	5
Temperature [K]	1023	1074	1073	1123	1126
Biomass consumption [kgh^{-1}]	46	46	56	26	56
Producer gas fraction (%, dry basis)					
H_2	5.44	7.27	7.03	12.19	12.20
CO	8.57	15.68	17.44	11.78	14.14
CH_4	1.13	3.27	3.81	1.34	2.07
CO_2	16.53	15.85	15.87	18.60	17.21

The CGE and tar content

Figure 3 illustrates the modeling results for CGE and tar content for the various reactor operating temperatures (from 1023 to 1123 K). Results show that gasification temperature has influence on CGE and tar content. The CGE increases with the gasification temperature, as the gaseous products yield come enhanced. This increase in gas yield is due to larger release of gases during the initial devolatilization stage and the additionally secondary reactions undergone by the char and tars (char gasification and tar cracking/reforming) [26, 27]. The olive pomace gasification process showed a low CGE, around 20%, making this process unfavorable for broad large-scale electricity production due to very low overall yields of the producer gas. However, it may be used to produce gas with certain characteristics for small-scale facilities, providing sufficient energy for rural household purposes in lightning and operation of small machinery.

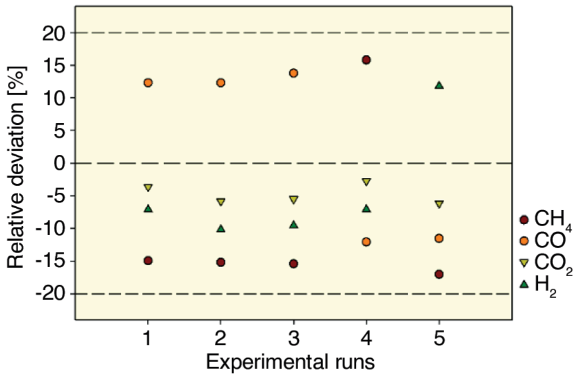

Figure 2. Experimental and numerical producer gas fraction relative deviations.

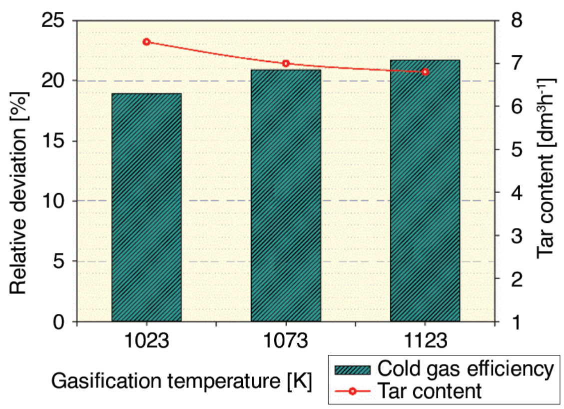

Figure 3. Influence of temperature on CGE and tar content.

Techno-economic analysis

Given the strong availability of olive pomace, as residue, in the Alentejo region and the suitability of its application for personal household use, the present paper analyzes the possibility for utilization of the olive pomace gasification, coupled with cogeneration, in rural small-scale facilities within an olive oil agriculture cooperative. Experimental results from olive pomace gasification in a quasi-industrial 250 kW_{th} fluidized bed reactor was a starting point to assess the technical capabilities of this feedstock. The following economic analysis was performed for two gasifying unit sizes, one with 100 kW and the other with 1000 kW, with attention to evaluate the feasibility of facilities for a certain lifetime period. The units in the range of 100 and 1000 kW were selected based on available olive pomace from average size of olive oil agriculture cooperatives. This analysis was built based on literature review concerning investment studies in olive pomace gasification in small cogeneration facilities [28, 29]. Plant lifetime is estimated to 10 years of operation. After that period, major plant overhaul is mandatory [30]. The olive pomace feedstock is collected from the associated farmers' country estates and then transported to the cooperative facilities for gasification coupled with cogeneration, therefore, in this analysis transportation costs are taken into consideration whereas biomass cost is not considered. An average olive pomace consumption of 1132 tons per year for the 100 kW unit and 11324 tons pre year for the 1000 kW unit are estimated, with an electric power output of 787 MWh per year and 7876 MWh per year, respectively, all considering a baseload annual operation time of 7160 hours (in accordance with the literature for forest biomass gasification, coupled with cogeneration, in small-scale facilities) [30]. According to the literature [30], it was assumed that the operation of both units would be monitored by laborers already performing other tasks in the cooperative. Therefore, neither units require dedicated labor/and laborers and the marginal cost of labor keeps low. Further, it was assumed that one part (around 45%) of electrical energy produced, in cogeneration facility, will be sold to the national grid and another part of electrical energy will be used for cooperative energy needs. Heat energy sales are not considered, as it is assumed that produced heat energy is used for biomass drying and producing additional electrical energy using an intern heat recovery system.

Three approaches are combined to evaluate the olive pomace gasification small-scale cogeneration facility viability over a lifetime period of 10 years, net present value (NPV), internal rate of return (IRR) and payback period (PBP). The NVP, IRR, and PBP are important common indicators in investment decisions [29]. An overview of main economic assumptions, considered for spreadsheet-based economic evaluation model development, is present in tab. 5. The considered cash flows for costs and revenues calculations were: initial investment (equity and borrowed capital); amortizations; operating and maintenance (O&M) costs (includes biomass transportation costs) and revenues from electrical energy sales to the grid. All cash flows, except the initial investment occurring only in the start-up phase, extend throughout the 10 years lifetime of the analysis, with all costs and revenues being updated to the year they correspond to. All the analysis is performed at current prices, revenues, and current value-added tax rates.

Figures 4(a)-4(b), show the economic model results for the NPV, IRR, and PBP calculations. The NPV is an indicator used to evaluate the profitability of investment by summing all inflows and outflows of cash over the facility's lifetime [17]. A positive NPV indicates that the facility is profitable, while a negative NPV will event in a net loss. The IRR stands as an indicator

Table 5. Economic assumptions for the 100 and 1000 kW small-scale cogeneration plants [17, 29-31].

Economic parameters	100 kW	1000 kW	Remarks
Discount rate [%]	10	10	-
Inflation rate [%]	1.6	1.6	Inflation rate applied in 2020.
Equity capital (30%) [k€]	52	396	Values applied during the investment period. Comprises costs related to credit opening, whole plant equipment acquisition (gasifier, turbine, producer gas cleaning system) and electrical energy line construction.
Borrowed capital (70%) [k€]	123	924	
Amortizations [k€]	11	88	Amortizations value in 2020. Comprises the regular debt payment throughout the plant lifetime and insurance.
O&M costs [k€]	12	92	Value applied in 2020 (7% of the capital cost). Comprises all consumption costs with the facility, namely olive pomace transportation to the agricultural cooperative, olive pomace pre-treatment, ash transport and deposition into landfill, and maintenance of the equipment and facility.
Total annual costs [k€]	24	181	Value for 2020.
Electrical energy output parameters			
Electrical energy production [MWh/year]	787	7876	Considering the baseload operation time of 7160 h.
Output sold to the grid [MWh/year]	354	3544	45% of the total electricity production is sold to the grid.
Electrical energy sales tariff [€/MWh]	121.34	121.34	Tariff applied in 2018.
Revenues			
Annual revenue [k€/year]	42	430	Revenues from electrical energy sales to the grid in 2020.

used to measure the profitability of an investment [17]. The higher the IRR, the greater the profitability of the facility will be. Additionally, the IRR is the expected return rate and is given by the moment at which the NPV equals zero. The PBP is the time required to reclaim the initial capital investments [17]. The shorter the PBP, the stronger is the financial feasibility of the facility. For the 100 kW gasification small-scale cogeneration facility the calculated NPV at the discount rate of 10% is –33 k€, the IRR rate is 5.92% and PBP is longer than the target timeframe (12.3 years) fig. 4(a). Concerning the 1000 kW gasification small-scale cogeneration facility, the NPV resulted in 481 k€, the IRR in 16.74% and PBP in 7.5 years fig. 4(b).

In general, the financial indicators clearly point out that only the 1000 kW facility is economically feasible, by presenting a positive NPV, an IRR higher than the discount rate, and a PBP shorter than the target timeframe. On the other hand, in this application, it is not economically feasible to operate a 100 kW facility resulting in a negative NPV, an IRR inferior to the discount rate and PBP longer than the target timeframe, as the cash inflows do not overcome the cash outflows, foreseeing negative future investment earnings. Focusing on the 1000 kW facility, one must now look beyond these indicators and assess the attractiveness of the facility

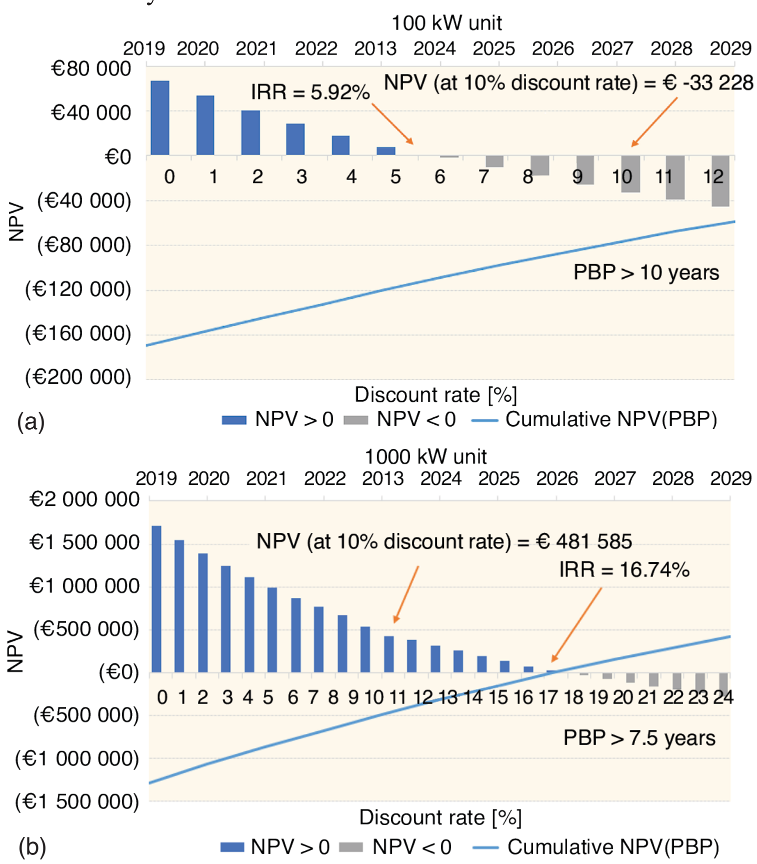

Figure 4. The NPV profile variation as a function of the discount rate, IRR and PBP given out by the cumulative NPV for: (a) 100 kW plant and (b) 1000 kW plant

from an investor standpoint. According to typical financial benchmarks for biomass projects present in the literature, the NPV must be positive, IRR greater than 10%, and PBP less than 10 years [29]. Indeed, these criteria may differ by country risk and facility-specific conditions, notwithstanding, these will be brought into consideration for reference purposes. Given these assumptions, one may assess that the 1000 kW facility successfully meets all main requirements for a biomass project be operated profitably.

Sensitivity analysis

In order to measure the risks associated with the facility, a Monte-Carlo sensitivity analysis is carried out to assess the most critical variables considered for the performance of the facility. The variables that most affect the viability of the facility are electrical energy sales tariff, electrical energy production, initial investment, discount rate and O&M costs. The five considered variables sensitivity bounds are defined as unfavorable or favorable by varying the baseline value up to a ±10% range. The simulation is conducted for a total of 10000 iterations. All other variables within the economic model are maintained unchanged during this analysis. A triangular distribution is considered for each variable due to its mathematical simplicity and ability to generate enough random samples, requiring the input of a minimum (favorable value), a mode (baseline value), and maximum (unfavorable value) [32]. Figures 5(a)-5(b) depict the NPV sensitivity analysis to each one of the considered critical variables for both units. For the purpose of simplification, only the sensitivity analysis to the NPV is presented since the analysis showed that higher risks of investment loss are more likely to occur due to NPV failure. The wider bars in the tornado plot are the ones that require special concern, thus, from all considered variables electrical energy sales tariff and electrical energy production are the ones that the NPV is more sensitive. These two variables may greatly compromise the NPV as compared to the remaining variables. The sensitivity analysis shows that the 100 kW facility is indeed condemned to failure, as a positive NPV would be unreachable even in the most favorable scenarios, while the 1000 kW facility proved to be an investment that may be worth considering with no negative NPV values being foreseen even in a most negative scenario. Unsurprisingly, for both 100 kW and 1000 kW facilities, electrical energy production and electrical energy sales tariff are the variables that carry greater impact over the NPV, as the calculated annual revenues (given by the product of the annual electrical energy production for the electrical energy` sales tariff) are strongly dependent on these. The conditional mean given by the vertical red line points the previously calculated NPV values, –33 k€ for 100 kW facility and 481 k€ for the 1000 kW facility.

This techno-economic analysis was based on a practical implementation mindset lodging the facility in an agriculture cooperative. This means more funds are available easing the acquisition of such an expensive piece of equipment as a small-scale cogeneration plant. Costs related to biomass and laborer are often a significant part of an investment of this nature, here these cost shares are not considered, otherwise, the viability of this analysis would be broadly hampered. Regardless of these positive economic factors, at least 45% of the generated electrical energy is considered to be sold to the national grid, contrarily, the viability of the analysis would be broadly compromised. In addition, the plant must be operated almost uninterruptedly with an annual baseload of 7160 operating hours being considered, so to guarantee a sufficient electrical energy output production capable of maintaining the feasibility of the analysis. The CGE generally comes as a great deal whenever conversion processes of this nature are involved, however, one must consider the best achievable CGE for the intended needs, in this analysis the low CGE (about 20%) does not hamper significantly the process at this rural small-scale [33]. Here, the system output aspect is particularly crucial once the study NPV relies considerably on revenues coming from the electrical energy production and national electrical energy sales tariff (which comprises a certain uncertainty due to its dependence on energy market price fluctuations

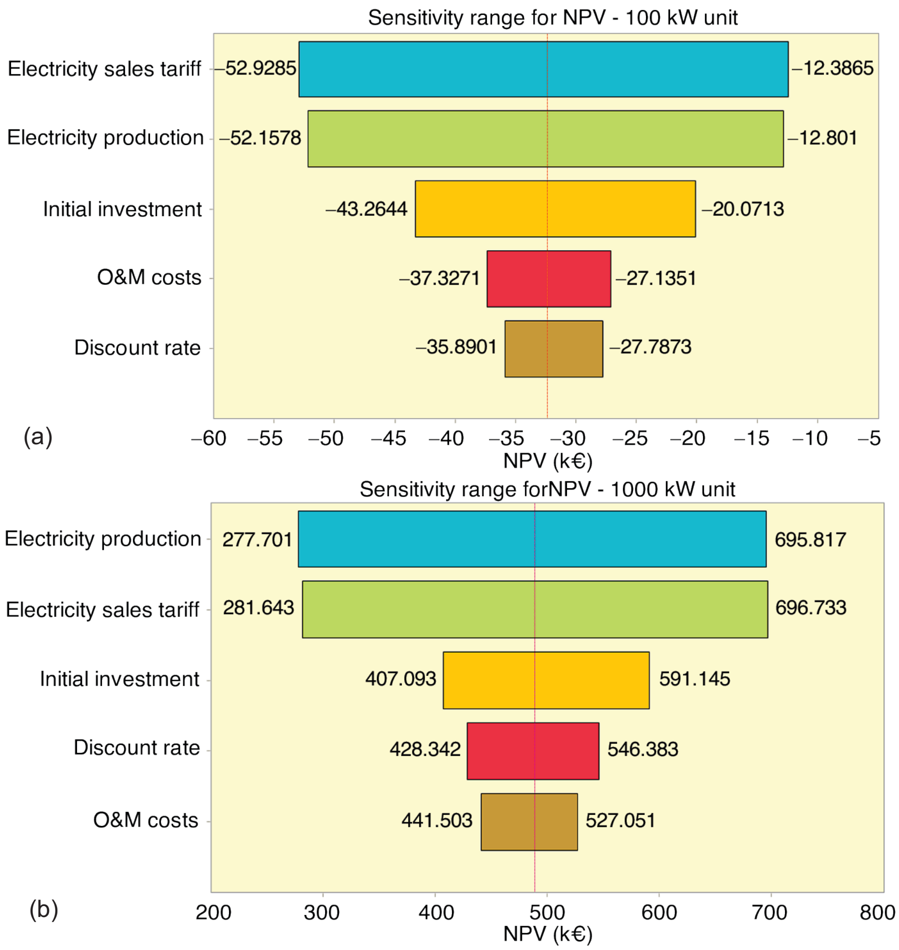

Figure 5. Sensitivity analysis range to input variables for NPV; (a) 100 kW facility, (b) 1000 kW facility

and subsidies). Hence, one must balance the pros and cons deeply, as in a real scenario most farmers could be discouraged from investing in a study whose evaluation despite predicting positive earnings for a 1000 kW small-scale facility, the associated uncertainties may not convince farmers less available to take risks, demanding higher assurances before moving towards such investment. In this manner, it is important to look beyond the numbers provided by the economic model, and assess each situation independently considering all potential factors that can easily reverse the initially predicted viability of the study.

Conclusions

The gasification process of olive pomace was analyzed in a quasi-industrial fluidized bed reactor by employing a 2-D CFD model. A set of experimental gasification runs were gathered from the fluidized bed reactor at different temperatures for validation purposes. The numerical model effectively predicted the acquired experimental data with generally good agreement. The low CGE of the process, around 20%, turns it more suitable for producer gas production in small cogeneration facilities, or even synthetic compounds production. Based on these assumptions two different size facilities with 100 kW and 1000 kW small-scale gasification plants were proposed, located in an olive oil agriculture cooperative. The techno-economic analysis showed that the 100 kW facility was economically impracticable under current market conditions, showing a negative NPV of –33 k€, an IRR of 5.92%, and PBP larger than the 10 years project lifetime, while the 1000 kW facility showed to be economically feasible with an NPV of 481 k€, IRR of 16.74% and PBP of 7.5 years. The sensitivity analysis showed a higher risk of failure in the NPV, with electrical energy sales tariff and electrical energy production causing higher impact change over this method. Furthermore, the 100 kW showed to be unable to reach a feasible scenario, while a rather steady economical behavior was foreseen for the 1000 kW facility. Final remarks point that, olive pomace gasification facility carries great potential in small facilities applications (at small power scales set around 1000 kW) in the Alentejo region with economic viability, however, special concerns must be considered regarding the project attractiveness to potential investors.

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Nomenclature

c_p – specific heat capacity [Jkg^{-1}K^{-1}]
D_0 – diffusion rate coefficient [m^{2}s^{-1}]
G_n – turbulence kinetic energy [m^{2}s^{-2}]
h_{pq} – heat transfer coefficient [Wm^{-2}K^{-1}]
J_i – diffusion flux [m^{2}s^{-1}]
k – thermal conductivity [Wm^{-1}K^{-1}]
$k_{\Theta a}$ – diffusion coefficient [m^{2}s^{-1}]
$k_{\Theta a}\nabla\Theta_s$ – diffusion energy
m – biomass flow [m^{3}s^{-1}]
M – total mole flow of carbon [gcm^{-2}s^{-1}]
M_c – molecular weight [kgmol^{-1}]
p – gas pressure [Pa]
q_q – heat flux [Wm^{-2}]
qth – specific enthalpy [Jkg^{-1}]
R – universal gas constant [Jmol^{-1}K^{-1}]
R_c – reaction rate [molL^{-1}s^{-1}]
S_n – source term
T – temperature [K]
U – mean velocity [ms^{-1}]
v – instantaneous velocity [ms^{-1}]
X_c – volume fraction [-]
Y – density [kgm^{-3}]

Greek symbols

α – energy exchange
ρ – collisional dissipation of energy [Wm^{-3}]
φ_{is} – carbon fraction in the biomass
$\gamma_{\Theta a}$ – mass fraction
τ – tensor stress [Nm^{-2}]
μ – viscosity [kgm^{-1}s^{-1}]
γ_c – stoichiometric coefficient

Subscripts

g – gas phase
s – solid phase
I – component
db – dry basis
wt – weight

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