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TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS OF BIOMASS COGENERATION FROM OIL PALM MILL

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Abstract. *The present study works with a cogeneration plant integrated into an oil palm mill, which handles 230 t/h of fresh fruit bunches. The system counts with a boiler for generation of steam, a steam turbine coupled with a generator, pumps, and heat exchangers. The heat exchangers are fed with steam from turbine extractions in order to dry the biomass to be burned in two stages. The work also presents the exergetic analysis of the devices working in the cycle, the economical attractiveness of the project, by means of the NPV methodology. And an environmental approach that shows the advantages and limitations of working with a biomass-fueled boiler. The calculus showed a huge electricity surplus to be explored, the payback is reached in one-third of the plant lifetime. The work also shows the pollution capacity of the combustion, and 62 % ecological efficiency in the power generation.*

Keywords: *cogeneration, biomass, ecological efficiency, oil palm mill, combined heat and power*

1. INTRODUCTION

The present work studies the residual biomass from the palm oil industry as a solid fuel for combined power and heat generation. According to the Brazilian Institute of Geography and Statistics (IBGE) in 2011, Brazil had 54 thousand hectares of cultivation area of palm in the state of Pará (Delivand and Gnansounou, 2013). In the year of 2017, the Food and Agriculture Organization of United Nations stated that Brazil produced 1,6 x 10^6 ton of oil palm which generates around 3,6 x 10^5 ton of Empty Fruit Bunches (Medina *et al.*, 2018). The growing interest in this kind of biomass is given to his versatility, low acquisition cost and the also growing production of biodiesel from palm oil (Gilbert, 2012).

The oil palm mill's residual biomass has a great energetic value in the form of the Empty Fruit Bunches (EFB), the mesocarp fibers (MF), palm kernel shells (PKS) and the palm oil mill effluents (POME). According to Talero *et al.* (2019) the cited kinds of biomass residue have a potential of 3150 kt of available to energy conversion for countries that extract the palm oil, such as Colombia. Arrieta *et al.* (2007) stated that the milling process produces more biomass than palm oil. And the study of Garcia-Nunez *et al.* (2016), pointed out that the solid residues are twice as much as the amount of extracted crude oil.

Heat and Power can be cogenerated in a palm oil mill using different types of fuel (Ayodele and Cheng, 2016). The MF and PKS are burned in boilers and the POME could be anaerobically digested to biogas (Garcia-Nunez *et al.*, 2016). Thermodynamically the cogeneration is an interesting procedure and technically viable, once that the fuel yield is enhanced. In many cases is also economically attractive, reducing the amount of energy purchase and, in consequence, the production costs (Arrieta *et al.*, 2007). Wu *et al.* (2017) found that the use of EFB and PKS as fuels to combined heat and power generation is self-sufficient for the production process and yet there is a surplus of 0,9 MW electricity that is produced and can be sold to the grid.

Harahap *et al.* (2019) defended the idea that palm oil bio-resources such as its residual biomass and effluents can be used as feedstock to cogeneration plants. In this line, the main goal of this work is to analyze the use of PKS, EFB and MF, milling residues, as fuel for steam generation and power through a back pressure turbine. All biomass coming from the 230 t/h mill shall be burned in the boiler for combined heat and power generation, then a generator coupled in the turbine shall produce power and the heat from the streams extracted from the steam turbine would be used in the procedure of biomass drying. The biomass is obtained with 50-60 % moisture, which reduces the calorific value of the sample and its combustion efficiency. Therefore a drying method is needed until the biomass reaches 10 % moisture content. For the thermal drying two heat exchangers were used in two separated processes, fed by steam extractions of the turbine, as done in (Luk *et al.*, 2013). This work also evaluates the system for economically and environmental points of view, based on operation parameters and emissions index.

2. METHODOLOGY

2.1 Problem formulation

It was evaluated a typical oil palm mill focusing on the biomass which is generated as a byproduct in the oil extraction. Once it was known that the gamma of wasted materials with energy generation potential was large, the decision was in the selection of the biomass of interest for investigation. It was decided to explore as solid fuels the empty fruit bunches (EFB), the mesocarp fibers and the palm kernel shells. Garcia-Nunez *et al.* (2016) indicates the data about the elemental composition of each one, and by this mean the Lower Heating Value can be calculated. Once the biomass shows a fine Heating Value for power generation, the cogeneration it is proposed. For a complete analysis of the cogeneration, a typical steam cycle was defined which have a boiler, a back pressure turbine, and pumps. The steam demand is given by the integrated drying process. The power demand is given by the amount of electricity consumed in a mill, up to 38 kWh/ton of FFB (Arrieta *et al.*, 2007). In agreement with models of Ayodele and Cheng (2016) and Luk *et al.* (2013), the steam enters the turbine at 6 MPa. The steam's extractions are 1,2 MPa and the exit 300 kPa (Luk *et al.*, 2013). The isentropic efficiency of pumps and turbine are set in 80 % and 85 %, respectively (Wylen *et al.*, 2003). The boiler's efficiency is 70 % and its work temperature is 350 °C (Coronado *et al.*, 2007). The flow chart presented in the Fig.(1) shows the step-by-step which was used in this work.

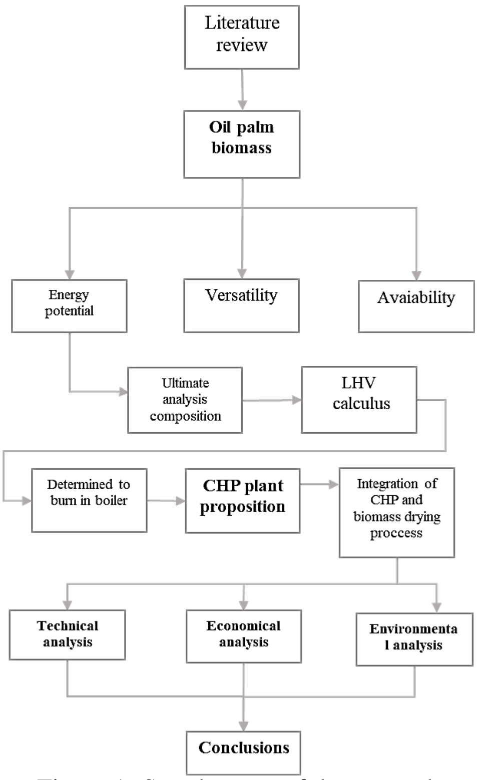


Figure 1: Step-by-step of the research

The residual biomass is given by a portion of the Fresh Fruit Bunches (FFB) processed in the mill. It is obtained 22 % EFB, 13,5 % MF and 5,5 % PKS (Chiew *et al.*, 2011), once the station works with 230 tons per hour (Delivand and Gnansounou, 2013). For the analysis of the biomass as a fuel, the Lower Heating Value (LHV) is calculated based on the composition by the Eq. (1) (Cortez, 1997). The composition and the available feedstock are shown in Tab. 1.

$$PCI = 339.C + 1030.H + 29000.(O - S) + 24.U \tag{1}$$

Table 1: Available feedstock and biomass' composition

	Available feedstock (kg/s)	Composition (%) C	H	O	N	S	Cinzas
EFB	8.625	47.5	6.8	37.9	0.9	0.1	6.9
MF	14.056	50.2	7.1	38.2	1.2	0.1	3.3
PKS	3.514	54.4	6.6	36.8	0.8	0.03	1.4

2.2 Biomass drying

According to the study of Luk *et al.* (2013), the palm oil residual biomass has a high moisture content, around 60 % and for a good combustion reaction, this value should be around 10 %. In this study, the results presented the information that the best procedure is drying by stages, first the mechanical procedure which reduces humidity by 10 to 12 %. After that it is usual to applicate thermal drying, the moisture content goes down from 48 % to 36 % in the first stage and after this, in the next stage, to 10 %. The thermal drying stages are named first and second and the heat of drying for both are calculated by Eq. (2).

$$\dot{Q}_{sec} = \dot{m}L_v(U_i - U_f) \tag{2}$$

The biomass to be dried flow rate is given by $\dot{m}$, the L_v is the latent heat of vaporization of water, 2264.7 kJ/kg. U_i and U_f are the moisture content before and after the drying process. The use of the Eq. (2) gives the minimum heat requirement for drying, in the first stage is 7118.723 kW and in the second 15423.9 kW.

2.3 Technical Analysis

The mass and energy balance in the boiler was given considering air excess of 160 %, thus the produced steam power the turbine. Are calculated shaft power and net power of the turbine the power consumed by the pumps and the flow of supplementary fuel, which is diesel. The electricity power production (E_P), the effective thermal power used for each drying process and the total quantity (E_C), the power supplied by the fuel (E_{comb}), the electrical, thermal and global efficiencies were also calculated parameters.

For each device in the cycle were determined the energetic and exergetic efficiencies. According to Tsatsaronis (2007), the exergetic efficiency (ζ) is a concept that indicates the ration between the exergy that leaves the system and the exergy effectively used.

2.4 Economical Analysis

For an oil palm mill integrated with cogeneration plant, the cost analysis includes equipment acquisition, maintenance, the production cost of heat and power and labor cost. To account the costs of acquisition and installation of boilers, turbines, pumps, and heat exchangers for biomass drying considering safety systems and isolation was applied the methodology and the cost function equations, developed by Frangopoulos (1992), Eqs. (3), (4), (5), and the Eq. (6) is based on the work of Calise *et al.* (2014). The main fuel cost varies with the chosen price for biomass acquisition (0-0,05 US$/kWh) and the supplementary, diesel oil, is the current market value. Garcia-Nunez *et al.* (2016) established that the cost of acquisition of residual biomass is zero because it is a product of palm oil extraction. However, in this study this value varies.

The total investment (I_{PL}) is the sum of all costs of acquisition plus a safety factor of 1,3 defined by Silveira (1994) that covers extra costs such as transportation and insurance. The maintenance cost for each devide is fixed in 3 % of its acquisition costs, and the cycle works for 6000 hours per year (Arrieta *et al.*, 2007). Coronado *et al.* (2007) explained that the cost of production of heat and power(C_V and C_{EL}) varies with the total investment, acquisition cost of fuel(C_{comb}) and thermal and electrical efficiencies (η_T and η_{El}). Therefore, the costs of production are calculated by the Silveira (1990) methodology, Eqs. (7), (8), (9), (10), (11), (12), (13), where F_{EP} and F_{EC} are balance factors, C_{PO} is the labor cost based on the salary(SAL_m) and the number of workers (N_T) and f is the annuity factor.

$$C_{boiler} = 784.H_v^{0,8}\left[1+\left(\frac{1-0,9}{1-\eta}\right)^7\right]\left[1+5.exp\left(\frac{T_{out}-866}{10,42}\right)\right]\left[exp\left(\frac{P_{out}-28}{150}\right)\right] \tag{3}$$

$$C_{ST} = 7490.E_P^{0,7}\left[1+\left(\frac{1-0,95}{1-\eta_{ST}}\right)^3\right]\left[1+5.exp\left(\frac{T_{out}-866}{10,42}\right)\right] \tag{4}$$

$$C_{pump} = 3540.\dot{W}_P^{0,71}\left[1+\left(\frac{1-0,8}{1-\eta_P}\right)^3\right] \tag{5}$$

$$log(C_{HE}) = 4,6656 - 0,1557.log(A) + 0,1547.[log(A)]^2 \tag{6}$$

$$F_{EP} = \frac{E_P}{E_P + E_C} \tag{7}$$

$$F_{EC} = \frac{E_C}{E_P + E_C} \tag{8}$$

$$C_{PO} = \left(\frac{SAL_m}{720}\right).N_T \tag{9}$$

$$q = 1 + \frac{r}{100} \tag{10}$$

$$f = \frac{q^k * (q-1)}{(q^k - 1)} \tag{11}$$

$$C_{EL} = \frac{I_{PL}.f}{H.E_P}.F_{EP} + \frac{C_{comb}}{\eta_{El}} + \frac{C_M.F_{EP}}{E_P} + \frac{C_{PO}.F_{EP}}{E_P} \tag{12}$$

$$C_V = \frac{I_{PL}.f}{H.E_C}.F_{EC} + \frac{C_{comb}}{\eta_T} + \frac{C_M.F_{EC}}{E_C} + \frac{C_{PO}.F_{EC}}{E_C} \tag{13}$$

As cited above and in accord with Arrieta *et al.* (2007), the electricity demand varies with the available feedstock in the mill, 38 kWh/t of FFB. Considering 230 t/h, the consumed power was 8740 kW. In this case, there is an electricity surplus, thereby this can generate income. The National Agency of Electriciy(ANEEL) indicated the medium purchase cost($C_{El,con}$ for industrial class in the year of 2018, 133,90 US$/MWh (ANEEL, 2018). The produced steam has a conventional price($C_{V,con}$) of 0,015 US$/kWh (Silveira and Stocco, 1997). The income for electricity(GP_{EL}) and heat(GP_V) is given by Equations (14) and (15). The Net Present Value (NPV) indicates the current value of the investment after each year, whereas the incomes are incorporated, Eq (16). The CF is the annual income from the produced heat and power, Eq (17).

$$GP_{EL} = E_r.H.(C_{El,con} - C_{El}) + (E_P - E_r).H.(P_{v,ele} - C_{El}) \tag{14}$$

$$GP_V = E_C.H.(C_{V,con} - C_V) \tag{15}$$

$$NPV = IPL - \sum_0^n \frac{CF}{(1+i)^n} \tag{16}$$

$$CF = GP_{EL} + GP_V \tag{17}$$

2.5 Environmental Analysis

The environmental approach quantifies the designated impact, what can it be or not a justification from the biomass use for power generation. In their study Aghbashlo *et al.* (2018) stated that the conversion of biomass to energy contributes to relief the environmental impact associated with its discard. The methodology developed by Cardu and Baica (1999) is called Ecological Efficiency (ε) and quantifies the pollution of a thermoelectrical plant considering the burn of 1 kg of fuel. First it is calculated the amount of equivalent carbon dioxide, which considers the emissions of carbon dioxide, sulfur dioxide, nitrogen oxides, and particulate material. by Eq. (18). Then the pollution indicator is calculated, Eq. (19), and then finally the Ecological Efficiency by Eq. (20) (Coronado *et al.*, 2014).

$$(CO_2)_{eq} = M_{CO_2} + 666.M_{SO_2} + 1000.M_{NO_x} + 222.MP \tag{18}$$

$$\Pi_g = \frac{(CO_2)_{eq}}{PCI} \tag{19}$$

$$\varepsilon = \left[c.\frac{\eta}{\eta + \Pi}.Ln(K - \Pi)\right]^Z \tag{20}$$

Table 2: Results of energy evaluation of cogeneration

Technical analysis	Unit	
Turbine's netpower output	MW	58.12
Electricity generation	MW	55.22
Thermal energy generation	MW	310
Power supplied by the fuel	MW	467.88
Electrical efficiency	%	11.8
Thermal efficiency	%	65.3
Global efficiency	%	77.1

Table 3: Exergetic efficiency of the devices

Device	Exergetic efficiency (ζ)
Boiler	62.2 %
Steam Turbine	73.2 %
Pump 1	51.8 %
Pump 2	51.8 %
First stage dryer	38.02 %
Second stage dryer	31.93 %

3. RESULTS

From the technical analysis, the generation of energy was mensurated. The number concerning the plant efficiency were consistent with the combined heat and power concept. The produced heat was more than enough to supply the drying processes and the amount of surplus electricity showed great potential as a source of income, once the plant offers 46.5 MW of excedent electricity. The results for energy supplied, produced and efficiencies are shown in Tab. (2).

From an exergetic point of view, among all the devices in the cycle, the heat exchangers used in the drying processes were the ones with the biggest irreversibilities. The exergy efficiency of both drying stages is 38 % and 31.9 % respectively. All the exergetic efficiencies of the devices on the system are presented in Tab. (3).

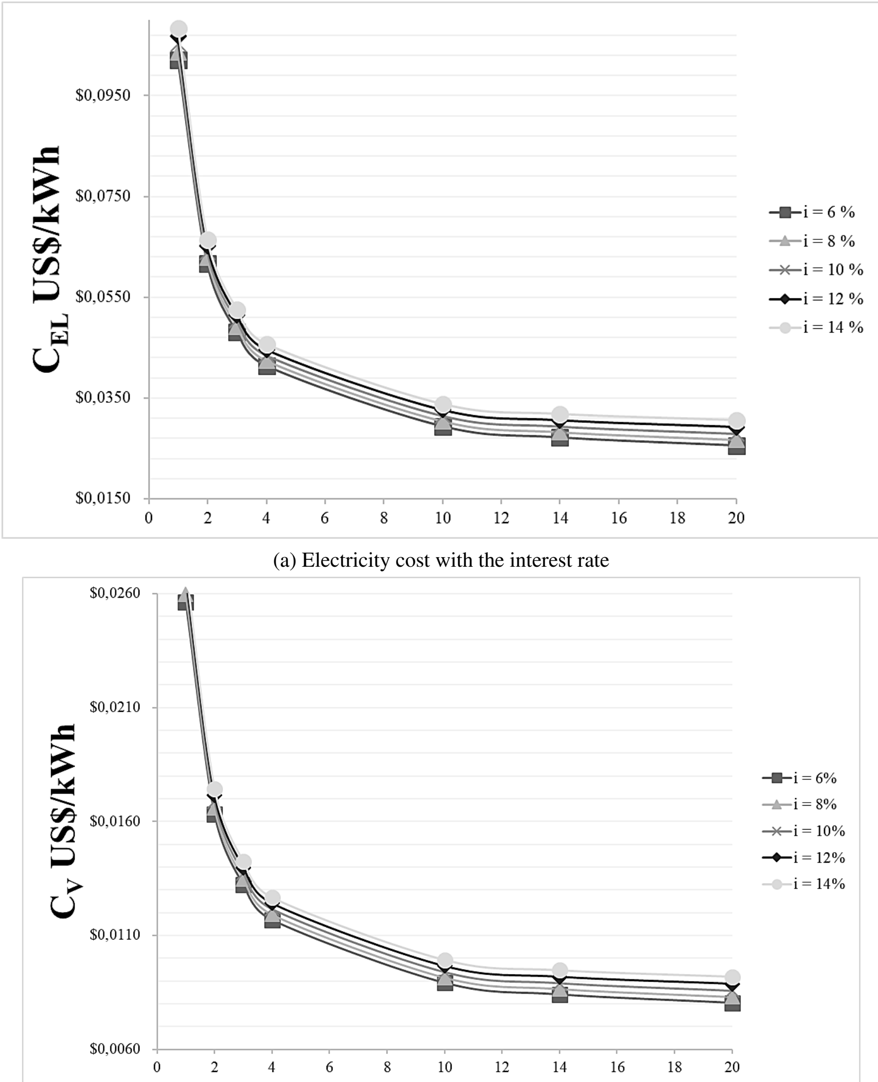
The total investment to integrate the cogeneration system passes 69 million dollars. The Tab. (3) presents the costs of acquisition and maintenance of the equipment that are set in the system, and also presents the cost with labor and the total investiment in the plant.

Fixating the selling price of the produced electricity in 0,107 US$/kWh the annual revenue and the payback period are calculated, varying the annual interest rate (i). The graphs in the Fig. (2) exhibits the variation of the production cost of electricity (C_{EL}) and heat (C_V) with certain interest rates.

As cited in the literature the acquisition of biomass usually happens without cost (Garcia-Nunez *et al.*, 2016), however, this work establishes a variation in these value for comparison purposes. The Fig. (3) shows the variation of the production cost for 6 % of interest rate considering different acquisition costs for the biomass.

Table 4: Costs associated with the presented plant

Parameter (Unit)	
Acquisition cost of the Steam Turbine (in million dollars)	16.207
Acquisition cost of the Boiler (in million dollars)	33.627
Acquisistion cost of the pumps (in million dollars)	2.941
Maintenance cost of the Steam Turbine (US$)	486,232.38
Maintenance cost of the Boiler (US$)	1,008,830.81
Maintenance cost of the Pumps (US$)	88,258.35
Maintenance total cost (US$/h)	268.32
Total labor cost (US$/h)	33.33
Total Investment on the Plant (in million dollars)	69.76



(a) Electricity cost with the interest rate

(b) Heat cost with the interest rate

Figure 2: Production cost of heat and electricity variation with the interest rate

The payback graphic plots the NPV after each year of the plant lifetime for an interest rate fixed, in this case, 6 %. With this, the plotted curves differ from each other by the acquisition cost of the biomass. And it is shown in Fig (4) that when is considered the zero cost of biomass the period of payback is shorter, and as expected, as higher this cost more time is needed to the investment pay off.

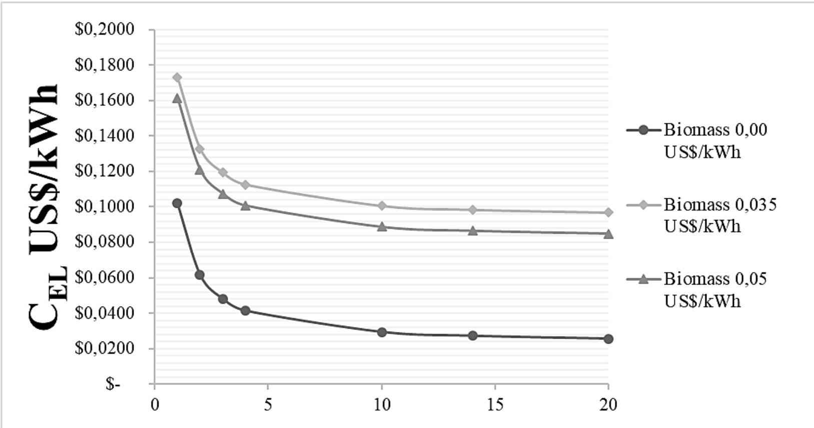
The ecological efficiency evaluates the designated environmental impact on thermoelectric powerplants by means of emissions of CO_2, NO_x, SO_2 and particulate matter. This parameter is assigned to a percentual scale and as greater the number the less polluter is the plant. The ecological efficiency also depends on the cycle's global efficiency in an almost linear way, as shown in Fig (5). From the technical analysis, the cogeneration plant's global efficiency is 77.2 % and for that, the ecological efficiency is 62 %. In order to calculate the efficiency of Cardu and Baica, the pollution index (Π) is determined for each kind of biomass (EFB, MF and PKS) based on the equivalent emissions of CO_2 and for the combination of them all (MIX). The Tab. (5) shows the emission comparison.

4. CONCLUSIONS

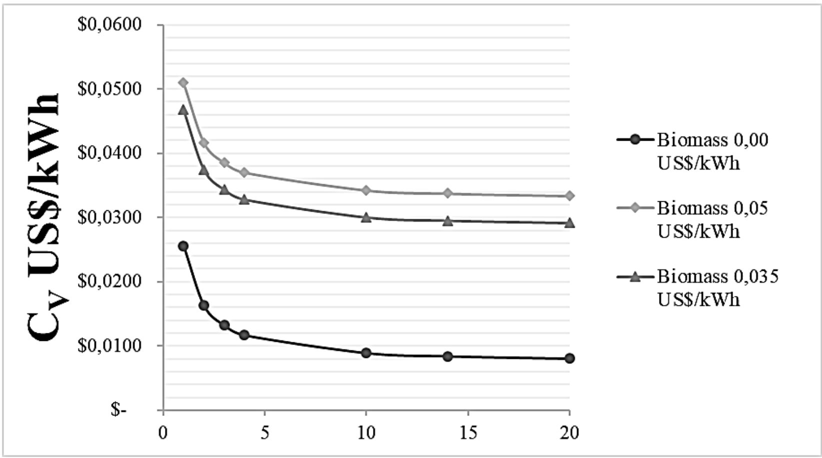
The work presented an integrated cogeneration station in the oil palm industry. The operation parameters were set, and analysis technical, economic, and environmental were carried out. The aim of this work was to utilize all the supply of residual biomass generated in the milling process in order to generates power and minimize the disposal issue. The palm cultivation is a seasonal culture and then the electrical power surplus may vary over the year.

The cogeneration coefficient beta, which is the ratio between the produced heat and power, was found to be 0.18 and thus consistent with what the literature presents in this kind of plant.

The calculated cost of production for heat and power were considered low, what can be justified by the biomass cost.



(a) Electricity production cost comparison



(b) Heat production cost comparison

Figure 3: Comparison of the cost of production for power and heat with the variation of biomass acquisition cost

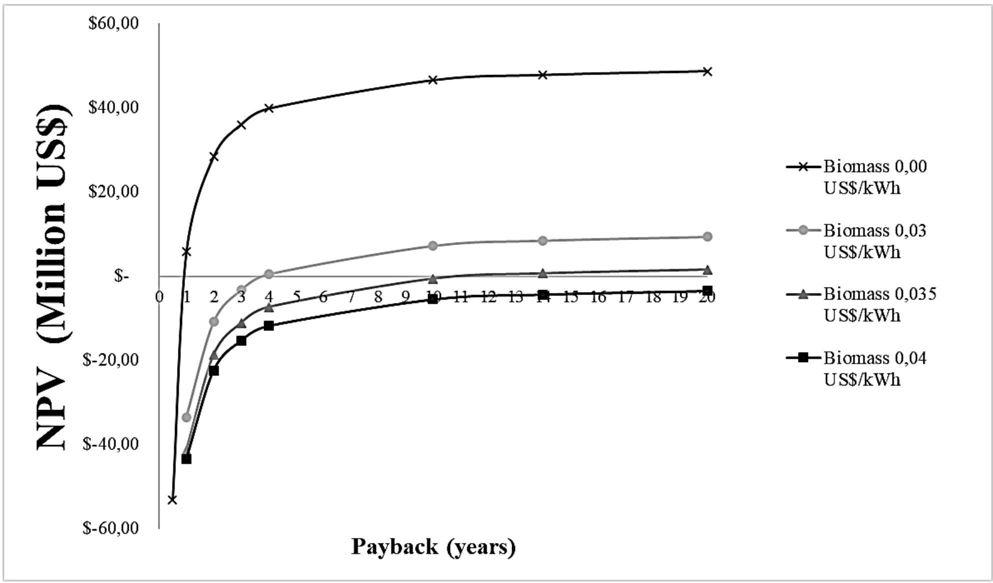


Figure 4: Payback period of the plant for different cases

For an interest rate of 8 % and payback period of 4 years, the production cost of heat and power were 0.012 US$/kWh 0.0425 US$/kWh, when is not considered the cost of biomass acquisition. For the electricity tariff, the calculated value is way smaller than the one charged by the power distribution company. And the produced heat show a bigger cost than the defined by Silveira and Stocco (1997) as conventional cost. The amount of heat produced is more than enough to supply the drying stages, therefore the surplus could be used to supply district heating or to supply a system that produces more electricity, as in Arabkoohsar and Nami (2019). Also, could be used along with ARS technology to produce cold water

Table 5: Equivalent emissions and pollution index of the biomass' fuel and their mixture

	$CO_{2\,eq}$ (kg CO_2/kg fuel)	Π_g
MF	6.7856	0.3645
PKS	7.1829	0.3651
EFB	6.4402	0.3696
MIX	6.7506	0.3726

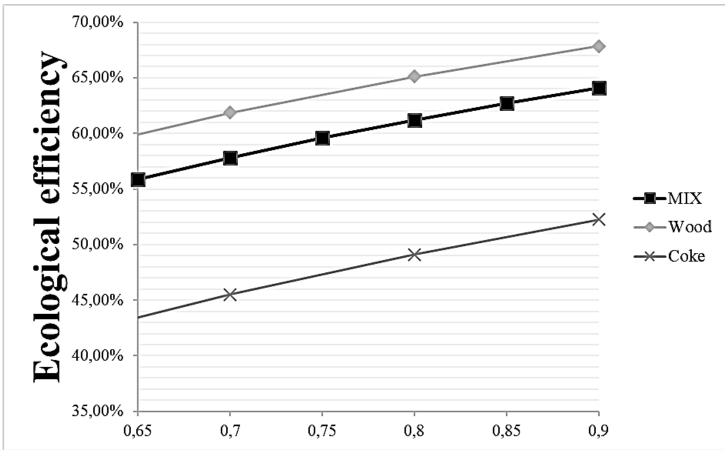


Figure 5: Variation of the ecological efficiency with the system's global efficiency

(Silva *et al.*, 2019)

The payback period varies with the respectively cost of production for heat and power. The scenario which the cost of biomass acquisition is 0,035 US$/kWh shows that the project pays off in ten years. The worst scenario was the one with biomass's cost of 0,04 US$/kWh, the plant does not pay itself. In the scenario where there is no cost for biomass acquisition the return of investment is obtained in the first year of operation. Compared to the work of Xavier *et al.* (2015) and Coronado *et al.* (2007) that pointed payback between 2 and 3 years, therefore, the integration is economically viable and even more seen that the system have a 25 years life.

In environmental matters, the biomass if compared with fossil fuels are less pollutant. Among the three types of fuel, the pollution indicator was bigger for PKS which showed bigger emissions of CO_2, SO_2, NO_x, and particulate matter. Regarding the ecological efficiency, the literature presents numbers very similar operating with diesel and also better results for glycerol and natural gas, as in Coronado *et al.* (2014) and Lora and Salomon (2004). Nevertheless, it is possible to conclude that environmentally the integration is promising because solves a disposal issue, make the mill self-sustainable, it is less polluting than fossil fuels in addition to being a source of income due to the surplus electricity.

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