Comparison of biomethane and syngas production as energy vectors for heat and power generation from palm residues: A techno-economic, energy and environmental assessment

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Abstract

The production of energy vectors such as syngas and biomethane from lignocellulosic feedstocks has been postulated as one alternative to produce heat and power to supply the energy needs of industrial processes. Nevertheless, the in situ production of these fuels in a cogeneration plant have not been deeply studied. The objective of this work was to compare from technical, economic, energy and environmental perspective the heat and power generation using syngas and biomethane as fuels produced from the gasification and anaerobic digestion of the oil palm rachis residues generated in Colombia. The heat and power production of these fuels was evaluated taken into account the conceptual design of a cogeneration plant. Then, the proposed processes were simulated using the software Aspen Plus to obtain the mass and energy balances to be used in the technical and energy assessment. Besides, the economic analysis was performed using the commercial software Aspen Process Economic Analyzer to calculate the CAPEX and OPEX of the proposed processes in the Colombian context. At last, the environmental assessment was realized through the global warming potential calculation. The obtained results shows that the biomethane use in a CHP plant can produce more power than the syngas only if a pretreatment step in the biomethane production process is accomplished. Finally, it was concluded that both energy vectors are good option to produce heat and power. However, the syngas from biomass gasification is a better option to produce industrial utilities due to the high steam yields and low implementation costs.

Keywords: Renewable energy, cogeneration, syngas, biomethane, palm residues.

1. Introduction

The increasing energy demand to provide the worldwide needs has increased due to the recent technological advances reached in the last years [1]. These needs have been supplied using non-renewable energy sources such as coal, oil and natural gas. However, the energy obtained from these products or its derivatives has caused many damages from the environmental point of view through the greenhouse gases emissions, solid waste generation and natural resources pollution [2], [3]. On the other hand, the task to ensure an uninterrupted and sufficient energy supply has been one of the most important and difficult challenges assumed by different countries. In accordance with the above, the alternative energy sources used to diversify the energy market and to reduce the oil-derived products dependence becomes an important issue [4], [5].

One of the most researched primary energy source is the lignocellulosic biomass generated in different agro-industrial processes due to its great potential to produce heat and power through combustion processes [6]. However, this process have some technological problems related with the combustor fouling and corrosion produced by the alkaline nature of biomass ash as well as health problems caused in small-scale applications [7], [8]. As alternative, lignocellulosic biomass can be processed to produce secondary energy sources in form of liquid and gaseous biofuels (e.g. bioethanol, biomethane and syngas) which are produced from biochemical and thermochemical pathways [9].

Nowadays, bioethanol is mainly used as complement of gasolines in the transport sector and it is not used for utilities generation [10]. In the other hand, syngas and biomethane are two energy carriers that are used in the energy sector as fuel for heat and power generation or even, these ones can be used as chemical platforms to produce high added-value products. It is for these reasons that different companies around the world produce them in small, middle and high scale, recently. [11]. The use of biomethane or syngas to produce heat and power, generally, is matching with a cogeneration plant composed by a gas turbine, heat recovery steam generator (HRSG) and a steam turbine [12].

Colombia is a developing country that generates a great amount of lignocellulosic biomass from the oil palm crop. The above is because of the oil palm crop is the third most important crop preceded by coffee and corn in this country. Oil palm crop covers 500,000 ha distributed in four zones (i.e. East, North, Central and South-West) and produced around of 1,272,522 tons of palm oil in 2015 [13]. From this crop a large quantity of residues such as empty fruit bunches (EFB), oil palm trunks (OPT), oil palm leaves (OPL) and oil palm rachis (OPR) are generated and they do not have any specific application [14]. Therefore, these agro-waste represent a source of lignocellulosic biomass that can be used to produce biomethane and syngas for heat and power generation at small, middle and high scale.

The objective of this work is to compare from technical, economic, energy and environmental perspective the heat and power generation using syngas and biomethane as fuels produced from the gasification and anaerobic digestion of the OPR residues produced in the central zone plantations of Colombia.

2. Methodology

2.1. *Characterization of OPR*

OPR was collected from oil palm crop located in the following coordinates at Puerto Salgar municipality, Cundinamarca, Colombia, localized at latitude 5°42'46.2" north and longitude 74°34'56.4" West. The raw material was dried at 50°C inside a convective furnace and it was subjected a grinding process using a knives mill to reduce the particle size until ASTM 40 sieve. The samples were stored until its characterization at room temperature.

A proximate analysis was carried out following the ASTM standards and the lignocellulosic content was reported according to the National Research Energy Laboratory (NREL) and Rabemanolontsoa and Saka protocols [15]–[17]. A briefly description of the last one procedures is presented. The moisture content was determined using the electronic moisture balance MOC-120H. For the extractives content was used a two steps soxhlet extraction with distilled water and ethanol (98%). Then, the OPR free-extractives was subjected at chlorination method to obtain the holocellulose content (i.e. cellulose and hemicellulose) and two step acid hydrolysis for the acid insoluble lignin. From the holocellulose the alpha-cellulose fraction was determined with acetic acid solution (10% v/v) and sodium hydroxide solutions (i.e. 17.5% w/v and 8.3% w/v). Both analysis were realized in order to perform the simulation and identify the energy potential of the OPR in terms of the high heating value (HHV) using the empirical equations proposed by Shen et al [18].

2.2. *Processes description and simulation procedure*

The proposed processes (i.e. heat and power production from syngas and biomethane) were conceptually designed using process engineering tools, reported yields and stoichiometric approaches. Thus, in this work three scenarios are performed in order to compare the biochemical and thermochemical pathways efficiencies. In the scenario 1, the gasification was selected as a thermochemical route to transform the OPR in syngas and in the other two the anaerobic digestion (AD) was used as a biochemical route to obtain a precursor of biomethane. However, in order to shows an improvement in its production the OPR in scenario 3 was submitted to a pretreatment stage. The scenarios were simulated using the software Aspen Plus with a plant capacity of 20 ton OPR/h. In the simulation, the liquid and vapor phase in each process were modelled using the Non Random Two Liquids activity model and the Soave Reldich-Kwong EoS. The thermodynamic properties of cellulose, hemicellulose and lignin were taken from the NREL reports [19].

2.2.1. *Syngas production*

Syngas is the main product obtained from biomass gasification. This is a carbon monoxide, carbon dioxide, hydrogen and methane gas mixture [20], [21]. However other gases such as nitrogen can be present depending of the gasifying agent (e.g air, oxygen and steam). The syngas production using OPR as raw material is composed by two stages mainly. The first stage is to reduce the raw material particle size from 15 cm to 2 cm using the crusher model available in the solids section of the software. The second stage is the OPR gasification using air as gasifying agent in a downdraft gasifier. The equivalence ratio used was 0.5. Nevertheless, the software does not have a gasifier model. For this reason, its simulation was divided in three steps: pyrolysis, combustion and reduction.

The pyrolysis step considers the raw material devolatilization in anoxic conditions. This was simulated using the stoichiometric approach reported by Sharma [22] applied to the lignocellulosic components (i.e. cellulose, hemicellulose and lignin). At last, it was considered that this process occurs at 600°C. The main products obtained are char (C), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water (H_2O), light hydrocarbons modelled as methane (CH_4), and heavy hydrocarbons (i.e. tar) modelled with the empirical formula ($C_6H_6O_{0.2}$) [22], [23].

The combustion step is related with the oxidation of the pyrolysis products. This one was modelled using the kinetic expressions reported by Tinaut et al [24] and it was simulated using a yields reactor (RYIELD block). Finally, the char produced in the pyrolysis and combustion passes to the reduction step where char gasification takes place to produce CO_2, CO, H_2 and CH_4 [20] using a RGIBBS reactor to describe the multiphase equilibrium of the system based on the free Gibbs energy minimization method. The remainder char and ashes from the gasification of the OPR are separated from the syngas using a cyclone. The overall syngas production process described above is presented in **Fig. 1**.

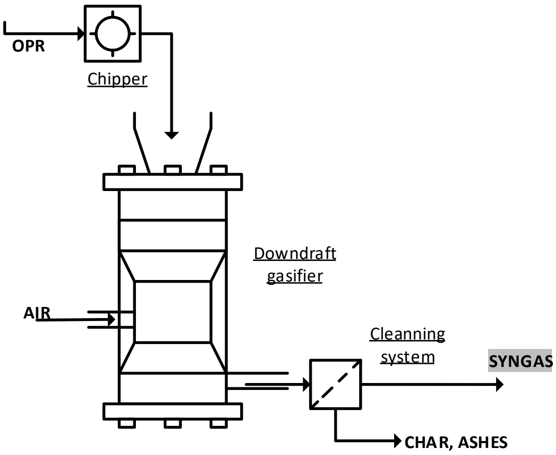

Fig. 1. Process flow diagram of the OPR gasification using a downdraft gasifier.

2.2.2. *Biomethane production*

Biomethane is the main product obtained from the organic matter decomposition in AD process after an upgrading step. However, its production can be improved using a pretreatment stage. Therefore, two scenarios were simulated. The scenario 2 consists in three stages: particle size reduction, AD and biogas upgrading, while for the scenario 3 a liquid hot water (LHW) pretreatment was applied previously to the AD as shows **Fig.** *2*. The selection of this technology was based in the pretreatment effect on oil palm fronds (OPF) and anaerobic digestion of materials with similar composition [25]–[29]. Moreover, the key factors mentioned by Alvira et al. 2010 also were considered [30].

In the particle size reduction was considered the milling with the help of shredders to obtain a maximum particle size of 2.0 mm and comminution to enable a particle size distribution between 0.1-1.0 mm [27]. After the physical unit operation, the ground OPR was submitted to the LHW pretreatment with conditions of 175 °C, 10 bar and liquid solid ratio of 8.0 (v/w) due to the improvement of the OPF digestibility [27]. The compositional changes in that work were assimilated during simulation as a conversion of each lignocellulosic component into lignocellulosic soluble and monosaccharides compounds. In the AD were used the yields and conditions reported by Kaparaju et al. [31] (i.e. thermophilic conditions and substrate inoculum ratio of 46.92 %wt. volatile solids). This assumption was used due to the similarity of OPR with wheat straw in its lignocellulosic composition, volatile solids content and fibril appearance. The AD and pretreatment stages were simulated with RSTOIC blocks applying for each lignocellulosic component the empirical and primary stoichiometric equations proposed by Buswell and Demirbas et al. 2005 (i.e. for the cellulose and hemicellulose hydrolysis during pretreatment) [32], [33]. Finally, in the biogas upgrading to biomethane was used the technology of water scrubbing where water absorbs CO_2 content of biogas [34]. The equipment involved in this stage were specified in the simulation as describe Cozma et al. [35].

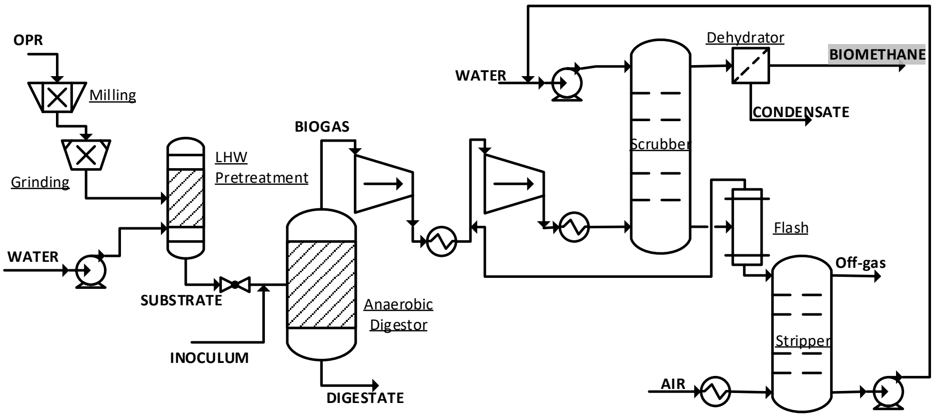

Fig. 2. Process flow diagram for the biomethane production with LHW pretreatment.

2.2.3. *Cogeneration system*

The cogeneration or CHP plant simulated is composed by a gas turbine, HRSG and steam turbine. Each one of these elements is described as follows and presented in **Fig. 3**. The gas turbine uses the fuels generated by gasification and AD to produce power and combustion gases. It is composed by a series of two compressors, one burner and two turbines in an intercooling, reheating and regenerative cycle (ICRHR). This type of turbine was selected to be used in the simulation due to the high thermal efficiencies obtained in comparison with the simple cycle gas turbines. The above is achieved due to this cycle decrease the heat input requirements of the system. The ICRHR gas turbine uses atmospheric air (288 K, 1 bar) in excess to ensure complete syngas or biomethane combustion. The compressors used in the cycle as well as the turbines have the same pressure ratio with the end to improve the power outputs and inputs, respectively [36]. The combustor was simulated using a RSTOIC block. The main characteristics of the simulated gas turbine are presented in **Table 1**.

Table 1
Main characteristics of the simulated gas turbine.

Item	Value	Item	Value
Compressors pressure ratio	10.0	Turbine pressure ratio	5.0
Compressor isentropic efficiency	85.0%	Turbines isentropic efficiency	90%
Intercooler pressure drop	1.0%	Reheater pressure drop	2.0%
Boiler pressure drop	5.0%	Turbine entrance temperature	1600.0 K
Air – fuel ratio	6.4	Equivalence ratio	4.0

The out gases from the gas turbine are mixed and combusted with more fuel (i.e syngas or biomethane) with the end to rise up its temperature. This secondary combustion is performed in a firing system that was modelled as a RSTOIC block. The hot gases from this system were carried out to HRSG system comprised for three steam generators that produces steam at different pressures and temperatures. All the steam generators are composed by an economizer to rise the water temperature until its saturation point, an evaporator that supplies the necessary heat to transform the saturated liquid in a saturated steam and a super heater that rises the steam temperature over its saturation point. Furthermore, only in the HP-steam generator was considered an attemporator with the end to prevent damages in the HP-turbine [12]. The HRSG system was modelled using the HeatX and Flash2 blocks to give a HP-Steam at 60 bar, IP-Steam at 30 bar and LP-Steam at 3 bar. Also, it was simulated taken into account a flue gases temperature of 60°C in all cases. Finally, the steam produced in the HRSG unit was sent to a high and middle pressure steam turbine with the end to produce more power.

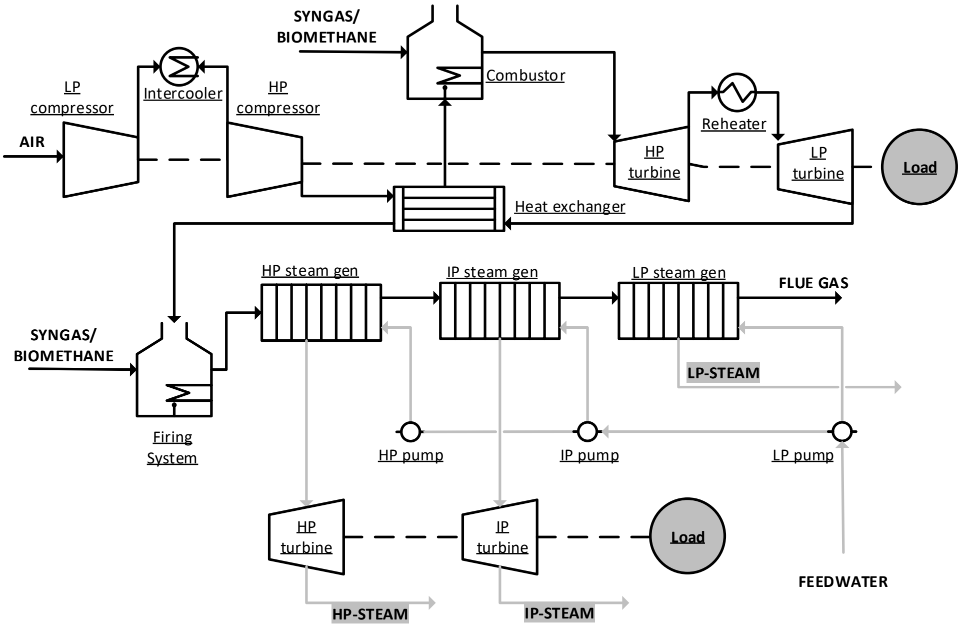

Fig. 3. Process flow diagram of cogeneration system plant**.**

2.3. *Energy assessment*

The energy evaluation of the proposed scenarios was developed taken into account the thermal efficiency of the gas turbine for all scenarios. This one was calculated as the ratio between the net work output of the system and the total heat input and it was denominated as n_{th}. Also, the net energy balance (NEV) was calculated taken into account the amount of energy in the products (i.e. steam and power) compared with the energy needs of the process [20].

2.4. *Economic and environmental assessment*

The economic assessment was performed using the commercial software Aspen Process Economic Analyzer (Aspen Technology Inc., USA) to calculate the Capital Expenditures (CAPEX) (i.e. equipment costs) and Operational Expenditures (OPEX) (i.e. utilities, maintenance, operating labor cost) of each scenario [37], [38]. As input data, the results of the material and energy balances are supplied. For developing the scenarios in the Colombian context were used the typical prices and economic data for this country. Thus, the water value was 0.74 USD/m3, HP-steam value was 9.86 USD/ton, IP-steam value was 8.18 USD/ton, LP-steam value was 1.57 USD/ton, electricity value was 0.1 USD/kWh [39] and the raw material considered price was 19.40 USD/ton [40]. The labor wages for operators and supervisors were 2.56 USD/h and 5.12 USD/h, respectively[41]. In addition, this analysis was performed considering the straight-line method for the capital depreciation calculation involving an annual interest rate of 17.0% and a 25.0% of tax rate in a 10-year period. The environmental assessment was achieved through the calculation of the global warming potential of all scenarios defined as the mass ratio between the CO_2 emissions and raw material [42].

3. Results and discussion

3.1. *OPR chemical composition*

The OPR composition results was compared with other oil palm residues such as EFB and palm press fibers (PPF) reported by Gutiérrez et al [43]. It was found that the OPR has a higher holocellulose content than the EFB and PPF. This means that this raw material can be used to produce C_5 and C_6 sugars that can be used in the AD process. On the other hand, it low ash content and physical appearance can be used in thermochemical applications. The same conclusions can be obtained from the proximate analysis results due to the high volatile matter and total solids ratio of the OPR. In addition, the HHV obtained for this raw material suggest that this one has a high energy content to be used.

Table 2
Chemical composition and proximate analysis of the OPR.

Oil palm rachis			
Chemical Composition [% wt.]		**Proximate analysis [% wt.]**	
Moisture	9.682	Moisture	11.713
Extractives*	15.157	Fixed Carbon*	14.728
Cellulose*	40.811	Volatile Matter*	80.458
Hemicellulose*	22.478	Ash*	4.814
Lignin*	16.838	HHV (MJ/kg)	18.565
Ash*	4.715		

*Dry basis.

3.2. *Technical and energy assessment*

The yields obtained from the simulations of scenarios 1, 2 and 3 were calculated and compared to each other. The syngas composition obtained from the simulation was 13.5%, 15.5%, 9.0% and 60.0% of CO, CO_2, H_2 and N_2, respectively. This results are in agreement with the syngas composition reported for OPF by Atnaw et al [21]. Also, it was obtained that the syngas production has the highest mass yield in terms of fuel and steam production. However, this situation is given by the high air flow that was needed to carry out a complete combustion of the syngas in the combustion chamber inside of the gas turbine to maintain an equivalence ratio of 4.0. In contrast, the biomethane composition obtained in both scenarios after the upgrading step was 94.4%. Nevertheless, the scenario 3 achieved a higher fuel and steam yields than the scenario 2. The summary of the mass yields obtained in each scenario is presented in **Table 3**.

Table 3.
Mass yields obtained from the simulation procedure

Scenario	**Fuel yield [kg fuel/kg OPR]**	**Total steam yield [kg steam/kg OPR]**
1	3.60	3.50
2	0.21	2.75
3	0.26	2.37

The above results do not necessary implies that the syngas production process is the best option to produce heat and power in the proposed cogeneration plant. The above is performed to give a series of characteristics from different points of view to identify the advantages and disadvantages that each technology can offer. In this sense, the energy analysis can provide more information related with the considered scenarios. The energy analysis was carried out calculating the low heating value of the syngas and biomethane generated, the thermal efficiency of the gas turbine, the net energy value and the global efficiency of the process. These results are presented in **Table 4**.

Table 4.
Energy parameters of the scenarios.

Scenario	**LHV [kJ/kg]**	**n_{th} [%]**	**Generated Power [MW]**	**NEV [kJ/kg OPR]**
1	6.98	41.8	23.7	28574

2	26.1	39.5	20.2	26603
3	47.4	52.2	43.5	23432

3.3. *Economic and environmental assessment*

The CAPEX and OPEX obtained from the economic evaluation are presented in **Fig. 4**. These results shows that the scenarios 1 and 2 have a similar capital and operational expenditures. Thus, these results suggest that the implementation of a gasification or AD without pretreatment for heat and power generation does not have a great difference under the gas turbine and HRSG stipulated conditions. Nevertheless, the amount of heat in steam form and generated power as well as the gas turbine thermal efficiency is higher than the AD process. Also, it is important to note the fact that the economic indicators are similar does not mean that the technology cost are the same. At last, these costs are related mainly with the gas turbine and HRSG capacity to allow the gas turbine stipulated conditions and the flue gases outlet temperature of 60°C. The above can be seen in the generated power in scenario 1 and the steam yield presented in **Table *3***.

Moreover, the scenario 3 has the highest CAPEX and OPEX compared with the other two scenarios. These results are attributed mainly to the gas turbine capacity due the amount of air that it is necessary to accomplish an equivalence ratio of 4.0. Therefore, the CAPEX and OPEX increase of the scenario 3 does not be related directly with the implementation of LHW pretreatment. The obtained results are in agreement with the costs of a commercial gas turbines prices which vary according to their capacity. For instance, scenarios 1 and 2 a can use a SGT-400 gas turbine to produce 15 MW and the scenario 3 can use a SGT A-45 TR gas turbine to produce 40 MW.

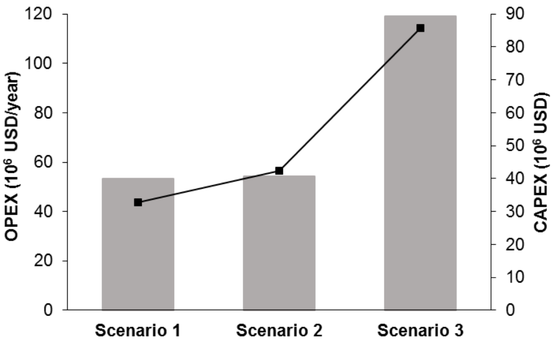

Fig. 4. Economic analysis of each scenario according to the OPEX (gray bars) and CAPEX (black line).

The global warming potential results for the evaluated scenarios implies that the amount of CO_2 generated in the outputs of scenario 3 is bigger than the CO_2 emissions in scenario 2 corresponding to 1346.93, 1294.79 kg CO_2/ ton OPR, respectively. This result is directly related with the flue gas composition leaving the CHP plant since during combustion of syngas can be produced more amount of CO_2. While the emissions of biochemical pathway are derived mainly for the biogas upgrading process which intensifies when the yield of biomethane is achieved having the scenario 3 a value of 1294.79 kg CO_2/ ton OPR

4. Conclusions

The results of this work leads to conclude the potential of the OPR as raw material to produce fuel gases through thermochemical and biochemical pathways. On the other hand the syngas and biomethane use to produce heat and power are possible from the techno-economic, energy and environmental point of view. Nevertheless, the syngas is a more suitable option because this one obtained the highest steam yields and low costs. The above is concluded without regarding that the AD process is an essential part of the future biorefineries and a technology that can be improved through the raw materials pretreatment.

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