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Technical-economic Analysis of Power Generation with Steam Cycles Fed with Residual Biomass from Rice and Corn

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ABSTRACT

Technical and economic aspects for power generation based on residual biomass from rice and corn were evaluated in the department of Córdoba. The physicochemical characteristics of the biomass were determined as a blend for power generation using a conventional Rankine cycle with co-combustion, and the energy potential of the system and mass flows were determined through energy balances. Subsequently, thermodynamic analysis allowed establishing that the proposed system's efficiency is 24.4%. Regarding the effect of co-combustion in the process, it was found that increasing the fraction of rice husk in the mixture led to a reduction in net power production and an increase in cost. Finally, it was estimated that to achieve economic feasibility, a plant with a minimum of 20 MW and a generation cost of 0.172 USD/kWh is required.

Keywords: Biomass, Co-combustion, Viability, Rankine Cycle, Generation Cost
JEL Classifications: C6, O3, Q3 and Q4.

1. INTRODUCTION

The use of biomass as fuel in energy generation has gained greater importance in recent years, as it is a renewable and carbon-neutral resource that directly or indirectly impacts at least 13 of the 17 sustainable development goals (Kumar and Bhattacharya, 2021). However, studies on renewable energy tend to focus on wind, solar, and hydraulic sources, neglecting the resource of biomass, which has high potential and is crucial in reducing greenhouse gas emissions (Robles Algarín et al., 2017; Sagastume et al., 2021).

In Colombia, the agro-industry contributes 6.9% of the gross domestic product (DANE, 2023), generating the equivalent of 331638,7 TJ of energy per year in waste (Hernández Hernández et al., 2006). However, a significant portion of this potential is not utilized, as reflected in the marginal 0.8% contribution of biomass energy to the installed energy capacity in the country (UPME, 2018). Specifically, in the department of Córdoba, agriculture and livestock are the main economic activities, contributing 10.6% of the gross domestic product, and there is a need to diversify the energy mix. Therefore, the residual biomass from these industries can contribute to achieving these objectives (Mendoza et al., 2021; Sagastume et al., 2021).

The corn agro-industry is one of the most representative sectors in the department of Córdoba. According to data from the National Federation of Cereal, Legume, and Soybean Growers (FENALCE), in 2021, 54600 hectares were planted, and 201900 tons of corn were produced in the department of Córdoba (FENALCE, 2021). Similarly, rice cultivation has a significant area. In 2016, the country's rice production was 2971971 tons of rice, and the production in the department of Córdoba corresponds to 1.6% of this value (Viera Rodriguez and Angulo Zabala, 2020).

The literature presents various technical and economic studies of biomass-based energy generation systems, including Barrera (2021), who evaluated the energy potential of residual biomass from oil palm in an extraction plant in northern Colombia through a combined system with extraction-condensation turbines. In their analysis, they found that the implementation of the system would lead to a reduction in emissions of 60-80% and an average cost of electricity generation between 0.028 and 0.048 USD/kWh, which is economically attractive compared to energy sales prices in Colombia of 0.024-0.069 USD/kWh.

On their part, Rhenals and Torres (2016) conducted a technical study in the department of Cordoba to implement a maize cob gasification plant using steam as the gasifying agent for energy generation. They found that an average of 42642,69 t/year of maize cobs are generated in the department. They also obtained that the optimal operating conditions of the system lead to a generation cost of 0.025 USD/kWh.

Peña and Cárdenas (2021) conducted an energy and exergy analysis on the Rankine cycle for electricity generation using dry rice husk as fuel. The analysis of the physicochemical properties of the biomass yielded a calorific value of 14.42 MJ/kg. They also proposed a rice drying system that utilizes excess thermal energy, improving thermal and exergy efficiencies of 53% and 66%, respectively. They determined that the generated power leads to a reduction in CO_2 emissions compared to conventional energy production.

According to Sagastume et al. (2021), they studied the potential of agricultural waste available for energy conversion in the department of Cordoba. The study found that the energy potential was 548 GWh annually through anaerobic digestion and 1159 GWh annually through direct combustion. With this potential, producing 9-18% of the current electricity needs would be possible. The biogas potential corresponds to 1.4 times the energy required to replace the firewood used for cooking in 32% of the homes in the department.

In literature, works have been found that present technical and economic analyses of energy generation systems fueled by biomass. However, these works do not evaluate co-combustion alternatives as a strategy to increase system capacity. This work aims to evaluate the technical and economic feasibility of using rice husks and corn cobs for energy generation, also considering co-combustion alternatives. In addition, parametric analyses will be carried out to determine the system capacity that guarantees its economic viability.

2. MATERIALS AND METHODS

Next, the materials and methods used in the technical and economic analysis of energy generation through biomass are described.

2.1. Thermochemical Characteristics of Biomass

To study power generation with biomass, it is necessary to define some relevant characteristics of the studied biomasses beforehand. Table 1 shows the elemental composition of rice husks and corn cobs used in this work.

In this study, the higher heating value of the biomass was determined with its elemental composition according to Equation (1) (Huang and Lo, 2020). Subsequently, Equation (2) was used to estimate the lower heating value (Koppejan and Van Loo, 2012).

$$HHV = 0.3491X_C+1.1783X_H+0.1005X_S-0.0151X_N-0.1034X_O-0.0211X_{ash} \quad (1)$$

Where X_C, X_H, X_S, X_N, X_O, and X_{ash} are the mass fractions of carbon, hydrogen, sulfur, nitrogen, oxygen, and ash, respectively.

$$LHV = HHV\left(1-\frac{w}{100}\right)-2,444\frac{w}{100}-2,444\frac{X_H}{100}-8,936\left(1-\frac{w}{100}\right) \quad (2)$$

Here, w is the percentage of moisture present in the biomass.

2.2. Biomass Co-firing Analysis

For the analysis of the co-combustion of rice husks and corn cobs, the heating value of the mixture of these two biomasses was determined based on the proportions of each biomass in the mixture, according to Equation (3).

$$LHV_{mix} = x_{hr}\,LHV_{hr} + x_{cc}\,LHV_{cc} \quad (3)$$

Where x_{hr} and x_{cc} are the percentages of rice husk and corn cob, respectively. Meanwhile, LHV_{hr} and LHV_{cc} are the lower heating values of rice husk and corn cob.

In calculating the combustion heat provided by this mixture, an 80% process efficiency was considered, meaning that 20% of the heat generated in biomass combustion is lost due to heat transfer effects on the environment, as shown in Equation (4).

$$Q_{comb} = 0.8\,(x_{hr}LHV_{hr} + x_{cc}LHV_{cc}) \quad (4)$$

2.3. Power Generation System

The system studied is a conventional Rankine cycle, which is composed of four elements. Initially, liquid water enters the pump as the saturated liquid. Then, the water enters the boiler as compressed liquid, where it receives heat from the combustion of the fuel and specific biomass and exits as superheated steam. This steam enters the turbine, expands, and produces mechanical power by turning a shaft, which can be connected to an electric generator. Finally, the high-quality liquid-vapor mixture enters the condenser, which behaves like a large heat exchanger, where the heat is rejected to a specific medium. The output of the condenser is saturated liquid, which enters the pump again to complete the cycle (Cengel and Boles, 2015). Figure 1 shows the diagram of the considered cycle.

The thermodynamic parameters of the cycle are shown in Table 2.

2.4. Thermodynamic Analysis of the System

Mass and energy balances were performed for the components of the system, and with this, the net power produced by the cycle and its thermal efficiency were calculated. Table 3 presents the balances for each component of the system.

Mass and energy balances were performed for the system components, and with this, the net power produced by the cycle

Table 1: Elemental composition of biomass (Berastegui and Ortega, 2016)

Biomass	C (%)	H (%)	O (%)	N (%)	S (%)	Ash (%)	Moisture (%)
Corn cobs	39.95	4.97	46.68	0.60	0.09	7.71	10.52
Rice husks	39.27	4.91	46.8	0.59	0.10	8.33	10.18

Table 2: Thermodynamic conditions of the evaluated cycle (Barrera, 2021)

Equipment	Temperature (°C)	Pressure (KPa)	Efficiency (%)
Pump		200	70
Boiler		3000	
Turbine	450	3000	90
Condenser		200	

Table 3: Mass and energy balance equations for the system components

Equipment	Balance equation	Units
Pump	$W_{pumb}=m_{water}\,(h_2-h_1)$	kW
Boiler	$\dot{m}_{water}=\frac{\dot{m}_{mix}\cdot LHV_{mix}\cdot \eta_{comb}}{h_3-h_2}$	
Turbine	$W_{turbine}=\dot{m}_{water}\cdot(h_3-h_4)$	kW
Condenser	$\dot{Q}_{cond}=\dot{m}_{water}\cdot(h_4-h_1)$	kW
Net system work	$W_{net}=W_{turbine}-W_{pum}$	kW
Cycle efficiency	$\eta_T=\frac{W_{net}}{Q_{comb}}$	--

and its thermal efficiency were calculated. Table 3 presents the balances for each component of the system.

2.5. Estimation of System Costs

In the economic evaluation of the system, the costs of investment, operation, and maintenance were estimated. Initially, the cost of the equipment was determined using equations derived from thermo-economics, which are described in Table 4.

The heat exchange area of the condenser was calculated with Equation (5).

$$A_s=\frac{\dot{Q}}{U\Delta T_{ml}} \quad (5)$$

Where ΔT_{lm} is the logarithmic mean temperature and is calculated as shown in Equation (6)

$$\Delta T_{lm}=\frac{(\Delta T_1-\Delta T_2)}{\ln\frac{\Delta T_1}{\Delta T_2}} \quad (6)$$

For the calculation, it was considered that heat was exchanged with air at 25°C, and the overall heat transfer coefficient (U) was 700 W/m^2-K (Ehyaei et al., 2021).

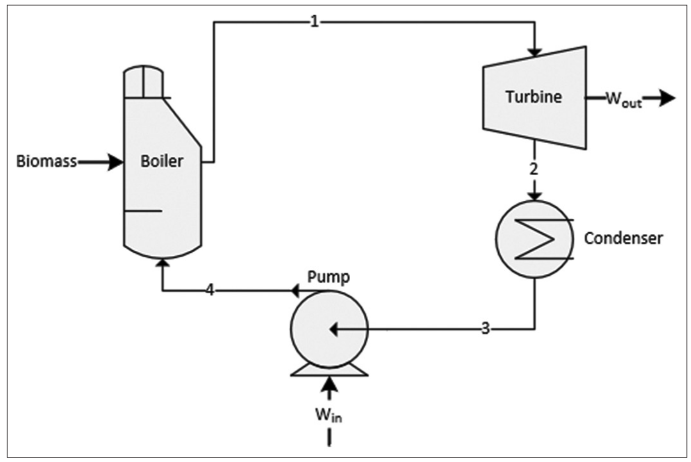
For the estimation of the biomass cost, the cost of equivalent energy compared to mineral coal was considered according to Equation (7).

$$C_{biomass}LHV_{mix}=C_{coal}LHV_{coal} \quad (7)$$

Table 4: Function for equipment costs

Equipment	Cost function	Reference
Pump	$1120\dot{W}_{pumb}^{0.8}$	(Ehyaei et al., 2021)
Turbine	$4405\dot{W}_{turbine}^{0.7}$	
Condenser	$588A_{condenser}^{0.8}$	
Boiler	$1541\dot{Q}_{comb}^{0.8}$	(Pina et al., 2021)

Figure 1: Diagram of the thermodynamic cycle



Where $C_{biomass}$ is the cost of biomass and C_{coal} is the cost of mineral coal. The average cost of coal in the first quarter of 2022 was 217 USD/t (UPME, 2022).

The lower heating value for bituminous coal is 24 MJ/kg (Hoyos Álvarez et al., 2019).

2.6. Economic Analysis

To perform the economic analysis of the biomass-fed energy generation system, it was necessary to initially estimate the system's generation cost (COE), which depends on the investment cost (IC), biomass cost, and consumption, as shown in Equation (8).

$$COE=\frac{\tau\cdot IC+C_{biomass}\dot{m}_{mix}}{\dot{W}_{net}} \quad (8)$$

The factor τ represents the distribution of the investment cost over the plant's lifetime and was calculated using Equation (9).

$$\tau=\frac{\gamma\varepsilon}{3600\,N} \quad (9)$$

γ is the operation and maintenance factor, usually between 2% and 6%. N is the number of operating hours per year of the plant, which for this case was considered 7000 h, and ε is the depreciation factor, which was calculated using Equation (10). Assuming a plant lifetime (n) of 20 years and a reference interest rate (i_0) of 10%.

$$\varepsilon = \frac{(1-i_o)^n i_o}{(1+i_o)^n - 1} \tag{10}$$

The internal rate of return (IRR) was finally evaluated for different plant capacities, in order to determine the minimum capacity of the generation system that would guarantee profitability, taking as a reference the maximum annual depreciation rate for renewable energies in Colombia of 20%, established in Law 1715 of 2014.

3. RESULTS AND DISCUSSION

3.1. Energy Characteristics of Biomass

Based on the elemental composition, the higher and lower heating values of each biomass were determined individually, allowing for the estimation of the heating value of biomass mixtures. Table 5 shows the heating value of rice husk, corn cob, and a reference mixture of 50% corn cob and 50% rice husk. The results show that rice husk has a lower heating value, thus reducing the overall heating value of the mixtures.

3.2. Thermodynamic Analysis of the System

The thermodynamic analysis of the system allowed for obtaining the net power per unit mass and the system's thermal efficiency. Table 6 shows the results for the 50% corn cob mixture and 50% rice husk. Studies in the literature, such as (Ismail et al., 2016; Schuster et al., 2009), present similar values for energy efficiency.

Afterward, a parametric analysis was carried out to determine the effect of the maize cob-rice husk co-combustion on the system's specific power, shown in Figure 2. It was found that as a higher percentage of rice husk was added to the mixture, the specific power of the system decreased due to the lower calorific value of the rice husk.

3.3. System Cost Estimates

With the results of the thermodynamic analysis, the costs of the components of the studied thermodynamic cycle were determined. The obtained results are shown in Table 7, where it can be observed that the most expensive elements are the turbine and the boiler. These results are consistent with those presented by (Patel et al., 2017).

In Table 8, the total investment cost in equipment purchases and the cost of biomass obtained with the equivalent energy method is shown. The results obtained by this method lead to values similar to those reported by (Algieri and Morrone, 2022).

3.4. Economic Evaluation of the Power Generation System

The generation cost of the system is 0.183 USD/kWh for the specific power of the system operating with a 50% maize cob and 50% rice husk mixture. Later, the system's power was varied to observe the impact on the generation cost, and the results are shown in Figure 3. The cost shows a significant reduction for plant sizes smaller than 45 MW, after which the cost tends to remain constant.

Table 5: Heating value calculated for the mass and mixture

Biomass	HHV (kJ/kg)	LHV (kJ/kg)
Corn cobs	14813	12027
Rice husk	14481	11795
50:50 mix	14647	11911

HHV: High heating value, LHV: Lower heating value

Table 6: Final results of the evaluated cycle

Parameter	Result	Unit
Specific net power	2790	kJ/kg
Cycle efficiency	0.244	---

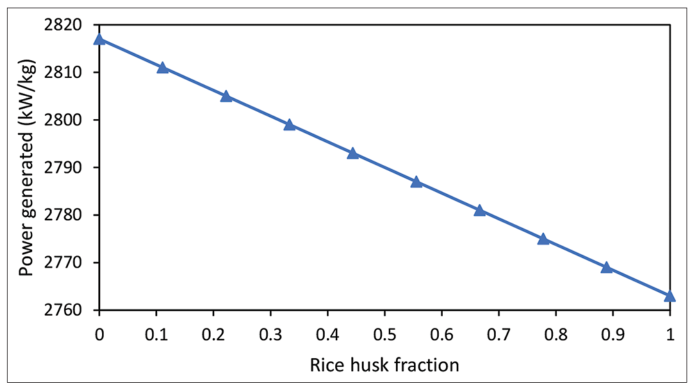
Table 7: Equipment costs

Equipment	Cost (USD)
Pump	8910
Boiler	2467000
Turbine	1141000
Condenser	9672

Table 8: Total investment costs and cost of biomass

Item	Total cost	Units
Investment cost	3630000	USD
Biomass	0.1236	USD/kg

Figure 2: Impact of rice husks on the specific power of the system



Keeping the system's specific power fixed, the rice husk percentage in the mixture was varied, and the behavior presented in Figure 4 was observed. As the percentage of rice husk in the mixture increases, the generation cost also increases. Although rice husk is less expensive, this reduction in cost does not compensate for the decrease in net power produced, resulting in the outcome presented in the figure.

Analyzing the results presented in Figures 2 and 4, it is evident that using rice husk in this specific case is detrimental in terms of energy and economics. However, co-firing may be a viable option to increase the system's size and add value to an agro-industrial residue like rice husk.

Considering the average energy auction cost in Colombia for 2022 and the obtained generation cost, the proposed system's internal rate of return (IRR) was determined. Figure 5 shows the

Figure 3: Impact of system capacity on generation cost

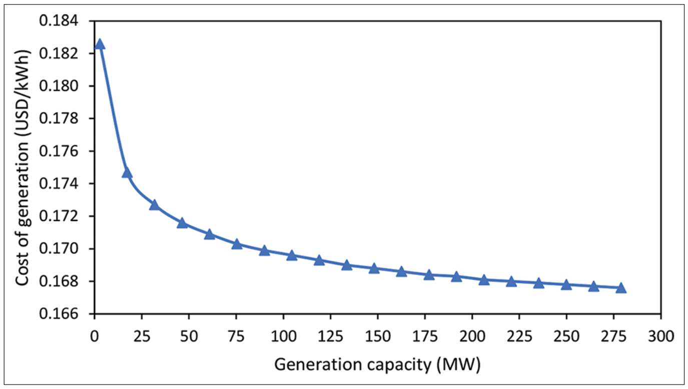


Figure 4: Effect of rice husk percentage on the cost of generation

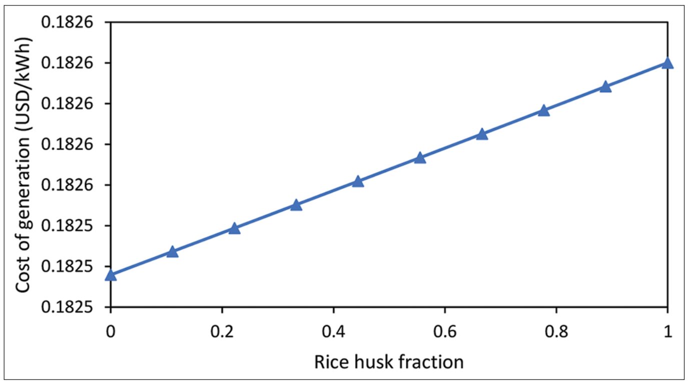
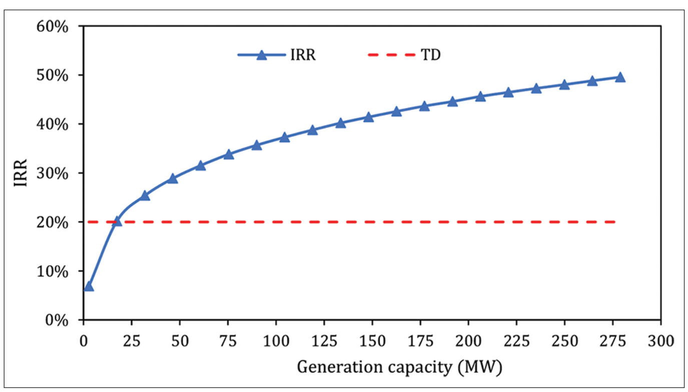


Figure 5: Impact of system capacity on internal rate of return



result in a co-firing scenario with a 50% maize cob and 50% rice husk mixture.

The figure also presents the maximum depreciation rate established by Law 1715 of 2014 for renewable energies in Colombia. In the most aggressive economic scenario, the depreciation rate (red line) is the target that must be exceeded to consider a generation plant viable. In this case, generation from 20 MW can be considered profitable. However, this would require a biomass energy amount of 574 GWh/year, which is not currently available from rice husk and maize cob, according to (Sagastume et al., 2021). This can be achieved by including other biomass sources, such as cotton stems and yucca rhizomes. Moreover, it is noteworthy that economic viability can be achieved for much smaller capacities than 20 MW in more flexible economic scenarios.

4. CONCLUSION

A conventional Rankine cycle fueled by co-firing rice husk and corn cob was studied to evaluate the technical and economic feasibility of the system. The analyzed cycle achieved an efficiency of 24.4% and a net specific power of 2.790 MW/kg. It was also found that the rice husk reduces the calorific value of the mixture and, therefore, the energy generated by the system. In economics, it was found that the cost of generation increases with higher percentages of rice husk.

The economic analysis showed that the system would be viable for generation capacities above 20 MW in the most aggressive scenario, which cannot be achieved with the available corn cob and rice husk. Therefore, it is recommended to include other biomass fuels, such as cassava rhizomes and cotton stalks. It is imperative to mention that feasibility can be achieved at lower capacities in other, more flexible scenarios, so this aspect should also be studied in more detail.

In conclusion, energy generation through the combustion of various biomass fuels is an attractive alternative for valorizing agricultural residues and, in some scenarios, can be technically and economically feasible.

5. ACKNOWLEDGMENTS

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