COB-2023-1756
ANALYSIS OF THE PROPOSED IMPLEMENTATION OF A COMBINED GENERATION SYSTEM IN A SUGAR AND ALCOHOL PLANT

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Abstract. The development of economic activities, along with the evolution of society, has generated a growing demand for electricity, resulting in an increase in pollution from the exploration and use of fossil fuels. One possibility to overcome such environmental issues lies in the utilization of renewable energy sources employed with combined generation systems. This study presents an energetic, exergetic, and economic assessment of a proposed combined generation system for a sugarcane plant located in the state of Pernambuco, Brazil. The base system consists of a set of boilers that use sugarcane bagasse as fuel. The proposed scenario includes the boilers, with the addition of (a) an absorption cooling system that uses the water-ammonia chemical pair as a refrigerant, with a cooling capacity of 17 kW; (b) an organic Rankine cycle that uses n-octane as the working fluid, with an equivalent electricity production capacity of 1110 kW. The main results of the exergetic analysis showed an exergetic efficiency of 16.8% and 2.5% for the ORC and chiller, respectively. The economic evaluation revealed that the investment has an average payback period of 9.05 and 7.45 years for the ORC and chiller, respectively.

Keywords: Biomass, Boiler, Combined generation, Economic Evaluation, Exergy efficiency.

1. INTRODUCTION

The growth of economic activities combined with the evolution of society has generated a growing demand for electricity, raising concerns about the environmental impacts due to the exploration and use of fossil fuels (Waheed et al., 2019).

One possibility to overcome such environmental problems lies in the utilization of alternative and renewable energy sources. Another possibility involves the use of combined generation systems, capable of converting waste energy from thermal machines into useful energy (Abbas et al., 2020). According to (Qian et al., 2021) combined generation systems involve the simultaneous production of different types of useful energy, efficiently meeting energy demands with minimal cost.

Brazil is one of the largest sugarcane producers in the world (Ajala et al., 2021). In 2021, the use of sugar cane corresponded to 14.7% of primary energy production in Brazil (EPE, 2022). By utilizing bagasse to meet their energy needs, sugarcane and ethanol industries can achieve energy independence while also having the opportunity to sell excess electricity produced internally and enjoy economic advantages (Cavalcanti et al., 2020).

Given the scenario of the energy availability of biomass in the sugar and alcohol sector, the implementation of combined generation systems appears as an alternative for improvements in the energy and economic performance of the plant. Studies of proposed implementation of components are often evaluated from an energetic, exergetic and economic point of view. As can be observed in works such as the one by (Di Fraia et al., 2019) who proposed a system for the production of electrical and thermal energy to supply water treatment plants. In addition to works such as the one by (Morais et al., 2020) that evaluated the performance of a system comprised of a solar collector, a biomass burner, an Organic Rankine Cycle (ORC), and an absorption cooling system, implemented in an industrial plant in the Midwest region of Brazil, among other studies.

In this context, this study presents a proposal for the implementation of a trigeneration system. The evaluated system consists of a set of boilers from an alcohol and sugar production plant, along with two equipment units that utilize waste energy from the plant's exhaust gases: an absorption chiller and an ORC (Organic Rankine Cycle). The proposal encompasses the energetic, exergetic, and economic assessment of the equipment utilizing waste energy from the boiler.

2. METODOLOGY

2.1 System description

The base case is a sugarcane plant evaluated in the study of (NETO, 2021), located in the state of Pernambuco in Brazil which operates according to the Rankine cycle. The plant has a capacity to generate 11.8 MW of electricity, using sugarcane bagasse as fuel. The system consists of a set of three water-tube boilers, a set of seven turbines, a desuperheater, a condenser, a deaerator, and two pumps. These components are represented on the right side of Figure 1.
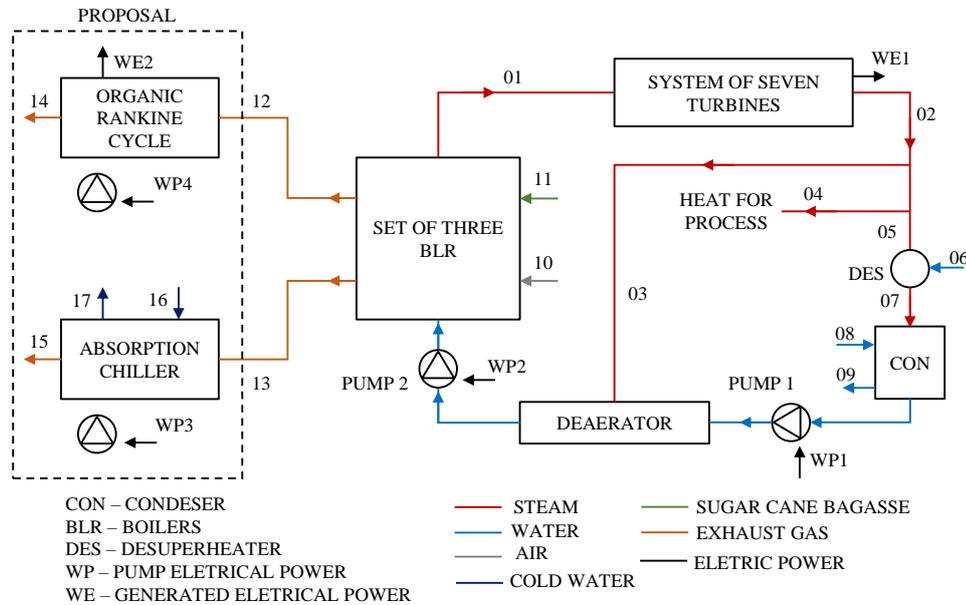

Figure 1. Proposed combined generation system for a sugarcane plant.

On the left side of Figure 1, the components of the proposed implementation of a trigeneration cycle are represented. It includes a single-effect absorption refrigeration system that uses the chemical pair (NH_3–H_2O) as the refrigerant fluid, and a generator based on an Organic Rankine Cycle (ORC) that operates with the working fluid octamethyltrisiloxane ($C_8H_{24}O_2Si_3$). According to (Prando et al., 2015) the thermophysical properties of octamethyltrisiloxane make it particularly suitable for low-temperature heat sources such as biomass combustion.

Both equipment units in the proposal utilize the waste heat from the exhaust gases of the boiler combustion chamber as input. The product generated by the refrigeration system is intended for thermal comfort applications in the environment, since environments such as control rooms are typically located near to the production line, making the air conditioning of these areas indispensable.

The electrical power of the ORC, on the other hand, can be sold to the grid or consumed by the plant itself, contributing to a more economical operation of the plant.

2.2 Boiler specifications

Boilers are industrial equipment whose main function is to convert the chemical energy of fuels into thermal energy through combustion. This thermal energy is transferred to water, resulting in the production of hot water or steam that can be used in various industrial processes (Aguilar Vizcarra et al., 2021). Table 1 indicates the main parameters of the boilers according to the manufacturers.

Table 1. Boilers parameters.

Equipment	Specific consumption ($kg_{bagasse}$ / kg_{steam})	T_{out} (ºC)	P_{out} (bar)	$\dot{m}$ (kg/s)
Boiler #1	0.45	320	21	22.22
Boiler #2	0.45	300	21	18.33
Boiler #3	0.45	350	21	15.28

In this case, the fuel used by the set of boilers is sugarcane bagasse (SCB) which, according to the studies by (Cavalcanti et al., 2020) and (Singh, 2019) has the following composition: 25,32% of C, 2,935% of H_2, 0,02% of S, 0,08% of N_2, 21,425 of O_2, 50% of $H_2O(l)$ e 1,22% of ash.

2.3 Organic Rankine Cycle specifications

The Organic Rankine Cycle operates similarly to the conventional Rankine Cycle, except for the use of an organic fluid as the working fluid instead of water (Figueredo et al., 2021). Among the various benefits of ORC, the utilization of low-temperature energy sources makes these cycles effective in recovering waste heat from thermal processes (Ahmadi et al., 2020).

The ORC generator used was evaluated in the study by (Prando et al., 2015). The thermal machine uses the working fluid octamethyltrisiloxane. The equipment specifications are presented in Table 2.

Table 2. ORC parameters.

Parameters	Value
Electricity generated, kW	828
Required thermal energy, kW	4148
Heat source temperature, °C	271.7
Electric power conversion rate, MW	1.0

2.4 Absorption chiller specifications

The main differences between absorption chillers and conventional chillers are: the use of heat to provide cooling, the absence of compressors in their working cycle, and the utilization of water mixed with either ammonia or lithium bromide as the refrigerant (Lahoud et al., 2021). These characteristics make the absorption chiller a good option for an environmentally friendly recovery of waste heat.

The absorption cooling system used in the proposal was evaluated in the study by (Marques et al., 2020). This equipment was analyzed in the laboratory at the Federal University of Paraíba (UFPB), employed in a trigeneration plant, which utilizes exhaust gases from an internal combustion engine as input. Table 3 indicates the main parameters of the refrigeration system.

Table 3. Refrigeration system parameters.

Parameters	Value
Refrigeration capacity, kW	17.58
Energy absorption, kW	58.03
Leaving temperature of chiller, °C	7.0
Entering temperature of chiller, °C	12.0

2.5 Thermodynamic assessment

For the thermodynamic evaluation were assumed the following simplifying assumptions listed below which were used for the balance of mass, energy and exergy.
- The system operates in steady state;
- The turbines and pumps were considered adiabatic;
- The change in potential and kinetic energy of the fluid at the inlet and outlet of the control volume were not considered;
- Complete combustion was considered;
- The addition of heat exchangers in the exhaust gases does not significantly change boiler operation.
- The reference state was considered 101 kPa for pressure and 25°C for temperature.

The analysis of mass balance for all equipment was conducted by Eq. 1 according with (Moran et al., 2014).

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \frac{dm_{VC}}{dt} \qquad (1)$$

Where $\dot{m}$ (kg/s) is the mass flow and dm_{VC}/dt is the mass change in the control volume.

The analysis of energy balance according to the first law of thermodynamics applied to the control volume under steady state and no change in change in potential and kinetic energy is describe by Eq. 2 as shown in Bornakke & Sonntag (2013).

$$\dot{Q}_{CV} + \sum_{in} \dot{m}_{in} h_{in} = \dot{W}_{CV} + \sum_{out} \dot{m}_{out} h_{out} \tag{2}$$

Where $\dot{Q}$ and $\dot{W}$ are the heat and work rates (kW) and h is the enthalpy (kJ/kg).

The exergy of the thermodynamic states was determined through Eq. 3 and the exergy destruction by Eq. 4. The exergy destruction represents the waste of energy sources, in other words, the potential of work that is wasted.

$$e_x = (h - T_o s) - (h_o - T_o s_o) \tag{3}$$

$$\dot{E}_D = \sum_{in} \dot{m}_{in} e_{x,in} - \sum_{out} \dot{m}_{out} e_{x,out} - \dot{W}_{CV} \tag{4}$$

Where e_x is the exergy (kJ/kg), s is the entropy (kJ/kgK) and $\dot{E}_D$ is the exergy destruction rate (kW).

From Eq. 1 to Eq. 4, it is possible to calculate the energy and exergy balances of the evaluated components.

2.6 Economic assessment

The economic assessment includes the calculation of Net Present Value (NPV) and Internal Rate of Return, both indicators were initially evaluated in power cycles in the study by (Bejan et al., 1996). The NPV takes into account costs associated with investments, expenses, cash flows, among others. From this indicator, it is possible to estimate the economic feasibility, profitability, and payback period, as indicated by (Cao et al., 2022).

This economic evaluation is a widely used tool to assess the feasibility of projects. As can be observed in the study by (Cao et al., 2022) that evaluated a heat recovery system for a diesel engine, and in the study by (Athari et al., 2022) that proposed a new seasonal multigeneration system that uses geothermal energy as input. The Eq. 5 describes the NPV adapted from (Bejan et al., 1996).

$$[NPV] = -([CI] + [WCI]) + \left[(NCI) * \sum_{Z=0}^{BL} (1+i)^{-z} \right] \tag{5}$$

Where CI is the capital investment, WCI is capital maintenance, NCI is annual capital inflow, i is the effective discount rate, BL is the useful lifetime and z is related to the i-th time period.

The Eq. 6 describes the Internal Rate of Return (irr) adapted from (Bejan et al., 1996).

$$([CI] + [WCI]) = \left[(NCI) * \sum_{Z=0}^{BL} (1+irr)^{-z} \right] \tag{6}$$

2.7 Economic assesment: Input data

The effective discount rate for both absorption chiller and ORC was considered 10 % per year. According to (Athari et al., 2022), this value represents an average rate adopted in proposals for implementing improvements in combined heat and power generation systems.

The annual capital inflow was calculated based on the energy savings provided by the implementation of the components. The energy saved from operating the proposed equipment was calculated based on the data provided by the annual report from (ANEEL, 2022). For the economic analysis, three scenarios were considered, which vary according to the availability of energy generated by hydroelectric power plants in Brazil (ANEEL, 2022). Table 4 shows the values used.

Table 4. Brazil electricity prices in 2022.

Scenario	Value
Scenario 01 (green flag), BRL[(1)]/kWh	0,618
Scenario 02 (red flag 01), BRL/kWh	0,658
Scenario 03 (water scarcity), BRL/kWh	0,760

[(1)] indicates the Brazilian real

Table 5 shows the input data used in the economic viability assessment of the absorption chiller and the ORC.

Table 5. Economic valuation input data.

Parameters	Value	Source
Capital investment (chiller), BRL	30,000	(Marques et al., 2020)
Capital maintenance (chiller), BRL/year	1,800	(Marques et al., 2020)
Annual capital inflow (chiller), BRL[1]	6,541	Manufacturer
Capital investment (ORC), BRL	7,409,700	(Wilailak et al., 2021)
Capital maintenance (ORC), BRL/year	185,240	(Wilailak et al., 2021)
Annual capital inflow (ORC), BRL[1]	1,383,848	Manufacturer
Useful lifetime (chiller e ORC), Year	10	(Marques et al., 2020)

[1] value from the average cost of energy: 0.658 BRL/kWh, shown in Table 4.

3. RESULTS

3.1 Results of energy anda exergy analysis

Table 6 presents the results for thermodynamic properties, exergy and exergy rate obtained by mass, energy, and exergy balances in all control volumes of the plant.

Table 6. Thermodynamic states for each location of the sugar cane plant.

Point	$\dot{m}$ (kg/s)	T (°C)	P (kPa)	h (kJ/kg)	s (kJ/kg)	e_x (kJ/kg)	$\dot{E}_x$ (MW)
1	40.83	333	2039	3097.41	6.883	1051	42.90
2	40.83	177	105	2829.12	7.712	535.40	51.86
3	1,32	177	105	2829.12	7.712	535.40	0.71
4	7.30	177	105	2829.12	7.712	535.40	3.91
5	32.21	177	105	2829.12	7.712	535.40	17.25
6	1.15	25	120	104.86	0.367	0.019	0.00
7	33.36	130	105	2735.88	7.493	507.40	16.93
8	47.20	90	170	377.01	1.192	26.20	1.24
9	47.20	110	150	461.34	1.419	43.11	2.04
10	60.92	130	101	404.49	7.166	15.30	0.93
11	17.55	25	101	-	-	15190	266.50
12	29.63	300	101	3718	-	949.80	28.14
13	0.41	300	101	3718	-	949.80	0.3894
14	29.63	184.1	101	3858	-	783.80	23.22
15	0.41	184.1	101	3858	-	783.80	0.3214
16	1.51	12	134	50.46	0.1874	1.96	0.0018
17	1.51	7	134	29.51	0.1063	2.328	0.0035

According to Table 6, it can be observed that sugarcane bagasse has the highest exergy (15190 kJ/kg), and this fuel is consumed at a rate of 17.55 kg/s by the set of boilers. The points of interest for the analysis of the proposal are between points 12 and 17.

Points 12 to 15 have a high exergy value because they are associated with the exhaust gas flows from the set of boilers. These gases contain the energy potential from combustion that is not fully utilized due to the irreversibilities associated with the set of boilers.

Figure 2 shows the exergetic efficiency results of each equipment component in the implementation proposal, as well as the overall exergetic efficiency of the plant in both scenarios.

It can be observed in Figure 2 that the highest exergetic efficiency value among the equipment components in the proposal is found in the organic Rankine cycle with 16.8%. On the other hand, the low exergetic efficiency value of the absorption chiller (2.5%) is due to the temperature difference between the exhaust gases and the working fluid.

Through exergetic analysis, it is possible to evaluate the effectiveness of the equipment and determine the relationship between the energy used and the maximum energy output. Thus, the low exergetic efficiency value of the original plant indicates the energy capacity that the plant can provide for the proposed equipment. By adopting the proposed configuration, the total exergetic efficiency of the plant increases by 5.45% from its normal value, and it could have even better performance if the entire exhaust gas flow were used for the conversion of useful energy.

The overall exergetic efficiency of the plant was 5.8%, comparing to the efficiencies found in Singh (2019) and in Cavalcanti et al. (2020) of 21.075% and 18.73%, respectively, the efficiency of the plant was considered low.
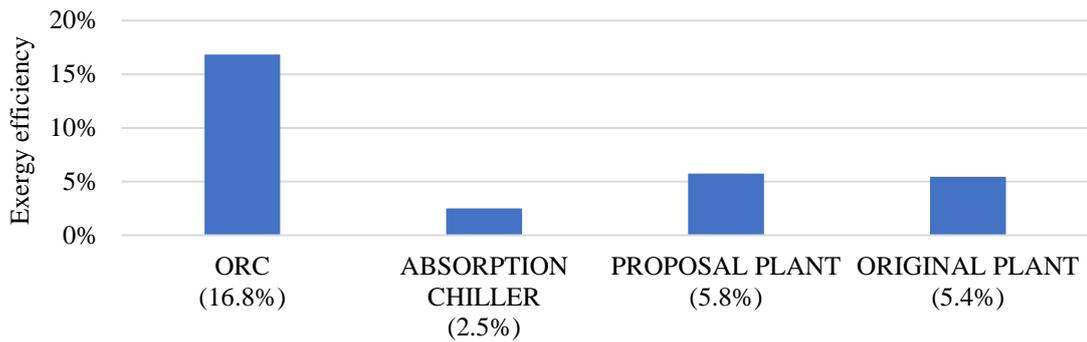
Figure 2. Results of exergy efficiency.

The exergy destruction of the proposed components is shown in Table 7, along with the exergy destruction of the plant in both scenarios.

Table 7. Results of exergy destruction.

Equipment	Fuel exergy (MW)	Product exergy (MW)	Exergy destruction (MW)
ORC	4.92	0.828	4.09
Absorption chiller	0.068	0.0017	0.07
Original plant	267.43	14.55	252.88
Proposal plant	267.43	15.3797	252.05

The exergy destruction of the proposed components is shown in Table 7, along with the exergy destruction of the plant in both scenarios.

It was determined that the highest values of exergy destruction are found in the equipment that constitutes the original plant compared to the proposed equipment. Only in the set of boilers, the exergy destruction was 151.53 MW, followed by the condenser (15.26 MW) and the set of turbines (10.09 MW), as shown by Neto (2021). When comparing only the proposed equipment, the organic Rankine cycle exhibited the highest value of exergy destruction (4.09 MW). Therefore, the main location of exergy destruction is in the set of boilers.

The results demonstrate that even with the 5.45% increase in the exergy efficiency of the plant with the proposed equipment, there is still room for improvement. However, the increase in efficiency is limited to a certain extent, due to the presence of irreversibilities that cannot be avoided due to technological and physical constraints.

3.2 Results of the econmic analysis of the absorption chiller

Figure 3 shows the NPV value of the investment associated with the absorption chiller as a function of the equipment's useful life.
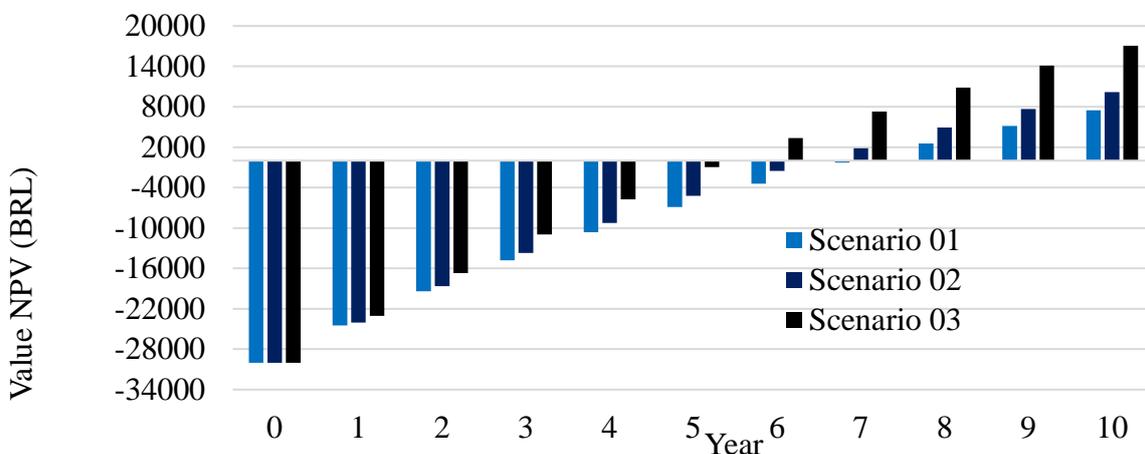

Figure 3. Results of the absorption chiller NPV by years.

It is possible to observe that in all scenarios the investment in the chiller presents positive NPV values, financially justifying the investment associated with the acquisition of this component.

Table 8 presents the main indicators of the economic viability analysis of the absorption chiller, considering the three energy cost scenarios.

Table 8. Economic indicators for the chiller investment.

Parameters	Scenario 01	Scenario 02	Scenario 03
NPV, BRL	7,503	10,192	17,051
IRR, %	15.05	16.76	20.95
Profitability rate, %	1.25	1.34	1.57
Payback time , Year	8.10	7.45	6.22

Scenario 02, which represents the average cost of energy production, shows an NPV value of 10,192 BRL and an IRR of approximately 16.76%. In the same scenario, a profitability ratio of 1.34 is observed (an investment of 1 monetary unit returns the invested amount plus 0.34), and a payback period equivalent to 1.34 years.

3.3 Results of the economic analysis of the ORC

Figure 4 shows the NPV value of the investment associated with the absorption chiller as a function of the equipment's useful life.
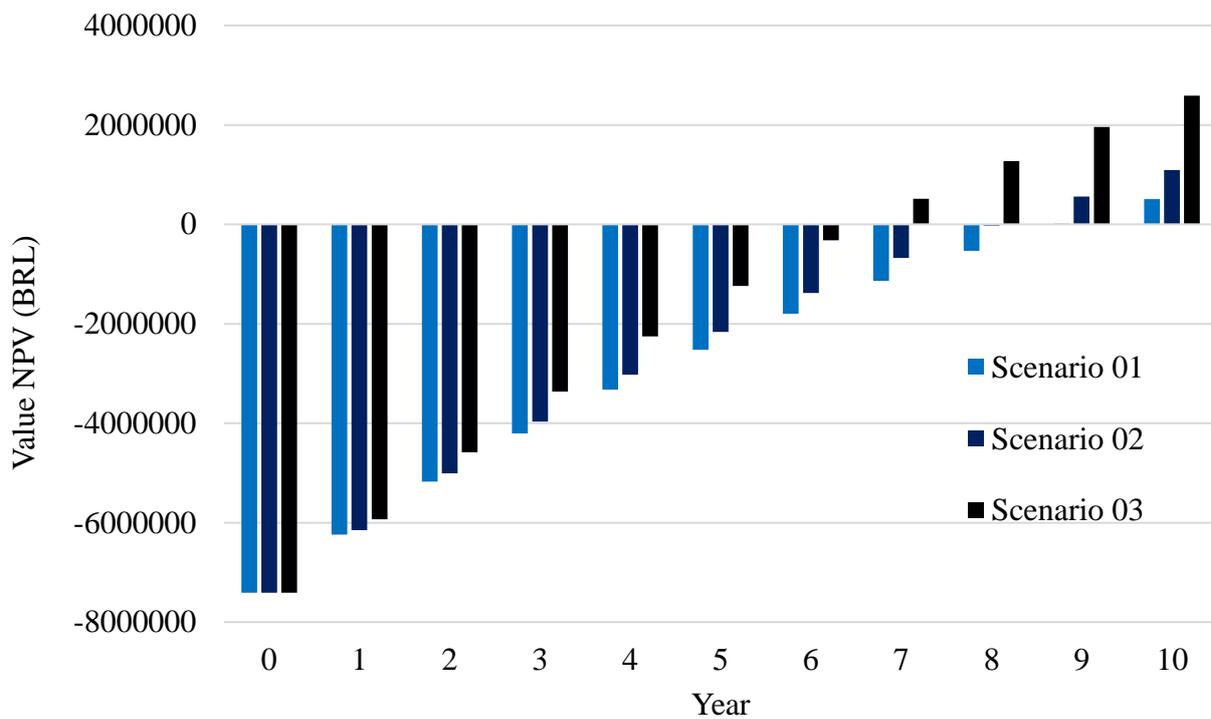

Figure 4. Results of the ORC NPV by years.

Similar to what was observed in the chiller investment, the implementation of the ORC results in positive NPV values, considering the 3 distinct scenarios for the cost of energy generated by the equipment. Table 9 shows quantitative values in the economic feasibility assessment of the ORC.

Table 9. Economic indicators for the ORC investment.

Parameter	Scenario 01	Scenario 02	Scenario 03
NPV, BRL	507,276	1,093,376	2,587,943
IRR, %	10.43	13.03	16.94
Profitability rate, %	1.07	1.15	1.35
Payback time, Year	9.98	9.05	7.39

Considering the average value of the cost of energy saved by the ORC (scenario 02), the investment presents an NPV value and an IRR rate equivalent to 1,093,376 BRL and 13.03%, respectively. It also shows a profitability rate and a payback period of approximately 1.15% and 9.05 years, respectively.

4. CONCLUSION

This study evaluated the implementation proposal of an absorption chiller and an organic Rankine cycle in a sugarcane plant located in the state of Pernambuco, Brazil. Energy, exergy, and economic analyses of the proposed equipment were conducted.

The main results of the exergy analysis show that the organic Rankine cycle (ORC) exhibits the highest exergy efficiency of 16.8%, while the absorption chiller has the lowest exergy efficiency of 2.5%. Regarding exergy destruction, the proposed components show values equivalent to 4.09 MW and 0.07 MW for the ORC and absorption chiller, respectively.

The economic analysis indicates that both equipment options have positive net present values (NPV), justifying the investment proposal. Considering the average value of energy saved by the equipment (scenario 2), the NPV is equivalent to 10,192 BRL and 1,093,376 BRL for the absorption chiller and ORC, respectively. The payback period for the same scenario is 7.45 years for the chiller and 9.05 years for the ORC.

These results demonstrate a high potential for improvement in the operating conditions of the base case. The use of auxiliary equipment that harnesses residual energy from the boiler contributes to changes that result in improved energy efficiency and economic performance of the plant. The proposed implementation contributes to more cost-effective and environmentally sustainable operating conditions.

5. ACKNOWLEDGEMENTS

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