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ANÁLISE ECONÔMICA DE CASOS DE COGERAÇÃO DE ENERGIA

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RESUMO: A proibição das queimadas para colheita alavancou o uso da palha da cana-de-açúcar em projetos de cogeração de energia. O presente trabalho teve como objetivo estudar a viabilidade do *retrofit* de uma usina para incremento de produção de energia elétrica pela queima dessa palha residual. Foram simulados 42 casos de cogeração após modificações no sistema térmico dessa usina, considerando condições de impureza vegetal e umidade do bagaço, e como resultado, obteve-se o incremento de energia elétrica produzida para cada caso. Em seguida, foi calculada a receita do incremento da venda de energia para cinco faixas de preço (R$ 150,00/MWh, R$ 180,00/MWh, R$ 210,00/MWh, R$ 240,00/MWh e R$ 270,00/MWh), bem como os custos operacionais, financeiros e de investimento. Na análise econômica foram estabelecidos fluxos de caixa para cada caso, nas cinco faixas de preço de energia. O estudo concluiu que, para o aproveitamento de palha em 10, 12 e 14% o projeto é atrativo e, no melhor dos casos obtêm-se a TIR de 23,12% com *payback* inferior a 6 anos. O valor da energia é um fator de impacto no estudo e o projeto viabiliza-se apenas para valores de energia superiores a R$ 210,00/MWh.

Palavras-chaves: bioeletricidade, biomassa, cogeração de energia, aproveitamento de palha, análise financeira.

ECONOMIC ANALYSIS OF ENERGY COGENERATION CASES

ABSTRACT: The ban on burning for harvesting leveraged the use of sugarcane straw in energy cogeneration projects. The present work aimed to study the feasibility of retrofitting a plant to increase the production of electricity by burning this residual straw. 42 cases of cogeneration were simulated after modifications in the thermal system of this plant, considering conditions of vegetable impurity and bagasse humidity, and as a result and as a result, the increase in the electric energy produced for each case was obtained. Then, the revenue from the increase in energy sales was calculated for five price ranges (R$ 150.00/MWh, R$ 180.00/MWh, R$ 210.00/MWh, R$ 240.00/MWh and R$ 270.00/MWh), as well as operating, financial and investment costs. In the economic analysis, cash flows were established for each case, in the five energy price ranges. The study concluded that, for the use of straw at 10, 12 and 14%, the project is attractive, and, in the best of cases an IRR of 23.12% is obtained with a payback of less than 6 years. The value of energy is an impact factor in the study, the project is only feasible for energy values greater than R$ 210.00/MWh.

Keywords: bioelectricity, biomass, energy cogeneration, straw use, financial analysis.

1 INTRODUCTION

Data from the National Energy Plan 2050 indicate that electricity consumption in Brazil could increase by up to 3.5% per year due to the country's economic growth, reaching an average of 241 GW. Actions that promote energy efficiency and distributed generation on

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the grid can meet part of this demand; however, it is estimated that the current centralized grid must increase its generation capacity by 2.6 times by 2050 (GOLDONI *et al*., 2022). Biomass can be one of the alternatives to boost the production of electrical energy in the country during this period.

In Brazil, energy generation through biomass is responsible for 8.8% of the installed capacity of the Electric Energy Matrix, and sugarcane bagasse has the largest share of this type of source, with 77% (DÍAZ PEREZ *et al.*, 2018). Planted forests (coal and cellulose industry) represent 22% of the energy produced by biomass, while 1% comes from other sources (DÍAZ PEREZ *et al*., 2018).

In central-southern Brazil, the sugarcane harvest takes place between April and November, so the bioelectricity produced by burning bagasse reaches its peak in the months in which there is a reduction in the levels of hydroelectric reservoirs. due to the lack of rain. Therefore, in addition to expanding the generation potential of the matrix, bioelectricity complements the system in the period of low availability of hydroelectric plants and consequently high prices in the energy market (AHMED; ELDIN, 2015; MACEDO; ENSINAS *et al*., 2007; LEAL; HASSUANI, 2001; MOREIRA *et al*., 2016;

Sugarcane bagasse has gained prominence in the energy matrix in the last 20 years with the ban on burning and the implementation of mechanized harvesting (SANTOS; RAMOS, 2020). This residual straw was identified as a valuable raw material for bioenergy production according to Carvalho *et al.* (2017) and Menandro *et al.* (2017). To enable efficiency in the conversion of energy from surplus biomass, the plants retrofitted *their* industrial systems, concentrating their investments on replacing boilers with 21 bar and 300 °C for more efficient models of 65 bar and 490 °C, with a capacity of 150 at 250 t/h of steam (DÍAZ PEREZ *et al*., 2018). The use of multistage turbines was also implemented to drive energy generators, and extraction equipment such as mills and shredders, traditionally driven by 21 bar single-stage turbines, began to be driven by electric motors (SANTOS; RAMOS, 2020).

The market potential of bioelectricity also provides financial benefits for plants and increases cash flow to address the crisis related to the price of ethanol and the decrease in the value of sugar on the international market (CERVI *et al.*, 2019; MARCELO *et al.*)., 2017; PINA *et al*., 2015; SANTOS, *2020*;

The present work aimed to study technologies and process conditions to increase energy generation from the burning of sugarcane bagasse and straw collected from farms and to carry out an economic analysis of the proposed process conditions by calculating the net present value (NPV), the internal rate of return (IRR), the *repayment rate* and the profitability rate to verify the viability of the investment.

The project is in line with the seventh of the Sustainable Development Goals (SDGs) promoted by the UN, which proposes ensuring access to energy in a reliable and modern way, increasing the share of renewable energy in the matrix and promoting investments in infrastructure and energy technologies. clean energy.

2 MATERIALS AND METHODS

2.1 Case 1 – Current Plant Configuration

The sugar and alcohol plant considered in the study has an hourly crushing capacity of 708 tons of chopped and unburned sugarcane. Approximately 4% of this total is classified as a vegetable impurity, which refers to chaff and leaves transported from the field to the plant. This vegetable impurity represents approximately 14.30% of all straw produced in the sugarcane field; that is, 85.70% of the straw remains in the field after mechanized harvesting.

When unloaded on the industrial unit's feeding table, the sugarcane goes through a dry cleaning system that separates approximately 28.33 t/h of straw. Bagasse production is 198.33 t/h after the process in two grinding lines of six mill suits, which results in a total biomass (straw and bagasse) of 226.66 t/h, of which 172.

25 t/h used in the boilers, 18.13 t/h sent to the technical reserve and 36.28 t/h reserved for use in the off-season.

The plant's current energy plant consists of two boilers with a steam production capacity of 170 t/h at 21 bar and 300 °C. This steam is used in turbines that drive equipment in the juice extraction process, such as choppers, shredders and mills; in the steam generation itself; and in fans and boiler pumps.

The turbine drive configuration has a low thermodynamic efficiency, as shown in Table 1.

Table 1. Characteristics of drive turbines.

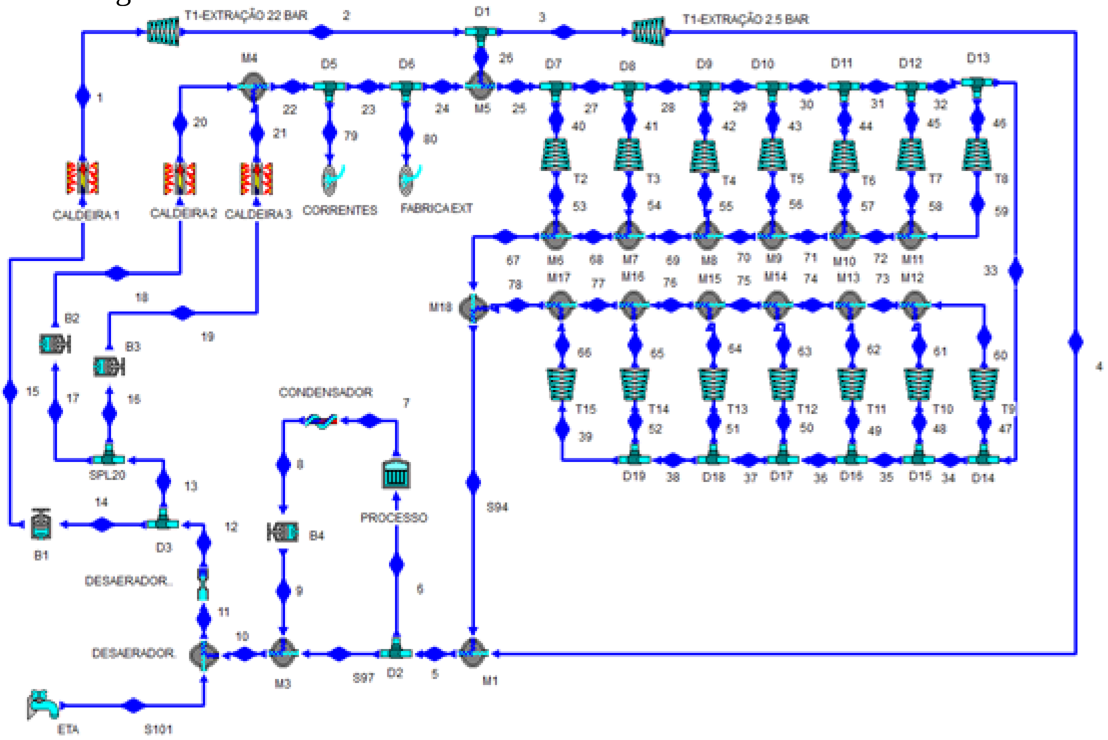
Equipment	Steam consumption (t/h)	Thermodynamic Yield (%)	Power (kW)	Speed Characteristic
Chipper A	7.85	45.0	418.23	Constant
Defibrator A	9.68	46.4	531.97	Constant
1st/2nd MA suits	13.12	46.1	716.72	Variable
3rd/4th MA suits	13.12	43.1	670.31	Variable
5th/6th MA suits	13.12	45.2	702.87	Variable
Chopper B	12.46	24.5	361.76	Constant
Defibrator B	12.46	48.2	711.69	Constant
1st MB suit	8.5	47.5	478.54	Variable
2nd MB suit	8.5	40.5	408.00	Variable
3rd/4th MB suits	14.35	40.5	688.67	Variable
6th MB suit	11.87	45.0	683.11	Variable
Turbo pumps	2.8	45.0	149.32	Variable
Exhaust fans	5.7	45.0	303.96	Variable

Source: Santos and Ramos (2020)

The plant also has a modern energy cogeneration system in a complex consisting of a boiler with a nominal capacity of 275 t/h of steam at 67 bar and 515 °C and a turbogenerator set with a nominal power of 50 MW. This system currently provides 39 MW of power. As the plant has an electrical energy demand of 12 MW for its activities, the surplus (27 MW) is exported to the National Interconnected System and adds to the plant's revenue as energy sales.

The configuration of the plant's thermal plant is shown in Figure 1.

Figure 1. Configuration Case 1.



Source: Author himself.

2.2 Case 2 – Proposal to modernize the plant

In this work, two 21 bar boilers are replaced with a boiler that produces 360 t/h of steam at 67 bar and 515 °C, in addition to the installation of an extraction-condensation turbine coupled to an energy generator with a nominal power of 80 MW.

The choice of this type of turbine is justified by the need to supply steam at a low pressure of 1.50 bar for the juice evaporation process. Of the total flow that passes through the turbine, a fraction of the steam is extracted from the process, and the other passes through the condenser and returns to the boiler. Thus, despite its higher cost, this type of turbine has greater flexibility for delivering electrical and thermal energy to the plant (SANTOS; RAMOS, 2020).

In addition to changing the energy generation process, it was proposed that all drives performed by 21 bar turbines be replaced by drives from high-efficiency electric motors. The sugarcane chopper was removed because the plant only processes chopped sugarcane, so the equipment currently has no relevance in the preparation process.

Santos and Ramos (2020) proposed the use of three-phase induction motors to drive equipment in a plant, adopting medium-voltage motors (MT - 4.16 kV) with direct starting for constant-speed drives and low-voltage motors. -voltage (BT - 690 V) for variable speed drives using frequency inverter devices.

The amount of additional electrical energy P_a required to replace the mechanical work performed by steam turbines W_t is given by Equation 1, taking into account the weighted electrification correction factor (F_c).

$$P_a = W_t \, . F_c \qquad (1)$$

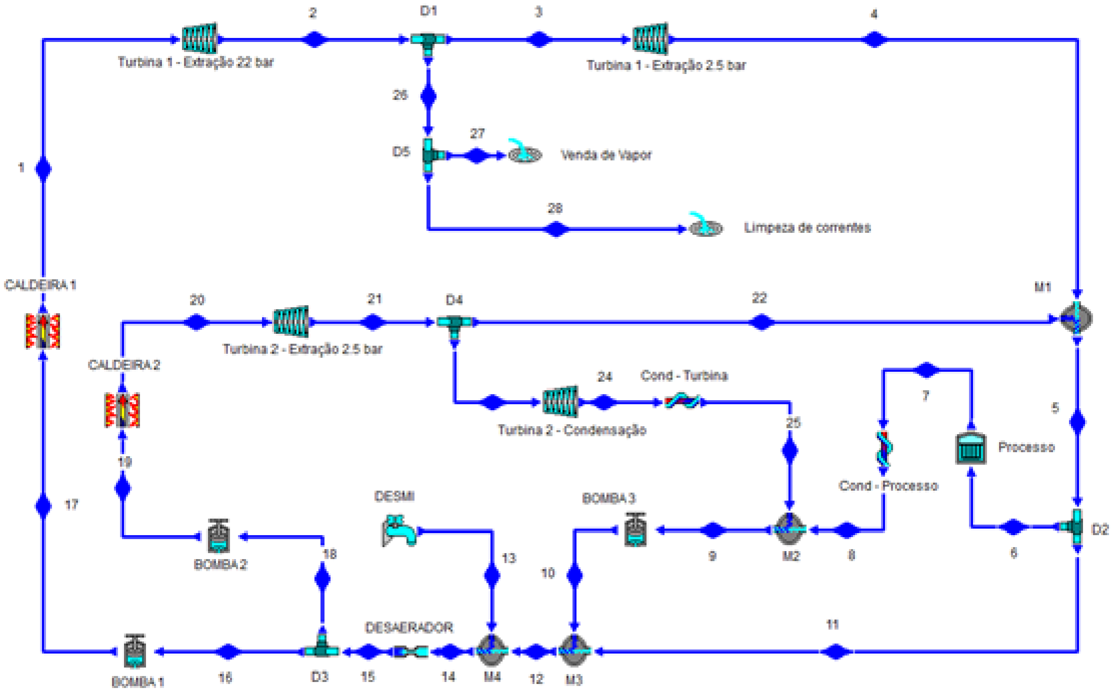
The weighted electrification correction factor (F_c) is determined according to consumption at medium voltage (C_m) and low voltage (C_b), in addition to the efficiencies at medium voltage (η_m) and low voltage (η_b) through Equation 2 (SANTOS; RAMOS, 2020).

$$F_c = \frac{1}{[(\eta_m . C_m) + (\eta_b . C_b)]} \qquad (2)$$

The model proposed for Case 2 is

presented in Figure 2.

Figure 2. Case 2 Configuration.



Source: Author himself.

With respect to the use of straw, six cases were considered for plant impurities. Vegetable impurities represent the fraction of straw brought from the field in relation to the total load transported. In Table 2, the percentage of vegetable impurities in the sugarcane load transported, the fraction of straw harvested from the field and the total flow of straw, in tons, unloaded on the feeder table for each case simulated in this work are listed.

Table 2. Straw use cases.

Cases	Vegetable impurity (%)	Crop straw (%)	Straw flow (t/h)
Case 2.1	4.00	14.29	28.32
Case 2.2	6.00	21.43	42.48
Case 2.3	8.00	28.57	56.64
Case 2.4	10.00	35.71	70.80
Case 2.5	12.00	42.86	84.96
Case 2.6	14.00	50.00	99.12

Source: Author himself.

Another important factor for the study is the humidity of the bagasse, which is sent for burning in the boilers, as it directly impacts the efficiency of steam generation. For each vegetable impurity, bagasse moisture values ranging from 54 to 48% were simulated, as shown in Table 3.

Table 3. Bagasse moisture.

Cases	**Bagasse moisture (%)**
2.X.1	54.00
2.X.2	53.00
2.X.3	52.00
2.X.4	51.00
2.X.5	50.00
2.X.6	49.00
2.X.7	48.00

Source: Author himself.

Therefore, for each case of straw use, seven cases of bagasse moisture were simulated, thus totaling 42 technical analyses, with the aim of verifying the increase in power available for export to the National Interconnected System after changing the configuration of the energy plant. of the plant.

2.3 Technical analysis

The technical analysis of this project consists of simulating the new energy flow proposed for the plant under the defined conditions of straw use and biomass humidity and, as a response, obtaining the mechanical power to be extracted from the turbines and made available for generating electrical energy.

First, the availability of biomass for burning in the boilers in Case 2 was verified. In this step, the amount of bagasse produced during milling was added to the amount of straw added for each case of straw use, as shown in Table 2.

Then, the PCI of the biomass to be burned was calculated according to Equation 3 (HUGOT, 1977).

$$PCI = 4250 - 12s - 48{,}5w \qquad (3)$$

where PCI is the lower calorific value, $s$is the biomass pol and $w$is the biomass moisture.

In the third step, the enthalpy values of the boiler feed water h_1(437.50 kJ/kg) and the output steam h_2(3,412.00 kJ/kg) were obtained.

Once the values of biomass available for burning were obtained, the PCI, calculated by Equation 2, which estimated the steam generator efficiency of 86.20%, as well as the input and output enthalpy of the steam generator, it was possible to estimate the production of boiler steam for each of the 42 cases.

The last step of the technical analysis was the simulation of the plant's energy flow using the *CyclePad program*, which was developed by the *Qualitative Reasoning Group* at *Northwestern University* (FORBUS *et al*., 1999).

The plant's modernization configuration was implemented as shown in Figure 2, establishing process conditions such as line pressure and temperature, as well as operating modes and performance of industry equipment, such as boilers, turbines, pumps and heat exchangers.

Finally, for each of the 42 steam flow rates considered, the Mechanical Work, in Watts, which can be extracted from the turbines to generate electrical energy, was obtained as an output from the simulation.

2.4 Financial analysis

Financial analysis is widely used in projects of the most diverse types, as it provides an overview that is considered indispensable, which allows the study of financial indicators that assist in decision-making as a whole.

Capital investment analysis techniques take into account the time factor in the value of money and involve supposedly known cash flow concepts that are used throughout the useful life of the project (GITMAN, 1984).

The net present value (*NPV*) represents the real net profit that the investor should obtain at the end of the project. In this method, the annual net inflow (ELC), which is obtained through revenues from the sale of energy minus operating expenses and taxes for each period k, in years, is updated for the base year through a discount rate called the minimum interest rate. attractiveness (*TMA*) and is then added to the capital to be invested (C). The variable $n$refers to the time of the project, and in this work, it was established at 20 years. A positive *NPV indicates that the project is viable.*

$$\text{VPL} = \sum_{k}^{n} \frac{ELC}{(1 + TMA)^{k}} - C \tag{4}$$

The internal rate of return (*IRR*) of an investment is the rate at which the net present value of the project equals zero, which is a more objective criterion for evaluation and is based on the cost of capital. The project will only be viable when the *IRR* is higher than the *MARR*, and we can also compare the return of the project in question with other projects in the company's portfolio or even with other types of financial investments available to the investor.

$$\sum_{\mathrm{k}}^{\mathrm{n}} \frac{ELC}{(1+TIR)^{\mathrm{k}}} - C = 0 \tag{5}$$

Another important factor is the project payback time, or project *payback*, which refers to the amount of time that must elapse for the updated cash flow to cancel the initial investment. In this work, we use the concept of discounted *payback*, which takes into account the cost of capital employed. The lower the discounted *payback is,* the more interesting the project will be.

The last indicator we use in this investment analysis is the return on invested capital (*ROIC - Return on Invested Capital*), which is the ratio between net operating profit minus adjusted taxes (L) and invested capital (C). The greater the *ROIC* of the project is, the more profitable and efficient the investment will be.

$$ROIC = \frac{L}{C} \tag{6}$$

The first step toward financial analysis was carrying out research to define the investment that the plant should make to increase energy generation. The simulation of the technical model defined the need to purchase a high-pressure boiler at 67 bar, 515 °C, and 360 t/h, in addition to an 80 MW turbogenerator to make maximum use of the thermal system. The entire investment for the purchase of this equipment and other items necessary for its operation, such as a water treatment plant (WTP), cooling towers and pipes, were estimated through research with suppliers and totaled R$ 141,856. 478.00.

As an investment for the implementation of Case 2, there is also a contribution to the electrification of the drives of equipment previously driven by low-efficiency turbines. This item considered electric motors, reducers, cables, inverters and the entire electrical power system to be installed, such as transformers, cubicles and motor control centers, totaling R$ 64,004,885.00.

It was considered that assets such as deactivated boilers and turbines could be sold, and this amount, valued at R$53,166,875.00, was used to amortize the investment.

Then, the cash flow for 20 years of project operation was established. Revenues from increased energy sales were calculated for five price ranges, R$ 150.00/MWh, R$ 180.00/MWh, R$ 210.00/MWh, R$ 240.00/MWh and R$ $270.00/MWh, for each of the 42 cases presented in the technical analysis. The expenses indicated in the cash flow were operational, such as straw transportation, operation and maintenance costs of the energy generation area; sales tax expenses (PIS, COFINS); and depreciation, amortization and income tax. Table 4 presents the costs of straw transportation, operation and maintenance of the energy generation system.

Table 4. Operating costs.

Vegetable impurity (%)	**Straw transportation cost (R$)**	**Operation and maintenance cost (R$)**
4.00	3,654,000.00	3,150,000.00
6.00	5,983,659.00	3,217,021.00
8.00	8,677,565.00	3,286,956.00
10.00	11,760,000.00	3,360,000.00
12.00	15,257,454.00	3,436,363.00
14.00	19,198,883.00	3,516,279.00

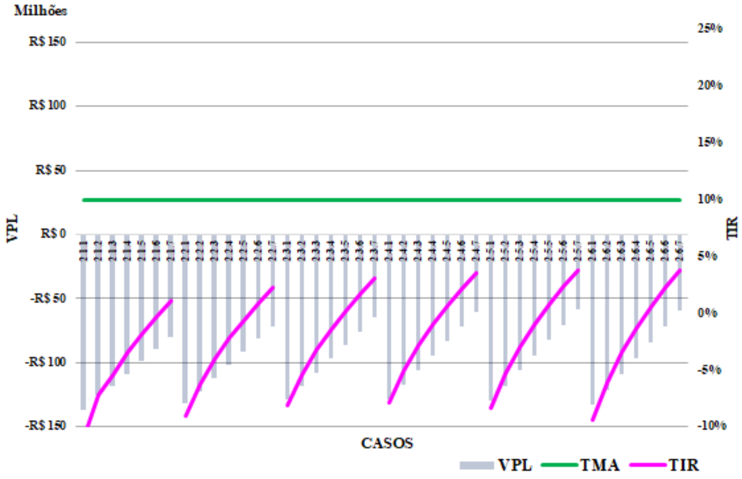
Source: Author himself.

Thus, 210 financial analyses were carried out with the objective of verifying the *NPV*, *IRR*, discounted *payback* and *ROIC* of the project. Such indicators, proposed outputs for the work, are essential for assertive decision-making by the investor and are presented in the following section.

RESULTS AND DISCUSSION

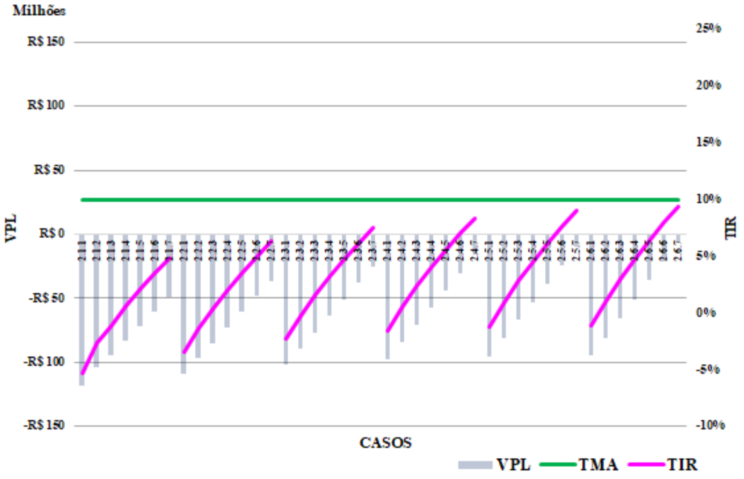
There were no cases of viability with energy sales prices of R$ 150.00/MWh and R$ 180.00/MWh, as shown in the graphs in Figures 3 and 4. The *IRR* in both cases does not cross the *TMA* line of 10%, represented in green, and the *VLP* is negative for all cases of straw use and bagasse moisture.

Figure 3. *NPV* and *IRR* for energy sales at R$ 150.00/MWh.



Source: Author himself.

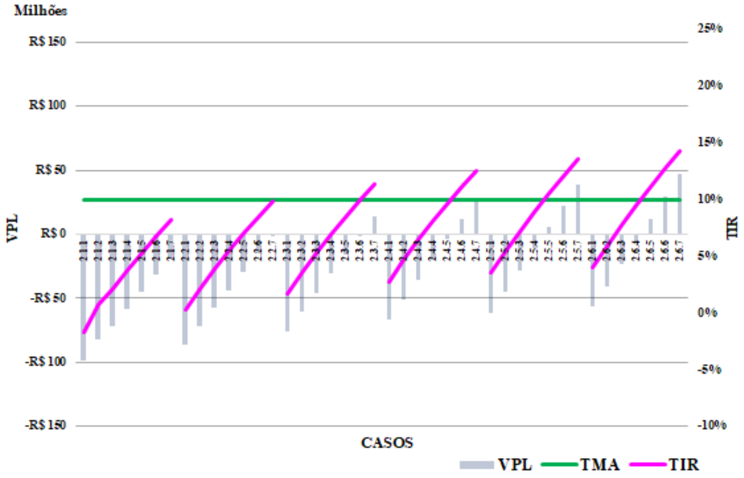
Figure 4. *NPV* and *IRR* for energy sales at R$ 180.00/MWh.



Source: Author himself.

The first cases of the feasibility of using straw appear in the simulations for the sales price of R$ 210.00/MWh, as shown in the graph in Figure 5. In nine of the 42 cases simulated for this value, the *IRR* exceeded 10%, indicating a positive *NPV* for cases using 8 to 14% vegetable impurities. The importance of controlling bagasse moisture in the process is noted, given that for the use of 8% vegetable impurities, with only 48% moisture, an excellent value for current operating standards, the project is viable.

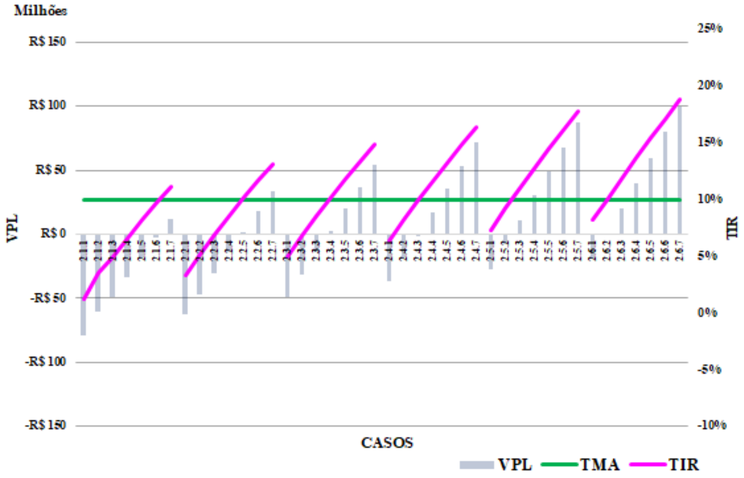
Figure 5. *NPV* and *IRR* for energy sales at R$ 210.00/MWh.



Source: Author himself.

Figure 6 shows the *NPV* and IRR for the energy sales value at R$ 240.00/MWh. For the 42 simulated cases, 22 were viable, including one case for the load transported with 4% straw and leaves, the current condition of the plant, demonstrating that investing in the modernization of industrial units with the electrification of drives and the use of high drainage rollers can be profitable, depending on external conditions such as rising energy prices. In a scenario of growing demand for energy and difficulty in expanding the energy park, the attractiveness of modernizing the industrial unit increases.

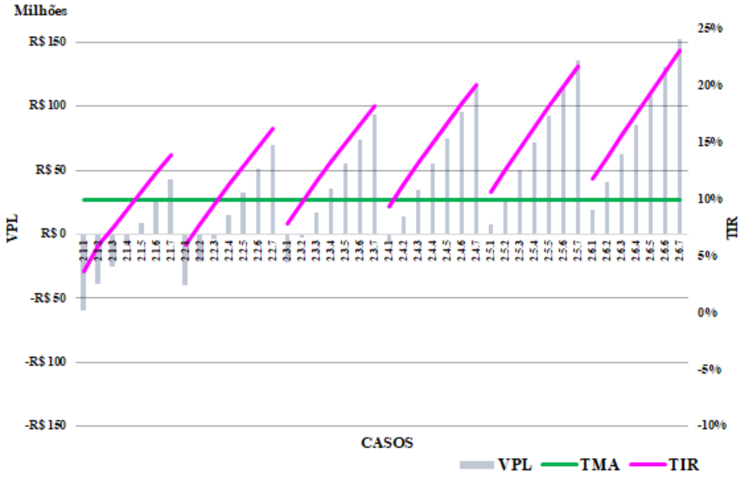
Figure 6. *NPV* and *IRR* for energy sales at R$ 240.00/MWh.



Source: Author himself.

Figure 7 presents the viability indicators for the energy sales value of R$ 270.00/MWh. Only 10 of the 42 cases were not viable; the *IRRs* for the profitable cases ranged from 10.69% to 23.12%, and the *NPVs* ranged from R$7,275,964.00 in Case 2.5.1 to R$152,673.914.00 in Case 2.6.7.

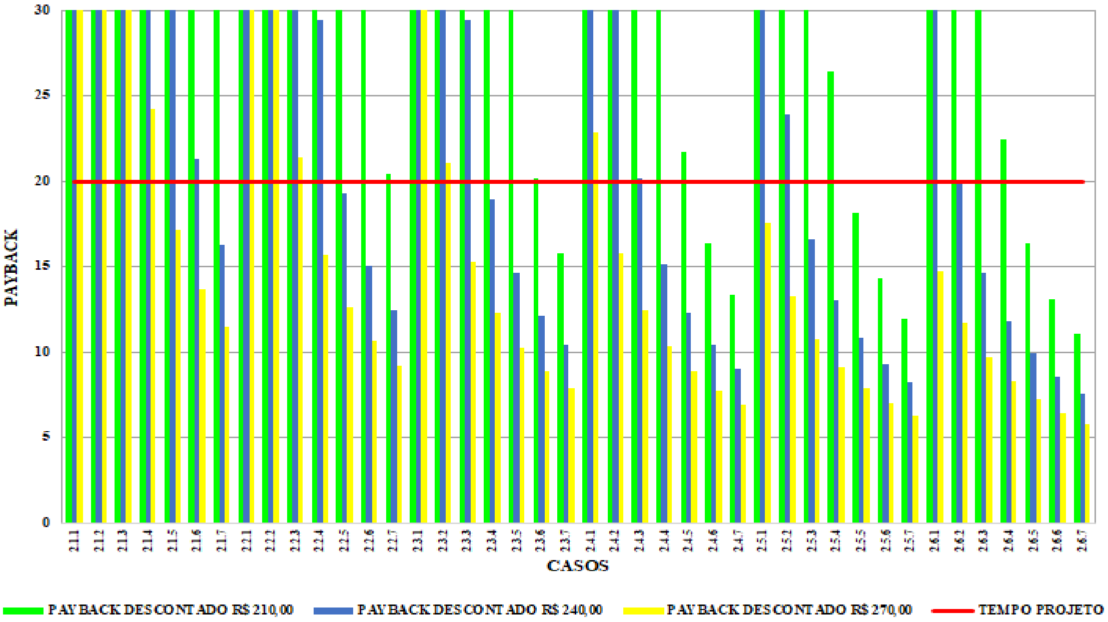
Figure 7. *NPV* and *IRR* for energy sales at R$ 270.00/MWh.



Source: Author himself.

To analyze the project's discounted *payback*, Figure 8 was used. The red line represents the project's time, stipulated at 20 years; that is, for cases where the discounted *payback* is less than 20 years, the project is viable.

Figure 8. *Payback* discounted from the project.



Source: Author himself.

This graph represents the discounted *payback* for simulations for energy sales values of R$ 210.00/MWh, R$ 240.00/MWh and R$ 270.00/MWh, as for the other values, there were no cases of viability, as shown in the graphs in Figures 3 and 4.

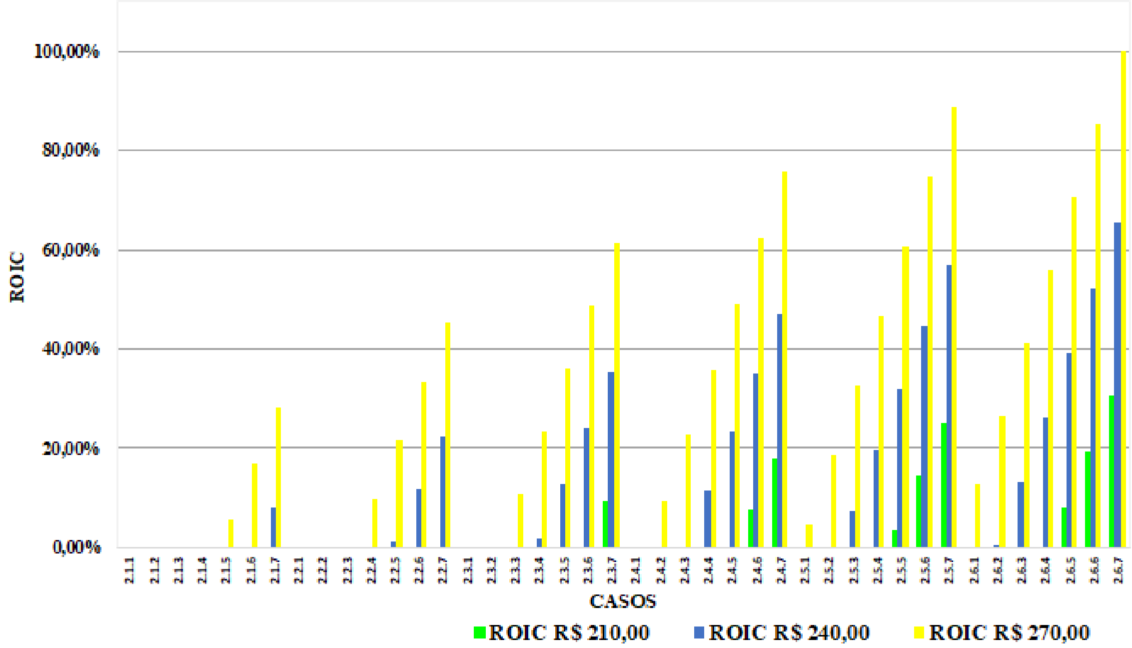
The lowest simulated value of the energy price that presents viability for the project is R$ 210.00/MWh; in case 2.3.7, the *payback* was 15.8 years. In this case, approximately 28% of the crop's straw must be used.

For sales values of R$ 240.00/MWh, we have a feasibility case for 14.29% use of crop straw but maintaining bagasse humidity at 48%, case 2.1.7. In the best case for this sales value, we reach a *payback* of 7.6 years, under the condition of 14% straw utilization in relation to the transported cargo and 48% bagasse moisture.

The first case with a feasibility of R$ 270.00/MWh is case 2.1.5, that is, using 14.29% crop straw and 50% bagasse moisture; however, under these conditions, the project would pay for itself in 17 years. For the same sales value, we have a *payback* of just under 6 years for case 2.6.7, 50% crop straw and 48% bagasse moisture.

Finally, the *ROIC analysis is* also presented for energy sales values of R$ 210.00/MWh, R$ 240.00/MWh and R$ 270.00/MWh. The ROIC represents how *much* profit the investor will make for every R$1.00 invested. Figure 9 shows the cases in which the viability had an *ROIC* greater than 0%.

Figure 9. Return on invested capital.



Source: Author himself.

For the case with greater use of straw and leaves from the crop (50%), and bagasse humidity of 48%, case 2.6.7, with an energy sales value of R$ 270.00/MWh, the projected *ROIC* is 100%; that is, the investor would have a profit, in 20 years, of R$ 1.00 for every R$ 1.00 invested, considering the *MARR* of 10% per year; in other words, the investor would double his capital by investing in this project.

4 CONCLUSIONS

As important as analyzing agricultural investment to send straw from the field to industry, it is necessary to modernize the industrial system for maximum cogeneration, replacing industrial equipment that uses steam as motive energy with equipment driven by electrical energy, in addition to investing in modern high-pressure boilers. We must also plan operational costs and taxes throughout the life of the project for the entrepreneur to make decisions.

The analyses carried out show the importance of the final humidity of the bagasse to be burned, as humidity levels above 52% compromise the combustion system and cause financial losses to the plants. A grinding system with high drainage rollers, such as the Lotus Roller, is a viable solution for increasing the energy generation yield, with a humidity close to 49% (SANTOS; RAMOS, 2020).

For the minimum attractiveness rate of 10%, only 32 of the 210 simulations (30.47%) presented a positive net present value; even so, half of those with the sale of energy at R$ 270.00/MWh, a value well higher than the current market average (R$ 185.00/MWh). No simulation showed attractiveness for energy sales values of R$ 150.00 and R$ 180.00.

As we increase the amount of straw sent from the field to the industry, the agricultural cost increases; even so, for the use of straw at 10, 12 and 14%, we can see an increase in attractiveness, with the internal rate of return reaching 23.12% and a discounted *payback* of less than 6 years in case 2.6.7 for an energy sales value of R$ 270.00/MWh.

This project, under the conditions studied, would have difficulties in leveraging on the part of the investor, as it presents a high initial contribution and profitability only in excellent conditions of the grinding process and with a high risk in relation to the market due to the variation in energy prices. The suggestion for future work is to study the external conditions that affect investment, such as the analysis of Brazil's energy situation for the next

20 years, establishing scenarios of growth in demand and expansion of the energy park to investigate the attractiveness of new projects of energy generation in sugar and alcohol plants.

5 THANKS

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