COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1033

NATURAL GAS COGENERATION SYSTEM ASSISTED BY SOLAR ENERGY INTEGRATED TO A MECHANICAL REFRIGERATION FOR MUSSEL FARMS APPLICATIONS

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Abstract. *In this study, the application of a natural gas cogeneration plant in mussel aquaculture farms is proposed with the objective of meeting electrical and thermal demands, specifically in the processes of declumping, washing, classification, pre-cooking, freezing, and packaging of the molluscs. Two scenarios were analyzed, the first one consisting of a natural gas cogeneration system integrated with a mechanical compression chiller, and the second one assisted by photovoltaic generation. The study was conducted considering real data collected at Cavalo Marinho farm, a producer of Perna perna mussels and Kappaphycus alvarezii macroalgae. Results obtained from simulations performed in the Engineering Equation Solver (EES) software confirm the technical viability of both scenarios. When subjected to economic evaluation based solely on electricity savings, the scenario assisted by photovoltaic energy shows a better return, on the order of 10 years or less assuming uninterrupted operation of the plant, including weekends. Considering the seasonality in mussel production, the surplus electricity can be commercialized with the potential for cost savings for the company.*

Keywords: *Mussel aquaculture, Natural gas cogeneration, Photovoltaic generation, Economic evaluation.*

1. INTRODUCTION

Aquaculture presents an opportunity to increase the global food supply by providing a significant source of animal protein (Gjedrem *et al.*, 2012). In 2020, global aquaculture production reached about 122 million tons, with approximately 2 million tons coming from mussel farming, representing about 12% of global molluscs production (FAO, 2022). In Brazil and worldwide, aquaculture is gaining increasing importance as a means of cultivating aquatic organisms. One prominent cultivated species in this activity is the *Perna perna* mussel, known for its high commercial value due to its nutritional properties.

An example of a sustainable mussel farming venture in Brazil is the Cavalo Marinho farm. Located in the Greater Florianopolis region in Santa Catarina, the state that concentrates about 95% of the country's production, the farm is one of the most well-known and traditional in mussel production (Campo & Negócios, 2022). With a cultivation area of approximately 150 hectares, Cavalo Marinho produces an average of 900 tons of mussels per year, which represents a significant portion of the total production in the state of Santa Catarina.

This current scenario, combined with the continuous improvement of the global energy grid and the constant enhancement of thermal areas, drives applied research in cogeneration to increase productivity and reduce costs on farms, documented in aquaculture since 1984 (Mercer, 1984).

Cogeneration, which involves harnessing the chemical energy from fuel to produce work and thermal energy, is an option for providing energy to an institution in place of a generator or local provider and is usually based on return on investment (Borba, 2002). Despite its potential in the aquaculture sector, there is still no installed unit/plant in Brazil for mussel farming.

With the use of natural gas, the economic applicability of cogeneration expands to industries that use heat and/or cold in the production process. In addition to the benefits of energy savings, environmental protection, flexible operation, and supply of energy during peak demand (Atanasoae, 2020), natural gas is a cleaner source compared to other fossil fuels, reducing greenhouse gas emissions and atmospheric pollutants.

The waste heat from the gas turbine is captured to produce steam or hot water, which can be used to power industrial processes. One of the main advantages of cogeneration is its high energy efficiency, which can reach up to 80%, compared to traditional power plants that generally have an energy conversion efficiency of about 30-40% (INEE, 2023).

Figure 1 shows a simplified flowchart of the post-harvest and processing of mussels, highlighting the points of electricity consumption and the need for thermal energy. From the initial post-harvest process, which involves the declumping, washing, and classification of the animals, to the final packaging stage, electricity plays a fundamental role (Cordeiro, 2007). There are also routine expenses for lighting and other equipment. However, the greatest electrical demands are related to the declumping, washing, and classification, which are usually performed in a single piece of equipment (Novaes *et al.*, 2011).

Thermal energy, on the other hand, is only used in the cooking processes, which involve pre-cooking the mussels, weakening the adductor muscle responsible for keeping the shells closed (Lima, 2012), and in the freezing process, where a mechanically compressed chiller is used for ice production.

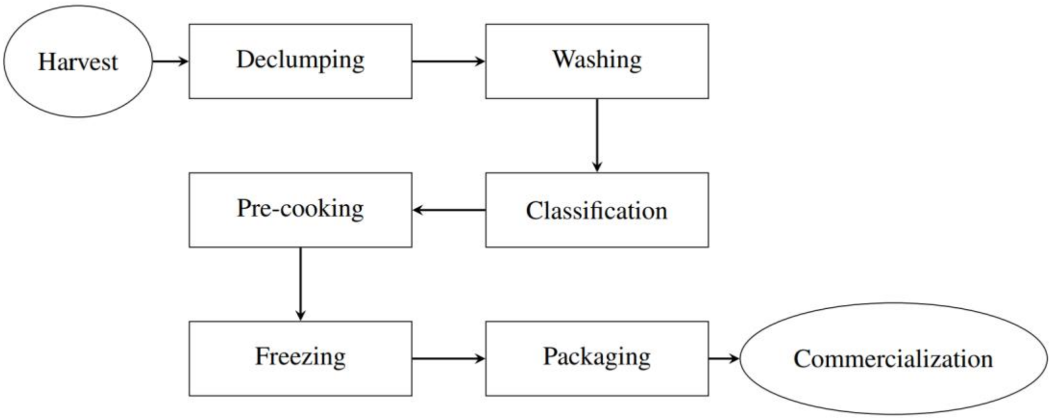

Figure 1. Post-harvest and processing flowchart of mussels.

Freezing mussels is essential due to their high perishability. These molluscs have many microorganisms in their viscera, along with their components, including proteins and lipids, which makes them prone to rapid decomposition. Therefore, after capture, it is necessary to cool them immediately or process them for consumption. For extended storage, freezing is the most suitable option (Beirão *et al.*, 2000).

In the process of freezing mussels, it is possible to use chillers, available in the market in different models, such as absorption and compression chillers. In this work, a compression chiller was considered for refrigeration purposes. The compression chiller is widely used in various industrial sectors, including food processing. Its flexibility in meeting different refrigeration demands and efficiently providing sub-zero temperatures, around -15°C, makes the compression chiller an attractive option for the Cavalo Marinho farm. With this purpose, this project aimed to present results for a cogeneration plant integrated with a mechanical compression chiller, aiming to meet the electrical, thermal, and steam demands of the Cavalo Marinho farm.

2. CONCEPTUAL DESIGN

2.1 Data Collection

For this proposed work, field data was collected to better evaluate and improve the post-harvest and processing of mussel cultivation at Cavalo Marinho Farm. This Farm already has a conventional steam generator and corresponding distribution system to meet the demand for steam, primarily used in mussel cooking. The steam generator uses eucalyptus wood chips as fuel, with a capacity to produce up to 3000 kg/h of saturated steam at effective pressure of 3 bar, to meet the current demand for mussel pre-cooking, with an assumed efficiency of 70%. During the low season, in the final stage of processing, approximately 800 kg/day of ice is consumed for mussel freezing, which is a routine process after each harvest. Additionally, during the low season, the company pays the local provider for an electricity consumption of approximately 5400 kWh, in addition to a contracted demand of 80 kW, which may increase during the high season. Furthermore, Cavalo Marinho Farm has plans for expansion, considering the recent approval for the cultivation of *Kappaphycus alvarezii* macroalgae in the municipality of the farm (EPAGRI, 2022).

2.2 Problem Formulation

Two scenarios were considered for the analysis of the proposed cogeneration system: (i) Scenario 1, consisting of a natural gas turbine (GT), a first heat exchanger (HE1) for preheating the air used in the existing steam generator, and a second heat exchanger (HE2) for heating the air used in the drying process of the macroalgae; (ii) Scenario 2, integrating solar panels into Scenario 1. In both scenarios, a mechanical compression chiller is used for ice production.

The gas turbine was chosen because of the availability of greater residual heat concentrated at higher temperatures in the exhaust gases if compared to internal combustion engines. The choice of a mechanical chiller, as previously highlighted, is due to its flexibility in meeting the required thermal demands as well as the lower initial investment. In the case under study, the chiller is integrated with an ice bank to supply the thermal demand for mussel freezing. Ice consumption is intermittent, according to the seasonality of the harvesting process. Additional complementary studies, not presented in this technical article, involve supplementary burning with the exhaust gases to export surplus electrical energy to the open electricity market.

In Scenario 1 (see Fig. 2), the exhaust gases are taken to the heat exchanger HE1, heating the atmospheric air to temperatures of about 100°C, and then to the heat exchanger HE2, heating the atmospheric air to temperatures of about 60°C. The drying air is led to a V-Groove forced convection drying chamber for algae drying (Ali *et al.*, 2017). The V-Groove chamber was recommended due to its better temperature homogeneity and utilization of the hot air. Previous studies have shown that drying chambers based on forced convection and "V" grooves, such as the V-Groove chamber, provide better performance in utilizing the air flow for drying *Kappaphycus alvarezii* (Felicidade *et al.*, 2020).

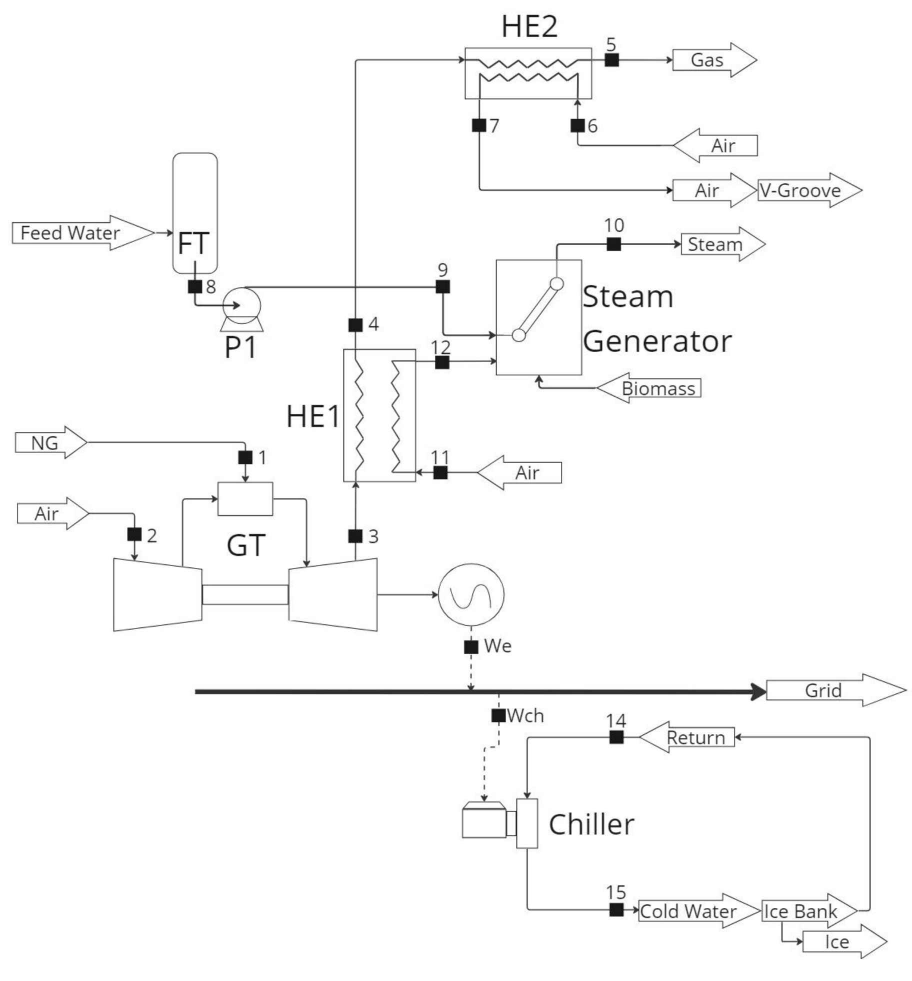

Figure 2. Scenario 1 – Natural gas cogeneration plant.

Scenario 2 (see Fig. 3) is analyzed here considering the hypothesis that the gas turbine does not meet the required demand in the plant. In the project, a total of 44 photovoltaic panels from Osda, model 550 W (NeoSolar, 2023) were considered with capacity to produce 2.676 kWh/month in the region of the farm, according to a simulation carried out on the Intelbras Solar company's website (Intelbras, 2023). Additionally, in this context, it is assumed that mussel processing occurs during daylight hours, eliminating the need to incorporate a battery for storing energy to be used at night.

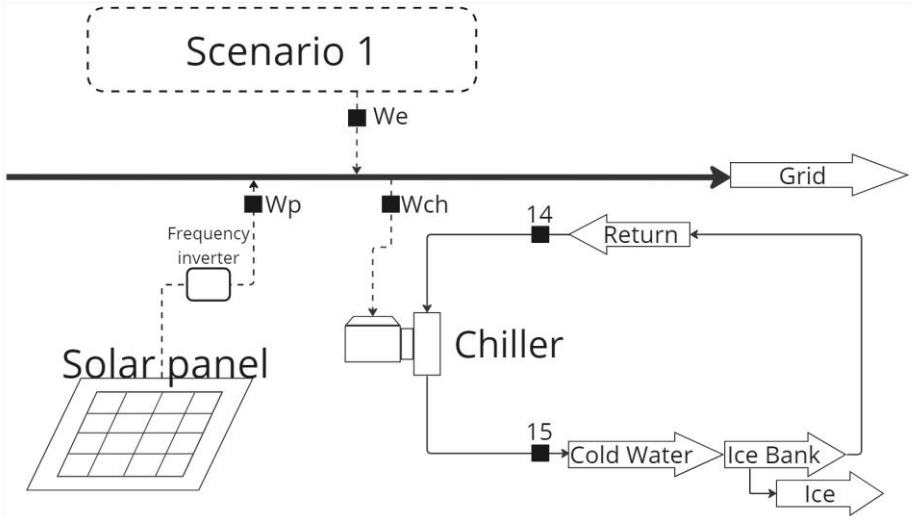

Figure 3. Scenario 2 – Natural gas cogeneration plant with photovoltaic generation.

Data regarding the gas turbine, chiller, and selected photovoltaic panels are shown in Table 1. The acquisition cost of the panels includes the installation costs of the plant.

Table 1. Characteristics of the selected equipment for both scenarios.

Data	**Gas turbine**	**Solar Panels**	**Chiller**
Manufacturer / Model	Capstone C65	Osda 550W	Euro Cold LTW 100
Electrical power, (kW)	65	-	-
Heat Rate, (kJ/kg)	12900	-	-
Efficiency, (%)	28	-	-
Exhaust gas flow rate, (kg/s)	0,49	-	-
Exhaust gas temperature, (°C)	329	-	-
Panel optical efficiency, (%)	-	21.3[1]	-
Cooling capacity, (kW)	-	-	5,7
Electricity Consumption, (kW)	-	-	8,75
Outlet temperature range, (°C)	-	-	-25 to -10
Unity cost, (R$ 1000)	500	100	30[2]

(1) technical catalog, irradiance 1000 W/m², AM 1.5, and cell temperature of 25°C
(2) value of ice bank included

The simulation model is based on the First Law of Thermodynamics, considering the mass and energy balances in the gas turbine, heat exchangers, steam generator, and chiller. The resulting equations were programmed and solved using the computational code EES (Engineering Equation Solver). The composition of the natural gas used corresponds to the one provided by SCGas (https://www.scgas.com.br/scgas/home/), as presented in a volumetric basis in Table 2.

Table 2. Natural gas composition (SCGas, 2023)

Composition	**(%)**	**Mass Molar (g/mol)**
Methane (CH_4)	89.2	16
Ethane (C_2H_6)	5.9	30
Propane (C_3H_8)	1.81	44
C_4^+	0.97	58[1]
CO_2	1.42	44
N_2	0.7	28

(1) In this work C_4^+ corresponds to butane (C_4H_{10})

The natural gas consumption was calculated considering the respective lower heating value (LHV) of natural gas (according to NBR 15213 standard) and the corresponding mass of water formed in combustion, according to the following equations:

$$\dot{m}_{NG}=\frac{\dot{W}_e}{LHV_{NG}\ \eta_{GT}} \tag{1}$$

$$LHV_{NG}=HHV_{NG}-2440m_{H_2O} \tag{2}$$

$$m_{H_2O}=\frac{2\ M_{molar}^{H_2O}}{M_{molar}^{CH_4}}f_m^{CH_4}+\frac{3\ M_{molar}^{H_2O}}{M_{molar}^{C_2H_6}}f_m^{C_2H_6}+\frac{4\ M_{molar}^{H_2O}}{M_{molar}^{C_3H_8}}f_m^{C_3H_8}+\frac{5\ M_{molar}^{H_2O}}{M_{molar}^{C_4H_{10}}}f_m^{C_4H_{10}} \tag{3}$$

where $\dot{W}_e$ e η_{GT} correspond to the power and efficiency of the gas turbine. The LHV_{NG} e HHV_{NG} are the lower and higher heating values of natural gas, respectively, and m_{H_2O} is the total mass water in the combustion products. M_{molar} corresponds to the molar mass of water and the specified hydrocarbons, and f_m is the mass fraction of hydrocarbons in the total composition.

The biomass used in the steam generator has a composition on a mass basis according to Table 3. The corresponding LHV_{bio} was considered equal to 19170 kJ/kg (Neiva *et al.*, 2018).

Table 3. Eucalyptus composition (Bazzo, 1995)

Composition	**(%)**
Carbon (C)	49
Oxygen (O)	44
Hydrogen (H)	6
Ash	1

The biomass consumption was then calculated using the equation

$$\dot{m}_{bio}=\frac{\dot{m}_{10}(h_{10}-h_9)}{\eta_{SG}\ LHV_{bio}} \tag{4}$$

where $\dot{m}_{10}$ corresponds to the mass flow rate at the outlet of the saturated steam, h_9 e h_{10} correspond to the water enthalpies at inlet and outlet of the steam generator, respectively, η_{SG} represents the steam generator efficiency, and LHV_{bio} is the lower heating value of biomass.

The combustion air flow rate of the steam generator was calculated considering the biomass composition, along with the amount of oxygen present in the air on the mass basis, as shown in the following:

$$\dot{m}_{air}=\dot{m}_{12}=e_{air}\ m_{air,th}\ \dot{m}_{bio} \tag{5}$$

$$m_{air,th}=\frac{100}{23.15}\ m_{O_2,th} \tag{6}$$

$$m_{O_2,th}=M_{molar}^{O_2}\left(\frac{f_m^C}{M_{molar}^C}+\frac{f_m^H}{4\ M_{molar}^H}-\frac{f_m^O}{2\ M_{molar}^O}\right) \tag{7}$$

where e_{air} is the excess air coefficient, $\dot{m}_{air,est}$ and $m_{O_2,est}$ are the theoretical air mass present in the biomass and the fraction of oxygen mass in the air (23.15%), respectively. M_{molar} and f_m correspond to the molar mass and mass fraction of oxygen, carbon, and hydrogen. Here, an excess air coefficient equal to 1.5 (50%) was considered in the analysis.

Finally, the overall efficiency of the plant in the case of Scenario 1, including the cooling load provided by the chiller, is calculated according to the equation

$$\eta_{global}=\frac{\dot{W}_e+\dot{Q}_{steam}+\dot{Q}_{air}-\dot{W}_{P1}+\dot{Q}_{CH}}{\dot{m}_{NG}\ LHV_{NG}+\dot{m}_{bio}\ LHV_{bio}+\dot{W}_{CH}} \tag{8}$$

where $\dot{W}_e$ e $\dot{W}_{CH}$ correspond to the power of the gas turbine and the chiller, respectively. $\dot{W}_{P1}$ is the power consumed by the water feed pump, $\dot{Q}_{steam}$ is the thermal power of the steam generator, $\dot{Q}_{air}$ is the thermal power provided by heat exchanger HE2, and $\dot{Q}_{CH}$ is the cooling load provided by the chiller.

Calculations related to air heating in heat exchangers HE1 and HE2 were performed according to the First Law of Thermodynamics, considering data available in the catalog and the exhaust gases from the turbine as ideal air. Regarding the cooling load, data from the selected mechanical chiller manufacturer's catalog were considered.

For the economic analysis, in this work only the Return on Investment (ROI) was used as a parameter for comparison both scenarios, according to the equation

$$\mathrm{ROI} = \frac{\mathrm{Revenue} - \mathrm{Cost}}{\mathrm{Cost\ of\ Investment}} \times 100 \tag{9}$$

This parameter was used to measure the profitability and effectiveness of initial investment, assessing the perspective of time required to recover the investment. In the case of this project, only the savings generated by self-production of electricity and ice were analyzed, without considering maintenance and depreciation expenses of equipment, acquisition of natural gas and wood chips, and other costs. In addition, it is worth noting that the economically analyzed number of hours aligns with the steam generator's utilization and the consumption value of 5,400 kWh for an 80 kW demand.

2.3 Cost of Electricity and Natural Gas

The current prices for electricity charged by the local provider (CELESC) were established through Resolution No. 3,094 of ANEEL on August 16, 2022 (ANEEL, 2022). These values, without the application of movement taxes, result in a value of 16.43 R$/kW for demand and 0.49071 R$/kWh for energy.

In order to encourage the use of cogeneration in Brazil, the purchase price of natural gas has a special tariff and readjustment conditions for supply intended for thermal generation and cogeneration systems. According to SCGas company, the base price of natural gas depends on consumption in cubic meters (m^3). For a daily consumption of up to 10,000 m^3, the price of natural gas is R$ 0.287/m^3, and for consumption greater than 90,000 m^3, it is R$ 0.1404/m^3 (SCGÁS, 2023), with a reference condition of 1 atm pressure, 20°C temperature, and higher calorific value of 9,400 kcal/m^3.

3. RESULTS AND DISCUSSION

Regarding technical viability, both systems proved to be viable, achieving the preheating of steam generator air up to 100°C solely through exhaust gases and reaching the required 60°C for seaweed drying at a flow rate of 0.3427 kg/s, releasing only exhaust gases at 110°C at the end of the pipeline. As for ice production, it exceeded the original value, with a daily production of 1353 kg of ice. The solar panel proved to be efficient in supplying the remaining energy.

The overall efficiency (η_{global}) of Scenario 1 reached a value of about 67.4% while Scenario 2 achieved 68.1%. These efficiencies are in line with values found in the literature for cogeneration projects (Carvalho and Pontes, 2014), limited by the performance of the turbine, steam generator, and chiller. Changes such as further extracting thermal energy available in the exhaust gases, adjusting the moisture content of eucalyptus wood chips, or modifying the ice bank connected to the chiller can be made to increase efficiency. However, these changes would prove to be costly in relation to the marginal increase in efficiency.

It should be noted that although the ice production exceeded the initial demand by 553 kg/day, due to its intermittent use, it is possible to produce ice up to the initial demand of 800 kg/day and store the remaining amount in the ice bank for future use. This margin is necessary considering periods of high shellfish harvesting, where the number of mussels to be frozen can easily reach tons. The same applies to electricity generation, as in Scenario 2 there is an excess of kWh from the solar panel, assuming it operates 24 hours a day, 7 days a week, which could easily be sold to producers in the region, as they are distributed along the coast. It is worth noting that Fazenda Cavalo Marinho is currently one of the most mechanized farms in the mussel farming area of Florianopolis bay, so adjacent producers would require smaller quantities of electricity and thermal energy.

Regarding the economic aspect, Table 4 presents the investments of the two proposed scenarios compared to the baseline system (initial), where all electrical demand would be covered by the local provider.

In the economic analysis, it was found that in scenario 1, where only the cogeneration plant and mechanical compression chiller were used, considering only the "discounts" received on electricity and thermal energy, the farm would start to see a return in 11 years and 6 months. However, this payback period may be considered invalid, as the market is expected to undergo significant changes during that time. Furthermore, it is important to note that with a negative ROI, the company would still be operating at a loss after 10 years.

On the other hand, in the second scenario, incorporating the assistance of solar panels, the system provides a monthly savings equivalent to the electricity bill, amounting to R$ 5,068.23, and the payback time would be shorter than in the first scenario, totaling 10 years and 6 months. Although it still shows a negative ROI, the reduced value of -3.5%, compared to the first scenario, reveals the potential of using solar panels in this type of application.

Table 4. Economic Analysis and Return on Investment

Data	Scenario 0	Scenario 1	Scenario 2
Description	Current provider	Cogeneration + Chiller	Cogeneration + Chiller + Solar Panels
Initial investment, (R$ 1000)	0.00	530	630
Demand to be paid, (kW)	80	23.91	0
Consumption to be paid, (kWh)	5,400	1,613.93	0
Demand cost, (R$)	1,314.40	392.84	0.00
Consumption cost, (R$)	2,649.83	791.97	0.00
Ice cost, (R$)(1)	1,104.00	0.00	0.00
Total, (R$/month)	5,068.23	1,184.81	0.00
Savings, (R$/month)	0.00	3,883.42	5,068.23
Months to pay off the investment	-	136.5	124.3
Years to pay off the investment	-	11.5	10.5
ROI in 10 years, (%)	-	-12.1	-3.5

(1) the price of ice was considered to be R$1.38 per kilogram

It is important to note that at first glance, the payback time may appear invalid. However, there are possibilities to reduce it by uninterrupted operating the cogeneration plant and solar panels, including weekends, and selling the surplus kWh and ice. Additionally, as the air used for burning eucalyptus is preheated, expenses related to steam generator components are reduced. Another advantage is the increased efficiency in seaweed drying, making the activity more profitable. During periods of large-scale harvesting, the cogeneration plant increases its economic performance, thus meeting the fluctuations in harvesting throughout the year and becoming viable.

4. CONCLUSION

Based on the obtained results, it can be concluded that both studied scenarios demonstrated technical viability, achieving the necessary preheating for saturated steam production and seaweed drying, as well as producing a significant amount of ice. However, the overall efficiency of the systems can still be improved through component modifications and further utilization of thermal energy from exhaust gases.

In terms of economic aspects, the proposed natural gas cogeneration system and mechanical chiller would result in significant savings compared to the current system, where the electrical demand is supplied by the local utility company. In scenario 1, the return on investment would occur in approximately 11 years and 6 months, while in scenario 2, with the incorporation of solar panels, the payback period would be reduced to around 10 years and 6 months. Although both scenarios showed a negative ROI, they demonstrate promising potential to be used in mussel farms.

It is important to consider that the payback time can be further reduced with additional measures, such as continuous operation of the cogeneration plant and the commercialization of excess energy and ice. Additionally, preheating the combustion air and increasing efficiency in seaweed drying can contribute to making the activity more profitable. Therefore, these additional improvements have the potential to bring the payback time to less than 10 years.

A more detailed economic viability analysis, considering steam production, hot air generation, and steam generator savings, can be the subject of future studies, as well as sensitivity analysis of the plant, the ideal hot air flow rate for seaweed drying, and the replacement of the chiller and ice bank by ice maker, which could provide a more economically efficient coefficient of performance (COP). By investigating these aspects and conducting further in-depth studies, a more comprehensive understanding of the potential of the proposed system can be obtained. This would help identify additional optimization opportunities and explore new alternatives to make the project even more economically viable.

5. ACKNOWLEDGEMENTS

We would like to express our gratitude to Engineer Rodrigo from Fazenda Cavalo Marinho for his valuable collaboration and technical support provided, as well as to Fazenda Cavalo Marinho itself for granting access to their processing equipment.

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