COMPARISON BETWEEN TWO ELECTRICITY COGENERATION ALTERNATIVE SCHEMES FOR A SUGARCANE ALCOHOL DISTILLERY

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Abstract. *Technical and economic evaluations of alternative schemes for increasing electricity cogeneration in a sugarcane distillery are discussed. The main purpose of this increase is to provide electricity self-sufficiency and surpluses for sale. The first alternative scheme consists in modifying the present steam generator, to increase steam generating capacity from 60 to 80 t/h, at the same state (340 ºC and 32 kgf/cm^2). In this case the investment required would be US$ 1,160,000.00, considering the installation of a new steam generator, feed water treatment process and the acquisition of larger cooling towers for the turbine condensers. The new system will provide about 18,262 MWh of surplus electricity, on average. In the second scheme, a new steam generator having a capacity of 100 t/h at 420 ºC and 42 kgf/cm^2, would allow a higher availability (available work). This alternative requires installation of cooling towers and a new steam generator feed water treatment system with demineralization, demanding approximately US$ 2,000,000.00, and could generate about 26,953 MWh of surplus electricity. Considering that the second system demands a larger investment than the first, a costly water treatment, and the low sale price of electricity, the first option appears to be economically more attractive.*

Keywords: *Sugarcane bagasse, increasing eletricity cogenaration, alcohol distillery*

1. INTRODUCTION

Cogeneration is known as the combined generation of process heat and (electromechanical) power from fuel, including residue. Today large and medium sized sugarcane plants already cogenerate all their energy requirements to achieve economic viability, using cane bagasse, a residue of high energy content. The increasing demand for fuel alcohol in domestic and foreign markets has stimulated the sector to expand capacity subject to energy and economic constraints. In this climate, when Japungu Agroindustrial S. A., a modern sugarcane alcohol distillery, decided to increase electricity cogeneration capacity to meet the 500 kW required to attain self-sufficiency and the máximum surplus possible. This publication describes the thermodynamic analysis of two alternative schemes with an evaluation of the modifications and capital investments required to attain the production targets established while trying to ensure that increased yields compensate the investment.

2. THE INDUSTRY

2.1. General Description

Japungu Agroindustrial S. A., in Santa Rita, Paraíba, has always sought technological leadership, having cogenerated 1 MWe surplus electricity in 1986 for sale to the utility. Presently the industry crushes 672,000 t of cane, Japungu (2003), producing 215,000 t of bagasse, 32 % of the input, cf. Camargo et al. (1990). An investigation indicated that 768,000 t of cane could be processed, constituting the new target for the intended increase in processed cane.

Plant activity occurs in two distinct periods. The season, between July and March,.where 145,000 t of bagasse are required to raise 58 t/h of steam, for the distillation process. In the off-season, April to June, molasses stored in season is processed and hydrated alcohol is converted to anhydrous alcohol, after which a complete plant maintenance is performed. In this period, 27,600 t of bagasse burned during 50 days raise 46 t/h of steam to process molasses and hydrated alcohol. A reserve of 500 t of bagasse is carried over to start the steam generator for the subsequent season.

2.2. Present Energy Generation

Figure (1) is a sketch of the present electricity cogeneration system. The steam generator raises steam at 3.14 MPa (32 kgf/cm^2) gauge pressure and 340 ºC temperature to feed two backpressure turbo-generators at (turbine inlet) 2.94 MPa (30 kgf/cm^2) gauge pressure and 328 ºC temperature. One generates 3,500 kVA (2,800 kWe), and the other 2,500 kVA (2,000 kWe), for the industry and the agro village. The average electricity demand of distillery and agro village is about 5,300 kW, leading to a deficit of 500 kW, corresponding to an expenditure of about US$ 60,000.00 per season on the purchase of grid electricity, Jaguaribe et al. (2002) . Steam exhausts the turbines at 149 ºC and 0.245 MPa (2.5 kgf/cm^2) whence the steam consumption was calculated as 9.9 kg/kWh for turbogenerator 1 and 12.2 kg/kWh for the turbogenerator 2, Hugot (1969).

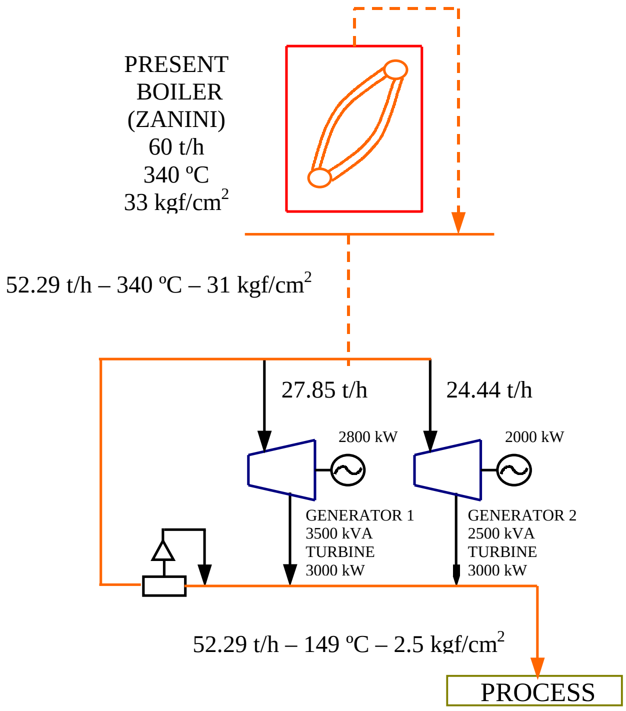

Figure 1. Present cogeneration system at Japungu Agroindustrial S/A.

3. FACTORS ANALYSED FOR THE INCREASED POWERPLANT CAPACITY

To co-generate more electricity, a significant increase in steam flow is required, which could be achieved either by modifying the existing steam generator or purchasing a new one. Modifying the existing steam generator, maintaining the design steam conditions of 3.14 MPa (32 kgf/cm^2) gauge and 340 ºC, the maximum steam flow possible would be 80 t/h, sufficient to meet the immediate demand. However to generate surplus electricity with an existing 15 MVA condensing/extraction turbo-generator operating in season, to meet the future plant goals, a more effective (energywise) steam generator, should be acquired, which should raise more than 80 t/h of steam.

4. ELECTRICITY COGENERATION SYSTEM INCREASING THE CAPACITY OF THE PRESENT STEAM GENERATOR

The backpressure turbo-generators would function both in- and off-season, supplemented by the condensing/extraction turbo-generator in-season. However, this would require the condensing/extraction turbo-generator to operate at less than half its design flowrate, with a drop in efficiency. Even an estimated 11% drop in condensing/extraction turbo-generator efficiency would significantly reduce electricity generation as compared to passing all the steam through the extraction stage. Steam conditions at turbine inlet are assumed at 340 ºC, 31 kgf/cm^2. Pressure values assumed are 2.5 kgf/cm^2 at turbine 1 and 2 exit and condensing turbine extraction, 1.054 kgf/cm^2 at condensing turbine exit. Temperatures 134 ºC e 2.5 kgf/cm^2 at turbine 1 exit and condensing turbine extraction, 166 ºC at turbine 2 exit and 111 ºC at condensing turbine exit. The scheme is described in Fig. (2) and would allow for operation at maximum capacity in and off-season subject to bagasse availability.

5. COSTS OF MODIFYING THE PRESENT STEAM GENERATOR AND INSTALLING THE NEW STEAM GENERATOR FOR THE COGENERATION SYSTEM

The estimated cost of modifying the present steam generator was US$ 125,000.00. Additionally, cooling towers must be installed for the turbine condensers and the steam generator feedwater must be softened at an additional cost of US$ 0.03/m^3.

The supplier of the new steam generator proposes to integrate it into the cogeneration system in Japungu on a "turn-key" basis, with the installation of a modern automation system to control and supervise the whole system, including steam generator and turbogenerators. The control room to be built would oversee the whole generating plant and the connection to the grid through a 69 kV substation. It would display system parameters and allow control of energy sold to the grid. The quotation was US$ 700,000.00, while the distillery would be responsible for all the civil engineering required. The total system installation costs with the new steam generator are estimated at about US$ 1,160,000.00. Aditionally, the feedwater demineralizer would cost US$ 0.40/m^3. The overall cost of new steam generator with the feed water demineralizer and auxiliary equipment for integration and control is estimated at about US$ 2,000,000.00.

6. BAGASSE AVAILABILITY, STEAM CONSUMPTION AND ELECTRICTY GENERATION WITH THE STEAM GENERATOR MODIFICATION

6.1. Bagasse Consumption

The total available bagasse for season and off-season, B_T, is about 32 % of the cane crushed in season, i.e.

$$B_T = 246{,}372 \text{ t} \tag{1}$$

The total bagasse produced, B_T, 206,950 t, is divided to meet the demands of three periods: in-season, B_S; off-season, B_{ES}; and the start of the following season, a 500 t reserve, B_R. Hence:

$$B_T = B_S + B_{ES} + B_R \tag{2}$$

6.1.1. Bagasse Required Off Season and in Available in Season

Bagasse off-season consumption, B_{ES}, is evaluated using Eq. (3):

$$B_{ES} = 24.N.\frac{C_{VES}}{C_E}, \tag{3}$$

where

C_{VES} is the average process steam consumption, 78.83 t/h of steam.

C_E is the specific generation of the modified steam generator, 2.1 kilograms of steam per kilogram of bagasse.

N is the duration of off-season activity in days, usually taken as 50.

With the values above,

B_{ES} = 45,044 t.

From Eq. (2), the available bagasse in season, B_S is calculated as:

B_{DS} = 200,828 t.

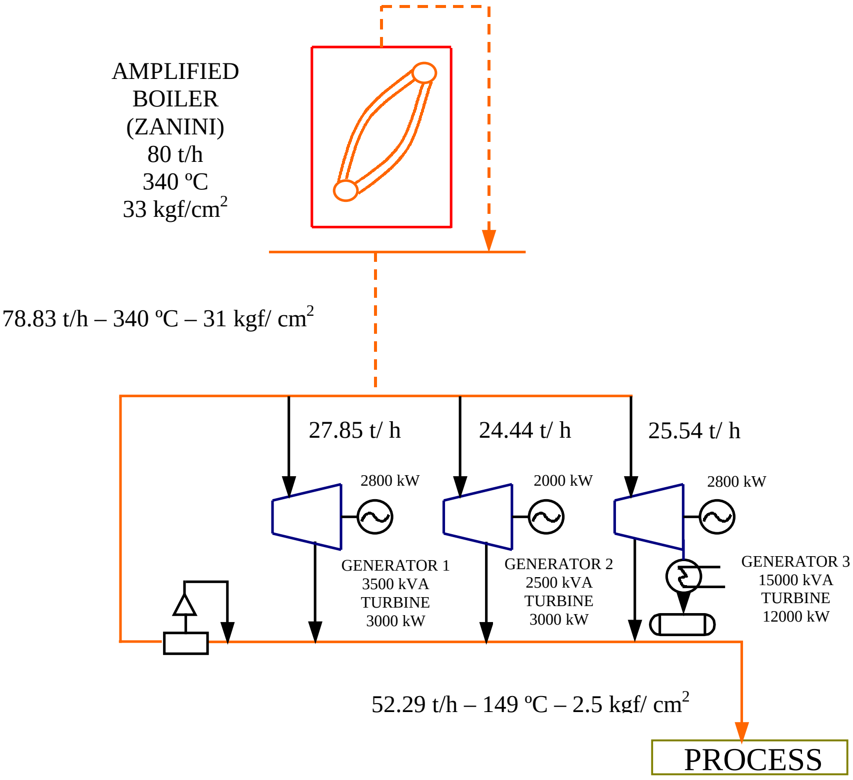

Figure 2. Cogeneration system increasing present steam generator capacity

6.1.2. Bagasse Required in Season, for Process Energy

The bagasse required to raise steam for electrical and process energy, B_P, is given by the total process operating time in hours, N_T, times the ratio of the average in-season process steam consumption, C_{VP}, to the specific steam generation, C_E, defined above:

$$B_P = \frac{C_{VP}}{C_E}.N_T \tag{4}$$

and

C_{VP} = 78.83 t/h of steam, N_T = 5,310 h.
Whence B_P = 199,319 t.

The surplus bagasse, B_C, is determined by subtracting the mass of bagasse required, B_P, from the available bagasse for the season, B_S, given by Eq. (2) , i.e., $B_C = B_S - B_P$ = 1,509 t.

6.2. Steam Consumption for Electricity Generation

6.2.1. Steam to Meet Turbine Requirements

The specific steam consumption of backpressure turbine 1, Faires (1966), is determined as

$$Ce_{cp1} = 9.95 \frac{kg}{kWh},$$

For backpressure turbine 2,

$$Ce_{cp2} = 12.22 \frac{kg}{kWh},$$

For the condensing stage of the extracting/condensing turbine it is assumed that

$$Ce_{cond} = 9.12 \frac{kg}{kWh}$$

From the specific steam consumptions and generated turbine power Pg, the steam consumption of the backpressure turbo-generators stages is determined by:

$$Cv = Pg.Ce, \qquad (5)$$

where Pg is the power output of turbines 1, 2 e 3, respectively 2,800 kW, 2,000 kW e 2,800 kW.

For the condensing turbine the maximum power generated was assumed at 2,800 kW, limited by the steam raised by the available bagasse.

With the steam consumptions for turbines 1, 2 and 3, respectively: Cvt_1 = 26.44 ts/h, Cvt_2 = 18.88 ts/h and Cvt_3 = 12.28 ts/kg, the steam generation required, Vc, is therefore:

$$Vc = Cvt_1 + Cvt_2 + Cvt_3 = 78.83 \text{ t/h} \qquad (6)$$

6.3. Electricity Generation

6.3.1. Electricity Generated by the Backpressure and Condensing Turbines

The average total power generated by the two backpressure turbines is:

$$Pg_T = Pg_1 + Pg_2 \qquad (7)$$

or Pg_T = 4,800 kW.

The total energy generated by these turbo-generators, E_{CP}, is the product of Pg_T and the total hours of operation (N_T),. 5,310 h, giving E_{CP} = 25,488 MWh.

The average power generated by the condensation section, P_{CD}, is estimated as:

$$P_{CD} = \frac{Cvt_3}{Ce_{cond}} \qquad (8)$$

or P_{ext} = 2,800 kW.

The energy generated by the condensation section is:

$$E_{CN} = P_{CD} \cdot N_T \tag{9}$$

Hence E_{CN} = 14,868 MWh.

6.3.2. Total Electricity Generated in Season, E_T

The total electricity generated in season, E_T, is the sum of E_{CN} e E_{CP}, whence E_T = 40,356 MWh.

6.3.3. Surplus Electricity Generated in Season

The product of the average electricity demand of 5, 300 kW, and 5,310 total crushing hours in season gives the total electricity consumption in the enterprise, E_{FS} = 28,143 MWh. Considering the average power from the condensing turbine, P_{MC} (= P_{CD}), and parasitic losses 5% of the new generator power, the parasitic energy loss is evaluated as:

$$E_P = P_{MC} \cdot 0.05 \cdot N_T \tag{10}$$

or E_P = 744 MWh.

The saleable electricity available in season, E_D, is determined from the relation:

$$E_D = E_T - E_{FS} - E_P \tag{11}$$

whence E_D = 11,470 MWh per season.

6.3.4. Surplus Electricity Generated Off-Season

During the off-season cane extraction does not operate and plant power demand drops to 1,800 kW. The total electricity consumption is then 2,160 MWh and the parasitic losses, E_{pe}, 168 MWh. steam and power demands are lower during the fifty days on average for this period.

A relation similar to Eq. (9), with a duration of 50 days calculates the energy generated in the period by the backpressure turbo-generators, E_{CE} = 9,120 MWh, and the surplus electrical energy available in the off season is

$$E_{DE} = E_{CE} - E_{TE} - E_{pe}\,, \tag{12}$$

whence, E_{DE} = 6,792 MWh.

6.3.5. Total Surplus Electricity Generated

Total surplus electricity generated is sold, usually to an utility, a practice stimulated by the Brazilian Government.

Adding Eqs. (11) and (12) determines the total electricity surplus, E_{ET}, generated during the year by the distillery:

$$E_{ET} = E_D + E_{DE}, \tag{13}$$

or E_{ET} = 18,262 MWh.

6.3.6. Average Surplus Power

Two other useful parameters for the technical and economic evaluation of the electricity generation are the average power surpluses in-season, P_{EXS}, and off-season, P_{EXES}, obtained by dividing Eqs. (11) and (12) by the respective hours of operation:

P_{EXS} = 5, 970 kW and P_{EXES} = 3, 000 kW.

7. COGENERATION SYSTEM WITH A NEW STEAM GENERATOR

The plant management opted for the acquisition of a new vertical water tube steam generator, Equipalcool (2001), with a nominal steam raising capacity of 100 t/h at 43 kgf/cm² and 420 ºC at 85% efficiency. It is planned to operate the turbines with steam inlet at 420 ºC and 41 kgf/cm² and conditions are estimated as 177 ºC and 2.5 kgf/cm² for turbine 1 outlet and turbine 3 extraction; 194 ºC e 2.5 kgf/cm² for turbine 2 outlet; and 117 ºC and 1.054 kgf/cm² at the exit of the condensing turbine. The new system is sketched in Fig. (3).

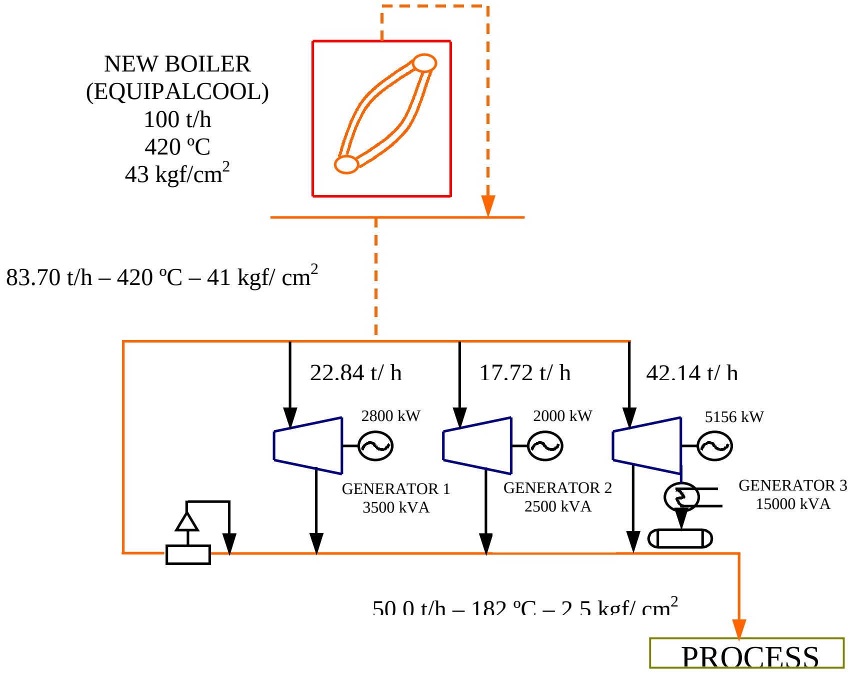

Figure 3. Scheme of the co-generation system under implementation at Japungu Agroindustrial S/A.

8. BAGASSE AVAILABILITY, STEAM CONSUMPTION AND ELECTRICTY GENERATION WITH THE NEW STEAM GENERATOR

8.1. Bagasse Consumption

The total available bagasse is assumed to be the same as above.

8.1.1. Bagasse Required Off-Season and in Available in Season

Bagasse off-season consumption, B_{ES}, is evaluated from Eq. (3):

where

C_{VES} is the average process steam consumption, 51.0 t/h.

C_E is the specific generation of the modified steam generator, 2.1 kilograms of steam per kilogram of bagasse.

N is the duration of off-season activity in days, usually taken as 50.

With the values above,

B_{ES} = 29,143 t.

From Eq. (2), the available bagasse in season, B_S is calculated as:
B_{DS} = 216,729 t.

8.1.2. In Season Bagasse Requirement for Process Energy

The bagasse required to raise steam for electrical and process energy, B_P, is given by Eq. (4), with C_{VP} = 83.70 t/h and N_T = 5,310 h, whence B_P = 211,639 t.

The surplus bagasse, B_C, that may be sold directly, processed for fodder, fertiliser, or surplus electricity, is determined by subtracting the mass of bagasse required, B_P, from bagasse produced, B_T:

$B_C = B_S - B_P$ = 5,090 t.

8.2. Steam Consumption for Electricity Generation

8.2.1. Steam to Meet Turbine Requirements

The specific steam consumption of backpressure turbine 1 and the extraction module of turbine 3 is determined as:

$$Ce_{cp1} = 8.14 \frac{kg}{kWh},$$

For backpressure turbine 2,

$$Ce_{cp2} = 8.86 \frac{kg}{kWh},$$

For the condensing stage of the extracting/condensing turbine it is assumed that:

$$Ce_{cond} = 32.45 \frac{kg}{kWh}$$

From the specific steam consumptions and generated turbine power Pg, the steam consumption of the backpressure turbo-generators is determined by Eq. (5), where Pg is the power output of turbines 1, 2 and extraction and condensation modules of turbine 3, respectively 2,800 kW, 2,000 kW 4,456 kW and 700 kW.

The power generated by the condensing turbine the maximum was assumed at 2,800 kW, limited by the steam raised by the available bagasse. The corresponding steam consumptions are Cvt_1 = 22.84 t/h, Cvt_2 = 17.72 t/h, Cvt_3 = 42.14 t/h and V_{cd} = 22.70 t/h. The steam generation required, Vc, is therefore:

$$Vc = Cvt_1 + Cvt_2 + Cvt_3 + V_{cd}, = 83.70 \text{ t/h} \quad (14)$$

8.3. Electricity Generation

8.3.1 Electricity Generated by the Backpressure and Condensing Turbines

The average total power generated by the two backpressure turbines is given by Eq. (7), i.e. 4,800 kW.

The total energy generated by these turbo-generators, E_{CP}, is the product of Pg_T and the total hours of operation (N_T),. 5,310 h, giving E_{CP} = 25,488 MWh.

For the condensing turbine average total power generated, E_{CN}, is given by:

$$E_{CN} = (P_{CD} + P_{ext}) \cdot N_T, \quad (15)$$

where P_{CD} is the average power generated by the condensing module, 700 kW, and P_{ext} the average power generated by the extraction module, 4,456 kW, calculated in a manner similar to Eq. (10). Substituting these values, E_{CN} = 27,377 MWh.

8.3.2 The Total Electricity Generated in Season, E_T

The total electricity generated in season, E_T, is the sum of E_{CN} e E_{CP}, whence E_T = 52,865 MWh.

8.3.3 Surplus Electricity Generated in Season

The product of the average electricity demand of 5, 300 kW, and 5,310 total crushing hours in season gives the total electricity consumption in the enterprise, E_{FS} = 28,143 MWh. Considering the average power from the condensing turbine, P_{MC} (= P_{CD}+ P_{ext}), and parasitic losses 5% of the new generator power, the parasitic energy loss is evaluated as:

$$E_P = P_{MC} \cdot 0.05 \cdot N_T \quad = 1{,}369 \text{ MWh} \tag{10}$$

or E_P = 1,369 MWh.
The surplus electricity available in season, E_D, is determined from the relation:

$$E_D = E_T - E_{FS} - E_P \; = \; 23{,}353 \text{ MWh} \tag{11}$$

8.3.4 Surplus Electricity Generated Off-Season

During the off-season cane extraction does not operate and the condensing turbine is desactivated through lack of bagasse. The backpressure turbines operate with stored bagasse and generate 4,800 kW altogether. Fig. (4), is a sketch of the off-season cogeneration scheme.

In this period the plant power demand drops to 1,800 kW and the total electricity consumption is then 2,160 MWh. The electricity generated in the period is given by Eq. (9), with N = 50 days, whence E_{CE} = 5,760 MWh. From Eq. (12), the available surplus power for sale off-season is E_{DE} = 3,600 MWh.

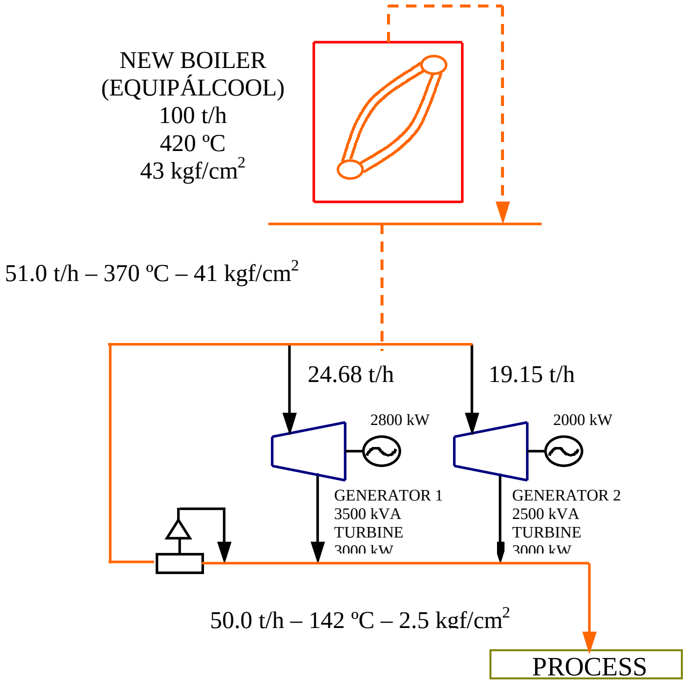

Figura 4. Scheme of the co-generation system used during off-season.

8.3.5. Total Surplus Electrical Energy Generated

Adding Eqs. (11) and (12) determines the total electricity surplus, E_{ET}, generated during the year by the distillery:

$$E_{ET} = E_D + E_{DE} = 26{,}953 \text{ MWh} \quad (13)$$

8.3.6. Average Surplus Power

Two other useful parameters for the technical and economic evaluation of the electricity generation are the average power surpluses in-season, P_{EXS}, and off-season, P_{EXES}, obtained by dividing Eqs. (11) and (12) by the respective hours of operation:

$P_{EXS} = 4{,}398$ kW and $P_{EXES} = 3{,}000$ kW.

9. DISCUSSION OF RESULTS AND CONCLUSIONS

The scheme with the modified steam generator would allow the generation of 40,356 MWh of electricity with a surplus of 11,470 MWh in season. Off season 9,120 MWh of electricity could be generated with a surplus of 6,792 MWh. Hence the total surplus electricity available for sale is 18,262 MWh. The annual increase in running costs for water softening (at US\$ 0.025/m^3) would be about US\$ 8,000.00. The total investment for the scheme is estimated at US\$ 1,150,000.00, and the increase in receipts at US\$ 540,000.00, based on the stipulated value of US\$ 30.00/MWh for bioelectricity, ANEEL (2001).

In the scheme with the new steam generator, 52,865 MWh of electricity would be generated, with a surplus of 23,353 MWh in season. Off season, 5,760 MWh of electricity could be generated with a surplus of 3,600 MWh. Hence the total surplus electricity available for sale is 26,953 MWh, with an increase of US\$ 800,000.00 in gross receipts. However, in this case the total investment for the scheme is estimated at US\$ 2,000,000.00 including the cost of demineralizing feedwater at an investment of US\$ 120,000.00.

A prelimnary economic evaluation would suggest that acquiring a new boiler would cost twice as much as modifying the existing boiler but would increase gross receipts by under 50%. If the time value of money is taken into account, the difference in net receipts would be even smaller. Hence the alternative recommended would be to modify the existing boiler.

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