A STUDY OF INCREMENT CASE OF THE COGENERATION IN SUGAR INDUSTRY FOR THE ECUADORIAN CONTEXT

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Abstract. *The sugar agribusiness presents a significant potential to increase the production of electric energy through cogeneration systems that can enhance the contribution of energy renewable resources in the electricity supply, substituting fossil fuels. In Equator, 31% of the electric energy is generated from oil derivatives and although the sugar plants already make some combined production of electromechanical power and useful heat, the installed systems can be improved. The aim of the present study is to evaluate the integral use of the sugar cane bagasse available from the productive process of the San Carlos Mill, reducing emissions of gases that contribute to the greenhouse effect and stimulating the efficient use of the biomass. In summary, this project intends to increase the generation capacity of electric energy from 7 to 35 MW, through the redesign of the cycle and incorporation of new turbo generators. A brief economic study of the production of electric energy and the sale of the excesses of 27 MW average were made. An operational analysis was realized by the convolution of the estimated curves of demand and generation of electric energy. From the results, it was concluded that the costs of the generated electricity estimated as 1.5 US cents/kWh, lower than costs of the supplied electric energy through fossil power plants with values in the range 3 - 15 US cents/kWh and the hydroelectric plants with a value of about 2 US cents/kWh.*

Keywords: *energy, cogeneration.*

1. Introduction

In the context of modernization policy of Ecuador, in October 1996 the Law of Electrical Sector went into effect (Official Registry Nº 43), establishing that the State assumes the task to regulate, standardize and control the service, whereas the projects of generation and distribution go to the hands of the private sector. According these new conditions, the private sector will be able to propose new projects of power generation the construction and operation of power stations of 50 MW or less will require only the permission granted by CONELEC; the power stations could use autogeneration or offer it to a public service. In the new free market the autogenerators can export the produced surpluses of electrical energy.

Within this framework of the electrical energy market of Ecuador, three sugar plants which have the greater participation in the local market, initiated plans to produce their own energy and to commercialize the excesses to the electrical market. Currently, these plants have in construction projects for an electrical generation of 88 MW. San Carlos intends to produce 35MW, whereas Valdez 25MW and La Troncal 28MW. In the case of San Carlos Mill, the accomplishment of the project is a way to stimulate the application of technologies based on the use of renewable resources (biomass), instead of nonrenewable (fossil fuels), for the generation of electrical energy that will be provided to the National Interconnected System of Ecuador. The project has as objective to produce energy from all bagasse produced in sugar cane milling process and to use it in the generation of electrical energy for the supplying of industrial consumption of the plant and to sell the energy excesses to Ecuadorian electrical market. In addition, it is expected to reduce the emissions of the gases that contribute to the greenhouse effect and to stimulate the investment in electrical projects based on the use of the biomass. The electrical production that will have the contribution of the sugar mills is not considered like part of the expansion plan of the energy supply in the country, but it can be an option that helps the demand that grows in more than 6.91% per year, according to data of the National Center of Energy Control of Ecuador (CENACE).

The San Carlos Mill is part of the 62 great consumers of electrical energy, which during the year 2004 had an energy consumption of 892.41 GWh that corresponds to the 7.22% of the whole electrical energy consumption in Ecuador, which was of 12,360.23 GWh. The energy consumed during the year 2004 by the San Carlos Mill was 9.39 GWh and in the month of December the Cogeneration Power Plant SAN CARLOS COGEN, entered in stage of test with 12 MW to the National Interconnected System of Ecuador with a production of 0.65 GWh. The electrical energy production costs of the Cogeneration Power Plant SAN CARLOS COGEN are competitive in relation to the costs of production of the Thermal Power Plant that use fuels derived from petroleum and one hopes that they enter to the National Interconnected System as primary load.

2. Technical characteristics and information of the Power Plant

2.1. Technical description of the project

The current time, San Carlos mill processes approximately 11,000 Ton cane/day, producing 3,300 Ton/day of cane bagasse. The operational cycle of the Power Plant will be from June to December, coinciding with the period of sugar-cane crop. The basic assumptions to evaluate the Repowering project are: the useful plant life is 20 years; the investment recovery time is 10 years. Modification of the boiler to satisfy the needs of electrical generation and steam for the mills and use of sugar cane bagasse as fuel to produce high-pressure steam for the turbo-generators. The project intends to increment the electric power generation capacity from 7 MW to 35 MW, in the following main steps:

- Reusability of one extraction/counterpresssure Turbo-generator of 7MW.
- Assembly of one extraction/counterpresssure Turbo-generator of 16 MW.
- Assembly of one condensation Turbo-generator of 12 MW.
- Construction of a substation of 69 kV.
- To sell to the National Interconnected System a surplus of 27 MW.
- The sugar-cane production is 4,662,322 MT.
- The grinding capacity is 11,000 MTC/day.
- Production of 3,300 MT/day of cane bagasse.
- The operational cycle of the Power Plant will be from June to December, coinciding with the period of sugar-cane crop.
- The operation hours of the Power Plant will be 5,110 hours/year.
- A diagram of the Thermal Cycle of the Power Plant is represented in the “Fig. 1”.

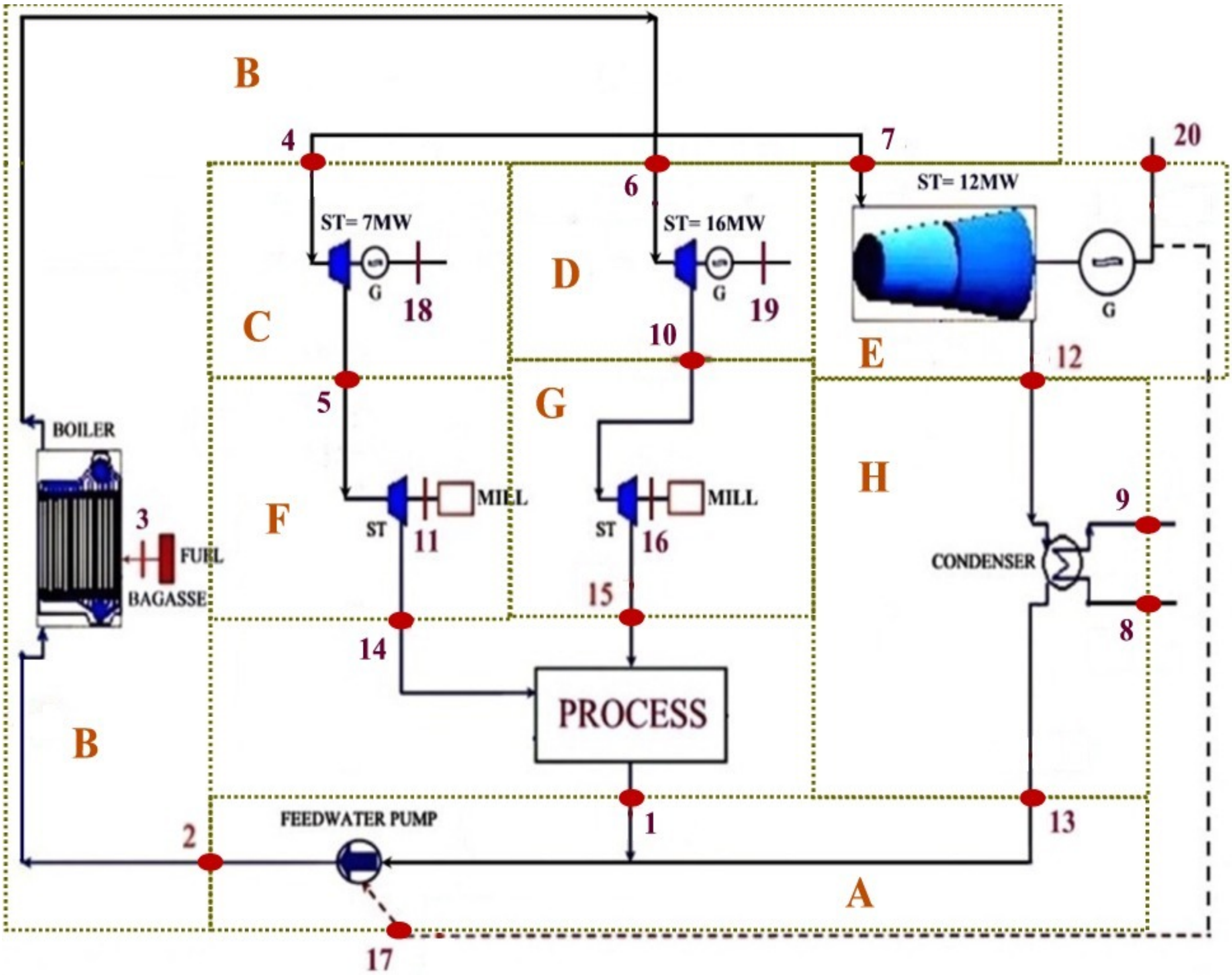

Figure 1. Thermal Cycle Diagram of the SAN CARLOS COGEN Power Plant

2.2. Methodology of energy balance evaluation

The balance energy will be realized to a cogeneration system composed of 4 Steam Turbine with generators to produce electricity and 2 Steam Turbine coupled to the mills for the sugar production process activities. The parameters that will be used for the Analysis of the Cogeneration system proposed are detailed in the “Tab. 1” and the basic chemistry composition of the sugar cane bagasse fuel is proposed in the “Tab. 2”.

Table 1. Input Parameters of SAN CARLOS COGEN Power Plant.

PARAMETERS	VALUE	UNIT
Mechanical working consumption (MWC)	18	kWh/Ton cane
Electricity consumption Power Plant (ECPW)	11	kWh/Ton cane
Isentropic Turbine efficiency (η_t)	75	%
Turbine efficiency to mechanical working (η_{MW})	65	%
Generator efficiency (η_G)	97	%
Output pressure Boiler (P_3)	85	bar
Output Temperature Boiler (T_3)	450	°C
PCI (Calorific Power cane bagasse)	7,340	kj/kg bagasse
Input Temperature of the Feed water Boiler (T_2)	90	°C
Output pressure of the 1º Extraction Steam Turbine (P_8, P_9, P_{10}, P_{11})	21	bar
Output pressure to process (P_{14}, P_{15}, P_{16})	2.5	bar
Pressure of condensation (P_{12})	0.08	bar
Boiler efficiency (η_B)	85	%
Milling capacity $(M_{cane})_{11}$, $(M_{cane})_{16}$	650	Ton cane/h
Steam process consumption (SP)	500	kg_{STEAM}/Ton cane
Conversion Factor from Cane to bagasse (CF)	0.3	Ton bagasse/Ton cane
Hours operation (H_{op})	5,110	hours
α Value (sugar and Alcohol)	0.11	adimensional

Table 2. Basic Chemistry composition of cane bagasse fuel

CANE BAGASSE FUEL
C^t = 22.4 %
H^t = 2.68 %
O^t = 19.77 %
N^t = 0.19 %
S^t = 0.01 %
W^t = 50 %

Using Thermodynamics Tables and Mollier's Diagram, we can find the thermodynamics state properties of all the points of the Thermal Cycle. A summary of them is in the “Tab. 3”. With the milling capacity and conversion factor from cane to bagasse data, we find the produced tons of bagasse per hour; we used the formula referred in the “Eq. (1)”. The value of bagasse tons per hour is in the “Tab. 3” as m_{30}.

$$Ton_{BAGASSE} = [M_{cane}] [CF] \tag{1}$$

With the thermodynamics state properties of the points 2 and 3, we found the steam flow generated in the boiler, with the formula referred in the “Eq. (2)”. The value of the steam flow m_S is in the “Tab. 3” as m_3.

$$m_S = \{[\eta_B] [Ton_{BAGASSE}] [PCI]\} / [h_3 - h_2] \tag{2}$$

Now it is necessary to find the steam flow that is required in the sugar production. For this purpose, it was used the mathematical expression described in the "Eq. (3)". This value is in the “Tab. 3” as m_{20}.

$m_{SP} = [SP]\ [Mcane]\ /\ 1{,}000$ (3)

We know the milling capacity of the mills and the thermodynamic properties of the 10, 13, 14 and 15 Thermal Cycle points that are indicated in the "Tab. 3". Applying these data in the "Eq. (4) and Eq. (5)" we find the steam flows used in the mills and using the "Eq. (6) and Eq. (7)" we determine the necessary mechanical power of these equipments. The obtained values of the steam flows and mechanical power are presented in the "Tab. 3".

$$m_{10} = \{[3.6]\ [MWC]\ [(M_{cane})_{16}]\}\ /\ \{[h_{10} - h_{15}]\ [\eta_{MW}]\} \quad (4)$$

$$m_{13} = \{[3.6]\ [MWC]\ [(M_{cane})_{11}]\}\ /\ \{[h_{13} - h_{14}]\ [\eta_{MW}]\} \quad (5)$$

$$P_{mec\text{-}11} = [m_{13}]\ [h_{13} - h_{14}]\ [\eta_{MW}]\ [1{,}000\ /\ 3{,}600] \quad (6)$$

$$P_{mec\text{-}16} = [m_{10}]\ [h_{10} - h_{15}]\ [\eta_{MW}]\ [1{,}000\ /\ 3{,}600] \quad (7)$$

Applying the Thermodynamic First law and a control volume regarding the steam turbines, it was made a balance of mass and we use the steam flows m_{SP} and m_S in the "Eq. (8)" to find the real power required for the studied system. With the obtained result we calculate the total mechanical power, installed electric power, consumed electric energy and the electricity generated by Power Plant. We use the "Eq. (9), (10), (11) and (12)" and the results are indicated in the "Tab. 3".

$$P_{real} = \{[m_{SP}]\ [h_3 – h_{10}] + [m_S - m_{SP}]\ [h_7 – h_{12}]\}\ [1{,}000\ /\ 3{,}600] \quad (8)$$

$$P_{total\ mec} = P_{mec\text{-}11} + P_{mec\text{-}16} + P_{real} \quad (9)$$

$$P_{inst} = [\eta_G]\ [P_{total\ mec}] \quad (10)$$

$$P_{cons} = [MWC]\ [M_{cane}] \quad (11)$$

$$P_{expor} = P_{inst} - P_{cons} \quad (12)$$

Table 3. Summary of Thermodynamics properties and results

POINTS	T (°C)	P (bar)	m (kg/h)	h (kJ/kg)	H (kJ/h)	s (kJ/kg.K)	b (kJ/kg.K)	B (kJ/h.K)	POWER (MW)
1	L.S.	0.08	3.24E+05	173.87	5.63E+07	0.5926	1.7874	5.8E+05	0
2	42	85	3.95E+05	183.36	7.24E+07	0.5956	10.39	4.10E+06	0
3	0	0	1.95E+05	0	1.43E+09	0	0	1.43E+09	0
4	450	85	98.7E+03	3,264.30	3.22E+08	6.5190	1,326.15	1.31E+08	0
5	260	21	98.7E+03	2,923.70	2.89E+08	6.5647	971.93	9.59E+07	0
6	450	85	2.25E+05	3,264.30	7.36E+08	6.5190	1,326.15	2.99E+08	0
7	450	85	7.13E+04	3,264.30	2.33E+08	6.5190	1,326.15	9.46E+07	0
8	25	1	3.7E+06	104.97	3.88E+08	0.3674	0	0	0
9	35	1	3.7E+06	146.76	5.43E+08	0.5052	0.7137	2.68E+06	0
10	260	21	2.25E+05	2,923.70	6.59E+08	6.5647	971.93	2.19E+08	0
11	0	0	0	0	14.4E+06	0	0	14.4E+06	4
12	X=0.95	0.08	7.13E+04	2,456.80	1.75E+08	7.8469	122.94	8.77E+06	0
13	L.S.	0.08	7.13E+04	173.87	1.24E+07	0.5926	1.7874	1.27E+05	0
14	128	2.5	98.7E+03	2,718.10	2.68E+08	7.0557	620.02	6.12E+07	0
15	128	2.5	2.25E+05	2,718.10	6.13E+08	7.0557	620.02	1.40E+08	0
16	0	0	0	0	28.8E+06	0	0	28.8E+06	8
17	0	0	0	0	5.04E+06	0	0	5.04E+06	1.4
18	0	0	0	0	25.2E+06	0	0	25.2E+06	7
19	0	0	0	0	57.6E+06	0	0	57.6E+06	16
20	0	0	0	0	38.2E+06	0	0	38.2E+06	10.6

2.3. Analysis of operation of the SAN CARLOS COGEN Power Plant

It was needed to make the analysis of the energy use factor (EUF) and the efficiencies according to the Public Utility Regulatory Policy Act (PURPA) and Cogeneration, to determine if the project qualifies as an efficient autogenerator and in that way to participate with the excess of energy in the Ecuadorian electrical energy market. With the values of the thermodynamic properties of the "Tab. (3)" and applying them in the formulas of the "Eq. (13), (14) and (15)", it was found the result of the energy use factor. The result is in the "Tab. 4".

$$EUF = [P_{total\ mec} + Q_u] / F \tag{13}$$

Where:

$$Q_u = [m_{SP}]\ [h_{15} - h_{20}]\ [1{,}000 / 3{,}600] \tag{14}$$

$$F = [Ton_{BAGASSE}]\ [PCI]\ [1{,}000 / 3{,}600] \tag{15}$$

With the values of the thermodynamic properties of the "Tab. (3)" and applying them in the formulas of the "Eq. (16) and (17)", it was found the result of the efficiency PURPA. The result is in the "Tab. 4".

$$\eta_{PURPA} = \{P_{total\ mec} + [Q_u/2]\} / Q_c \tag{16}$$

Where:

$$Q_c = [Ton_{BAGASSE}]\ [PCI]\ [1{,}000 / 3{,}600] \tag{17}$$

With the values of the thermodynamic properties of the "Tab. (3)" and applying them in the formulas of the "Eq. (18) and (19)", it was found the result of the cogeneration efficiency (η_{CG}). The result is in the "Tab. 4".

$$\eta_{CG} = \{P_{total\ mec} + E_H + [\Phi]\ [Q_u + E_H]\} / F \tag{18}$$

where:

$$\Phi = 0.12$$

$$E_H = [m_{SP}]\ \{[h_{15} - h_{20}] - [298]\ [s_{15} - s_{20}]\}\ [1{,}000 / 3{,}600] \tag{19}$$

Table 4. Cogeneration efficiencies of the SAN CARLOS Power Plant

METHODS	PERCENTAGE (%)
EUF	78
P U R P A	47
Cogeneration efficiency (η_{CG})	41

The operation analysis of the cogeneration systems which is in function of the time uses instantaneous values or duration curve of the demands and availabilities of thermal and electric energy. This shows a better knowledge of the energy flows among the autogenerator system, the consumer and the company of electric power distribution. In this case, the operation analysis of the Cogeneration SAN CARLOS COGEN Power Plant has as objective the study of the thermal and electrical demands duration curves and it is known all the time that, through the production electrical energy it is possible to determine the deficits and the excesses of energy in the course of time. Based on the report energy preliminary of the Control Energy National Center of Ecuador, the duration curves of the thermal and electric energy demands and electric energy generation of SAN CARLOS COGEN Power Plant were elaborated and appear in the "Fig. 2". Besides, we mentioned next the maximum, average and minimum values of these demands:

- Maximum electric energy demand : 4 MW
- Average electric energy demand: 3 MW
- Minimum electric energy demand: 1 MW
- Maximum thermal energy demand: 35 MW
- Average thermal energy demand: 27 MW
- Minimum thermal energy demand: 19 MW
- Load factor of electric demand: 0.75
- Load factor of thermal demand: 0.77
- Rate between the consumed electric energy and consumed heat (α): 0.11
- Rate between the produced electric energy and produced useful heat (β): 0.45

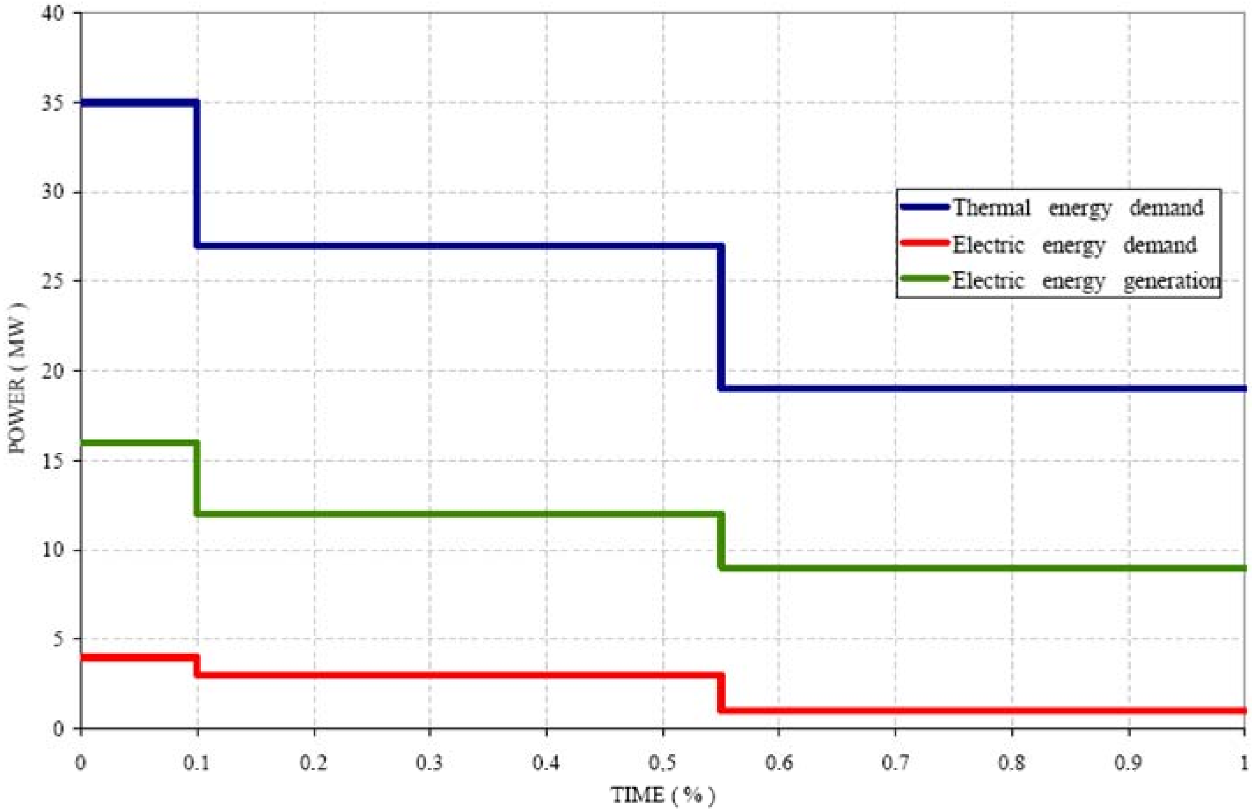

Figure 2. Duration curves of the thermal and electric energy demands and electric energy generation of SAN CARLOS COGEN Power Plant

With the maximum, average and minimum values of the duration curves of the thermal and electric energy demands and electricity generation, it is possible to make the convolution operation, comparing one by one the levels of the curves shown in the "Fig. 2" and determining the surpluses for every moment in the time.

With the values obtained in the convolution operation, the surplus values of electrical energy can be found, as it is shown in the "Tab. 5", and besides to make the duration curve of these surpluses at all moment in the time, as it is possible to be observed in the "Fig. 3".

Table 5. Surplus values of electrical energy

PRODUCED ELECTRIC POWER Pp	% ANNUAL TIME PRODUCTION Tp	CONSUMED ELECTRIC POWER Pc	% ANNUAL TIME CONSUMPTION Tc	SURPLUS POWER Pp - Pc	% ANNUAL TIME Tp. Tc	ACUMULATED SURPLUS Pacs	% ANNUAL TIME Tacs
16	0.12	4	0.10	12	0.012	15	0.054
16	0.12	3	0.45	13	0.054	13	0.108
16	0.12	1	0.45	15	0.054	12	0.12
12	0.44	4	0.10	8	0.044	11	0.318
12	0.44	3	0.45	9	0.198	9	0.516
12	0.44	1	0.45	11	0.198	8	0.56
9	0.44	4	0.10	5	0.044	8	0.758
9	0.44	3	0.45	6	0.198	6	0.956
9	0.44	1	0.45	8	0.198	5	1

We can observe in the "Tab. 5" that values of the surplus power column are always positive and it indicates that in all moment the SAN CARLOS COGEN Power Plant will have electrical energy to satisfy its energetic demands and surpluses to sell in the Ecuadorian electrical market.

As last operational analysis, it is expected that this project will reduce the burning of fossil fuel by displacing conventional thermoelectric plants and reducing the CO2 emission. This will have global environmental benefits through the reduction of the emissions of gases that contribute to the greenhouse effect. Local environmental benefits include the emissions reduction of NOx and SO_2, which causes acid rain, and will, reduces emission of particulate matter, causing respiratory illness. To estimate of greenhouse gases abated in metric tons of CO_2 equivalent emissions, it was utilized the formula of the "Eq. (20), (21) and (22)". The result is in the "Tab. 6".

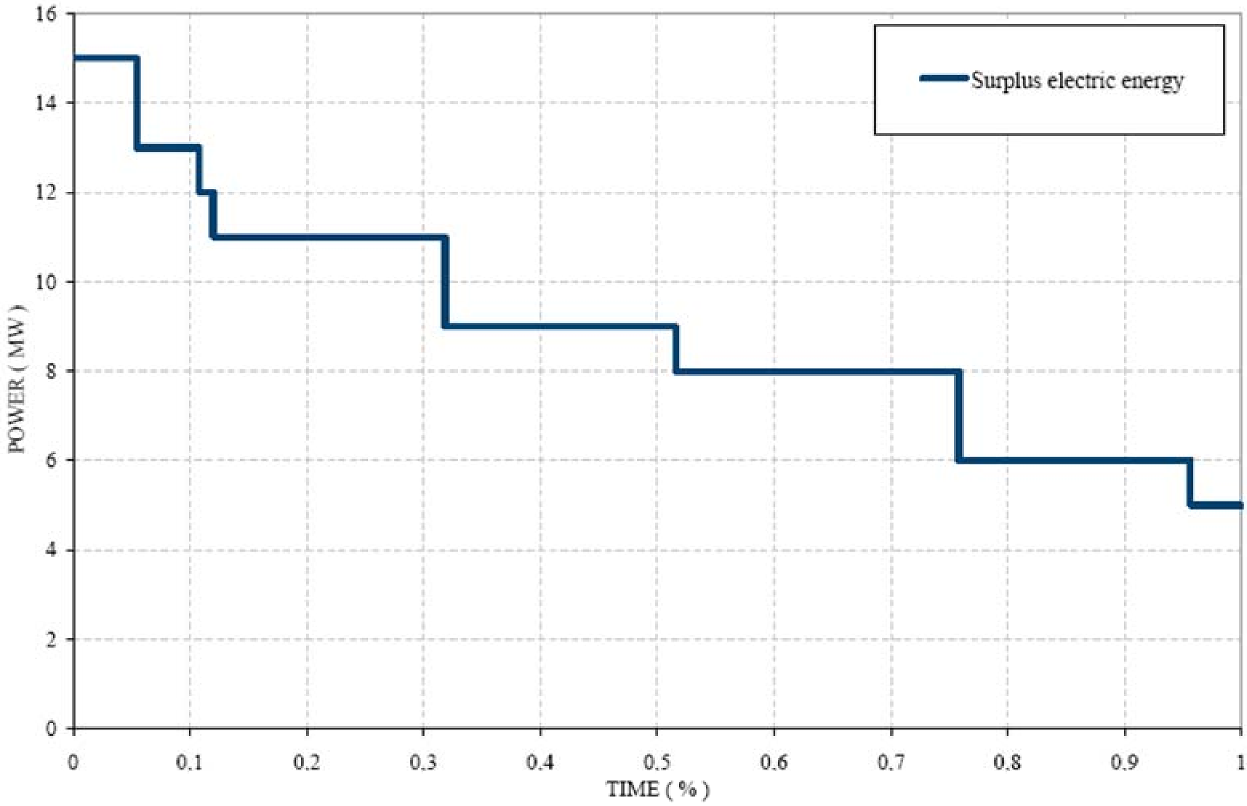

Figure 3. Duration curve of the electric power surpluses

$$Tons\ CO2\ avoid\ annually = [Emission\ Factor\ t\ CO2/MWh]\ [Annual\ Generation] \quad (20)$$

Where:

$$Emission\ Factor\ t\ CO2/MWh = 0.9 \quad (21)$$

$$Annual\ Generation = [5{,}110\ h/year]\ [Surplus\ electrical\ energy] \quad (22)$$

Table 6. Estimate of Greenhouse gases abated

Annual Generation (MWh)	Emission Factor *t CO2/MWh*	Tons CO2 avoid annually
61,320	0.9	55,188

3. Production costs of the electricity generation and heat

Studies made by the National Council of Electrification of Ecuador (CONELEC) and by the great consumers association of energy (EGRANCONEL), for this type of Power Plant the following costs of investment are had:

- By each 1 MW installed \$1,000,000.00 USD is invested.
- The SAN CARLOS COGEN Power Plant is installing 28 MW, and then its investment in equipment (I_{TOTAL}) is approximately \$28,000,000.00 USD.
- The period of amortization of the investment (n) is 10 years.
- The amortization factor (a) is 0.1.
- The annual interest (i) is 12%
- The factor referring to the maintenance (ma) is 0.03
- The bagasse cost (BC) is \$852,348.00 USD/year

With the previously data mentioned and using the formulas of the "Eq. (23), (24), (25) and (26)", it is possible to find the costs of the electricity and heat generated, the sold electrical energy and the specific investment. The results are resumed in the "Tab. 7".

$$C_{ele} = (\{[I_{TOTAL}]\ [ma + a]\ [1 + i]^n\}/[n + BC]) / \{[P_{inst}]\ [H_{op}]\} \quad (23)$$

$$C_{heat} = \{[I_{TOTALBOILER}]\ \ [ma + a + i]\ \ + BC\ \} / \{[Q_u\ ]\ [H_{op}]\} \quad (24)$$

$$EE = \{[80/1.8]\ [P_{expor}]\ [H_{op}]\} / 1{,}000 \quad (25)$$

$$EI = \ I_{TOTAL} / P_{inst} \quad (26)$$

Where:
C_{ele} : Electricity cost
C_{heat}: Heat cost
EE : Sold electrical energy
EI : Specific investment

Table 7. Economic parameters of the project

ELECTRICITY COST $USD/kWh	HEAT COST $USD/kWh	SOLD ELECTRICAL ENERGY $USD/year	SPECIFIC INVESTMENT $USD/kW
0.013	0.0112	7,449,244.44	800

4. Conclusions

The accomplishment of this project can have a catalytic effect in the development of similar projects in other agro-industrial companies, which would allow that Ecuador benefits with the increase of energy generated from resources renewable (bagasse, husk of rice and others), displacing progressively the nonrenewable fuels.

The electrical generation starting from the biomass requires of a great investment initial and the introduction of a new technology in Ecuador. This initial investment requires that by each kWh generated $800 USD is necessary, the double of the initial investment of conventional Thermoelectric that is $400 USD by each kWh and almost similar to the initial cost of Hydroelectric Power Plant that is $1,000 USD/ kWh. Although initial investment of Cogeneration Power Plant that uses bagasse like fuel is greater than Thermoelectric Power Plant that burns fossil fuel, the cost of the energy generated is less, since for example, the costs of the generated electricity of SAN CARLOS COGEN Power Plant are 1.5 US cents/kWh, in comparison with the costs of the supplied electric energy through Fossil Power Plants with values in the range 3 - 15 US cents/kWh and the Hydroelectric Plants with a value of about 2 US cents/kWh.

It is expected that this project contributes with the provision of electrical energy to the Interconnected National System of Ecuador; likewise it contributes to the mitigation of climatic change, with the reduction of the prospective emissions of greenhouse effect gases in an amount of 551,880 t of CO_2 equivalent.

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