Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45055

FUNCTIONAL ANALYSIS AND EXERGOECONOMIC EVALUATION FOR THE COMBINED PRODUCTION OF ELECTROMECHANICAL POWER AND USEFUL HEAT OF A COGENERATION POWER PLANT

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ABSTRACT

In the Ecuadorian electrical market, several sugar plants, which significantly participate in the local electricity market, are producing their own energy and commercializing the surplus to the electrical market.

This study evaluates the integral use of the sugar cane bagasse for productive process on a Cogeneration Power Plant in an Ecuadorian Sugar Company [8].

The electrical generation based on biomass requires a great initial investment. The cost is around US$ 800/kW installed, twice the US$ 400/kW initial investment of conventional thermoelectric power plant and almost equal to the US$ 1,000/kW initial cost of hydroelectric power plant [5].

A thermoeconomic study was carried out on the production of electricity and the sales of the surplus of 27 MWe average produced by the power plant. An operational analysis was made using instantaneous values from the estimated curves of demand and generation of electricity.

From the results, it was concluded that the generated electricity costs are 0.0443 US$/kWh, while the costs of the electricity from Fossil Power Plants (burning fuel oil, diesel fuel and natural gas) are in the range 0.03 – 0.15 US$/kWh and from Hydroelectric Plants are about 0.02 US$/kWh.

Cogeneration power plants burning sugar cane bagasse could contribute to the mitigation of climatic change. This specific case study shows the reduction of the prospective emissions of greenhouse gases, around 55,188 ton of CO_2 equivalent yearly for this cogeneration power plant.

INTRODUCTION

The Sugar Industry has great potential to contribute to increase the production of electricity through cogeneration systems, incorporating the renewable energy resources to the electricity supply [1].

In the Ecuadorian electrical market there are three sugar plants with the most significant participation in the local market. They produce energy from all the bagasse ground in the sugar cane milling process and use it for generation of electricity to supply the plant industrial consumption and to sell the energy surplus to the Ecuadorian electrical market.

For this cogeneration facility, it is expected reduction of emissions of the gases that contribute to the greenhouse effect and to stimulation of investment in electrical projects based on the use of biomass, because the accomplishment of such facility may affect positively the development of other projects in agro-industrial companies and increase the energy use from renewable resources [8].

Although the electricity production of the sugar mills is not considered as part of the expansion plan of the energy supply in the country, it can be seen as an option that will help to supply the demand that is growing in excess of 6.9% per year [6].

NOMENCLATURE

A	Losses
A_E	Equipment annual cost, US$
A_{OM}	Operation and maintenance annual cost, US$
B	Exergy, kJ/h.K

B*	Exergetic cost
C	Unit cost, US$/kWh
CAM	Mechanical working consumption, kWh/ton
CEE	Electricity consumption, kWh/ton
C_{OM}	Operation and maintenance investment, US$
F	Inputs
F_c	Conversion factor, ton bagasse/ton cane
FWB	Feedwater boiler
FWP	Feedwater pump
h	Specific enthalpy, kJ/kg
H_{OP}	Operation hours, hours
i	Annual interest
LHV	Lower heating value, kJ/kg
$\dot{m}$	Mass flow rate, kg/h
M	Milling capacity, ton cane/h
MP	Mechanical power, MWe
MWe	Megawatt
MWh	Megawatt hour
n	Depreciation, years
N	Number flow
P	Pressure, bar
P_E	Equipment price, US$
ST	Steam process consumption, kg/ton cane
T	Temperature, ºC
t	Time, hours
$\dot{W}$	Power, MWe
$\dot{W}_{SEE}$	Surplus power output, MWe

Greek symbols

η	Efficiency, %

Subscripts and superscripts

1, 2, 3, ...	Flow number one, two, etc
acs	Accumulated
b	Boiler
bag	Bagasse
c	Cane
con	Consumption
e	Installed
E	Equipment
g	Electric generator
gen	Generated
GE	Generated electricity
m	Mill
MW	Mechanical working
OM	Operation and maintenance
p	Sugar production
pro	Production
PS	Process steam
r	Real
s	Steam
t	Turbine
tm	Total mechanical

Matrices and Vectors

I'^{-1}	Matrix inverse I
Π	Monetary cost vector, US$/s
I_A	Matrix of irreversibilities
I_F	Matrix of inputs
I_P	Matrix of products
V_F	Inputs vector
V_I	Irreversibilities vector
V_P	Products vector
Z'	External cost vector

THERMAL SCHEME DESCRIPTION

June to December was the period of study of the operational cycle of the cogeneration power plant, to coincide with the period of sugar-cane crop [8]. The assumptions to evaluate the repowering project are:

- The useful plant life is 20 years after the repowering project;
- The investment recovery time is 10 years and the overall operational time is 20 years;
- The existing boiler would be modified to satisfy the needs of electrical generation and steam production for the mills and to use 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 MWe to 35 MWe;
- Reusability of one extraction/counterpressure Turbo-generator of 7 MWe;
- Assembly of one extraction/counterpressure Turbo-generator of 16 MWe and one condensation Turbo-generator of 12 MWe;
- The sugar-cane production is 4,662,322 metric tons;
- The grinding capacity is 11,000 metric tons of cane/day;
- Production of 3,300 metric tons of cane bagasse/day;
- The power station would operate 5,110 hours/year;

The simplified thermal layout of the facility is represented in Fig. 1.

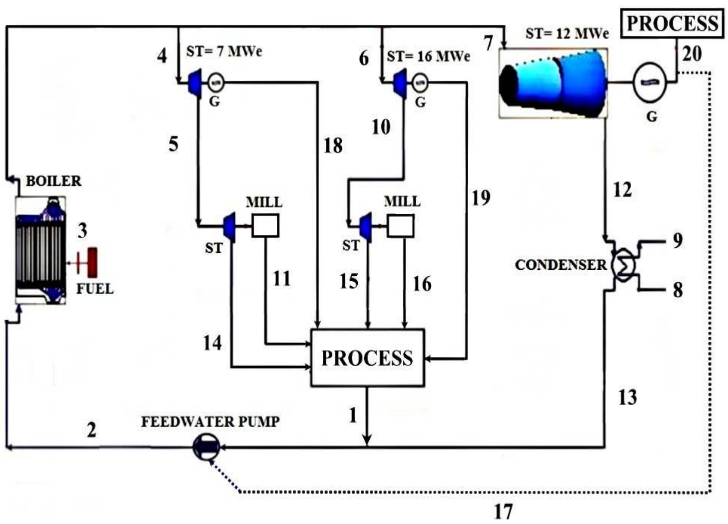

Figure 1. Thermal scheme of cogeneration power plant.

ENERGY BALANCE

According to the thermal scheme shown in Fig. 1 the energy balance was realized for a cogeneration power station composed of three turbo-generators to produce electricity and two steam turbines coupled to the mills for the activities in the process of sugar production.

Table 1 shows the parameters used for the analysis of the cogeneration system.

Table 1. Input parameters of cogeneration facility [8].

Parameters	Value	Unit
Mechanical working consumption (CAM)	18	kWh/ton c
Electricity consumption (CEE)	11	kWh/ton c
Turbine efficiency (η_t)	75	%
Turbine efficiency to mechanical working (η_{MW})	65	%
Generator efficiency (η_g)	97	%
Output pressure boiler	85	bar
Output temperature boiler	450	°C
LHV	7,340	kJ/kg bag
Input temperature FWB.	90	°C
Output pressure of the first extraction steam turbine	21	bar
Output pressure to process	2.5	bar
Pressure of condensation	0.08	bar
Boiler efficiency (η_b)	85	%
Milling capacity $(M_c)_{11}$, $(M_c)_{16}$	650	ton c/h
Steam process consumption (ST)	500	kg/ton c
Conversion factor from cane to bagasse (F_c)	0.3	ton bag/ton c
Hours operation (H_{OP})	5,110	Hours
α Value	0.11	Dimensionless
Fuel characteristics:		Bagasse
Carbon content	22.4	%
Hydrogen content	2.68	%
Oxygen content	19.77	%
Nitrogen content	0.19	%
Sulfur content	0.01	%
Water	54.95	%

With the use of the Thermodynamics Tables and Mollier's Diagram, it can to make the balance of energy and it was found the thermodynamics properties of all points of the Thermal Cycle [8]. A summary of them is in Tab. 2.

Table 2. Thermodynamics properties.

N	T (°C)	P (bar)	$\dot{m}$ (kg/h)	h (kJ/kg)	B (kJ/h.K)
1	S.L.	0.08	3.239E+05	173.87	5.799E+05
2	42	85	3.950E+05	183.36	4.104E+06
3	0	0	1.948E+05	NA	1.431E+09
4	450	85	9.870E+04	3,264.30	1.309E+08
5	260	21	9.870E+04	2,923.70	9.593E+07
6	450	85	2.250E+05	3,264.30	2.984E+08
7	450	85	7.129E+04	3,264.30	9.455E+07
8	25	1	3.699E+06	104.97	0.000E+00
9	35	1	3.699E+06	146.76	2.685E+06
10	260	21	2.250E+05	2,923.70	2.187E+08
11	NA	NA	NA	NA	1.440E+07
12	0.95	0.08	7.130E+04	2,456.80	8.766E+06
13	S.L.	0.08	7.132E+04	173.87	1.276E+05
14	128	2.5	9.870E+04	2,718.10	6.119E+07
15	128	2.5	2.249E+05	2,718.10	1.395E+08
16	NA	NA	NA	NA	2.880E+07
17	NA	NA	NA	NA	5.040E+06
18	NA	NA	NA	NA	2.520E+07
19	NA	NA	NA	NA	5.760E+07
20	NA	NA	NA	NA	3.820E+07

The calculation of the produced tons of bagasse per hour, from the milling capacity and conversion factor from cane to bagasse data, was made using Eqn. 1.

$$Ton_{bag} = M_c \cdot F_c \quad (1)$$

With the thermodynamics state properties of the points 2 and 3, it has been found the steam flow generated in the boiler, with the formula referred in Eqn. 2.

$$\dot{m}_b = 1{,}000 \cdot \eta_b \cdot \left(\frac{Ton_{bag} \cdot LHV}{h_4 - h_2} \right) \quad (2)$$

Equation 3 is used for the calculation of the steam flow which is required in the sugar production [5 and 9].

$$\dot{m}_p = \frac{ST \cdot M_c}{1{,}000} \quad (3)$$

For the milling capacity of the mills and the thermodynamic properties at stations 10, 13, 14 and 15, Eqn. 4 and 5, give the steam flows used in the mills, while Eqn. 6 and 7 give the necessary mechanical power [1 and 4].

$$\dot{m}_{m_{11}} = \frac{3.6 \cdot CAM \cdot M_c}{\eta_{mw} \cdot (h_{10} - h_{15})} \quad (4)$$

$$\dot{m}_{m_{16}} = \frac{3.6 \cdot CAM \cdot M_c}{\eta_{mw} \cdot (h_{13} - h_{14})} \quad (5)$$

$$MP_{11} = 0.28 \cdot \eta_{mw} \cdot \dot{m}_{m_{11}} \cdot (h_{10} - h_{15}) \quad (6)$$

$$MP_{16} = 0.28 \cdot \eta_{mw} \cdot \dot{m}_{m_{16}} \cdot (h_{13} - h_{14}) \quad (7)$$

From the First Law of Thermodynamics and a control volume regarding the steam turbines, a balance of mass was made and used for the calculation of the steam flows $\dot{m}_p$ and $\dot{m}_b$ by Eqn. 8, to find out the actual required power for the system under study.

$$\dot{W}_r = 0.28 \cdot \left[\dot{m}_p (h_3 - h_{10}) + (\dot{m}_b - \dot{m}_p)(h_7 - h_{12})\right] \quad (8)$$

The total mechanical power, installed electric power, consumed electric energy and the electricity generated by power plant were calculated using Eqn. 9, 10, 11 and 12.

$$\dot{W}_{tm} = MP_{11} + MP_{16} + \dot{W}_r \quad (9)$$

$$\dot{W}_e = \eta_g \cdot \dot{W}_r \quad (10)$$

$$\dot{W}_{con} = CEE \cdot M_c \quad (11)$$

$$\dot{W}_{gen} = \dot{W}_e - \dot{W}_{con} \quad (12)$$

OPERATION ANALYSIS OF COGENERATION

The operation analysis of the cogeneration systems, which are function of the time, uses instantaneous values or duration curve of the demand and availability of thermal energy and electricity, in order to best represent the energy flows among the generation system, the consumer and the distribution company.

Operational analysis allows the study of the thermal and electrical demands duration curves behavior. It is possible to continuously determine, through the production of electrical energy, the deficit and the excess of energy in the course of time for the cogeneration facility [9].

Based on the duration curve of the thermal demand, it is possible to obtain the duration curve of the generated electricity and combine them with the duration curve of the electrical demand to determine the surplus of electricity at any time. This is called the convolution operation [5].

The time is measured in percentage of the number of hours in a year that a surplus level had been reached.

The duration curves of the thermal and electricity demand and electricity generation were elaborated based on the report of the National Center for Energy Control of Ecuador, as shown in Fig. 2.

With the maximum, average and minimum values of the duration curves of the thermal and electricity demand and electricity generation, it is possible to compare one by one the levels of the curves shown in Fig. 2 and to determine the surpluses at each time.

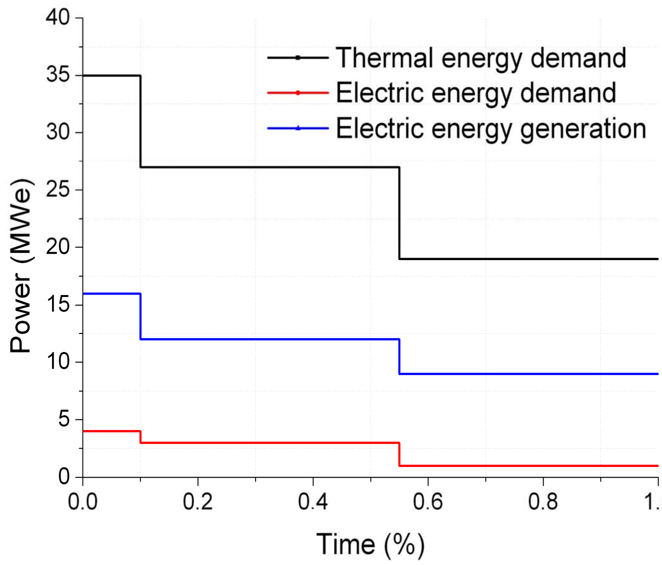

Figure 2. Curves of the thermal and electricity demand.

Electricity surpluses are shown in Tab. 3. In addition, the duration curve of these surpluses can be observed in Fig. 3.

Table 3. Surplus values of electricity.

P_{pro}	% Annual time consumption T_{con}	P_{pro}-P_{con}	% Annual time T_{pro}-T_{con}	% Annual time T_{acs}
6	0.10	12	0.012	0.054
16	0.45	13	0.054	0.108
16	0.45	15	0.054	0.12
12	0.10	8	0.044	0.318
12	0.45	9	0.198	0.516
12	0.45	11	0.198	0.56
9	0.10	5	0.044	0.758
9	0.45	6	0.198	0.956
9	0.45	8	0.198	1

Values of the surplus power column are always positive. This indicates that this power plant will produce electrical energy to satisfy its thermal and electricity demand and will always have surpluses to sell in the Ecuadorian electrical market.

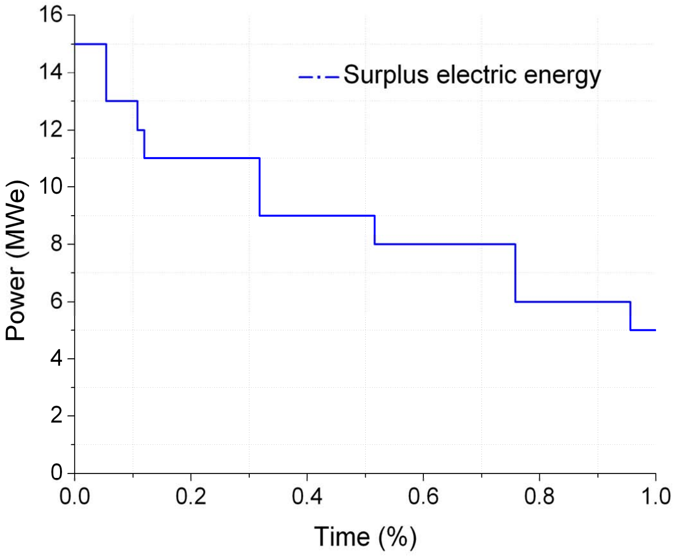

Figure 3. Curve of the electric power surpluses.

EXERGOECONOMIC EVALUATION

Based on the Second Law of Thermodynamics, it is possible to quantify the higher or lower irreversibility and efficiency of processes in a power station using an exergy function [3].

In this context, the exergy of a thermodynamic system is defined as the minimum amount of useful work needed to set the system from the reference environment, using resources provided by nature, in quantities that can be considered as unlimited with null extraction costs [12].

The system exergetic efficiency can be calculated from the exergy function and the mass, heat and work flows. It may be said that the exergy efficiency is the ratio of the exergy contained in the products and the resources consumed exergy.

This thermodynamic property is destroyed due to real processes irreversibilities. The inverse function represents the unitary exergy cost of the final products.

The economic cost of a particular process flow is the result of two contributions:

- First, the exergetic cost, which can be defined as the energy monetary cost to produce a particular flow;
- Second, the production process costs associated to the obtention of such flow (capital depreciation, operation, maintenance, etc.).

Using the exergetic function it is possible to make the exergetic analysis to calculate the efficiency of the studied facility, based on the exergetic efficiency and a given industrial process, such as a cogeneration power station [7].

A Thermal Power Plant, in this case a Cogeneration Power Plant, can be considered as a system comprised of equipment groups with defined production objective.

These equipments, or subsystems, are associated with energy flows and/or inputs and their processes with the formation of the product costs [11 and 13].

The products are the final effects and the available resources are the material causes. The modeling and the eventual optimization of this structure seeks the characterization, to measurement and the evaluation of these effects and their causes in the energy systems and the application of a general criterion to measure the efficiency of the project or the actual operation of such installation [6, 12 and 14].

The Second Law of Thermodynamics quantifies the irreversibility and the efficiency of the processes by means of the exergy function. The first step was the definition of the logical structure of the Cogeneration Power Plant for the elaboration thermoeconomic analysis [12, 13 and 14].

In Figure 4 the desegregation in subsystems and the diagram flows of the facility can be observed.

The First and Second Laws of Thermodynamics applied to a cogeneration facility allow us to define such facility as a set of equipments or subsystems related through mass flow, heat and work.

According to the general systems theory, as used by several authors [6, 9 and 13], any energy system is composed of subsystems or equipments and matter or energy flows.

This relationship can be mathematically modeled using the incidence matrix ($I_{j,k}$), where (j) represents the number of subsystems or equipments and (k) represents the number of flows [8 and 14].

The matrix elements $I_{j,k}$ assume the value +1 if the flow (k) enters into the subsystem (j); -1 if it leaves the subsystem and 0 if there is no direct physical relationship between them.

According to Fig, 4 the desegregation in subsystem of the cogeneration power plant is utilized to make the incidence matrix $I_{j,k}$ associated to the facility, as observed in Tab. 4.

The incidence matrix $I_{j,k}$, determined in Tab. 4 is used as basis. One passes, then, to the definition of the inputs, products and losses, for all equipments, as function of energetic and exergetic efficiency, by means of the incidence matrices of the inputs, products and losses that occur in the cogeneration facility, as shown in Tables 5, 6, 7 and 8.

Table 5. Inputs, products and irreversibilities flows.

Subsystems	Products P	Inputs F	Losses A
A: FWP	$B_2 – B_1 – B_{13}$	B_{17}	-
B: Boiler	$B_4 + B_6 + B_7 – B_2$	B_3	-
C: ST 7 MWe	B_{18}	$B_4 – B_5$	-
D: ST 16 MWe	B_{19}	$B_6 – B_{10}$	-
E: ST 12 MWe	$B_{20} + B_{17}$	$B_7 – B_{12}$	-
F: ST 4 MWe	B_{11}	$B_5 – B_{14}$	-
G: ST 8 MWe	B_{16}	$B_{10}– B_{15}$	-
H: Condenser	0	$B_{12} – B_{13}$	$B_9 – B_8$

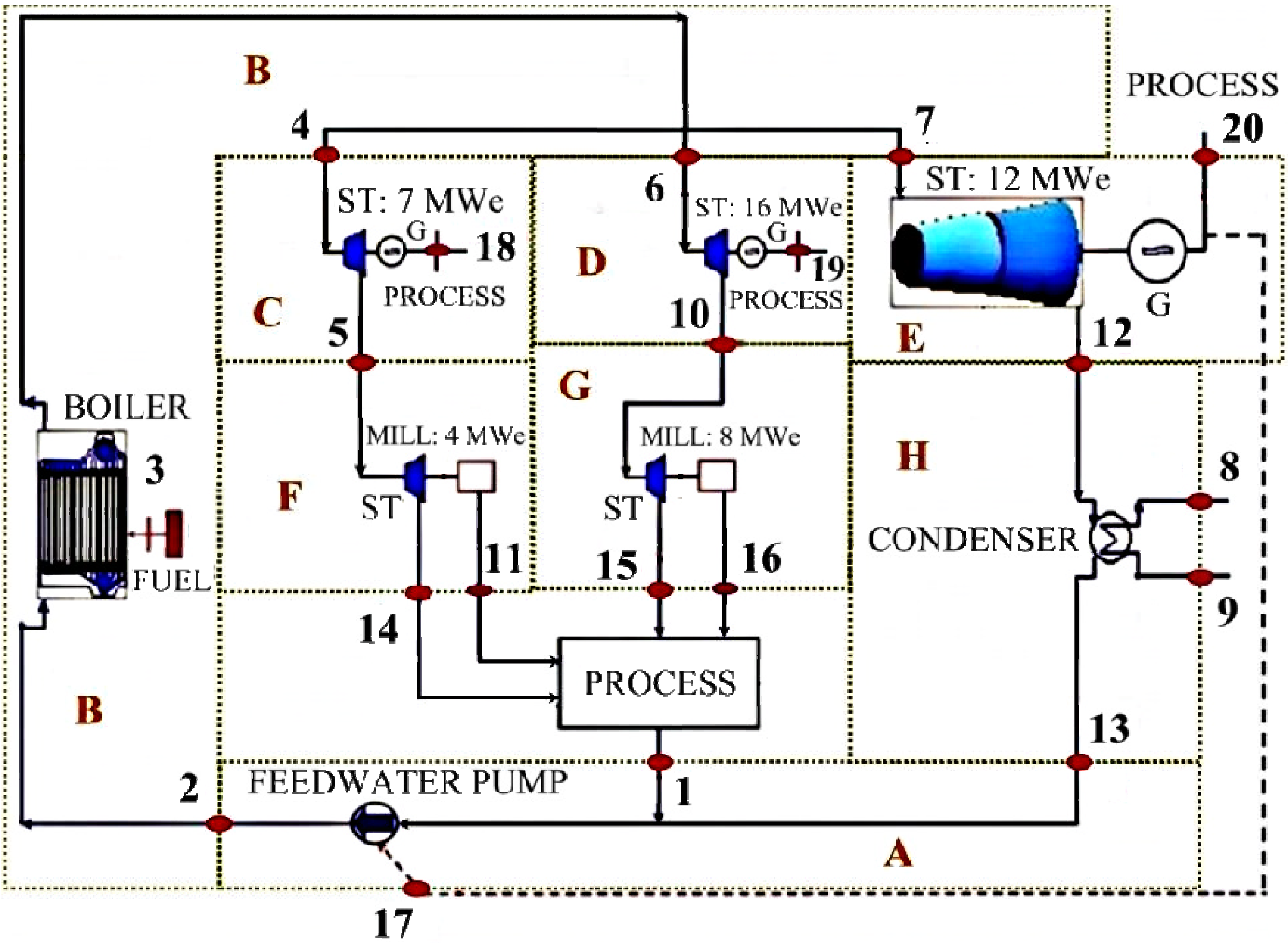

Figure 4. Logical structure of the cogeneration power plant.

Table 4. Incidence matrix I of the inputs, products and losses.

Flows / Systems	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A: FWP	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
B: Boiler	0	1	1	-1	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
C: ST 7 MWe	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
D: ST 16 MWe	0	0	0	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	-1	0
E: ST 12 MWe	0	0	0	0	0	0	1	0	0	0	0	-1	0	0	0	0	-1	0	0	-1
F: ST 4 MWe	0	0	0	0	1	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0
G: ST 8 MWe	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	-1	0	0	0	0
H: Condenser	0	0	0	0	0	0	0	1	-1	0	0	1	-1	0	0	0	0	0	0	0
Σ Subsystems	1	0	1	0	0	0	0	1	-1	0	-1	0	0	-1	-1	-1	0	-1	-1	-1

Table 6. Matrix of the products I_P for the cogeneration facility.

Flows / Systems	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A: FWP	-1	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
B: Boiler	0	-1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C: ST 7 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
D: ST 16 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
E: ST 12 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
F: ST 4 MWe	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
G: ST 8 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
H: Condenser	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7. Matrix of the inputs I_F for the cogeneration facility.

Flows / Systems	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A: FWP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
B: Boiler	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C: ST 7 MWe	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D: ST 16 MWe	0	0	0	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
E: ST 12 MWe	0	0	0	0	0	0	1	0	0	0	0	-1	0	0	0	0	0	0	0	0
F: ST 4 MWe	0	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
G: ST 8 MWe	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	0	0	0	0	0
H: Condenser	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0

Table 8. Matrix of the losses I_A for the cogeneration facility.

Flows / Systems	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A: FWP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B: Boiler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C: ST 7 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D: ST 16 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E: ST 12 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F: ST 4 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G: ST 8 MWe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H: Condenser	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0

For the next step, the exergy values of all flows were calculated, as shown in Tab. 2, from which the input and product vectors for each subsystem or equipment were determined by matrix multiplication using Eqn. 13, 14 and 15.The results are shown in Tab. 9.

$$V_P = I_P \times B \tag{13}$$

$$V_F = I_F \times B \tag{14}$$

$$V_I = I_A \times B \tag{15}$$

Table 9. Inputs, products and irreversibilities vectors [13].

Products vector V_P	Inputs vector V_F	Irreversibilities vector V_I
3.393E+06	5.040E+06	0.000E+00
5.205E+08	1.430E+09	0.000E+00
2.520E+07	3.510E+07	0.000E+00
5.760E+07	8.000E+07	0.000E+00
4.324E+07	8.583E+07	0.000E+00
1.440E+07	3.470E+07	0.000E+00
2.880E+07	7.900E+07	0.000E+00
0.000E+00	8.643E+06	2.680E+06

Table 10 shows the annual investment costs, the annual fuel consumption and the annual operation and maintenance costs for the cogeneration power plant. These values were calculated using the Present Value Method applied to the facility total investment. The mathematical formulae used are shown by Eqn. (16) and (17).

$$A_E = \frac{(P_E)\cdot(1+i)^n \cdot (i)}{(1+i)^n - 1} \tag{16}$$

$$A_{OM} = \frac{(C_{OM})\cdot(1+i)^n \cdot (i)}{(1+i)^n - 1} \tag{17}$$

The power station total investment is distributed according to each equipment investment cost, for each subsystem constituting the cogeneration power plant. The source for these values was the reference prices in the Ecuadorian industrial market.

Usually, according to Electric Power Research Institute, the operation and maintenance costs are related to a percentage of the equipment investment. For this case, the operation and maintenance costs were estimated at 2.2% of the total investment cost for each equipment of the facility.

Other important issue is related to the fuel costs. When the facility produces sugar cane bagasse to be burnt in the boiler, it is not necessary to buy bagasse for the process steam and surplus electricity.

The grinding produces 195 tons of bagasse per hour and the consumption of bagasse in the boiler is 194.8 tons per hour. Thus, the fuel demand is satisfied by the bagasse production.

Based on the information from the thermal scheme description, where it is shown that the power station operates 5,110 hours per year, then the economy due to fuel total cost for a study period of 20 years is US$ 55,345,796.80.

Table 10. Investment and fuel annual costs.

Equipment	Annual cost (US$)	A_{OM} (US$)
FW Pump	7.188E+05	1.581E+04
Boiler	2.957E+06	6.506E+04
ST 7MWe	0.000E+00	1.482E+04
ST 16MWe	1.245E+06	2.738E+04
ST 12MWe	1.004E+06	2.209E+04
ST 4MWe (process)	0.000E+00	5.964E+03
ST 8MWe (process)	0.000E+00	9.713E+03
Condenser	6.818E+05	1.499E+04
Fuel	0.000E+00	0.000E+00

The next step is to establish the auxiliary equations to resolve the system of matrices. Initially, the incidence matrix is the matrix I_{20x8}. Therefore, the unknowns' number is greater than the number of equations. Using the auxiliary equations for the expanded incidence matrix I (Tab. 11), it is possible to resolve the system of equations given by the matrix I_{20x20}

According to several authors [4 and 10], the exergoeconomic cost balance can be calculated, for any individual equipment of the cogeneration power station, by

$$\Pi = I'^{-1} \times Z \tag{18}$$

The elements of the vector Π correspond to the exergoeconomic costs of the (k) flows for the inputs and products of each subsystem.

The elements of the vector Z represent additional costs, for example, costs related to maintenance, operation and capital depreciation.

Using the expanded incidence matrix I, the investment annual cost of the facility, the fuel consumption annual cost and the operation and maintenance annual cost, it was possible to set up the system of equations shown in Tab. 12.

This system was solved using standard computational methods, from which resulted the thermoeconomic costs vector for the process. These results are shown in Tab. 13.

Table 11. Auxiliary equations for the matrix I [14].

Number	Equation
1	$B^*_3 = A_{FUEL}$
2	$B^*_1 = 0$
3	$B^*_8 = 0$
4	$B^*_9 = 0$
5	$(B^*_5 / B_5) - (B^*_{18} / B_{18}) = 0$
6	$(B^*_{10} / B_{10}) - (B^*_{19} / B_{19}) = 0$
7	$(B^*_{12} / B_{12}) - (B^*_{20} / B_{20}) = 0$
8	$(B^*_{12} / B_{12}) - (B^*_{17} / B_{17}) = 0$
9	$(B^*_{14} / B_{14}) - (B^*_{11} / B_{11}) = 0$
10	$(B^*_{15} / B_{15}) - (B^*_{16} / B_{16}) = 0$
11	$(B^*_4 / B_4) - (B^*_6 / B_6) = 0$
12	$(B^*_4 / B_4) - (B^*_7 / B_7) = 0$

Table 12. System of equations for the calculation of the thermoeconomic costs.

$$\Pi = I'^{-1} \times Z$$

$$\begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \\ \pi_6 \\ \pi_7 \\ \pi_8 \\ \pi_9 \\ \pi_{10} \\ \pi_{11} \\ \pi_{12} \\ \pi_{13} \\ \pi_{14} \\ \pi_{15} \\ \pi_{16} \\ \pi_{17} \\ \pi_{18} \\ \pi_{19} \\ \pi_{20} \end{bmatrix} = \begin{bmatrix} I_{11} & . & . & I_{1n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & I_{k-1,p-1} & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ I_{m1} & . & . & I_{mn} \end{bmatrix}^{'-1} \times \begin{bmatrix} 7.346E+05 \\ 3.022E+06 \\ 1.482E+04 \\ 1.272E+06 \\ 1.026E+06 \\ 5.964E+03 \\ 9.713E+03 \\ 6.968E+05 \\ 0.000E+00 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

Table 13. Thermoeconomic costs of the power station.

Flows	Π (US$/s)	C (US$/kWh)	Equipments
1	1.335E-17	2.982E-16	
2	1.053E-01	3.328E-01	
3	0.000E+00	0.000E+00	Boiler
4	6.703E-02	6.631E-03	
5	5.952E-02	8.043E-03	
6	1.547E-01	6.705E-03	
7	4.788E-02	6.559E-03	
8	0.000E+00	0.000E+00	
9	0.000E+00	0.000E+00	
10	1.772E-01	1.049E-02	
11	1.113E-02	1.002E-02	Mill 4 MWe
12	1.749E-02	2.585E-02	
13	5.537E-02	5.650E+00	
14	4.871E-02	1.032E-02	
15	1.474E-01	1.365E-02	
16	3.035E-02	1.366E-02	Mill 8 MWe
17	1.000E-02	2.572E-02	FWP
18	1.557E-02	8.005E-03	ST 7 MWe
19	4.660E-02	1.049E-02	ST 16 MWe
20	7.618E-02	2.584E-02	ST 12 MWe

Using the unit costs shown in Tab. 13, Eqn. 19 and 20, the cost allocation of the final products were calculated, that is, generated electricity cost and process steam cost [7].

$$C_{GE} = C_{18} + C_{19} + C_{20} \tag{19}$$

$$C_{PS} = C_{11} + C_{16} \tag{20}$$

GREENHOUSE GASES ABATED

Due to the use of sugar cane bagasse instead of fossil fuel, it is expected that this cogeneration power plant would reduce CO_2 emissions. Such benefits impact in the global environment through the reduction of the gases emissions that contribute to the greenhouse effect. Local environmental benefits include the emissions of NO_X and SO_2 reduction, which cause acid rain, and reduction of particulate matter emissions, which cause respiratory diseases [2].

Equation 21 was used for the calculation of abated CO_2 equivalent emissions. The results are shown in Tab. 14 [2].

$$Tons\ CO_2 = 0.9 \cdot H_{OP} \cdot \dot{W}_{SEE} \tag{21}$$

Table 14. CO_2 equivalent emissions abated.

Annual Generation (MWh)	Emission Factor (tons CO_2 / MWh)	Tons of CO_2 avoid annually
61,320	0.9	55,188

CLOSING REMARKS

Electrical generation using biomass requires great initial investment, in the order of US$ 800/kW, twice the US$ 400/kW initial investment of conventional thermoelectric power plant, and almost equal to the US$ 1,000/kW initial cost of hydroelectric power plant.

Although initial investment for cogeneration power plant that uses bagasse as fuel is greater than the thermoelectric power plant that burns fossil fuel counterpart, the cost of the generated electricity is competitive, about 0.0443 US$/kWh, compared to the 0.03 - 0.15 US$/kWh of fossil fuel based power plants, and to 0.02 US$/kWh of the electricity from hydroelectric power plants.

The total fuel cost is an important issue because it has a great impact on the generated electricity and the process steam cost. Due to the fact that the power station burns the bagasse produced in the same facility, the fuel has a zero cost for the cost allocation of the cogeneration power plant. As a result, the generated electricity cost is 0.0443 US$/kWh and the process steam cost is 0.0237 US$/kWh.

If the facility had to buy the bagasse at the local market, then the total fuel cost, for a period of 20 years with a referential price of 2.78 US$/ton of bagasse, would be US$ 55,345,796.80 or 2,767,289.84 US$/year. The impact of the fuel cost on the generated electricity cost would be 0.0598 US$/kWh and the process steam cost 0.0344 US$/kWh.

Supposing that the facility burns fuel oil instead of sugar cane bagasse then, the total fuel cost, for a period of 20 years with a referential price of 0.2154 US$/kg of fuel oil, would be US$ 732,003,490.50 or 36,600,174.52 US$/year.

If this additional fuel cost had to be added, it would produce an incremented value for the generated electricity cost of 0.2482 US$/kWh and for the process steam cost of 0.1655 US$/kWh. Therefore, the operation of the cogeneration power plant would be virtually unjustifiable.

Although, the Ecuadorian carbon credit market is very incipient, there are some advantageous laws for facilities involved on these activities, like: income tax and some municipal tax waivers during 10 to 12 years; import duties waiver for machinery and equipments; special price for non-conventional energy during a period of 12 years; guaranteed payment for generated electricity from renewable resources and privilege in the dispatch order, (the facilities burning renewable resources are dispatched ahead of power stations using fossil fuels).

The success of this facility can be seen as a catalytic effect for the development of similar projects in other agro-industrial companies, and would allow Ecuador to benefit from the increase of energy generated from renewable resources.

It is expected that this facility will contribute for the mitigation of climatic change, with the reduction of the prospective emissions of greenhouse gases effect in the amount of 55,188 ton of CO_2 equivalent per year.

ACKNOWLEDGMENTS

The authors acknowledge the support from the CNPq (National Council for Scientific and Technological Development) and the Center for Reference on Gas Turbines and Energy (ITA).

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