ENERGETIC, EXERGETIC AND COGENERATON FEASIBILITY ANALYSIS OF A GRANULATED BLAST FURNACE SLAG DRYING SYSTEM

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Abstract. *Granulated blast furnace slag is an important raw material on production of cement. Drying this material is a necessary process before its aggregation to the cement, requiring high thermal energy consumption. In this work, energetic and exergetic analyses are developed to a composed system for a hot gas generator and an agitated continuous dryer. The results point to an energetic efficiency of 73 % and an exergetic efficiency of 20% of the slag dryer. The main irreversibilities of the process are identified and quantified. Alternatives to improve the whole process are proposed and a brief technical study of cogeneration feasibility is presented, pointing to four years payback time.*

Keywords*: Blast furnace slag, drying, agitated continuous dryer, energy, exergy, cogeneration.*

1. Introduction

Blast furnace slag is a reject in the iron manufacture. It comprises about 20 percent by mass of iron production. Different forms of slag are produced depending on the method used to cool the molten slag. It can be air-cooled blast furnace slag, expanded slag, pelletized slag, and granulated blast furnace slag. Granulated blast furnace slag (GBFS) has become a raw material widely used in the manufacture of the cement for 30 years. Special cements have being manufactured with up to 70 % of GBFS. Density of the GBFS grain is very dependent on its moisture content and has important influence in grinding energy consumption. Beyond GFBS properties, relations between granulation factors, such as water temperature, granulator type, water quantity and pressure and spraying nozzle type, influence grain density. Production of Portland Cement added with Slag (PCS) requires two main processes: drying and grinding. These processes can occur simultaneously, depending on the equipment used. Compared with clinker, main raw material of the cement that demands a great structure for its production, slag reduces significantly the cement manufacture complexity.

Traditional equipment for drying granulated and mineral materials are used to dry slag, as rotary dryer, flash-dryer, and continuous agitating dryer. The drying system is composed basically by dryer, hot gas generator, bag filter, exhaust gas fan, slag feeding and extraction, storage and transport of the slag until the mill.

2. Objectives

The work motivations are:

- blast furnace slag represents today an important raw material in the cement production, which get up to 70% of slag in its composition;
- slag drying consumes around 550 MJ of fuel for ton of humid slag and is the biggest aggregate cost to cement manufacture process;
- few works are found in literature concerning this process analysis.

The objectives of this work are:

i. result presentation of energetic and exergetic analysis of a slag drying system, quantifying efficiencies and sources of irreversibilities detected;

ii. experimental measurements accomplishment and comparison with theoretical results;

iii. proposal for modification in the system using the cogeneration concept and evaluation of economic viability

3. Granulated Blast Furnace Slag Characterization

Blast furnace slag consists primarily of silicates, aluminosilicates, and calcium-alumina-silicates. Granulated blast furnace slag is a glassy granular material that varies, depending on the chemical composition and production method, from a coarse, popcornlike friable structure to dense, sand-size grains passing a 4.75 mm sieve. Figure 1 presents granulometry and moisture characteristics of the humid slag fed in a slag dryer. While the average humidity in the dry period is of 7.5 %, it's observed that in the rainy season it has great variation of the humidity that can reach superior values to 14 %.

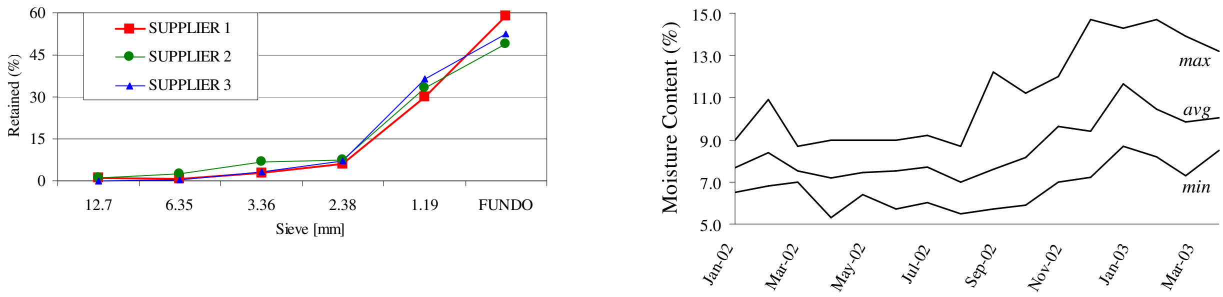

Figure 1. Granulated Blast Furnece Slag Granulometry and Moisture Content
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4. Energetic and Exergetic Balance of Slag Drying System

Aiming thermodynamic analysis, mass, energy and exergy balance of the slag drying system have been made. Figure 2 shows control volumes considered and some datum of this process.

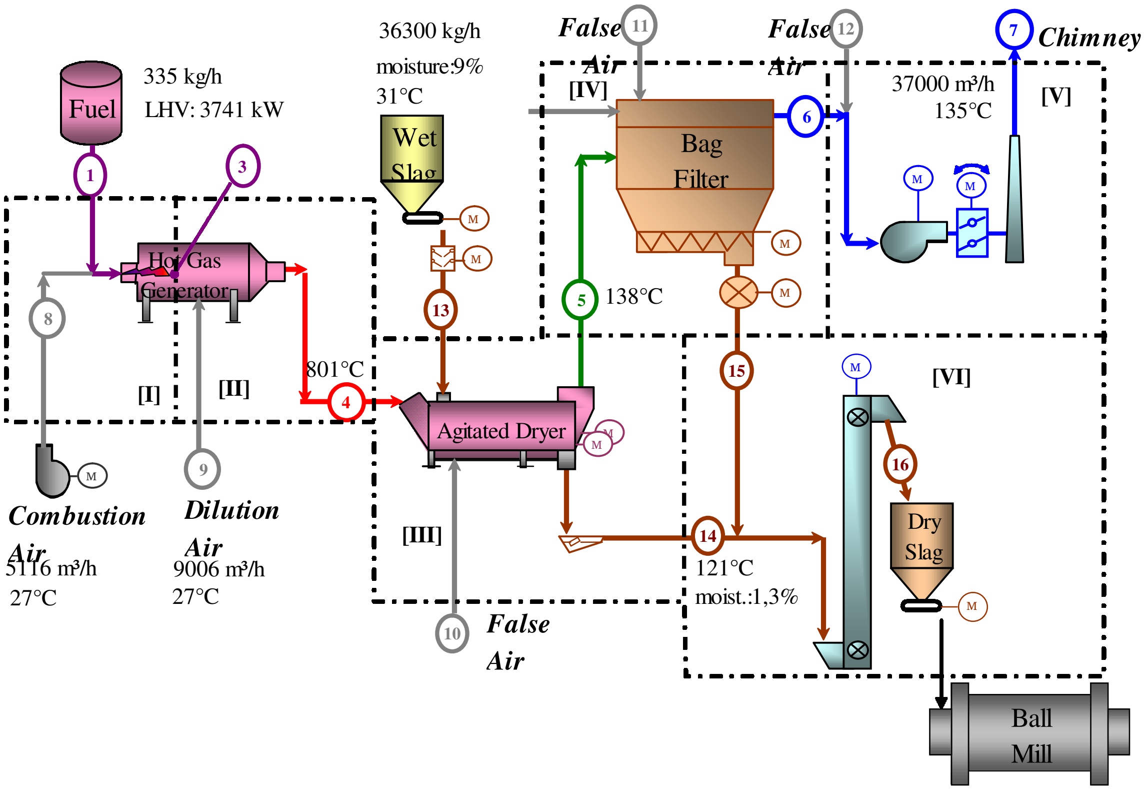

Figure 2. Process control volume.

In the energetic balance, a reference state of gas is considered. The reference state is based on historical averages of temperature, pressure and relative humidity of local ambient air. In the reference state, the thermal energy of a gas, liquid or solid is zero. Initially, then, all thermal energy is in the hot gas, and all air from the environment, has zero energy. In the exergetic balance, the state of reference of local ambient air is used in the calculation of the physical exergy and dead state, or either, ambient air with all its natural components is used in the calculation of the chemical exergy. To avoid negative exergy in any flow of the process, slag exergy with its maximum moisture content is considered to be equal zero. Some authors, however, as Dincer and Sahin (2004), suggest the use of the water exergy with a negative value.

Potential and kinetic energies and exergies of fluids have been neglected due to its low representation in the thermodynamic system balance.

In the hot gas generator two control volumes I and II have been created. In the first control volume, the air is supplied for the equipment blower. The dilution air necessary to guarantee the hot gas operational temperature in the dryer is complemented by natural blow up through variable vanes installed in the hot gas generator. This is possible because hot gas generator works with negative chamber pressure.

Table 1 presents nomenclature indicating variables used in this calculation.

Table 1. Nomenclature

cp_s	– Specific heat of slag	y	– Molar fraction of chemical component
$\dot{E}n$	– Energy rate	y_{00}	– Molar fraction of chemical component in the reference state, ambient air at dry base
$\dot{E}x$	– Exergy rate	y_v^{00}	– Absolute humidity of air in the reference state
h	– Specific Enthalpy of gas	ε^{ph}	– Specific physical exergy
$\dot{I}$	– Irreversibility	ε^{0}	– Specific chemical exergy
$\dot{m}_{ev}$	– Evaporated water rate by mass	Δh^0	– Specific enthalpy in relation to the reference state of the ambient air
$\dot{m}_g$	– Humid gas rate by mass	Δs^0	– Specific entropy in relation to the reference state of the ambient air
$\dot{m}_s$	– Solid rate by mass	η	– Energy efficiency
$\dot{m}_w$	– Moisture in the solid rate by mass	ϕ_0	– Relative humidity of air in the reference state
$\dot{Q}$	– Loss of heat at the equipment wall	ψ	– Exergy efficiency
R	– Gas constant		Subscripts
T	– Temperature of the gas	g	– Gas with humidity
T_0	– Temperature in the reference state of ambient air	q	– Chemical element
T_R	– Temperature in the reference state of the solid for energy analysis	s	– Solid
T_X	– Temperature in the reference state of the solid for exergy analysis	v	– Vapor of the gas
$\dot{W}$	– Work, electric power consumed in the control volume	w	– Moist of the solid

Energy and exergy flows in the dryer control volume can be calculated by typical equations (Kotas, 1995; Szargut, Morris and Steward, 1988) . The energy balance is:

$$\dot{E}n_4+\dot{E}n_{10}+\dot{E}n_{13}+\dot{Q}_5-\dot{W}_5=\dot{E}n_5+\dot{E}n_{14} \quad (1)$$

where $\dot{Q}_5$ is defined as the loss of heat measures at the equipment wall and $\dot{W}_5$ is the electric power consumed by the two agitator shafts which disperse the feed material throughout the drying chamber. For humid gas flow, $\dot{m}_g$, with solid particulate flow, $\dot{m}_s$, with its moisture content, $\dot{m}_w$, representing the most general case, the energy equation rate becomes:

$$\dot{E}n_5=\dot{m}_{g;5}.\Delta h^0_{g;5}+\dot{m}_{s;5}.cp_s\left[T_5-T_R\right]+\dot{m}_{w;5}.\Delta h^0_{w;5} \quad (2)$$

Exergy balance can be closed by the control volume irreversibilities, $\dot{I}_5$, which includes the heat loss at the wall, and is given by:

$$\dot{E}x_4+\dot{E}x_{13}+\dot{E}x_{10}-\dot{W}_5=\dot{E}x_5+\dot{E}x_{14}+\dot{I}_5 \quad (3)$$

where t he gas flow exergy rate on outlet control volume, $\dot{E}x_5$, is defined by:

$$\dot{E}x_5 = \dot{m}_{g;5}.\left[\varepsilon_{g;5}^{ph} + \varepsilon_{g;5}^{0}\right] + \dot{m}_s.\varepsilon_{s;5}^{ph} + \dot{m}_{w;5}.\left[\varepsilon_{w;5}^{ph} + \varepsilon_{w}^{0}\right] \tag{4}$$

Moisture dust physical exergy parcel, $\varepsilon_{w;5}^{ph}$, is given by:

$$\varepsilon_{w;5}^{ph} = \Delta h_{w;5}^{0} - T_0.\Delta s_{w;5}^{0} \tag{5}$$

Physical exergy of solid dust, $\varepsilon_{s;5}^{ph}$, is defined by:

$$\varepsilon_{s;5}^{ph} = cp_s\left[T_5 - T_X + T_X\, ln\left(T_5/T_X\right)\right] \tag{6}$$

and chemical exergy of the moisture dust, ε_{w}^{0},is given by:

$$\varepsilon_{w}^{0} = R\,T_0\, ln\left(1/\phi_0\right) \tag{7}$$

For the flows 4, 5 and 10, gas flow physical exergy, ε_{g}^{ph}, can be calculated with:

$$\varepsilon_{g}^{ph} = \Delta h_{g}^{0} - T_0.\Delta s_{g}^{0} \tag{8}$$

Humid gas flow chemical exergy, ε_{g}^{0}, is given by:

$$\varepsilon_{g}^{0} = R.T_0.\left(\sum_q y_q\, ln\frac{y_q}{y_q^{00}} + y_v.ln\frac{y_v}{y_v^{00}} + ln\left(1 + y_v^{00}\right)\right) \tag{9}$$

For the solid in flows 13 and 14, the exergy is calculated by:

$$\dot{E}x = \dot{m}_s.\varepsilon_{s}^{ph} + \dot{m}_w\left[\varepsilon_{w}^{ph} + \varepsilon_{w}^{0}\right] \tag{10}$$

where moisture solid exergy, ε_{w}^{ph}, is given for:

$$\varepsilon_{w}^{ph} = \Delta h_{w}^{0} - T_0.\Delta s_{w}^{0} \tag{11}$$

and solid exergy, ε_{s}^{ph}, is defined by:

$$\varepsilon_{s}^{ph} = cp_s\left[T_s - T_X + T_X\, ln\left(T_s/T_X\right)\right] \tag{12}$$

5. Drying Efficiency

Dryer energetic efficiency, η, is defined as:

$$\eta = \frac{1}{\dot{E}n_4}\left\{\dot{m}_{ev}.\left(h_{v;5} - h_{w;13}\right) + cp_s\left[\dot{m}_{s;14}.\left(T_{14} - T_{13}\right) + \dot{m}_{s;5}.\left(T_5 - T_{13}\right)\right]\right\} \tag{13}$$

Dryer exergetic efficiency, Ψ will be defined as (Dincer and Sahin, 2004):

$$\Psi = \frac{\dot{m}_{ev}.\left(\varepsilon_{w;5}^{ph} - \varepsilon_{w;13}^{ph}\right)}{\dot{E}x_4} \tag{14}$$

In this equation numerator, only the exergy of removed water of the solid added to dry material is considered as product exergy. In the denominator, inlet exergy is the hot gas generator outlet exergy.

6. Results and Discussion

Table 2 shows mass, energy and exergy flows extracted from balance performed on the each control volume (Fig. 2)

Table 2. Mass, Energy and Exergy Balance Results

	Line	Gas/Solid kg/s	Water kg/s	Energy kW	Exergy kW
Fuel oil	1	0.093		3,741.0	3,965.0
Combustion product	3	1.522	0.099	3,744.0	2,714.0
Dryer inlet hot gas	4	4.178	0.132	3,734.0	2,006.0
Dryer outlet gas	5	7.437	0.959	1,177.0	489.0
Bag filter outlet gas	6	7.600	0.961	1,052.0	413.4
Chimney	7	7.614	0.961	1,052.0	412.9
Combustion air	8	1.509	0.019	3.1	0.1
Dilution air	9	2.657	0.033	5.5	0.2
Dryer false air	10	3.259	0.040	6.7	0.2
Bag filter false air	11	0.162	0.002	0.3	0.0
Exhaust fan false air	12	0.015	0.000	0.0	0.0
Dryer Inlet moist slag	13	9.176	0.908	32.5	
Dryer outlet slag	14	8.809	0.121	2,526.0	1,439.0
Bag filter slag dust	15	0.367	0.000	119.7	68.9
Total Outlet slag	16	9.176	0.053	2,440.0	941.8

Figures 3 and 4 shows Sankey and Grassmann diagrams regarding to energetic and exergetic balance, respectively.

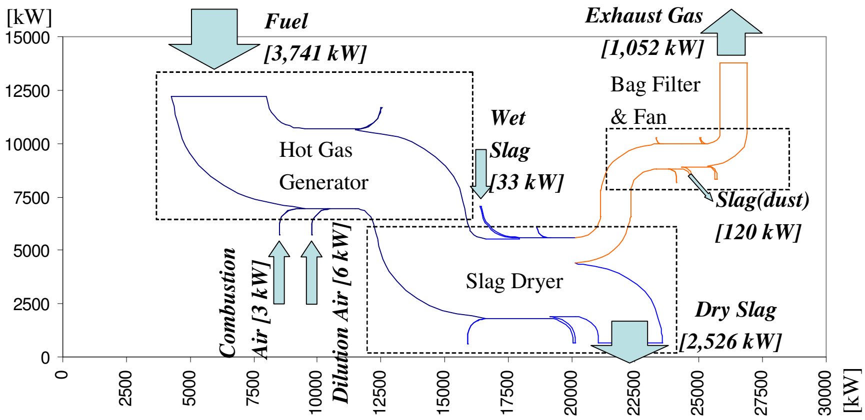

Figure 3. Energy system diagram (Sankey diagram).

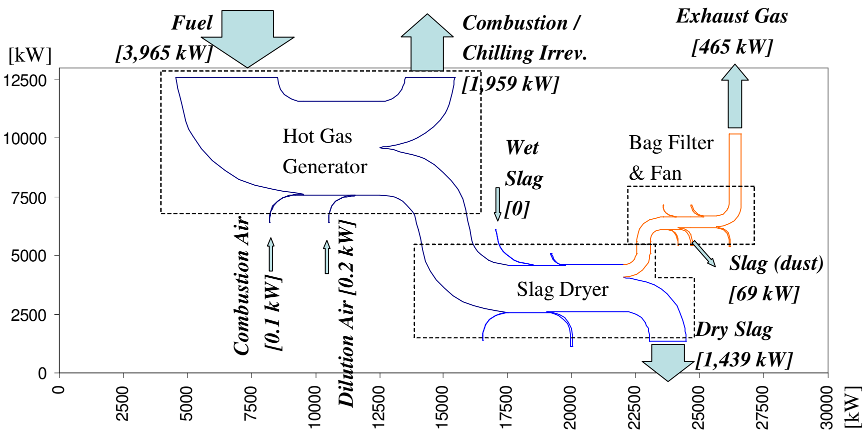

Figure 4. Exergy system diagram (Grassmann diagram).

Comparing energetic and exergetic balances, it is observed that it does not have energy variation associated with reduction of combustion gas temperature in the mixture with ambient air. However, a great irreversibility associated with this process is identified in the exergy diagram.

Generally, energy and exergy flows at dryer outlet are similar, with proportionality between gas flow and solid flow.

Figure 5 presents diagrams quantifying energy losses and irreversibilities in the slag dryer.

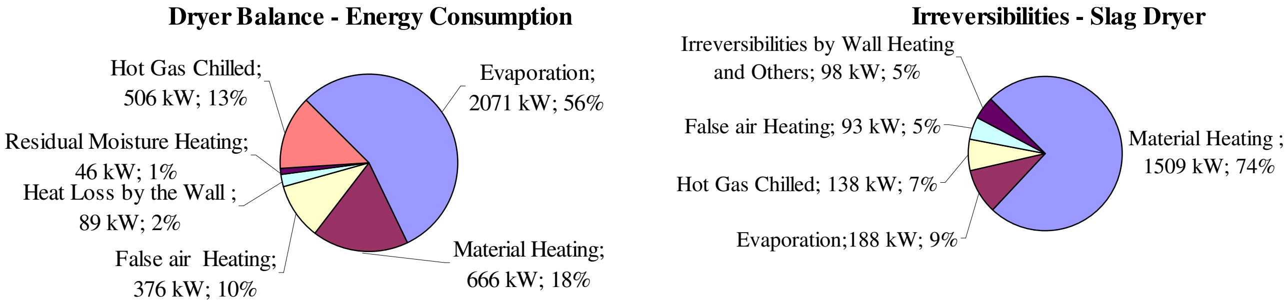

Figure 5. Distributions of Energy and Irreversibilities in the Slag Dryer.

It is observed in these diagrams that, while the evaporation process is the great energy consumer, material heating is the main responsible for the irreversibilities, or either, for the process exergetic inefficiency.

Table 3 presents slag dryer energetic and exergetic efficiencies.

Table 3. Slag Dryer Efficiencies

$\eta = 73.0$ %	Energetic efficiency
$\Psi = 19.9$ %	Exergetic efficiency

Efficiency criterion defined for Dincer and Sahin (2004), follows from the concept that product exergy is the exergy associated with removed water of the solid. It is in agreement to rational efficiency definition, which represents the ratio of outlet exergy of the product to inlet exergy. It is a reasonable criterion to compare distinct drying plants.

Irreversibilities analysis indicated in Fig. 4 let to a feasibility study to a cogeneration system installation to use the lost exergy in the hot gas generator due to reduction of combustion gas temperature to operational temperature in the inlet dryer.

Table 4 and Fig. 6 present data and results of analysis made considering cogeneration with Rankine cycle.

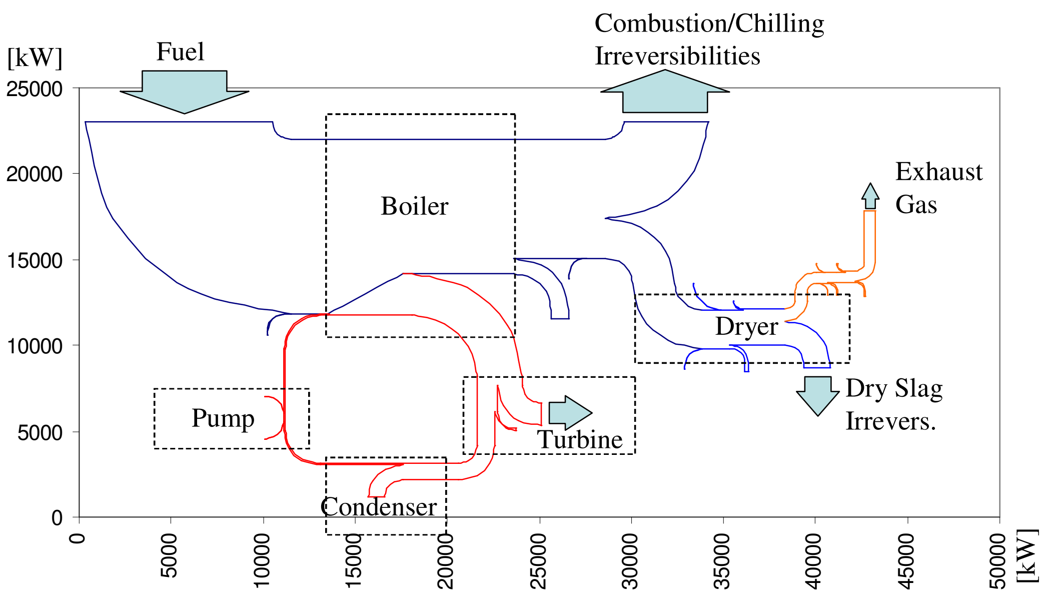

Figure 6. Grassmann Diagram – Drying System with Cogeneration.

Analysis showed that cogeneration is not economically viable considering electric energy cost of 130.00 R$/MWh. Table 4 shows that cost with global energy in the system would increase in R$ 258,000.00 per month. One disadvantage of increasing fuel consumption is to raise the amount of CO_2 in the chimney gases, what can be harmful to the company in the future in terms of carbon credit (Kioto convention).

Furthermore, the possibility to increase turnover with saturated vapor sale that leaves the turbine was evaluated. Neighborhood plants that need saturated vapor, as candy plants, textile, milk product plants, cooperatives, etc., beyond restaurants, hospitals, clubs and water heating communitarian central offices could acquire saturated vapor instead of investing in a house of boilers and its operational costs. In this case, turbine outlet vapor pressure would need to be bigger to allow vapor commercialization and a reduction in the turbine power would occur compared with the previous case. Moreover, pump inlet water must be considered at ambient temperature, since condensed liquid water may not return to the system.

Table 5 presents results of a feasibility study for cogeneration central plant implantation with sale of turbine outlet saturated vapor. Cogeneration in this case would be viable.

Table 4. Analysis of drying plant with and without cogeneration

	Unity	Conventional	With Cogeneration
Fuel oil by mass	kg/h	334.5	895.2
Heat value of fuel	kW	3,741	9,608
Combustion air	m³/h	5,116	13,634
Combustion Temperature	°C	1,852	1,800
Dilution air	m³/h	9,006	0
Total air in combustion and dilution	m³/h	14,122	13,634
O2 at dryer inlet	$\%_{DB}$	14.9	4.3
Gas humidity at dryer inlet	kg/kg	3.2	6.3
Gas exergy at dryer inlet	kW	2,006	2,279
Gas energy at dryer inlet	kW	3,734	3,858
Humid gas at dryer inlet by mass	kg/s	4.31	4.31
Gas temperature at dryer inlet	°C	801.0	801.0
Electric energy at turbine-pump	kW	0	1348.0
Deduced energy consuming	kW	3,741	8,260
Vapor of cogeneration system by mass	kg/s		1.99
Fuel oil cost of the plant by month	R$/month	224,115	599,784
Electric energy produced by month	R$/month	0	117,411
Total plant energy cost by month	R$/month	224,115	482,373
Difference increased in energy cost by month	R$/month		258,258
Factors: A1 oil: 1,00R$/kg; Electric energy: 130,00R$/MWh; Operation: 670 h/month			

Figure 7 complements the study results, presenting two curves of investment return alternatives in function of electric energy price.

Table 5. Cogeneration plant implantation feasibility study

Description	Unity	Value
Produced liquid power	kW	855
Vapor produced in the plant	kg/s	1.915
Availability factor of cogeneration plant		0.92
Internal consumption factor of cogeneration plant		10 %
Income tax aliquot		0.35
Complementary investment cost	R$/kW	1350
Global cost of plant (turn-key)	R$/kW	2.700
Sale value of saturated vapor	R$/kg	0.10
Addition in the fuel cost	R$/year	4,512,000
Recovery for prescription of saturated vapor sale	R$/ year	5,542,776
Operational cost plant	R$/ year	217.589
Total investment for plant implantation	R$	3.462.750

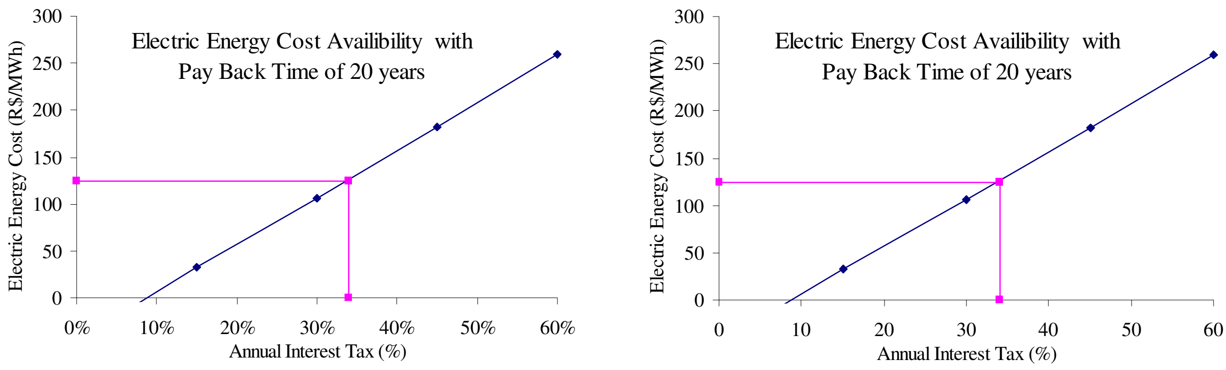

Figure 7. Payback of Cogeneration Central Plant

It is observed that, with tariff of R$ 130.00/MWh, payback would occur in 46 months considering an interest tax of 20 % per year. If investment return can be admitted during the useful life of 20 years of the equipment, a return internal tax of the annual investment above 30 % can be considered.

7. Conclusion

Thermodynamic analysis of a granulated slag drying system points to a dryer energetic efficiency around to 73 % and an exergetic efficiency about 20 %. While in the energy balance the evaporation process appears as the great energy consumer, in the exergetic balance the slag heating is the main process for irreversibility generation, or either, for exergetic inefficiency of the process. The energetic analysis does not detect loss associated with the mixture process of combustion gas and ambient air for drying gas production, while the exergetic analysis identifies a great irreversibility in this process, revealing a possible exergy recovery (electric energy) in a thermal cogeneration plant.

Consideration of mixture slag-water energy and exergy for condition of maximum moisture content equal to zero allows to show and analyze energetic and exergetic balance on an easier way.

Feasibility study of a cogeneration plant with Rankine cycle showed that it would be an important addition in the fuel account of the company, beyond an increase in CO_2 emission. The simple cogeneration would not be, then, a recommendable investment.

However, considering a decurrent additional sale prescription of turbine exhaustion saturated vapor for neighboring industries or hospitals, clubs, cooperatives, water heating communitarian central offices of the neighborhood, the investment would start to be sufficiently attractive with 4 years payback time. In a general way, this type of steam offer, not usual in Brazil, seems to be a good industrial option, because it brings many advantages as cost reductions in boilers, fuel storage, and with its operation and maintenance, besides industrial accidents risk reductions and consumption reduction of electric energy for water heating.

8. Acknowledgements

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