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ANALYSIS OF ELECTRICITY GENERATION AS A FUNCTION OF ENVIRONMENTAL CONDITIONS FROM THE BOTTOMING CYCLE ENERGY METHODOLOGY

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Abstract. *This article aimed to develop an analysis of the electric power generation as a function of environmental conditions based on a calculation methodology for cogeneration in a bottoming cycle. The analysis considers: the trigeneration, with the possibility of cold production through absorption and/or compression chillers; the curve of energy demands of the process; the storage of thermal energy in the form of cold; as well as local environmental conditions such as altitude, ambient temperature, and humidity. The calculations that were done includes: the electric power generated; the chiller performance coefficients; the commercialization of electricity and carbon credits. In addition, was assessed the environmental gains with the reduction of* CO_{2eq} *emissions. The methodology was applied in a small steel factory whose average monthly production is 5,500 tons of pig iron from charcoal, and it is in the state of Minas Gerais, Brazil. The time analyzed period was one year and a Rankine cycle with thermal efficiency of 20% for electricity generation was considered. The results show that the variables of environmental conditions, ambient temperature and altitude are the ones that most impact the electric power generation. Considering an altitude at 725 m and analyzing the values of electric power generation for a typical summer and winter day the results are as follow. In a summer day the electric power at 6 h was 1,323 kW, for 21.6 °C and 96 % of ambient temperature and relative humidity respectively and, at 18 h was 1,303 kW, for 30.5 °C and 53 % of ambient temperature and relative humidity respectively. In a winter day the electric power at 6 h was 1,364 kW, for 12.5 °C and 87 % of ambient temperature and relative humidity respectively and, at 18 h was 1,334 kW, for 23.8 °C and 37 % of ambient temperature and relative humidity respectively. This way it is possible to concluded from the results, obtained with the proposed methodology, that at lower ambient temperatures higher values of electric power are produced while the relative humidity does not influence the generated power.*

Keywords: *Bottoming cycle, Cogeneration, Energy efficiency, Industrial processes*

1. INTRODUCTION

Industrial waste heat recovery is one of the most relevant alternatives in the contemporary world to improve energy efficiency in industrial processes. Better efficiency leads to more conscious use of natural resources and, consequently, to reduction of environmental impacts. The latter are reduced by reducing greenhouse gas emissions. Thus, according to (de Campos et al. 2020) and (Viana et al. 2012) the search for energy efficiency is encouraging those who want to develop and improve the recovery of existing waste heat in numerous industries. With the waste heat recovery it is possible to generate electricity through a cogeneration process.

According to (Lora and Nascimento 2004), cogeneration is the combined, sequential and simultaneous production of useful heat and power, which can be electrical or mechanical. (Çakir, Çomakli, and Yüksel 2012) state that when cogeneration in topping cycle is compared to separate generation of heat and electricity, it results in an energy saving generally in the range of 10 % to 30 %. Still according to (Çakir, Çomakli, and Yüksel 2012) emissions of CO_2 avoided with cogeneration in the topping cycle are, in a first approximation, proportional to the amount of energy savings.

The production of power, in the form of electrical or mechanical power and useful heat in cogeneration, can happen in two ways: in topping cycle, mentioned in the previous paragraph, or in bottoming cycle. According to (Nogueira, Teixeira, and Carvalho 2004), in the topping cycle there is the production of power upstream of the production of useful heat. In the bottoming cycle is the production of useful heat that is upstream to the production of power. This work focuses on applications that use cogeneration systems with bottoming cycle because this form of cogeneration is applicable in the industrial waste heat recovery.

Cogeneration with bottoming cycle, defined by (Noordermeer, n.d.) can be applied to industrial processes in which some type of fuel is required for the generation of heat or chemical reactions, whose energy residue in the form of waste heat is used to generate electricity and/or cold. According to process (DFIC - Dr. Fromme International Consulting 2016) this additional power generation (whether electricity, cold or both) is returned to the process.

From the niche market of application of cogeneration in bottoming cycle, this work aims to analyze the generation of electricity from a methodology that takes into account in a comprehensive way: a) trigeneration, in which cold can be generated by absorption and/or compression chillers; b) the curves of energy demands of the process; c) the storage of thermal energy in the form of cold; d) local environmental conditions for the calculations of the electricity generated and the performance coefficients of chillers; e) the commercialization of electricity and carbon credits; f) efficiency indicators; g) calculations of the minimum requirements for the qualification of the cogeneration unit in the ANEEL; h) environmental gains and; i) economic gains. With the defined methodology, an industrial process will be chosen with data and information available in which cogeneration can be used in a bottoming cycle in order to analyze the generation of electricity from the proposed methodology.

2. METHODOLOGY

This work will be applied to cogeneration in a bottoming cycle, which is defined according to the (Noordermeer, n.d.), as the one where power generation (mechanical or electrical) is located downstream of the thermal demand of industrial processes. This methodology will include the thermal and environmental models to perform the evaluation of cogeneration in bottoming cycle. The following are described (i) the energy interactions in the system and its components with the presentation and description of the generic diagram of the cogeneration system in bottoming cycle; (ii) the description of the calculation procedure for performing the analysis of electricity generation and; (iii) the explanation of the applied model.

(Roque Díaz, Benito, and Parise 2010) mention the complexity of cogeneration systems, where it is necessary, for projects and application monitoring, to take into account the following information: a) the curves of thermal and electrical demands of the process over time, which can be depending on the day, week, year, climatic conditions, productive seasonality, economic market, among others; b) the efficiency of the process depending on the efficiencies of the machines and equipment available on the market, their possibilities of simultaneous use or not, in addition to variations in operational efficiencies in full or partial load; c) the supply of fuels taking into account their availability and costs; d) environmental impacts due to fuels, drive technologies and local legislation where the plant is being designed or operated; e) the definition of the efficiency indicators to be used in the measurement and; f) the definition of project and operational financial indicators to demonstrate the economic viability.

The methodology used for cogeneration in bottoming cycle takes into account: a) the trigeneration, which is the generation of heat, cold and electricity through the reuse of the residual heat of the industrial process, in which the cold can be generated through absorption and/or compression chillers; b) process energy demands curves; c) the storage of thermal energy in the form of cold; d) local environmental conditions for the calculations of the electricity generated and the performance coefficients of chillers; e) the commercialization of electricity and carbon credits; f) efficiency indicators; g) calculations of the minimum qualification requirements with the ANEEL; h) environmental gains and; i) economic gains. This study will take into account part of the methodology cited that refers to: a) electricity generation through the reuse of waste heat from the industrial process; b) curves of electrical and fuel energy demands of the process and; c) local environmental conditions for the calculations of electricity generated. At the end, an analysis of electricity generation will be presented according to environmental conditions for a case study in which the methodology applies. The case study refers to the steel process of manufacturing pig iron from high charcoal oven.

2.1 Energy Interactions in the System

The methodology has as its starting point a generic diagram that is proposed in order to be applicable to any cogeneration system in a bottoming cycle interconnected to an industrial process. The proposed diagram can be seen through the Fig. 1.

An industrial process, for its generalized operation, demands an energy potential in the form of fuels that is defined by the variable *WCombD* in the diagram of the Fig. 1. These fuels may be liquid, gaseous and/or solid. Another energy demand in the process is the electricity defined by the variable *WEleD*, which is supplied through the electric power connection system (ECS), as represented in the diagram of the Fig. 1 by dotted lines. The ECS aims to receive the electricity generated in the power cycle of the cogeneration plant in bottoming cycle and the coming of the power grid of the concessionaire and distribute it to meet the demand of the process (*WEleD*) and compression chiller (*WEleC*). The electricity generated in the power cycle of the cogeneration plant and the cold generated by the compression chiller will be described in detail later. The electricity in the connection between the ECS and the concessionaire's electricity grid is defined by the variable *WEleM* and can be sale or purchase, depending on the electricity generated in the power cycle of the cogeneration plant in bottoming cycle. Another demand that the process may require is thermal energy in the form of cold defined by the variable *QcolD*.

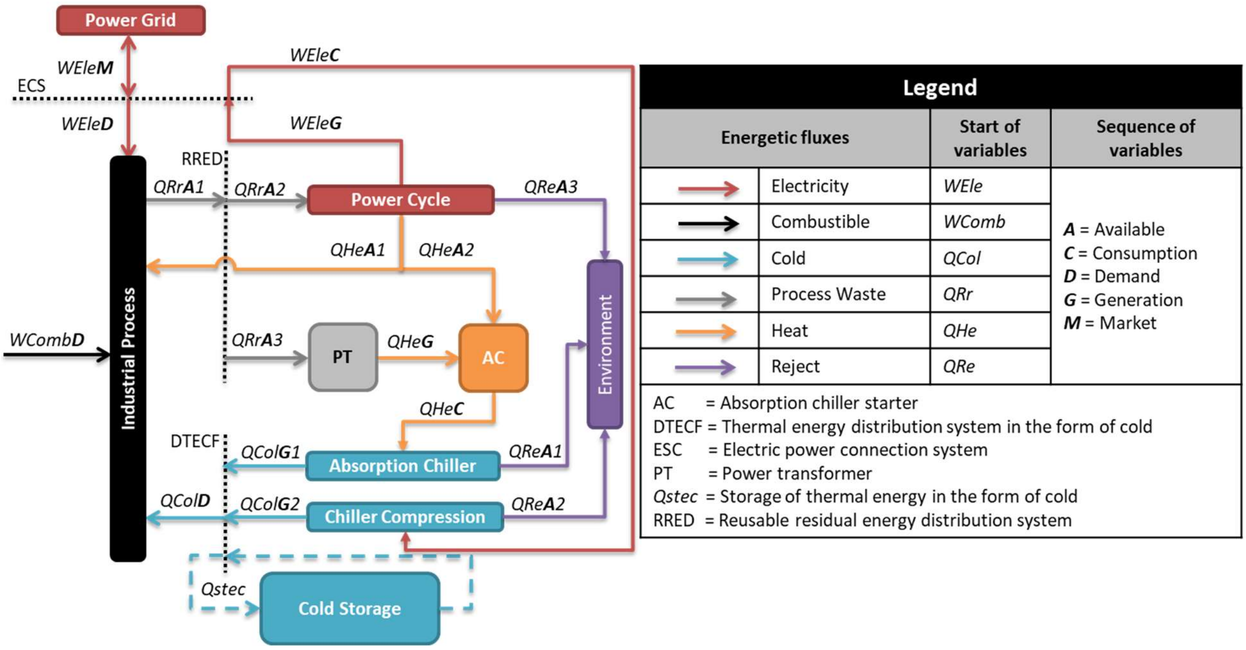

Figure 1. Generic diagram of bottoming cogeneration

As a result of the specific production of the process, one can have a residual energy not used by the process, but that can be reused for application of cogeneration in bottoming cycle. This energy is defined by the variable *QRrA1* and one can have it in a variety of ways such as: a) in the form of hot exhaust gases such as a clinker oven for cement production; b) in the form of solid waste as chemical energy from the petroleum coke in a refinery and; c) or in the form of liquid as black liquor in the manufacture of cellulose paper etc. *QRrA1*, through a reusable residual energy distribution system (RRED) in the bottoming cycle, which is represented in the diagram of the Fig. 1 by dotted lines. The RRED can feed the connections for use in absorption/adsorption chiller generator (*QRrA3*) or use in the power cycle (*QRrA2*). For cases where *QRrA3* is a chemical residue and needs to go through a process of transformation, in order to generate thermal energy in the form of heat (*QHeG*), in order to feed the absorption/adsorption chiller trigger (AC), it is necessary to have a power transformer (PT) that can be a boiler, for example. AC can also be powered by the thermal energy provided by the power cycle defined by the variable *QHeA2*. Other thermal energy that can be made available by the power cycle, defined by QHeA1, can be used in the process for, for example, heating water.

The absorption chiller, which can also be adsorption, consumes thermal energy in the form of heat (QHeC) to generate thermal energy in the form of cold. This energy is defined by the variable *QColG1*. The heat rejection generated by the chiller, *QReA1*, is dissipated in the environment. *QColG1* is sent to the thermal energy distribution system in the form of cold which will be described later.

As already mentioned, *QRrA1* can also feed the connection *QRrA2* providing thermal energy for the power cycle with intention to generate electrical or mechanical power. In this work will be considered only the generation of electrical power, defined by the variable *WEleG*. The power cycle can also generate the available energies already described (*QHeA1* and *QHeA2*) plus heat dissipation, *QReA3* in the environment. The power cycle can be a cycle Kalina, Rankine or Rankine Orgonic, por example. The choice of cycle type will depend on the thermo-physical characteristics of industrial residual heat defined with *QRrA1*. Greatness *WEleG*, through the distribution system ECS, can trigger the compression chiller by the power set by *WEleC,* return to the consumption of the process through *WEleD* or be sold to the concessionaire through *WEleM*.

The compression chiller driven by *WEleC* product is the thermal energy in the form of cold defined by the variable *QColG2*. Already *QReA2* is your heat dissipation to the environment. *QColG2* plus *QColG1* are sent to the power distribution system in the form of cold, DTECF, whose objective is to supply the cold demand of the industrial process (*QcolD*). Depending on the priorities of energy types demanded by the industrial process, like the kind of cold, one can have a storage of thermal energy in the form of ice water for example, defined by the variable *Qstec*. Storage is intended to store the excess of *QcolD* to be used when the sum of *QColG2* and *QColG1* is not sufficient to supply *QcolD*.

2.2 Definition of demand levels

To set demand levels (*D*), the curves of electrical power demands are used. The generic way to express demand curves can be observed through the Eq. (1) of Tab. 1.

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Table 1. Levels and demands

Generic	Electric	Combustible
$D^n = \mathrm{f}(t_n, D_n)$ (1)	$WEleD^n = t_n \cdot WEleD_n$ (2)	$WCombD^n = t_n \cdot WCombD_n$ (3)

Each level (n) demand (D^n) is defined as a function of a time (t_n) that's a fraction (interval) of the total time analyzed (TT), multiplied by a demand (D_n), which is a fraction of the maximum demand of each type of energy demanded in the process. Thus, the levels of electrical power and fuel demands of the industrial process are expressed in the Tab. 1 through equations Eq. (2) e (3) respectively.

To correlate the demand levels with the residual energy curves generated for use in cogeneration in bottoming cycle, defines itself $QRrA1$ as:

$$QRrA1^n = t_n \cdot WCombD_n \cdot (1 - \eta_{Pr}) \tag{4}$$

As can be seen in the Eq.(4), $QRrA1^n$ can be calculated depending on the thermal efficiency of the process utilization (η_{Pr}), or obtained by means of measurements made on it. The thermal efficiency of the use of the industrial process is calculated by dividing the energy potential demanded by the energy potential consumed in the industrial process.

2.3 Definition of environmental conditions for the calculation of adjustment factors for the correction of electricity generated by the power cycle

In order to approximate the real values of electricity generation by the cogeneration system in a bottoming cycle, in such a way that environmental conditions are taken into account, this work makes use of the corrections of the performance coefficients. These corrections apply to both the power cycle and cooling cycles and are proposed by (Brown, Katipamula, and Konynenbelt 1996). These authors propose correlations of performance coefficients based on the response that a steam cycle in combined cycle with a gas turbine and waste heat recovery boiler would have before the variations in environmental conditions. This methodology will use the corrections as (Brown, Katipamula, and Konynenbelt 1996), however it is recommended to use specific correlations in accordance with the nature of the process from which the input energy to the Rankine cycle is derived in the cogeneration in bottoming cycle.

The adjustment factors for the correction of the electricity generated by the power cycle, which uses a steam turbine, require a more complicated format. Because of this complexity, (Brown, Katipamula, and Konynenbelt 1996) assume that the power of the steam turbine is proportional to the steam production of the waste heat recovery steam generator or boiler, with an adjustment for the impact of ambient temperature on the temperature of the condenser. Thus, the equation for calculating the electricity generated with the correction factor, P_{Adjusted}, can be expressed through the Eq. (5) of Tab.2.

Table 2. Electricity correction factors generated by power cycle

$P_{\text{Adjusted}} = P_{\text{ISO}} \cdot PCCF$ (5)	$PCCF = EFF \cdot ETF \cdot CTF$ (6)	
Exhaust Flow Adjustment Factor	Exhaust Temperature Adjustment Factor	Condenser Temperature Adjustment Factor
$EFF = F1 \cdot F2 \cdot F3 \cdot F4 \cdot F5$ (7)	$ETF = \dfrac{T_{\text{Exhaust}} - 550}{542}$ (8)	$CTF = 1 - (1{,}9 \times 10^{-4}) \cdot (T_{\text{wb}} - 54) \rightarrow for\ T_{\text{wb}} \leq 54°F\ or$ (9)
$F1 = 1{,}0 - (3{,}33 \times 10^{-5}) \cdot h$ (10)	$T_{\text{Exhaust}} = 1054 + 0{,}517 \cdot T_{\text{db}} + Pi + 0{,}8 \cdot Pe \rightarrow for\ T_{\text{db}} \leq 60°F$ (11)	
$F2 = 1{,}12 - (2{,}15 \times 10^{-3}) \cdot T_{\text{db}}$ (12)		
$F3 = 1{,}0$ (13)	$T_{\text{Exhaust}} = 1085 + 0{,}850 \cdot (T_{\text{db}} - 60) + Pi + 0{,}8 \cdot Pe \rightarrow for\ T_{\text{db}} > 60°F$ (14)	$CTF = 1 - (9{,}0 \times 10^{-4}) \cdot (T_{\text{wb}} - 54) \rightarrow for\ T_{\text{wb}} > 54°F$ (15)
$F4 = 1{,}0 - (2{,}5 \times 10^{-3}) \cdot Pi$ (16)		
$F5 = 1{,}0$ (17)		

Where P_{ISO} is electrical power generated under ISO conditions (dry bulb temperature = 59 °F, relative humidity = 60 % and altitude at sea level) and $PCCF$ is the correction factor of the electricity generated by the power cycle when the steam turbine is used. The variable $PCCF$ can be calculated through the Eq. (6) expressed in the Tab.2.

Where EFF is Exhaust Flow Adjustment Factor, ETF o Exhaust Temperature Adjustment Factor and CTF o Condenser Temperature Adjustment Factor. The adjustment factor EFF is defined according to the Eq. (7) of Tab.2.

Where $F1$ is the adjustment factor for altitude, $F2$ for dry bulb temperature, $F3$ for humidity, F4 for excess pressure drop of the fluid at the turbine inlet and $F5$ for excess pressure drop in exhaustion. These factors can be calculated through the Eq. (10), (12), (13), (16) e (17) of Tab.2. In these equations, *h* is the altitude, converted to feet, T_{db} the dry bulb temperature, converted to °F and *Pi* is the drop in fluid pressure at the turbine inlet in in of H_2O. For calculating the Exhaust Flow Adjustment Factor, *ETF*, there is the Eq (8) of Tab.2.

Where $T_{Exhaust}$, also converted to °F is obtained through the Eq. (11) or (14) of Tab.2.

Where *Pe* is the pressure drop of the exhaust flow in in of H_2O. The Condenser temperature adjustment factor, *CTF*, is obtained through the Eq. (9) or (15) also of the Tab.2. Where T_{wb} is the temperature of wet bulb, converted to °F.

2.4 Calculation of maximum energy consumption and electricity generation

Once the demand levels are defined and calculated the correction factor for the electricity generated, it is necessary to define the variable efficiency of the power cycle, η_{CP}, in which it is stipulated according to the type of cycle used and may preferably be Rankine Conventional, Organic Rankine or Kalina.

With η_{CP} defined, it is necessary to determine the priority of the flow of *QRrA1*. In terms of priority, *QRrA1* should be directed first in the amount *QRrA2* to feed the cogeneration power cycle into a bottoming cycle through the RRED, as shown in the generic diagram of the Fig. 1. Thus, MEC_{CP}, the maximum energy consumption of the cogeneration power cycle in bottoming cycle, can be expressed:

$$MEC_{CP} = QRrA2 \quad (18)$$

With the maximum power consumption of the calculated or defined power cycle, with the efficiency coefficient of the defined cycle and with the calculated correction factor, the generation of electrical power is obtained for each level of baseline through the equation (19) or (20) expressed in the Tab.3.

Table 3. Electricity generation calculation

Condition	Result	
$QRrA1_n > MEC_{CP}$	True	$WEleG_n = MEC_{CP} \cdot \eta_{CP} \cdot PCCF \cdot 1{,}015$ (19)
	False	$WEleG_n = QRrA1_n \cdot \eta_{CP} \cdot PCCF \cdot 1{,}015$ (20)

It is observed, through the condition column of the Tab.3, that the equation for calculating power generation depends on the amount $QRrA1_n$ be bigger or not that MEC_{CP}. As a consequence, the electric power generation equations meet the following operating conditions: a) in atypical situation of the process, in that $QRrA1_n$ may be greater than the capacity that the power cycle is able to consume; b) the value of MEC_{CP} is determined for reasons other than to consume as much as possible $QRrA1_n$; c) the value of MEC_{CP} is determined to consume as much $QRrA1_n$ and; d) in the cogeneration project there is the generation of thermal energy in the form of cold by the absorption/adsorption chiller and part of *QRrA1* will be directed to *QRrA3*.

2.5 Applied model

In a process where you have a power generation downstream of useful heat, the steel process of pig iron manufacturing from high charcoal oven was chosen for the application of, for example, the proposed methodology. The production data was made available by a company in the state of Minas Gerais (Brazil), its high oven considered small. This process was chosen due to the state of Minas Gerais be the largest producer of pig iron in the country. According to (Sindicato da Indústria do Ferro no Estado de Minas Gerais 2019), in 2019 the state had 42 mills that produced 3 520 142 tons of pig iron, Representing 76% of national production. In the process of pig iron manufacturing, according to (Rizzo 2009), The power inputs can be coke, charcoal, coke oven and/or high-oven gas, steam, sintered material and electricity platoons. Depending on the high oven used, the inlets will be restricted to charcoal, high-oven gas and electricity. It is seen, through the Tab.4, data parameterized and defined for the application of the model.

Table 4. Case study industry data

Variable	Description	Value	Reference
Times and levels			
TT	Total annual time analyzed	8 322 h	
n	Number of levels	2	
t_1	Fractional times	2 774 h (33 % de *TT*)	
t_2		5 548 h (66 % de *TT*)	

Demands			
$WCombD_1 = WCombD_2$	Combustible demand	69 163 kW	
$QRrA1_1 = QRrA1_2$	High-oven gas (HOG) harnessed by cogeneration in bottoming cycle	7 608 kW	
$WEleD_1$	Demand for electrical power by the industrial process (without cold)	908 kW	
$WEleD_2$		823 kW	
Environmental conditions			
h	Local altitude	725 m	(Meteorologia) n.d.)
T_{db}	Average dry bulb temperature	21.83 °C	(Meteorologia) n.d.)
T_{wb}	Average temperature of wet bulb	19.69 °C	(Meteorologia) n.d.)
ϕ	Average relative humidity	0.747 (-)	(Meteorologia) n.d.)
Power cycle			
	Type of power cycle	Rankine	
Pi	Gas current pressure drop	1.3 (in H_2O)	(Brown, Katipamula, and Konynenbelt 1996)
Pe	Exhaust flow pressure drop	0 (in H_2O)	(Brown, Katipamula, and Konynenbelt 1996)
η_{CP}	Power cycle efficiency	0.20	(DFIC - Dr. Fromme International Consulting 2016)
$WEleG$	Rated maximum output power	2 000 kW	(TGM 2021)
MEC_{CP}	Maximum power consumption of the power cycle	10 000 kW	

3. RESULTS AND DISCUSSIONS

In the case specifically of the HOG, which is one of the energy wastes generated in the steel process, has taken advantage of itself in the process itself when burned in the chambers of glendons. After the burning of the HOG in the chambers of the glendons, another energy residue is generated in the form of hot gas. Part of this hot gas is used in ore drying and the rest is discarded in the environment. The discarded part in the environment is study able in order to implement an organic Kalina or Rankine cycle for electrical power generation, thus increasing the efficiency of cogeneration in bottoming cycle.

Considering the data of the Tab.4, increased data on energy waste that can be reused, but that is discarded in the environment, it is possible to increase 83 kW electric power in cogeneration in bottoming cycle. The properties of the discarded gas are at a temperature of 300 °C, atmospheric pressure, enthalpy of 631.9 kJ/kg and density of 0.544 kg/m^3. With these properties it is possible to achieve an average conversion efficiency of 10 % with organic cycles (DFIC - Dr. Fromme International Consulting 2016).

Another way to take advantage of the HOG, specifically in large steel mills, is to install a top recovery turbine system (Kawasaki Heavy 2017). This technology uses the thermodynamic properties of the gas, although the gas washing system coming out of the high oven should be changed. According to the manufacturer (Mitsubishi Hitachi Power Systems n.d.) considering only the power generated in the turbine the efficiency can reach 37 % and if applied to a combined cycle, 57 %. This technology does not yet apply to the steel maker under analysis because the size of the tall oven is small.

In the case of the HOG part, that is not taken advantage of by the process, but that can be reused in cogeneration with bottoming cycle, *QRrA1*, the best power conversion technology as a function of HOG quality is the Rankine power cycle. The HOT has a lower heating value (LHV) according to the type of pig iron produced, whose value informed by the company under analysis of 750 kcal/Nm³ refers to the pig tying steel. This value, according to Ferreira (Ferreira 2015), can come to 835 kcal/Nm³, which could increase the efficiency of the system. *QRrA1* is a gaseous energy residue, rich in CO, that needs to be burned to convert into thermal energy. It is also an impure gas depending on the particulate matter that carries, making it impossible to use the conventional gas turbine, whose efficiency is greater than the steam turbine. According to DFIC (DFIC - Dr. Fromme International Consulting 2016), an average efficiency for cycles with steam turbines is 20 %.

On the market there are several suppliers and models of steam turbines, as if it has, according to TGM (TGM 2021), the series of turbines "Ação TG", which are turbines specially developed to meet drives of small electric power generators, case of the condition of the steel mill. This series operates with a maximum of up to 22 bar pressure, 320 °C temperature and 2 MW maximum power. The turbine needs to be powered by steam generated by a boiler, then, in turn, will be fed with the part of the HOG reused by the cogeneration with bottoming cycle and also needs to be connected with an electric power generator. For the production of electricity using the boiler set, turbine and generator, environmental conditions affect this production, and a correction factor is required for the calculations, according to the equation Eq. (5).

Assessing the environmental conditions of which the steel maker is located in the case study, can be observed through the equations of the Tab.2, that dry bulb temperature (T_{db}), the altitude (h) and air humidity (ϕ) directly interfere with the generation of electricity.

The value of the *h* is used in the calculation of the adjustment factor for the altitude, *F1*, as expressed in the Eq. (8), *F1* in turn influences the adjusted power of the power cycle, $P_{Adjusted}$, through the Eq. (7), (6) and (5). The T_{db} is used in the dry bulb adjustment factor, *F2*, as expressed in the Eq. (9), which also equals *F1*, will interfere with the calculation of $P_{Adjusted}$ through the Eq. (7), (6) and (5). On the other than ϕ, is one of the variables used to obtain the temperature of wet bulb, T_{wb}, which in turn is used in the calculation of the condenser temperature adjustment factor, *CTF*. These variables are expressed by the Eq. (16) or (17), that will also interfere with the calculation of $P_{Adjusted}$ through the Eq. (6) and (5). Thus, it is shown that environmental conditions, $T_{db,}$ *h* and ϕ interfere with the *WEleG*, Eq. (19) and (20), through *PCCF*. From the definition of the geographical location of the installation of the cogeneration system in bottoming cycle, *h* may no longer vary, getting a fixed value that, in the case study, as already mentioned, is 725 m. In this condition where only environmental conditions T_{db} and ϕ interfere with *WEleG* one can observe, through the Fig. 2, the hourly variation of these environmental conditions *WEleG*, during the period of one year. The year evaluated was 2020 and the graphics of the Fig. 2 are divided by the seasons to better observe the interferences of environmental conditions in *WEleG*. The seasons were based in the south hemisphere.

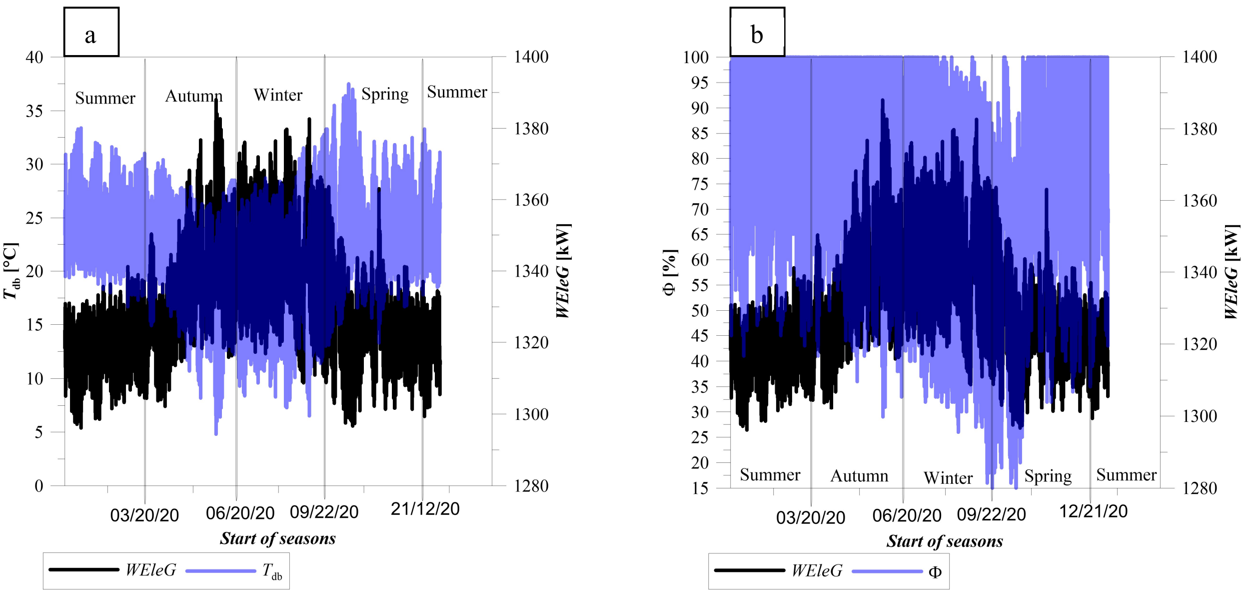

Figure 2. Annual hourly variation of T_{db} and ϕ versus *WEleG*

On the chart "a" of Fig. 2, there is a variation of T_{db} with *WEleG* and on the chart "b" the variation of ϕ with *WEleG*. It is perceived, through the chart "a", that in the seasons whose T_{db} are lower, autumn and winter, you have the greatest *WEleG*. In the spring when T_{db} increases compared to winter, decreases *WEleG* and in the summer you have the smallest *WEleG* and larger T_{db}. At all hours of the year *WEleG* is higher than *WEleD*, indicating a surplus of electricity in the whole year evaluated. On the chart "b" of Fig. 2, it is perceived that in the summer, whose ϕ is higher, have one smaller *WEleG* and at the end of winter with early spring when the ϕ is smaller, one also has a smaller *WEleG*. These extremes of ϕ indicates that in a value of ϕ next to 40 % there is a greater *WEleG*. In order to assess in more detail, the relation between environmental and environmental conditions*, WEleG*, one typical day of each season was chosen to evaluate *WEleG* in a 24 hour period. This relation of environmental conditions versus *WEleG* can be seen through the Fig. 3.

Just as in the Fig. 2, on the chart "a" of Fig. 3, there is a variation of T_{db} with *WEleG* and on the chart "b" the variation ϕ with *WEleG*. It is perceived, through the chart "a", every day evaluated and sharper, then *WEleG* is bigger when T_{db} is smaller. It should be noted that *WEleG* increases in the period of 22 h from one day to 10 h the other day and decreases from the 10 h up to the 22 h. Evaluating the ϕ on the chart "b" of Fig. 3 there is generally an increase in the number of ϕ in the period of 22 h from one day to 10 h the other day and a decrease between 10 h and 22 h every day, accompanying *WEleG*. Analyzing the charts "a" and "b" of Fig. 3 simultaneously, to 6 h and the 18 h, in the days when *WEleG* obtained the maximum and minimum values, the minimum *WEleG* for the two hours evaluated were in the summer, getting into 1 323 kW for the 6 h and 1 303 kW for the 18 h. At these times, in the summer, environmental conditions have been: a) for the 6 h, T_{db} = 21,6 °C and ϕ = 96 % and; b) for the 18 h T_{db} = 30,5 °C and ϕ = 53 %. Analyzing the maximum values of *WEleG*, for the two hours evaluated, it is noted that they occurred in the winter, getting *WEleG* in 1 364 kW for the 6 h and 1,334 kW para as 18 h. At these times, in winter, environmental conditions have been: a) for the 6 h T_{db} = 12,46 °C and ϕ = 87 % and; for the 18 h T_{db} = 23,8 °C and ϕ = 37 %. Correlated these extremes of *WEleG* with environmental conditions, T_{db} and ϕ, *it* can be perceived that the variation in the condition *T*db has a greater impact on *WEleG* than the variation of ϕ.

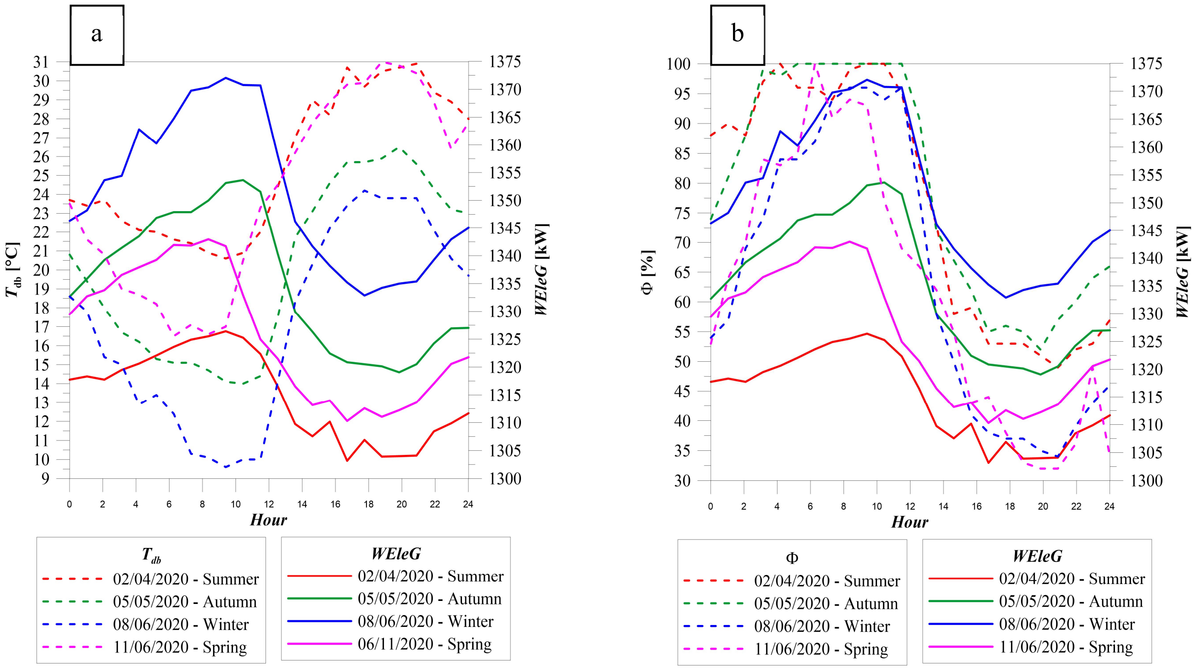

Figure 3. Daily hourly variation of T_{db} and ϕ versus *WEleG*

4. CONCLUSIONS

By analyzing the results obtained, using cogeneration methodology in bottoming cycle applied in a small steel mill with a production capacity of 5,500 tons of pig iron per month, it was possible to verify that:

- The variables of environmental conditions, ambient temperature and altitude, are the ones that most impact on the generation of electricity;
- The smaller T_{db} and *h,* the largest is the generation of electricity;
- Considering *h* as constant, 725 m, and analyzing the generation of electricity for a typical summer and winter day, to 6 h and 18 h, in the summer there was a generation of electricity from 1,323 kW, with T_{db} = 21.6 °C and ϕ = 96 %, for the 6 h and of 1,303 kW for the 18 h, with T_{db} = 30.5 °C and ϕ = 53 %; already in winter for the 6 h, with T_{db} = 12.46 °C and ϕ = 87 %, electricity generation has reached 1,364 kW and for the 18 h, 1,334 kW, with T_{db} = 23.8 °C and ϕ = 37 %.

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