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PROPOSAL OF AN EXERGOECONOMIC PERFORMANCE INDICATOR FOR EXISTING COGENERATION SYSTEMS

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Abstract. *Brazil is facing an important energy transition, not only in matters of clean technologies but also concerning regulatory modernisation, bringing new policies and methodologies to the sector. For instance, the electricity spot prices will be hourly based from January 2021, which will provide empowerment for consumers and generators in periods of excess supply or scarcity throughout the day. This work focuses on developing an advanced exergoeconomic methodology for existing cogeneration power plants using the Specific Exergy Costing (SPECO) method, by quantifying their generation cost performance in comparison to the electricity price on the grid. The exergoeconomic analysis was constructed and exemplified to the CGAM cogeneration cycle as two new concepts are proposed: the unavoidable part of exergy destruction, which is the exergy destruction calculated under design conditions, and the Exergoeconomic Performance Indicator (EPI) for existing cogeneration power plants. The investment costs were considered as sunk costs and the operation and maintenance costs were neglected for simplicity. Therefore, only fuel cost was taken into account to the analytical development of the EPI. Finally, the proposed EPI can be used to measure the inefficiencies of existing plants and their impacts on generated power costs in comparison to external electricity spot prices.*

Keywords: *advanced exergoeconomic analysis, Exergoeconomic Performance Indicator, energy transition, energy market, cogeneration power plants.*

1. INTRODUCTION

Energy is the driving force of human development. The studies of its transformations to heat and useful work, along with the development of decent policies and new technologies, hold a peculiar relevance for economic growth. The term "energy transition" is widely used to describe the transformation of the world's energy mix by substituting traditional polluting sources, such as coal and oil, for renewable and clean energy. However, Bridge et. al (2013) bring the discussion about energy futures and their relation to different concepts for energy transition according to national policies. Brazil, for instance, is facing an energy transition, in not only matters of clean energy but also a regulatory and organisational transformation.

The National Power System Operator (ONS) used to run only two computational programs to plan and operate the National Interconnected System (SIN): NEWAVE and DECOMP. The last one is performed once a week, to provide information about how the national grid and its power plants will be conducted. One of these parameters is the Imbalance Settlement Price, in other words, the marginal cost of the electricity for that specific week. However, with the relevant embeddedness of intermittent energy sources in the country's power mix, mainly wind, and the actual behaviour of the demand, a new third program for day-ahead planning was developed by the Electricity Research Centre (Cepel) and started running on January 2020 for scheduling. The daily planning along the hourly prices, which will be implemented by January 2021, will provide empowerment for consumers, power self-producers and independent producers that are not dispatched by the ONS since they will be able to optimise consumption and generation in times of excess supply or scarcity throughout the day. Furthermore, it will also expand investments in distributed generation, storage technologies, as well as enable new power plants and compact systems driven by renewables.

Therefore, there is need for change likewise the way existing power plants from self-producers and independent producers are managed in terms of efficiency and dispatch. A technique called Exergoeconomics was established in the 1960s to measure the quality of energy conversion systems by transforming primary energy in electricity for example, and the economic value associated with these processes (Sciubba, 2004). Wolfgang Fratzscher (Germany), Jan Szargut (Poland) and Valeriy Brodyanskii (USSR), as pioneer authors, contributed to the launch of research and development in the field of thermal systems optimisation with mathematical costing procedures associated with the second law of thermodynamics. Consequently, the embeddedness of this method, also improved by other notable authors over the years, benefited the establishment of new technical-economic solutions for energy transition technologies.

This research develops and proposes an Exergoeconomic Performance Indicator (ζ) for existing thermal power plants considering the spot prices of electricity, and lying on the Specific Exergy Costing (SPECO) method and current policy changes in the Brazilian electricity sector.

2. LITERATURE REVIEW

2.1 Brazilian Power Market

In 1999, the National Interconnected System (SIN) was created by the connection between transmission lines that linked the South, Southeast and Midwest grid to the North and Northeast grid (Silva, 2012). Figure 1 shows the SIN in 2017.

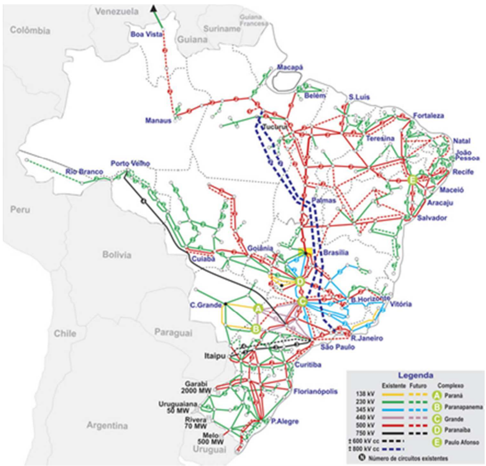

Figure 1. National Interconnected System (SIN). Adapted from ONS (2019).

After the Brazilian energy crisis in 2001, the government set up a team, led by Mauricio Tolmasquim, to propose a new model for the electricity sector. This regulatory framework represented the improvement of several aspects of the sector, as the creation of the Free Contracting Environment (ACL) and the Regulated Contracting Environment (ACR), and the establishment of other organizational agents such as the ONS, the Chamber of Electric Energy Commercialization (CCEE) and the Energy Research Company (EPE). These new adjustments were necessary to generate regulatory stability, bringing investments, reducing risks and expanding the market (Tolmasquim, 2015).

One of the main responsibilities of the CCEE is to calculate the spot market price, which is based on the Marginal Cost of Operation (CMO) simulated by the ONS. This spot price is called Imbalance Settlement Price (PLD). The PLD today is weekly calculated for each of the system load levels (off peak, peak and super peak) and four submarkets (South, Southeast/Midwest, Northeast and North) shown in Fig. 2.

Figure 2. Brazilian electricity submarkets. Adapted from CCEE (2019).

The financial accounting of the electricity generation and consumption, that were not contracted, is performed monthly. For example, a power producer that has generated more than its contracts receives this amount of MWh in the PLD price [BRL/MWh] from the CCEE. On the other hand, a consumer that has consumed more than it has contracted must pay this amount of MWh in the spot price to the CCEE.

A chain of optimization models calculates the PLD (power spot price): NEWAVE, DECOMP and DESSEM (mid-term, short-term and day-ahead planning, respectively). The DESSEM model is being developed by the Electricity Research Centre (Cepel). It is in operation since January 2020 and, as aforementioned, it will calculate the PLD in an hourly basis from January 2021. Since April 2018, the ONS and the CCEE are performing this model alongside the DECOMP model to verify the modelling inconsistencies, behaviour and its impacts on daily prices (CCEE, 2019). This so-called “Shadow Operation” is also testing the DESSEM accuracy on reducing the thermal generation, consequently the system operational costs. Various interests led to the development of this model, such as a need of greater detailing of the system, a better market price that reflects the generation and consumption fundamentals over the day, as well as the significant immersion of intermittent energies on the grid (wind and solar energy).

2.2 Exergoeconomics

Exergy defines the maximum available work that can be developed between one system and the environment at different states until they come into equilibrium. Although exergy is generally not conserved, it can be compared to mass, energy and entropy in a matter of transfer between systems (Bejan et al., 1996).

Bejan et al. (1996) define that the exergy can be divided into four components: physical exergy, kinetic exergy, potential exergy and chemical exergy. The physical exergy can be split into thermal and mechanical exergy, associated with the system temperature and pressure, respectively. The chemical exergy can be split into reactive and nonreactive exergy, associated with chemical reactions and nonreactive processes, respectively. Moreover, the sum of physical, kinetic and potential exergy is referred to thermomechanical exergy (Moran and Shapiro, 2004).

The nomenclature used in exergy studies must be carefully specified since there are numerous publications from different authors that cover different variable names for the same concept. Tsatsaronis (2007) summarises the main Latin and Greek letters used to describe exergy and emphasises that a simple approach is crucial for journals and conference proceedings. This present work uses the terminology proposed by Tsatsaronis (2007).

Thermoeconomics is the concept that combines economic evaluation to exergy analysis. This engineering tool is widely used for improving the cost-effectiveness of systems, by associating costs to thermodynamic inefficiencies, i.e. exergy destructions and exergy losses (Bejan et al., 1996).

In 1990, a group of four specialists in the field of exergoeconomics created a problem of a simple cogeneration cycle to compare their methodologies. This problem was called CGAM, which corresponds to the first initial of each author’s name. Its results were presented at the “Efficiency, Costs, Optimization, and Simulation of Energy Systems (ECOS 92)” Conference (Valero et al., 1994) to show different approaches to improve partition criteria. Figure 3 illustrates the CGAM system.

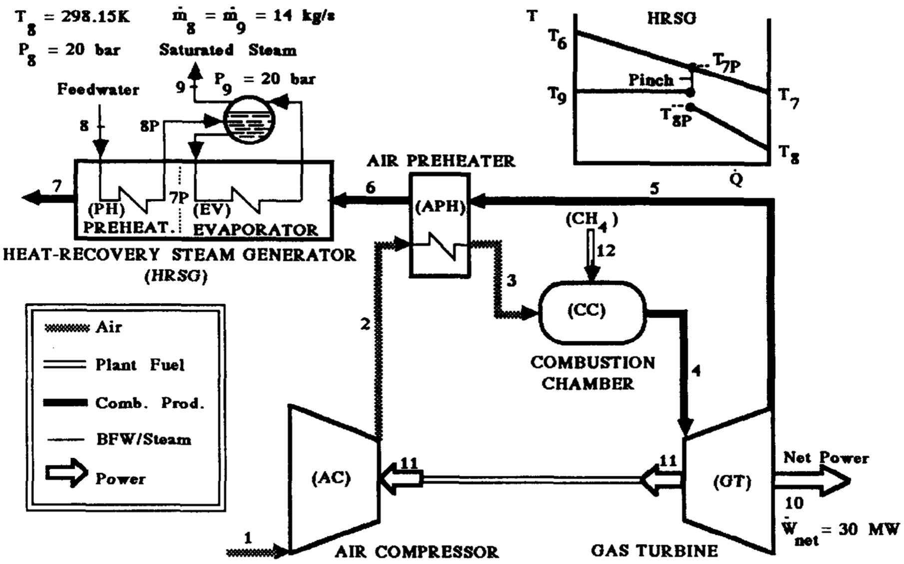

Figure 3. CGAM cogeneration cycle (Valero et al., 1994).

Although the main contributions of the CGAM problem lie on optimisation results, Tsatsaronis’ solution brings a very concise and detailed analysis of the exergoeconomic evaluation before the exergoeconomic optimisation methodology (Tsatsaronis and Pisa, 1994). Furthermore, the exergoeconomic evaluation presented by Tsatsaronis (1993) is based on the concept of fuel and product of each component of the energy system. This approach is suitable for the performance evaluation of associated cost flow rates, which is the focus of this present study.

In addition, the evolution of exergy studies over the years instigated researchers to develop advanced exergy-based analyses, due to the fact that conventional exergy-based analyses demonstrate some important limitations applied to complex systems (Petrakopoulou et al., 2012). A substantial contribution was to split the exergy into four new concepts: avoidable, unavoidable, endogenous and exogenous parts.

3. METHODOLOGY

In this study, a methodology for the exergoeconomic performance is proposed for the evaluation of existing plants immersed in electricity markets with hourly-based prices. The method is applied for the CGAM cogeneration problem. Therefore, some assumptions are considered as follows.

Only fuel costs are considered in the method, as the capital of investment represents sunk costs for existing systems. In economics, sunk costs are costs that have already been spent and cannot be recovered. This concept is linked to the framing effect in economic psychology, where sunk costs should not influence on future decision-making (Tversky and Kahneman, 1986). For instance, the power plant to be analysed is already in operation. Therefore, the capital of investment should be neglected whereas the electricity sale profit should be optimised.

The CGAM cogeneration cycle is fired with natural gas (taken as methane) with a supposed lower heating value *LHV* of 50000 kJ/kg (Valero et al., 1994). This plant generates 30 MW of electricity and 14 kg/s of saturated steam at 20 bar. The environmental conditions are defined at a temperature T_o = 298.15 K and pressure p_o = 1.013 bar. The air relative humidity is considered 60%, and mole fractions as $x^o_{O_2}$ = 0.2059, $x^o_{N_2}$ = 0.7748, $x^o_{CO_2}$ = 0.0003 and $x^o_{H_2O}$ = 0.0190. The cycle decision variables for the optimization problem (pressure ratio, isentropic efficiencies of the air compressor and the gas turbine, temperatures of the air-preheater T_3 and the combustion gas at the turbine inlet T_4) are considered as in the initial case presented by Valero et al. (1994).

3.1 Advanced exergy analysis

The specific physical exergy e^{PH} associated with a stream of matter is defined in Eq. (1) and Eq. (2), for water/steam and gas streams, respectively.

$$e^{PH} = (h - h_0) - T_0 (s - s_0) \tag{1}$$

$$e^{PH} = c_p T_0 \left\{ \left[\frac{T}{T_0} - 1 - \ln\left(\frac{T}{T_0}\right) \right] + \ln\left(\frac{p}{p_0}\right)^{\frac{\gamma_{gas}-1}{\gamma_{gas}}} \right\} \tag{2}$$

where γ is the specific heat ratio between the specific heat at constant pressure c_p and the specific heat at constant volume c_v. The variables h and s denote enthalpy and entropy, respectively. The subscript o corresponds to the environmental conditions.

The specific chemical exergy e^{CH} for gaseous species considered as ideal gases can be expressed as in Eq. (3) and the specific chemical exergy for the fuel (methane) is modelled as in Eq, (4) and Eq.(5).

$$e^{CH} = RT_0 \sum_i y_i \ln \frac{y_i}{y_{0i}} \tag{3}$$

$$e^{CH} = \beta\, LHV \tag{4}$$

$$\beta = 1.0334 + 0.0183 \frac{H}{C} - 0.0694 \frac{1}{N_C} \tag{5}$$

where y_i is the mole fraction of each component in the working fluid. N_C is the mean number of carbon atoms in the molecule (Szargut et al., 1988).

For the exergy balance and exergetic efficiencies of the overall system and its components, the fuel-product approach are considered. The fuel should not be restricted to actual fuels (i.e. natural gas), in other words, it is the exergy needed to generate the required product. The product, in turn, expresses the desired result produced by the fuel. For the *k*-th component:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} + \dot{E}_{L,k} \tag{6}$$

$$\varepsilon_k = \frac{desired\ result\ (product)_k}{resources\ spent\ to\ generate\ this\ result\ (fuel)_k} = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{7}$$

where ε is the exergetic efficiency and $\dot{E}_F$, $\dot{E}_P$, $\dot{E}_D$ and $\dot{E}_L$ denote the rates of fuel, product, exergy destruction and exergy loss, respectively.

The exergy destruction in the analysis was split into endogenous and exogenous parts, avoidable and unavoidable parts (superscripts EN, EX, AV, UN, respectively), and a combination of two concepts was applied (e.g. unavoidable endogenous). This advanced analysis enables a better comprehension of the different sources of the exergy destruction, as well as it gives a more accurate idea of how and how much one can improve the thermal system.

Endogenous is the part of the exergy destruction that is inherent to the *k*-th component of the system, i.e. the amount of exergy destruction due to irreversibilities in its control volume when all other components operate ideally. Therefore, exogenous is the difference between the total exergy destruction and the endogenous part, i.e. the exergy destruction within the *k*-th component caused by inefficiencies of the remaining system. Table 1 shows the parameter for each component of the CGAM that must be idealised for the calculation of the endogenous exergy destructions.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \tag{8}$$

Table 1. Theoretical values assumed for ideal operation of components.

Component	Parameter [Unit]	Theoretical Processes
AC:	η_C [-]	1
CC:	η_{CC} [-]	1
	Δp_{CC} [K]	0
APH:	ΔT_{5-3} [K]	0
	$\Delta P_{air,APH}$ [K]	0
	$\Delta P_{gas,APH}$ [K]	0
GT:	η_T [-]	1
HRSG:	ΔT_{Pinch} [K]	0
	$\Delta P_{gas,APH}$ [K]	0

The traditional concept of unavoidable exergy destruction states that this part of exergy destruction cannot be further reduced due to technological limitations, such as availability, cost of materials and manufacturing methods (Gaspar and Silva, 2015). Therefore, the avoidable exergy destruction is the difference between the total exergy destruction and the unavoidable part, being the most relevant term for the system improvement procedure. Figure 4 shows the specific unavoidable exergy destruction as a function of the exergetic efficiency and the investment cost per unit of product exergy (Tsatsaronis and Park, 2002).

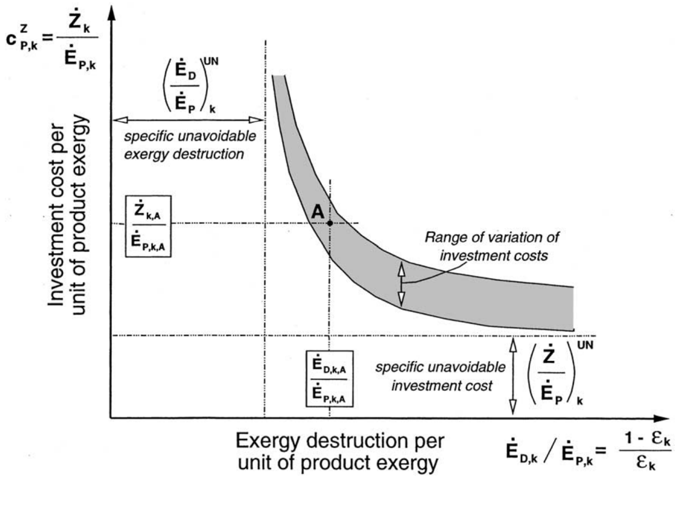

Figure 4. Relationship between investment cost and exergy destruction for a component *k* (Tsatsaronis and Park, 2002).

As mentioned above, only fuel costs are considered in the method and the capital of investment represent sunk costs for existing systems. Since this work evaluates the performance of existing plants and, Tsatsaronis and Park (2002) propose that the unavoidable part is a function of the capital of investment, the traditional concept of unavoidable exergy destruction has no longer applicability. Therefore, a new concept for the unavoidable part is proposed by being the exergy destruction of the design point before operation.

Suppose the design point A on Fig. 4 was calculated as the optimal condition for the power plant and all equipment was selected. As real components, they already present their inefficiencies and, consequently, a fixed exergy destruction for fixed parameters at design conditions. However, these inefficiencies can increase over time due to physical and chemical processes such as corrosion or incrustation. The rise in exergy destruction could be avoidable and further reduced when, for instance, maintenance is performed. In this case, the exergetic performance is to be determined over time and the highest possible exergetic efficiency is achieved when the components operate in design conditions. The further decrease of the exergy destruction could be otherwise enabled only by substituting the desired component, turning the system into a new design B and requiring the traditional approach due to new investment costs.

In conclusion, the unavoidable exergy destruction for the temporal performance analysis is exactly the original exergy destruction of the design point, shown in Fig. 5.

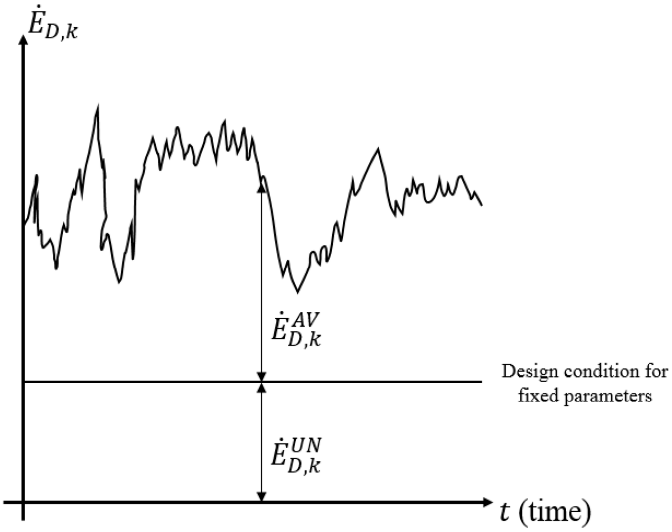

Figure 5. Proposed concept for unavoidable exergy destruction in existing plants.

Considering that the unavoidable exergy destruction cannot be reduced, it is left as a single term, whereas the avoidable exergy destruction is split into two terms: avoidable endogenous and avoidable exogenous. Therefore:

$$\dot{E}_D = \sum_{k=1} \left(\dot{E}_{D,k}^{AV,EN} + \dot{E}_{D,k}^{AV,EX} + \dot{E}_{D,k}^{UN} \right) \tag{9}$$

The main target is to reduce the avoidable endogenous exergy destruction because it will consequently decrease the avoidable exogenous exergy destruction when applied to all components.

3.2 Exergoeconomic Performance Indicator formulation

An analogy to the exergy concept can be made to an economic parameter. In other words, if exergy is the potential of work generation due to the difference between its physicochemical state and the external environment, the exergoeconomic cost flow to generate electric power has also a difference compared to the external system, i.e. the electricity prices in the grid. Therefore, to evaluate the economic efficiency of the existing plant, i.e. the economic potential to generate profit, the Exergoeconomic Performance Indicator (EPI) ζ is proposed:

$$\zeta_t = \Omega_t - \Gamma c_{W_{el},t} \tag{10}$$

where Ω_t is the electricity price on the grid and $c_{W_{el,t}}$ is the specific cost of electric power, at a time t. Γ is a unit conversion constant, since $c_{W_{el,t}}$ is usually expressed in currency (dollar, euro, real…) per GJ and the electricity prices expressed in currency per MWh or kWh. Furthermore, the EPI must be expressed with the same unit as the electricity prices for a better understanding of economic profit potential. In this present study, the Brazilian currency is used, where electricity prices are measured in BRL/MWh.

Considering the general exergoeconomic balance in Eq. (11) based on the Specific Exergy Costing method (SPECO) (Lazzaretto and Tsatsaronis, 2006), the balance for a cogeneration cycle in Eq. (12), Eq. (13) could be reached.

$$c_{P,sys}\dot{E}_{P,sys} = c_{F,sys}\dot{E}_{F,sys} + \dot{Z}_{sys}^{OM} \tag{11}$$

$$c_{P,sys}\dot{E}_{P,sys} = c_{W_{el}}\dot{W}_{el} + c_{W_{th}}\dot{W}_{th} \tag{12}$$

$$c_{W_{el}} = \frac{c_{F,sys}}{\varepsilon_{sys}}\frac{\left(\dot{W}_{el}+\dot{W}_{th}\right)}{\dot{W}_{el}} - c_{W_{th}}\frac{\dot{W}_{th}}{\dot{W}_{el}} + \frac{\dot{Z}_{sys}^{OM}}{\dot{W}_{el}} \tag{13}$$

where $c_{P,sys}$, $c_{F,sys}$ and $c_{W_{th}}$ represent the specific average cost per unit of exergy of the product, fuel and thermal power of the system, respectively. The variable $\dot{Z}_{sys}^{OM}$ is the cost rate associated to the operation and maintenance of the system, $\dot{W}_{el}$ is the electric power and $\dot{W}_{th}$ is the thermal power.

Substituting and applying the concepts of Eq. (6) and Eq. (7) in Eq.(13):

$$c_{W_{el}} = \frac{c_{F,sys}}{\left(\dot{W}_{el}+\dot{W}_{th}\right)}\left(\dot{W}_{el}+\dot{W}_{th}+\dot{E}_{D,sys}+\dot{E}_{L,sys}\right)\frac{\left(\dot{W}_{el}+\dot{W}_{th}\right)}{\dot{W}_{el}} - c_{W_{th}}\frac{\dot{W}_{th}}{\dot{W}_{el}} + \frac{\dot{Z}_{sys}^{OM}}{\dot{W}_{el}} \tag{14}$$

Therefore,

$$c_{W_{el}} = \frac{1}{\dot{W}_{el}}\left\{c_{F,sys}\left[\left(\dot{W}_{el}+\dot{W}_{th}\right) - \frac{c_{W_{th}}}{c_{F,sys}}\dot{W}_{th} + \sum_{k=1}\left(\dot{E}_D^{AV,EN}+\dot{E}_D^{AV,EX}+\dot{E}_D^{UN}\right)_k + \dot{E}_{L,sys}\right] + \dot{Z}_{sys}^{OM}\right\} \tag{15}$$

Substituting Eq.(15) in Eq.(10), the Exergoeconomic Performance Indicator as a function of exergoeconomic parameters of a cogeneration power plant can be expressed as

$$\zeta_t = \Omega_t - \frac{\Gamma}{\dot{W}_{el}}\left\{c_{F,sys}\left[\left(\dot{W}_{el}+\dot{W}_{th}\right) - \frac{c_{W_{th}}}{c_{F,sys}}\dot{W}_{th} + \sum_{k=1}\left(\dot{E}_D^{AV,EN}+\dot{E}_D^{AV,EX}+\dot{E}_D^{UN}\right)_k + \dot{E}_{L,sys}\right] + \dot{Z}_{sys}^{OM}\right\}_t \tag{16}$$

To exemplify this proposed parameter according to the Brazilian energy prices, the methodology was applied to the CGAM cycle. A sensitivity analysis was performed based on ten different natural gas tariffs (SCGÁS, 2019) and ten different Brazilian power market spot prices ranging between the lower (42.35 BRL/MWh) and upper (513.89 BRL/MWh) legal limits for 2019 (CCEE, 2019). For simplicity, the operation and maintenance costs were neglected.

4. RESULTS

For the algebraic exemplification of the proposed concept for unavoidable exergy, it is considered that the hypothetical CGAM system is already in operation and, at a time *t*, all components have deteriorated 5 % decrease of their exergetic efficiencies. Therefore, supposing the original design is 5 % more efficient than the CGAM parameters, the calculated exergy destruction for the CGAM is the unavoidable destruction for the operation in *t*.

According to results shown in Tab. 2 and Fig. 6, it can be observed that the greatest part of the exergy destruction lies in the unavoidable part of the proposed methodology, apart from the HRSG. The target for this cycle would be the decrease of the endogenous avoidable exergy destruction, which presents higher values for the turbine and the steam generator, 39.82 % and 31.08 %, respectively, since the reduction of the exogenous part will be a consequence and the unavoidable part cannot be reduced due to design conditions. Consequently, the endogenous avoidable exergy destruction is the parameter that will indicate the components that deserve the main attention for the exegetic improvement of the entire plant.

Table 2. Splitting the exergy destruction for the *k*-th component of the simulated CGAM cycle.

[MW]	$\dot{E}_D^{UN}$	%	$\dot{E}_D^{AV,EN}$	%	$\dot{E}_D^{AV,EX}$	%
AC	1.86	63.51	0.60	20.57	0.47	15.92
APH	1.70	74.81	0.04	1.60	0.54	23.59
CC	13.28	82.35	0.76	4.74	2.08	12.91
GT	1.16	53.96	0.86	39.82	0.13	6.21
HRSG	1.55	32.63	1.48	31.08	1.73	36.29

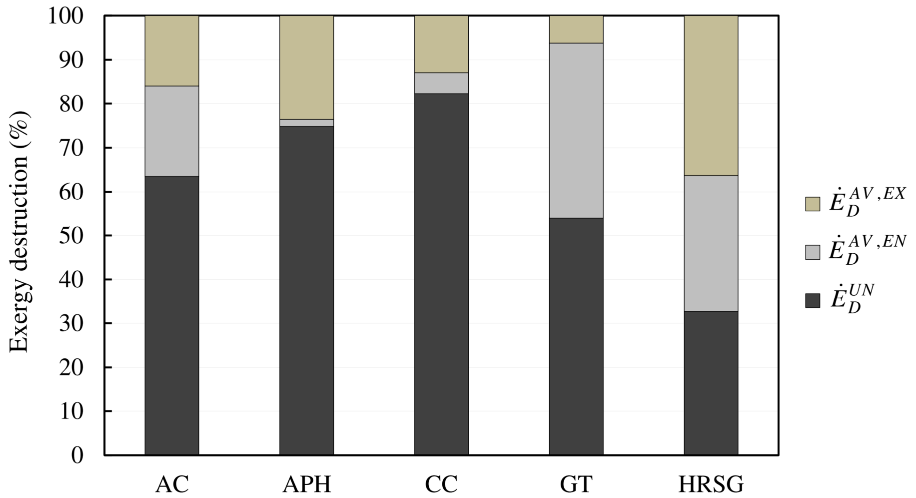

Figure 6. Porcentage distribution of the exergy destruction splitting for the *k*-th component of the simulated CGAM cycle.

The sensitivity simulation results of the Exergoeconomic Performance Indicator for the CGAM as a function of natural gas tariffs and electricity spot prices are presented in Tab. 3 and, graphically in Fig. 7.

Table 3. Exergoeconomic Performance Indicator in BRL/MWh sensitivity analysis**.**

PLD	**Natural gas tariff [BRL/m³]**									
[BRL/MWh]	**0.34**	**0.57**	**0.79**	**1.02**	**1.25**	**1.47**	**1.70**	**1.92**	**2.15**	**2.38**
42.35	-35	-87	-138	-190	-241	-293	-344	-396	-447	-499
100	23	-29	-80	-132	-184	-235	-287	-338	-390	-441
150	73	21	-30	-82	-134	-185	-237	-288	-340	-391
200	123	71	20	-32	-83	-135	-187	-238	-290	-341
250	173	121	70	18	-33	-85	-137	-188	-240	-291
300	223	171	120	68	17	-35	-86	-138	-190	-241
350	273	221	170	118	67	15	-36	-88	-140	-191
400	323	271	220	168	117	65	14	-38	-90	-141
450	373	321	270	218	167	115	64	12	-40	-91
513.89	437	385	334	282	230	179	127	76	24	-27

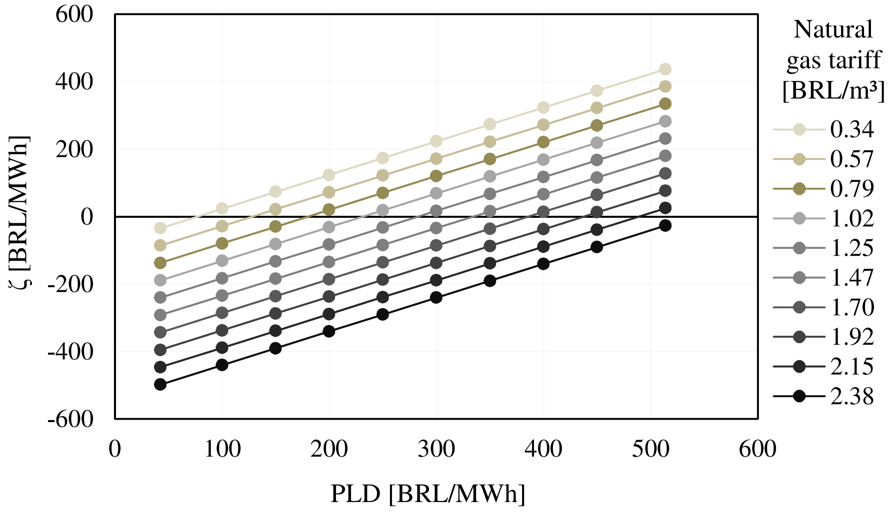

Figure 7. Exergoeconomic Performance Indicator as a function of natural gas tariffs and electricity spot prices.

It can be observed that, the higher the fuel price, the worse the system exergoeconomic performance. On the other hand, the higher the power price performed in the electricity power market, the more advantageous is the performance of power generation. In cogeneration cycles, however, it must be carefully observed that the power generation decision is also modulated by the heat demand.

For the CGAM case, partial loads cannot be simulated to verify the changes in the exergy destruction parts. This can be related to the fact that the pressure drop in each component was previously fixed and therefore cannot be easily calculated with partial loads.

5. CONCLUSIONS

An advanced exergoeconomic analysis allowed proposing the Exergoeconomic Performance Indicator and applying the concept of unavoidable exergy destruction. The proposed methodology and the Exergoeconomic Performance Indicator can be used as a parameter to measure inefficiencies of existing plants over time and their impacts on generated power costs in comparison to external electricity spot prices. Its equation is consistent and gives a signal to the plant if it makes economic sense to generate power according to this price on the grid. This will be particularly relevant with the embeddedness of the hourly-based prices at the Brazilian power market as of January 2021.

This work was further applied to a real case study with time series data of market assessment and in partnership with a cogeneration power plant from one of the largest generators in Brazil.

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