

POWER SURPLUS IN AN HYBRID DESALINATION PLANT

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***Abstract.** Desalination is a process to be considered in the water planning - its use is year by year worldwide and must be considered as an opportunity even for Brazil. Associated to the perspectives of implementing such technology, advances such as integrating energy generation systems to desalination processes in the so-called hybrid systems have been suggested to obtain a more efficient process. The power surplus generated by hybrid technologies is an interesting index to be considered in the context of produced fresh water. In this paper, several gas turbine systems were considered in a hybrid system; the power surplus of these configurations in a Brazilian case is presented and analyzed.*

***Keywords:** desalination, hybrid, power surplus, gas turbine, optimization.*

1. INTRODUCTION

Desalination processes aims at not only fresh water production, taking advantage of seawater as plenty raw material, but also a more useful and better energy and cost of the equipments that are part of the whole desalination unit structure to which its various components will be used.

As a result, current settings of the desalination processes deal with the dual purpose and hybrid systems. In the first case, there is a need to produce both electricity and fresh water. For the second, there will be a combination of two desalination processes, different in their techniques, as a hybrid system, including:

- a- a multi-stage flash distillation (MSF) and reverse osmosis (RO), as can be seen in study on the use of distillers MSF process coupled to RO (Cardona, Culotta and Piacentino, 2003), aimed at the water produced cost reducing by the distiller; this also can be showed in the study of Karagiannis and Soldatos (2008), that present more recent relative costs by cubic meter of produced water or
- b- a multiple effect distillation (MED) and reverse osmosis (RO), as presented in Andrianne and Alardin (2003) showing the relations relevant to the increased demand both water and energy, utilities existing, produced water and energy ratio, among other relations. Khawaji, Kutubkhanah and Wie (2008) show that the MED desalination is very efficient from the heat transfer and thermodynamic point of view and with lower power consumption when compared with the MSF desalination process, becoming a hybrid MED-RO desalination process a good and feasible alternative.

Despite the previous systems are the most common, other combinations can become feasible, such as those proposed by Hamed (2005), which, besides the settings MSF/RO, presents situations in which the nanofiltration (NF) can be adapted to the MSF system or a triple hybrid, leaving the configuration NF/MSF/RO. Pellegrino, Gorman and Richards (2007) analyze a speculation of a possible hybrid system comprising a reversal electro dialysis (EDR) with reverse osmosis.

The present paper aims to present the data acquired during the hybrid plant optimization analysis by Ferreira (2008), whose objective was to produce a certain flow of water, using one of two alternative options above referred, as well as the possibility of producing electric power surplus due to the use of turbines from the thermal plant.

An interesting approach was made in regard to the power surplus generated by the turbines, which can be used to sell the concessionaire, which is the focus of this work.

2. SUPERSTRUCTURE

The proposed unit, shown in Fig. 1, is planned like a superstructure containing a thermal plant associated with a desalination unit, in which components may or may not be present, depending on the optimization process and on the possibility of choosing a component instead of another.

In the superstructure there is a boiler (B) and one or more (depending on the number of gas turbines, n_{GT}) gas turbines (GT), associated to heat recovery steam generators, which provide the superheated steam; the superstructure also have steam turbines (ST) as alternatives to produce process steam and power, as well as desalination plants with

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thermal (MED and MSF) and membrane (RO) processes. At this point, there is a distinction on the reverse osmosis technology, that can be either thermally (ROS) or electrically (ROE) driven, as proposed by Altman (1997) and analysed by Ferreira, Balestieri and Zanardi (2010) in a superstructure that aimed to determine the best choice of coupling a desalination and cogeneration system to supply the power, thermal energy and fresh water requirements. The fuels proposed to be used in this work are gasified biomass (BIG), natural gas (NG), fuel oil (FO) and biomass *in natura* (BIO).

The choice of final configuration components is obtained by using Boolean variables in the mathematical model, since they allow or restrict the presence of equipments in the final configuration. Thus:

- a- to generate superheated steam, boiler or gas turbines will be chose. This choice is closely linked to the fuel type selected, and only one of the aforementioned should be defined as the thermal energy source, capable of supplying all the superstructure needs.
- b- In the process steam production sector, the model will choose between the backpressure steam turbine (BPST) and extraction and condensing turbine (ECST).
- c- In the desalination sector, one of the membrane processes will be chose (ROS or ROE), as well as just one of the thermal processes (MSF or MED). If the ROS unit is chosen, the condensing steam turbine (CST) will be part of it.

Lingo, software developed by Lindo System (2001), was used for the optimization process, a tool to solve optimization problems, whose techniques include linear, nonlinear, integer and mixed programming problems. In this study, it was used the mixed and integer non-linear programming (MINLP) approach.

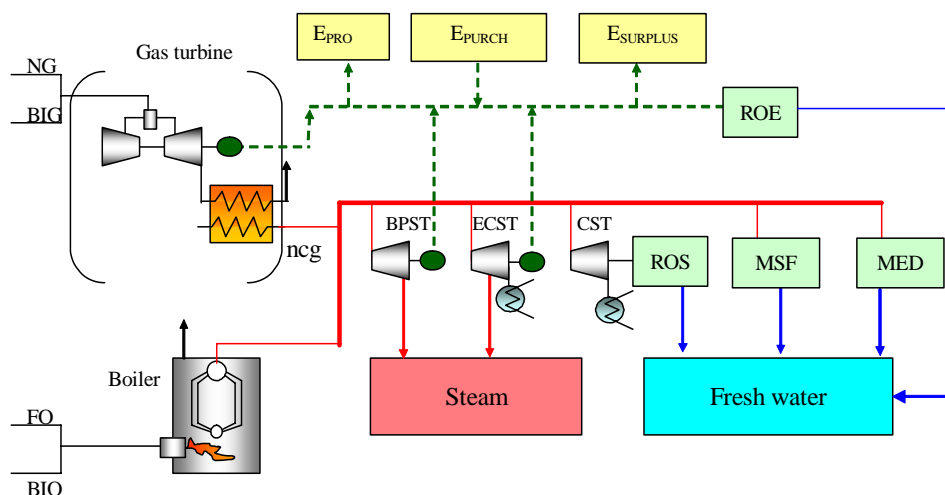


Figure 1 – Proposal superstructure.

Before optimization process starts, database optimization model was fed with information about the different gas turbines used, as the Heat Rate (HR), the power generated by the turbine (W_e), the exhaust gas mass flow (m_g) and temperature (T), parameters usually employed for this equipment selection. After an optimization running, the analysis results are obtained. For this paper it will be evaluated only the power surplus, which refers to the energy difference between turbines production, plus a possible power purchase, and withdrawing from that consumed by the process (considered as 5,000 kW).

An alternative analysis is also realized because of the chosen fuel. When natural gas is used, burning is easily obtained by direct injection in the gas turbine by a connection to the city gate. Unlike, when using gasified biomass, it must be taken into account the biomass gasifier cost, which can lead to infeasibility in choosing this fuel type, if its cost is too expensive. It must also take into account the prospective characteristic of this analysis, since this technology is under development.

Thus, two cases could occur, according to Ferreira (2008), depending on the investment cost of the biomass gasification:

- a- In the first case (Case 1), the investment cost is about 2,100 US\$/kW, as a future value perspective (Balestieri, 2001). Ordorica-Garcia et al. (2005) presents similar values of the gasification, but treating an integrated gasification combined cycle (IGCC) plant and considering the possibility to capture CO_2 , to reduce the greenhouse gas effects. Another study (Gimenes, 2007) shows the gasification cost of a gasifier coupled to a Diesel power generator, with lower costs than the others mentioned above, but in a small scale;
- b- And in the second case (Case 2), the investment is about 4,000 US\$/kW, an appropriated and currently accepted value, according to Lora, Andrade and Aradas (2004).

3. MODELLING

The full plant is divided in five sectors for a better understanding of the equations governing the superstructure to be optimized. The five sectors, as described in Ferreira, Balestieri and Zanardi (2010), are:

Sector 1 - steam generator equipment sector – this is the sector that will be responsible for generate superheated steam for entire plant. As described above, the Boolean variable (0 or 1) will be included in the model to restrict the fuel to be admitted in only one steam generator, the boiler or gas turbine.

Sector 2 - steam process production – is the sector that aims to produce steam, by passing the superheated steam from the sector 1, in just one steam turbine selected by the Boolean variables, a backpressure steam turbine or extraction and condensing steam turbine.

Sector 3 - drinking water production – is the sector that the desalination plant is analysed, to produce fresh water. In this point, the Boolean variable must be carefully applied. Two options to be considered are:

- a- the sum of Boolean variables of desalination must be equal to 1 – this characterize a dual purpose power plant, that aims to produce fresh water and power, but it isn't the focus on this paper.
- b- the sum of Boolean variables of desalination mustn't be equal to 1 – this condition will determine the hybrid plant and it's needed defining new equations to the desalination process chosen. It was adopted that just one membrane process will be chose together with one thermal process. So, the sum of ROS and ROE Boolean variables must be equal to 1, as well as MSF and MED Boolean variables too. The sum of thermal and membrane Boolean variables will be equal 2.

Sector 4 - electricity production – all the plant requirements can be satisfied for the electricity production generated by the steam and gas turbines. If the balance energy is insufficient, electricity can be purchased; if there is a surplus energy, it can be sold to the concessionaire.

Sector 5 - other balance and constraints equations – in this sector is treated all the constraints, costs and other balance that weren't still considered.

Put simply, a way to represent the different equations of the above sectors that are coupled with the Boolean variables, depending on their availability or not, and respecting the particularities of each technology considered, it follows the equation below.

$$\varphi_t = (\varphi Y)_{\omega_1} + (\varphi Y)_{\omega_2} + \dots + (\varphi Y)_{\omega_n}$$

The Y variable represents the Boolean variable, in which their sum must be equal 1. The variable φ represents the variable under study, which can be the mass flow rate, investment cost, lower heating value (LHV), power generated and water produced, as example. The subscript t means the total of the variable φ , and the subscripts ω_1 , ω_2 , ω_n represent the points in analysis, which can be:

- a- an equipment as a turbine, a boiler or a desalination process, when φ is a cost variable;
- b- turbines, when φ is power generated;
- c- fuels, when φ is mass flow rate, low heat value or fuel cost;
- d- desalination process, when φ is the water produced by this equipment.

Other supporting equations are not considered by this representation, like thermodynamic equations, as example.

Due to the high non-linearity from the superstructure equations, a mixed and integer non-linear programming is used to obtain the objective function results, that is to minimize total cost of the installation, that includes the fuel gas turbine and boiler costs (c_{comb_TG} and c_{comb_B}), total investment costs (c_{TOTAL}) from the gas turbines, steam turbines and the boiler and the costs of purchasing or selling the electricity (E_{purch} or $E_{surplus}$, respectively), according to their respective prices (Pe_{purch} or Pe_{sell}). H is the operational time of the hybrid plant.

$$\text{Min} = c_{Total} + [c_{comb_TG} + c_{comb_B}]H3600 \\ + Pe_{purch} E_{purch} - Pe_{sell} E_{surplus}$$

It should be emphasized that the focus of this work lies in the energy surplus and not in considerations about the objective function or any other variable

The modeling, details about the equipment and fuel selections and other information can be seen in Ferreira (2008).

4. RESULTS

The results present the main seven power surplus of the hybrid systems for Cases 1 and 2, as well as the type of fuel burned by the gas turbine, natural gas (NG) or gasified biomass (BIG). For both cases, the water production of the hybrid unit was considered about 100,000 m³/day of fresh water, for 8,000 h/year of operation. Although the gas

turbines availability in the database is greater than the presented ones (with 56 gas turbines), it was decided to limit the results presentation to a smaller set of equipment considering just the best results.

Table 1 shows the values of the power surplus obtained for Case 1, in kWh/year, after the optimization analysis for the considered turbines, beholding that these generated the major surpluses. It's also shown the fuel type selected to be burned in the gas turbine.

Table 1- Relation between power surplus-gas turbine – Case 1.

Turbine	Model	Fuel	Power surplus (kWh/year)
GTR & PC Zorya-Mashproekt	UGT6000	BIG	185,325,000
MAN TURBO AG	THM 1304-12	BIG	155,245,000
Solar Turbines Incorporated	Taurus 70	BIG	151,405,000
Solar Turbines Incorporated	Mercury 50	NG	228,525,000
Rolls-Royce	501-KH5	NG	177,229,000
Solar Turbines Incorporated	Taurus 65	NG	162,925,000
Solar Turbines Incorporated	Taurus 60	NG	152,365,000

It must be noted that LHV for gasified biomass is lower than the natural gas, leading a greater consumption of the gasified biomass to acquire the same level of power generated by the gas turbine, when natural gas is used.

So, it is implicit that the mass consumption of gasified biomass in Taurus 70 it will be greater than the Taurus 60, which works with natural gas and, analyzing the data in Ferreira (2008), the gasified biomass/natural gas ratio is almost 3.

Consequently, this becomes a point of cost analysis, so gasifier and biomass cost must be attractive to the company invest in this technology.

Table 2 shows the ratios obtained between the power surplus generated and the fresh water produced for the same set of equipment. Such information allows deciding which turbine can generate a better energy surplus per cubic meter of produced water.

This information can be useful if the company intends to sell its power surplus, or just use it for other demands, while producing the mainly product, the fresh water. Instead, if the company does not intends a large power surplus, can work with lower values of this ratio and a greater focus on water production

Table 2- Ratio power surplus-produced fresh water – Case 1.

Turbine	Model	Power surplus-fresh water ratio (kWh/m³)
Solar Turbines Incorporated	Mercury 50	6.8558
GTR & PC Zorya-Mashproekt	UGT6000	5.5598
Rolls-Royce	501-KH5	5.3169
Solar Turbines Incorporated	Taurus 65	4.8878
MAN TURBO AG	THM 1304-12	4.6574
Solar Turbines Incorporated	Taurus 60	4.5710
Solar Turbines Incorporated	Taurus 70	4.5422

Table 3 shows the level of desalinated water obtained per kWh. It is important to note that the turbine with the highest rate of water produced is not the same that generates the largest surplus energy. Rather, it is not possible to obtain both values of produced water and excess energy in high levels, not only by mathematical inconsistency so the values are inverses, but the physical and logical analysis of the problem itself. An increase in water productivity will mean increased energy consumption and thereby lower power surplus tends to be obtained. Conversely, a rise in power surplus implies a low level of desalinated water produced, which is expected to a thermoelectric unit rather than a hybrid desalination unit. Thus, it will not be in accordance with the originally proposed objective.

Moreover, a high value of power generated characterizes a thermoelectric plant, which is not usually the focus of a desalination unit, even if it is dual-purpose or hybrid.

Figure 2 shows the curves obtained from the data of Tab. 2 and Tab. 3. The figure presents two curves, one named "Energy", considering the surplus energy generated per cubic meter of freshwater produced (kWh/m³) for each turbine gas. The second curve, named "Water", is the inverse of first one, indicating the volume of fresh water produced by power surplus obtained (in 10⁻³ m³/kWh) for each gas turbine considered by the optimization process.

Table 3- Ratio produced fresh water-power surplus – Case 1.

Turbine	Model	Fresh water-power surplus ($10^{-3} \text{ m}^3/\text{kWh}$)
Solar Turbines Incorporated	Mercury 50	145.8630
GTR & PC Zorya-Mashproekt	UGT6000	179.8642
Rolls-Royce	501-KH5	188.0806
Solar Turbines Incorporated	Taurus 65	204.5931
MAN TURBO AG	THM1304-12	214.7144
Solar Turbines Incorporated	Taurus 60	218.7729
Solar Turbines Incorporated	Taurus 70	220.1601

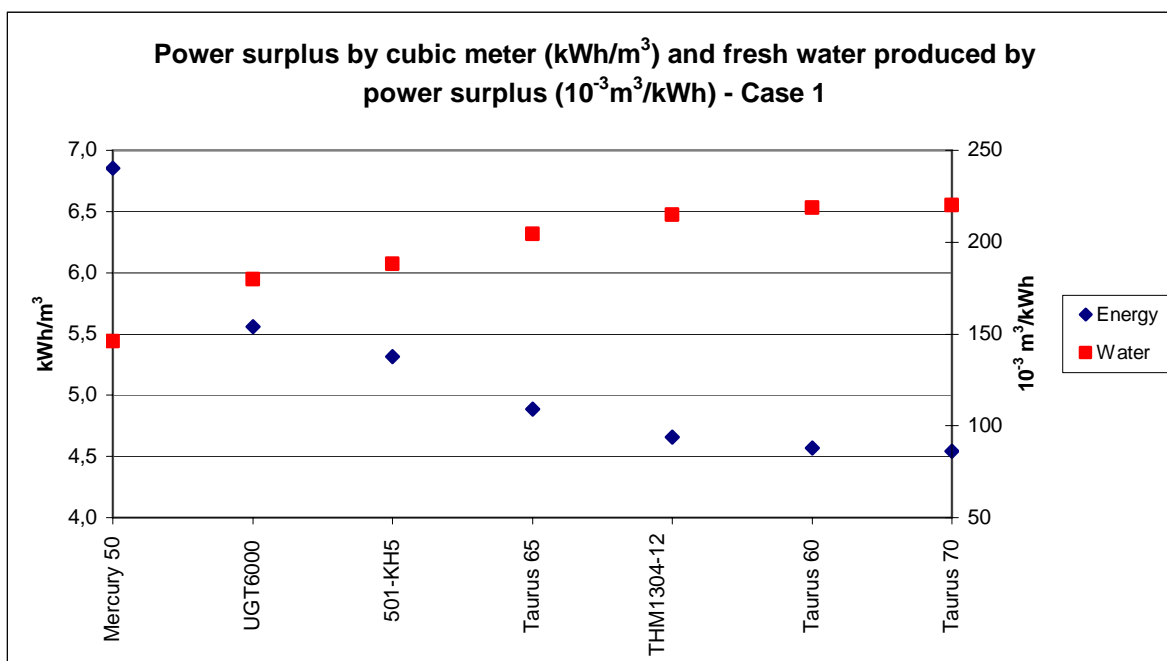


Figure 2 – Relations power surplus-fresh water – Case 1.

Using the same assumptions and analysis for Case 2, Tab. 4 presents the turbines with higher levels of power surplus and fuel used for each one of these gas turbines. It can be noted that, for this case, gas turbines aren't operated with gasified biomass, which was expected due to the high biomass gasifier cost, compared with that practiced in the first case. In other words, with high costs in the gasifier, the presence of biomass gasified becomes impractical.

Looking for the results obtained by Ferreira (2008), just 2 gas turbines burned gasified biomass, but the generation power surplus of the plant it was lower than that showed in Tab. 4. In accordance with the above mentioned, this will be ideal if there was no interest in selling surplus and there is good availability of biomass to be gasified.

Table 4- Relation between power surplus-gas turbines – Case 2.

Turbine	Model	Fuel	Power surplus (kWh/year)
Solar Turbines Incorporated	Mercury 50	NG	228,525,000
Dresser-Rand	DR60G	NG	191,325,000
Siemens AG	SGT-400	NG	176,941,000
GTR & PC Zorya-Mashproekt	UGT6000+	NG	170,125,000
Solar Turbines Incorporated	Taurus 65	NG	162,925,000
Siemens AG	SGT-300	NG	160,741,000
Siemens AG	SGT-100	NG	158,565,000

Table 5 shows the relationship between power surplus and fresh water produced for Case 2, that exhibit a higher biomass gasifier cost. It may be noted that these results, despite the cost of biomass gasifier, are not very different from those obtained in case 1.

Complementing the previous data, Tab. 6 reports the relationship between fresh water produced per kWh of power surplus generated, showing no major distortions in relation to case 1, and Fig. 3 illustrates this and the data from Tab. 5 data, for each gas turbine analyzed.

Table 5- Ratio power surplus-fresh water produced – Case 2.

Turbine	Model	Power surplus-fresh water ratio (kWh/m ³)
Solar Turbines Incorporated	Mercury 50	6.85575
Dresser-Rand	DR60G	5.73975
Siemens AG	SGT-400	5.30823
GTR & PC Zorya-Mashproekt	UGT6000+	5.10375
Solar Turbines Incorporated	Taurus 65	4.88775
Siemens AG	SGT-300	4.82223
Siemens AG	SGT-100	4.75695

Table 6- Ratio produced fresh water-power surplus – Case 2.

Turbine	Model	Fresh water-power surplus (10 ⁻³ m ³ /kWh)
Solar Turbines Incorporated	Mercury 50	145.8630
Dresser-Rand	DR60G	174.2236
Siemens AG	SGT-400	188.3867
GTR & PC Zorya-Mashproekt	UGT6000+	195.9344
Solar Turbines Incorporated	Taurus 65	204.5931
Siemens AG	SGT-300	207.3729
Siemens AG	SGT-100	210.2187

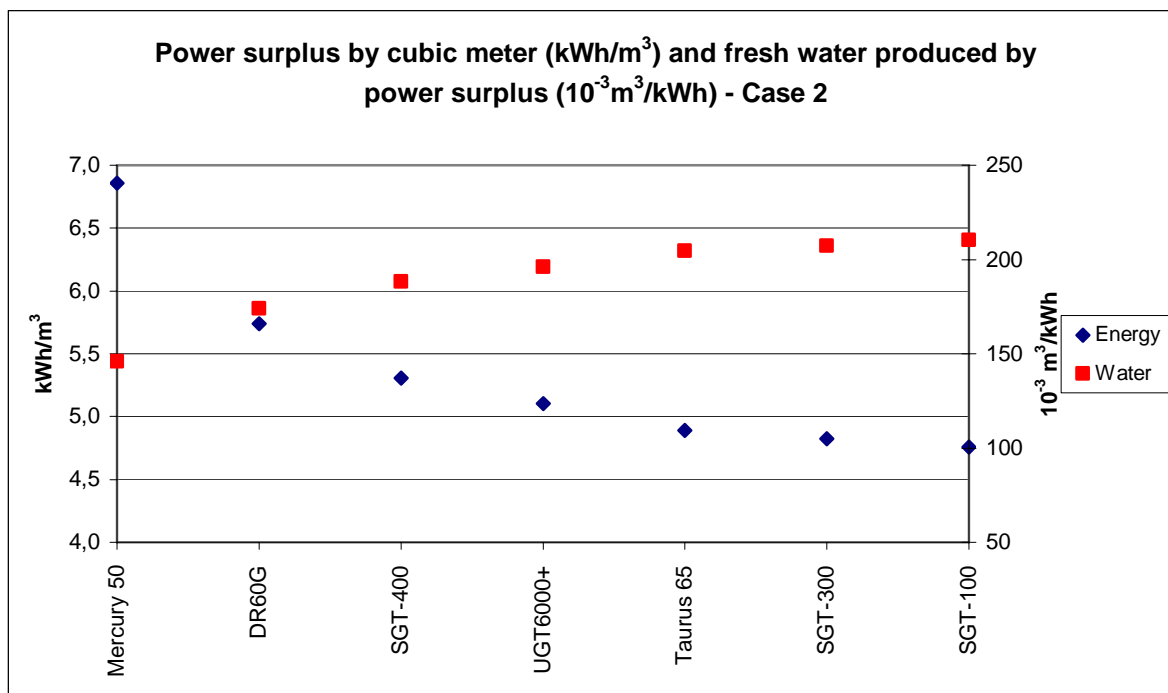


Figure 3 – Relations power surplus-fresh water – Case 2.

On similar analysis, carried out by Ferreira (2008), and considering a dual purpose power plant, in a superstructure similar to that one presented in Fig. 1, and considering the gasifier costs that of the case 1, 48 gas turbines were

analyzed and just three burned natural gas, leaving the vast majority of choices with the gasified biomass as main fuel. It shows that although the equipment result in a higher cost of desalination unit, the use of biomass can be feasible.

5. CONCLUSIONS

It was analyzed the possibilities of generating power surplus in hybrid desalination plants, from a superstructure comprising thermal, electricity and fresh water generation. It was also considered the option of choosing one of four types of fuels, with leading choice for natural gas and gasified biomass. If the biomass were chose, a biomass gasifier needs to be installed whose cost could turn the use of this fuel unfeasible. However, sometimes the optimization model has opted for this choice of fuel and with considerable generating power surplus, considering that its lower heating value is smaller than that of natural gas.

Although gasified biomass usage is less in the cases examined, it is an option that cannot be ignored. With the natural evolution of technology and environmental issues increasingly present in our day, the biomass cost tends to become more attractive.

Whatever type of fuel used, the power surplus becomes a new index to be taken into account when sizing or plan a desalination unit, such as hybrid as dual purpose, in order to reduce costs in purchasing electricity. As a result, the sale of such power surplus can be of great value to the company's revenue.

One issue to be defined by the company is the power level to be obtained for a possible sale or internal use, so it can direct its surplus and achieve a better energy use. So it could make the analysis of different gas turbines available so that a particular model would meet its requirements

Finally, with a comparative analysis of several gas turbines that could be used in this superstructure, it is possible to scale the power surplus that may be of interest and, therefore, plan ahead for the possibility of selling this surplus or even a future and possible expansion of the production unit.

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