DESALINATION ANALYSIS FOR BRAZILIAN COASTAL CITIES

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Abstract. *With the increasing of fresh water requirements, both for human consume and for industrial or sanitation applications, water resources management becomes essential for public and for private supply, that have to keep their activities without compromising the productive chain. Hence, studies concerning to alternative water sources, such as water reuse, seawater treatment, etc, seen to be attractive. In this way, seawater desalination appears to be a technological opportunity to solve part of these problems. The aim of this paper is to perform a comparative analysis between the present practice based on water supplied by municipal and state concessionaries and the use of seawater desalination associated to cogeneration systems. These systems, named dual purpose systems, could provide partial water demand to coastal cities and, at the same time, the generated electric energy surplus would be sold. Also steam could be obtained and used as heat source on the water supply installation. Based on analyzed data the results showed to be very revealing. With more detailed studies and suitable public polices, new perspectives in the Brazilian water supply can be visualized.*

Keywords*: desalination, optimization, dual purpose, cogeneration*

1. INTRODUCTION

Nowadays world is becoming the center of several natural occurrences that are harming its local population, with impacts that sensitize the world population. Among so many adversities, one can become preoccupying: the shortage in the availability of water.

The human water requirements in a daily basis are increasing for sanitation, consumption or industrial use. Many references report data for the consumption water availability with a common viewpoint: the human beings do not have the amount of fresh water they are supposed to, and also they do waste it too much. Pegorim (2005) points out that salty water is responsible for 97.5% of the global water. From the remaining, only 0.007% of the total is suitable for drinking. According to the author, Brazil counts with 13.7% of the world's fresh water sources, 70% of them located in the Amazonia, what hinders its access due to the low demographic distribution. Beside this, the waste that occurs in the country is another critical point, so the discarded parcel represents about 40% of the produced water.

As alternative to the water supply, many countries are using alternative production methods, such as desalination processes, to obtain fresh water in which the salt of the seawater is removed and, consequently, water for human consumption is produced.

Desalination processes need an energy source, thermal or electric, and the use of cogeneration systems coupled to the desalination is gaining space in researches and in actual applications as a consequence of its energetic rationality. These desalination and cogeneration coupled systems are named dual purpose systems, and their objectives are the production of fresh water and electric power (and in some cases, thermal energy such as process steam). The number of published papers related to this theme is increasing, as seen in Darwish and Al-Najem (2000), Poullikkas (2005), Kamal (2005), as well Uche, Serra and Valero (2001), that coupled thermoeconomic analysis to the dual purpose system.

In this paper it is presented an optimization tool for the project of a dual purpose system with the aim of supplying water for a Brazilian coastal city. A superstructure composed of some different feasible technologically alternatives for the drinking water, steam and electric power supply is proposed; starting from an consistent group of thermodynamic and technological constraints (such as equipment operational limits and conditions of electric interconnection with the local concessionary). An objective function, which consists of the minimization of the investment and operational costs, guides the selection processes (synthesis) of the components that will be incorporated to the project.

Electrical demand and water supply values collected from the Ubatuba city local concessionaries, located at São Paulo state north coast, are utilized; the steam demand is evaluated as a necessary portion for cleaning processes. This set of demands serves as parameter for the optimization process, as well as to perform comparative analysis for other coastal cities, similar to Ubatuba's size and to forecast the behavior for larger cities.

2. OPTIMIZATION ANALYSIS

Figure 1 illustrates the analyzed superstructure, in which thermodynamic and economic aspects are detailed in the sequence.

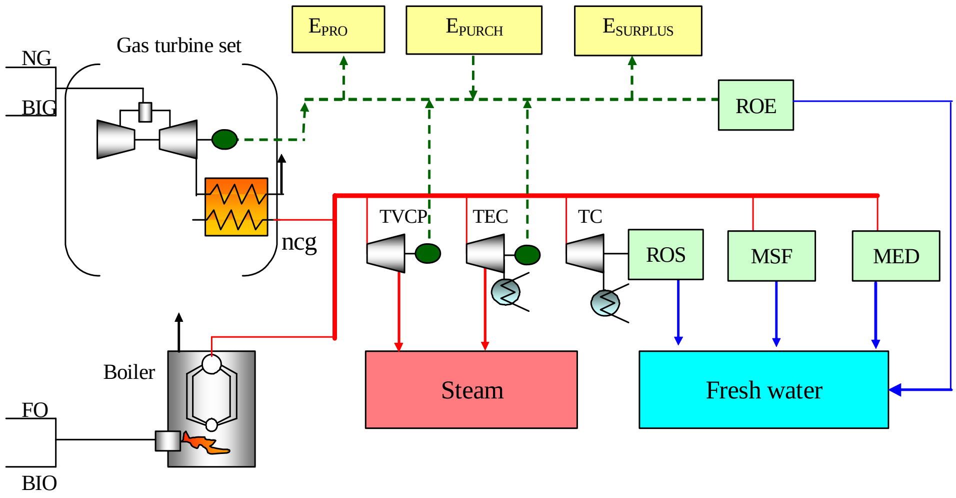

Figure 1 – Proposed dual-purpose installation.

The analyzed desalination technologies for water production were the multistage flash distillation (MSF), the multiple effects distillation (MED) and the thermally driven (ROS) or electrically driven (ROE) reverse osmosis. Their concepts were described in details by Marcuello (2000), Buros (2000) and Altmann (1997). The ROS unit is coupled to a condensation turbine, in order to have the required power to its operation. The ROE unit is driven by the use of the electric energy generated at superstructure installed turbines.

The cogeneration technologies available at the superstructure refers to a conventional boiler (B) burning, optionally, biomass in natura (BIO) or fuel oil (FO), and a commercially available gas turbine associated to a heat recovery steam generator (GT-HRSG), burning in its combustion chamber, optionally, the gasified biomass (BIG) or the natural gas (NG). These equipments will generate steam to feed the whole superstructure. The gas turbine, besides the hot gases, will also produce power, which could be used to generate electric energy. It must be noticed in Fig. 1 that the gas turbine number (ncg) indicates the possibility of using more than one gas turbine in the system.

Two steam turbines, an extraction and condensation steam turbine (TEC) and a backpressure steam turbine (TVCP), are coupled to the system at the steam distribution network. They will provide the required process steam.

Besides the water and thermal energy generation, electric power production will occur at the electric generators of all the turbines. The process unit has its energy needs (E_{PRO}) which must be supplied. There is still the possibility of using the electricity produced by the electrically driven reverse osmosis, in the case this equipment is selected as a feasible desalination process. The electric balance that takes into account the electricity produced by the turbines and the electricity consumed by ROE and by the process will determine the need of electricity buying from (E_{PURCH}), or in case of surplus ($E_{SURPLUS}$), the electricity to be sold to the concessionary.

As mathematical tool for the proposed problem resolution, an optimization analysis was used based in mixed integer and non-linear programming (MINLP), since the model presents several non-linear equations. To solve this problem, the optimization software LINGO (version 10) was used, whose main characteristic is the resolution of optimization problems, aiming the resolution of linear, non-linear, integer and mixed programming problems (Lingo, 2001).

Due to the extension of the problem, the equations that govern the proposed model it will not be presented here but they are available in Ferreira (2008). The objective function, represented by the Eq. (1), refers to the minimization of the sum of the costs of the equipment (cTotal), the fuels burned in the gas turbine and in the boiler (c_{comb_GT} and c_{comb_B}) considering an annual operation period of H = 8,000 h / year, and the electricity purchase or sale price (Pe_{PURCH} and Pe_{SELL}) respectively to the purchase or surplus electricity (E_{PURCH} e $E_{SURPLUS}$).

$$\text{Min} \; = cTotal^{(i)} + 3{,}600(c^{(i)}_{comb\_GT} + c^{(i)}_{comb\_B})H + Pe_{PURCH}E^{(i)}_{PURCH} - Pe_{SELL}E^{(i)}_{SURPLUS} \tag{1}$$

The superscript “i” is used to indicate the analyzed turbine values set. Such values set are available in Diesel & Gas Turbine Publication (2006), and a database with turbines catalogs values of the turbine power, We in kW, Heat Rate, HR in kJ/kWh, exhaust gas mass flow rate, mg in kg/s, and the gas exhaust temperature, Tg in ºC, was created inside the numerical procedure. The superscript “i” in the Eq. (1) indicates which variable will be affected by the choice of one or other gas turbine. In this paper, 10 turbines were selected for an analysis relative to finding optimized values.

As previously exposed, the installation will aim the production of fresh water and the electric power to supply their needs and, if possible, electric surplus to be sold to a local concessionaire.

Technological constraints were implemented, with the objective of selecting the equipments that will be part of the installation. The Boolean variable Y assumes 1 or 0 values, indicating that technology will be present or not, respectively, in the proposed installation. The Eq. (2) indicates that just one fuel will be able to be admitted in the steam generators. With this constraint, it’s defined the presence of the gas turbine or the conventional boiler, exclusively.

$$Y^{(i)}_{NG\_TG} + Y^{(i)}_{BIG\_TG} + Y^{(i)}_{FO\_B} + Y^{(i)}_{BIO\_B} = 1 \tag{2}$$

Equation 3 is similar to the previous equation, so it restricts the desalination equipments, ensuring that just one of them will produce drinking water.

$$Y^{(i)}_{MSF} + Y^{(i)}_{MED} + Y^{(i)}_{ROS} + Y^{(i)}_{ROE} = 1 \tag{3}$$

Equation 4 restricts the use of steam turbines, backpressure or extraction and condensation, so just one of them it will supply the process heat.

$$Y^{(i)}_{TVCP} + Y^{(i)}_{TEC} = 1 \tag{4}$$

In the mass and energy balance equations, as well as in the cost equation, the Boolean variables will be present, avoiding or allowing the presence of the technologies above mentioned, relative to each one of the "i" values set of the i^{th} analyzed turbine.

One of the analysis parameter of the possible configurations refers to the use of the gasified biomass, so it's necessary to use a biomass gaseificador coupled to the gas turbine. In this way, it is necessary to specify this technology cost associated to the gas turbine presence. Two analysis are presented, one relative to the investment cost of the biomass gasification of 2,100 US$/kW (Case 1) and the other for an investment cost of 4,000 US$/kW (Case 2). Although the investment cost of 2,100 US$/kW is pointed out as a perspective value for a near future (Balestieri 2001), the gasifier currently accepted data is among 3,000-4,000 US$/kW (Lora, Andrade and Aradas, 2004) and a comparison study is presented.

The production of drinking water should fulfill, totally or partially, the demand of a city like Ubatuba. In the Fig. 2 the real water measured volumes (Kuncevicius 2005) and the electric demand (Semolini 2005), for the city of Ubatuba and considering some years, are shown. Although more recent data should be desirable but not available, the data relative to the years from 2000 to 2004 showed to be useful as analysis parameter. It is important to mention that in this paper there is no analysis relative the availability of natural gas or biomass to be gasified; it is assumed that both are available with no constraints for their use.

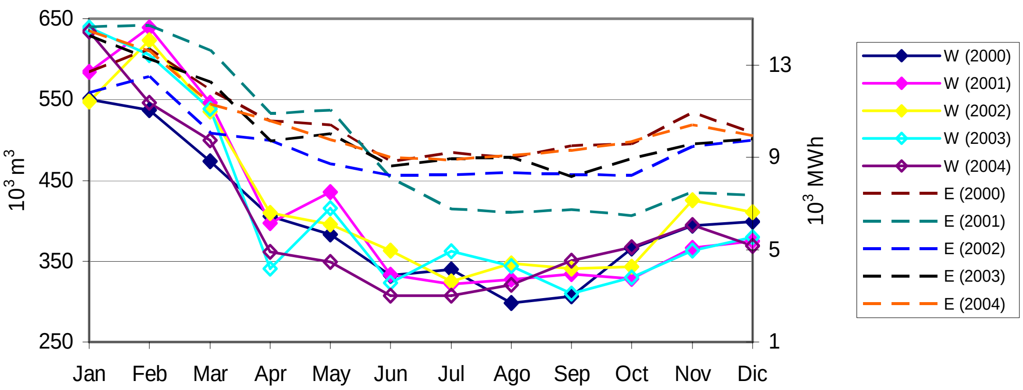

Figure 2 – Water and electricity demands from the Ubatuba city.

3. RESULTS

The MINLP analysis presents some relevant features when it is used for some real problems. According to Weise (2008), the solution's convergence for nonlinear problems could be of simple and easy, but sometimes its result reveals to be difficult to be obtained or even not obtainable. For this study, the modeling was adapted to the multimodal problem, which can present multiple local optimum and global optimum (Weise, 2008), as visualized by the Fig. 3.

Therefore, the presented solutions for the objective function, given by the Eq. (1), refer to the local optimum obtained for a certain set of catalogs values related to one gas turbine, and they do not necessarily exclude the existence of other optima values that were eventually skipped by the software due to the value sets be located in a different curve valley not explored by the software.

Results obtained for the Cases 1 and 2 present similarities, mainly in relation to the gas and steam turbines features. The main difference is the significant presence of the gasified biomass in the case 1, due to a smaller cost of the biomass gasifier, comparatively to the case 2. On the other hand, the presence of the natural gas in case 2 is mandatory for the 10 analyses. Table 1 display the possible configurations obtained by the cases 1 and 2 optimization analysis.

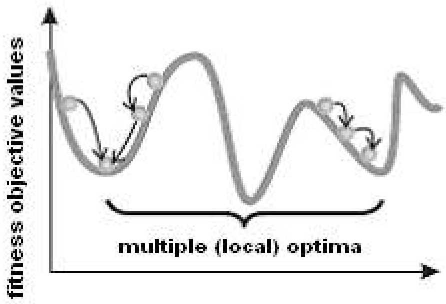

Figure 3 – Multimodal problem.

Table 1 – Possible configurations for Cases 1 and 2.

CONFIGURATION	CASE 1	CASE 2
YNG+YTVE+YROE	1	10
YBIG+YTVE+YROE	8	-
YBIG+YTVE+YMED	1	-

In the Tab. 2 the values obtained after the optimization analysis are shown. The number of gas turbines proposed (ncg), the gas turbine generated power ($\dot{W}e$), in kW, and the produced mass flow rate by the heat recovery steam generator ($\dot{m}_{V\_HRSG}$), in kg/s, were common to the two analyzed cases. The fuel proposed to be burnt in the Case 1 was the gasified biomass (with the exception for a single solution) and, in Case 2, the natural gas. Their mass flow rates, in kg/s, are also represented in Tab. 2.

Table 2 – Installations general features for the Cases 1 and 2.

Manufacturer	Model	NCG	$\dot{W}e$	$\dot{m}_{V\_HRSG}$	Case 1	Case 2
					$\dot{m}_{BIG}$	$\dot{m}_{NG}$
Dresser-Rand	DR60G	3	41,325	15.591	6.3840	2.1280
GE Energy Oil & Gas	GE10	4	45,000	20.240	7.7570	2.5850
GTR & PC Zorya-Mashproekt	UGT16000	3	48,900	18.761	8.5270	2.8420
Man Turbo AG	THM 1203A	4	23,040	16.617	5.5420	1.8470
	THM 1304-11	3	32,280	16.869	5.8600	1.9530
Mitsui Engineering & Shipbuilding	MSC90	4	37,160	15.730	6.3380	2.1120
	SB60	3	37,470	16.101	2.2800*	2.2800
Siemens AG	SGT-400	3	38,628	15.583	6.0060	2.0020
Solar Turbines Incorporated	Mars 90	4	37,800	16.187	6.4140	2.1370
	Mars 100	4	42,760	18.100	7.1200	2.3730

* Natural gas is chosen, instead of gasified biomass.

In the Tab. 3 the obtained values for the power generated via the extraction/condensation steam turbines ($\dot{W}e_{TEC}$), in kW, in function of their respective selected gas turbines, are shown.

In the Tab. 4 the installation generated total power ($\dot{W}ger$), in kW, and the surplus electric ($E_{SURPLUS}$), in kWh/year, that can be sold for the local concessionaire or used for analysis of future enlargements in other sections or activities of the company, are presented. As the $\dot{W}ger$ values are dependent of the possible power generated by the selected steam turbine and by the gas turbine, this it will affect the $E_{SURPLUS}$ that will improve the electricity amount sold to the local concessionaire.

Although some of the values previously presented are quite the same for both cases, the difference among them was in the fuels chosen by the model for being burnt and their mass flow rates. Other differentiating points are the involved costs of the gas turbine fuel (c_{comb_TG}), in US$/s, the gas and steam turbines cost (c_{total_T}) and the installation total cost (c_{TOTAL}), both in US$/year, which can be seen in the Tab. 5.

Table 3 – Extraction/condensation steam turbine generated power.

Manufacturer	**Model**	$\dot{W}e_{TEC}$	
		Case 1	**Case 2**
Dresser-Rand	DR60G	9,116	9,116
GE Energy Oil & Gas	GE10	12,596	12,596
GTR & PC Zorya-Mashproekt	UGT16000	11,481	11,489
Man Turbo AG	THM 1203A	9,884	9,884
	THM 1304-11	10,072	10,072
Mitsui Engineering & Shipbuilding	MSC90	9,220	9,220
	SB60	9,497	9,497
Siemens AG	SGT-400	9,110	9,110
Solar Turbines Incorporated	Mars 90	9,562	9,562
	Mars 100	10,994	10,994

Note: $\dot{W}e_{TEC}$ – extraction/condensation turbine generated power, kW.

Table 4 – Installation total generated power and energy surplus.

Manufacturer	**Model**	**Case 1**		**Case 2**	
		$\dot{W}ger$	$E_{SURPLUS}$	$\dot{W}ger$	$E_{SURPLUS}$
Dresser-Rand	DR60G	50,441	350,197,200	50,441	350,239,900
GE Energy Oil & Gas	GE10	57,596	407,438,300	57,596	407,434,400
GTR & PC Zorya-Mashproekt	UGT16000	60,381	443,047,900	60,389	429,778,700
Man Turbo AG	THM 1203A	32,924	210,062,800	32,924	210,062,800
	THM 1304-11	42,352	285,488,300	42,352	285,488,300
Mitsui Engineering & Shipbuilding	MSC90	46,380	317,713,500	46,380	317,709,600
	SB60	46,967	322,407,500	46,967	322,407,500
Siemens AG	SGT-400	47,738	328,572,900	47,738	328,572,900
Solar Turbines Incorporated	Mars 90	47,362	325,563,400	47,362	325,579,300
	Mars 100	53,754	376,703,100	53,754	376,703,100

Table 5 –Installation costs.

Manufacturer	**Model**	**CASE 1**			**CASE 2**		
		c_{comb_TG}	c_{total_T}	c_{TOTAL}	c_{comb_TG}	c_{total_T}	c_{TOTAL}
Dresser-Rand	DR60G	0.354	12,351,400	14,864,740	0.683	2,898,329	5,411,663
GE Energy Oil & Gas	GE10	0.431	13,589,200	16,102,540	0.830	3,295,474	5,808,807
GTR & PC Zorya-Mashproekt	UGT16000	0.473	14,651,680	17,685,020	0.913	3,466,248	5,979,582
Man Turbo AG	THM 1203A	0.308	7,137,103	9,650,436	0.593	1,866,713	4,380,046
	THM 1304-11	0.325	9,802,162	12,315,500	0.627	2,418,126	4,931,460
Mitsui Engineering & Shipbuilding	MSC90	0.352	11,159,970	13,673,310	0.679	2,659,640	5,172,974
	SB60	0.732	2,692,290	5,205,624	0.732	2,692,290	5,205,624
Siemens AG	SGT-400	0.333	11,576,070	14,089,410	0.643	2,739,934	5,253,267
Solar Turbines Incorporated	Mars 90	0.356	11,361,730	13,875,070	0.687	2,715,001	5,228,334
	Mars 100	0.395	12,861,870	15,375,200	0.762	3,080,539	5,593,873

The objective functions' values, in US$/year, resultant from the Eq. (1), are presented in the Tab. 6; an analysis about them reveals that although the diversity of equipments and manufacturers, a restrict value range was obtained; it is also important to note that the schemes proposed in Cases 1 and 2 are very similar. Figures 4 and 5, illustrate the Cases 1 and 2 final optimized schemes as the result of optimization process. In technological terms, both cases show the same configuration, differing just by the use of gasified biomass as the fuel in the Case 1 and of natural gas as the fuel for the Case 2. This result is significant because a robust solution was obtained for the project, and this is an important decision criterion in terms of the enterprise planning and project.

Table 6 – Objective function for the proposed installation.

Manufacturer	Model	Case 1	Case 2
Dresser-Rand	DR60G	14,563,450	14,586,970
GE Energy Oil & Gás	GE10	16,278,870	17,501,670
GTR & PC Zorya-Mashproekt	UGT16000	18,022,600	19,373,620
Man Turbo AG	THM 1203A	12,206,970	15,164,120
	THM 1304-11	13,117,210	14,432,480
Mitsui Engineering & Shipbuilding	MSC90	14,273,200	15,182,760
	SB60	16,625,100	16,625,100
Siemens AG	SGT-400	13,832,980	13,913,850
Solar Turbines Incorporated	Mars 90	14,359,530	15,233,590
	Mars 100	15,455,110	16,244,250

In the Fig. 4 it is selected as optimal solution a configuration that presents the gasified biomass as the main fuel to be burnt in the gas turbine for generating power and producing steam in the heat recovery steam generator to be expanded in the steam turbine. The power generated in the steam and gas turbines is directed to meet the process energy needs (E_{pro}) and for driving the electrically driven reverse osmosis (ROE) to produce the fresh water. The eventual electric surplus ($E_{SURPLUS}$) can be sold to the local concessionaire.

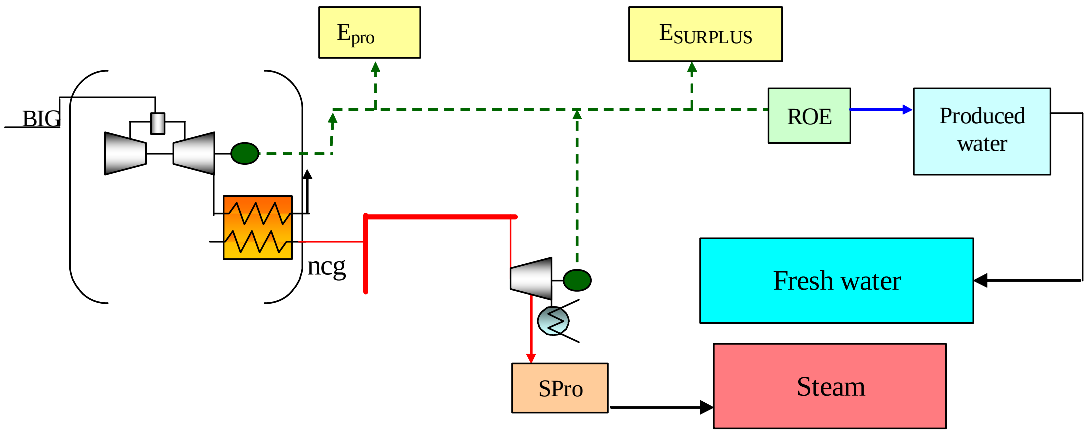

Figure 4 – Predominant installation for the case 1.

In the Fig. 5 the same configuration of the Fig. 4 is selected as the optimal solution, with the exception of the fuel chosen by the model. In this case, natural gas was the main fuel to be burnt in the gas turbine. Likewise the Case 1, in the Case 2 it was generated a surplus of electricity to be sold to the local concessionaire.

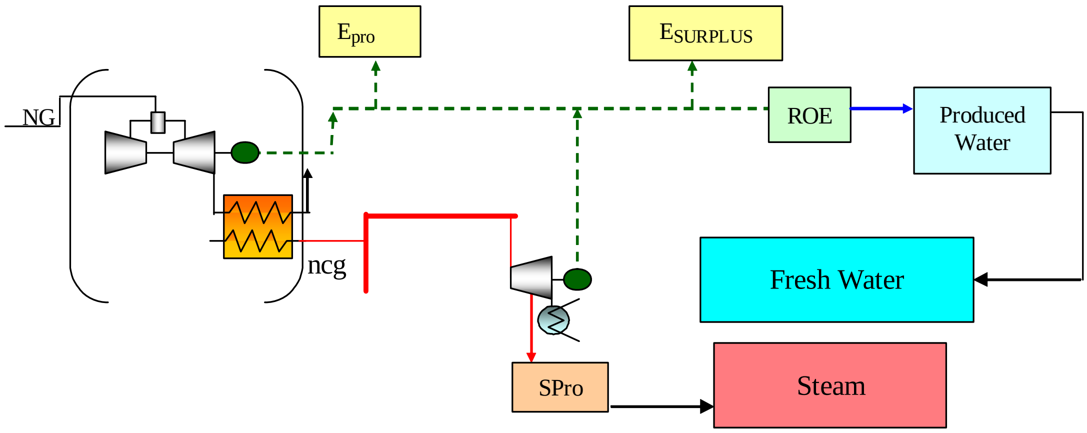

Figure 5 – Predominant installation for the case 2.

4. CONCLUSIONS

A dual purpose unit feasibility study, aiming the fresh water and electric power production with the use of turbines installed in an initial superstructure, was proposed to be analyzed in this paper. The Ubatuba city electric and water demands were analyzed, intending to design a system suitable to coastal cities of that size.

Two cases were proposed, with different biomass gasifier costs, to evaluate the effect of this equipment in the costs obtained with the proposed analysis. No considerations concerning to the availability of any of the two fuels were made, and it was admitted as a premise that in both cases there were no constraints for their use in the project.

Although it was not necessarily expected, the optimization of both cases resulted in two installations with identical technologies, among the several options that were available. The only difference was the use of gasified biomass, for the Case 1, and natural gas for the Case 2. The other technologies that compose the dual purpose system were the extraction/condensation steam turbine and the reverse osmosis electrically driven. This result reinforces the condition of obtaining a robust solution in terms of the recommended technologies for the project, which is an important decision criterion in terms of the enterprise planning and project.

By the presented results, it is noticed that the elaboration and the availability of a computational tool that analyzes and evaluates an installation containing the cogeneration and desalination technologies can be very useful, mainly for the possibility of integrating the different cogeneration thermal cycles with the different desalination technologies options. With such tool, it can be determined different schemes, such as the superstructure proposed in Fig. 1, changing productivity characteristics, fuels, available technologies or other peculiar characteristics of the entrepreneur's conception of its business. Another option of this modeling tool would be the induction of new technology integration with pre-existent conditions in a real installation for obtaining an improved process condition or for verifying the behavior of a desalination unit installation in a pre-existent cogeneration unit, or vice versa.

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