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On the Negentropy Application in Thermoeconomics: A Fictitious or an Exergy Component Flow?*

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Abstract

The introduction of the negentropy in thermoeconomics represented a great advance in the discipline, since this magnitude allows quantifying the condenser product in a steam cycle plant, which was not possible before because the condenser is a dissipative component, whose product cannot be expressed in terms of exergy. However, most authors have been applying the negentropy as a fictitious flow, joined up with the exergy flow. This paper aims at opening a discussion about the procedure for negentropy application in thermoeconomics, by showing that: (i) the original procedure leads to some inconsistencies; and (ii), a more recent approach takes all the negentropy advantages, without leading to inconsistencies, by applying the negentropy as a physical exergy component flow.

Keywords: *Thermoeconomics, negentropy, fictitious flow, exergy component.*

1. Introduction

Thermoeconomics can be considered a new science which, by connecting Thermodynamics and Economics, provides tools to solve problems in complex energy systems that can hardly or not be solved using conventional energy analysis techniques based on the First Law of Thermodynamics (mass and energy balance), as for instance a rational price assessment to the products of a plant based on physical criteria (Erlach et al., 1999).

Most analysts agree that exergy, instead of enthalpy only, is the most adequate thermodynamic property to associate with cost (originally an economic property) since it contains information from the Second Law of Thermodynamics and accounts for energy quality. An exergy analysis locates and quantifies the irreversibilities (Valero et al., 2006).

According to Torres et al. (1996), sometimes, under a thermoeconomic analysis point of view, it is necessary to consider a mass or an energy flow rate consisting of several components, for example thermal, mechanical or chemical exergy, or even to include fictitious flows (negentropy).

The negentropy flow was applied in thermoeconomics by Frangopoulos (1987), joined up with exergy flow. This application represented a great advance in the discipline, since it allowed one to quantify the condenser product in a steam cycle plant, which was not possible before because the condenser is a dissipative component, whose product cannot be expressed in terms of exergy. The same steam cycle power plant was analyzed by Lozano et al. (1993), also using the negentropy concept. The concept of negentropy was also used by Lozano and Valero (1993) and by von Spakovsky (1994) in order to define the productive structure of a gas turbine cogeneration system.

The productive structure defined by Lozano et al. (1993) is basically the same used by Frangopoulos (1987), i.e., the condenser produces negentropy and consumes exergy. Thus, the product of the condenser is always greater than its fuel, which seems that the condenser efficiency is greater than 100%. Contradictorily, Lozano et al. (1993) used an equation named the condenser efficiency, consisting of the ratio between negentropy and enthalpy, which implicitly shows that the condenser product is the negentropy, but its fuel is the enthalpy. A doubt arises: what is the condenser fuel, the enthalpy or the exergy?

In fact, the negentropy and the enthalpy as the product and the fuel of the condenser (respectively) seem more consistent, because the condenser efficiency in an actual steam power cycle will always be less than 100%, and this efficiency would only be 100% in case it were possible to transfer heat in the condenser at the same temperature, i.e., if the condensation temperature and the reference temperature were the same (in a reversible steam power cycle).

The steam cycle analyzed by Lozano et al. (1993) and by Frangopoulos (1987) was a simple power plant, i.e., without heaters and deaerator. However, the negentropy concept was used by Uche et al. (2001) in order to define the productive structure of an actual and complex steam cycle cogeneration plant with heaters, deaerator, condensing steam turbine, and steam extraction to feed a desalination plant. In this case, there were other negentropy producer components, besides the condenser. Because these other components (negentropy producers) have other purposes in the plant, which can be expressed in terms of exergy, auxiliary equations are needed in order to attribute cost to the negentropy flows. Santos et al. (2006) showed that, depending on the criteria used to formulate these auxiliary equations, the unit cost of power will be overcharged, and therefore the value of the exergetic unit cost of power contradicts the well-known cogeneration advantages. In the productive structure of a regenerative gas turbine cogeneration system, these auxiliary equations are also needed, because the regenerator (air preheater) and the heat recovery steam generator produce both exergy and negentropy (Lozano and Valero, 1993; Santos et al., 2008a).

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Different thermoeconomic methodologies can provide different cost values when they define different productive structures. Cost validation is a key issue in thermoeconomics which has not been properly solved yet. However, we consider that cost validation can be designed using the physical behavior of the plant together with thermodynamics, because irreversibility is the physical magnitude generating the cost (Valero et al., 2006). Thus, in order to be consistent with the thermodynamics, in the productive structure of an irreversible cogeneration plant, defined by any thermoeconomic approach, the fuel of each component must be greater than the product (the efficiency is less than 100%) and the exergetic unit cost of power and heat must be less than their exergetic unit costs when they are produced in a power-only plant and in a conventional boiler.

According to Valero et al. (1995), the fuels and the products (productive structure) of a system must be defined based on the trajectories the flows describe in the (h,s) plane when they work for the specific purpose of the plant. Valero et al. (2006) stated that, although the magnitudes applied by most thermoeconomic approaches are exergy, negentropy and money, other magnitudes, like enthalpy and entropy, can also be used. According to Alves and Nebra (2003), physical exergy has two components, the enthalpy ($h - h_0$) and the negentropy $-T_0.(s - s_0)$. The aim of Lazzaretto and Tsatsaronis (2006) was to propose a systematic and general methodology for calculating efficiency and cost in thermal systems. By joining these ideas, Santos et al. (2006) proposed a new approach (H&S Model) that takes all the known advantages of negentropy application and avoids the inconsistencies cited above. In the H&S Model, negentropy is applied together with the enthalpy (instead of exergy), i.e., negentropy is considered a physical exergy component.

Aiming at opening a discussion about the procedures for negentropy application, this work compares three different thermoeconomic approaches by applying them to cost allocation in a dual-purpose power and desalination plant. The first approach defines the productive structure by using exergy flow only (E Model). The second uses negentropy as a fictitious flow, joined up with exergy (E&S Model). The third is the new approach proposed by Santos et al. (2006), which uses the negentropy as an exergy component flow, together with enthalpy (H&S Model). The goal is to determine the exergetic and the monetary unit cost of the internal flows and the final products (electric net power and desalted water). In the final analysis, this paper shows the inconsistencies of the E&S Model, the limitations of the E Model, and the advantages of the H&S Model.

2. Plant Description

The plant consists of an extraction-condensing steam turbine cogeneration system coupled with a MED-TVC (multiple-effect thermal vapor compression) desalination unit. At design point, the plant produces 4,075 kW of electric net power and 2,400 m^3/d of desalted water. The external fuel exergy consumption is 24,873 kW.

2.1 Physical Model

Figure 1 shows the physical structure of the analyzed dual-purpose power and desalination plant. For the energy and mass balance, the cogeneration system was modeled and simulated using the Thermoflex Software.

The plant can also operate in pure condensing mode (the desalination plant is off) producing 5,300 kW of net power and consuming the same amount of fuel (24,873 kW).

At 25 bar and 330°C, the boiler generates 8.597 kg/s of steam, out of which 4.552 kg/s are completely expanded through the turbine down to the condenser pressure (0.056 bar) and 4.045 kg/s are extracted from the intermediate stage of the turbine (at 2 bar and 136°C). The extracted steam is used to feed the desalination plant (3.194 kg/s), the deaerator (0.657 kg/s) and the heater (0.193 kg/s). The condenser is cooled by using sea water, which enters at a temperature of 25°C and leaves at 32°C. The quality of the steam at the outlet of the low pressure steam turbine is 92.9%. The temperature of the boiler feed water is 106°C.

The desalination unit has 8 effects and returns the condensate at 60.2°C (1.013 bar). The process steam passes through the thermal compressor (TC), where it is mixed with the steam generated in the last effect and this mixture condenses in the first effect (E1), transferring heat to continue the distillation process in the remaining seven effects and in the auxiliary condenser (E2:8-C). This desalination unit consumes 200 kW of electric power.

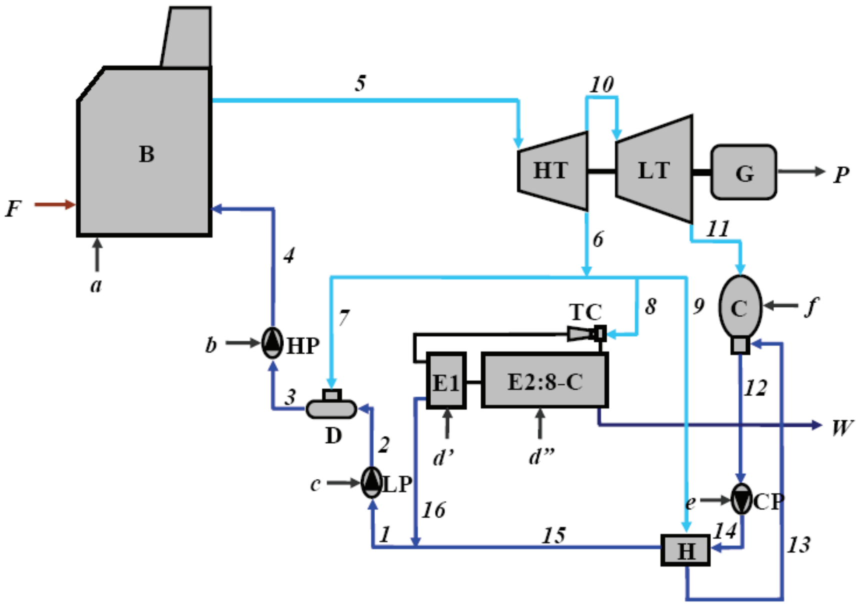

Figure 1. Physical Structure of the Dual-Purpose Power and Desalination Plant.

2.2 Economic Model

The specific capital cost of the cogeneration system is 950 \$/kW, the fixed operation and maintenance cost is 32 \$/kWy and the variable operation and maintenance cost is 0.0035 \$/kWh. The specific capital cost of the desalination plant is 1,760 \$/m^3/d (12 \$/gpd) and the operation and maintenance cost is 0.1 \$/m^3 (El-Nashar, 2001). In order to calculate the hourly cost of the equipment (Z), the economic parameters are: plant factor (0.9), plant lifetime (25 year) and interest rate (0.08) (El-Nashar, 2001). The hourly cost of the cogeneration system is distributed among each subsystem as function of the percentages of their contributions to its total capital cost, as shown Table 1.

Table 1. Distribution of the Cogeneration Plant Total Cost.

Cogeneration Subsystem	Percentage (%)
Boiler (B)	55.00
Turbine and Generator (HT, LT and G)	35.40
Condenser (C)	5.40
Deaerator (D)	1.50
Heater (H)	1.00
High Pressure Pump (HP)	1.00
Low Pressure Pump (LP)	0.50
Condensate Pump (CP)	0.20

In the desalination unit, the first effect of the evaporator and the thermal compressor (E1-TC) are responsible for 12.5% of its total capital cost, and the remaining seven effects of the evaporator together with the auxiliary condenser (E2:8-C) are responsible for the remaining 87.5%. The fuel consumed is natural gas and the unit cost assumed for this fuel is 7.20 \$/MWh (Uche et al., 2001).

3. Thermoeconomic Modelling

The thermoeconomic model is a set of equations which describes the cost formation process of the system. But, the physical model is not enough to identify the cost formation process of the dissipative component. Perhaps the fundamental limitation of the theory of exergetic cost, as it was originally formulated, consisted of defining the productive structure in relation to the same flows and component present in the physical structure. The resulting difficulties lie mainly in the adequate treatment of the dissipative units (Lozano and Valero, 1993).

To carry out a thermoeconomic analysis of a system, it is convenient to make up a thermoeconomic model, which defines the productive propose of the subsystems (products and fuels), as well as the distribution of the external resources and internal product throughout the system. It could be represented by means of the productive diagram. The only limitation which must be imposed is that it must be possible to evaluate all the flows of the productive structure in relation to the state of the plant as defined by the physical structure (Lozano and Valero, 1993).

As mentioned above, in order to define the productive structure, this paper considers three different methodologies, i.e., three ways to define the internal flows. The first uses exergy flow only (without negentropy). The second uses the negentropy as a fictitious flow (joined up with exergy flow) and the third uses the negentropy as a physical exergy component flow (joined up with enthalpy flow).

3.1 E Model: Exergy Flow Only

Figure 2 shows the productive structure defined for the dual-purpose power plant, which graphically depicts its cost formation process. The external resource is the natural gas exergy (Q_F) and the products are the electrical net power (P_{NP}) and the produced desalted water volumetric flow (V_W). The rectangles are the real units that represent the actual components of the system. The rhombus and the circles are fictitious units called junction (J_E) and bifurcations (B_E and B_P), respectively. Each productive units of Figure 2 has inlet and outlet arrows, that represent its fuels (or resources) and products, respectively. There are real components that have a small junction to receive their two or more fuels. The internal flows of the productive structure are exergies that represents electric power flows (P_a, P_b, P_c, P_d, P_e and P_f), the external fuel consumption (Q_F), or the exergy added to and removed from the working fluid ($E_{j:k}$ and $E_{j:k'}$). Each flow present in the productive structure is defined based on physical flows. The flows of the productive structure that represent the exergy added to and removed from the working fluid are always exergy variations between two physical flows, as show Eqns (1a) and (1b). The subsystems that add exergy to the working fluid produce exergy and the subsystems that remove exergy from the working fluid consume exergy.

$$E_{j:k} = m_j \cdot [h_j - h_k - T_0 \cdot (s_j - s_k)] \tag{1a}$$

$$E_{j:k'} = m_k \cdot [h_j - h_k - T_0 \cdot (s_j - s_k)] \tag{1b}$$

Since the E Model uses only exergy to describe the fuels and the product of the subsystems, and the condenser does not have a product that can be measured in exergetic terms, the low pressure turbine (LT) and the condenser (C) must be analysed as a single unit (LT-C), because the authors generally assume that the function of the condenser is to increase the low steam turbine capacity to produce work (Arena and Borchiellini, 1999; Serra, 1994). When the productive structure is defined by using exergy flows only, the desegregation of the desalination plant does not make any difference from the point of view of cost allocation to the final products (water and electricity), since each subsystem has only one product, which is the fuel of another desalination plant subsystem. Thus, in Figure 2, the desalination unit is represented by means of only one actual productive unit (E1:8-C-TC).

The productive structure (Figure 2) shows that some of the component (B, HP, LP, CP, D and H) inject exergy into the cycle and this exergy is consumed to produce electricity (in HT, LT-C and G) and water (in E1:8-C-TC). Part of the electricity produced is consumed in the plant itself.

The mathematical model for cost allocation is obtained by formulating the cost equations balance in each actual and fictitious units of the productive structure, as shows Eqn (2), where c is the monetary unit cost of each flow of the productive structure (unknown variable) and Y is a generical way to represent the flows of the productive structure, which can be electric power (P), natural gas (Q), desalted water (V) or exergy variation due to the exergy added to and removed from the working fluid (E). The variable Z is the hourly cost of each unit due to the capital cost (including civil works), operation and maintenance.

$$\sum (c_{out} \cdot Y_{out}) - \sum (c_{in} \cdot Y_{in}) = Z \tag{2}$$

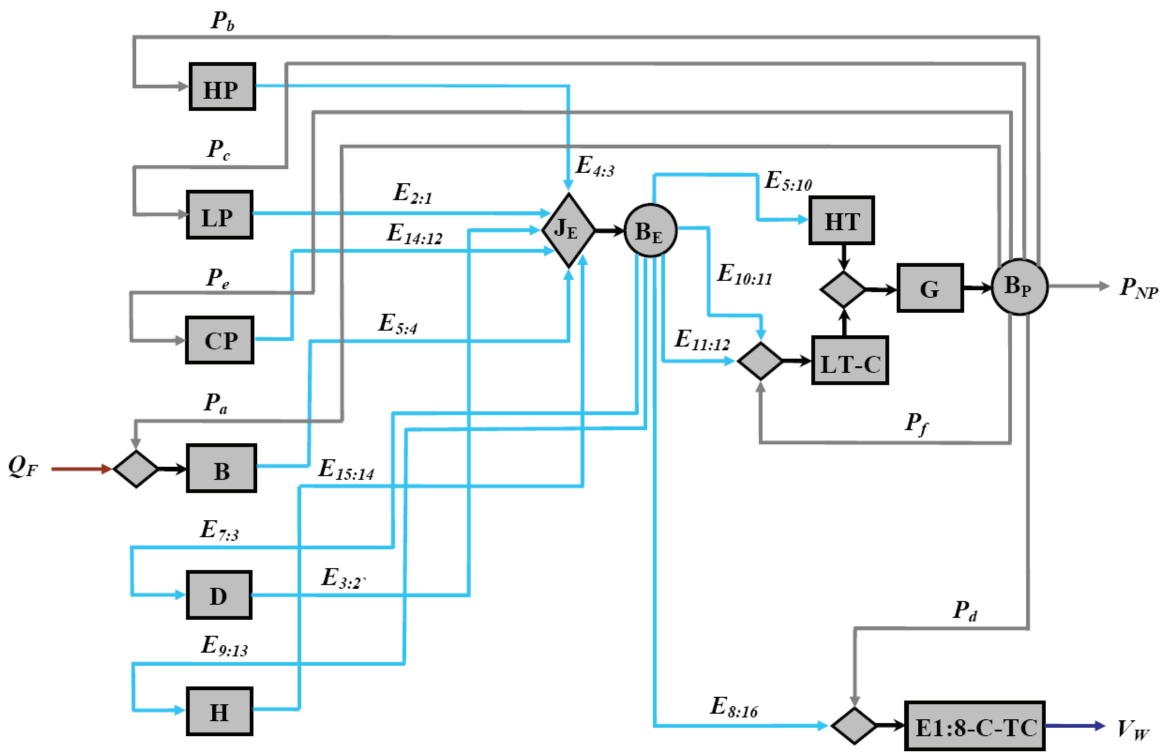

Figure 2. Productive Structure of the Dual-Purpose Plant considering Total Exergy Only (E Model).

Once the number of flows is always greater than the number of units (real and fictitious), in order to determinate the set of cost equations some auxiliary equations are needed. The auxiliary equations attribute the same exergetic unit cost to all of the flows leaving the same unit. In this case, only the bifurcations have more than one exit flow. Thus, the auxiliary equation is formulated only in the two bifurcations (B_E and B_P). This is the common rules used (or accepted) by all thermoeconomic practitioners to formulate the auxiliary equations in thermoeconomics.

Equation (3) is obtained by modifying Eqn (2) in order to formulate cost balance to provide the exergetic unit cost (k) of each flow of the productive structure. In this case, the hourly cost of the subsystem due to the capital cost, operation and maintenance must be neglected ($Z = 0$) and the monetary unit cost of the natural gas is replaced by the exergetic unit cost of an external resource, which is equal 1.00 kW/kW. The auxiliary equations are the same as used to obtain the monetary unit cost of the internal flows.

$$\sum(k_{out} \cdot Y_{out}) - \sum(k_{in} \cdot Y_{in}) = 0 \tag{3}$$

Table 2 shows the values of the flows of the productive structure shown in Figure 2, as well as their respective monetary and exergetic unit cost obtained by solving the set of equation defined by the E Model (exergy flow only).

The monetary unit cost of an internal flow or a final product in a plant is the amount of money consumed to generate one unit of this flow, which takes into account the economic cost of the consumed fuel (i.e., the market price) as well as the cost of the installation and the operation of the plant. This cost could be considered as a measure of the economic efficiency of a process (Valero et al., 2006).

The exergetic unit cost of a flow in a plant represents the amount of external resource (in terms of exergy) required to obtain one unit of this flow, e.g., the exergetic unit cost of the net power is the exergy provided by the natural gas to generate each unit of the power. This cost is a measure of the thermodynamic efficiency of the production process generating a flow. Thus, if the exergetic unit cost of the electricity is three, it means that three units of plant exergy resources are consumed to obtain one unit of electrical power (Valero et al., 2006). Considering that all real processes are irreversible, the exergetic unit cost of the internal flows should be greater than one (kW/kW or kJ/kJ).

Usually, the unit of the exergetic unit cost is kJ/kJ. Other units can also be used according to the specific situation. In a dual-purpose system, the interest is in the quantity of the produced fresh water, not its exergy (Wang and Lior, 2007). Consequently, in this analysis, the exergetic unit cost of desalted water has the unit of kWh/m^3. This unit represents the amount of natural gas exergy (in kWh) consumed in order to produce each unit of desalted water (in m^3).

According to Wang and Lior (2007), there are methods to set the range of exergetic unit cost of power and water in a dual-purpose power and desalination plant, based on the known thermodynamic advantage of cogeneration regarding the separated production of heat and power. The Heat-Generation-Favored method, in which power is assumed to be generated in a power-only plant, sets the upper limit of the exergetic unit cost of power. The Power-Generation-Favored method, in which the desalination unit is assumed to be run by the thermal energy from a conventional boiler with the auxiliary power obtained from a power plant, sets the upper limit of the exergetic unit cost of water. According to Wang and Lior (2007), an allocation method producing values outside this range will hence be unreasonable.

As mentioned above, when the analyzed dual-purpose power plant (Figure 1) operates as a power-only plant (in pure condensing mode), it produces 5,300 kW of net power and consumes 24,873 kW of fuel exergy. Consequently, the exergetic unit cost of power is 4.69 kW/kW. This value is the upper limit for the exergetic unit cost for the power in the analyzed plant when it operates as a dual-purpose plant.

Table 2. Unit Cost of the Internal Flows and Products of the Dual-Purpose Power Plant according to the E Model.

Flow	Value [kW]	Unit Cost	
		Exergetic, k [kW/kW]	Monetary, c [$/MWh]
$E_{1:2}$	0.14	9.17	2,963.77
$E_{3:2'}$	243.57	4.39	44.09
$E_{4:3}$	25.17	7.10	107.78
$E_{5:4}$	8,817.38	2.85	24.90
$E_{5:10}$	4,063.67	2.93	26.03
$E_{7:3}$	365.21	2.93	26.03
$E_{8:16}$	1,873.52	2.93	26.03
$E_{9:13}$	114.65	2.93	26.03
$E_{10:11}$	2,372.30	2.93	26.03
$E_{11:12}$	331.80	2.93	26.03
$E_{14:12}$	0.54	6.52	375.61
$E_{15:14}$	34.91	9.61	109.01
P_a	53.46	4.54	47.99
P_b	39.39	4.54	47.99
P_c	0.29	4.54	47.99
P_d	200.00	4.54	47.99
P_e	0.77	4.54	47.99
P_f	6.09	4.54	47.99
P_{NP}	4,075.00	4.54	47.99
V_W	100.00*	63.92**	1.20***

*[m^3/h] **[kWh/m^3] ***[$/m^3]

If the desalination unit is run by the thermal energy from a conventional boiler with the auxiliary power obtained from the dual-purpose plant operating in pure condensing mode, the exergetic unit cost of water would be 97.46 kWh/m^3. This value is the upper limit for the exergetic unit cost for the water in the analyzed plant when it operates as a dual-purpose power plant. The operation of the convectional boiler was simulated using the Thermoflex Software and considering the same boiler thermal efficiency of the dual-purpose power and desalination plant.

The fact that the exergetic unit cost of each internal flow is greater than 1.00 kW/kW, and the exergetic unit cost of the final products (power and water) does not contradict the well known energetic advantages of cogeneration, the approach that defines the productive structure of the dual-purpose power and desalination plant using exergy flow only (E Model) can be considered as a consistent approach. However, this model does not permit the isolation of the condenser to carry out a local optimization and diagnosis of malfunctions. This is the limitation of the E Model.

3.2 E&S Model: Negentropy as a Fictitious Flow

When negentropy flow is used in order to define the productive structure, the condenser can be isolated from the low pressure steam turbine, because this magnitude allows defining the product for this dissipative component. Figure 3 shows the productive structure of the dual-purpose power and desalination plant using the negentropy as a fictitious flow, joined up with exergy (E&S Model).

This kind of productive structure using the negentropy and the exergy flows was introduced in thermoeconomics through the Thermoeconomic Functional Analysis approach, developed by Frangopoulos (1987). This technique, which was originally utilized for optimization purposes, has been extended and used by other researchers (Lozano and Valero, 1993), in order to develop another approach (the Structural Theory of Thermoeconomics) aimed at both cost allocation and diagnosis of energy system (Lozano et al., 1996).

The steam cycle power plant analyzed by Lozano and Valero (1993) and by Frangopoulos (1987) was a simple Rankine power plant, i.e., without heaters and deaerator. In a simple Rankine power plant, the feeding pump and the boiler produce exergy. The steam turbine consumes part of this produced exergy to generate work. The operation of these units increases the entropy of the working fluid. This increase of entropy must be rejected to the environment through the condenser. In other words, the condenser provides the necessary negentropy for the correct cyclical operation of the system (Lozano and Valero, 1993).

According to Frangopoulos (1987), the condenser is supplying the system with the negative of entropy (negentropy, as introduced by Brillouin in 1962 and used by Smith in 1981 to quantify the function of the condenser). When the negentropy is introduced as a fictitious flow, joined up with the exergy flow, in order to define the productive structure, the costs associated with the condenser are distributed between all the productive units of the steam cycle that increase the working fluid entropy, instead of being charged only to the steam turbine.

By means of the Structural Theory of Thermoeconomics, the E&S Model was also applied for cost allocation (Zhang et al., 2006) and for thermoeconomic diagnosis (Valero et al., 2002; Zhang et al., 2007) of actual steam power plants. Uche et al. (2001) applied the E&S Model, by means of the Structural Theory of Thermoeconomics, in order to define the productive structure of an actual and complex dual-purpose power plant composed of heaters, deaerator, condensing steam turbine, and steam extraction to run the MSF (Multi-Stage Flash) desalination plant. Thus, besides the pumps, the boiler and the turbine, there are other subsystems that increase the working fluid entropy, such as the deaerator and the heaters (in the water side). In this case, besides the condenser, there are other subsystems that decrease the working fluid entropy, such as the desalination unit. The deaerator and the heaters also decrease the working fluid entropy (in the steam side). In other words, these subsystems and the condenser provide the necessary negentropy for the correct cyclical operation of the system.

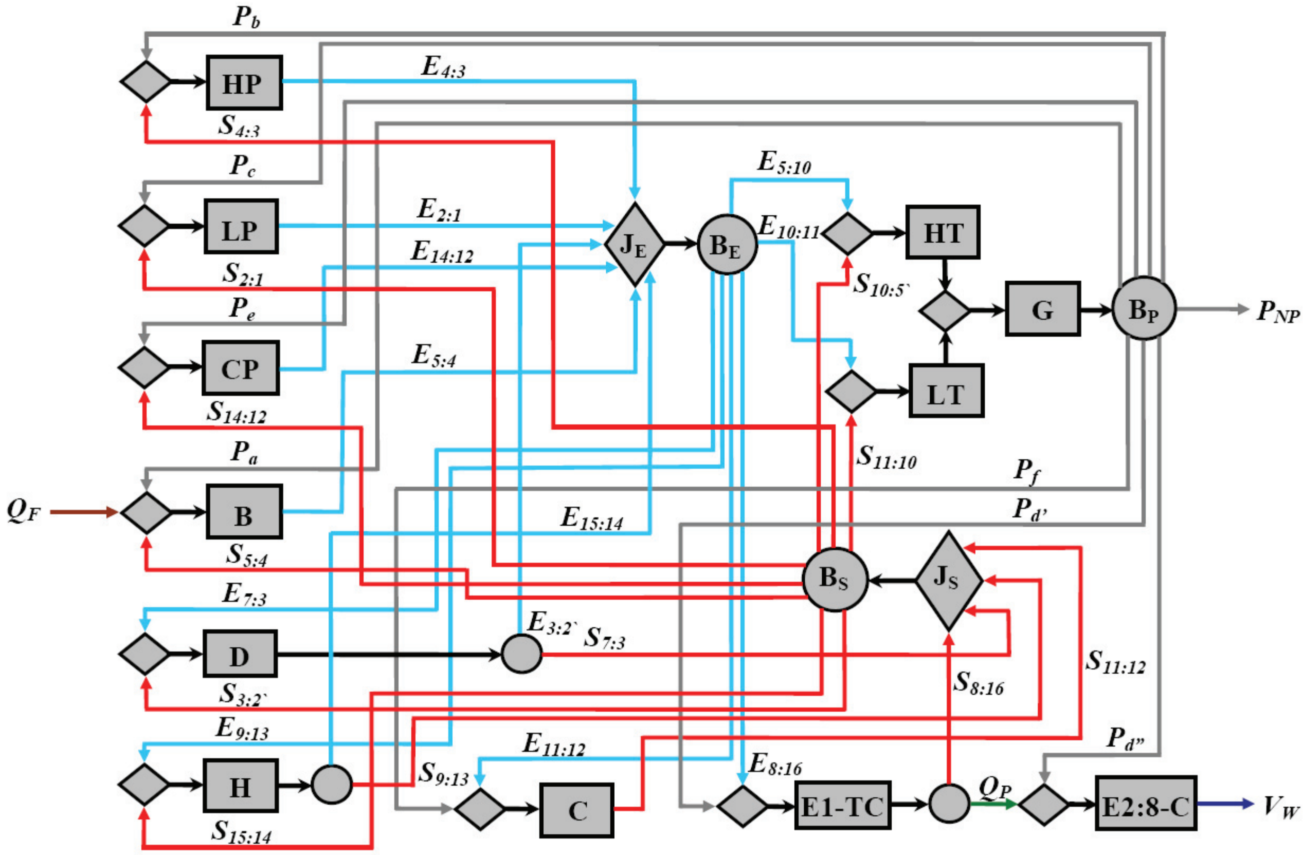

Figure 3. Productive Structure of the Plant considering Negentropy as a Fictitious Flow (E&S Model).

Comparing the productive structure defined with exergy flow only (Figure 2) to this one that include negentropy flow (Figure 3), some new flows and units appear: the negentropy flows ($S_{j:k}$), the bifurcation (B_S) and the junction (J_S) of negentropy, the condenser (C) separated from the low pressure steam turbine, and also the first effect (E1) and the thermal compressor (TC) are disaggregated from the desalination plant. In other words, the desalination plant is disaggregated into two units: the interface between the cogeneration and the desalination plant (E1-TC) and the remaining seven effects together with the auxiliary condenser (E2:8-C). Once the negentropy flows are included in the productive structure, the real productive units have small junctions to indicate that they have two types of fuel. The heater (H), the deaerator (D) and the interface (E1-TC) have small bifurcations to indicate that they have two outlet flows (negentropy and exergy).

The productive structure in Figure 3 graphically shows that the exergy flow ($E_{j:k}$ and $E_{j:k'}$) is defined as a product of the subsystems that increase the exergy of the working fluid. The subsystems that decrease the working fluid exergy have an exergy flow ($E_{j:k}$ and $E_{j:k'}$) as a fuel. On the other hand, the negentropy flow ($S_{j:k}$ and $S_{j:k'}$) is defined as a product of the subsystems that decrease the entropy of the working fluid. The subsystems that increase the working fluid entropy have a negentropy flow ($S_{j:k}$ and $S_{j:k'}$) as their fuel. Thus, the heater (H) and the deaerator (D) produce exergy and consume negentropy in the water side, while they produce negentropy and consume exergy in the steam side. The interface between the cogeneration and the desalination plant (E1-TC) decreases the exergy and the entropy of the working fluid, while it absorbs exergy, as useful heat (Q_P) to feed the distillation process in the remaining seven effects and in the auxiliary condenser (E2:8-C) of the desalination plant. In other words, the interface consumes exergy from the working fluid of the cogeneration plant, it absorbs the useful heat (exergy) to feed the desalination process and returns negentropy to the cogeneration cycle.

The negentropy flows ($S_{j:k}$ and $S_{j:k'}$) of the productive structure represent the negentropy added to and removed from the working fluid. They are defined based on physical flows, as show Eqns (4a) and (4b). The heat (exergy) absorbed to the process (Q_P) is calculated using the Eqn (5).

$$S_{j:k} = m_j \cdot T_0 \cdot (s_j - s_k) \tag{4a}$$

$$S_{j:k'} = m_k \cdot T_0 \cdot (s_j - s_k) \tag{4b}$$

$$Q_P = E_{8:1} \tag{5}$$

The mathematical model for cost allocation is obtained by formulating the cost equations balance in each actual and fictitious units of the productive structure, as described above in Section 3.1. Equation (2) and Eqn (3) allow formulating the cost equation balance in order to obtain the monetary and the exergetic unit cost of each internal flow of the productive structure, respectively. The E&S Model also uses the auxiliary equations that attribute the same unit cost to all of the flows leaving the same bifurcation (B_E, B_P and B_S). As mentioned above, in Section 3.1, these are the common rules used (or accepted) by all thermoeconomic authors to formulate the auxiliary equations. Because the heater (H), the deaerator (D) and the interface (E1-TC) have two types of outlet flows (exergy and negentropy), three other auxiliary equations are needed in order to determine the set of cost equations. There are two different ways to obtain these auxiliary equations: the Byproduct (Bp) and the Equality (Eq) criteria. Table 3 shows the values of the internal flows of the productive structure (Figure 3), as well as their respective monetary and exergetic unit cost obtained by solving the set of equation defined by the E&S Model, considering these two different criteria to attribute the unit cost to the negentropy flows.

The Byproduct (Bp) criterion considers that each plant subsystem can have only one product and the main function of these productive units is to produce exergy. Thus, the negentropy flows exiting these subsystems are considered byproducts. Therefore, these byproducts (negentropy flows) assume the same unit cost as the product of the condenser, which is the subsystem that produces only negentropy flow.

The Byproduct (Bp) criterion was proposed and used by the Structural Theory of Thermoeconomics approach to attribute cost to the negentropy flows in a dual-purpose power plant (Uche et al., 2001). This criterion was also applied to attribute unit cost to the thermal exergy flow produced by the compressor in a gas turbine cogeneration system (Lozano and Valero, 1993), because this approach considers that the product of the compressor is the mechanical exergy, and consequently, the thermal exergy is the byproduct, which is costed at the same unit cost as the product of the subsystems whose main function is to produce thermal exergy (air preheater and combustor).

Many authors (Tsatsaronis and Pisa, 1994; Torres et al., 1996; Wang and Lior, 2007) do not use the Byproduct criterion criteria, i. e., they attribute the same unit cost to the flows produced by the compressor (thermal and mechanical exergy), which is in accordance with one of the propositions of the Exergetic Cost Theory approach proposed by Valero et al. (1994).

The Equality (Eq) criterion considers that the flows that exit the same productive unit are products, which must have the same unit cost, since they were produced under the same resources and, consequently, under the same costs.

In Table 3, the exergetic unit cost of some internal flows is less than unity, because the products of some subsystems (the condenser and the interface) are greater than their fuels, which can be interpreted as an inconsistency. The value of the condenser product is more than 29 times its total fuel, and the total product of the interface is more than 4 times its total fuel. It is important to recognize that, according to the second law efficiency, the product of an actual subsystem (irreversible process) should be less than its fuel.

Comparing the unit costs of the final products obtained by the E Model (Table 2) to those obtained by the E&S Model (Table 3), the later overcharges the cost of power to the detriment of the cost of water, because the negentropy flows penalizes the steam turbine due to the increase of the working fluid entropy and awards the desalination plant (the interface) due to the reduction of the working fluid entropy.

Table 3. Unit Cost of the Internal Flows and Products of the Dual-Purpose Power Plant according to the E&S Model.

Flow	Value [kW]	Unit Cost			
		Exergetic, k [kW/kW]		Monetary, c [$/MWh]	
		Byproduct (Bp)	Equality (Eq)	Byproduct (Bp)	Equality (Eq)
$E_{1:2}$	0.14	9.35	11.17	2,966.08	2,984.23
$E_{3:2'}$	243.57	4.70	1.39	48.29	14.43
$E_{4:3}$	25.17	7.26	8.77	109.96	125.06
$E_{5:4}$	8,817.38	3.02	3.63	27.14	33.29
$E_{5:10}$	4,063.67	3.10	3.57	28.36	33.04
$E_{7:3}$	365.21	3.10	3.57	28.36	33.04
$E_{8:16}$	1,873.52	3.10	3.57	28.36	33.04
$E_{9:13}$	114.65	3.10	3.57	28.36	33.04
$E_{10:11}$	2,372.30	3.10	3.57	28.36	33.04
$E_{11:12}$	331.80	3.10	3.57	28.36	33.04
$E_{14:12}$	0.54	7.03	9.76	382.57	409.90
$E_{15:14}$	34.91	10.42	1.52	119.83	16.81
P_a	53.46	4.61	5.47	49.00	57.61
P_b	39.39	4.61	5.47	49.00	57.61
P_c	0.29	4.61	5.47	49.00	57.61
$P_{d'}$	25.00	4.61	5.47	49.00	57.61
$P_{d''}$	175.00	4.61	5.47	49.00	57.61
P_e	0.77	4.61	5.47	49.00	57.61
P_f	6.09	4.61	5.47	49.00	57.61
$S_{1:2}$	0.03	0.11	0.49	1.43	5.32
$S_{3:2'}$	1,265.42	0.11	0.49	1.43	5.32
$S_{4:3}$	10.53	0.11	0.49	1.43	5.32
$S_{5:4}$	13,819.79	0.11	0.49	1.43	5.32
$S_{10:5'}$	1,142.84	0.11	0.49	1.43	5.32
$S_{7:3}$	1,144.28	0.11	1.39	1.43	14.43
$S_{8:16}$	6,071.93	0.11	0.86	1.43	8.94
$S_{9:13}$	385.82	0.11	1.52	1.43	16.81
$S_{11:10}$	792.90	0.11	0.49	1.43	5.32
$S_{11:12}$	9,892.54	0.11	0.12	1.43	1.59
$S_{14:12}$	2.06	0.11	0.49	1.43	5.32
$S_{15:14}$	462.95	0.11	0.49	1.43	5.32
Q_P	1,873.52	2.82	0.86	28.47	8.94
P_{NP}	4,075.00	4.61	5.47	49.00	57.61
V_W	100.00*	60.85**	25.68**	1.16***	0.80***

*[m³/h]   **[kWh/m³]   ***[$/m³]

When the Equality (Eq) criterion is used to formulate the additional auxiliary equations, the value of the exergetic unit cost of power obtained by the E&S Model (5.47 kW/kW) is greater than the value defined above (in Section 3.1) as the upper limit for the exergetic unit cost of power (4.69 kW/kW) in this dual-purpose power plant. Therefore, this value of the exergetic unit cost of power contradicts the well known thermodynamic advantage of cogeneration. When these auxiliary equations are formulated by using the Byproduct (Bp) criterion, the negentropy flow that penalizes the steam turbine due to the increasing of the working fluid entropy assumes the low cost of the negentropy flow produced by the condenser. Therefore, the exergetic unit cost of power (4.61 kW/kW) is not greater than the upper limit for the exergetic unit cost of power (4.69 kW/kW).

3.2 H&S Model: Negentropy as an Exergy Component Flow

Figure 4 shows the productive structure defined for the dual-purpose power plant considering the negentropy as an exergy component flow. This model is a modification of the E&S Model aimed at avoiding the inconsistency and the unreasonable values cited above, i.e., the enthalpy flows ($H_{j:k}$ and $H_{j:k'}$) replaces the exergy flows ($E_{j:k}$ and $E_{j:k'}$).

The H&S Model is a recent thermoeconomic approach proposed by Santos et al. (2006). The authors of this model believe that, by using the negentropy joined up with the exergy (E&S Model), some productive subsystems (such as the turbines) are twice penalized due to the increase of the work fluid entropy, while others (such as the desalination plant) are twice awarded due to the reduction of the work fluid entropy, because the exergy flow already contains the term ($m.T_0.\Delta s$) that defines the negentropy flow and, consequently, there are productive units (such as the condenser and the interface) whose the fuels are less than the products, which, from the thermodynamic point of view, can be interpreted as an inconsistency. This inconsistency is avoided by using the negentropy flow ($m.T_0.\Delta s$) joined up with the enthalpy flow ($m.\Delta h$) to define the productive structure. The combination of these two magnitudes defines the physical exergy, as shown in Eqns (1a) and (1b).

By considering the negentropy as an exergy component flow, the H&S Model takes all the advantages due to the use of negentropy flow to define the productive structure, i.e., this model allows defining the product of the condenser and, consequently, to isolate this dissipative component.

According to Valero et al. (1995), the fuels and the products (productive structure) of a system must be defined based in the trajectories that the flows describe in the (h,s) plane when they work for the specific purpose of the plant. Valero et al. (2006) stated that, although the magnitude applied by most thermoeconomic approaches are exergy, negentropy and money, other magnitudes, like enthalpy and entropy, can also be used. Lazzaretto and Tsatsaronis (2006) aimed at proposing a systematic and general methodology for calculating efficiency and cost in thermal systems. Other authors (Tsatsaronis and Pisa, 1994; Frangopoulos, 1994) define the productive structure by using physical exergy disaggregated into thermal and mechanical components flows. But, this kind of disaggregation does not allow the isolation of the dissipative component (e.g., the condenser). Furthermore, according to Lazzaretto and Tsatsaronis (2006), this splitting might not be always meaningful because of the arbitrariness that might be involved in the separate calculation of mechanical and thermal exergies, particularly when working fluids that can change phases are used in the process being considered. Alves and Nebra (2003) stated

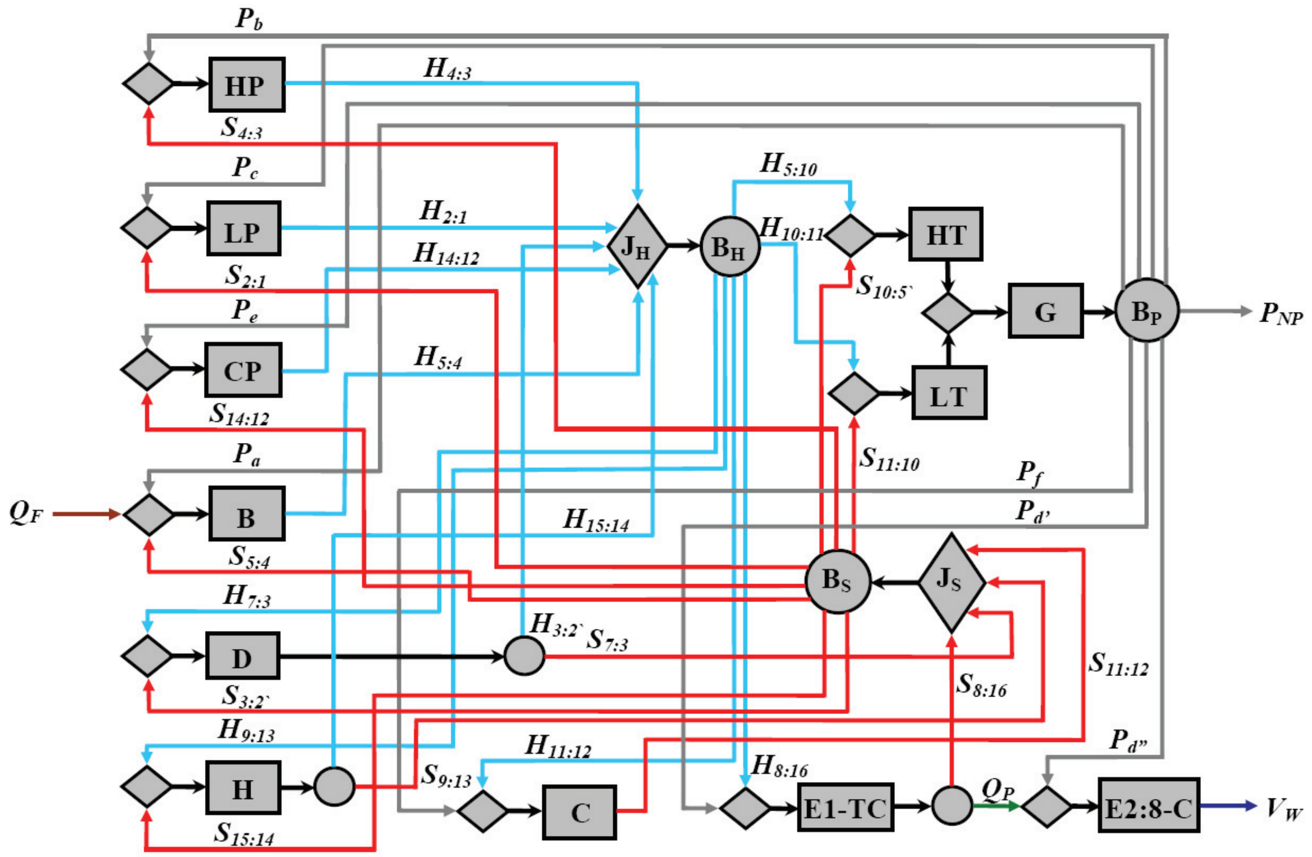

Figure 4: Productive Structure of the Plant considering Negentropy as an Exergy Component Flow (H&S Model).

that physical exergy has two components, the enthalpy and the negentropy. However, the H&S Model, proposed by Santos et al. (2006), was the first approach to propose the productive structure by splitting the physical exergy into enthalpy and negentropy.

The products and the fuels of each equipment, in terms of enthalpy ($H_{j:k}$ and $H_{j:k'}$), are defined by the Eqns (6a) and (6b), according to the quantity of this magnitude added to and removed from the working fluid, respectively.

$$H_{j:k} = m_j \cdot (h_j - h_k) \tag{6a}$$

$$H_{j:k'} = m_k \cdot (h_j - h_k) \tag{6b}$$

Once the negentropy is the negative of entropy, the equipments that decrease the working fluid entropy are negentropy producers, and those that increase the entropy of the working fluid are negentropy consumers. Thus, the H&S Model awards credit to the processes that decrease the working fluid entropy; and penalizes those that increase the working fluid entropy. The heater (H) and the deaerator (D) produce enthalpy and consume negentropy on the water side, while they produce negentropy and consume enthalpy on the steam side. The interface between the cogeneration and the desalination plant (E1-TC) decreases the enthalpy and the entropy of the working fluid, while it absorbs exergy as useful heat (Q_P) to feed the distillation process in the remaining seven effects and in the auxiliary condenser (E2:8-C) of the desalination plant. In other words, the interface consumes enthalpy from the working fluid of the cogeneration plant; absorbs useful heat (exergy) to the desalination process; and returns negentropy to the cogeneration cycle. The product of the condenser (C) is the negentropy, but its fuel is the enthalpy.

The mathematical model for cost allocation is obtained by formulating the cost equations balance in each actual and fictitious unit of the productive structure, as described above in Section 3.1. Equation (2) and Eqn (3) allow formulating the cost equation balance in order to obtain the monetary and the exergetic unit cost of each internal flow of the productive structure, respectively. The H&S Model also uses the auxiliary equations that attribute the same exergetic unit cost to all of the flows leaving the same bifurcation (B_H, B_P and B_S).

Because both enthalpy and negentropy are considered as physical exergy component flows, in order to formulate the additional auxiliary equations that attribute cost to the flows exiting the same subsystem (heater, deaerator and interface), the H&S Model uses the same criterion adopted by other authors (Tsatsaronis and Pisa, 1994; Torres et al., 1996; Wang and Lior, 2007) to attribute cost to the mechanical and thermal exergy produced by the compressor of a gas turbine cogeneration plant, i.e., the Equality (Eq) criterion. The H&S Model considers that the flows that exit the same productive unit are both products, which must have the same unit cost, because they were produced under the same resources and, consequently, under the same costs. This criterion is also in accordance with one of the propositions of the Exergetic Cost Theory (Valero et al., 1994). In the H&S Model, each internal flow of the productive structure should be costed directly by the subsystem that produces it, as function of the resources consumed by this subsystem.

Although the authors of the H&S Model do not agree with the Byproduct (Bp) criterion to formulate the auxiliary cost equations, in this paper this criterion is also applied to the H&S Model in order to compare their results. The Byproduct (Bp) criterion considers that each plant subsystem can only have one product. Thus, the negentropy flows exiting the heater, the deaerator and the interface are byproducts, which must be costed at the unit cost as the negentropy produced by the condenser.

Table 4 shows the values of the internal flows of the productive structure (Figure 4), as well as their respective monetary and exergetic unit cost obtained by the H&S Model, considering these two different criteria to attribute the unit cost to the negentropy flows. The exergetic unit cost of the internal flows is greater than unity, because the products of the subsystems are less than their fuels. The criterion (Byproduct or Equality) used in order to formulate the additional auxiliary equations does not make significant differences in the unit cost of the internal flows.

Comparing the unit costs of the final products obtained by the E&S Model (Table 3) to these obtained by the H&S Model (Table 4), when the auxiliary equations are formulated based on the Byproduct (Bp) criterion, the unit cost (monetary and exergetic) of the two final products (power and water) are practically the same for both models, i.e., the auxiliary equation using the Byproduct criterion is more relevant than the thermodynamic magnitude used to define the fuel and the product of the subsystem. Therefore, the use of the Byproduct criterion to formulate the auxiliary equations can be interpreted as a way to disguise any thermodynamic inconsistency during the definition of the fuel and products in thermoeconomics.

Comparing the unit costs (exergetic and monetary) of the final products by the E Model (Table 2) to these by the H&S Model (Table 4), the results are similar. The small difference is due to the purposes defined for the interface (E1-TC) and the condenser (C). The E Model allocates the costs associated with the condenser to the power only and the costs associated with the interface to the water only. In the H&S Model, the costs associated with the interface are allocated to the two products and the costs of the condenser are redistributed through the negentropy flows.

The exergetic unit cost of power obtained by the H&S Models using the Byproduct (4.61 kW/kW) and the Equality (4.51 kW/kW) criterion to formulate the additional auxiliary equations is not greater than the upper limit (4.69 kW/kW) for the exergetic unit cost of power.

4. Comparison of the H&S Model with Other Approaches

Different thermoeconomic methodologies can provide different cost values when they define different productive structures. At this point a question arises: What are the best cost values? Validation of cost is a key issue in thermoeconomics which has not been properly solved yet. However, we consider that validation procedure of cost can be designed using the physical behavior of the plant together with thermodynamics, because irreversibility is the physical magnitude generating the cost (Valero et al., 2006).

Figure 5 shows and compares the exergetic unit cost of desalted water and net electric power produced by the dual-purpose power and desalination plant, obtained by the application of each of the methodologies. The higher the unit cost of power, the lower the unit cost of water, and vice-versa.

As explained above (see Section 3.1 for details), there are methods to set the range of exergetic unit cost of power and water in a dual-purpose power and desalination power

Table 4. Unit Cost of the Internal Flows and Products of the Dual-Purpose Power Plant according to the H&S Model.

Flow	Value [kW]	Unit Cost			
		Exergetic, k [kW/kW]		Monetary, c [$/MWh]	
		Byproduct (Bp)	Equality (Eq)	Byproduct (Bp)	Equality (Eq)
$H_{1:2}$	0.17	8.35	8.16	2,499.06	2,498.46
$H_{3:2'}$	1,508.99	3.36	3.22	31.57	30.57
$H_{4:3}$	35.70	6.03	5.89	85.87	85.44
$H_{5:4}$	22,637.17	3.07	3.01	27.88	27.75
$H_{5:10}$	2,920.82	3.10	3.04	28.36	28.12
$H_{7:3}$	1,509.49	3.10	3.04	28.36	28.12
$H_{8:16}$	7,945.45	3.10	3.04	28.36	28.12
$H_{9:13}$	500.47	3.10	3.04	28.36	28.12
$H_{10:11}$	1,579.41	3.10	3.04	28.36	28.12
$H_{11:12}$	10,224.33	3.10	3.04	28.36	28.12
$H_{14:12}$	2.60	3.91	3.81	101.38	101.11
$H_{15:14}$	497.86	3.61	3.36	34.77	32.35
P_a	53.46	4.61	4.51	48.99	48.66
P_b	39.39	4.61	4.51	48.99	48.66
P_c	0.29	4.61	4.51	48.99	48.66
$P_{d'}$	25.00	4.61	4.51	48.99	48.66
$P_{d''}$	175.00	4.61	4.51	48.99	48.66
P_e	0.77	4.61	4.51	48.99	48.66
P_f	6.09	4.61	4.51	48.99	48.66
$S_{1:2}$	0.03	3.21	3.12	29.78	29.56
$S_{3:2'}$	1,265.42	3.21	3.12	29.78	29.56
$S_{4:3}$	10.53	3.21	3.12	29.78	29.56
$S_{5:4}$	13,819.79	3.21	3.12	29.78	29.56
$S_{10:5'}$	1,142.84	3.21	3.12	29.78	29.56
$S_{7:3}$	1,144.28	3.21	3.22	29.78	30.57
$S_{8:16}$	6,071.93	3.21	3.05	29.78	29.24
$S_{9:13}$	385.82	3.21	3.36	29.78	32.35
$S_{11:10}$	792.90	3.21	3.12	29.78	29.56
$S_{11:12}$	9,892.54	3.21	3.14	29.78	29.55
$S_{14:12}$	2.06	3.21	3.12	29.78	29.56
$S_{15:14}$	462.95	3.21	3.12	29.78	29.56
Q_P	1,873.52	2.82	3.05	28.48	29.24
P_{NP}	4,075.00	4.61	4.51	48.99	48.66
V_W	100.00*	60.88**	65.08**	1.16***	1.17***

*[m³/h] **[kWh/m³] ***[$/m³]

plant, based on the well known thermodynamic advantage of cogeneration regarding the separated production of heat and power. According to Wang and Lior (2007), an allocation method producing values outside this range will hence be unreasonable. The analyzed dual-purpose power and desalination plant operating as a power-only plant sets the upper limit for the exergetic unit cost of net power (4.69 kW/kW), and the same desalination unit running by the thermal energy from a conventional boiler with the auxiliary power obtained from the power-only plant sets the upper limit for the exergetic unit cost of water (97.46 kWh/m^3).

Figure 5 shows that the E&S Model, with the auxiliary equation formulated based on the Equality (Ep) criterion, obtains exergetic unit cost of the final products outside the acceptable range, according to the well known energetic advantage of cogeneration. In other words, this approach (E&S-Eq) contradicts the known thermodynamic advantage of cogeneration. According to this indicator, the remaining approaches are reasonable, because they obtain exergetic unit costs of power less than 4.69 kW/kW, and exegetic unit costs of water less than 97.46 kWh/m^3.

Regarding the exergetic unit cost of other internal flows (Tables 2, 3 and 4), the E&S Model (E&S-Eq and E&S-Bp) produces some exergetic unit cost less than unity.

The exergetic unit cost less than unity seems strange regarding the concept of cost formation process in thermoeconomics. According to Valero et al. (2006), irreversibility is the physical magnitude generating the cost. The unit cost of the fuel entering the plant is unity because there is no exergy destruction before the productive process is performed (Valero et al., 2006). Since the actual processes are irreversible, the exergetic unit cost of the internal flows and product should be greater than unity. Therefore, in a reversible plant, the exergetic unit cost of the internal flows and final products should be equal unity.

In the E&S Model, the exergetic unit cost of some internal flows (Table 3) is less than unity, because the products of some subsystems (condenser and interface) are greater than their fuels, which can be interpreted as an inconsistency. According to the second law efficiency, the product of an actual subsystem (irreversible process) should be less than its fuel (Çengel and Boles, 2006). In the E&S Model, the condenser produces negentropy and consumes exergy. Thus, its product-fuel efficiency defined by the Eqn (7a) is greater than 100%, i.e., its efficiency is 2,981.50 %.

$$\eta_C^{E\&S} = 100 \cdot \frac{S_{11:12}}{E_{11:12}} \tag{7a}$$

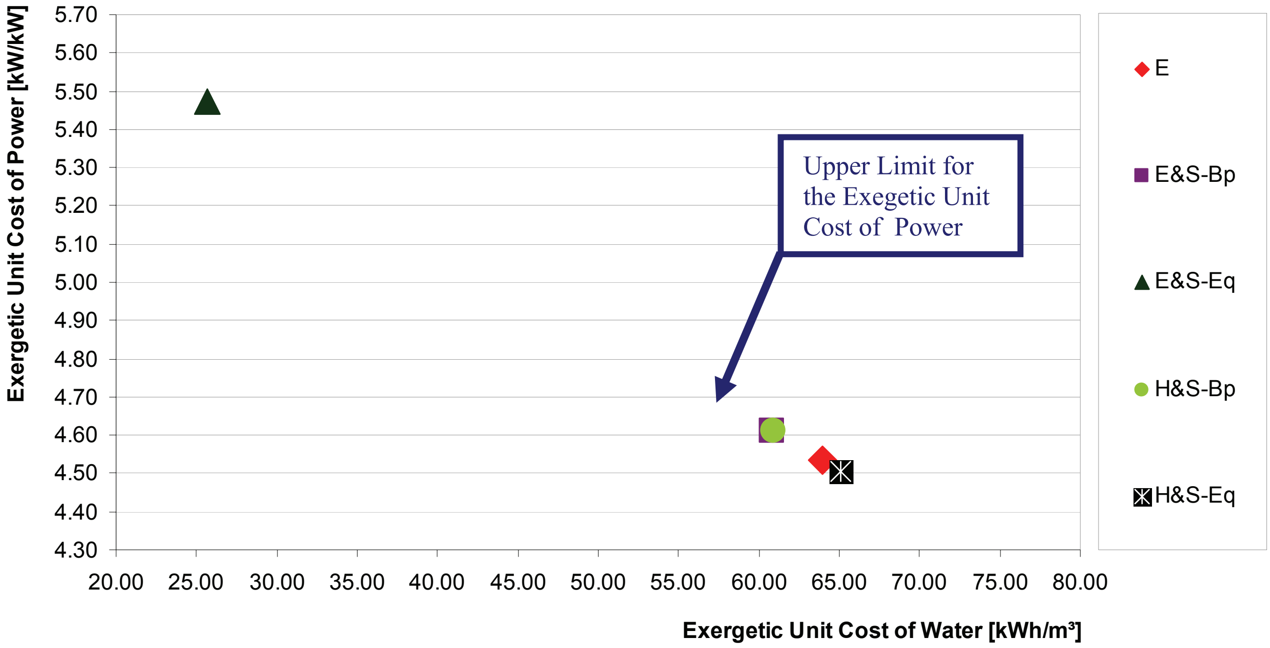

Figure 5. Exergetic Unit Cost of Power and Water obtained by the use of Different Methodologies.

The fuel and the product of the subsystems must be defined by taking into account that the second-law efficiency ranges from zero for a totally irreversible process to 100 percent for a totally reversible process (Çengel and Boles, 2006). On the other hand, the product-fuel efficiency of the condenser, according to the H&S Model, as shown by Eqn (7b), is 96.75 %. This value of efficiency means that 3.25 % of the exergy is dissipated.

$$\eta_C^{H\&S} = 100 \cdot \frac{S_{11:12}}{H_{11:12}} \tag{7b}$$

The negentropy and the enthalpy, as the product and the fuel of the condenser (respectively), seem more consistent, since the condenser efficiency in an actual steam power cycle will always be lower than 100%, and this efficiency would only be 100% if it were possible to transfer heat in the condenser at the same temperature, i.e., if the condensation temperature and the reference temperature were the same (in a reversible steam power cycle).

Lozano et al. (1993) also used Eqn (7b) to define the condenser efficiency. Contradictorily, Lozano et al. (1993) defined a productive structure using the E&S Model where the condenser fuel is the exergy dissipated. According to Çengel and Boles (2006), efficiency is defined as the ratio of the desired result for an event to the input required to accomplish such event. According to Moran and Shapiro (2004), efficiency gauges how effectively the input is converted to the product and the value of the second law efficiency is generally less than 100%.

The H&S Model can easily justify quantitatively the function of the interface between the cogeneration and the desalination plant (E1-TC): it receives 7,945.45 kW of fuel ($H_{8:16}$) from the cogeneration plant, out of which 1,873.52 kW are absorbed as useful heat exergy to the desalination process (Q_U) and 6,071.93 kW are retuned as negentropy ($S_{8:16}$) to the cogeneration cycle. According to the E&S Model, the products of the interface ($S_{8:16}$ = 6,071.93 kW and Q_U = 1,873.52 kW) are greater than its fuel ($E_{8:16}$ = 1,873.52 kW), as shown by Eqn (8).

$$H_{8:16} - S_{8:16} = Q_P = E_{8:16} \quad \text{and} \quad S_{8:16} >> E_{8:16} \tag{8}$$

This discussion using Eqns (7a), (7b) and (8) justify the inconsistencies of the E&S Model regarding the fuel and the product definition. Consequently, the exergetic unit cost of some internal flows is less than unity. By applying the negentropy flows joined up with the exergy flows, the model that considers the negentropy as a fictitious flow uses the term that defines the negentropy flow twice because this term ($T_0.\Delta s$) is already in the exergy flow. Thus the condenser and the interface are awarded twice due to the reduction of the working fluid entropy, as shown by Eqns (7a) and (8). Therefore, the products of these subsystems are greater than their fuels. On the other hand, the E&S Model penalizes the steam turbines twice due to the increase of the working fluid entropy. According to the E&S Model, the product-fuel efficiency obtained by Eqn. (9) for the low pressure steam turbine is 49.90 %, since this model uses twice the flow $S_{11:10}$ as the fuel of the low steam turbine.

$$\eta_{LT}^{E\&S} = \frac{100 \cdot W_{LT}}{E_{10:11} + S_{11:10}} = \frac{100 \cdot W_{LT}}{(H_{10:11} + S_{11:10}) + S_{11:10}} \tag{9}$$

Eqn (10) shows that, according to the H&S Model, the product-fuel efficiency of the low pressure turbine coincides with the well known exergetic efficiency, which is 66.58 %.

$$\eta_{LT}^{H\&S} = \frac{100 \cdot W_{LT}}{H_{10:11} + S_{11:10}} = \frac{100 \cdot W_{LT}}{E_{10:11}} = \eta_{LT}^{E} \tag{10}$$

This discussion about the efficiency of the subsystem and the reasonable value for the exergetic unit cost of the internal flows shows that, using the exergy disaggregated into enthalpy and negentropy, the H&S Model proposed by Santos et al. (2006) takes all the well known and recognized advantages of the negentropy application and avoids the inconsistencies of the E&S Model regarding the subsystem fuels and products definition in thermoeconomics.

One of the advantages of the H&S Model, with respect to the model that uses total exergy only (E Model), is the isolation of the dissipative component (e.g., the condenser) to define the productive structure, which was not possible using total exergy only. Furthermore, the disaggregation of physical exergy in enthalpy and negentropy improves the accuracy of the results in the thermoeconomics analysis. Although the consideration of the physical exergy separated into its chemical, thermal and mechanical component also improves the accuracy of the results, this splitting might not be always meaningful because of the arbitrariness that might be involved in the separate calculation of mechanical and thermal exergies, particularly when working fluids that can change phase are used in the process being considered (Lazzaretto and Tsatsaronis, 2006). On the other hand, the physical exergy disaggregated into thermal and mechanical components (without the negentropy concept) does not solve the problem of cost apportioning of the condenser.

With respect to the idea of a systematic and general procedure for fuel and product definition and for calculating efficiencies and costs in thermal systems, the authors of the H&S Model agree with Lazzaretto and Tsatsaronis (2006) that there is a significant need for using, at the component level, an unambiguous thermoeconomic procedure that is independent of the purpose of the analysis and independent of the system configuration. In this aspect, the H&S Model has advantages with respect to the other approaches, since it is applicable to any thermal system and allows the isolation of the condenser during the optimization or diagnosis. The E&S Model joined up with the Byproduct (Bp) criterion for cost attribution (E&S-Bp), is not applicable to a back pressure cogeneration plant because there is no condenser. When the Equality (Eq) criterion is used to attribute cost to the negentropy flows, this approach (E&S-Bp) overcharges the unit cost of power and the value obtained for the exergetic unit cost contradicts the known thermodynamic advantages of cogeneration (Santos et al., 2008b).

According to Valero et al. (1995), the cost, efficiency and behavior of the system are based in the trajectory in the (h,s) plane any flow performs when it works for the specific purpose of the plant. The H&S Model defines the products and the fuels of the system based on the enthalpy ($m.\Delta h$) added to and removed from the working fluid, and also based on the negentropy ($m.T_0.\Delta s$) due to the decrease and the increase of the working fluid entropy – a pure combination of first and second law of thermodynamic, which defines the physical exergy concept. Therefore, the H&S Model is applicable to any thermodynamic cycle whose processes can be represented in the (h,s) plane, including a reversible steam power cycle. The E&S Model does not allow the definition of the productive structure of a reversible steam power cycle once there is no dissipated exergy in the condenser. Consequently, any thermoeconomic approach considering the exergy dissipated as the fuel or the product of the condenser is not applicable to a reversible steam power cycle. The approach using exergy flow only (E Model) is applicable to a reversible steam power cycle, however, the condenser and the turbine should be analyzed as a single unit, because this thermoeconomic approach does not allow defining the product of the reversible condenser.

Because auxiliary equations in thermoeconomics are unavoidable and they may be more or less arbitrary (Tsatsaronis and Pisa, 1994), the H&S Model reduces the arbitrariness in thermoeconomics because only one criterion is adopted to attribute cost. The Equality (Eq) criterion is used to cost the flows exiting the same bifurcation and also to cost flows exiting the same subsystem. This criterion is in accordance with one of the propositions of the Exergetic Cost Theory (Valero et al., 1994), and is also used by other authors (Tsatsaronis and Pisa, 1994; Torres et al., 1996; Wang and Lior, 2007) to attribute cost to the thermal and mechanical exergy produced by the compressor and other subsystems having more than one product (Lazzaretto and Tsatsaronis, 2006). The E Model uses the Equality (Eq) criterion to cost the flows exiting the same bifurcation. The E&S Model uses the Equality criterion in the bifurcation, but uses the Byproduct (Bp) criterion in the subsystems that have two or more exit flows. The Byproduct (Bp) criterion costs the flows exiting a subsystem at the same cost as the cost of a flow exiting another subsystem. This criterion can be interpreted as arbitrary since it contradicts the purpose of the isolation principle. Furthermore, this criterion is not applicable to any system (Santos et al., 2008b).

5. Closure

Exergy is an adequate thermodynamic property to associate with cost because it contains information from the second law of thermodynamics. In order to improve the accuracy of the results, sometimes, under a thermoeconomic analysis point of view, it is necessary to disaggregate the exergy into thermal, mechanical and chemical components.

Because the exergy flow only (E Model) does not allow isolation of the condenser in a steam power plant in order to apportion its cost to the productive component and products of the system, it is necessary to include the negentropy flow in the productive structure. The use of negentropy flow in thermoeconomics represented a great advance in the discipline, because it allowed one to quantify the condenser product, which was not possible before because the product of the condenser cannot be expressed in terms of exergy.

However, when the negentropy is applied as a fictitious flow, joined up with the exergy flows (E&S Model), the term that defines the negentropy ($m.T_0.\Delta s$) is used twice because this term is already present in the exergy flow. Therefore, this approach penalizes the steam turbines twice due to the increase of the working fluid entropy, while the subsystems that decrease the working fluid entropy (the condenser and the desalination plant) are awarded twice. Thus, the condenser and the desalination plant products are greater than their fuels, i.e., the E&S Model suggest that the efficiency of these two subsystems is greater than 100%, which can be interpreted as an inconsistency. Consequently, the E&S Model obtains unreasonable values of exergetic unit cost for the internal flow and product.

On the other hand, when the negentropy is applied as an exergy component flow joined up with enthalpy (H&S Model), the exergetic unit cost of the internal flows and final products is coherent, and there are no subsystems whose products is greater than the fuels. The unit cost of the final product obtained by the H&S Model is similar to the unit cost obtained by the model that uses total exergy flow only (E Model). The small difference between the unit costs of the final product obtained by these two models (H&S and E) is due to the isolation level by isolating the condenser and the interface between the cogeneration and the desalination plant. In the E Model, the condenser is analyzed together with the low pressure steam turbine, and the interface is included in the desalination plant. Comparing with the model that uses exergy flow only (E

Model), the model using the negentropy as an exergy component flow (H&S Model) incorporates both strategies used in order to improve the accuracy of the results during the thermoeconomic analysis: (i) the disaggregation of the exergy into its components; and, (ii) the use of negentropy.

This paper aims at opening a discussion about the negentropy application in thermoeconomics, since we believe the application of this magnitude, in order to quantify the condenser product, is elegant and properly based from a thermodynamic view point. However, we strongly believe that the second-law efficiency serves as a measure of approximation to reversible operation. Bearing this in mind, we define the second-law efficiency of a system as the product-fuel ratio. Therefore, when we define the fuel and the product during the thermoeconomic modeling, we take into account that the second-law efficiency ranges from zero (for a totally irreversible process) to 100 percent (for a totally reversible process). In this aspect, the product and the fuel of the subsystems, using the negentropy as an exergy component flow (H&S Model), are in accordance with this concept of second-law efficiency, and consequently, the H&S Model is a consistent thermoeconomic approach.

Nomenclature

C	Monetary Unit Cost [\$/kWh and \$/m^3]
E	Exergy Flow [kW]
H	Enthalpy Flow [kW]
H	Specific Enthalpy [kJ/kg]
K	Exergetic Unit Cost [kW/kW and kWh/m^3]
M	Mass Flow [kg/s]
P	Electrical Power [kW]
Q	Heat Exergy [kW]
S	Negentropy Flow [kW]
S	Specific Entropy [kJ/kg.K]
T	Temperature [K]
W	Mechanical Power [kW]
Y	Productive Structure Flow [kW and m^3/h]
Z	Hourly Cost of each Equipment [\$/h]

Greek

η	Efficiency [%]

Subscripts

C	Condenser
In	Inlet Flow
J	Physical Flow
j:k	From Flow *k* to Flow *j*
K	Physical Flow
LT	Low Pressure Steam Turbine
O	Reference (25^{o}C and 101,32kPa)
out	Outlet Flow
P	Absorbed to the Process (heat)

Superscripts

E	E Model
E&S	E&S Model
H&S	H&S Model

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