# ON THE ADEQUATE THERMODYNAMIC PROPERTY TO ASSOCIATE WITH COST IN THERMOECONOMICS FOR COST ALLOCATION IN A STEAM CYCLE DUAL-PURPOSE POWER AND DESALINATION PLANT

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***Abstract.*** *Most analysts agree that exergy, instead of enthalpy only, is the most adequate thermodynamic property to associate with cost since it contains information from the second law of thermodynamics and accounts for energy quality. A second law analysis allows locating and quantifies the irreversibilities. Most analysts are in favor of the negentropy application in thermoeconomics, since they believe that the application of this magnitude, in order to quantify the condenser product, is elegant and properly based from a thermodynamic view point. On the other hand, some thermoeconomic practitioners already 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. Aiming at evaluating the most adequate thermodynamic property to associate with cost in thermoeconomics, this work compares four different thermoeconomic approaches by applying them to cost allocation in a steam cycle dual-purpose power and desalination plant. The first approach defines the productive structure by using enthalpy flow only (H Model). The second uses exergy flow only (E Model). The third uses negentropy flow, joined up with exergy (E&S Model). The fourth uses enthalpy flow, joined up with negentropy (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). The results obtained from H Model overcharge the cost of water to the detriment of the cost of power. On the other hand, dependent on the criterion to formulate the auxiliary equations, the results obtained from E&S Model can overcharge the cost of power to the detriment of the cost of water. The costs of the final products obtained by H&S Model are the closest results in relation to the E Model, independent on the criterion to formulate the auxiliary equations.*

***Keywords****: Thermoeconomic Modeling, Thermodynamic Property, Cost Allocation, Exergy, H&S Approach.*

## 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 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, such as 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 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), also joined up with exergy, 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.

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 $-T_0.(s - s_0)$. By joining these ideas, Santos et al. (2006) proposed a new approach (H&S Model), in which the negentropy is applied together with the enthalpy (instead of exergy), i.e., negentropy is considered a physical exergy component. 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.

Aiming at evaluating the most adequate thermodynamic property to associate with cost in thermoeconomics, this work compares four different thermoeconomic approaches by applying them to cost allocation in a steam cycle dual-purpose power and desalination plant. The first approach defines the productive structure by using exergy flow only (E Model). The second uses enthalpy flow only (H Model). The third uses negentropy flow, joined up with exergy (E&S Model). The fourth uses enthalpy flow, joined up with negentropy (H&S Model). The goal is to determine the exergetic and the monetary unit cost of the internal flows and of the final products (electric net power and desalted water).

## 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 4,073 kW of electric net power and 2,400 $m^3$/day 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.

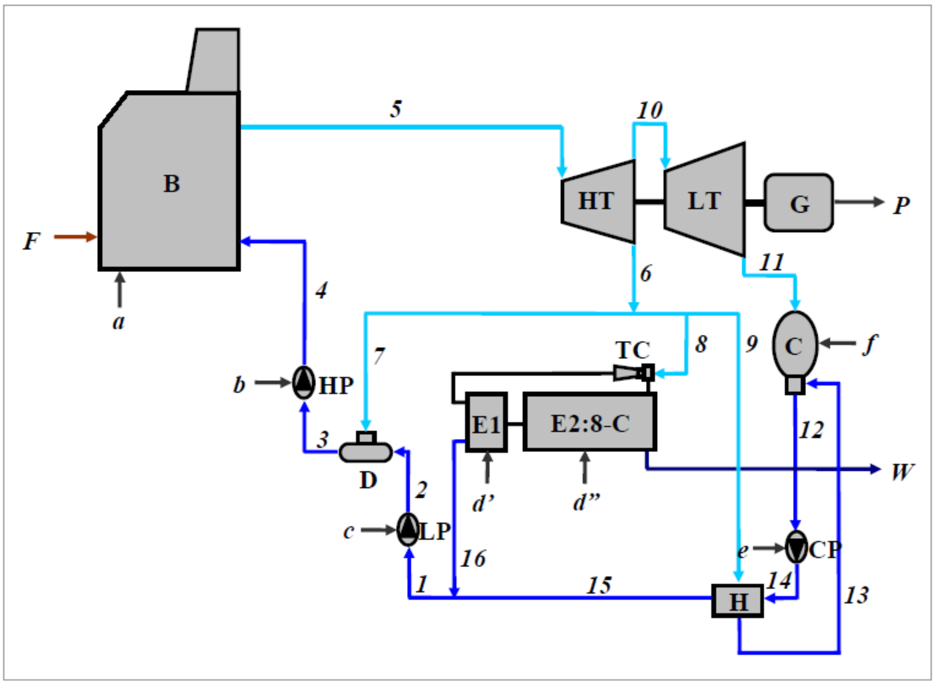


Figure 1. Physical Structure of the Dual-Purpose Power and Desalination Plant

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.

### 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 in Tab. 1.

Table 1. Distribution of the Cogeneration Plant Total Cost (Capital, Operation and Maintenance)

| 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 MODELING

The thermoeconomic model is a set of equations which describes the cost formation process of the system. 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, to define the productive structure, this paper considers four different models, i.e., four ways to define the internal flows.

### 3.1. E Model: Exergy Flow Only

Figure 2 shows the productive structure defined for the dual-purpose power plant. 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 Fig. 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 Eqs. (1a) and (1b).

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

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

Since 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 function of the condenser is to increase the low steam turbine capacity to produce work (Arena and Borchiellini, 1999; Serra, 1994). 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 Eq. (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. The variable *Z* is the hourly cost of each unit due to the capital cost (including civil works), operation and maintenance.

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

The number of flows is always greater than the number of units. Thus, some auxiliary equations attribute the same unit cost to all of the flows leaving the same unit. In this case, only the bifurcations ($B_E$ and $B_P$) have more than one exit flow. This is the common rules used (or accepted) by all thermoeconomic practitioners to define the auxiliary equations.

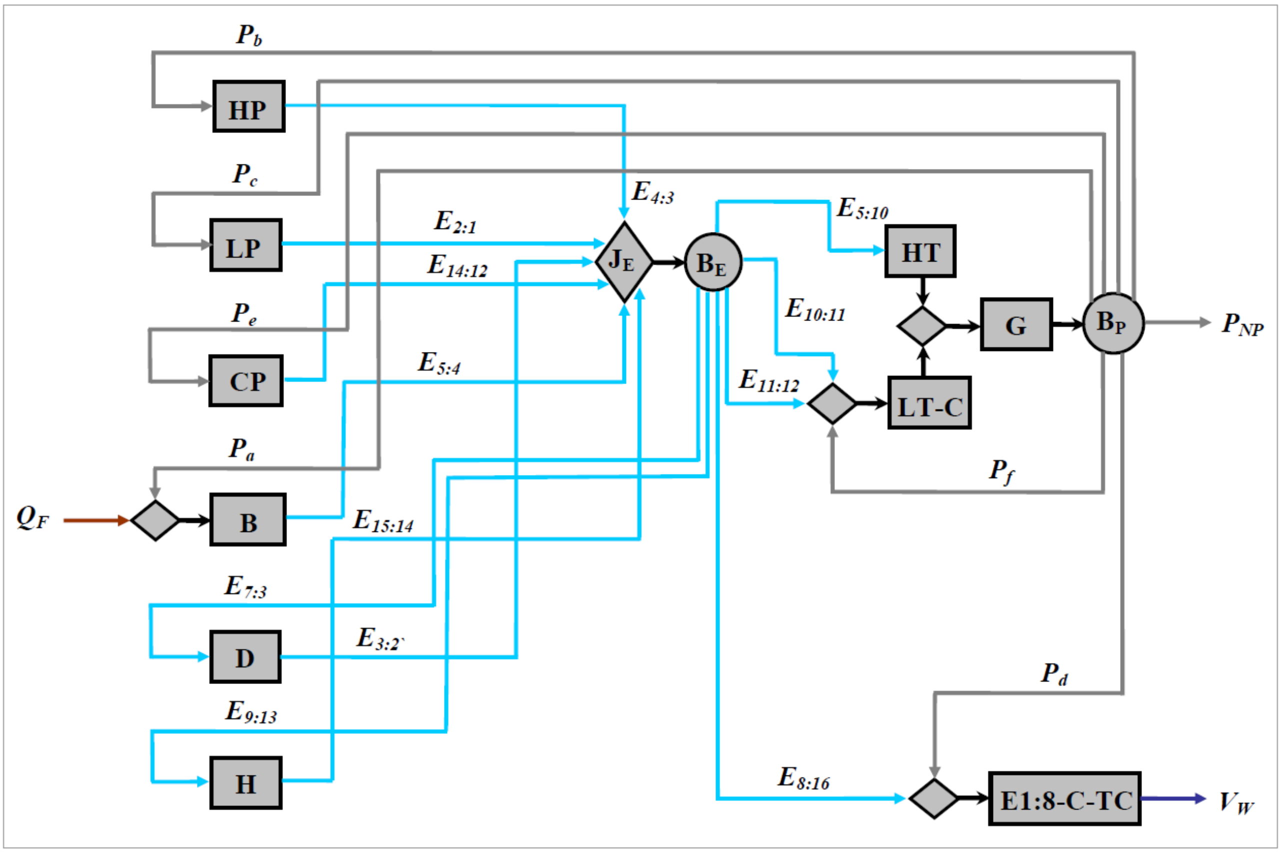


Figure 2. Productive Structure of the Dual-Purpose Plant considering Total Exergy Only (E Model)

Equation (3) is obtained by modifying Eq. (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.

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

Table 2 shows the values of the flows of the productive structure, as well as their respective monetary and exergetic unit cost obtained by solving the set of equation defined by the E Model.

### 3.2. H Model: Enthalpy Flow Only

The productive structure of the plant using enthalpy only (H Model) is basically de same obtained for the E Model that uses exergy only (Fig. 2). Comparing these two productive structures, the difference is that the exergy flows ($E_{j:k}$ and $E_{j:k'}$) of the productive structure of the E Model must be replaced by the enthalpy flows ($H_{j:k}$ and $H_{j:k'}$) in H Model.

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] |
| $E_{1:2}$ | 0.12 | 6.22 | 3,598.93 |
| $E_{3:2'}$ | 243.57 | 4.39 | 44.10 |
| $E_{4:3}$ | 25.17 | 7.10 | 107.78 |
| $E_{5:4}$ | 8,817.38 | 2.85 | 24.89 |
| $E_{5:10}$ | 4,063.67 | 2.93 | 26.04 |
| $E_{7:3}$ | 365.21 | 2.93 | 26.04 |
| $E_{8:16}$ | 1,873.52 | 2.93 | 26.04 |
| $E_{9:13}$ | 114.65 | 2.93 | 26.04 |
| $E_{10:11}$ | 2,372.30 | 2.93 | 26.04 |
| $E_{11:12}$ | 331.80 | 2.93 | 26.04 |
| $E_{14:12}$ | 0.54 | 24.56 | 566.37 |
| $E_{15:14}$ | 34.91 | 9.62 | 109.03 |
| $P_a$ | 53.46 | 4.54 | 48.00 |
| $P_b$ | 39.39 | 4.54 | 48.00 |
| $P_c$ | 0.16 | 4.54 | 48.00 |
| $P_d$ | 200.00 | 4.54 | 48.00 |
| $P_e$ | 2.90 | 4.54 | 48.00 |
| $P_f$ | 6.09 | 4.54 | 48.00 |
| $P_{NP}$ | 4,073.00 | 4.54 | 48.00 |
| $V_W$ | 100.00* | 63.94** | 1.20*** |

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

The mathematical model is obtained by formulating the cost equations balance in each actual and fictitious units of the productive structure, as described above for the E Model. Table 3 shows the values of the flows, as well as their respective monetary and exergetic unit cost obtained by solving the set of equation defined by the H Model.

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

| Flow | Value [kW] | Unit Cost | |
|---|---|---|---|
| | | Exergetic, *k* [kW/kW] | Monetary, *c* [$/MWh] |
| $H_{1:2}$ | 0.14 | 4.17 | 2,910.91 |
| $H_{3:2'}$ | 1,508.99 | 1.11 | 10.71 |
| $H_{4:3}$ | 35.70 | 4.14 | 68.28 |
| $H_{5:4}$ | 22,637.17 | 1.11 | 9.68 |
| $H_{5:10}$ | 2,920.82 | 1.11 | 9.89 |
| $H_{7:3}$ | 1,509.49 | 1.11 | 9.89 |
| $H_{8:16}$ | 7,945.45 | 1.11 | 9.89 |
| $H_{9:13}$ | 500.47 | 1.11 | 9.89 |
| $H_{10:11}$ | 1,579.41 | 1.11 | 9.89 |
| $H_{11:12}$ | 10,224.33 | 1.11 | 9.89 |
| $H_{14:12}$ | 2.60 | 4.19 | 108.98 |
| $H_{15:14}$ | 497.86 | 1.12 | 11.60 |
| $P_a$ | 53.46 | 3.75 | 41.02 |
| $P_b$ | 39.39 | 3.75 | 41.02 |
| $P_c$ | 0.16 | 3.75 | 41.02 |
| $P_d$ | 200.00 | 3.75 | 41.02 |
| $P_e$ | 2.90 | 3.75 | 41.02 |
| $P_f$ | 6.09 | 3.75 | 41.02 |
| $P_{NP}$ | 4,073.00 | 3.75 | 41.02 |
| $V_W$ | 100.00* | 95.94** | 1.48*** |

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

The products and the fuels of each equipment, in terms of enthalpy ($H_{j:k}$ and $H_{j:k'}$), are defined by the Eqs. (4a) and (4b), according to the quantity of this magnitude added to and removed from the working fluid, respectively.

$$H_{j:k} = m_j \cdot (h_j - h_k) \tag{4a}$$

$$H_{j:k'} = m_k \cdot (h_j - h_k) \tag{4b}$$

Although enthalpy only does not contain information from the second law of thermodynamics, it does not account for energy quality and it does not locate nor quantifies the irreversibilities, this model is used here for comparison only.

### 3.3. E&S Model: Exergy Flow and Negentropy Flow

Figure 3 shows the productive structure of the plant using the negentropy as a fictitious flow, joined up with exergy. In this case, the condenser can be isolated from the low pressure steam turbine, because negentropy allows defining the product for this dissipative component. The entropy is rejected to the environment through the condenser, i e, the working fluid entropy decreases in 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). 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 (Uche et al., 2001).

Consequently, 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). 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 or more outlet flows (external fuel and negentropy and/or exergy).

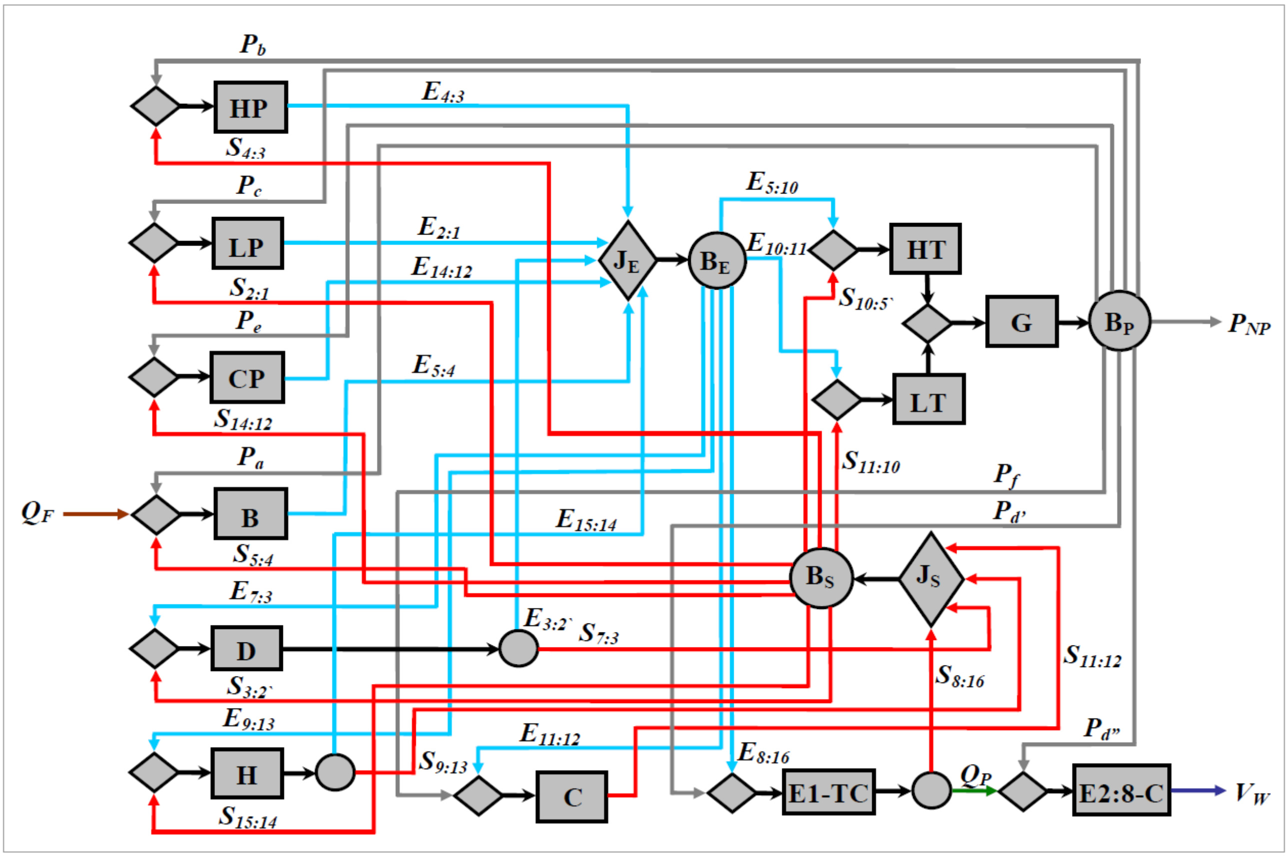


Figure 3. Productive Structure of the Dual-Purpose Plant considering Negentropy joined up with Exergy (E&S Model)

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 fuel.

The negentropy flows ($S_{j:k}$ and $S_{j:k'}$) of the productive structure represent the entropy added to and removed from the working fluid. They are defined based on physical flows, as show Eqs. (5a) and (5b). The heat (exergy) absorbed to the process ($Q_P$) is calculated using the Eq. (6).

$$S_{j:k} = m_j \cdot T_0 \cdot (s_j - s_k) \quad (5a)$$

$$S_{j:k'} = m_k \cdot T_0 \cdot (s_j - s_k) \quad (5b)$$

$$Q_P = E_{8:1} \quad (6)$$

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. 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 $B_S$).

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 4 shows the values of the internal flows of the productive structure (Fig. 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. This criterion was used to attribute cost to the negentropy flows in a dual-purpose power plant (Uche et al., 2001).

Table 4. 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) |
| $E_{1:2}$ | 0.12 | 6.34 | 7.62 | 3,600.64 | 3,613.35 |
| $E_{3:2'}$ | 243.57 | 4.71 | 1.39 | 48.31 | 14.43 |
| $E_{4:3}$ | 25.17 | 7.26 | 8.78 | 109.96 | 125.07 |
| $E_{5:4}$ | 8,817.38 | 3.02 | 3.63 | 27.14 | 33.29 |
| $E_{5:10}$ | 4,063.67 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{7:3}$ | 365.21 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{8:16}$ | 1,873.52 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{9:13}$ | 114.65 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{10:11}$ | 2,372.30 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{11:12}$ | 331.80 | 3.10 | 3.57 | 28.37 | 33.06 |
| $E_{14:12}$ | 0.54 | 25.38 | 31.54 | 577.34 | 638.95 |
| $E_{15:14}$ | 34.91 | 10.43 | 1.52 | 119.85 | 16.81 |
| $P_a$ | 53.46 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_b$ | 39.39 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_c$ | 0.16 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_{d'}$ | 25.00 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_{d''}$ | 175.00 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_e$ | 2.90 | 4.61 | 5.48 | 49.01 | 57.63 |
| $P_f$ | 6.09 | 4.61 | 5.48 | 49.01 | 57.63 |
| $S_{1:2}$ | 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 | 28.48 | 8.94 |
| $P_{NP}$ | 4,073.00 | 4.61 | 5.48 | 49.01 | 57.63 |
| $V_W$ | 100.00* | 60.87** | 25.70** | 1.16*** | 0.80*** |

*[m³/h] **[kWh/m³] ***[$/m³]

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. This criterion is in accordance with one of the propositions of the Exergetic Cost Theory approach (Valero et al., 1994).

### 3.4. H&S Model: Enthalpy Flow and Negentropy Flow

This model is a modification of the E&S Model, i.e., the enthalpy flows ($H_{j:k}$ and $H_{j:k'}$) replaces the exergy flows ($E_{j:k}$ and $E_{j:k'}$), because the exergy flow already contains the term ($m.T_0.\Delta s$) that defines the negentropy. Thus, H&S Model takes all the advantages due to the use of negentropy ($m.T_0.\Delta s$) by using it joined up with the enthalpy ($m.\Delta h$).

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.

In accordance with this idea, 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.

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 its results with the Equality (Eq) criterion. Table 5 shows the values of the internal flows of the productive structure, as well as their respective monetary and exergetic unit cost obtained by the H&S Model, considering these two different criteria

Table 5. 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) |
| $H_{1:2}$ | 0.14 | 5.73 | 5.60 | 2,925.42 | 2,925.01 |
| $H_{3:2'}$ | 1,508.99 | 3.36 | 3.22 | 31.58 | 30.57 |
| $H_{4:3}$ | 35.70 | 6.04 | 5.90 | 85.88 | 85.44 |
| $H_{5:4}$ | 22,637.17 | 3.07 | 3.02 | 27.88 | 27.75 |
| $H_{5:10}$ | 2,920.82 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{7:3}$ | 1,509.49 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{8:16}$ | 7,945.45 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{9:13}$ | 500.47 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{10:11}$ | 1,579.41 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{11:12}$ | 10,224.33 | 3.10 | 3.04 | 28.37 | 28.13 |
| $H_{14:12}$ | 2.60 | 7.69 | 7.51 | 141.54 | 140.99 |
| $H_{15:14}$ | 497.86 | 3.62 | 3.36 | 34.78 | 32.36 |
| $P_a$ | 53.46 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_b$ | 39.39 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_c$ | 0.16 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_{d'}$ | 25.00 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_{d''}$ | 175.00 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_e$ | 2.90 | 4.61 | 4.51 | 49.00 | 48.67 |
| $P_f$ | 6.09 | 4.61 | 4.51 | 49.00 | 48.67 |
| $S_{1:2}$ | 0.03 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{3:2'}$ | 1,265.42 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{4:3}$ | 10.53 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{5:4}$ | 13,819.79 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{10:5'}$ | 1,142.84 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{7:3}$ | 1.144.28 | 3.21 | 3.22 | 29.79 | 30.57 |
| $S_{8:16}$ | 6,071.93 | 3.21 | 3.05 | 29.79 | 29.25 |
| $S_{9:13}$ | 385.82 | 3.21 | 3.36 | 29.79 | 32.36 |
| $S_{11:10}$ | 792.90 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{11:12}$ | 9,892.54 | 3.21 | 3.14 | 29.79 | 29.55 |
| $S_{14:12}$ | 2.06 | 3.21 | 3.12 | 29.79 | 29.57 |
| $S_{15:14}$ | 462.95 | 3.21 | 3.12 | 29.79 | 29.57 |
| $Q_P$ | 1,873.52 | 2.82 | 3.05 | 28.49 | 29.25 |
| $P_{NP}$ | 4,073.00 | 4.61 | 4.51 | 49.00 | 48.67 |
| $V_W$ | 100.00* | 60.90** | 65.11** | 1.16*** | 1.17*** |

*[m³/h] **[kWh/m³] ***[$/m³]

## 4. DISCUSSIONS AND COMPARISON OF THE RESULTS

Figure 4 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.

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).

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.

For the analyzed dual-purpose power and desalination plant the upper limit for the exergetic unit cost of net power is 4.69 kW/kW, and the upper limit for the exergetic unit cost of water is 97.46 kWh/$m^3$, as shown in Fig. 4. This figure shows that the E&S Model, when the auxiliary equation are based on the Equality (Ep) criterion, obtains exergetic unit cost of electicity 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.

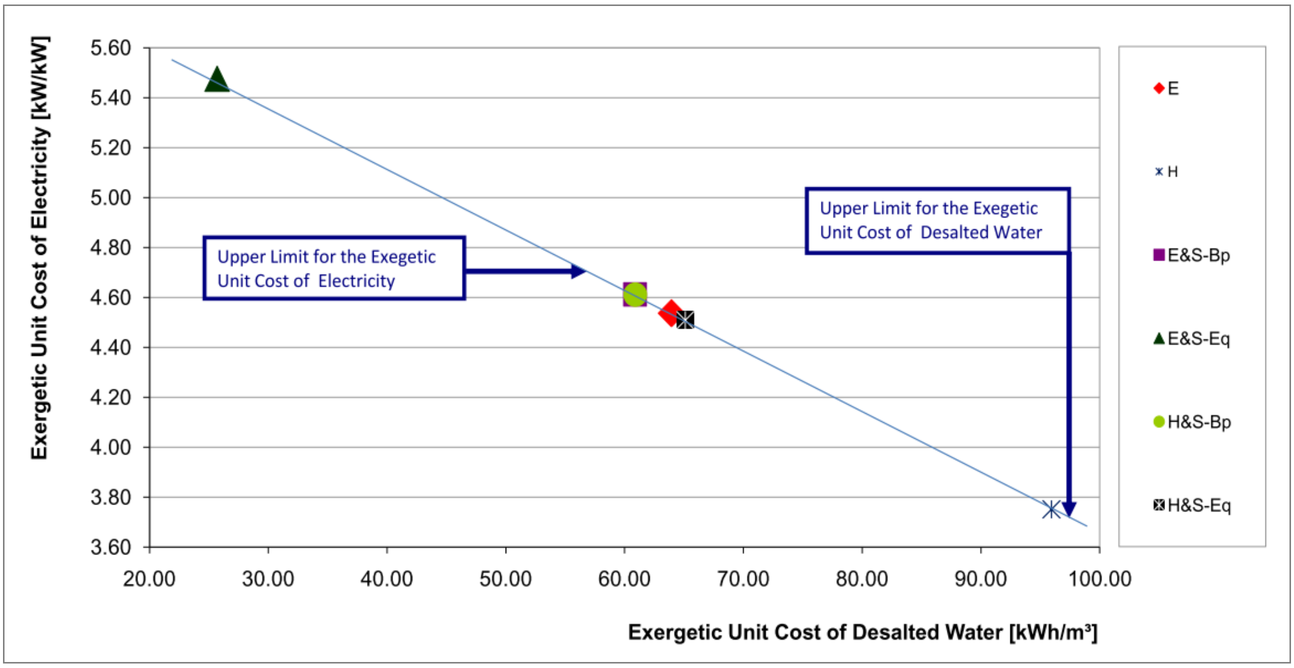


Figure 6. Exergetic Unit Cost of Electricity and Desalted Water obtained by the use of Different Methodologies

According to this range, the remaining approaches are reasonable, because they obtain exergetic unit costs of electricity 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 (Tabs. 2, 3, 4 and 5), the E&S Model (Tab. 4) obtained 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 (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, i e., the exergetic unit cost of the internal flows and product should never be less than unity.

But we know that, in the E&S Model, the exergetic unit cost of some internal flows is less than unity (Tab. 4), because the products of some subsystems (condenser and interface) are greater than their fuels. 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 Eq. (7a) is greater than 100%, i.e., its efficiency is 2,981.50 %.

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

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 Eq. (7b), is 96.75 %. This value of efficiency means that 3.25 % is the exergy dissipated in the condenser.

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

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 Eq. (7b) to define the condenser efficiency. 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 second law efficiency is generally less than 100%.

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 is awarded twice due to the reduction of the working fluid entropy. Therefore, the product of this subsystem is greater than its fuel. 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 Eq. (8a) 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.

$$\eta_{LT}^{E\&S} = \frac{100 \cdot W_{LT}}{E_{10:11} + S_{11:10}} = \frac{100 \cdot W_{LT}}{(H_{10:11} + S_{11:10}) + S_{11:10}} \tag{8a}$$

Equation (8b) 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 %.

$$\eta_{LT}^{H\&S} = \frac{100 \cdot W_{LT}}{H_{10:11} + S_{11:10}} = \frac{100 \cdot W_{LT}}{E_{10:11}} = \eta_{LT}^{E} \tag{8b}$$

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, shows that the H&S Model takes all the well known and recognized advantages of the negentropy application, it is consistent regarding the subsystem fuels and products definition, and the exergetic unit cost obtained for the final product (electricity and desalted water) does not contradict the energetic advantage of cogeneration.

## 5. CLOSURE

Exergy, instead of enthalpy only, is an adequate thermodynamic property to associate with cost because it contains information from the second law of thermodynamics. However, 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. This isolation is very important when a thermoeconomic optimization or/and diagnosis is carried out.

In order to isolate the condenser it is necessary to use 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. But, 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 or its terms; and, (ii) the use of negentropy flow.

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## 7. REFERENCES

Alves, L. G. and Nebra, S. A., 2003, “Thermoeconomic Evaluation of a Basic Optimized Chemically Recuperated Gas Turbine Cycle”, Int. J. Thermodynamics, Vol. 6, No. 1, pp. 13-22.

Arena A. P. and Borchiellini R., 1999, “Application of Different Productive Structures for Thermoeconomic Diagnosis of a Combined Cycle Power Plant”, Int. J. Therm. Sci., Vol. 38, pp. 601-612.

Çengel, Y. A. and Boles, M. A., 2006, Thermodynamics: An Engineering Approach, 5th ed, McGraw-Hill.

El-Nashar, A. M., 2001, “Cogeneration for Power and Desalination – State of the Art Review”, Desalination, Vol. 134, pp. 7-28.

Erlach, B., Serra, L. and Valero, A., 1999, “Structural Theory as Standard for Thermoeconomics”, Energy Conversion and Management, Vol. 40, pp. 1627-1649.

Frangopoulos, C. A., 1987, “Thermo-Economic Functional Analysis and Optimization”, Energy, Vol. 12, No. 7, pp. 563-571.

Lozano, M. A., Valero, A. and Serra, L., 1993, “Theory of Exergetic Cost and Thermoeconomic Optimization”, Energy Systems and Ecology, Eds. J. Szargut, Z. Kolenda, G. Tsatsaronis and A. Ziebik, Cracow, Poland, Vol. 1, pp. 339-350.

Lozano, M. A. and Valero, A., 1993, “Thermoeconomic Analysis of a Gas Turbine Cogeneration System”, ASME Book, No. H00874, WAM 1993, AES, Vol. 30, pp. 312-20.

Moran M. J. and Shapiro, H. N., 2004, Fundamentals of Engineering Thermodynamics, 5th ed, John Wiley & Sons, New York.

Santos, J. J. C. S., Nascimento, M. A. R. and Lora, E. E. S., 2006, “On The Thermoeconomic Modeling for Cost Allocation in a Dual-Purpose Power and Desalination Plant”, Proceedings of ECOS 2006, Aghia Pelagia, Crete, Greece, Vol. 1, pp. 441-448.

Serra, L., 1994, “Exergoeconomic Optimization of Thermal Systems (Optimización Exergoeconômica de Sistemas Térmicos)”, PhD Thesis, University of Zaragoza, Spain.

Torres, C., Serra, L., Valero, A. and Lozano, M.A., 1996, “The Productive Structure and Thermoeconomic Theories of System Optimization”, ME’96: International Mechanical Engineering Congress & Exposition (ASME WAN’ 96).

Uche, J., Serra, L. and Valero, A., 2001, “Thermoeconomic Optimization of a Dual-Purpose Power Plant”, Desalination, Vol. 136, pp. 147-158.

Valero, A., Lozano, M. A. and Serra, L., 1994, “Application of the Exergetic Cost Theory to the CGAM Problem”, Energy, Vol. 19, No. 3, pp. 365-381.

Valero, A., Royo, J. and Lozano, M. A., 1995, “The Characteristic Equation and Second Law Efficiency of Thermal Energy Systems”, International Conference Second Law Analysis of Energy Systems: Towards the 21st Century, Eds. E. Sciubba, M.J. Moran. Roma "La Sapienza", pp. 99-112.

Valero, A., Serra, L. and Uche, J., 2006, “Fundamentals of Exergy Cost Accounting and Thermoeconomics. Part I: Theory”, Journal of Energy Resources Technology, Vol. 128, pp. 1-8.

von Spakovsky, M. R., 1994, “Application of Engineering Functional Analysis to the Analysis and Optimization of the CGAM Problem”, Energy, Vol. 19, No. 3, pp. 343-364.

Wang, Y. and Lior, N., 2007, “Fuel Allocation in a Combined Steam-Injected Gas Turbine and Thermal Seawater Desalination System”, Desalination, Vol. 214, pp. 306-326.

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