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Abstract:

All thermoeconomic methodologies need to define the productive purpose (products and fuels) of the plant, at both system and subsystem levels. Some of them use a productive diagram in order to represent the productive purpose of the plant and assess the cost of internal productive flows and final products. In other words, they use productive flows (instead of physical flows), although all the productive flows are defined in relation to the physical flows presented in the flow sheet of the plant. Other thermoeconomic methodologies do not use productive diagrams and, consequently, they use physical diagram and assess the cost of the internal physical flows (instead of productive flows). In the productive diagrams the subsystems are connected using internal productive flows (fuels and products) and fictitious components (junctions and separators), without taking into account the interconnection of the subsystem using the same physical flows presented in the flow sheet of the plant. This work presents a comprehensive thermoeconomic diagram in which both physical and productive internal flows are represented, the subsystems are connected using the same physical flows presented in the flow sheet of the plant and allows the assessment of unit costs of both physical and productive flows. This comprehensive diagram avoids the arbitrariness and criticism related to the interconnection of subsystems by means of flows and components that do not exist in the flow sheet of the plant. Furthermore, the results show that the unit costs of both physical and productive flows obtained using this comprehensive diagram are the same as the ones obtained, separately, using the conventional physical and productive diagram, respectively.

Keywords:

Thermoeconomics, Internal Flow Cost, Physical Diagram, Productive Diagram, Comprehensive Diagram.

1. Introduction

Thermoeconomics can be considered a new science which, by connecting Thermodynamics and Economics, provides tools to solve problems in complex energy systems, as for instance a rational cost assessment of the internal flows and final products of a plant, based on physical criteria. Various thermoeconomic methodologies have been developed, all of them having in common the cost, calculated from a rational basis (Second Law of Thermodynamics), for this purpose [1].

In 1990s, the most systematic and widespread thermoeconomic methodologies developed until now [2–5] were applied in a specific and previously defined thermal system, called CGAM problem [6]: Exergetic Cost Theory [2], Exergoeconomics [3], Thermoeconomic Functional Approach [4] and Engineering Functional Analysis [5]. Later, when comparing these thermoeconomic methodologies, various authors [7–11] have agree that there were two main groups of thermoeconomic methods: (a) assessment of the cost of the physical flows represented in a physical diagram [2,3] and (b) assessment of the cost of the productive flows in a defined productive or functional diagram [4,5].

According to Lozano and Valero [12], perhaps the fundamental limitation of the Exergetic Cost Theory, as it was originally formulated, consisted of defining the productive structure in relation to the same flows and component present in the physical structure, since the resulting difficulties lie mainly in the adequate treatment of the dissipative units and residues. In order to overcome this limitation another approach based on productive or functional diagram, called the Structural Theory of Thermoeconomics [1,12], was proposed. During the last ten years, some new thermoeconomic methodologies [13,14], based on productive or functional diagram, were proposed as consistent alternatives to deal with dissipative components and residues in thermoeconomics.

Aiming at the unification of the Exergoeconomic methodologies (AVCO approach and LIFO approach) [3], which are based on physical diagram, Lazzaretto and Tsatsaronis [15] proposed a new thermoeconomic methodologies, called SPECO approach, based on physical diagram too. However, it should be mentioned that most thermoeconomic methodologies were founded based on productive diagram [4,5,13,14] or was extended in order to deal with productive diagram [12].

Given a flow sheet of a thermal system, all thermoeconomic methodologies need to define a product and a fuel for each subsystem of the plant. Although the productive diagrams offer the advantage of showing clearly and graphically how the product of a given subsystem is distributed in order to be used as an input to another subsystem or as a final product of the plant, and it should be possible to evaluate all the flows of the productive diagram in relation to the state of the plant as defined by the physical diagram, the cost of the internal physical flows are not calculated with this model. On the other hand, a thermoeconomic model based on physical diagram do not allow calculate the costs of product and fuel at subsystem level, i. e., the costs of the internal productive flows are not calculated.

Bearing this in mind, this work shows and discuss a different thermoeconomic model, based on a comprehensive thermoeconomic diagram, which shows clear and graphically the product and fuel of the subsystem, as well as the interrelation among the subsystem, and allows assess the costs of both physical and productive internal flows of a thermal system. For the sake of comparison and simplicity, the exergetic and monetary unit costs of the internal flows and final products are calculated using a simple dual-purpose power and desalination plant as case study. In the final analysis, this paper aims at unifying both group of thermoeconomic methodologies by combining both physical and productive internal flows in a single and comprehensive thermoeconomic diagram in a single model.

2. Thermoeconomic Modeling

Thermoeconomic model is a set of equations which describes mathematically the cost formation process of the system final products, generally used for exergy and/or monetary costs of the external resources allocation to the final products and, consequently, for the assessment the exergetic unit cost and the monetary unit cost of both internal flows and final products, respectively.

Given the flowsheet of an energy system (Fig. 1), it is convenient to pick up a thermoeconomic model based on a diagram that reflect the productive purpose of the subsystems (products and fuels), as well as the interaction among them. All thermoeconomic methodologies need to define the productive purpose of the subsystems, as well as the distribution of the external resources throughout the system, which can be represented by means of a diagram (Figs. 2 to 4). Some thermoeconomic models are based on the physical diagram (Fig. 2), and others are formulated using a productive diagram (Fig. 3).

No matter a physical or productive diagram is used for thermoeconomic model, in order to calculate the monetary unit cost of each internal flow and final products, the mathematical model for cost allocation, which is a set of cost equations obtained from the thermoeconomic cost balance in each subsystem of the diagram, is given by (1). The solution of this set of cost equation is the monetary unit costs of each internal flow and each final product. The monetary unit cost of a flow is the amount of external monetary unit required to obtain one unit of this flow, i.e., the monetary unit cost of a flow is a measure of the economic efficiency of the production process when producing this flow [16].

$$\sum(c_{out}\cdot Y_{out})-\sum(c_{in}\cdot Y_{in})=Z+c_F\cdot E_F \qquad (1)$$

In (1), c_{out} and c_{in} are unknown variables representing the monetary unit cost of the internal flows at the outlet and the inlet of each subsystems (in *$/kWh*), respectively; Y_{out} and Y_{in} represent the generic internal flows (in *kW*) at inlet and outlet of each subsystems, respectively, which can be assessed using any thermodynamic magnitude, such as, power (*P*), total exergy (*E*), negentropy (*S*), enthalpy (*H*), etc.; *Z* represents the external hourly cost of the subsystem due to the capital cost, operation and maintenance cost of each subsystem (in *$/h*); c_F is a known market unit cost of the external fuel exergy (in *$/kWh*) and E_F is the amount of the plant external fuel exergy consumption (in *kW*).

Since the number of internal flows is always greater than the number of subsystems, auxiliary equations are required. The thermoeconomic models based on productive diagram [4,5,12–14] consider that all internal productive flows exiting the same subsystem must have the same unit cost, since they were produced under the same resources and irreversibility. For the thermoeconomic models based on physical diagram [2,3,15], the criteria for auxiliary equations are the fuel and product principle. According to the fuel principle it is considered that a component uses a part of inlet flow exergy to produce a given product. Thus, the remaining part of the exergy inlet flow (which is one of the outlet flows) carries the same unit cost of the inlet flow. On the other hand, the product principle considers that all the outlet flows defined as products of the same subsystem have the same unit cost.

By modifying (1) in order to formulate the cost equation balances to provide the exergetic unit cost (k_{out} and k_{in}) of each internal flow and final products of the diagram, (2) is obtained.

$$\sum(k_{out}\cdot Y_{out})-\sum(k_{in}\cdot Y_{in})=k_F\cdot E_F \qquad (2)$$

The exergetic unit cost of a flow (in *kW/kW*) is the amount of exergy required to obtain one exergy unit of this flow. This cost is a measure of the thermodynamic efficiency of the production process generating this flow [16]. In this case (2), the hourly cost of the subsystem due to the capital cost, operation and maintenance must be zero ($Z = 0$) and the monetary unit cost of the external fuel exergy is replaced by the exergetic unit cost of the external fuel exergy, which is 1.00 *kW/kW*, because there is no exergy destruction before the productive process is performed [16]. The auxiliary equations and the internal flows and final products (Y_{out} and Y_{in}) remain the same as used for the monetary unit cost.

3. Plant Description

The beauty of a theory is usually shown in the simplicity of its forms and the generality of its message, but its power resides in its capacity to solve practical cases [17]. Thus, in this paper, a simple Dual-Purpose Power and Desalination Plant is used to illustrate the application. The thermal system analysed consist of a Backpressure Steam Turbine Cogeneration System, combined with a MED-TVC (Multiple-Effect Distillation with Thermal Vapor Compression) desalination plant, represented by the flowsheet in Fig. 1. Furthermore, this plant was chosen to avoid unnecessary disagreements related to treatment of residues (recovery boiler) and dissipative components (condenser, valves, etc.).

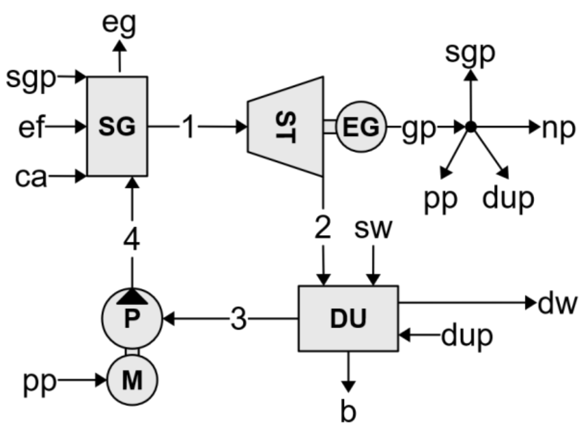

Fig. 1. Flow Sheet of the analysed Dual-purpose Power and Desalination Plant

Generally conventional thermoeconomic methodologies [2–5] did not consider the in-depth analysis of the cost allocation of residues and dissipative components. Although the proposal of Structural Theory of Exergetic Cost [1,12] and Specific Exergy Costing [15], none of them give a general solution to the problem. In 2008, Torres and co-workers [18] stated that the need was evident for either developing new techniques or extending the existing ones that include both the cost allocation of residues and dissipative components. During the last ten years, some works in the literature were focused on this subject [18–21], some of them [18,19] extends the conventional approaches to deal with the residues and dissipative components and others [20,21] are based on new approach proposals based on exergy disaggregation. However, this problem still open, leading to some disagreements.

At design point, the plant represented in Fig. 1 produces 811.40 *kW* of electric net power (*np*) and 2,400 m^3/d of desalted water (*dw*). The external fuel exergy consumption (*ef*) is 10,480.31 *kW*. The plant is defined as having six components: the steam generator (SG), the steam turbine (ST), the electric generator (EG), the desalination unit (DU), the pump (P) and the motor (M). The plant generates 1,052.91 *kW* of gross electric power (gp), whereas 27.21 *kW* are consumed to drive the steam generator fans (*sgp*), 14.30 *kW* are consumed to drive the pump motor (*pp*) and 200 *kW* in the desalination unit (*dup*). Table 1 shows the parameters and exergy of the working fluid states.

Table 1. Parameters and Exergy of the Physical Streams representing de Plant Working Fluid

i	m (*kg/s*)	T (*ºC*)	p (*bar*)	E (*kW*)
1	3.194	330	25	3,409.52
2	3.194	136	2	1,899.27
3	3.194	60.2	1.013	25.75
4	3.194	60.7	26.01	34.42

The hourly cost of the total cogeneration system is distributed among its subsystems as function as the percentages of their contributions to its total cost, as shown in Table 2. The external fuel is natural gas, whose cost assumed is 18 *$/MWh*. The economic parameters used to calculate the hourly cost of each subsystem (Z), are: plant factor (0.92), plant lifetime (20 year) and interest rate (0.12). The specific capital cost of the cogeneration system is 1,011.40 *$/kW*, the fixed operation and maintenance cost is 56.80 *$/kWh* and the variable operation and maintenance cost is 0.005 *$/kWh* [22].

Table 2. Subsystem External Hourly Costs due to Capital, Operation and Maintenance Costs

Components and Productive Units	External Hourly Costs ($/h)			
	Value ($/h)		Percentage (%)	
Steam Generator (SG)	20.33	29.90	68	100
Pump and Motor (PM)	0.60		30	
Steam Turbine and Electric Generator (STEG)	8.97		2	
Desalination Unit (DU)	81.23		100	

The specific capital cost of the desalination plant, including all auxiliary equipment as a single unit, is 1,682 $\$/m^3/d$ (11.42 *$/gpd*). In this case, the total operation and maintenance cost is 0.14 $\$/m^3$ [22].

4. Conventional Thermoeconomic Diagrams

Conventionally, the thermoeconomic models for cost allocation are formulated based on physical or productive diagram. Differences notwithstanding, no matter the kind of diagram used, the methodologies have some remarkable similarities. The division of the system into subsystems is one of them, but perhaps the most important is the need to define the products and fuels for each of those subsystems. The product and fuels can be defined as the variation in the thermodynamic magnitude of a stream, shaft and electric power, external fuel consumption and final useful products and raw materials. Table 3 shows the subsystem fuels and products using both physical and productive flows.

Table 3. Definitions of the Fuels and the Products using both Physical and Productive Flows

System and Subsystems	**Fuel**		**Product**	
	Physical	**Productive**	**Physical**	**Productive**
Steam Generator (SG)	$E_{ef} + E_{sgp}$	$E_{ef} + E_{sgp}$	$E_1 - E_4$	$E_{1:4}$
Pump and Motor (PM)	E_{pp}	E_{pp}	$E_4 - E_3$	$E_{4:3}$
Steam Turbine and Electric Generator (STEG)	$E_1 - E_2$	$E_{1:2}$	E_{gp}	E_{gp}
Desalination Unit (DU)	$E_2 - E_3 + E_{dup}$	$E_{2:3} + E_{dup}$	$\dot{Q}_{dw}$	$\dot{Q}_{dw}$
Dual-Purpose Power and Desalination Plant	E_{ef}	E_{ef}	$E_{np} + \dot{Q}_{dw}$	$E_{np} + \dot{Q}_{dw}$

According to Torres and co-workers [23], sometimes, under a thermoeconomic analysis point of view, it is necessary to consider a component as a group of subsystems (made up of a group of subsystems) or a mass or an energy flow rate consisting of several components, for example thermal, mechanical or chemical exergy, or even including fictitious flow streams (negentropy) without a physical existence in the flow sheet of the plant. In other words, depending on the analysis, different levels of accuracy of the results are required, i.e., each thermoeconomic analysis requires a specific aggregation level of the components, and of the flows of the plant. However, exergy disaggregation increases the analysis complexity and there are some disagreements related to negentropy [13,15].

For the sake of simplicity and to avoid disagreements, the thermodynamic magnitude used in this paper, to describe the fuels and the product of the subsystems, is total exergy. Usually, only thermodynamic magnitudes are used for this purpose. However, according to Wang and Lior [24], other magnitudes or units can also be used according to the specific situation, such as in a desalination subsystem, in which the interest is in the volumetric flow of the produced fresh water (Q_{dw}), not the desalted water exergy. Except the desalted water, the products and fuels of the subsystem, in Tab. 3, are total exergies of internal flows and final products that represent electric power and external fuel consumption (presented in the flowsheet) or the exergy added to and removed from the working fluid in a subsystem. Each productive flow is defined based on a physical flow or based on the difference between two physical flows. The productive flows that represent the exergy added to and removed from the working fluid ($E_{j:k}$) are always exergy variations between two physical flows (E_j and E_k).

Nowadays, there is a certain degree of agreement and unification related to the procedure to define the product and fuel at subsystem level. A general, systematic and didactic procedure can be found in Lazzaretto and Tsatsaronis [15]: (i) the product is defined to be equal to the sum of all the exergy of energy streams generated in the subsystem plus all the exergy increases between inlet and outlet of the respective material streams that are in accord with the purpose of the subsystem; and (ii) the fuel is defined to be equal to all the consumed exergy of energy streams supplied to the subsystem plus all the exergy decreases between inlet and outlet of the respective material streams minus all the exergy increases (between inlet and outlet) that are not in accord with the purpose of the subsystem.

4.1. Physical Diagram

Figure 2 shows the physical diagram of the analysed Dual-purpose Power and Desalination plant. The physical diagram (Fig. 2) can be considered a simplification of the flow sheet (Fig. 1), in which the subsystems are defined and represented, and the streams that do not appear in the definition of fuels and products at system nor subsystem levels (Tab. 3), are eliminated.

Some streams of the flow sheet do not appear in the physical diagram because they are losses whose cost are automatically charged to the products of the subsystems in which each of them was generated, for instance, the exhaust gases (*eg*) in the steam generator and brine (*b*) in the desalination unit. There are other kind of streams of the flow sheet that do not appear in the physical diagram because their exergy is zero or there are not costs associated with them, for instance, combustion air (*ca*) and seawater (*sw*). Thus, these streams are not product nor fuel of any subsystem of the plant.

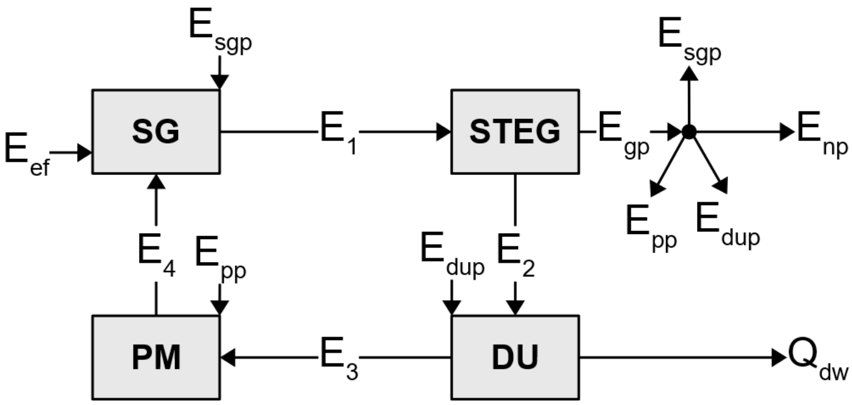

Fig. 2. Physical Diagram of the analysed Dual-purpose Power and Desalination Plant

Given the physical diagram, for each subsystem, it is possible to write, respectively, the exergetic and monetary thermoeconomic cost balances, according to (1) and (2), and the auxiliary equations based on fuel and product principle. The fuel principle attributes the same unit cost for three exergy streams representing working fluid (E_1, E_2 and E_3), and the product principle attribute the same unit cost for all the five exergy streams representing electrical power (E_{gp}, E_{np}, E_{pp}, E_{dup} and E_{sgp}).

4.2. Productive Diagram

Figure 3 shows the productive diagram defined for the dual-purpose power plant, which graphically depicts its cost formation process. The external resource is the natural gas exergy (E_{ef}) and the products are the electrical net power (E_{np}) and the produced desalted water volumetric flow ($\dot{Q}_{dw}$). The rectangles are the actual subsystems. The rhombus and the circles are fictitious subsystems called junction (J) and bifurcation (B), respectively. Each productive units in Fig. 3 has inlet and outlet arrows, that represent its fuels (or resources) and products, respectively. The flows of the productive diagram are exergies that represents electric power flows (E_{gp}, E_{np}, E_{pp}, E_{dup} and E_{sgp}), the produced desalted water ($\dot{Q}_{dw}$), and the exergy added to and removed from the working fluid ($E_{1:4}$, $E_{2:3}$, $E_{1:2}$ and $E_{4:3}$). All the flows presented in the productive diagram are defined based on physical flows.

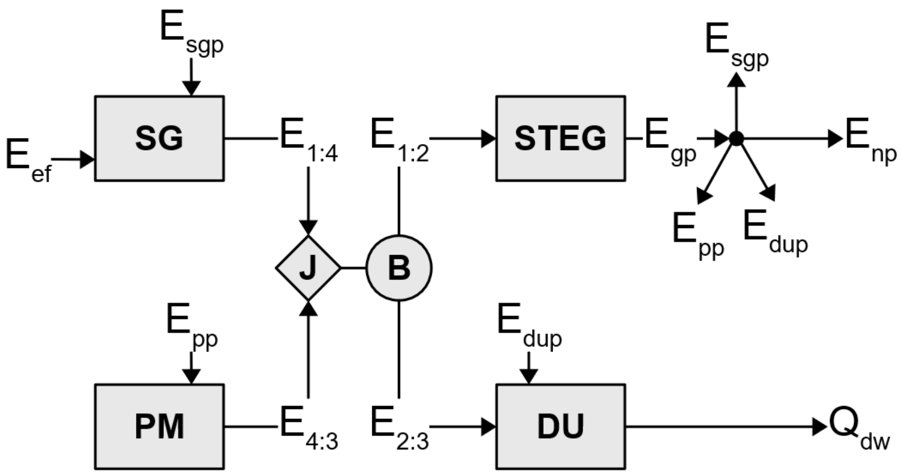

Fig. 3. Productive Diagram of the analysed Dual-purpose Power and Desalination Plant

The mathematical model for exergetic and monetary cost allocation is obtained by formulating cost equations balance in each actual and fictitious subsystem of the productive diagram, according to (1) and (2), and the auxiliary equations consider that the productive flows exiting the same subsystem have the same unit cost. Thus, auxiliary equations attribute the same unit cost for exergy flows exiting the bifurcation ($E_{1:2}$ and $E_{2:3}$) and the ones exiting the electric generator (E_{gp}, E_{np}, E_{pp}, E_{dup} and E_{sgp}).

5. Comprehensive Thermoeconomic Diagram

Figure 4 is a combination of the concept of both physical and productive diagram in a comprehensive thermoeconomic diagram representing the analysed Dual-purpose Power and Desalination plant.

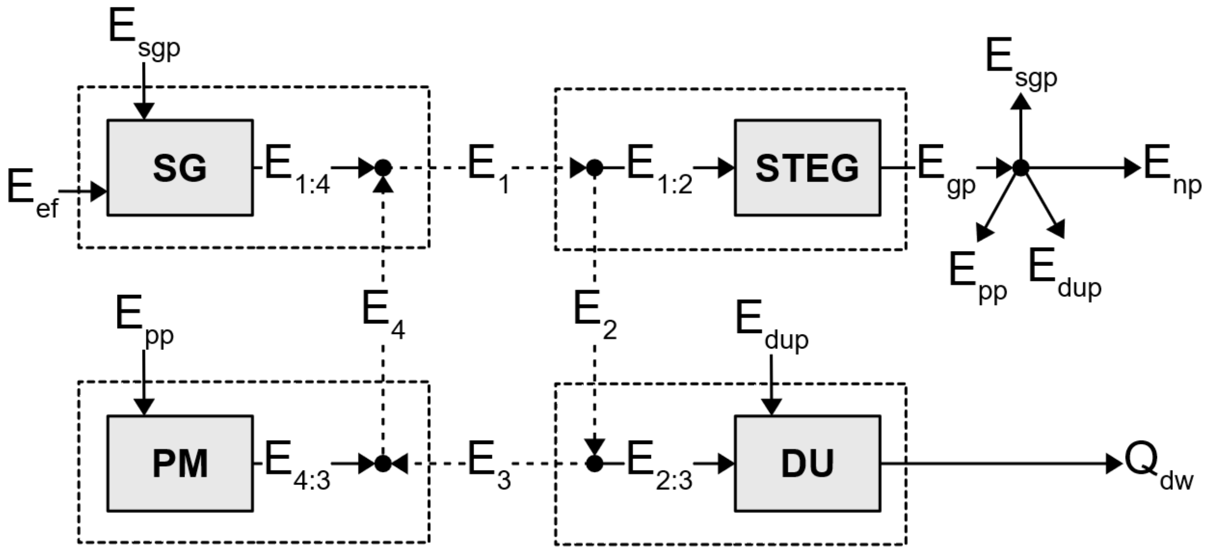

Fig. 4. Comprehensive Diagram of the analysed Dual-purpose Power and Desalination Plant

The comprehensive thermoeconomic diagram, in Fig. 4, shows clear and graphically the product and fuel of the subsystems, as well as the interrelation among the subsystems, by combining both physical and productive internal flows in a single diagram. However, in this comprehensive thermoeconomic diagram, there are no the fictitious subsystems, called junction (J) and bifurcation (B), and the subsystems are interconnected using the same physical exergy flows presented in the flow sheet.

The comprehensive diagram preserves the main characteristics of both physical and productive diagrams. From the first, the subsystems are connected using the same flows present in the flow sheet. From the second, the product and fuels of each subsystem are presented in the diagram.

In the comprehensive diagram, in Fig. 4, each subsystem acts as both a productive unit (continuous line) and as a component (dotted line) combining the characteristic of both productive and physical diagram, respectively. Lazzaretto and Tsatsaronis [15] discussed the concepts of productive unit and component. However, these authors do not use the concept of productive unit for cost calculation.

Different from the comprehensive diagram, the physical diagram considers the subsystems as a component (dotted line) only. On the other hand, in the productive diagram, each subsystem acts as a productive unit (continuous line) only. In the comprehensive diagram, all the subsystems are both productive units and components, assessing the unit costs of both productive and physical flows.

The mathematical model for exergetic and monetary cost allocation is obtained by formulating cost equations balance in each subsystem of the comprehensive diagram, according to (1) and (2). However, each subsystem allows formulating two cost equation, one as a productive unit (continuous line) and other as a component (dotted line). The auxiliary equations are formulated at the component boundary as well as in the physical diagram, i.e., the same unit cost for three streams of working fluid (E_1, E_2 and E_3), and for all the five streams representing electrical power (E_{gp}, E_{np}, E_{pp}, E_{dup} and E_{sgp}).

Although, for the sake of simplicity and to avoid disagreements, in this work, the thermodynamic magnitude is total exergy (E), this diagram cam be applied no matter the thermodynamic magnitude (Y), since each productive flow ($Y_{j:k}$) is always the deference between two physical flows (Y_j and Y_k).

6. Unit Cost Results for Internal Flows and Final Products

Table 4 and 5 shows the values of the physical and productive flows (in kW) presented in the three kinds of thermoeconomic diagrams analysed, as well as their respective exergetic unit cost (in kW/kW)

and their monetary unit cost (in *$/kWh*), respectively. These unit costs were calculated by solving the set of thermoeconomic cost equations defined by considering each of the thermoeconomic diagram shown in Fig. 2 (physical), Fig. 3 (productive) and Fig. 4 (comprehensive).

Table 4. Exergy and Exergetic Unit Costs of the Physical and Productive Flows of the Diagrams

Flow	Value (kW)	Exergetic Unit Cost (*kW/kW*)		
		Diagram		
		Physical	Productive	Comprehensive
E_1	3,409.02	3.15	-	3.15
E_2	1,899.27	3.15	-	3.15
E_3	25.75	3.15	-	3.15
E_4	34.42	4.24	-	4.24
$E_{1:2}$	1,509.75	-	3.15	3.15
$E_{2:3}$	1,873.52	-	3.15	3.15
$E_{4:3}$	8.67	-	7.46	7.46
$E_{1:4}$	3,374.60	-	3.14	3.14
E_{gp}	1,052.91	4.52	4.52	4.52
E_{sgp}	27.21	4.52	4.52	4.52
E_{np}	811.40	4.52	4.52	4.52
E_{udp}	200.00	4.52	4.52	4.52
E_{pp}	14.30	4.52	4.52	4.52
$\dot{Q}_{dw}$	*100.00	**68.12	**68.12	**68.12

* (m^3/h); ** ($\$/m^3$)

Usually, the unit of the exergetic unit cost is *kJ/kJ* or *kW/kW*. Once that, according to Wang and Lior [24], other units can also be used according to the specific situation, such as in a dual-purpose system in which the interest is in the quantity of the produced fresh water, not its exergy, consequently, in this work, the exergetic unit cost of desalted water was calculated in kWh/m^3. This cost represents the amount of natural gas exergy (in *kWh*) consumed in order to produce each unit of desalted water (in m^3). Analogically, in this work, the monetary unit cost of desalted water was calculated in $\$/m^3$, since in a desalination subsystem, the interest is the cost of each volumetric flow of the desalted water.

Table 5. Exergy and Monetary Unit Costs of the Physical and Productive Flows of the Diagrams

Flow	Value (kW)	Monetary Unit Cost (*$/MWh*)		
		Diagram		
		Physical	Productive	Comprehensive
E_1	3,409.02	63.16	-	63.16
E_2	1,899.27	63.16	-	63.16
E_3	25.75	63.16	-	63.16
E_4	34.42	105.80	-	105.80
$E_{1:2}$	1,509.75	-	63.16	63.16
$E_{2:3}$	1,873.52	-	63.16	63.16
$E_{4:3}$	8.67	-	232.6	232.6
$E_{1:4}$	3,374.60	-	62.72	62.72
E_{gp}	1,052.91	99.08	99.08	99.08
E_{sgp}	27.21	99.08	99.08	99.08
E_{np}	811.40	99.08	99.08	99.08
E_{udp}	200.00	99.08	99.08	99.08
E_{pp}	14.30	99.08	99.08	99.08
$\dot{Q}_{dw}$	*100.00	**2.194	**2.194	**2.194

* (m^3/h); ** (kWh/m^3)

The results in Tabs. 4 and 5 show that the unit costs of both physical and productive flows obtained using comprehensive diagram (unit cost of E_j, E_k and $E_{j:k}$) are the same as the ones obtained, separately, using physical diagram (unit cost of E_j and E_k) and productive diagram (unit cost of $E_{j:k}$).

7. Conclusions and Closure

This work presented and discussed the concepts and fundamentals of a thermoeconomic model, based on a comprehensive thermoeconomic diagram, which shows clear and graphically the product and fuel of the subsystem, as well as the interrelation among the subsystems, and allows assess the costs of both physical and productive internal flows of the system. This paper showed that a comprehensive thermoeconomic diagram takes advantages of both conventional physical and productive diagrams.

For the sake of comparison and simplicity, the exergetic and monetary unit costs of the internal flows and final products were calculated using a simple dual-purpose power and desalination plant as case study. The results showed that the results obtained using the thermoeconomic model based on the comprehensive diagram are the same as the ones obtained using the conventional diagram, separately. However, all these results can be obtained using a single and comprehensive thermoeconomic model, which is not possible using a thermoeconomic model based on productive or physical diagram only.

In the final analysis, this paper contributed to the unification of two group of thermoeconomic methodologies that differs mainly in the kind of diagram (physical or productive) used to formulate the cost equations, which can be formulated using this comprehensive thermoeconomic diagram.

Once that nowadays the thermoeconomic methodologies have achieved a certain advance in the unification and agreement related to a systematic procedure to define fuels and products at the subsystem level, the comprehensive diagram avoid the use of the criticized fictitious subsystems (junctions and bifurcations) generally used in the conventional productive diagram in order to interconnect the actual subsystems. At this point, the comprehensive diagram, here presented, reduces this arbitrariness, by connecting the subsystems using the same physical flows as in the flow sheet.

In this work, the obtained unit costs of the final products (net power and desalted water) was the same for the three thermoeconomic models based on three the different diagrams (physical, productive and comprehensive). These results confirm that, no matter the thermoeconomic methodology, if the productive purpose (fuel and product) of the subsystem are the same, and the interconnection among the subsystem is consistently defined, the cost of the final product will be unavoidable the same. At this point, it should be pointed that, although the certain degree of agreement related to a systematic procedure to define fuels and products at the subsystem level, the interconnection among them still more or less arbitrariness in the conventional productive diagram. This arbitrariness is avoided by using the comprehensive diagram in which the subsystems are connected using physical flows.

Acknowledgments

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Nomenclature

c monetary unit cost, $/kWh

k exergetic unit cost, kW/kW

E total exergy flow, kW

Y generic thermodynamic magnitude, kW

Z hourly equipment cost, $/h

Subscripts

in inlet

out outlet

F external fuel

Abbreviations

b brine
ca combustion air
dup desalination unit power
dw desalt water
ef external fuel
eg exhaust gases
gp gross power
np net power
pp pump power
sgp steam generator power
sw seawater
DU desalination unit
EG electric generator
M motor
P pump
SG steam generator
ST steam turbine

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