COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1737
THE IMPORTANCE OF THE ENVIRONMENT IN THE THERMOECONOMIC MODELING: A CONVENTIONAL BOILER WASTE AND ENVIRONMENTAL COSTS ALLOCATION

Igor Chaves Belisario
Carlos Eduardo Silva Abreu
Federal Institute of Espírito Santo (IFES) – São Mateus-ES, Brazil
igor.belisario@ifes.edu.br, carlos.abreu@ifes.edu.br

Rodrigo Guedes dos Santos
Pedro Rosseto de Faria
Federal Institute of Espírito Santo (IFES) and Federal University of Espírito Santo (UFES) – Vitória-ES and Cariacica-ES, Brazil
rodrigo.guedes@ifes.edu.br, pedro.faria@ifes.edu.br

Marcelo Aiolfi Barone
José Joaquim Conceição Soares Santos
Federal University of Espírito Santo (UFES) – Vitória-ES, Brazil
mabacz@gmail.com, jjcssantos@yahoo.com.br

Abstract. *Cost allocation is an important field in thermoeconomics since it allows to define an equal basis comparison of different thermoeconomic methodologies. Traditionally, monetary and exergetic costs are allocated for cost assessment of the final products. Nevertheless, environmental charges and waste cost allocation has been gained importance and it has also been taken into account in the analyzes. In addition, energy systems can be defined as a set of components that interact with each other and with the environment through a set of flows of matter, work or heat. The way in which the productive structure is defined is a key point in thermoeconomics. Therefore, this work aims to contribute to this field by discussing and testing the consistency of the environment as a subsystem, especially regarding the treatment of waste and environmental charges. A thermoeconomic analysis is carried out in a sugarcane boiler by disaggregating the system into subsystems. Three thermoeconomic models (E, E&S and H&S), using productive diagrams, are studied and compared. Although the E&S Model uses the stack as a fictitious subsystem in the productive structure, the results highlight the advantage of using the H&S Model, as a consistent exergy disaggregation methodology, that intrinsically includes the environment as a real subsystem in its productive structure and allows a rational environmental cost allocation.*

Keywords: *Waste treatment, Environmental cost, Conventional boiler, Cost allocation, Thermoeconomics.*

1. INTRODUCTION

Energy systems analysis is generally associated with thermodynamics and economics concepts to evaluate and offer crucial information for design, optimization and plant operation. However, these isolated concepts cannot provide enough information to assess internal flows and final products costs of the systems. Thus, thermoeconomics, by combining thermodynamics and economics concepts, arises as a powerful tool to solve complex energy systems problems based on physical criteria (Erlach, 1998; Erlach *et al.,* 1999). Most practitioners agree that exergy is the most adequate thermodynamic magnitude to be associated with economic concepts since it contains information from both first and second thermodynamic laws (Valero *et al.,* 2006). In addition, several authors have been demonstrating the potential of exergy concept in environmental science by proposing ecological indicators based on this thermodynamics magnitude (Dincer & Rosen, 2007).

Cost allocation, optimization and diagnosis are the main areas of thermoeconomics application. The cost allocation method defines and evaluates the consistency of the cost formation process since it distributes the overall costs of the plant to the final products using a rational partition. It is considered an important field in thermoeconomics since it defines an equal basis comparison of different thermoeconomic methodologies and flow types.

Various thermoeconomic methodologies were developed in the 1990s. Some of them use productive diagrams to assess the cost of the productive flows (Frangopoulos, 1994; von Spakovsky 1994). Other methodologies (based on exergy disaggregation) were proposed in the last two decades (Lourenço *et al.,* 2015; Santos *et al.,* 2009) based on productive diagrams and presenting a consistent alternative to provides a proper treatment for dissipative components and residues.

In thermoeconomics, the waste cost allocation still remains open to criticism since different methodologies deal with the theme by applying different criteria. The waste cost depends on their formation process and the responsibility of each subsystem on it. Thus, the waste cost allocation requires disaggregation of the system and depends on where and how wastes are formed (Agudelo *et al.,* 2012). Some methodologies need to define the residue cost distribution ratio (ψ_{jr}) that is defined in different ways and presenting arbitrariness in its definition. The H&S Model (Santos *et al.,* 2006, 2009) has already been proposed taking into account the treatment of waste and dissipative component. Recently, an improved methodology of reallocating waste cost through the comprehensive diagram (Avellar *et al.,* 2018b, 2018a) was presented by (Faria *et al.,* 2020, 2021). Despite the improvements in this field, there are no established general criteria for waste treatment.

Generally, thermoeconomic models are used for external resources allocation, such as exergy or monetary costs to the final products of an energy system. This process consists of the definition of the productive purpose of each subsystem that composes the system in a productive structure. Nonetheless, environmental considerations have been gained more relevance in the past years making thermoeconomic models adapt their calculation methodologies to incorporate specific emissions (CO_2, NO_x and SO_x) to the costs of the final products (von Spakovsky, 1994).

According to Lozano and Valero (1993), any energy system can be defined as a set of components that interact with each other and with the environment through a set of flows of matter, work or heat. Moreover, the environment has a relationship with energy systems whereas they do not achieve their useful products without rejecting waste to surroundings. Environmental charges associated with legal issues and costs of resources employed to waste treatment must be distributed to the productive units and reflects on the final products.

From an environmental point of view, a great concern about boilers is associated with the specific pollutants emission. This equipment produces useful steam by using chemical exergy available on the fuel with a large volume of intake air to promote correct combustion. This process generates a large amount of flue gas residue released to the environment, as an exergy waste (physical and chemical). Usually, some environmental control equipment, such as ash handling systems, or even fluidized bed boilers are employed to deal with the specific emissions.

Moreover, thermoeconomic analysis is usually carried out considering the boiler as a subsystem (single box) in the modeling without taking inside components and processes into consideration. Consequently, it is difficult to visualize the thermodynamic relationship between the boiler and the environment. Thus, as well as any energy system, there is an intrinsic relationship between boilers and the environment.

Bearing this in mind, this work aims to apply three thermoeconomics models (E, E&S and H&S) in a sugarcane conventional boiler (disaggregated in subsystems) to emphasize that regardless of the thermal cycle (gas or steam), there is the environment as a subsystem in the thermoeconomic modeling. It is especially important regarding the waste treatment and environmental charges. The discussion aims to compare the exergetic unit cost of the internal flows and the final product (useful heat) highlighting the importance of the environment as a subsystem to connect the treatment of environmental charges in the thermoeconomic modeling.

2. THERMOECONOMIC MODELING

The thermoeconomic modeling is defined as a set of balance cost equations that describes the productive purpose of each subsystem related to the final products of the plant. The equations are based on some thermodynamic magnitude and unitary costs, generally, exergetic and monetary are obtained. In addition, the equations represent the relation between products and fuels of each subsystem of the plant that describes the cost formation process by the distribution of external resources to the flows. All methodologies agree that it is necessary to define the productive structure of the system since it shows clearly the products and the fuels of each subsystem.

The productive structure can be represented graphically in diagrams that show clearly the relation among the subsystems by means of products and fuels. A productive diagram is a graphical representation of the productive structure once it uses geometries to show the same productive purpose of the subsystems. In addition, the productive diagram is based on productive flows to define products and fuels through some thermodynamic magnitude variation.

The thermodynamic model basically is represented by Eq. (1). Taking exergy allocation into consideration, k represents the exergetic unit costs that are unknown variables; Y represents a generic productive flow at inlet (in) and outlet (out) of each subsystem which can assume any thermodynamic magnitude such as power (P), total exergy (E), enthalpic (H) and entropic (S) components of exergy, etc. On the right side of the equation is allocated all external resources. Thus, Q_f is the external fuel exergy consumption and k_f is the exergetic unit cost of the external resource. Generally, k_f is assumed to be 1,00 kW/kW since there is no exergy destruction in the process before the plant (Valero *et al.,* 2006). The solution of the set of equations is the exergetic unit costs of each internal productive flow and final product of the plant.

$$\sum(k_{out} \cdot Y_{out}) \quad - \sum(k_{in} \cdot Y_{in}) \quad = k_f \cdot Q_f \tag{1}$$

By the set of equations, each subsystem allows describing one cost equation by means of products and fuels. Nevertheless, the number of internal flows is always greater than the number of subsystems, thus auxiliary equations must be formulated for a single solution. For productive diagrams, the auxiliary equations are based on the Equality Criteria (Frangopoulos, 1994; Wang & Lior, 2007) that considers all productive flows leaving the same productive unit produced under the same resources and irreversibility, thus they must have the same cost.

According to (Valero *et al.,* 2006), the exergetic unit cost is the amount of exergy required to produce one exergy unit of a specific flow. This cost is a measure of the thermodynamic efficiency of the production process. Equation (1) can be adapted to allocate monetary costs, such as fuel costs, investments, operation and maintenance. Furthermore, considerations such as pollution, the availability of natural resources and so-called gray exergy associated with the manufacture and recycling of the capital equipment used by an energy system can be incorporated into the model (von Spakovsky, 1994). Thermoeconomic modeling adapted to assess the specific emission of products in cogeneration plants can be found in (Santos *et al.,* 2013, 2015, 2016).

3. CASE STUDY

Figure 1 represents the physical structure of the sugarcane boiler, which is defined by the following units (or subsystems): Economizer (ECO), Air Heater (AH), Steam Drum (SD), Convective tubes (CT), Membrane Wall (MW), Super Heater (SH) and Combustion Chamber (CC). The boiler enclosures all these subsystems in an adequate arrangement to produce useful steam (Q_U) to supply the cogeneration system. At this point, it is important to emphasize that, despite not being represented in the physical structure, the environment relates with the boiler since it provides the air stream to guaranty the combustion of the bagasse and receives all exhaust gases from the boiler after internal heat exchanges. The main parameters of the boiler are presented in Table 1. More information is available in (Lora and Nascimento, 2004).

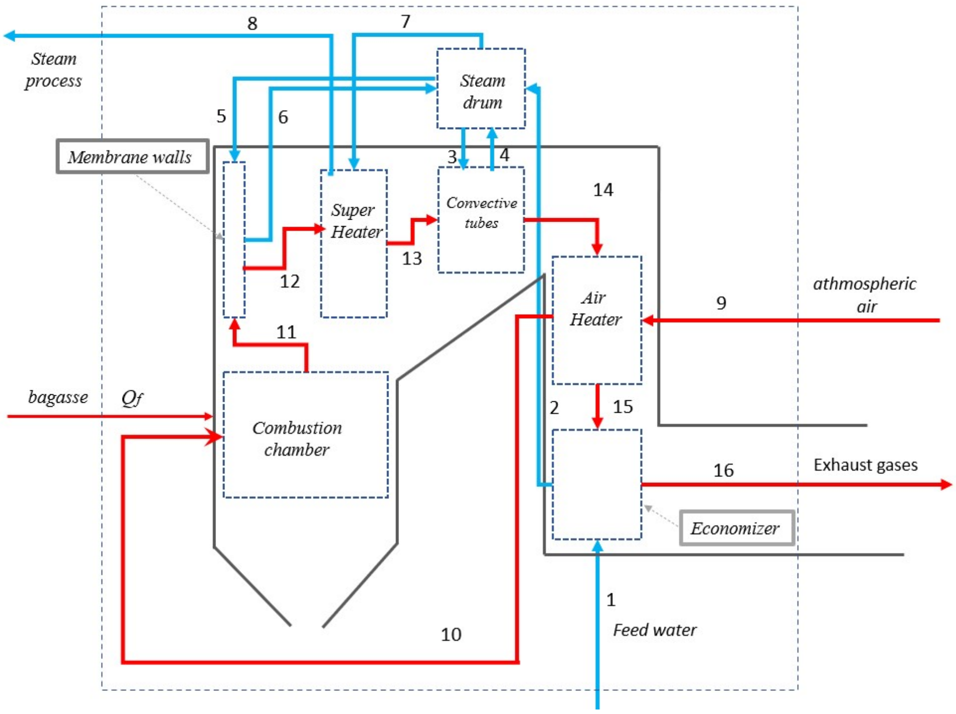

Figure 1. Physical structure of the sugarcane boiler.

Table 1. Design parameters of the sugarcane boiler.

Parameter	***Value***	***Unit***
Nominal Steam Production	120	t/h
Nominal Pressure Steam	4.2	MPa
Steam Temperature	400	ºC
Feed Water Temperature	95	ºC
Exhausting gases Temperature	157	ºC
Steam Generator Ratio $kg_{steam}/kg_{bagasse}$	2.31	$kg_{steam}/kg_{bagasse}$
Excess Air	30	%

The combustion process uses chemical exergy of the bagasse (Q_f) mixed with combustion air and it is a chemical reaction that results in energy liberation and combustion gases are released. The elemental composition of the moist bagasse used in this paper is presented in Table 2 (Lora and Nascimento, 2004). The humidity of the biomass, W, is 50%, on a mass basis. For the combustion, the atmospheric air is considered in dry bases, with volumetric percentage of 21% oxygen and 79% nitrogen.

Table 2. Elemental analysis of the sugarcane bagasse.

Bagasse composition (dry basis)	
Carbon	44.8
Hydrogen	5.35
Oxygen	39.55
Nitrogen	0.38
Sulfur	0.01
Ash	9.79

The Low Heating Value (LHV) was calculated through the Mendeleev correlation presented in (Lora and Nascimento 2004), showed in Eq. (2), where C, H, O and S are the moist bagasse mass basis composition.

$$LHV = 339 \cdot C + 1030 \cdot H - 109(O - S) - 24 \cdot W \quad (2)$$

The exergy of a thermodynamic system is the maximum theoretical useful work that can be produced by a system or flow or mass or energy in equilibrium with a reference environment (Rosen *et al.,* 2008; Bilgen, 2014). The exergy of materials streams is composed of chemical and physical exergies components. For water flows throughout the system, physical exergy is obtained, with non-significant chemical exergy. The chemical exergy of the sugarcane bagasse, shown in Eq. (3), is estimated using the correlation presented in Lora and Nascimento (2004), where ash and water content was negligible. The coefficient β is the ratio of chemical exergy and the low heating value. The present paper assumes the value of 1.157 considering the composition presented in Table 2. The chemical exergy of the flue gas is calculated according to (Moran *et al.,* 2011). The fuel consumption (Q_f), in exergetic basis, is 138,239.4 kW. The physical exergy flow of air and exhaust gases was calculated through a constant specific heat of 1.119.and 1.332 kJ/kgK, respectively, and the thermodynamic states of the boiler and their flows are exposed in Table 3.

$$e_{bagasse}^{CH} = \beta \cdot (LHV + 24 \cdot W) + 9682 \cdot S \quad (3)$$

Table 3. Parameters of physical flows of the boiler.

Physical Flow		***m***	***T***	***P***	***e***	***h***	***s***	***e^CH***
streams	***description***	***(kg/s)***	***(ºC)***	***(kPa)***	***(kJ/kg)***	***(kJ/kg)***	***(kJ/kgK)***	***(kJ/kg)***
0	fuel	14.43	25	101.3	0	0	0	9,580
1	water	33.33	95	5,691	35.37	402.4	1.246	
2	water	33.33	214.7	5,467	190.6	920.2	2.462	
3	saturated liquid	8.77	254.7	4,445	267.6	1,109	2.836	
4	saturated steam	8.77	254.7	4,445	1,003	2,799	6.039	
5	saturated liquid	28.28	254.7	4,445	267.6	1,109	2.836	
6	saturated steam	28.28	254.7	4,445	1,003	2,799	6.039	
7	saturated steam	33.33	254.7	4,445	1,003	2,799	6.039	
8	superheated steam	33.33	400	4,301	1,207	3,209	6.732	
9	air	49.06	25	101.3	0	0	0	
10	air	49.06	334	101.3	99.07	315.7	0.7267	
11	exhaust gases	63.49	1,402	101.3	1,250	1,834	2.299	101.8
12	exhaust gases	63.49	881.1	101.3	704.6	1,140	1.803	101.8
13	exhaust gases	63.49	719.5	101.3	549.2	925.1	1.602	101.8
14	exhaust gases	63.49	544.3	101.3	392.9	691.7	1.343	101.8
15	exhaust gases	63.49	361.1	101.3	249.7	447.7	1.005	101.8
16	exhaust gases	63.49	157	101.3	132.1	175.8	0.4882	101.8

3.1 Productive Diagram

The productive diagram is a graphical representation of the productive structure. It clearly shows the fuel and product of each productive unit and the relations among them for achieving the productive purpose of the plant. The systems components are represented by means of rectangles that are real units or subsystems. The rhombus and circles are fictitious units called junctions (J) and bifurcations (B), respectively, Valero *et al.* (1994). The fuels and products in the productive diagram use productive flows to define the productive purpose of each subsystem.

Different productive diagrams can be designed according to their fuels and products as well as how the resources are shared to the productive units. Thus, the same physical structure can be related to different productive diagrams depends on the analyst's criterion. However, a physical meaning is required for the productive structure, in order to be sensitive to the plant behavior and to obtain exergy costs with physical meaning (Valero *et al.,* 2006).

3.2 E Model

Considering total exergy (E Model), the productive flows used in the productive diagram interconnect the productive units, and these exergy flows can be represented by the variation of exergy ($E_{i:j}$), or exergy of the useful heat (Q_U). The productive flows are defined by the variation between two physical states (Ei and Ej), as shown in Eq. (4).

$$E_{i:j} = E_i - E_j \tag{4}$$

For the productive structure definition, once the exergy variation in a productive unit is negative, it is classified as fuel, and the opposite, as product (Lazzaretto and Tsatsaronis, 2006). By applying Eqs. (1) and (4), a set of equations are obtained. For the auxiliary equations, the Equality Criteria (Frangopoulos,, 1994; Wang and Lior 2007) is applied. Figure 2 shows the productive diagram according to the E Model.

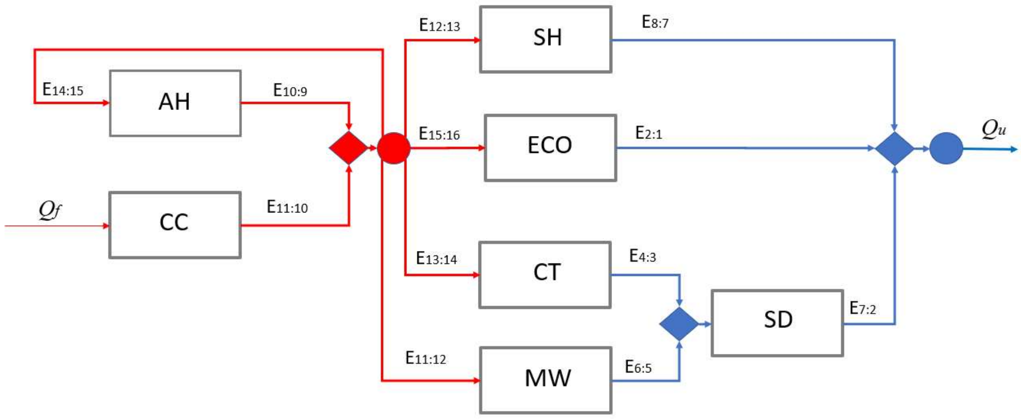

Figure 2. Productive diagram for the system according to the E Model.

The left side represents the equipments that increase the exergy of the gas/air streams, air heater (AH) and combustion chamber (CC). The heat exchangers, super heater (SH), economizer (ECO), convective tubes (CT) and membrane wall (MW) use the flue gas as fuel to increase the exergy of working fluid. Steam drum receives the products of evaporative surfaces (MW and CT) to separate liquid/steam phases. The residue E_{16} as a physical flow is implicitly allocated at economizer and by the equality criteria, assumes the same unit cost of the flows leaving the gas bifurcation. In other words, the residue cost allocation is implicitly allocated proportionally to the exergy consumption in the productive unit that produces the final products.

3.3 E&S Model

The productive diagram according to the E&S Model is shown in Figure 3. The productive flows are represented by total exergy and negentropy as a variation of exergy and entropy of the stream flows, respectively. The methodology used to define products and fuels is the same as in the E Model. However, the negentropy flows consider an increment of entropy as fuel and the opposite as product. The negentropy flows are defined based on Eq. (5).

(Frangopoulos, 1987) proposed an elegant solution defining a dissipative component (condenser) product in steam cycles based on the negentropic terms (called here by E&S Model) and which was later used by other authors. (Lozano and Valero, 1993b) and (von Spakovsky, 1994) had used it in a gas turbine cogeneration system. In this case, a fictitious dissipative component (stack or chimney in the gas cycles) was incorporated into the productive diagram and its product is based on the negentropic term. These methodologies were applied by (Pablo Arena and Borchiellini, 1999) in a combined cycle power plant. However, in these cases the negentropic term was used together with exergy or exergy components (mechanical and thermal), generating some uncommon values of exergetic unit cost (Santos *et al.,* 2006, 2008, 2009).

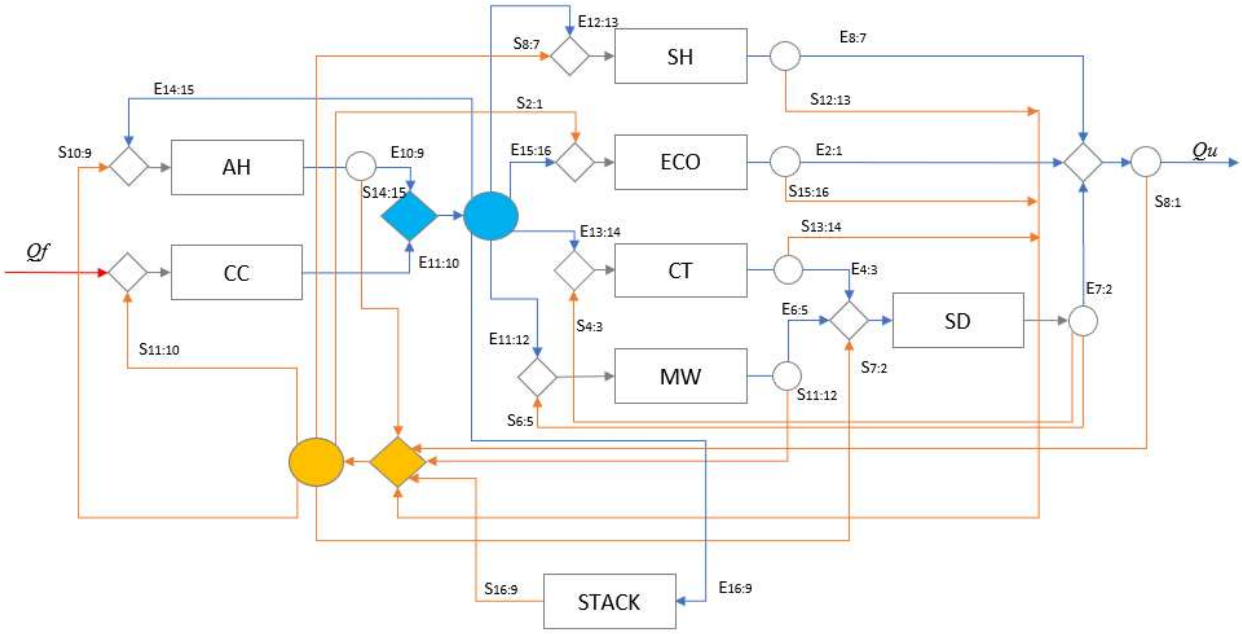

Figure 3. Productive diagram for the system according to the E&S Model.

$$S_{i:j} = S_i - S_j = T_0 m_i (s_i - s_j) \tag{5}$$

The E&S Model uses the negentropy as a fictitious flow to distribute the residue cost in open cycles whereas the exhaust gases are released in the STACK (or chimney) which acts as a dissipative component and redistributes the residue cost proportionally to the entropy increment on the working fluid.

Considering the productive diagram in Figure 3 the dissipative unit (stack) was included. The product of the unit is the negentropy productive flow $S_{16:9}$ and its fuel $E_{16:9}$. This component is the only one that has negentropy as an exclusive product. Despite exist two types of streams on the boiler (air/gas and water), there are only one junction and bifurcation for each exergy and negentropy productive flows.

3.4 H&S Model

The H&S Model uses enthalpic (H) and entropic (S) components of physical exergy to define productive flows of an energy system. According to Santos *et al.,* (2006) the H&S Model was the first thermoeconomic methodology capable of defining fuel and product, in addition to isolating the dissipative equipment (condenser) in the productive diagram without inconsistencies.

In the H&S Model the negentropic concept, introduced by (Frangopoulos, 1987), was approached with a different perspective, i.e., it is used as the entropic component to be used together with enthalpy, both considered as components of exergy (Lourenço *et al.,* 2014), which allowed isolating the dissipative component without uncommon values presented by the E&S Model where it is a fictitious flow.

The fuel and product definition of the productive units respects the same idea presented in the previous models: an enthalpy positive variation between two states means a product while a negative variation is a fuel. The entropy, as already mentioned, is exactly the opposite due to the negative contribution in the exergy equation definition, Eq. (6). For combustion processes the H&S Model incorporates the chemical exergy with respect to the total exergy disaggregation in physical (enthalpic and entropic) and chemical ($Ch_{i:j}$) components and the model is defined by Eq. (6).

$$E_{i:j} = H_{i:j} - S_{i:j} + Ch_{i:j} \tag{6}$$

In the H&S Model, Figure 4, there is a subsystem called environment (ENV), which has the function of dissipating the flue gas residue, thus making the cost allocation of waste explicitly. From the environment, the entropic component is distributed to those units that increase the working fluid entropy. The chemical exergy caused by the combustion process in the combustion chamber ($Ch_{11:10}$) is dissipated in the environment. Therefore, the residue of the boiler has two components: the chemical and the enthalpic (physical). Both are dissipated in the environment to reduce the gaseous entropy from exhaust gases state to atmospheric air conditions. Besides being considered a dissipative component, the environment is responsible for provides combustion air.

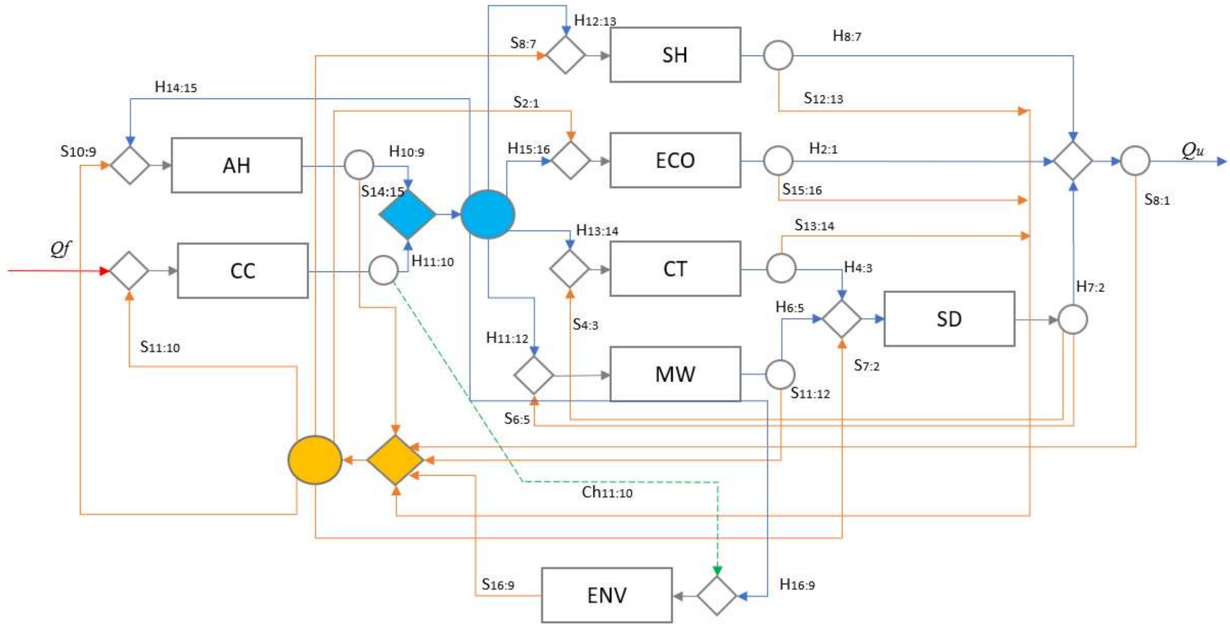

Figure 4. Productive diagram for the system according to the H&S Model.

4. RESULTS AND DISCUSSIONS

This paper applied three thermoeconomic models in a sugarcane boiler (disaggregated into subsystems) using productive diagram to assess the cost formation process of internal flows and final product (useful heat). Besides determining and compare the exergetic unit costs obtained by the models, it aims to discuss waste cost allocation and highlight the importance of the environment as a subsystem in the thermoeconomic modeling.

Table 4 shows the exergetic unit costs for the flows according to the models applied. As expected, all the methodologies determine the same unit cost, 3.54 kW/kW, for the useful heat, because its product is the only final product of the system.

Regarding the unit cost of the internal flows, all of them are greater than the unit, which could indicate coherence from a thermodynamic point of view. However, each model presents particularities which one may summarize as follow:

- E Model:
  It is not able to carry out an explicit waste cost allocation, which is a disadvantage regarding the allocation of the environmental costs in thermoeconomics. At this model, the waste cost allocation is implicit to the useful heat proportionally to the fuels of SH, CT, MW and ECO. Besides, there is no subsystem to specifically handle the waste cost and consequently, it does not allow explicit treatment of them.
- E&S Model:
  Although the E&S Model uses the STACK, which could be interpreted as the environment, this component is a fictitious one and other works have already shown that this model presents uncommon values of exergetic unit costs in cogeneration plants. For example, (Santos *et al.,* 2016) obtained negative values of specific emissions when allocating CO_2 in a gas turbine cogeneration with the E&S Model. In addition, the relation between product and fuel (efficiency) for the subsystem STACK achieves a value of 110.22% which means a product greater than its fuel, indicating an inconsistency in the thermodynamic point of view. It occurs due to the entropic flow which is duplicated in this model, thus penalizing twice the equipment that consume negentropy flow.
- H&S Model:
  It is a methodology that has already been proposed taking into account the waste cost allocation, in a systematic way through the definition of its productive structure as an inherent feature of the model. It uses the environment and exergy disaggregation to explicitly allocate the waste cost that can be done in both gas and steam cogeneration plants. In the case of steam plants, it is necessary to disaggregate the boiler into subsystems to use the environment as a subsystem for the allocation of environmental charges. In the case of this paper, the ENV as a subsystem presented a product/fuel ratio of 52.24%.

Table 4. Exergetic unit costs for E, E&S and H&S models.

E Model			E&S Model			H&S Model		
Flow	**Value [kW]**	**Exergetic unit cost [kW/kW]**	**Flow**	**Value [kW]**	**Exergetic unit cost [kW/kW]**	**Flow**	**Value [kW]**	**Exergetic unit cost [kW/kW]**
$E_{2:1}$	5,174	3.23	$E_{2:1}$	5,174	7.04	$H_{2:1}$	17,260	3.26
$E_{4:3}$	6,449	3.44	$E_{4:3}$	6,449	10.65	$H_{4:3}$	14,820	3.47
$E_{6:5}$	20,804	3.72	$E_{6:5}$	20,804	13.32	$H_{6:5}$	47,808	3.69
$E_{7:2}$	27,085	3.67	$E_{7:2}$	27,085	8.84	$H_{7:2}$	62,628	3.64
$E_{8:7}$	6,779	3.25	$E_{8:7}$	6,779	8.17	$H_{8:7}$	13,664	3.43
$E_{10:9}$	4,860	4.18	$E_{10:9}$	4,860	9.29	$H_{10:9}$	15,489	3.58
$E_{11:10}$	74,494	1.86	$E_{11:10}$	74,494	4.42	$H_{11:10}$	100,913	2.40
$E_{11:12}$	34,625	2.23	$E_{11:12}$	34,625	4.72	$H_{11:12}$	44,008	2.56
$E_{12:13}$	9,862	2.23	$E_{12:13}$	9,862	4.72	$H_{12:13}$	13,664	2.56
$E_{13:14}$	9,922	2.23	$E_{13:14}$	9,922	4.72	$H_{13:14}$	14,820	2.56
$E_{14:15}$	9,092	2.23	$E_{14:15}$	9,092	4.72	$H_{14:15}$	15,489	2.56
$E_{15:16}$	7,469	2.23	$E_{15:16}$	7,469	4.72	$H_{15:16}$	17,260	2.56
-	-	-	$E_{16:9}$	8,384	4.72	$H_{16:9}$	11,162	2.56
-	-	-	$S_{2:1}$	12,086	5.81	$S_{2:1}$	12,086	3.64
-	-	-	$S_{4:3}$	8,371	8.84	$S_{4:3}$	8,371	3.64
-	-	-	$S_{6:5}$	27,004	8.84	$S_{6:5}$	27,004	3.64
-	-	-	$S_{7:2}$	35,542	5.81	$S_{7:2}$	35,542	3.64
-	-	-	$S_{8:7}$	6,885	5.81	$S_{8:7}$	6,885	3.64
-	-	-	$S_{10:9}$	10,629	5.81	$S_{10:9}$	10,629	3.64
-	-	-	$S_{11:10}$	32,882	5.81	$S_{11:10}$	32,882	3.64
-	-	-	$S_{11:12}$	9,383	13.32	$S_{11:12}$	9,383	3.69
-	-	-	$S_{12:13}$	3,802	8.17	$S_{12:13}$	3,802	3.43
-	-	-	$S_{13:14}$	4,897	10.65	$S_{13:14}$	4,897	3.47
-	-	-	$S_{14:15}$	6,396	9.29	$S_{14:15}$	6,396	3.58
-	-	-	$S_{15:16}$	9,790	7.04	$S_{15:16}$	9,790	3.26
-	-	-	$S_{16:9}$	9,241	4.28	$S_{16:9}$	9,241	4.77
-	-	-	$S_{8:1}$	54,513	3.54	$S_{8:1}$	54,513	3.54
-	-	-	-	-	-	$Ch_{11:10}$	6,463	2.40
Q_U	39,038	3.54	Q_U	39,038	3.54	Q_U	39,038	3.54

5. CONCLUSIONS

Due to the growing environmental concerns, a thermoeconomic model that describes the cost formation process, uses exergy as the magnitude, and allocates environmental issues in the modeling is required. However, only unite these concepts is not enough. It must be thermodynamically consistent, provides in-depth analysis for cost allocation and properly incorporates environmental charges in the modeling.

In this paper, three thermoeconomic models were applied and compared regarding the exergetic unit cost of internal flows and final product and waste cost allocation in a sugarcane boiler. The three models are able to determine the exergetic unit costs. Nevertheless, the E Model cannot allocate waste explicitly and the E&S Model despite using the important concept of negentropy and the STACK as a subsystem that could be interpreted as the environment, this model presents thermodynamics inconsistencies.

The H&S Model took advantage of the concept of negentropy, but as an exergy component to be used with the enthalpic one, and through the environment as a subsystem (ENV), the environmental burdens are allocated exactly to this unit defined as the environment. In this way, the waste cost is explicitly allocated and the model can be also adapted for specific emissions allocation, for instance, in both gas and steam cogeneration plants. For steam plants, the boiler must be disaggregated into subsystems to use the environment for the allocation of environmental charges.

Furthermore, only the H&S Model handles the environment as a consistent subsystem, acting as a dissipative component to receives the chemical and the physical contents of the boiler exergy waste besides providing atmosphere air to the combustion process. Moreover, the internal flows presented reasonable results considering useful steam, internal flows and equipment efficiencies.

The environment as an H&S subsystem can play an important role to allocate environmental charges and redistributes them to the final products. For instance, sugarcane boilers use some environmental control equipment, such as ash handling systems, scrubbers and desulfurization techniques for SO_2 control to deal with specific emissions. Thus, the costs associated with acquisitions, investments, operations and maintenance of these techniques and control systems can be charged in the environment as a subsystem in order to distribute them to the useful steam costs.

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