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DISAGGREGATION OF THE PHYSICAL EXERGY TO IMPROVE THE ACCURACY OF THE RESULTS IN THERMOECONOMICS

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Abstract. Thermoeconomics connects thermodynamic and economic concepts to solve problems in complex energy systems. Exergy is the thermodynamic magnitude used in thermoeconomics. Sometimes, exergy flows have been disaggregated into thermal and mechanical components, in order to improve the accuracy of the results. However, in the last years, new kinds of physical exergy disaggregation have been introduced in thermoeconomics as alternatives for the treatment of the dissipative components and residues. This paper aims at evaluating the improvement of the accuracy of the results in thermoeconomics due to physical exergy disaggregation, by applying four different level of physical exergy disaggregation, for exergy and monetary cost allocation to the final products in six different cogeneration systems, five of them incorporating dissipative components (condenser or valve) or residues (recovery boiler exhaust gases). The plants studied are three different steam turbine cogeneration systems and three different gas turbine cogeneration systems.

Keywords: *Improvement of the Accuracy of the Results*, *Physical Exergy Disaggregation*, *Thermoeconomics*

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 of the processes and systems (Valero *et al*., 2006).

Sometimes, under a thermoeconomic analysis, it is necessary to consider the components as a group of subsystems and/or the exergy flows consisting of several components, because the more disaggregated is the system the more accurate are the results (Torres *et al*., 1996). Depending on the type of analysis, different levels of accuracy of the results are required, i.e., each thermoeconomic analysis requires a specific aggregation level of the components and flows. For local optimization and diagnosis, for instance, total disaggregation of the components of the system is generally required.

According to Lazzaretto and Tsatsaronis (2006), by considering physical exergy disaggregated into thermal and mechanical components, we improve the accuracy of the results in thermoeconomic analysis and we increase the complexity of the model. However, in the last years, new kinds of physical exergy disaggregation have been introduced in thermoeconomics as consistent alternatives in order to disaggregate the dissipative components of the systems and to allocate the cost of the residues to the final products (Santos *et al.,* 2006 and Lourenço *et al.,* 2011) which were thermoeconomic challenges ten years ago.

At this point, some questions arise related to physical exergy disaggregation in thermoeconomic analysis: (i) what kind of physical exergy disaggregation allows the total disaggregation of the components of the systems? (ii) the accuracy improvement of the results is significant? (iii) the increase in the complexity of the model is considerable? (iv) is physical exergy disaggregation necessary for extracting the main conclusions in thermoeconomic analysis?

This paper aims at answering these and others questions related to physical exergy disaggregation in thermoeconomics, by applying the maximum of four different level of physical exergy disaggregation, for exergy and monetary cost allocation to the final products (net power and useful heat) in six different cogeneration systems, most of them including dissipative components (condenser or valve) or residues (recovery boiler exhaust gases). The different monetary and exergy unit costs obtained for the two final products of each cogeneration plant are compared and analyzed.

2. PHYSICAL STRUCTURE OF THE COGENERATION SYSTEMS ANALYZED

The gas turbine cogeneration plants were chosen in order to lead with ideal gas as working fluid and because this kind of plant allows leading with de problem of allocation of the residues (exhaust gases of the recovery boiler). On the other hand, the steam turbine cogeneration plants allows leading with working fluid modelled as real fluid and two of them incorporate a dissipative components, such as a condenser or a bypass valve, in the system studied. All cogeneration systems were modelled considering actual cycle, i.e., there are pressure drop and irreversibilities in processes.

2.1 Gas Turbine Cogeneration Systems

Figure 1(a) represents the physical structure of the CASE 1, which is a Simple Gas Turbine Cogeneration System (SGT) defined as having four units or subsystems: the air compressor (AC), the combustion chamber (CC), the gas turbine (GT) and the recovery boiler (RB). The thermodynamic modelling of the physical structure in Fig. 1 considers Could Air-Standard. The pressure ratio is 5 and the maximum cycle temperature is 850 °C. The plant produces 1,612.5 kW of net power (P_N) and 2,233.59 kW of heat (Q_U). The external fuel (Q_F) is 9,761.85 kW.

Figure 1(b) represents the physical structures of two other CASES (2 and 3), which are two different Regenerative Gas Turbine Cogeneration Systems (RGT I and RGT II). The regenerator (R) in Fig. 1(b) differs this kind of gas turbine cogeneration plant from the one represented in Fig. 1(a).

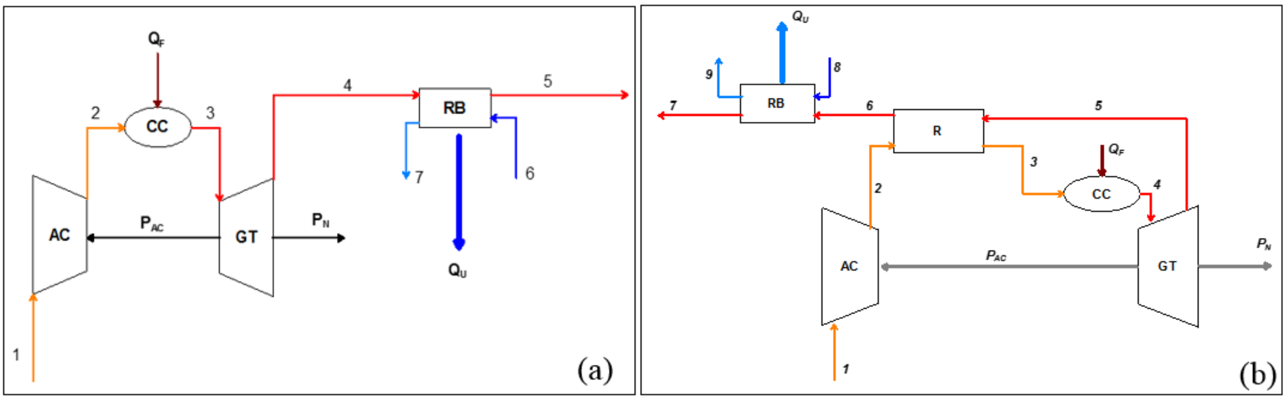


Figure 1. Physical Structure for Gas Turbine Cogeneration Systems with: (a) SGT (Simples Gas Turbine) and (b) RGT (Regenerative Gas Turbine)

CASE 2 is a Regenerative Gas Turbine Cogeneration System (RGT I), which is the well known GGAM problem (Valero *et al*., 1994), i. e, the pressure ratio is 8.5, the maximum cycle temperature is 1,492.63 K, about 30 MW of net power (P_N) and 12.74 MW of heat (Q_U). The external fuel (Q_F) is 84.38 MW.

The Regenerative Gas Turbine Cogeneration System (RGT II), which represents the CASE 3, was defined by Cerqueira (1999). The pressure ratio is 5.89, the maximum cycle temperature is 1,484 K, about 2760 kW of net power (P_N) and 390 kW of heat (Q_U). The external fuel (Q_F) is 5560 kW.

2.2 Steam Turbine Cogeneration Systems

Figure 2 represent the physical structures of three different steam turbine cogeneration plants studied. The first, Fig. 2(a), is CASE 4, a Backpressure Steam Turbine Cogeneration Plant (BPT). The Extraction-Condensig Steam Turbine (ECT) is the second, Fig. 2(b), which represents the CASE 5. CASE 6 is the third, Fig. 2(c), a Backpressure Steam Turbine Cogeneration Plant with a Bypass Valve (VBPT).

All boilers operate under the same parameters (pressures, temperatures, and thermal efficiencies). They use the same natural gas. However, the steam mass flows produced are different. The backpressure steam are the same. In Fig. 2(c), the steam mass flows expanded in both turbine and valve are the same. The net power produced are, respectively, 1,011 kW, 3,963 kW and 964 kW. The steam pressures to the processes are the same and the parameters (pressure and temperature) of the condensate returning the process are the same too. The useful heat are 1,876 kW, 1,876 kW and 4121 kW, respectively. In Fig. 2(b), the condenser pressure is 5.62 kPa. More details of all these six different CASES studied can be found in the master degree dissertation of Faria (2014).

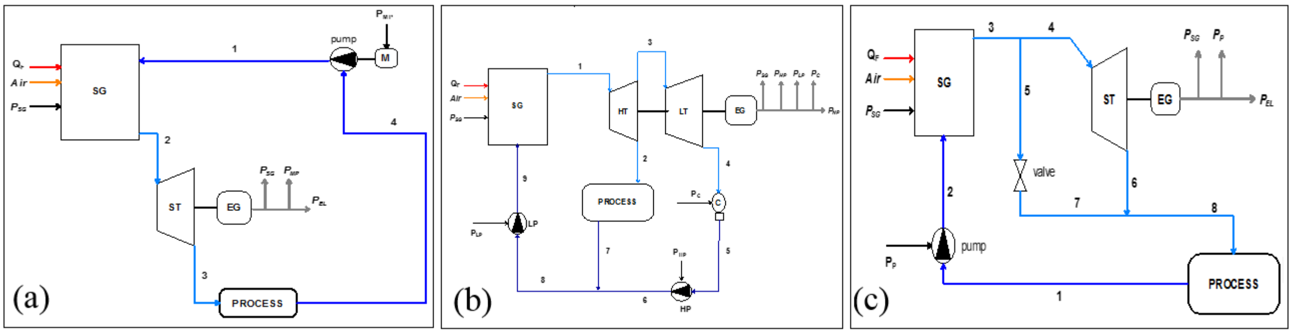


Figure 2. Physical Structures for Steam Turbine Cogeneration Systems with: a) BPT (Backpressure Turbine) (b), CET (Condensing-Extraction Turbine) and VBPT (Valve and Backpressure Turbine)

3. PHYSICAL EXERGY DISAGGREGATION

In order to carry out the thermoeconomic modeling aimed by this paper, the total physical exergy and its components need to be calculated. Figures 3(a) and 3(b) summarise the procedures in order to calculate the physical exergy and its components for the physical flows representing air or gases (modelled as ideal gases) and water or steam (modelled as real fluid), respectively. The reference temperature and pressure are assumed and fixed at 25°C and 101.32 kPa, respectively.

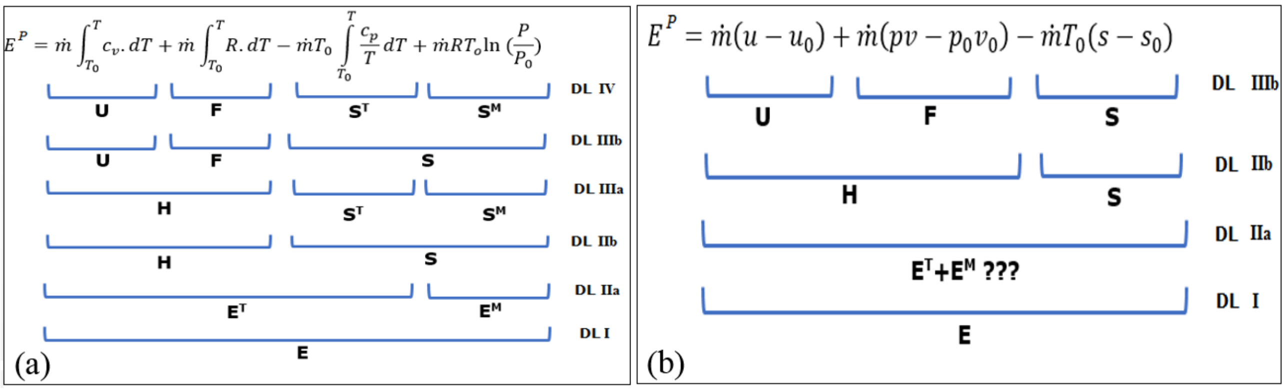


Figure 3. Methodology of Physical Exergy Disaggregation for: a) Ideal Gas and (b) Real Fluid

The first level (DL I) is the total physical exergy (E). In one of the second level (DL IIa) the physical exergy is disaggregated into thermal and mechanical components. However, as shown in Fig. 3(b), these components are not explicit in the physical exergy equation for real fluid.

Thus the thermal and mechanical components of physical exergy for water and steam were obtained according to Morosuk and Tsatsaronis (2008). They proposed that the thermal component of physical exergy (E^T) should be calculated along the isobaric line from its initial state $[T, p_0]$ until $[T_0, p_0]$. On the other hand, the mechanical component of physical exergy (E^M) should be calculated along the isothermal line from its initial state $[T_0,\ p]$ until $[T_0, p_0]$. Once that, using this procedure, the sum of the thermal and mechanical components does not correspond to the total physical exergy, theses authors proposed calculated the mechanical component along the isothermal line and the thermal is the difference between total physical exergy and the mechanical component (DL IIa).

However, one of the authors of this methodology has already admitted that this procedure contain arbitrariness (Lazzareto e Tsatsaronis, 2006). For comparison, in this work, for water and stem, these component were calculates using an alternative path, i. e., calculate the thermal component along the isobaric line, and the mechanical one as the difference between total exergy and its thermal component (DL IIa*).

This arbitrariness does not occur when the physical exergy is disaggregated into its enthalpic (H) and entropic (S) terms (DL IIb) as proposed by Santos *et al*., 2006. Once that the enthalpy can be defined in terms of internal energy (U) and flow work (F), the physical exergy can be disaggregated into three components (DL IIIb), as proposed by Lourenço *et al*., 2011.

Once that, for ideal gas, the entropic term can be disaggregated into its thermal (S^T) and mechanical (S^M) terms, two more disaggregation level (DL IIIa and DL IV) can be defined used, as proposed by Santos *et al.*, 2010. In this paper, these two disaggregation levels (DL IIIa and DL IV) is not used for water and steam in the steam turbine cogeneration plants in order to avoid unnecessary arbitrariness during the calculation of the thermal and mechanical components of entropy.

4. 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, it is convenient to make up a thermoeconomic model, which define the productive propose of the subsystems (products and fuels), as well as the distribution of the external resources and internal product throughout the system.

The thermoeconomic model could be represented by means of the productive or functional diagram, showing clearly and graphically how the product of a given subsystem is distributed to be used as input to another subsystem or as a final product of the plant.

To define the productive structure is necessary to analyze the flows of exergy (total or in components), described in Fig. 3, crossing each subsystem of the plant to determine if it is input (fuel) or output (product). For this definition, it takes into account if the contribution of the exergy component under consideration is positive or negative in the total exergy equation (Fig. 3) and if it is increasing or decreasing between the initial and final state of the subsytem. If the contribution of the exergy component is positive in the total exergy equation (for instance, in Fig. 3, E, E^T, E^M, H, U, F and S^M), increasing flows of this magnitude are output and decreasing flows are input. If the contribution is negative (for instance, S and S^T), increasing flows of this magnitude are input and decreasing flows are output. The only limitation with must be imposed it that it should 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. The way in which we define the productive structure is a key point in thermoeconomic analysis. In other words, the deeper the conceptual disaggregation of the system in components and flows, the better the results.

According to Çengel and Boles (2006), there is some disagreement on a general definition of the second-law efficiency, and thus a person may encounter different definitions for the same device, but it serves as a measure of approximation to reversible operation, and thus its value should range from zero in the worst case (totally irreversible process) to one (100%) in the best case (totally reversible process). This theoretical limit of one (100%) could be attained only if there were no irreversibility (*Ir*) or losses (*Lo*). Thus, in thermoeconomics the concept of fuel (*Fu*), product (*Pr*), irreversibility (*Ir*), losses (*Lo*) and efficiency (η) are not independents, as shown in Eq. (1) and (2).

$$Fu - Pr = Ir + Lo \tag{1}$$

$$\eta = {}^{Pr}/_{Fu} \tag{2}$$

These concept and limits were taken into account during the definition of the subsystem fuels and products for the productive structure using the different exergy disaggregation levels.

4.1 Gas Turbine Cogeneration Plants

Figure 4 shows the productive structure of the gas turbine cogeneration systems (SGT and RGT) at the first level (DL I), i. e., in which the fuel and products are defined using total physical exergy only. The external exergy resource consumed by the system (Q_F), the mechanical net power (P_N) and useful heat exergy (Q_U) are the same flows represented in the physical structure in Fig. 1.

The rectangles are the real units (or subsystems) that represent the actual equipment 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. 4 has inlet and outlet arrows, that represent its fuel (or resource) and products, respectively. Each productive flow is defined based on physical flows. The productive flows representing the working fluid ($E_{j:k}$) are always exergy variations between two physical flows (E_j and E_k). The total physical exergy of the physical flows (E_j and E_k) are calculated using the equation in Fig. 3(a) and 3(b) for gases and water/steam streams, respectively. The mathematical model for cost allocation is obtained by formulating the cost equations balance in each actual and fictitious units of the functional diagram, as shown in Eq. (3), where c is the monetary unit cost of each flow of the productive structure (unknown variable) and Y is a generically way to represent the inlet and outlet flows of the functional diagram. The variable Z is the hourly cost of each unit due to the capital cost, operation and maintenance. The monetary unit cost of the external fuel is a known variable. As shown in Eq. (3), the model attributes the same monetary unit cost (c_{ufd}) to all of the flows leaving the same productive unit or leaving the same bifurcation (Y_{out}).

$$c_{ufd}.\sum Y_{out} - \sum(c_{in}.Y_{in}) = Z \tag{3}$$

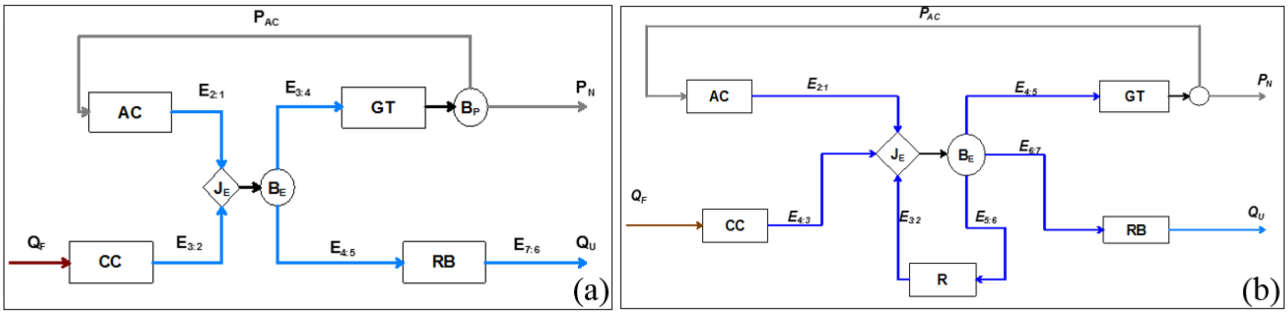


Figure 4. Productive Structures for Gas Turbine Cogeneration Systems considering Disaggregation Level I (DL I) for: a) SGT (Simple Gas Turbine) and (b) RGT (Regenerative Gas Turbine)

By modifying Eq. (3) in order to formulate the cost balances to provide the exergetic unit cost (k) of each flow of the productive structure, we obtain Eq. (4). In this case, the hourly cost of the subsystem due to the capital cost, operation and maintenance must be equals zero (Z = 0) and the monetary unit cost of the external fuel is replaced by the exergetic unit cost of an external resource, which is equal 1.00 kW/kW, because there is no exergy destruction before the productive process is performed.

$$k_{ufd}.\sum Y_{out} - \sum(k_{in}.Y_{in}) = 0 \qquad (4)$$

The solution of the sets of cost equations obtained by applying Eq. (3) and (4) in each device allows the attainment of the monetary and exergetic unit cost of each internal flow and final product.

For the remain productive diagrams representing the more disaggregated physical exergy levels, the external exergy resource consumed by the system (Q_F), the mechanical net power (P_N) and useful heat exergy (Q_U) are the same flows represented in the physical structure (in Fig. 1) and in the productive diagram for the first disaggregation level (in Fig. 4). The main differences are the productive flows representing the fuel and the product defined by taking into account the variation of the physical exergy component of the physical flows between inlet and outlet of the subsystems. Furthermore, due to physical exergy disaggregation, some subsystems incorporate a small junction and/or a small bifurcation to indicate that they have more than one fuel and/or product, respectively.

In the productive structure of the Disaggregation Level IIa, there are productive flows representing the thermal and/or mechanical components ($E^T_{j:k}$ and/or $E^M_{j:k}$) due to these magnitude variations between two physical flows (E^T_j and E^T_k and/or E^M_j and E^M_k).

Analogically, the productive diagram of the Disaggregation Level IIb includes flows representing the enthalpic ($H_{j:k}$) and the entropic ($S_{j:k}$) terms of the physical exergy and the productive diagram of the Disaggregation Level IIIa includes flows representing the respective physical exergy components ($H_{j:k}$, $S^T_{j:k}$ and $S^M_{j:k}$). In the Disaggregation Level IIIb, the productive flows represents the variation of internal energy ($U_{j:k}$), flow work ($F_{j:k}$) and entropic ($S_{j:k}$) terms of the physical exergy between the inlet and the outlet state of the physical subsystems.

Figure 5 shows the productive structure of the gas turbine cogeneration systems at the highest physical exergy disaggregation level (DL IV), in which the working fluid allows the definition of the fuel and products taking into account four different components ($U_{j:k}$, $F_{j:k}$, $S^T_{j:k}$ and $S^M_{j:k}$).

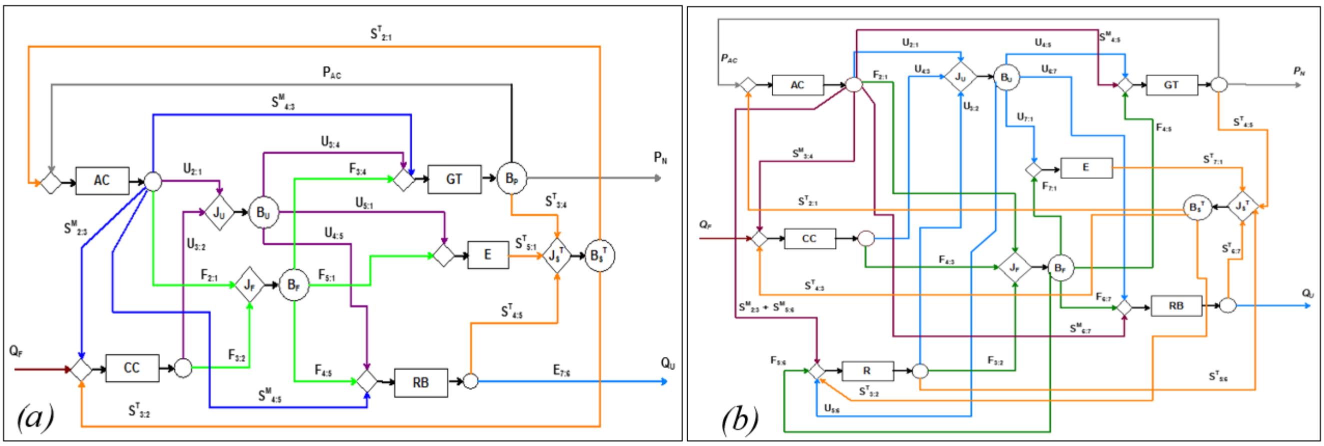


Figure 5. Productive Structures for Gas Turbine Cogeneration Systems considering Disaggregation Level IV (DL IV) for: a) SGT (Simple Gas Turbine) and (b) RGT (Regenerative Gas Turbine)

Although the first disaggregation level (DL I) already allows the total disaggregation of the system in all their subsystem, this one (DL IV) increases considerably the number of internal flows. Furthermore, the last one (DL IV) incorporates a fictitious subsystem, called environment (E), with do not exist in the physical structure of the system. This fictitious subsystem (E) is part of the productive diagrams of all others disaggregation levels (DL IIb, DL IIIb and DL IIIb) in which the entropic components ($S_{j:k}$, $S^T_{j:k}$ and $S^M_{j:k}$) are used as physical exergy component.

4.2 Steam Turbine Cogeneration Plants

Figure 6(a) shows the productive structure of the Back Pressure Steam Turbine Cogeneration Plant at disaggregation level I (DL I). The external resource is natural gas. The final products are electric net power (P_{EL}) and heat exergy (Q_U). All of the flows of the productive structure represent total exergy. The productive flows ($E_{j:k}$) are always exergy variations between two physical flows (E_j and E_k).

A more disaggregated model based on the decomposing of the exergy physical flows in their thermal and mechanical components (DL IIa and DL IIa*) was analyzed too. Another kind of exergy disaggregation (DL IIb) was performed, considering two components too (enthalpic and entropic).

Figure 6(b) represents the most disaggregated productive structure (DL IIb) performed for the steam plants, which considers the physical exergy disaggregated into internal energy ($U_{j:k}$), flow work ($F_{j:k}$) and entropic term ($S_{j:k}$). For Backpressure Steam Turbine cogeneration plant, Fig. 2(a), the first disaggregation level (DL I) is enough for total disaggregation of the system component, once that there are no dissipative components. The remaining disaggregation level (DL IIa, DL IIa* and DL IIIb) were analyzed in order to evaluate the accuracy improvement of the results only.

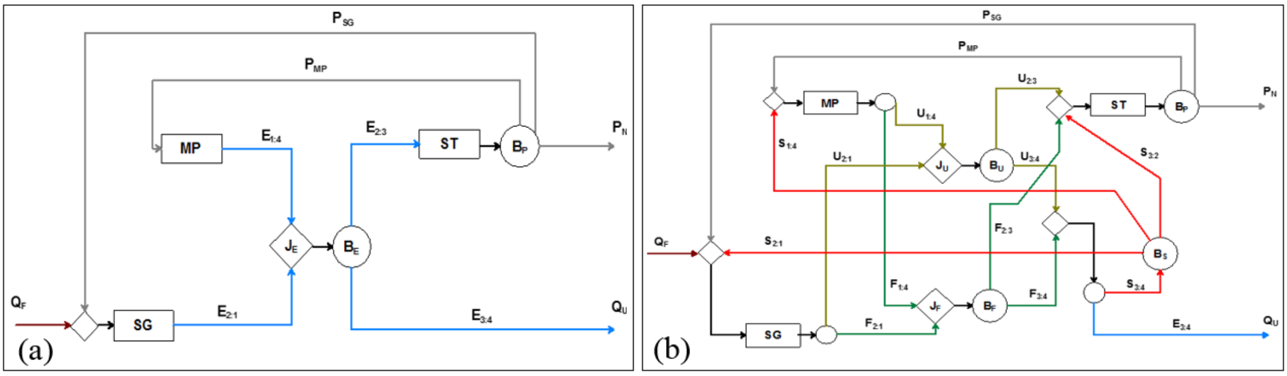


Figure 6. Productive Structures for the Backpressure Steam Turbine Cogeneration System (BPT): a) Disaggregation Level I (DL I) and (b) Disaggregation Level III (DL III)

Figure 7(a) shows the productive structure for the System with Extraction Condensing Steam Turbine using Disaggregation Level I. This level cannot define a product for the condenser (C) and consequently cannot isolate it. So, this component is allocated together with the low turbine (LT) because most analyst agree that the condenser helps the turbine make vacuum increasing the expansion process for additional power production. The disaggregation of physical exergy into thermal and mechanical components (DL IIa and DL IIa*) have the same limitation of DL I, i., e., they cannot isolate the condenser and this component is allocated together with the low turbine too. However, the disaggregation of physical exergy into enthalpic and entropic component (DL IIb) allows isolating the condenser. Thus, the most complex productive structure, Fig. 7(b), based on the most disaggregated level (DL IIIb) was used in order to evaluate the accuracy improvement only. However, this is the unique exergy disaggregation level capable of defining a product for the valve and isolate it in the productive structure, Fig. 8(c). Thus, for the Bypass Valve and Backpressure Steam Turbine Cogeneration Plant, the previous levels (DL I, DL IIa, DL IIa* and DL IIb) must allocate the valve together with another subsystem. In this work, in each of these levels the valve was firstly allocated with the turbine and then with the process, to analyze the influence of the allocation of valve using these different ways. The first way is here called “ST-VLV” and the second, “Proc-VLV”. These two forms follow the idea that if it is impossible to disaggregate the dissipative equipment, it should be allocated together with some productive equipment. Figure 8(a) and 8(b) shows these two ways to allocate the valve using the productive structure according to the first level (DL I).

The allocation of the valve together with the process, Fig. 8(b), follows the idea that the valve helps the process to maintain the parameters according to its requirement. On the other hand, the allocation of the valve with the backpressure steam turbine, Fig. 8(a), follows the idea that the valve is used because of inability of the system power demand to consume the full power generated in the turbine.

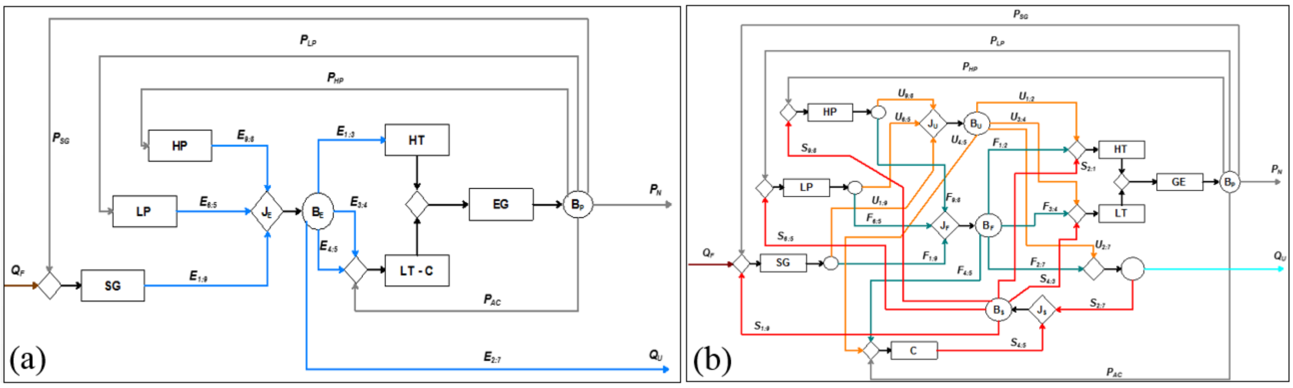


Figure 7. Productive Structures for the Condensing-Extraction Steam Turbine Cogeneration System (CET): a) Disaggregation Level I (DL I) and (b) Disaggregation Level III (DL III)

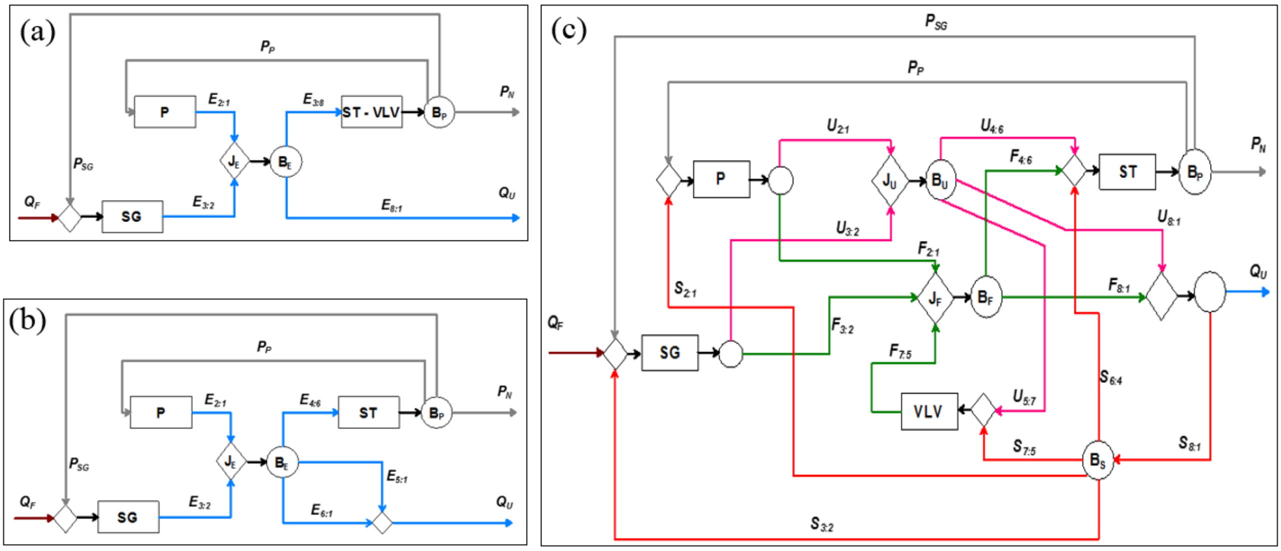


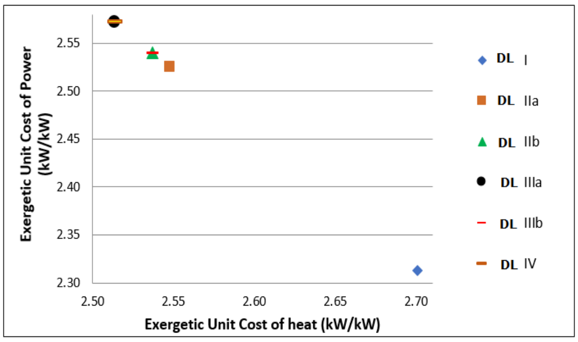
Figure 8. Productive Structures for the Bypass Valve and Backpressure Steam Turbine Cogeneration System (VBPT): a) Disaggregation Level I (DL I) for Valve with Turbine, b) Disaggregation Level I (DL I) for Valve in the Process and (c) Disaggregation Level III (DL III)

5. RESULTS AND DISCUSSIONS

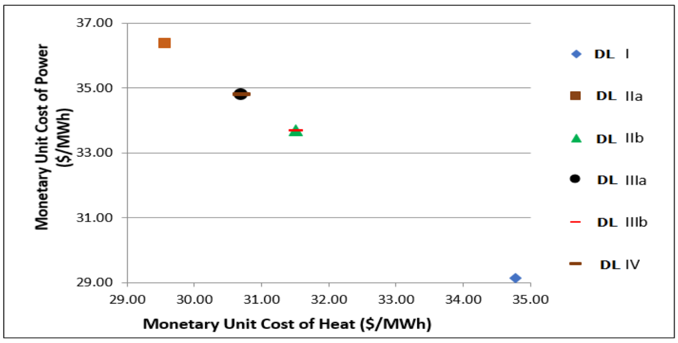
Figure 9 and 10 compare the exergetic and monetary unit cost of the final products (heat and power), obtained by the application of each disaggregation level for gas turbine plants and steam turbine plants, respectively. As expected, in any cogeneration plants, different productive structures provide different unit costs of the finals products. For the same operation condition of a plant, the higher the unit cost of power, the lower the unit cost of heat, and vice-versa. Although, monetary unit costs were calculated, the analysis should be made based on the exergetic unit cost in order to take into account thermodynamics concept only and avoid market influences in the calculation of monetary unit cost.

Figure 9 shows that from the minimum desegregation level (DL I) to any more disaggregated level, the exergetic unit cost of heat decreases and, consequently, the exergetic unit cost of power increases. However, when the difference between the disaggregation levels is due to the disaggregation of enthalpy into internal energy and flow work only (DL IIb and DL IIIb or DL IIIa and DL IV), the results are the same, because for ideal gas, enthalpy, internal energy and flow work depend on the temperature only. This fact explain why DL IIIa and DL IIIb provide different results.

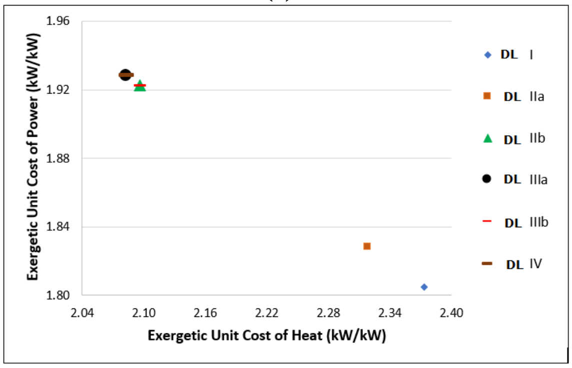
On the other hand, the difference between the productive structures is not due to the exergy disaggregation level only. Part of the difference is due to the criterion used to allocate the residues (exhaust gases). For example, using DL I or DL IIa, the residue cost is implicitly distributed to the final products (power and heat) proportionally to the exergy (total or partial) removed from the working fluid by the gas turbine and recovery boiler (respectively). When the remaining disaggregation levels (DL IIb, DL IIIa, DL IIIb and DL IV) are used, the productive structures define explicitly that the enthalpic content of the exhaust gases (or residues) is delivered to an imaginary productive unit, here called environment (E), and afterwards it is redistributed to the real productive units proportionally to the increase of entropy in the working fluid (partial or total) caused by these productive units. These different criteria for residue allocation explain why DL IIa and DL IIb provide different results.



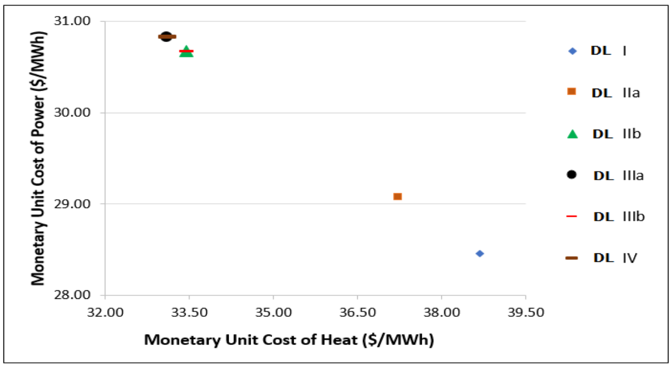
(a)



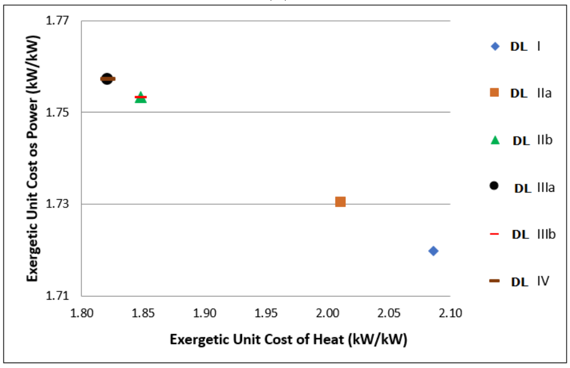
(b)



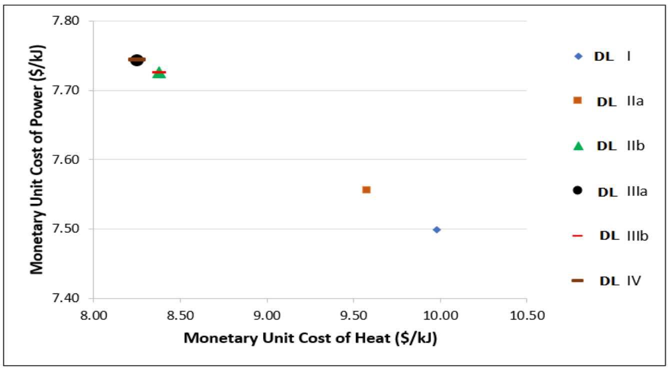
(c)



(d)



(e)



(f)

Figure 9. Exergetic and Monetary Unit Cost of the Final Products for the Gas Turbine Cogeneration Systems: a) SGT, b) SGT, c) RGT I, d) RGT I, e) RGT II and f) RGT II

For the three gas turbine cogeneration plants analyzed in this work, the results, Fig. 9(a), 9(c) and 9(e), show that, from the minimum disaggregation level (DL I) to the maximum disaggregation level (DL IIIa or DL IV) the exergetic unit cost of power increases (10.09%, 6.41% and 2.23%) and the exergetic unit cost of heat decreases (7.44%, 13.97% and 14.25%).

Figure 10(a) and 10(b) compare the exergetic unit cost and the monetary unit cost, respectively, of the final products (useful heat and net power), obtained by the application of each model used in this paper for the Backpressure Steam Turbine Cogeneration Plant. The maximum difference is not for the maximum disaggregation level. The maximum differences are obtained when the physical exergy is disaggregated in thermal and mechanical components (DL IIa and DL IIa*). However, these splitting involve arbitrariness in the calculation of these separated forms of physical exergy, and the maximum difference (in DL IIa) is very small, i. e., the exergetic unit cost of power increases 0.46% and the exergetic unit cost of heat decreases 0.36%. For the maximum disaggregation level (DL IIIb), the exergetic unit cost of power increases 0.07% and the exergetic unit cost of heat decreases 0.06%.

Figure 10(c) and 10(d) compare the exergetic unit cost and the monetary unit cost, respectively, for the Condensing Extraction Steam Turbine Cogeneration Plant. The three disaggregation levels that cannot isolate the condenser in the productive structure (DL I, DL IIa and DL IIa*) allocate it together with the turbine and, consequently, overcharge the unit cost of power in detriment of the unit cost of heat. On the other hand, from the minimum disaggregation level (DL I) to the disaggregation levels that isolate this dissipative component (DL IIb and DL IIIb), the exergetic unit cost of power decreases (1.16% and 1.14%) and the exergetic unit cost of heat increases (3.67% and 3.60%).

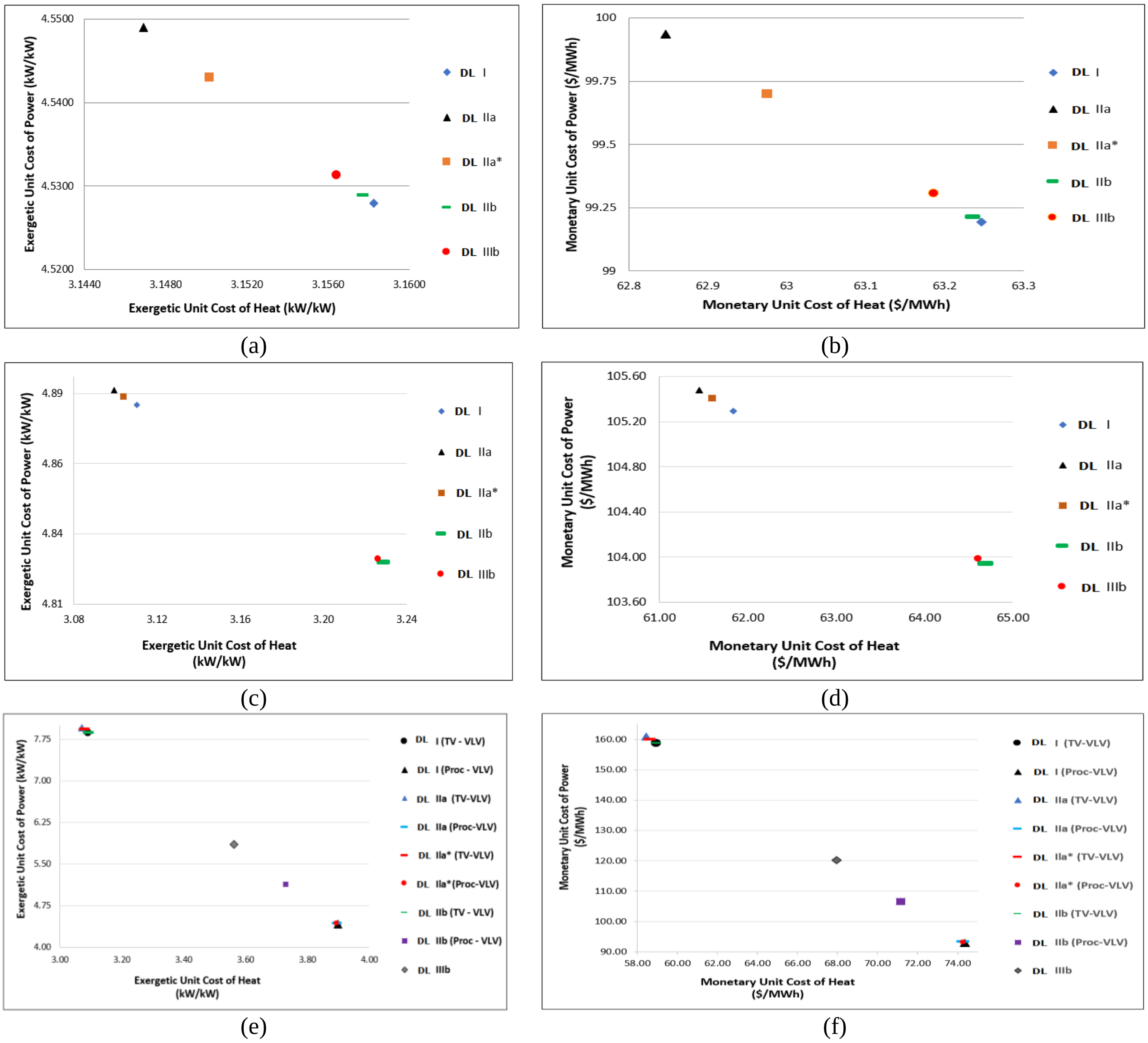


Fig. 10. Exergetic and Monetary Unit Cost of the Final Products for the Steam Turbine Cogeneration Systems: a) BPT, b) BPT, c) CET, d) CET, e) VBPT and f) VBPT

Figure 10(e) and 10(f) show the exergetic and monetary unit cost for the Bypass Valve and Backpressure Steam Turbine Cogeneration Plant. For the four disaggregation levels that cannot isolate the valve in the productive structure (DL I, DL IIa, DL IIa* and DL IIIb), it can be allocated together with the turbine (TV-VLV), overcharging the unit cost of power in detriment of the unit cost of heat, or it can be allocated together with the process (Proc-VLV), overcharging the unit cost of heat in detriment of the unit cost of power. In the first case (TV-VLV), from the minimum disaggregation level (DL I) to the remaining disaggregation levels that do not isolate this dissipative component (DL IIa, DL IIa* and DL IIIb), the difference in the unit cost of the final products is very small (< 1.13%). In the second case (Proc-VLV), from DL I to DL IIa and DL IIa*, this difference is small too (< 0.39%) but, comparing with DL IIIb, the exergetic unit cost of power increases 14.01% and the exergetic unit cost of heat increases 4.52%.

Figure 10(e) shows that the maximum disaggregation level (DL IIIb) is the only one able to isolate the valve in the productive structure of the Bypass Valve and Backpressure Steam Turbine Cogeneration Plant. In this case, from the minimum disaggregation level (DL I) when the valve is allocated together with the turbine (TV-VLV), the exergetic unit cost of power decreases 34.44% and the exergetic unit cost of heat increases 13.23% and when the valve is allocated together with the process (Proc-VLV), the exergetic unit cost of heat decreases 9.39% and the exergetic unit cost of power increases 24.45%. All results presented in Fig. 9 and 10 are based on exergy accounting analysis. Figure 11 compares these results based on exergy disaggregation with an energy accounting result based on total enthalpy analysis (H), or based on the enthalpy disaggregated into internal energy (U) and flow work (F).

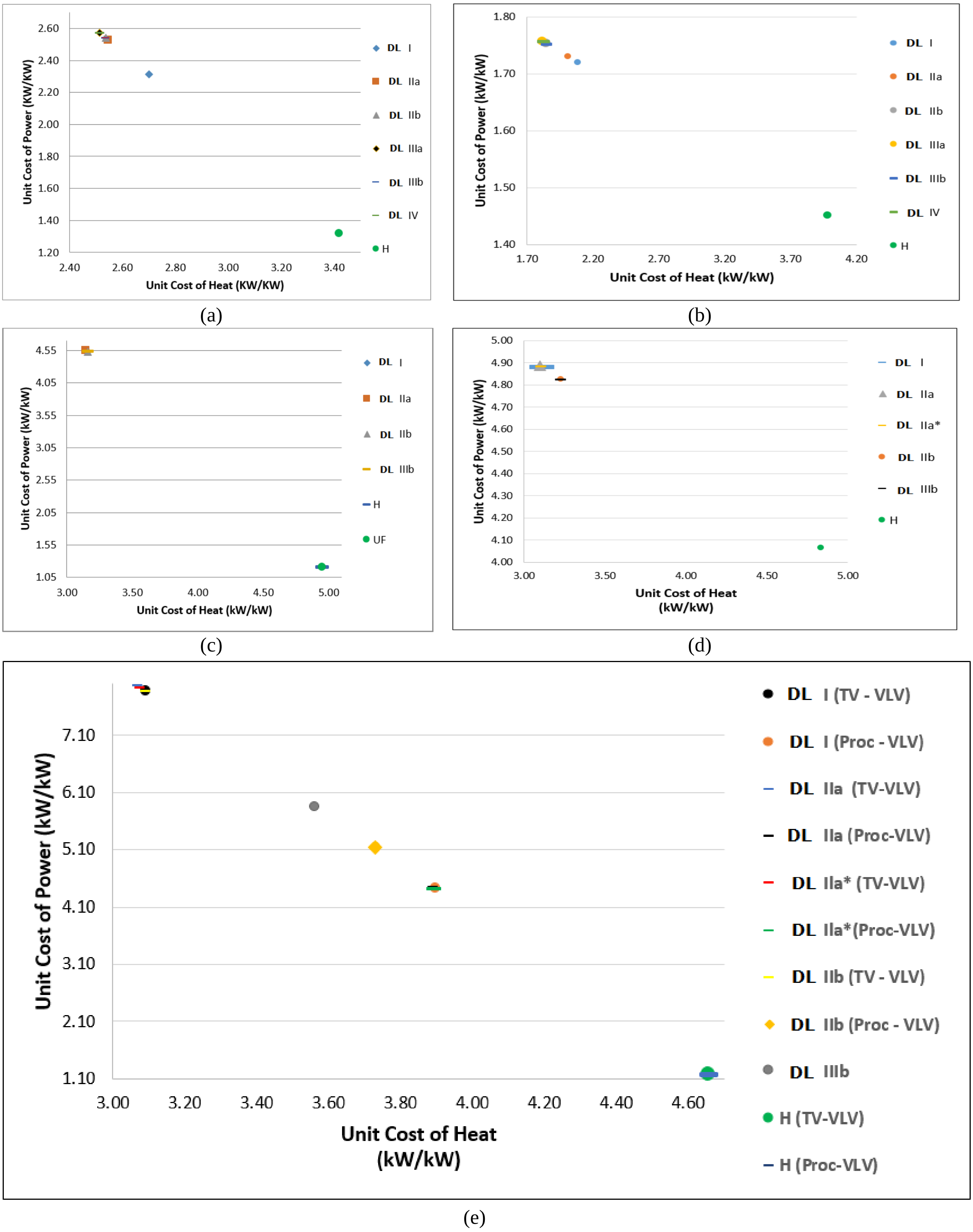


Fig. 11. Accuracy Improvement of the Results obtained for Exergetic Unit Cost of the Final Products due to use of Exergy for: a) SGT, b) RGT II, c) BPT, d) CET and e) VBPT

Figure 11 shows that the accuracy improvement due to physical exergy disaggregation is small related to the big improvement comparing exergy analysis with energy analysis based on enthalpy only.

6. CLOSURE

Results shows improvement in the accuracy of the results of cost allocation according to the level of physical exergy disaggregation. However, as the level of disaggregation increases, the productive structures complexity also increases, as the complexity involved in the modeling. Some physical exergy disaggregation levels are necessary to allows disaggregating the system in component. The others are useful for accuracy improvement of the results for cost allocation only.

For the three Gas Turbine Cogeneration Plants analyzed, the minimum disaggregation level is enough to disaggregate the system components for diagnosis and local optimization. In this case, physical exergy disaggregation is useful for improvement of the accuracy of the results during cost allocation only. The improvement is significant, but the increase in the complexity is considerable. Thus, the decision depend on the accuracy required for the analysis and on the preference of the analyst.

In the case of Backpressure Steam Turbine Cogeneration Plant, there is no dissipative component. Thus, the minimum disaggregation level is also enough to disaggregate the system components for diagnosis and local optimization. In this case, the physical exergy disaggregation is useful only for improvement of the accuracy of the results during cost allocation too. However, the improvement is very small. In this case, physical exergy disaggregation can be unnecessary.

For Extraction Condensing Steam Turbine Cogeneration Plant the accuracy improvement in the results of cost allocation is small. However, for diagnosis and local optimization the disaggregation of the condenser is generally required. At this point, at least, the disaggregation of the physical exergy into enthalpic and entropic component (DL IIb) can be useful and necessary.

However, if there is a bypass valve in the system being analyzed it is necessary the maximum physical exergy disaggregation, as used in this work. In other words, for Bypass Valve and Backpressure Steam Turbine Cogeneration Plant, the physical exergy disaggregation into internal energy, flow work and entropic term (DL IIIb) is necessary for cost allocation, local optimization and diagnosis.

Moreover, the accuracy improvement due to physical exergy disaggregation is small in comparison to the big improvement comparing exergy analysis with energy analysis based on enthalpy only

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