frontiers
in Sustainability

ORIGINAL RESEARCH
published: 09 April 2021
doi: 10.3389/frsus.2021.656818

Delving Into Thermoeconomics: A Brief Theoretical Comparison of Thermoeconomic Approaches for Simple Cooling Systems

Ana Picallo-Perez[1]*, *José Mª Sala*[1], *Luis del Portillo*[1] *and Raquel Vidal*[2]

[1] *Research Group ENEDI, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country (UPV/EHU), Bilbao, Spain,* [2] *Faculty of Engineering of Bilbao, University of the Basque Country (UPV/EHU), Bilbao, Spain*

Thermoeconomics combines the concepts of economics and thermodynamics to assess the cost formation process of thermal systems. It has great applicability in the allocation, optimization and diagnosis of product costs. However, some aspects need to be gathered and solved, to have common criteria for its implementation. That is precisely what happens with dissipative components, which are part of cooling systems being so that different criteria are given to evaluate their impact in the cost distribution. In this paper, the state of art regarding the application of thermoeconomics in simple cooling systems is briefly evaluated, by giving the main characteristic of each approach, resolving that there is no a common criterion on the subject of the treatment of dissipative equipment and, therefore, neither on the costs accounting. Therefore, this work compiles and compares the different thermoeconomics methodologies. Consequently, it aims to serve as a tool for the appropriate selection of the thermoeconomics methodology for the analysis of real cooling systems.

Keywords: thermoeconomics, cooling systems, thermoeconomics methodologies, dissipative components, negentropy

Edited by:
Eduardo Antonio Pina,
University of Zaragoza, Spain

Reviewed by:
Atilio Barbosa Lourenço,
Federal University of Espirito Santo, Brazil
Rodrigo Guedes Santos,
Federal Institute of Espirito Santo, Brazil

***Correspondence:**
Ana Picallo-Perez
ana.picallo@ehu.eus

Specialty section:
This article was submitted to Quantitative Sustainability Assessment, a section of the journal Frontiers in Sustainability

Received: *21 January 2021*
Accepted: *10 March 2021*
Published: *09 April 2021*

Citation:
Picallo-Perez A, Sala JM, Portillo Ld and Vidal R (2021) Delving Into Thermoeconomics: A Brief Theoretical Comparison of Thermoeconomic Approaches for Simple Cooling Systems. Front. Sustain. 2:656818. doi: 10.3389/frsus.2021.656818

INTRODUCTION

Since the 17th century, when the Industrial Revolution began, societies started working in the relationship between industrial development and energy resources. Historically, energy plays a key role as an input resource to production processes, becoming an essential and basic good for development.

However, in a world with finite natural resources and an increase in energy demand from developing countries (Shen et al., 2019), it is necessary to investigate the development of techniques for the design, optimization and diagnosis of energy systems to minimize these finite natural resources consumption since. In recent decades, there has been a growing concern about how to manage the energy and a requirement to define the relationships between concepts such as economic growth, environmental pollution and energy consumption (Zhang and Cheng, 2009). Regarding the relationship between the economy (understood as an object of production) and energy consumption, they should be jointly developed, since there is a very strong relationship that unites them; after all, the greater the economic development, the greater the use of energy is required (Halicioglu, 2009). It should not be forgotten, additionally, that the environmental impact is also greater.

This public awareness regarding the degradation of the environment, the acute shortage of raw materials, the competitiveness of prices in the market and the high prices of fuels make necessary the exhaustive control of industrial processes, in a way that processes can be controlled to the maximum. All this has motivated the study of advanced tools to solve complex energy problems, as it is the case of thermoeconomics (Verma et al., 2019).

From a wide perspective, thermoeconomics combines thermodynamics, including exergy analysis, with economics. Specifically, the combination of exergy analysis and economics is known as exergoeconomics (Tsatsaronis, 1993). Due to such combination, information that would not be achieved through conventional energy, exergy or economic analyses separately obtained (Valero et al., 1992). This discipline allows calculating, for example, the total cost of the final product of any plant, whatever the number of flows and equipment. Besides, it associates the costs of internal flows by defining the productive configuration and it can be used for optimizing variables of specific components as well as optimizing the system as a whole (Serra de Renobales, 1995). That is, thermoeconomics can be applied to evaluate the impact of thermodynamic inefficiencies on the cost formation process and final products' cost, aiming to reduce it.

The main hypothesis of exergoeconomics is that costs are transported with the exergy carriers, which can be physical and/or productive. Accordingly, there are different thermoeconomic methodologies, but all of them are built from that hypothesis. Thus, the purpose of this work is to analyze those different thermoeconomics methodologies for making a rational cost accounting along a cooling system. Since there is no a unified criterion when it comes to thermoeconomics calculations, the idea is to have a clear vision of the different approaches to be able to choose the one that best suits each case. All this will be applied in a future paper to a real industrial cooling installation, which is monitored and prepared for an exhaustive analysis. Therefore, another tasks will be the treatment and analysis of the dynamic data obtained through the data acquisition system. This work describes the first steps to take before applying thermoeconomics in cooling systems.

OBJECTIVES AND SCOPE OF THE WORK

As mentioned, this work is a pioneer work that gathers the different thermoeconomics methodologies with dissipative components. As realized, a common consensus does not exist on how to apply cost accounting methodologies in those specific systems. After all, dissipative components can be treated under different points of view, were among all of them two are distinguished: distribution ratio (Structural Theory), negentropy or entropy; each one with their own sub- methodologies.[1] Along this research, the reader can have a global perspective, of the current thermoeconomics methodologies to apply in cooling systems. Hence, this work helps to select, properly and critically, the thermoeconomics methodology that best adapt to each system; similar to what it was done with Combined Cycle Power Plants in references (de Fariaa et al., 2020).

Therefore, this work aims to be the first part on a research of thermoeconomics applied to cooling systems. The future purpose is to select, with critical criteria, the thermoeconomics methodology that best fits to cooling systems to solve the problem.

Design, optimization, and diagnosis purposes are also indirectly linked to such objective.

THEORETICAL BASES OF THERMOECONOMICS

Cost and price are two different concepts that must be distinguished. Cost refers to the amount of resources consumed to obtain the product it is an objective quantity and costs are formed because the process to generate that product is irreversible. Price has a part of subjectivity (influenced by market and utility concepts), which change with history and culture (Serra de Renobales, 1995). Therefore, the price contains some external factors not related to the production process. Consequently, when monetary units are introduced in the cost formation process, not only the resources consumed are included but also the price is allocated to natural resources, so that it always contains a subjective component. After all, oil, coal, minerals and natural resources are subject to market laws and international agreements.

Because of that, when cost is only related to energy-terms such as the enthalpy, entropy, or exergy, the cost formation process can be objectively described along the conversion chain, and when currency prices are included, a certain degree of subjectivity will always be added (Serra de Renobales, 1995). When the economic cost of external resources (i.e., market price) and the conversion and maintenance costs of the system are considered, this final cost reflects the amount of money consumed to generate one unit of a flow (from internal flows to the final products).

Exergy for Cost Accounting

In 1932 Keenan discussed about the advantages and disadvantages of using exergy vs. energy in energy systems, by proposing exergy as a rational parameter to assign costs to the products of a cogeneration plant. Nevertheless, the important advance of the different thermoeconomic methodologies took place in 1983 (Gaggioli), as a result of the oil crisis that prompted the development of these approaches (Serra de Renobales, 1995). Nowadays, exergy analyses are widely used in industrial processes and in power plants, with numerous references applied to the analysis, design and optimization of processes (Sala, 1984; Costa et al., 2001; Nikulshin et al., 2002).

During the last decade, studies applying exergy in energy systems have increased markedly. These are dedicated, above all, to evaluate complex systems and to quantify irreversibilities.

---

[1] Another point of view to be mentioned is SPECO methodology (Lazzaretto and Tsatsaronis, 2006), which does not use negentropy neither entropy and may not use distribution ratio. In SPECO, if a dissipative component serves a productive component directly, then the associated cost of the dissipative component should be charged to the productive component. For example, a valve that controls the flow produced by a pump.

There are numerous areas of exergy application with their corresponding conclusions and, due to the rise of these applications, there are publications that collect reviews of them. Those related to energy plants are numerous: cogeneration cycles powered by fossil fuels are reviewed in Eboh et al. (2017); those fed by alternative engines (such as PEM) are collected in Özgür and Yakaryilmaz (2018); a review of combined cycles is also carried out in Abuelnuor et al. (2017) and Ibrahim et al. (2018).

However, in everyday industrial practice only energy balances are considered and not exergy. Indeed, depending on the type of analysis and the required results, some times, it is more convenient to use parameters related to energy, and other times, with exergy. It is also clear that exergy provides more information than energy and for cost accounting it is a more appropriate property.

Thermoeconomics for Cost Accounting

The identification and quantification of irreversibilities are obtained from an exergy analysis. Thermoeconomics (exergoeconomics) analyses the relationship between such information and costs. This information is the basis for cost calculation, optimization, in short, for the thermoeconomic analysis of the installation.

All thermoeconomic methodologies calculate costs by adding to the conventional physical and economic models a series of additional considerations (propositions). Lozano and Valero formulated the mature version of the Exergetic Cost Theory (ECT) that describes a rational procedure to determine costs, based on the following four propositions (Sala and Picallo, 2020):

- P1: The exergy cost is a conservative property, so it can be formulated as many exergetic cost balances as there are equipment or subsystems in a system.
- P2: In the absence of an external evaluation, the exergy cost of the flows entering a system is equal to its exergy ($Bi^* = Bi$). This allows to formulate as many equations as incoming flows to the system are.
- P3: All costs generated in the process must be assigned to the final products. It means that in the absence of external evaluations, a zero value should be assigned to the cost of losses ($Li^* = 0$), so that for each unit the cost is: $Fi^* = Pi^*$. This allows to formulate as many equations as there are flows of losses.

If all components have a single non-loss outflow, the propositions presented provide as many equations as flows, which are sufficient to solve the problem. Otherwise, additional equations are required, defined by the fourth proposition.

- P4: The ECT's fourth proposition is split into two statements. The first one says that if an outgoing flow from a subsystem is part of the incoming fuel to that unit, its unit cost is equal to the incoming fuel's unit cost. The second one states that the outlet flows from a subsystem have the same unit cost in the absence of information (Lozano and Valero, 1993).

These propositions lead to a production model and the definition of the productive structure. These additional considerations determine the value and meaning of the costs and come from interpreting the purpose of the equipment in the installation as a whole, which is not always easy to specify. Each thermoeconomic methodology makes its own cost distribution according to the defined productive structure. Therefore, a question arises: what is the best productive structure? Validation of cost is a key issue in thermoeconomics which has not been properly solved yet.

Thermoeconomic Methodologies

The costs obtained through thermoeconomics are associated with structural restrictions that are also the result of the productive formulation. In general, the productive formulation uses two conceptual properties to represent the behavior of each subsystem: fuel and product. Only with those parameters it is difficult to describe in detail the actual physical behavior of a component and, therefore, is considered as an approximate description and a discrepancy exists between the costs of the physical model and the productive model.

So, if costs can be directly calculated from the physical model, why do we introduce a productive formulation if the costs obtained do not really reflect the physics of the production process? if one only applies a "physical model" method, then internal productive information is difficult to be observed.[2] By introducing the productive formulation, information regarding the structure of the system is added (Serra de Renobales, 1995). This allows defining the interactions between the subsystems and determining the costs of all flows.

The way in which we define the productive structure is a key point for the thermoeconomic modeling. Nevertheless, there is not a unique alternative and depending on the type of analysis, different levels of accuracy in the results can be required.

All thermoeconomic methods calculate the cost by adding physical and economic models and other considerations. Therefore, the system has a unique physical structure, but can have several representations of its productive structure. These representations will imply different costs and depend on the analyst's goals. In any case, whatever decision is made to define products and fuels for each component of the system, it should be emphasized that once defined, they will lead to clearly defined auxiliary equations (Sagastume Gutierrez et al., 2018).

Productive Structure With Dissipative Components

In any energy system, in the same way as there are productive components there are also dissipative components. One of their purpose can be to partially, or completely, eliminate residues or undesirable flows (chimneys) (Torres et al., 2008) and another reason can be in order to close the thermodynamic cycle (condenser in a Rankine cycle). Therefore, they are necessary because of legal or physical reasons and their usefulness lie in their interactions with the other components, which in some cases allows the system to have a higher output or higher efficiency.

---

[2] Although, in the paper on SPECO (Lazzaretto and Tsatsaronis, 2006), it is shown that productive information can be obtained from physical information; therefore, it is concluded that productive information is not mandatory to solve the model.

Nevertheless, it is needed to clarify that there are some residue flows (wastes) that are not associated with dissipative components. For instance, exhaust gases from a gas turbine. On the other hand, there are dissipative subsystems that are not associated with waste, for example, throttling devices. Finally, there is waste associated with dissipative units, as the mentioned Rankine cycle's condenser.

Kotas (1995) classifies dissipative components into three categories (Sagastume Gutierrez et al., 2018): (1) those components whose main function is to exchange heat with the environment; (2) those designed to accelerate spontaneous processes; and, (3) those components precisely introduced for dissipative purposes. These involve inherently irreversible processes, such as throttling valves.

Besides, the flows related to dissipative components can be interpreted in different ways according to the nature of the flow:

- Some authors call them residues and attribute its cost to the productive components that generate them (Torres et al., 2008). The distribution is done proportionally to the exergy by the so-called residue cost distribution ratios, which are associated with the productive structure of the plant.
- Other authors, conversely, use the term of negentropy and allocate their cost to the rest of equipment according to their entropy generation. Indeed, the first thermoeconomic approach that applied negentropy to distribute the cost associated with the Rankine cycle's condenser was Thermoeconomic Functional Analysis (TFA), which was formulated by Frangopoulos (Frangopoulos, 1987). This work was a milestone contribution to the development of thermoeconomics.

Unfortunately, there is not a common agreement to treat these kind of flows and the possible alternatives are still an open research line. Nevertheless, all methodologies concur that the exit flows of a dissipative component are related to other components of the system, that is, they depend on the productive structure of the system. Because of that, the formation process of the flows need to be identified and the contribution of the other related components needs to be shared. Once again, it is necessary to remember that the cost of such flows deals with the amount of resources consumed to obtain it.

Cost Distribution Ratio Point of View

According to this point of view, residues are related to the damage they cause or to the inability to convert them into something useful. Therefore, instead of relating them to their exergy content (or to the entropy content, as it is done in the negentropy point of view) they should be related to their formation process (Agudelo et al., 2012). Consequently, the aim is to assess the additional amount of exergy required to get rid of them, or what is the same, to assess the exergy cost of residues. Accordingly, as thermoeconomics uses exergy for distributing costs, residues are also accounted under the exergy perspective.

This viewpoint is related to the methodology called ECT which was latterly improved with the Structural Theory implementation. Structural Theory is based on common mathematical formulae valid for all thermoeconomics methodologies that satisfy the premises on which it is built. Its strength is that it establishes the general concept of costs; accordingly, the costs are calculated by applying the chain rule of derivation and, therefore, the costs are defined by means of derivatives that describe their formation process based on the structure of the system (Serra de Renobales, 1995). ECT and Structural Theory were enhanced by including Symbolic Thermoeconomics (Picallo et al., 2016).

When dissipative components are included in a system, the ECT cost propositions are extended. In such case, apart from the $\langle FP \rangle$ matrix operator that represents the productive structure, the $\langle RP \rangle$ matrix operator representing the dissipative structure is included (Agudelo et al., 2012); indeed, this last matrix contains the residues cost distribution ratios (ψ).

In consequence, the key point of this approach is to define those ψ ratios.

- In reference (Torres et al., 2008) the ratios are calculated directly with the $\langle FP \rangle$ table. The main advantage of this criterion is that the ratios are obtained directly from the productive diagram but it is not clear if this is the best way to allocate wastes.
- An alternative criterion is to allocate the cost of residues among the productive components proportionally to their exergy destruction. In this way, the allocation can be easily programmed. Nevertheless, the contribution of a productive component to the cost of waste is not necessarily proportional to its irreversibility. Indeed, this fact gains strength as the number of residues rises (Agudelo et al., 2012).

Negentropy Point of View

Negentropy is defined as the negative variation of entropy multiplied by the temperature of the environment. It is a fictious flow that is included in order to define the productive structure of dissipative components (Frangopoulos, 1987).

As an example, the condenser of a refrigeration cycle does not properly have a product expressed in terms of exergy. Its function is to transfer to the environment the entropy accumulated by the operation of the other components in the plant. Therefore, in economic terms, the function of the condenser is to supply the other components with negative entropy that compensates for the one produced in the component under consideration. Hence, in addition to the electricity used by the refrigeration system, another resource needed for its operation is the negentropy that compensates for the increase in entropy in the rest of the components (Sala and Picallo, 2020).

This sharing is right for closed cycles, like Rankine or refrigeration cycles, but it fails for open systems like gas turbines. In order to overcome this fact, the environment can also be regarded as a virtual dissipative component. Indeed, the function of the atmosphere is to redistribute the flow of outgoing gases, so that the turbine could use a flow of fresh air. In this way, the environment plays the role of a dissipative component, that is, it closes the entropy cycle, in a way that generates the negentropy that makes it possible for the turbine to take fresh air from the environment (Sala and Picallo, 2020).

Therefore, the product of a dissipative equipment is the negentropy that it generates. Because of that, most authors apply the negentropy as a fictitious flow, and use exergy flows to represent the productive components. Notwithstanding the advances of negentropy, Santos et al. (2009b) starts a discussion showing that the original procedure leads to some incongruences. After all, some components have an exergy unit cost less than unity, which can be interpreted as an inconsistency.

The reason is that any exergy flow already contains the term "$m \cdot T_0 \cdot .\Delta s$," which is, precisely, the way to define the negentropy flow. Hence, when the negentropy flow coming from the dissipative components is included to the productive subsystems, some are twice penalized due to the increase of the working fluid entropy, while others are twice awarded due to the reduction of the work fluid entropy.

Consequently, new methodologies were developed in order to overcome such inconsistencies[3]. Those approaches are hereafter listed, in a chronological order, to resolve systems with dissipative components under the negentropy point of view. Each approach has their cons and pros, and are the following:

- The E Model uses only exergy to define fuels and products of the subsystems so that the computational effort is reduced but the dissipative components (such as condenser) cannot be described. Because of that, the dissipative components need to be considered together with the productive component.
- Other authors divide the physical exergy term into its thermal and mechanical components. However, this disaggregation still does not allow isolating the dissipative components. In addition, this division may not always make sense, because separating mechanical and thermal terms may invol ve arbitrariness, especially when working fluids change phases (Santos et al., 2009b). Besides, exergy relies on the properties that move away from the reference state as well as on the kind of reversible process to achieve its equilibrium with the environment (Serra de Renobales, 1995). Therefore, if mechanical and thermal terms are divided that disequilibrium may not be considered depending on the split method.
- The E&S Model combines the exergy and negentropy flows so it allows defining the dissipative components. Therefore, the costs related to the dissipative components are distributed along the productive components of the system. However, as already explained, this approach is inconsistent since entropy generation is twice considered and for some components the product can be higher than their fuel.

Entropy Point of View

Although each negentropy model enhances the previous one, some researches are reticent against the negentropy point of view (Agudelo et al., 2012). They argue that those models simplify to some extent the productive structure, because they allocate residues based explicitly on entropy changes. Besides, the linkages between components can be more complex than entropy sharing, affecting the residue cost formation in a way that can be better represented by a parallel residual structure cost formation. In addition, the breakup of exergy flows may cause that the parts of an exergy flow (enthalpy, negentropy and chemical exergy) have different unit exergy costs, which is arguable because all these parts belong to the same physical stream and were generated simultaneously in the same physical process (Santos et al., 2009a). Even though this criticism was rebutted by the following H&S and USF models:

- The H&S Model uses the entropy term together with enthalpy. In such way, the incongruences of the previous approach are solved inasmuch as enthalpy replaces the exergy flows. Nevertheless, this model cannot define the productive structure of expansion valves (Lourenço et al., 2015) since the only way to describe them it is by disaggregating the physical term into its thermal and mechanical parts.
- The UFS Model separates the physical exergy into an internal energy term, a flow work term and an entropic term (Lourenço et al., 2011). In such situation, the productive structure of an expansion valve (modeled as an isenthalpic process) is defined as follows: its fuel (resource) is the sum of the internal energy term and the entropic term while the product is the increase of the flow work (Santos, 2006; Lorenzoni et al., 2020). Hence, both terms have the same magnitude and the previous problems related to the division of exergy into its thermal and mechanical parts are now avoided.
- If the ideal gas model is utilized in the system, this model can be enhanced through the UFS+ Model approach (Agudelo et al., 2012).

It was proved that H and S can be interpreted as fractions of the physical flow exergy, as the thermal and mechanical fractions are (Lourenço et al., 2014). Moreover, U and F can be interpreted as physical flow exergy's fractions as well (Lourenço et al., 2015).

Case Study of a Simple Vapor Compression Cooling System

Let us suppose a typical cooling-system example whose cooling purpose is obtained through an evaporator (EV) which cools the outside air by evaporating the refrigerant flow. Then, a compressor (CP), thanks to the electricity, increases the refrigerant's pressure and consequently the temperature of the fluid also increases. The fluid condensates in the condenser (CND) and the pressure decreases by means of a throttling valve (VA), where the temperature also decreases as a result and a partial evaporation takes place, see **Figure 1**.

As mentioned, the condenser is a dissipative component whose aim is to close the cycle by ejecting heat to the environment ($b_6 = b_{heat}$); this heat is finally dissipated through the environment so that, if system limits are extended, its associated exergy is totally destroyed.

The objective of this section is to explain the approach of each point of view in order to have a global vision of residues from the dissipative unit treatment, i.e., the condenser. As already said, there is not a unique option and the definition of the productive structure is under the researcher's scope and experience.

---

[3] It is implicit that the cited methodologies are based on the drawing of the functional/productive diagram, i.e., TFA and ST. For instance, SPECO is not included in these methodologies.

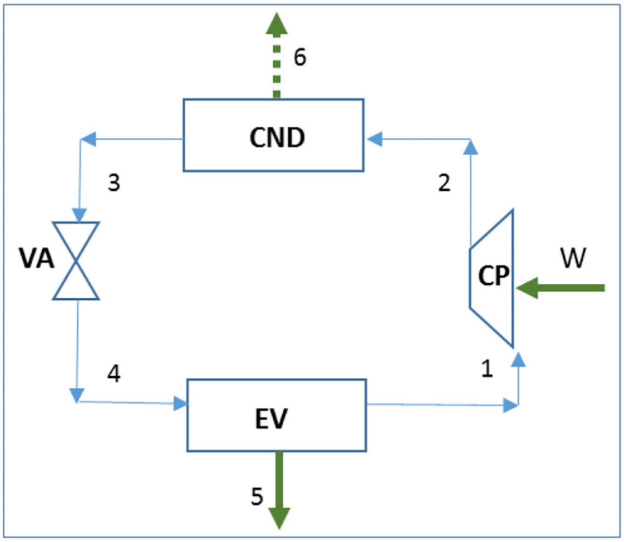

FIGURE 1 | Scheme of a vapor compression refrigeration system, where exergy flows are drawn.

Distribution Ratio Point of View

The external resource is the electricity that enters to the compressor (w) and the final product is the cooled air in the evaporator ($b_5 = b_{cool}$). The condenser is taken as a dissipative component whose residue is the heated air ($b_D = b_6$) and should be shared with the productive components associated to it, according to the ψ residue distribution ratios. The problem arises when the throttling valve is analyzed since it can be understood in two ways:

- it is a productive component whose aim is to prepare the incoming conditions of the evaporator, see **Figure 2**;
- or it can be interpreted as a dissipative component that decreases the refrigerant work to adapt to the evaporator conditions (i.e., destroys exergy, being the residue equal to $b_{D2} = b_3 - b_4$); hence, it is a fully irreversible process, see **Figure 3**.

Additionally, the key point of this perspective is related to the ψ residue distribution ratio definition.

Negentropy Point of View

The second point of view is applied according to the different approaches:

- The E model uses only exergy to define fuels and products of the subsystems, see **Figure 4**. Then, it does not allow to describe dissipative components, i.e., both condenser and throttling valve. Therefore, CND and VA are joined together with CP and EV.
- The E&S model combines the exergy and negentropy flows. **Figure 5** represents the E&S model extracted according to the aforementioned bibliography, where the condenser (considered as a dissipative component) can be isolated by defining its product as entropy generation and sharing it to the rest of the components.
- As previously mention, each exergy flow can be disaggregated into its mechanical and thermal part, **Figure 6**. This division allows defining the throttling valve in which the mechanical term is the fuel and is used to increase the thermal part[4] (Lazzaretto and Tsatsaronis, 2006).

As mentioned, the entropic term is incorporate in both (in negentropy an exergy) flows so some components are penalized or rewarded twice.

Entropy Point of View

- The H&S model uses the entropy flow together with enthalpy, see **Figure 7**. This approach overcomes the problem of counting twice the entropy term. The valve is integrated together with the evaporator.
- The UFS Model separates the physical exergy into an internal energy term, a flow work term and an entropic term, see **Figure 8**.

Overview of Thermoeconomics Application in Cooling Systems

In summary, these are the thermodynamic properties taking part in each configuration, see **Table 1**:

Distribution ratio point of view:

- Works with total exergy (b) values. The key point of this perspective is related to the ψ residue distribution ratio definition.

Negentropy point of view:

- The E model uses only exergy (b) to define fuels and products of the subsystems.
- The E&S model combines exergy (b) and negentropy (s) flows; or what is the same, the dissipative component, which is the condenser, is isolated by defining its product as entropy generation.
- As previously mentioned, each exergy flow can also be disaggregated into its mechanical (b^P) and thermal (b^T) part in order to isolate the throttling valve.

Entropy point of view:

- The H&S model uses the entropy (s) together with enthalpy (h).
- The UFS model separates the physical exergy into an internal energy term (u), a flow work term (f) and an entropic term (s).

UPCOMING RESEARCH LINE

This work attempts to be the theoretical base for further thermoeconomic application in industrial cooling systems. Accordingly, the historical development of thermoeconomics has

---

[4] The thermal exergy term $\dot{B}_T$ is defined to be in the same isobaric P line and moves from state [T,P] to state [T_0,P] ($\dot{B}_T = \dot{m} \cdot \left[\left(h - h_m\right) - T_0(s - s_m)\right]$). The mechanical exergy term $\dot{B}_P$ is considered to be in the T_0 isothermal line from state [T_0,P] to state [T_0, P_0] (Mendes et al., 2020), ($\dot{B}_P = \dot{m} \cdot \left[\left(h_m - h_0\right) - T_0(s_m - s_0)\right]$). h_m and s_m are the auxiliary specific enthalpy and entropy defined for state [T_0,P].

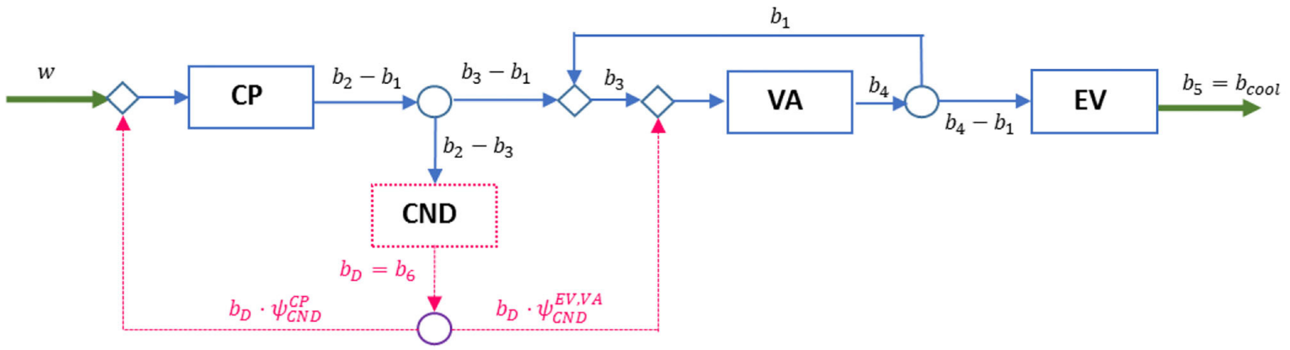

FIGURE 2 | Condenser as a unique dissipative component.

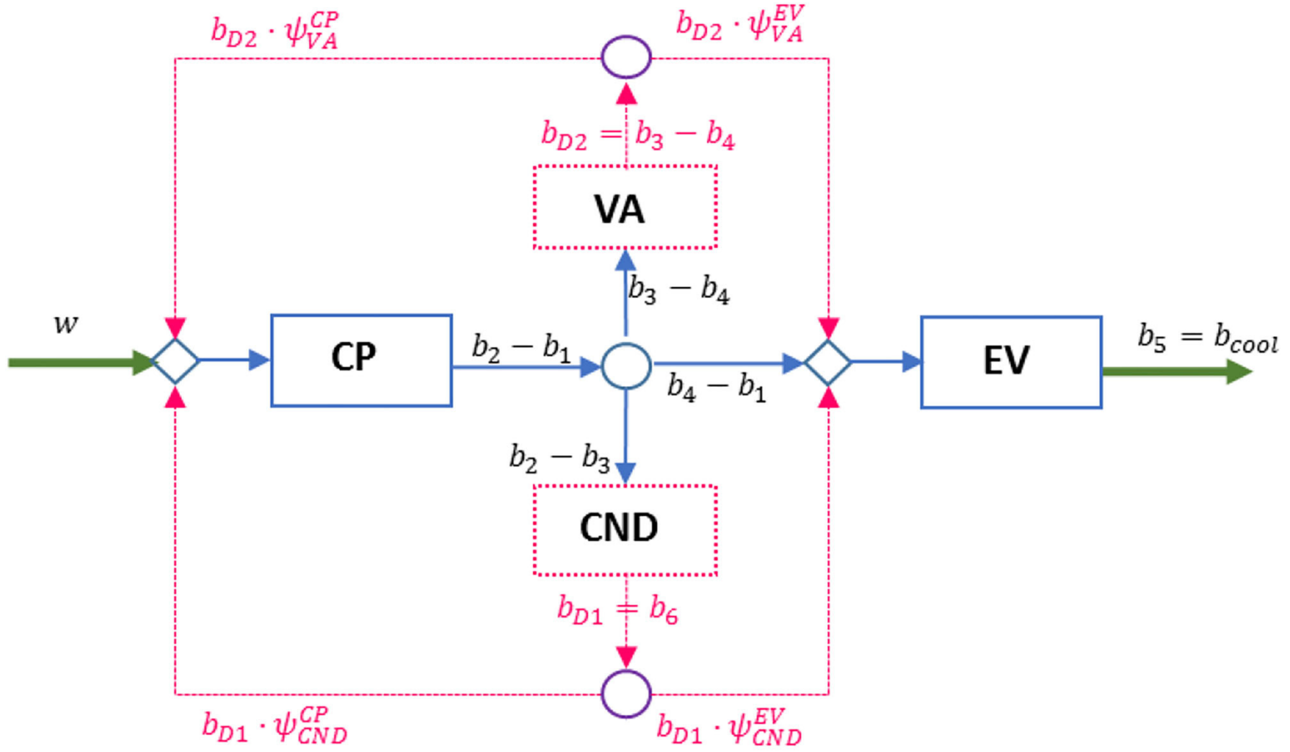

FIGURE 3 | Condenser and throttling valve as dissipative components.

been analyzed by focusing on cooling systems and comparing the strategies from different points of view.

In consequence, the upcoming research deals with its application in a real monitored cooling system. These are the steps to be followed for the proper application of thermoeconomics:

- The first step is to analyse the selected real cooling system; the specific components to be thermoeconomicaly defined need to be studied according to the sensors available along the facility. Using the appropriate software and physics, the dynamic thermodynamic data (temperatures, pressures, mass flow rates, etc.) of the different flows can be acquired as well as the system's configurations.
- Next step is to treat the data obtained from sensors and to depict the tendencies of different properties in order to check the correct functioning of the system and its control.
- The following task refers to the calculation of thermoeconomic properties such us, enthalpy, entropy and exergy values. These properties are calculated according to the previous thermodynamic data of sensors, the characteristics of the refrigerant fluid and the balances.

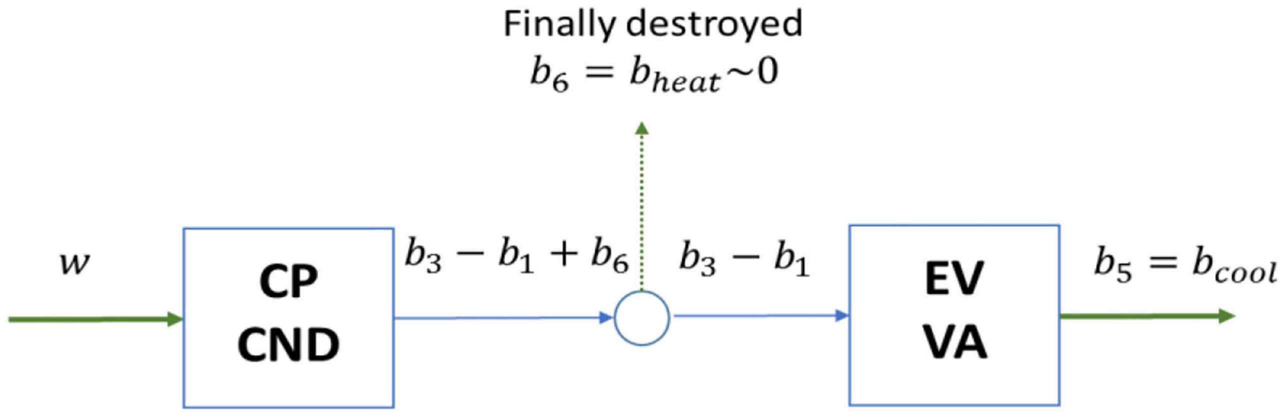

FIGURE 4 | E Model approach.

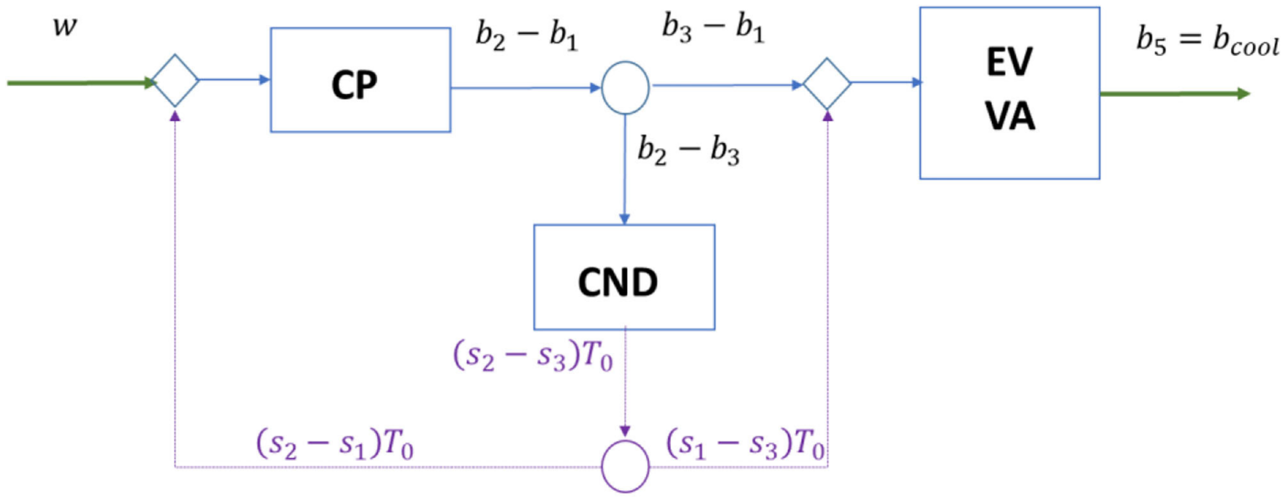

FIGURE 5 | E&S model approach with total exergy.

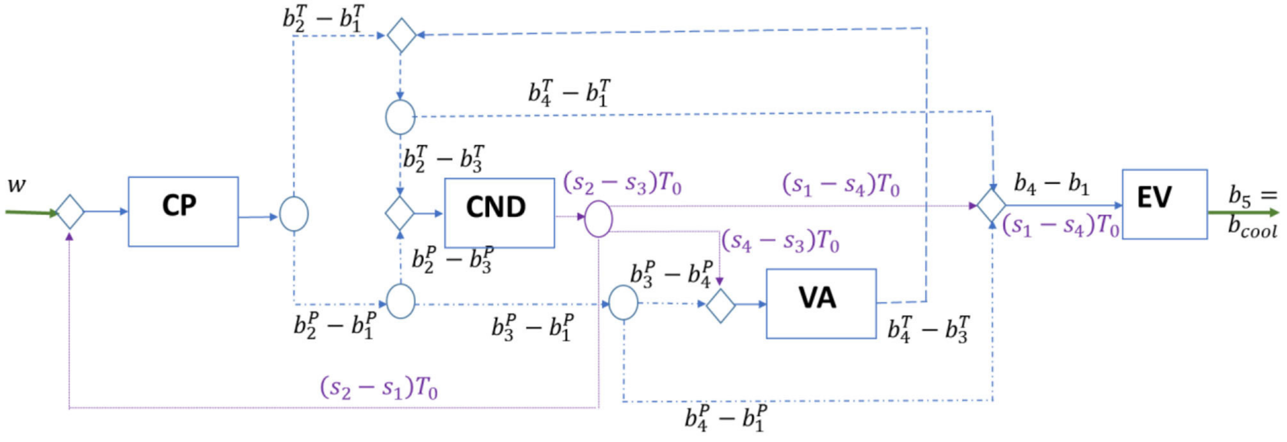

FIGURE 6 | E&S model approach with exergy disaggregation.

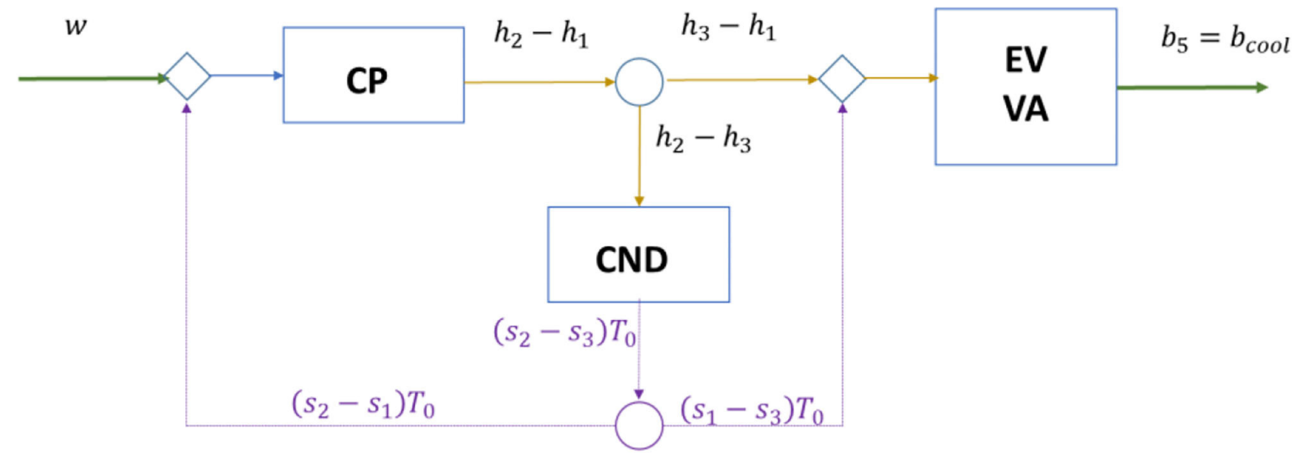

FIGURE 7 | H&S model approach.

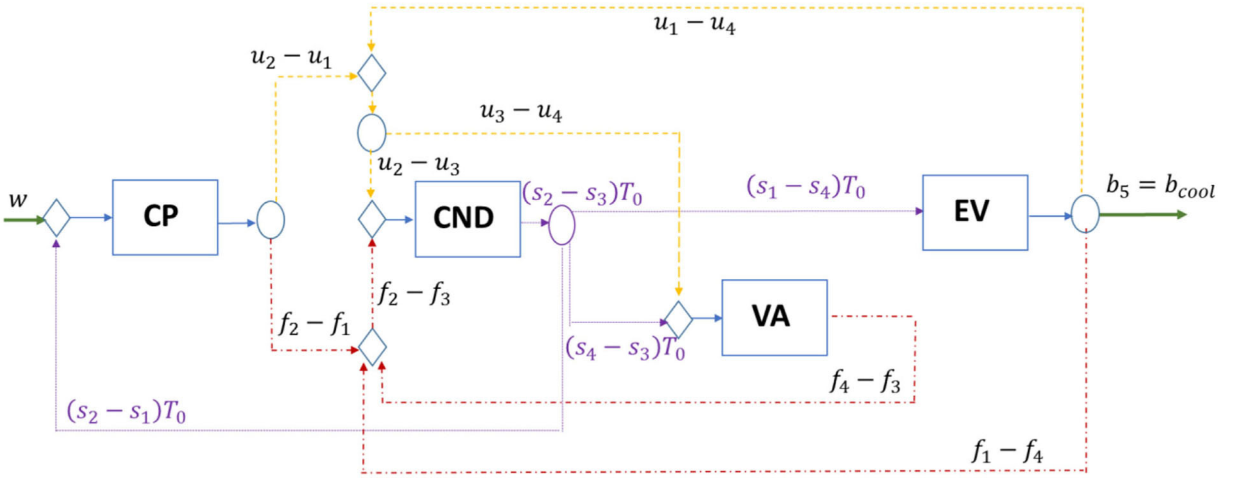

FIGURE 8 | UFS Model.

- After that, the different thermoeconomic strategies need to be applied in order to analyse the best criteria for distribution of the cost.
- According to the results, the main advantages and drawbacks of each point of view can be analyzed and the best configuration can be selected.
- The last task is related to a deeper thermoeconomic implementation for diagnosis and optimization purposes.

Following such instructions, thermoeconomics can be implemented not only for making a rational cost distribution along the system but also for fault detection, diagnosis and control optimization. Therefore, thermoeconomics is a powerful tool to thoroughly analyze cooling systems.

TABLE 1 | Required thermodynamic properties for each thermoeconomic configuration.

Point of View	Model	Properties	Abbreviation
Distribution ratio	–	Total exergy	b
Negentropy	E Model	Total exergy	b
	E&S Model	Exergy & negentropy	b, s
		Mechanical & thermal ex. & negentropy	b^P, b^T, s
Entropy	H&S Model	Enthalpy & entropy	h, s
	UFS Model	Internal energy, flow work & entropy	u, f, s

CONCLUSIONS

This work corresponds to a thermoeconomic application in cooling systems, precisely in a simple vapor compression refrigeration cycle. As it has been showed along the text, some aspects of thermoeconomics need to be gathered and solved in order to have common criteria for its implementation in cooling systems.

The main objective of this work is to describe the different alternatives that currently appear in thermoeconomics related to the dissipative units of simple cooling systems. Dissipative components are part of cooling systems being so that different criteria exist to analyse their impact in the cost distribution. One of the achievements of this work is that the reader has, a paper that encompasses the different ways thermoeconomics addresses the issue of dissipative components in cooling systems. Hence, this work facilitates the comparison of the different perspectives to tackle that issue.

Overall, this work is the first part of a pioneering research whose aim is to agree on a unique path to apply thermoeconomics in simple cooling systems. A future work is expected with a whole analysis on how and which configuration to be applied in each specific cooling system.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AP-P, JS, LP, and RV: conceptualization: ideas, formulation or evolution of overarching research goals and aims. AP-P, JS, and RV: methodology: development or design of methodology, creation of models and writing - original draft: preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation). AP-P and RV: software: programming, software development, designing computer programs, implementation of the computer code and supporting algorithms, testing of existing code components, formal analysis: application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data and investigation: conducting a research and investigation process, specifically performing the experiments, or data/evidence collection. JS, LP, and RV: validation: verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs. JS and LP: resources: provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools, supervision: oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team, and project administration: management and coordination responsibility for the research activity planning and execution. All authors contributed to the article and approved the submitted version.

FUNDING

All sources of funding received for the research are being submitted.

ACKNOWLEDGMENTS

The authors acknowledge the support provided by the Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government, as well as the support provided by the collaboration of the Technological Institute of Castilla and Leon (ITCL).

REFERENCES

Abuelnuor, A. A. A., Saqr, K. M., Mohieldein, S. A. A., Dafallah, K. A., Abdullah, M. M., and Nogoud, Y. A. M. (2017). Exergy analysis of Garri "2" 180 MW combined cycle power plant. *Renew. Sustain. Energy Rev.* 79, 960–969. doi: 10.1016/j.rser.2017.05.077

Agudelo, A., Valero, A., and Torres, C. (2012). Allocation of waste cost in thermoeconomic analysis. *Energy* 45, 634–643. doi: 10.1016/j.energy.2012.07.034

Costa, M. M., Shaeffer, R., and Worrell, E. (2001). Exergy accounting of energy and materials flows in steel production systems, *Energy* 26, 363–384. doi: 10.1016/S0360-5442(01)00004-4

de Fariaa, P. R., dos Santosc, R. G., Santosd, J. J. C., Baronee, M. A., and Miottof, B. M. F. (2020). "On the allocation of residues cost in thermoeconomics using a comprehensive diagram," in *Proceedings of ECOS 2020. June 29-July 3, 2020* (Osaka).

Eboh, F. C., Ahlström, P., and Richards, T. (2017). Exergy analysis of solid fuel-fired heat and power plants: a review. *Energies* 10:165. doi: 10.3390/en10020165

Frangopoulos, C. A. (1987). Thermo-economic functional analysis and optimization. *Energy* 12, 563–571. doi: 10.1016/0360-5442(87)90097-1

Halicioglu, F. (2009). An econometric study of CO_2 emissions, energy consumption, income and foreign trade in Turkey. *Energy Policy* 37, 1156–1164. doi: 10.1016/j.enpol.2008.11.012

Ibrahim, T. K., Mohammed, M. K., Awad, O. I., Abdalla, A. N., Basrawi, F., Mohammed, M. N., et al. (2018). A comprehensive review on the exergy analysis of combined cycle power plants. *Renew. Sustain. Energy Rev.* 90, 835–850. doi: 10.1016/j.rser.2018.03.072

Kotas, T. J. (1995). *The Exergy Method of Thermal Plant Analysis*, 2nd Edn. Krieger Publishing Company.

Lazzaretto, A., and Tsatsaronis, G. (2006). SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. *Energy* 31, 1257–1289. doi: 10.1016/j.energy.2005.03.011

Lorenzoni, R. A., Santos, J. J. C. S., Lourenço, A. B., and Donatelli, J. L. M. (2020). On the accuracy improvement of thermoeconomic diagnosis through exergy disaggregation and dissipative equipment isolation. *Energy* 194:116834. doi: 10.1016/j.energy.2019.116834

Lourenço, A. B., Nebra, S. A., Santos, J. J. C., and Donatelli, J. L. M. (2015). Application of an alternative thermoeconomic approach to a two-stage vapour compression refrigeration cascade cycle. *J. Braz. Soc. Mech. Sci. Eng.* 37, 903–913. doi: 10.1007/s40430-014-0210-7

Lourenço, A. B., Nebra, S. A., and Santos, J. J. C. S. (2014). "Another perspective on the physical exergy of a flow," in *Proceedings of ECOS 2014. June 15–19, 2014* (Turku).

Lourenço, A. B., Santos, J. J., and Donatelli, J. L. (2011). "Thermoeconomic modeling of a simple heat pump cycle: an alternative approach for valve isolation," in *Proceeding of the Fifteenth Symposium on Thermal Science and Engineering of Serbia* (Sokobanja: SimTerm), 18–21.

Lozano, M. A., and Valero, A. (1993). Theory of the exergetic cost. *Energy* 18, 939–960. doi: 10.1016/0360-5442(93)90006-Y

Mendes, T., Venturini, O. J., da Silva, J. A. M., Orozco, D. J. R., and Pirani, M. J. (2020). Disaggregation models for the thermoeconomic diagnosis of a vapor compression refrigeration system. *Energy* 193:116731. doi: 10.1016/j.energy.2019.116731

Nikulshin, V., Wu, C., and Nikulshina, V. (2002). Exergy efficiency calculation of energy intensive systems. *Exergy* 2, 78–86. doi: 10.1016/S1164-0235(01)00042-5

Özgür, T., and Yakaryilmaz, A. C. (2018). A review: exergy analysis of PEM and PEM fuel cell based CHP systems. *Int. J. Hydrog. Energy* 43, 17993–18000. doi: 10.1016/j.ijhydene.2018.01.106

Picallo, A., Escudero, C., Flores, I., and Sala, J. M. (2016). Symbolic thermoeconomics in building energy supply systems. *Energy Build.* 127, 561–570. doi: 10.1016/j.enbuild.2016.06.001

Sagastume Gutierrez, A., Cabello Eras, J. J., and Hernandez Herrera, H. (2018). *Thermoeconomic Evaluation and Exergy Efficiency of Dissipative Components: A New Approach*. Barranquilla: REDICUC Universidad de la Costa. Available online at: http://hdl.handle.net/11323/1206

Sala, J. M. (1984). *Termodinámica de Fluido y el Método de Análisis Exergético, Servicio Editorial.* Bilbao: Universidad del País Vasco.

Sala, J. M., and Picallo, A. (2020). *Exergy Analysis and Thermoeconomics of Buildings. Design and Analysis for Sustainable Energy Systems*. Oxford: Elsevier.

Santos, J, Nascimento, M, and Lora, E. (2006). "On the thermoeconomic modeling for cost allocation in a dual-purpose power and desalination plant," in *19th Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst - ECOS 2006*, 441e8.

Santos, J. J. C. S., Nascimento, M., Lora, E., and Je, M. J. (2009a). "On the treatment of dissipative components and residues in thermoeconomic modeling," in *Proceedings of ECOS 2009* (Foz do Iguaçu), 63–72.

Santos, J. J. C. S., Nascimento, M., Lora, E., and Reyes, A. M. (2009b). On the negentropy application in thermoeconomics: a fictitious or an exergy component flow? *Int. J. Thermodyn.* 12:163.

Serra de Renobales, L. M. (1995). *Optimización Exergoeconómica de Sistemas Térmicos* (Doctoral dissertation). Universidad de Zaragoza, Zaragoza, Spain.

Shen, J., Feng, G., Xing, Z., and Wang, X. (2019). Theoretical study of two-stage water vapor compression systems. *Appl. Ther. Eng.* 47, 972–982. doi: 10.1016/j.applthermaleng.2018.11.012

Torres, C., Valero, A., Rangel, V., and Zaleta, A. (2008). On the cost formation process of the residues. *Energy* 33, 144–152. doi: 10.1016/j.energy.2007.06.007

Tsatsaronis, G. (1993). Thermoeconomic analysis and optimization of energy systems. *Progr. Energy Combust. Sci.* 19, 227–257. doi: 10.1016/0360-1285(93)90016-8

Valero, A., Torres, C., and Serra, L. (1992). "A general theory of thermoeconomics: Part I: Structural analysis," in *International Symposium ECOS* (Zaragoza) Vol. 92, 137–145.

Verma, O.P., Manik, G., and Sethi, S. K. A. (2019). Comprehensive review of renewable energy source on energy optimization of black liquor in mse using steady and dynamic state modeling, simulation and control. *Renew. Sustain. Energy Rev.* 100, 90–109. doi: 10.1016/j.rser.2018.10.002

Zhang, X., and Cheng, X. (2009). Energy consumption, carbon emissions, and economic growth in China. *Ecol. Econ.* 68, 2706–2712. doi: 10.1016/j.ecolecon.2009.05.011

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

NOMENCLATURE

ACRONYMS

CND, Condenser

CP, Compressor

ECT, Exergy Cost Theory

EV, Evaporator

ITCL, Technological Institute of Castilla y León

PEM, Proton exchange membrane

VA, Valve

MATHEMATICS AND PHYSICS

b (kJ/kg), Exergy

h (kJ/kg), Enthalpy

s (kJ/kgK), Entropy

u (kJ/kg), Internal energy

v (m^3/kg), Specific

P (bar), Pressure

T(°C), Temperature

$\dot{\mathbf{Q}}$ (kW), Heat flow

$\dot{\mathbf{W}}$ (kW), Work flow

$\dot{\mathbf{m}}$, Mass flow rate

$\langle \mathbf{F} \quad \mathbf{P} \rangle$, Dependent matrix of *xij* (*n*, *n*) distribution parameters, FP rep.

$\langle \mathbf{R} \quad \mathbf{P} \rangle$, Dependent matrix of *xij* (*n*, *n*) distribution parameters, RP rep.

F, Fuel

P, Product

L, Losses

R, Residues

I, Irreversibilities

$\boldsymbol{\psi}$, Cost ratio

$\boldsymbol{\Delta}$, Increase