PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON

EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS

28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

Exergy Disturbance Cost Analysis Applied to the Air Refrigeration Machine Process

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Abstract:

This paper presents the Exergy Disturbance Cost Analysis (EDCA), an objective and advanced exergy-based framework grounded in an active Second-Law perspective, that combines two recently developed methodologies with complementary roles: (i) Exergy Entity Cost Analysis (EECA), which determines the monetary cost of all exergy streams throughout an energy conversion system without the need for auxiliary cost equations; and (ii) Exergy Disturbance Analysis (EDA), which quantifies the mutual exergetic disturbances among irreversibility sources, thereby revealing the actual system-wide received and generated exergy degradation attributable to each source (structural disturbance), and its strength relative to the corresponding endogenous value. Their integration enables a more refined analysis by quantifying the cost of each exergy disturbance, thus allowing the determination of the monetary waste associated with structural exergy degradation and the assessment of the corresponding structural cost in relation to the endogenous one. An air refrigeration machine with five irreversibility sources is used to demonstrate the method and evaluate the effect of design variables on these costs and on the cost-effectiveness of the process.

Keywords:

Exergy; Exergy Entity; Exergy Disturbance; Castillo Paz Diagram; Thermoeconomics; EDCA.

1. Introduction

Exergy analysis is widely recognized as the most effective tool for revealing the true thermodynamic performance of an energy conversion system (ECS), since it identifies the location and magnitude of thermodynamic inefficiencies while assessing the real usefulness of energy forms and the rationality of their utilization—insights that conventional energy analysis cannot provide [1–3]. On this basis, and on the premise that exergy constitutes the most rational basis for assigning monetary costs to thermodynamic interactions, several exergy-based costing methodologies have been developed [4–7]. Among them, conventional exergoeconomic analysis has been widely used to determine the costs associated with thermodynamic inefficiencies, exergy streams, and final products [3,8]. At the component level, this methodology is generally formulated through cost balances supported by auxiliary cost equations based on local exergetic fuel and product definitions [9].

Over the past 25 years, this framework has been further refined through advanced exergoeconomic analysis, which considers both the interactions among system components and the real potential for improvement. This approach extends the conventional formulation by splitting exergy destruction, its associated costs, and component-related capital investment into endogenous/exogenous and avoidable/unavoidable parts [10–20]. In this way, it seeks to provide deeper insight into the formation of inefficiencies and costs, as well as into the opportunities for system improvement.

Despite their usefulness, both conventional and advanced exergoeconomic analyses present important limitations. (i) Since the fuel and product definitions used in cost balances and auxiliary equations are not derived from any fundamental physical law, they are inherently conventional and introduce a degree of subjectivity into the formulation [21]. (ii) The cost of exergy destruction is not explicitly included in the component-level cost balances and therefore remains a hidden cost; only approximate average values can be determined indirectly [3]. (iii) Evaluating endogenous and exogenous effects under operating conditions different from those of the real system is inconsistent with a rigorous application of the superposition principle and may yield negative interaction values [22]. (iv) The division of exergy destruction and capital investment into avoidable and unavoidable parts is also affected by subjectivity, because the definition of “best” and “worst” operating conditions relies on engineering judgment, experience, and expectations [20]. (v) The adoption of different operating conditions increases the methodological complexity and the computational effort of the analysis.

Recent advances have led to Exergy Entity Cost Analysis (EECA) [23,24], which determines the cost of exergy entities objectively from the process topology (thermodynamic cost), and to Exergy Disturbance Analysis (EDA) [22], which adopts an active Second-Law perspective to reveal the structural propagation of exergy degradation through the interactions among irreversibility sources. However, these two advances have so far remained separate.

To bridge this gap, this paper introduces the Exergy Disturbance Cost Analysis (EDCA) approach, an advanced exergoeconomic framework that integrates EECA with EDA. The method makes it possible to evaluate not only the location and magnitude of exergy degradation, but also how its effects spread thermodynamically and economically throughout the system. In addition, EDCA defines two advanced indicators—the exergy disturbance strength and the structural-to-endogenous cost ratio—which reveal the thermodynamic and economic relevance of each irreversibility source from a system-wide perspective.

To demonstrate its practical implementation, a closed-cycle air refrigeration machine (ARM) is adopted as an academic case study. After presenting the theoretical framework, the method is applied to the ARM and then used in an advanced parametric assessment to evaluate how selected design variables affect exergy entities, exergy disturbances, and their associated costs.

2. The Exergy Disturbance Cost Analysis

The Exergy Disturbance Cost Analysis (EDCA) approach is an advanced exergy-based method, grounded in an active Second-Law perspective, that integrates Exergy Entity Cost Analysis (EECA) [24] and Exergy Disturbance Analysis (EDA) [22] to determine the monetary cost of all exergetic disturbances caused by each irreversibility source throughout an energy conversion system (ECS). Figure 1 illustrates the main steps of this method, which are described in the following sections.

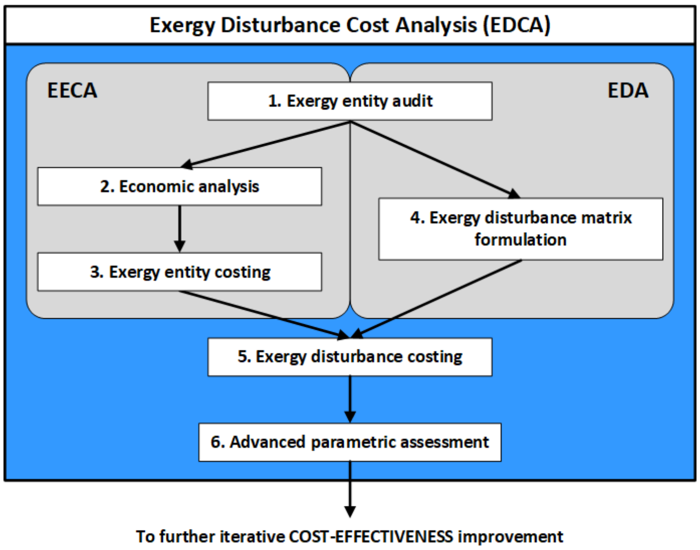

Figure 1. Workflow of the Exergy Disturbance Cost Analysis (EDCA) methodology.

2.1. Exergy entity audit

An exergy entity is a structural constituent of an exergy stream, defined on the basis of the thermodynamic role performed by exergy as it flows through an energy conversion system (ECS). Exergy entities can be classified into three types: (i) the product exergy stream, which is the part of exergy that contributes to the useful output of the system and extends from the supplied fuel (exergy source) to the point where the useful effect is delivered; (ii) the degraded exergy stream, which is the part of the supplied fuel exergy that does not become useful product but instead extends to the point where it is degraded, namely at an irreversibility source; and (iii) the recirculated exergy stream, which is the part of exergy that circulates internally within the system rather than coming directly from the supplied exergy source and typically originates from previous transient operating conditions, such as start-up or load changes.

The main objective of the exergy entity audit is to identify the magnitude of the exergy entities and trace the paths they follow throughout the process. This step comprises: (i) thermal system conditioning, in which the process diagram is adapted so that each exergetic fuel, product, or loss crossing the plant boundary is represented by the corresponding single inlet or outlet exergy stream; (ii) the exergy balance audit, in which the magnitudes of the exergy entities are calculated. At this stage, recirculated exergy streams can be recognized from the process diagram, since recirculation becomes evident when an exergy stream returns to a previous location in the process instead of following the direct downstream exergy path; and (iii) the construction of the Castillo Paz diagram, which graphically represents the paths of the single-pass exergy streams (product and degradation), together with the recirculating exergy streams.

Throughout the procedure, each irreversibility source is associated with either exergy destruction or exergy loss. It is important to highlight that at the source level, the exergy balance is not formulated within the conventional fuel–product framework, but instead through an input–output representation based on the net exergy rates entering and leaving the corresponding control volume, $\dot{E}^{IN}_i$ and $\dot{E}^{OUT}_i$. Thus, the exergy degradation within the *i-th* irreversibility source is expressed as:

$$\dot{D}_i = \dot{E}_i^{IN} - \dot{E}_i^{OUT} \tag{1}$$

Rather than using exergetic efficiency, the thermodynamic performance of irreversibility sources is assessed by means of the exergetic imperfection, β_i, which is directly associated to the exergy degradation and provides an objective measure based solely on inlet and outlet exergy rates:

$$\beta_i = \frac{\dot{D}_i}{\dot{E}_i^{IN}} \tag{2}$$

Because of its inherent input-output nature, only the exergetic fuel and exergetic product defined for the plant as a whole are considered. Thus, the coefficient of exergetic imperfection is expressed as:

$$\theta_{tot} = \frac{\dot{E}_{F,tot}}{\dot{E}_{P,tot}} \tag{3}$$

2.2. Economic analysis

The economic analysis utilizes engineering-economic principles to estimate the major costs involved in a plant such as investment, fuel, operation and maintenance. Because these costs evolve over the plant lifetime, levelized annual values are used to provide a consistent basis for comparison. In this work, the economic evaluation is carried out using the Total Revenue Requirement (TRR) method, following the procedure proposed by EPRI [8], and the analysis may be performed in either current or constant monetary units. Detailed information on this methodology can be found in [3,8]. Figure 2 shows the cost allocation of the levelized TRR.

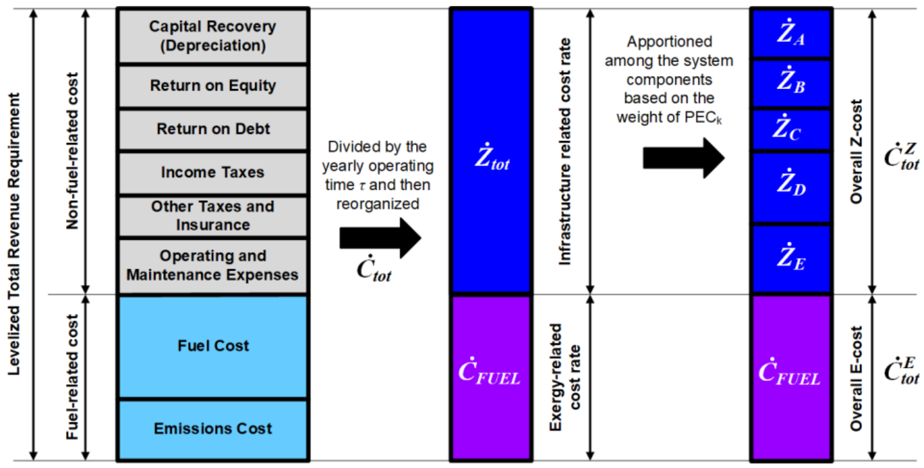

Figure 2. Breakdown and allocation of the levelized total revenue requirement (TRR).

2.3. Exergy entity costing

Exergy entity costing is based on the premise that exergy provides the most appropriate basis for assigning monetary costs to transfers of mass, heat, and work between systems, as well as to thermodynamic inefficiencies. The main purpose of this step is to estimate the thermodynamic cost of exergy entities, together with the production cost of each exergy product delivered by the plant. Here, thermodynamic cost is defined from a system-wide perspective as the monetary expenditure incurred in making a unit of exergy available through resource acquisition and in transporting it throughout the thermodynamic process.

In this step, the fuel-related and non-fuel-related components of the levelized TRR—namely, the E-cost and the Z-cost, respectively—are distributed independently and objectively among all participating exergy entities. The **Z-cost fraction f_z** expresses the share associated with investment-related charges. The unit exergetic cost of a generic exergy entity *j* is:

$$c_j = c_j^E + c_j^Z \tag{4}$$

and the corresponding cost rate is:

$$\dot{C}_j = c_j . \dot{E}_j \tag{5}$$

Here, c^E_j represents the unit E-cost, that is, the cost associated with the exergy content itself and therefore corresponding to a fuel-related cost. Only the product and degraded exergy streams carry this cost, since both originate from the supplied fuels, whereas for recirculated exergy streams this value is zero. For an ECS supplied by multiple fuels (e.g., electricity, natural gas, coal, or heat), the exergy rate of a generic exergy entity j can be expressed as the sum of the contributions associated with each fuel source:

$$\dot{E}_j = \dot{E}_j^{F_1} + \dot{E}_j^{F_2} + \dot{E}_j^{F_3} + \cdots + \dot{E}_j^{F_n} = \sum_{i=1}^{n} \dot{E}_j^{F_i} \tag{6}$$

where $\dot{E}^{F_i}_j$ denotes the portion of the exergy entity $\dot{E}_j$ that originates from fuel F_i. On this basis, the unit E-cost of exergy entity j is obtained as the weighted sum of the specific costs of all fuels, with the weighting factors given by their respective exergy contributions:

$$c_j^E = \sum_{i=1}^{n} c_{F_i} \left(\frac{\dot{E}_j^{F_i}}{\dot{E}_j} \right) \tag{7}$$

On the other hand, c^Z_j denotes the unit Z-cost, that is, the cost associated with the use of the plant infrastructure and therefore corresponding to a non-fuel-related cost. For each plant component k, the unit cost due to its utilization is defined as:

$$c_k^Z = \frac{\dot{Z}_k}{\dot{E}_k^{IN}} \tag{8}$$

where $\dot{E}^{IN}_k$ denotes the net incoming exergy rate, while Z_k, represents the levelized cost rate associated with the capital investment and operating and maintenance of component k. For an ECS supplied by multiple fuels, the unit Z-cost of a single-pass exergy entity j must be determined separately for the portion supplied by each fuel F_i, since each contribution $\dot{E}^{F_i}_j$ may follow a different path through the plant. Thus, for each contribution, the corresponding unit Z-cost is obtained by summing the unit Z-cost of all system components visited along its particular pathway in the Castillo Paz diagram:

$$c_j^{Z,F_i} = \sum c_k^Z \quad (k \in \dot{E}_j^{F_i} \; pathway) \tag{9}$$

Accordingly, the unit Z-cost of a single-pass exergy entity j is given by:

$$c_j^Z = \sum_{i=1}^{n} c_j^{Z,F_i} \left(\frac{\dot{E}_j^{F_i}}{\dot{E}_j} \right) \tag{10}$$

Likewise, for a recirculated exergy stream Rj the unit Z-cost is obtained directly from its circulation path as:

$$c_{R_j}^Z = \sum c_k^Z \quad (k \in \dot{E}_{R_j} \; pathway) \tag{11}$$

As an example, Figure 3 illustrates the pathways followed by a generic single-pass exergy entity $\dot{E}_j$ when it is formed from two different fuels.

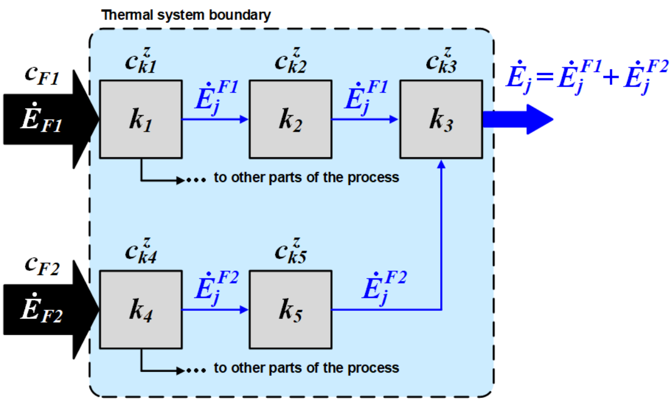

Figure 3. Pathways of a generic single-pass exergy entity $\dot{E}_j$ formed from two different fuels.

In the general case of a multiproduct plant, production costs are obtained by allocating the computed exergy entity costs among the different production units according to their structural relationships. For the single-product system considered in this study, the sum of all entity costs directly gives the overall production cost.

2.4. Exergy disturbance matrix formulation

At this stage, the method attains its advanced character by adopting an **active Second-Law perspective**, through which the interdependent thermodynamic influence among the irreversibility sources is explicitly evaluated. In essence, an exergy disturbance is a form of exergy degradation. Thus, for two irreversibility sources i and j, an **exogenous exergy disturbance** $\boldsymbol{\dot{D}_i^j}$ represents the additional exergy degradation occurring in source i due to the presence and thermodynamic influence of source j within the same system. Conversely, the **endogenous exergy disturbance** $\boldsymbol{\dot{D}_i^i}$ accounts for the exergy degradation generated intrinsically by source i, independently of the influence exerted by the remaining sources. For a generic source i, the total disturbance **received** $\boldsymbol{\dot{D}_i}$ and the total disturbance **generated** $\boldsymbol{\dot{D}^i}$ are expressed as:

$$\dot{D}_i = \underbrace{\dot{D}_i^i}_{endogenous} + \underbrace{\sum\nolimits_{j\neq i}\dot{D}_i^j}_{received\ exogenous\ contribution} \tag{12}$$

$$\dot{D}^i = \underbrace{\dot{D}_i^i}_{endogenous} + \underbrace{\sum\nolimits_{j\neq i}\dot{D}_j^i}_{generated\ exogenous\ contribution} \tag{13}$$

The Exergy Disturbance Matrix (EDM) provides a compact representation of the disturbance structure of an ECS. For a system with n irreversibility sources, it is defined as:

$$\boldsymbol{D} = \left[\dot{D}_i^j\right]^{nxn} = \underbrace{\left[\dot{D}_i^j\right]_{i=j}^{nxn}}_{D^{EN}} + \underbrace{\left[\dot{D}_i^j\right]_{i\neq j}^{nxn}}_{D^{EX}} \tag{14}$$

The **endogenous disturbance matrix** $\boldsymbol{D^{EN}}$ contains only the diagonal terms ($i = j$), whereas the **exogenous disturbance matrix** $\boldsymbol{D^{EX}}$ contains only the off-diagonal terms ($i \neq j$). Note that the terms $\dot{D}_i$ and $\dot{D}^i$ are obtained by summing the elements in row i and column i, respectively.

The **structural exergy disturbance** $\boldsymbol{\dot{D}_i^{ST}}$ represents the actual exergy degradation associated with that source when its thermodynamic interactions with the rest of the system are taken into account. It combines the endogenous contribution and all the received and generated exogenous disturbances, and can be written as:

$$\dot{D}_i^{ST} = \dot{D}_i^i + \sum\nolimits_{j\neq i}\left(\dot{D}_i^j + \dot{D}_j^i\right) = \dot{D}_i + \dot{D}^i - \dot{D}_i^i \tag{15}$$

Using the endogenous disturbance as a reference, the **structural exergy disturbance strength** $\boldsymbol{\sigma_i^{ST}}$ measures how much the structural disturbance departs from its self-induced value. It is defined as:

$$\sigma_i^{ST} = \frac{\dot{D}_i^{ST}}{\dot{D}_i^i} \tag{16}$$

2.4.1. The Equivalent Reversible Reference System (ERRS) approach

In order to disclose exergy disturbances, it is first necessary to define the best thermodynamic counterpart of the real system, which serves as the reference for the calculations. This ideal benchmark, termed the **Equivalent Reversible Reference System (ERRS)**, is characterized by two fundamental features: (i) **reversibility**, meaning that it behaves as a thermodynamic black box free of irreversibility sources and is therefore incapable of generating disturbances by itself; and (ii) **equivalence**, meaning that it is uniquely defined to preserve the intensive properties of the actual supplied fuels while delivering the same products as the real system. Under these conditions, the total supplied fuel exergy is equal to the total delivered product exergy, as shown in Figure 4.

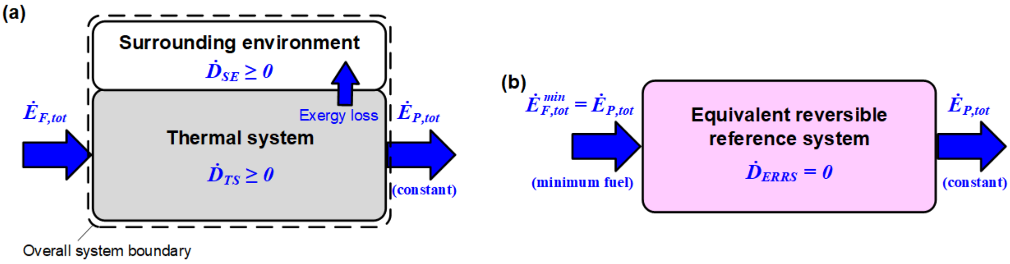

Figure 4. Energy conversion system: (a) real system, (b) Equivalent Reversible Reference System (ERRS).

The ERRS is used as a controlled reference framework in which irreversibility sources are allowed to operate either individually or in combination, so that self-induced and interaction-induced exergy degradations can be distinguished. In this context, each set of active sources defines a **combined system**, while preserving **thermodynamic invariability**, namely the real operating conditions, such as chemical composition, temperature and pressure. For every combined system, the product exergy stream is kept constant, whereas the corresponding mass flow rates may vary. Under this framework, the **endogenous disturbance** $\boldsymbol{\dot{D}_i^i}$ is obtained by evaluating source i operating alone with the ERRS. By contrast, the **exogenous disturbances** $\boldsymbol{\dot{D}_i^j}$ are computed through a more elaborate procedure based on the **superposition principle** applied to multiple source configurations (binary, ternary, quaternary, etc), which makes it possible to isolate the additional degradation induced in source i by the presence of other irreversibility sources. Further details on these calculations, as well as on the axioms and theorems governing exergy disturbances, are provided in the previous paper [22]. Figure 5 illustrates this procedure for the case of a single active source i, and for two active sources i and j.

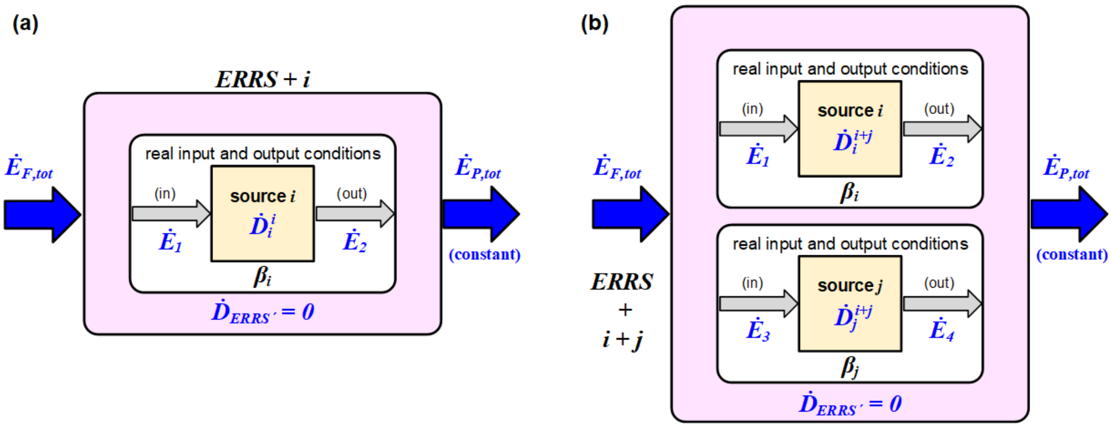

Figure 5. Combined systems for (a) single-source operation and (b) binary-source operation.

2.5. Exergy disturbance costing

In this step, the cost of exergy disturbances is determined by combining exergy entity costing with the EDM. The former provides the specific monetary cost of each exergy degradation stream, whereas the latter describes how that degradation is distributed into endogenous and exogenous components for each irreversibility source. Because each row of the EDM corresponds to the degradation stream associated with source i, the monetary value of each term is obtained by multiplying that row by the corresponding unit cost c_i. This yields the **Exergy Disturbance Cost Matrix (EDCM)**, where all disturbance components are expressed in monetary terms:

$$\boldsymbol{C} = \left[\dot{C}_{D,i}^{j}\right]^{nxn} = \left[c_i . \dot{D}_i^j\right]^{nxn} \quad (17)$$

The **structural exergy disturbance cost** $\boldsymbol{\dot{C}_i^{ST}}$ represents the true monetary impact associated with source i, when all associated received and generated disturbances are taken into account:

$$\dot{C}_{D,i}^{ST} = \dot{C}_{D,i}^{i} + \sum\nolimits_{j\neq i}\left(\dot{C}_{D,i}^{j} + \dot{C}_{D,j}^{i}\right) = \dot{C}_{D,i} + \dot{C}_{D}^{i} - \dot{C}_{D,i}^{i} \quad (18)$$

where $\boldsymbol{\dot{C}_{D,i}}$ and $\boldsymbol{\dot{C}_D{}^i}$ are the net cost rates of received and generated disturbances, respectively. The **structural-to-endogenous cost ratio** $\boldsymbol{\tau_i^{ST}}$ compares the total structural disturbance cost of an irreversibility source with its purely endogenous cost. It can be defined as:

$$\tau_i^{ST} = \frac{\dot{C}_{D,i}^{ST}}{\dot{C}_{D,i}^{i}} \quad (19)$$

The structural disturbance cost $\dot{C}_i^{ST}$ can be used to rank irreversibility sources according to their true economic relevance, while τ_i^{ST} can be used to identify those sources whose costs are strongly amplified by structural interactions. In terms of cost-effectiveness improvement, priority should be given to sources with high structural cost, especially when accompanied by high τ_i^{ST}, since reducing their irreversibility is expected to produce broader economic benefits at the system level than those suggested by their endogenous cost alone.

2.6. Advanced parametric assessment

In this final step, exergy entities, together with exergy disturbances and their corresponding costs, are assessed for different values of the selected design variables. This enables a more comprehensive understanding of how design changes affect the thermodynamic and economic behavior of the system, thereby supporting the identification of more effective improvement strategies.

3. Case study: the Air Refrigeration Machine process

A closed-cycle air refrigeration machine (ARM), shown in Figure 6, is selected as the academic case study for applying the EDCA methodology. The main components of the system are the air compressor (AC), mechanically coupled to an expander (EXP) and assisted by an electric motor (M), the heat exchanger (HE), which cools the recirculating air by means of water, and the refrigerator (REF), which uses the working fluid to cool the product air entering at −10∘C. Under steady-state conditions, the ARM provides a cooling capacity of 100 kW and delivers 9.9 kg/s of product air at 1 bar and −20°C.

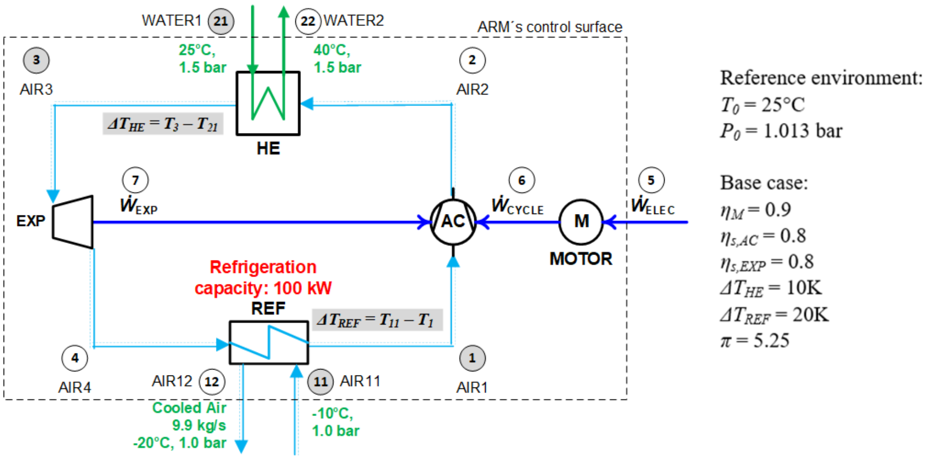

Figure 6. Process diagram of the ARM.

The ARM was simulated in Aspen Plus, with air modeled as an ideal-gas mixture composed of 79% nitrogen and 21% oxygen. The base-case operating conditions were adopted from [13,15]. A pressure drop of 4.75% was assumed in both the heat exchanger (HE) and the refrigerator (REF). The base-case design variables are listed in Figure 6. Table 1 reports the thermodynamic properties of the process streams; the exergy values listed correspond only to physical exergy. The resulting coefficient of performance is relatively low, with COP_{ARM} = 0.223.

Table 1. ARM process: thermodynamic data (base-case).

N°	Stream ID	$\dot{m}$, kg/s	T, °C	p, bar	h, kJ/kg	$e^{\Delta T}$, kJ/kg	$e^{\Delta p}$, kJ/kg	e, kJ/kg	$\dot{E}$, kW
1	AIR1	4.20	-30.00	1.00	-56	5.86	-1.11	4.75	19.93
2	AIR2	4.20	153.04	5.25	130	21.91	141.36	163.27	685.58
3	AIR3	4.20	35.00	5.00	10	0.17	137.18	137.35	576.74
4	AIR4	4.20	-53.60	1.05	-79	12.76	3.08	15.84	66.51
11	AIR11	9.90	-10.00	1.00	-35	2.25	-1.11	1.14	11.33
12	AIR12	9.90	-20.00	1.00	-45	3.82	-1.11	2.71	26.84
21	WATER1	8.04	25.00	1.50	-15 866	0.00	0.05	0.05	0.40
22	WATER2	8.04	40.00	1.50	-15 803	1.53	0.05	1.58	12.67

3.1. Exergy entity audit

In this case, the overall system is supplied by a single fuel exergy stream (electricity, 448.80 kW) and contains eight circulating exergy entities: one product stream (cold: 15.51 kW), two recirculated streams fed back to the AC unit (R1, corresponding to the expander power output, 375.75 kW, and R2, corresponding to the exergy of stream AIR1, 19.93 kW), and five degradation streams associated with the M, AC, HE, EXP, and REF irreversibility sources, whose degradation rates are reported in Table 2.

The process exhibits a high exergetic imperfection of 96.54%, as a result of the large degradation rate of 433.29 kW, mainly associated with the EXP (134.48 kW), AC (114.02 kW), and HE (108.83 kW) units. The total circulating exergy rate amounts to 844.48 kW, of which 396.68 kW corresponds to recirculated exergy streams. All exergy entities involved are shown in the Castillo Paz diagram presented in Figure 7. For clarity, the single-pass exergy entities (product and degradation streams, both supplied by the fuel) are presented separately from the recirculated exergy streams.

Table 2. ARM process: exergetic results (base-case).

Source i	Type	β_i, %	$\dot{E}^{IN}_i$, kW	$\dot{E}^{OUT}_i$, kW	$\dot{D}_i$, kW	Ranking
M	destruction	10.00	448.80	403.92	44.88	4
AC	destruction	14.26	799.60	685.58	114.02	2
HE	loss	15.87	685.58	576.74	108.83	3
EXP	destruction	23.32	576.74	442.27	134.48	1
REF	destruction	46.72	66.51	35.44	31.08	5
Plant		**96.54**	**448.80**	**15.51**	**433.29**	

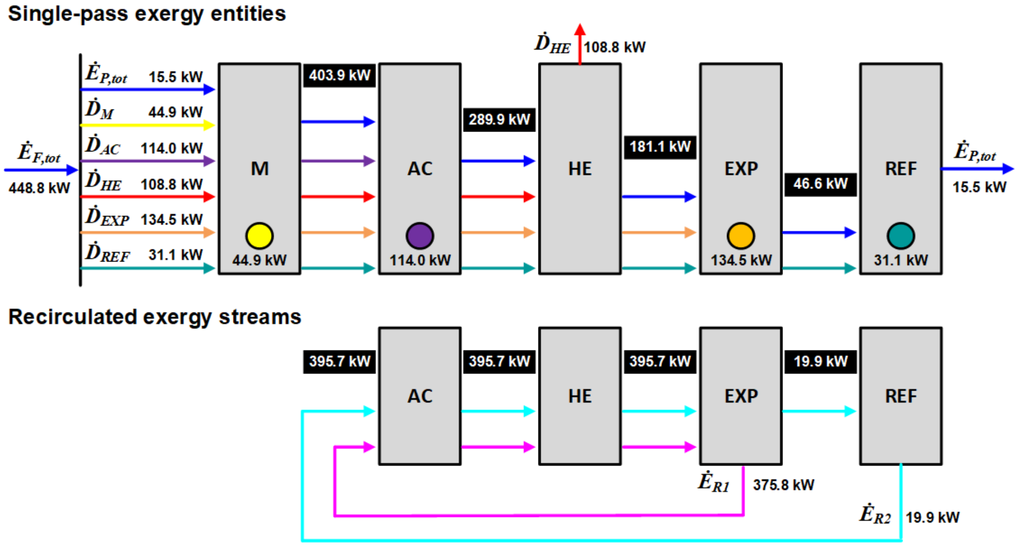

Figure 7. Castillo Paz diagram of the ARM (base-case).

3.2. Exergy entity costing

The economic assumptions used to estimate the levelized costs of the ARM, as well as the cost equations required to determine the Z-costs at different design conditions, can be found in a previous paper [24]. Table 3 presents the calculated TRR levelized cost categories, expressed in current euros over a 15-year period, together with the allocation of the non-fuel related costs (Z-cost) among the plant components.

Table 3. Results of economic analysis (base-case).

Cost category		$\dot{C}_i$, €/year	$\dot{C}_i$, €/h	%
Carrying charges	(Z-cost)	94 851	13.55	9.27
Electricity cost	(E-cost)	927 827	132.55	90.73
TRR		**1 022 678**	**146.10**	**100**
c_{elec} = 82.04 €/GJ (fuel)				
Capacity factor: 80% (7 000 h/year)				
$t_z = PEC_{tot} / \dot{Z}_{tot} = PEC_k / \dot{Z}_k$ = 53 251 h (constant)				

k	PEC_k, €	$\dot{Z}_k$, €/h	%
M	28 351	0.53	3.93
AC	189 005	3.55	26.19
HE	119 219	2.24	16.52
EXP	203 835	3.83	28.25
REF	181 154	3.40	25.11
Plant	**721 563**	**13.55**	**100.00**

Table 4. Cost structure of exergy entities (base-case)

$\dot{E}_j$	Exergy rate, kW	c^E_j, €/GJ	c^Z_j, €/GJ	c_j, €/GJ	$\dot{C}^E_j$, €/h	$\dot{C}^Z_j$, €/h	$\dot{C}_j$, €/h	f^Z_j, %
$\dot{E}_{P,tot}$	15.51	82.04	18.52	100.56	4.58	1.03	5.61	18.42
$\dot{D}_M$	44.88	82.04	0.33	82.37	13.25	0.05	13.31	0.40
$\dot{D}_{AC}$	114.02	82.04	1.56	83.60	33.67	0.64	34.32	1.87
$\dot{D}_{HE}$	108.83	82.04	2.47	84.51	32.14	0.97	33.11	2.92
$\dot{D}_{EXP}$	134.48	82.04	4.31	86.35	39.72	2.09	41.80	4.99
$\dot{D}_{REF}$	31.08	82.04	18.52	100.56	9.18	2.07	11.25	18.42
$\dot{E}_{R1}$	375.75	0.00	3.98	3.98	0.00	5.39	5.39	100.00
$\dot{E}_{R2}$	19.93	0.00	18.19	18.19	0.00	1.30	1.30	100.00
$\dot{E}_{tot}$	**844.48**	**43.60**	**4.46**	**48.06**	**132.55**	**13.55**	**146.10**	**9.27**

Based on Eq. 8, the specific **component utilization cost** c_k^Z for the AC, M, HE, EXP, and REF units is 1.23, 0.33, 0.91, 1.84, and 14.21 €/GJ, respectively. Table 4 reports the allocation of E-cost and Z-cost among all exergy entities involved in the process. The results show that the thermodynamic cost associated with the useful product is only 5.61 €/h, whereas its production cost reaches 146.1 €/h. This means that 140.48 €/h is wasted with degraded and recirculated exergy streams, rather than with useful production. Such a large difference reveals a pronounced cost inefficiency, quantified by 96.2%. Since the overall **Z-cost fraction** f_z is relatively low, at 9.3%, these results clearly indicate that increasing investment to reduce the non-productive exergy streams is economically justified, since the plant cost is governed primarily by exergy degradation rather than by capital-related charges.

3.3. Exergy disturbance costing

Table 5 shows that exogenous disturbances dominate the ARM: of the total exergy degradation of 433.29 kW, only 19.76 kW is endogenous, whereas 413.53 kW results from source interactions. This is reflected in the high structural disturbance strengths, which reveal strong interdependence among irreversibility sources. Table 6 confirms this behavior in monetary terms. The total disturbance cost is 133.79 €/h, of which only 6.24 €/h is endogenous and 127.55 €/h is exogenous. The resulting high structural-to-endogenous cost ratios, especially for the REF and M units, show that the economic impact of irreversibilities is governed mainly by structural interactions. Therefore, reducing exergy degradation in any key source is expected to produce significant thermodynamic and economic benefits at the plant level.

Table 5. EDM and structural disturbance strengths (base-case)

$i\,/\,j$	$\dot{D}_i^j$, kW					$\dot{D}_i$, kW	$\dot{D}_i^{ST}$, kW	σ_i^{ST}, -	ST Ranking
	M	**AC**	**HE**	**EXP**	**REF**				
M	**1.72**	11.67	11.55	12.10	7.84	44.88	126.15	73.20	4
AC	23.94	**5.28**	31.24	32.88	20.69	114.02	201.31	38.11	2
HE	22.81	30.07	**4.97**	31.28	19.72	108.83	196.64	39.61	3
EXP	28.41	37.68	37.23	**6.64**	24.52	134.48	218.88	32.99	1
REF	6.11	7.87	7.79	8.15	**1.15**	31.08	103.84	89.99	5
$\dot{D}^j$, **kW**	82.99	92.57	92.77	91.04	73.92	**433.29**			

Table 6. EDCM and structural-to-endogenous cost ratios (base-case)

$i\,/\,j$	$\dot{C}_{D,i}^j$, €/h					$\dot{C}_{D,i}$, €/h	$\dot{C}_{D,i}^{ST}$, €/h	$\tau_{D,i}^{ST}$, -	ST Ranking
	M	**AC**	**HE**	**EXP**	**REF**				
M	**0.51**	3.46	3.42	3.59	2.33	13.31	38.49	75.33	4
AC	7.20	**1.59**	9.40	9.89	6.23	34.32	61.49	38.68	2
HE	6.94	9.15	**1.51**	9.51	6.00	33.11	60.33	39.94	3
EXP	8.83	11.71	11.57	**2.06**	7.62	41.80	67.75	32.85	1
REF	2.21	2.85	2.82	2.95	**0.42**	11.25	33.42	80.01	5
$\dot{C}_D^j$, **€/h**	25.70	28.76	28.73	28.01	22.59	**133.79**			

3.4. Advanced parametric assessment

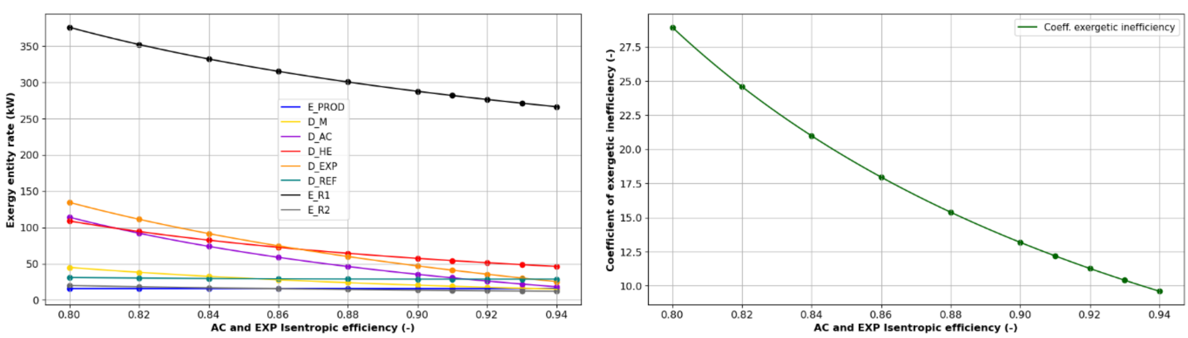

Figure 8. Exergy entities and coefficient of exergetic inefficiency θ_{tot} vs. isentropic efficiency.

Since the EXP and AC sources exhibit the highest structural disturbances, the advanced parametric assessment is directed toward analyzing the effect of simultaneously increasing their isentropic efficiencies from 80 to 94%. Figure 8 shows that improving the isentropic efficiencies of the AC and EXP units leads to a clear thermodynamic improvement of the ARM. The main degradation and recirculated exergy streams decrease, while the overall coefficient of exergetic inefficiency θ_{tot} is substantially reduced from 28.9 to 9.6.

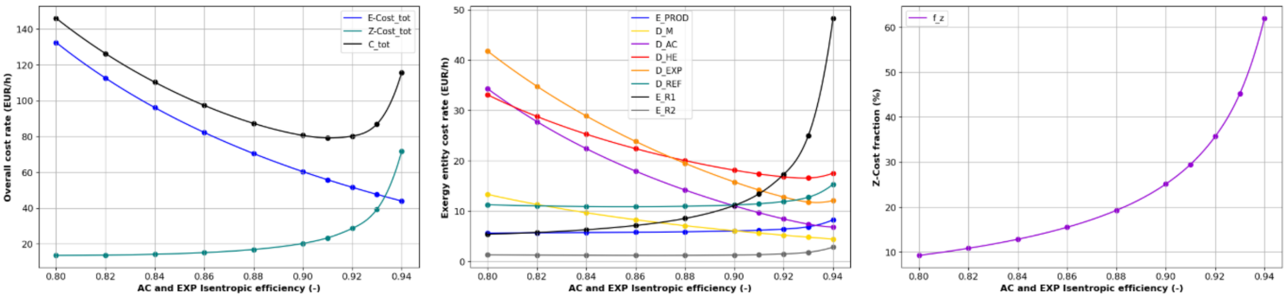

Figure 9. Overall cost categories, exergy entity costs, and Z-cost fraction vs. isentropic efficiency.

However, Figure 9 shows that this thermodynamic improvement is accompanied by a marked change in the cost structure of the system. The E-cost decreases significantly as exergy degradation is reduced, whereas the Z-cost increases due to the higher investment required to achieve better component efficiencies. The total cost reaches a minimum at an isentropic efficiency of about 91%. The middle plot shows that the costs of degradation in the EXP, AC, and M units decrease markedly as the isentropic efficiency increases, whereas the cost of the recirculated exergy stream R1 (expander mechanical power) increases strongly. This opposite behavior highlights the progressive transfer of economic burden from irreversibility sources to internal exergy recirculation, as the Z-cost fraction of the plant rises from 9.3% to 62%.

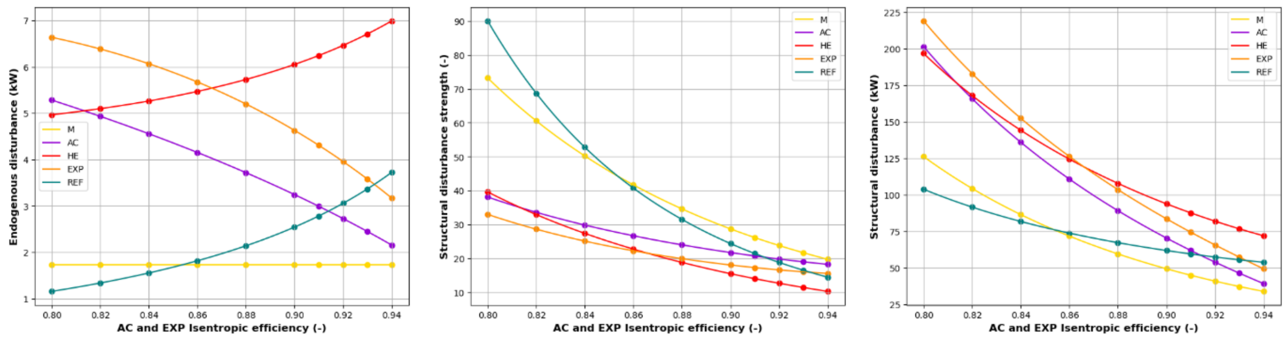

Figure 10. Endogenous and structural exergy disturbances vs. isentropic efficiency.

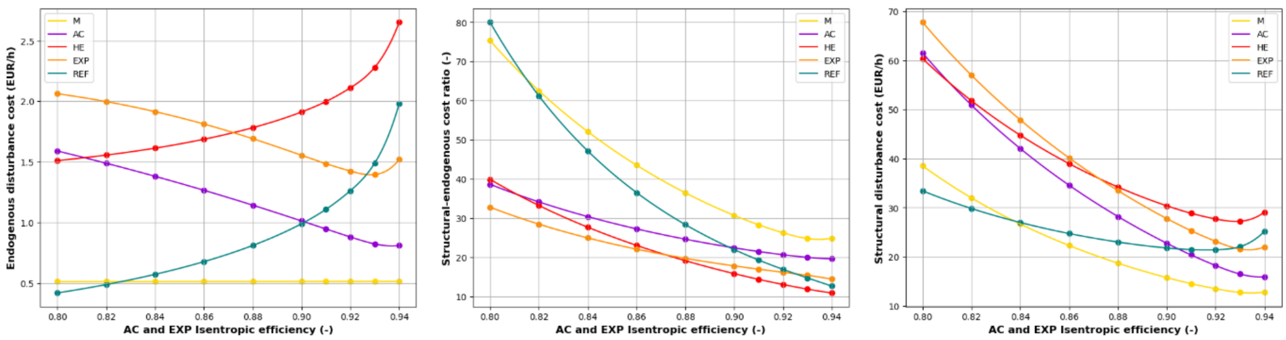

Figure 11. Endogenous and structural disturbance costs vs. isentropic efficiency.

Figure 10 and Figure 11 show that increasing the isentropic efficiencies of the AC and EXP units generally reduces the structural disturbances and their associated costs. The progressive decrease in both the disturbance strengths and the structural-to-endogenous cost ratios follows a similar trend, revealing a close link between the thermodynamic and economic behavior of the system. As these two advanced indicators decrease, the influence of structural interactions becomes weaker, but the remaining improvement potential also becomes smaller. However, beyond an isentropic efficiency of about 0.92, the endogenous disturbance costs of the HE and REF units become dominant, causing their structural disturbance costs to rise again. Therefore, improving AC and EXP reduces the propagation and economic amplification of irreversibilities only up to a certain point, after which the thermodynamic and economic burden is shifted to other parts of the system. For the most cost-effective operating condition evaluated (η_s = 91%), the thermodynamic cost of the product exergy is 6.2 €/h, while its production cost reaches 79.2 €/h, resulting in a cost inefficiency of 92.4%.

4. Conclusions

The Exergy Disturbance Cost Analysis (EDCA) approach provides an advanced exergoeconomic framework that integrates exergy entity costing with exergy disturbance analysis, making it possible to evaluate not only the location and magnitude of exergy degradation, but also how its effects spread thermodynamically and economically throughout the system, as represented by the EDM and EDCM, respectively.

In contrast to earlier exergy-based costing approaches, cost allocation in EDCA is determined objectively according to the process topology, without relying on local fuel and product definitions at the plant-component level or on auxiliary equations, thereby avoiding the introduction of arbitrariness. It also enables the explicit costing of fundamental recirculated exergy streams, whose fundamental role in the system had not been previously accounted for in such approaches.

Thanks to its active Second-Law perspective, the approach defines two advanced indicators: the exergy disturbance strength and the structural-to-endogenous cost ratio. The first shows how much the degradation of a source is amplified by its interactions with the rest of the system, while the second shows the same effect in economic terms. The larger these indicators are, the greater the potential for effective improvement.

Furthermore, the proposed method does not introduce arbitrariness associated with the definition of avoidable and unavoidable parts, since such a decomposition is not part of the formulation.

Although EDCA does not directly optimize the process, it provides deeper thermodynamic and economic insight, enabling a better understanding of the ECS and supporting more effective design decisions.

The objectivity and methodological simplicity of the approach give it significant academic value in energy engineering. Although the present study deals with a relatively simple system, these features give the method a general character that makes it suitable for more complex ECS configurations, including configurations with multiple fuels and multiple products. Such applications should be examined in future work.

The main limitations associated with the implementation of the method are not intrinsic to the method itself, but arise from the accuracy of the economic analysis—especially the TRR evaluation—and from the proper formulation of PEC equations. Both aspects may involve a considerable degree of subjectivity, since economic information is often difficult to obtain and not always straightforward to generate consistently.

AUTHOR CONTRIBUTIONS: *Conceptualization*, R.C.P.; *methodology*, R.C.P.; *validation*, R.C.P.; *formal analysis*, R.C.P.; *investigation*, R.C.P.; *writing-original draft preparation*, R.C.P.; *writing-review and editing*, R.C.P. and G.T.; *visualization*, R.C.P.; *supervision*, R.C.P. and G.T. All authors have read and agreed to the published version of the manuscript.

Nomenclature

Abbreviations

AC	air compressor
ARM	air refrigeration machine
COP	coefficient of performance
ECS	energy conversion system
EDA	exergy disturbance analysis
EDCA	exergy disturbance cost analysis
EDCM	exergy disturbance cost matrix
EDM	exergy disturbance matrix
EECA	exergy entity cost analysis
EPRI	electric power research institute
ERRS	equivalent reversible reference system
EXP	turbine expander
HE	heat exchanger
M	electrical motor
PEC	purchased equipment cost
REF	refrigerator
TCA	thermodynamic cost accounting
TRR	Total revenue requirement

Symbols

c	unitary exergy cost, EUR/GJ
$\dot{C}$	exergy cost rate, EUR/h
$\dot{D}$	exergy degradation rate, kW
e	specific exergy, kJ/kg
$\dot{E}$	exergy rate, kW
f	fraction, %
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow, kg/s
p	pressure, bar
T	temperature, °C
$\dot{W}$	power, kW
$\dot{Z}$	non-fuel-related cost rate, EUR/h

Greek Symbols

β	exergetic imperfection, %
θ	coefficient of exergetic performance, -
π	compressor pressure ratio, -
σ	exergy disturbance strength, -
τ	structural-to-endogenous cost ratio, -

Subscripts and superscripts

$CYCLE$	thermodynamic cycle
D	exergy degradation
E	E-cost related
$ELEC$	electrical
EN	endogenous
EX	exogenous
F	fuel
i	irreversibility source
IN	incoming
j	generic exergy entity
k	component-related source
OUT	outgoing
P	produt
R	recirculated stream
s	isentropic
SE	surrounding environment
ST	structural
tot	overall
TS	thermal system
Z	Z-cost related

References

[1] Kotas T.J., The exergy method of thermal plant analysis. London: Butterworths; 1985.

[2] Szargut J., Chemical exergies of the elements. Appl Energy 1989;32:269–86.

[3] Bejan A., Tsatsaronis G., Moran M.J., Thermal design and optimization. New York: Wiley; 1996.

[4] Von Spakovsky M.R., Application of engineering functional analysis to the analysis and optimization of the CGAM problem. Energy 1994;19:343–64.

[5] Valero A., Lozano M.A., Serra L., Torres C,. Application of the exergetic cost theory to the CGAM problem. Energy 1994;19:365–81.

[6] Frangopoulos C.A., Application of the thermoeconomic functional approach to the CGAM problem. Energy 1994;19:323–42.

[7] Tsatsaronis G., Pisa J., Exergoeconomic evaluation and optimization of energy systems — application to the CGAM problem. Energy 1994;19:287–321.

[8] Tsatsaronis G., Cziesla F., Thermoeconomics. In: Meyers, Robert A., editor. Encycl. Phys. Sci. Technol., vol. 16. Third Edition, San Diego, California, USA: Elsevier; 2002, p. 659–80.

[9] Lazzaretto A., Tsatsaronis G., SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006;31:1257–89.

[10] Kelly S., Tsatsaronis G., Morosuk T., Advanced exergetic analysis: Approaches for splitting the exergy destruction into endogenous and exogenous parts. Energy 2009;34:384–91.

[11] Morosuk T., Tsatsaronis G., Advanced exergetic evaluation of refrigeration machines using different working fluids. Energy 2009;34:2248–58.

[12] Morosuk T., Tsatsaronis G., Advanced Exergy Analysis for Chemically Reacting Systems – Application to a Simple Open Gas-Turbine System. Int J Thermodyn 2009;12:105–11.

[13] Morosuk T., Tsatsaronis G., Advanced Exergoeconomic Analysis of a Refrigeration Machine: Part 1—Methodology and First Evaluation. Vol. 4 Energy Syst. Anal. Thermodyn. Sustain. Combust. Sci. Eng. Nanoeng. Energy Parts B, Denver, Colorado, USA: ASMEDC; 2011, p. 47–56.

[14] Morosuk T., Tsatsaronis G., Advanced Exergoeconomic Analysis of a Refrigeration Machine: Part 2—Improvement. Vol. 4 Energy Syst. Anal. Thermodyn. Sustain. Combust. Sci. Eng. Nanoeng. Energy Parts B, Denver, Colorado, USA: ASMEDC; 2011, p. 57–65. https://doi.org/10.1115/IMECE2011-62689.

[15] Morosuk T., Tsatsaronis G., 3-D Exergy-Based Methods for Improving Energy-Conversion Systems. Int J Thermodyn 2012;15:201–13.

[16] Petrakopoulou F., Tsatsaronis G., Morosuk T., Carassai A., Conventional and advanced exergetic analyses applied to a combined cycle power plant. Energy 2012;41:146–52.

[17] Petrakopoulou F., Tsatsaronis G., Morosuk T., Carassai A., Advanced Exergoeconomic Analysis Applied to a Complex Energy Conversion System. J Eng Gas Turbines Power 2012;134:031801.

[18] Petrakopoulou F., Tsatsaronis G., Morosuk T., Advanced Exergoeconomic Analysis of a Power Plant with CO2 Capture. Energy Procedia 2015;75:2253–60.

[19] Penkuhn M., Tsatsaronis G., A decomposition method for the evaluation of component interactions in energy conversion systems for application to advanced exergy-based analyses. Energy 2017;133:388–403.

[20] Morosuk T., Tsatsaronis G., Advanced exergy-based methods used to understand and improve energy-conversion systems. Energy 2019;169:238–46.

[21] Szargut J., Exergy method: technical and ecological applications. Southampton: Wit press; 2005.

[22] Castillo Paz R., Tsatsaronis G., Exergy Disturbance Analysis Applied to the Air Refrigeration Machine Process. Proc. ECOS 2025, Paris, France: 2025.

[23] Castillo Paz R., Tsatsaronis G., The exergy-based Thermodynamic Cost Accounting (TCA) approach for improving the design of thermal systems. Proc. ECOS 2023, Las Palmas De Gran Canaria, Spain: 2023.

[24] Castillo Paz R., Tsatsaronis G., Exergy Entity Cost Analysis: Application to the Air Refrigeration Machine. Proc. ECOS 2024, Rhodes, Greece: 2024.