

Advanced Exergy Analysis

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Introduction

The persistent growth in global energy demand, largely driven by industrial expansion, population increase, and advances in technology, continues to exert tremendous pressure on current energy infrastructures. Simultaneously, the impacts of climate change and environmental degradation have intensified the urgency of adopting sustainable and efficient energy strategies. According to the International Energy Agency (IEA, 2022), the energy sector remains the dominant source of global greenhouse gas emissions, responsible for approximately three-quarters of the total. In this light, enhancing the performance of energy systems is therefore not only an economic objective but a strategic necessity aligned with international frameworks such as the Paris Agreement and the United Nations Sustainable Development Goals.

In the field of engineering sciences, numerous performance indicators and analytical techniques have been developed to evaluate and improve system efficiency. Among them, exergy analysis has emerged as one of the most comprehensive and insightful thermodynamic approaches. Unlike traditional energy balances, which are based solely on the first law of thermodynamics and treat all forms of energy equivalently, exergy analysis incorporates the second law. This allows for an assessment of energy quality and the inevitable irreversibilities that occur during energy conversion processes. As a result, exergy analysis provides a more meaningful evaluation of not only the quantity of energy consumed but also the effectiveness with which it is transformed into useful work.

The principal strength of conventional exergy analysis (CEA) lies in its ability to highlight the true thermodynamic inefficiencies of a system by quantifying irreversibilities. Over the past several decades, CEA has been extensively applied to diverse energy systems, including gas turbines, steam power plants, refrigeration cycles, and renewable energy technologies (Bejan, 2017; Ozen et al., 2020; Rosen & Dincer, 2001). These studies have consistently demonstrated that exergy analysis delivers deeper insights into system performance compared to analyses based solely on the first law. For example, in combined cycle power plants, while the reported energy efficiency may reach 55-

60%, exergy efficiency values often fall within the range of 35-45%, clearly exposing significant hidden irreversibilities that a first-law perspective fails to capture.

Nonetheless, despite its recognized benefits, CEA suffers from notable limitations. While it provides the total magnitude of exergy destruction within a system, it does not distinguish between avoidable and unavoidable portions of irreversibility. In practical terms, this means that CEA cannot differentiate losses that may be realistically reduced through improved designs or operational strategies from those that are inherently irreducible due to thermodynamic constraints. Furthermore, conventional analysis does not separate endogenous irreversibilities, which arise from within a specific component, from exogenous ones, which are caused by the interaction of that component with others. This lack of resolution diminishes the decision-making power of CEA, particularly in complex systems with high levels of integration.

To illustrate this issue, consider a gas turbine within a broader power generation system. Conventional exergy analysis may reveal that the turbine exhibits the largest share of exergy destruction. Yet such a result leaves key questions unanswered: How much of the destruction is unavoidable due to the fundamental physics of gas expansion, how much is avoidable through design modifications such as advanced blade geometry, cooling techniques, or optimized operation, and importantly, what share of the destruction originates internally within the turbine itself, and what share is imposed by other components such as upstream compressors or downstream heat exchangers? Because CEA cannot provide these distinctions, it falls short of guiding targeted engineering interventions.

To overcome these shortcomings, Advanced Exergy Analysis (AEA) was developed as a refinement of conventional methods. Its origins can be traced to the pioneering contributions of George Tsatsaronis in the late 1980s and early 1990s, who emphasized the need to classify different types of irreversibilities for improved decision-making in design and optimization (Tsatsaronis, 1993). The methodology was subsequently extended and formalized through the work of Morosuk and Tsatsaronis (2009), Vučković et al. (2012), and numerous others. Over time, AEA has matured into a robust framework widely recognized for its ability to deliver deeper insights into system inefficiencies and to support decision-making at both the component and system levels.

The essence of AEA lies in its two-dimensional classification of exergy destruction. It separates irreversibilities into avoidable versus unavoidable and endogenous versus exogenous categories. When combined, these classifications generate a fourfold partition: avoidable-endogenous, avoidable-exogenous, unavoidable-endogenous, and unavoidable-exogenous. This refined categorization not only quantifies the overall magnitude of losses but also identifies their origin and reducibility, thereby offering

engineers actionable insights into where system improvements can most effectively be pursued.

In this way, AEA transforms exergy analysis from a diagnostic tool into a decision-support framework. By revealing the nature and source of inefficiencies, it provides clear guidance for prioritizing engineering strategies. For instance, if analysis reveals that a compressor's losses are predominantly avoidable-exogenous, this indicates that upstream components are the true focus for improvement, as their inefficiencies propagate downstream. Conversely, if the majority of losses are avoidable-endogenous, direct efforts on the compressor's design or operation will be most effective.

Since its introduction, AEA has been applied to a broad array of energy systems. In industrial processes such as natural gas liquid (NGL) recovery, AEA has helped pinpoint compressors and heat exchangers as critical targets for improvement (Jovijari, Kosarineia, Mehrpooya, & Nabhani, 2022a). In power generation applications, including organic Rankine cycles (ORC) and combined heat and power (CHP) systems, it has clarified the distribution of irreversibilities and guided optimization of system integration (Azubuike, Njoku, Eke, & Ekechukwu, 2025; Yan et al., 2019). More recently, the method has also been adopted in unconventional sectors such as food processing, where Bühler et al. (2018) demonstrated its utility in identifying hidden inefficiencies in milk processing plants—opportunities that conventional analysis had overlooked.

Beyond thermodynamic insights, AEA has been extended into the economic and environmental domains. The development of advanced exergoeconomic analysis (AECA) and advanced exergoenvironmental analysis (AEEA) allows simultaneous consideration of cost-related and environmental implications of irreversibilities (Petrakopoulou, Tsatsaronis, Morosuk, & Paitazoglou, 2012; Qi et al., 2024). These integrated approaches are particularly valuable in the context of the global energy transition, where technical efficiency must align with economic feasibility and sustainability objectives.

AEA has also proven valuable in education. Introducing students to the distinctions between avoidable and unavoidable, and endogenous and exogenous irreversibilities, nurtures a deeper understanding of energy systems and promotes systems-oriented thinking. This prepares future engineers and scientists to confront the complex realities of modern energy infrastructures, where interactions among components often dictate overall performance more than individual component efficiencies.

In conclusion, Advanced Exergy Analysis represents a paradigm shift in the assessment of energy systems. By distinguishing between the nature and reducibility of irreversibilities, it generates actionable insights for the design, optimization, and operation of energy technologies. Its successful application across a wide range of industrial, renewable, and unconventional systems highlights its versatility, while its extensions to economic

and environmental dimensions demonstrate its broad relevance. The following sections of this work will provide a detailed account of the methodological framework of AEA, beginning with a closer examination of the limitations of conventional exergy analysis, and then elaborating on the theoretical foundations, decomposition strategies, and hybrid cycle approaches employed in advanced applications.

Limitations of Conventional Exergy Analysis

Conventional exergy analysis (CEA) has long been recognized as a significant step beyond traditional energy balances, as it incorporates the second law of thermodynamics and evaluates not only the quantity but also the quality of energy flows. It quantifies the irreversibilities within a system and indicates where thermodynamic performance is being compromised. Despite these advantages, however, CEA presents several important limitations that restrict its usefulness as a decision-support tool in engineering practice. These limitations become particularly critical when dealing with complex energy systems such as combined heat and power (CHP) units, gas turbine plants, or novel cycles integrating renewable and cryogenic sources.

Aggregated representation of irreversibilities

One of the primary shortcomings of CEA is that it provides only the total magnitude of exergy destruction in each system component. While this information highlights the most inefficient components, it does not clarify the nature of these inefficiencies. For instance, in a simple Brayton cycle, CEA may show that the combustion chamber exhibits the largest share of exergy destruction. Yet this result alone does not explain whether these losses are fundamentally unavoidable due to entropy generation inherent in combustion or whether they can be significantly reduced through better design or operational improvements. Thus, the aggregated representation of irreversibilities prevents engineers from identifying realistic improvement potentials (Kelly, Tsatsaronis, & Morosuk, 2009).

Lack of distinction between avoidable and unavoidable losses

CEA does not distinguish between avoidable irreversibilities, which can be reduced through engineering actions, and unavoidable irreversibilities, which are constrained by thermodynamics or the current state of technology. This lack of distinction often leads to misleading conclusions. For example, when analyzing a heat exchanger, conventional exergy analysis may report a certain level of exergy destruction. However, part of this destruction is unavoidable due to the finite temperature difference required for heat transfer, while another part could be avoided with better heat exchanger design or operating conditions. Without separating these two, CEA risks overstating or understating the true improvement potential of the component (Morosuk & Tsatsaronis, 2009).

Inability to differentiate endogenous and exogenous contributions

A further limitation lies in the inability of CEA to account for interactions between components. Exergy destruction in a given component is not always the result of its own inefficiencies; rather, it can also be influenced by upstream or downstream components. For instance, a turbine may appear highly irreversible under conventional analysis. Yet a portion of this irreversibility may be caused by non-ideal performance of the upstream compressor, which alters the inlet conditions to the turbine. Since CEA attributes all irreversibilities to the turbine itself, it fails to capture such exogenous effects, leading to inaccurate or incomplete diagnostics (Yousefizadeh Dibazar, Salehi, & Davarpanah, 2020).

Limited decision-making value in complex systems

Because of the above limitations, the practical decision-making value of CEA is restricted. In real-world engineering practice, decision-makers require precise answers to questions such as:

- Which losses should be prioritized for improvement?
- Which losses are technologically unavoidable and therefore not worth further investment?
- Are the inefficiencies caused by the component itself, or are they imposed by interactions with other parts of the system?

CEA cannot provide definitive answers to these questions. As a result, it may misdirect investment and design efforts. For example, in a combined cycle power plant, CEA may suggest focusing on the gas turbine due to its high exergy destruction. However, without distinguishing avoidable from unavoidable losses and endogenous from exogenous contributions, such an approach could lead to costly design modifications with limited actual benefit (Kelly et al., 2009).

Illustrative examples from literature

Numerous studies have highlighted these limitations. Petrakopoulou et al. (2012) demonstrated that in a combined cycle power plant, conventional exergy analysis identified the heat recovery steam generator (HRSG) as one of the dominant sources of inefficiency. However, when advanced exergy analysis was applied, it was revealed that a large fraction of the HRSG's losses were unavoidable, thereby shifting the focus of improvement efforts to other components such as the turbine and condenser. Similarly, Kelly et al. (2009) showed that in gas turbine systems, CEA often overstated the contribution of certain components (e.g., combustion chamber) to total exergy destruction, while AEA clarified that much of this destruction was unavoidable and endogenous, leaving only a smaller fraction as truly avoidable.

Another example is provided by Yousefizadeh Dibazar et al. (2020), who analyzed three different organic Rankine cycles (ORCs). Conventional analysis indicated the expander as the most critical component. However, advanced analysis showed that a significant part of the expander's irreversibilities originated from exogenous interactions with the evaporator, highlighting the need for system-level improvements rather than component-level redesign.

Summary of limitations

In summary, the main limitations of conventional exergy analysis can be outlined as follows:

1. It provides only aggregated values of irreversibilities without explaining their causes.
2. It does not separate avoidable from unavoidable losses, making it impossible to quantify true improvement potentials.
3. It cannot differentiate between endogenous inefficiencies and exogenous interactions, limiting its diagnostic accuracy.
4. It offers limited decision-making support in the design and optimization of complex energy systems.

For these reasons, while CEA remains a valuable preliminary tool, it is insufficient for guiding detailed design improvements or strategic decisions. This recognition paved the way for the development of Advanced Exergy Analysis (AEA), which directly addresses these shortcomings by introducing a refined framework capable of decomposing exergy destruction into more meaningful categories. The theoretical basis of this framework is presented in the following section.

Conceptual Framework of Advanced Exergy Analysis

Advanced Exergy Analysis (AEA) goes beyond conventional exergy analysis by not only measuring the magnitude of irreversibilities but also clarifying why and where they occur and to what extent they can be reduced. To achieve this, AEA employs a two-dimensional classification:

- Avoidable and Unavoidable
- Endogenous and Exogenous

The combination of these two dimensions results in a fourfold categorization that has become the conceptual backbone of modern exergy research.

Avoidable and unavoidable destruction

This dimension addresses the most practical question for engineers: *“How much of this loss can actually be reduced?”*

- Avoidable destruction refers to the portion of losses that can be reduced by technological improvements, better component design, or optimized operation strategies. For instance, pressure losses in a heat exchanger due to outdated design can be minimized with compact modern geometries.
- Unavoidable destruction represents irreversibilities that remain even under the best available technology and are fundamentally constrained by thermodynamics. An example is the minimum entropy generation that inevitably occurs in compression processes. This classification was systematically introduced by Tsatsaronis (1999), providing a foundation for later AEA studies.

Endogenous and exogenous destruction

The second dimension deals with the origin of losses:

- Endogenous destruction originates within the component itself, such as aerodynamic or frictional losses in turbine blades.
- Exogenous destruction, on the other hand, arises due to the influence of other system components. For example, a compressor receiving non-ideal inlet conditions from an upstream heat exchanger suffers exogenous penalties.

This classification highlights the importance of system integration and was further clarified by Vučković et al. (2012) in their analyses of industrial plants.

Fourfold classification

By combining both dimensions, AEA provides a comprehensive four-part framework:

1. Avoidable-Endogenous (AV-EN): Internal inefficiencies that can be reduced by redesign or improved operation.
2. Avoidable-Exogenous (AV-EX): Losses induced by other components but still reducible, often by better system integration.
3. Unavoidable-Endogenous (UN-EN): Intrinsic irreversibilities of a component that cannot be further reduced with current technology.
4. Unavoidable-Exogenous (UN-EX): External inefficiencies imposed by other subsystems, persisting even if the component itself operates ideally.

Studies such as Petrakopoulou et al. (2012) have shown the relevance of this categorization in real applications, illustrating its diagnostic and optimization potential.

Practical value of the conceptual framework

The importance of this framework lies in its guidance for engineering decisions. When the dominant share of losses falls into the avoidable-endogenous category, redesign of the component is a rational priority. If avoidable-exogenous losses dominate, then system-level integration and coordination strategies should be emphasized. Conversely, high

unavoidable fractions indicate that significant improvements would require technological breakthroughs rather than incremental modifications.

In this sense, AEA becomes more than an analytical tool it acts as a strategic compass for engineers and researchers, pointing not only to where inefficiencies occur but also to which losses can realistically be reduced and how system performance can be improved in practice (Alibaba et al., 2020).

Theoretical Foundations of Advanced Exergy Analysis

Theoretical foundations of advanced exergy analysis

The theoretical basis of Advanced Exergy Analysis (AEA) lies in the second law of thermodynamics and the concept of irreversibility. Conventional exergy balances provide information about the total exergy destruction in a component or system, but they do not explain whether these losses are reducible, to what extent they originate from the component itself, or how much is induced by interactions with other system elements. AEA addresses these shortcomings by decomposing total exergy destruction into two dimensions: avoidable vs. unavoidable and endogenous vs. exogenous. The combination of these two dimensions leads to four distinct categories: avoidable–endogenous (AV-EN), avoidable–exogenous (AV-EX), unavoidable–endogenous (UN-EN), and unavoidable–exogenous (UN-EX).

Over the years, several methodological approaches have been proposed in the literature to perform this decomposition. The most common ones are the engineering approach, the thermodynamic approach, and the hybrid cycle approach. Each differs in terms of accuracy, computational effort, and the type of information it can provide.

Engineering approach

The engineering approach represents the simplest and most approximate method. In this framework, the endogenous destruction of a component is estimated based on assumed values, such as typical isentropic efficiencies or design catalog data. For example, if a compressor is considered to have a nominal efficiency of 85%, the irreversibilities corresponding to this efficiency are assigned as endogenous. The exogenous destruction is then calculated as the difference between the real destruction and the assumed endogenous part (Morosuk & Tsatsaronis, 2009):

$$\dot{Ex}_{D,k}^{EX} = \dot{Ex}_{D,k} - \dot{Ex}_{D,k}^{EN} \quad (1)$$

This method does not simulate interactions explicitly and thus provides only rough approximations. While it requires minimal computational effort and is useful for preliminary assessments or educational purposes, it lacks accuracy and may be misleading

for highly integrated systems (Kelly et al., 2009; Morosuk & Tsatsaronis, 2009).

Thermodynamic approach

The thermodynamic approach provides a more rigorous distinction between endogenous and exogenous destruction. The procedure is as follows:

1. The real system is simulated to obtain the total exergy destruction for each component: $\dot{Ex}_{D,k}$
2. The component under study is kept at its real performance, while all other components are assumed to operate under ideal reversible conditions. The resulting destruction is the endogenous part: $\dot{Ex}_{D,k}^{EN}$
3. The exogenous destruction is obtained by subtraction:

$$\dot{Ex}_{D,k}^{EX} = \dot{Ex}_{D,k} - \dot{Ex}_{D,k}^{EN} \quad (2)$$

This approach improves the understanding of interactions among system components and provides useful information for improving an exergy conversion system. However, as highlighted by Kelly et al. (2009), this method only splits exergy destruction into endogenous and exogenous parts, and information about avoidable and unavoidable fractions must be obtained separately through additional analysis.

Hybrid cycle approach

The hybrid cycle approach builds upon the thermodynamic approach and is now considered the most comprehensive and reliable method. It retains the endogenous–exogenous decomposition but extends the framework by incorporating the avoidable/unavoidable distinction through simulations under unavoidable operating conditions (Liu, Liu, Cao, Luo, & Yang, 2020; Yousefizadeh Dibazar et al., 2020).

The stepwise procedure is outlined below for a component k:

Step 0 – Real cycle

The system is solved under actual operating conditions: $\dot{Ex}_{D,k}$

Step 1 – Endogenous destruction (EN)

Component k operates at its real performance, while all other components are ideal (reversible). The resulting destruction is the endogenous part: $\dot{Ex}_{D,k}^{EN}$

Step 2 – Exogenous destruction (EX)

The exogenous part $\dot{Ex}_{D,k}^{EX}$ is found using the following equation after the endogenous part is found.

$$\dot{Ex}_{D,k}^{EX} = \dot{Ex}_{D,k} - \dot{Ex}_{D,k}^{EN} \quad (3)$$

Step 3 – Unavoidable destruction (UN)

Unavoidable operating conditions are defined based on technological limits (e.g., maximum achievable efficiencies, minimum temperature differences (Petrakopoulou, Tsatsaronis, Morosuk, & Carassai, 2012; Tsatsaronis, 1999): $\dot{Ex}_{D,k}^{UN}$

Step 4 – Avoidable destruction (AV)

The avoidable part $\dot{Ex}_{D,k}^{AV}$ is found using the following equation after the unavoidable part is found.

$$\dot{Ex}_{D,k}^{AV} = \dot{Ex}_{D,k} - \dot{Ex}_{D,k}^{UN} \quad (4)$$

Step 5 – Partitioning of UN into UN-EN and UN-EX

Component k operates at its unavoidable performance, while all other components are ideal (reversible). The resulting destruction is the endogenous part $\dot{Ex}_{D,k}^{UN,EN}$ (Hançer Güleriyüz & Özen, 2022; Morosuk & Tsatsaronis, 2009):

The exogenous part $\dot{Ex}_{D,k}^{UN,EX}$ is found using the following equation after the endogenous part is found.

$$\dot{Ex}_{D,k}^{UN,EX} = \dot{Ex}_{D,k}^{UN} - \dot{Ex}_{D,k}^{UN,EN} \quad (5)$$

Step 6 – Partitioning of AV into AV-EN and AV-EX (Morosuk & Tsatsaronis, 2009; Özen, Hançer Güleriyüz, & Acılar, 2024)

$$\dot{Ex}_{D,k}^{AV,EN} = \dot{Ex}_{D,k}^{AV} - \dot{Ex}_{D,k}^{UN,EN} \quad (6)$$

$$\dot{Ex}_{D,k}^{AV,EX} = \dot{Ex}_{D,k}^{AV} - \dot{Ex}_{D,k}^{AV,EN} \text{ or } \dot{Ex}_{D,k}^{UN,EX} = \dot{Ex}_{D,k}^{AV,EX} - \dot{Ex}_{D,k}^{UN,EN} \quad (7)$$

Finally, the complete decomposition is obtained:

$$\dot{Ex}_{D,k} = \dot{Ex}_{D,k}^{AV,EN} + \dot{Ex}_{D,k}^{AV,EX} + \dot{Ex}_{D,k}^{UN,EN} + \dot{Ex}_{D,k}^{UN,EX} \quad (8)$$

This approach allows engineers to distinguish not only the origin of irreversibilities (EN/EX) but also their reducibility (AV/UN). As a result, it provides precise guidance on whether design improvements should target the component itself or system-level

integration.

Comparative Summary

In summary, the engineering approach estimates endogenous destruction based on assumptions or typical efficiencies and assigns the remainder as exogenous, without any avoidable/unavoidable split. The thermodynamic approach rigorously calculates endogenous destruction by assuming the component real and all others ideal, and exogenous as the difference, but it also stops short of avoidable/unavoidable classification. The hybrid cycle approach combines both dimensions, producing a fourfold subdivision (AV-EN, AV-EX, UN-EN, UN-EX) that is now the standard in advanced exergy studies (Liu et al., 2020; Petrakopoulou, Tsatsaronis, Morosuk, & Carassai, 2012; Yousefizadeh Dibazar et al., 2020).

The development of these methods can be traced through several key contributions. The idea of distinguishing avoidable and unavoidable exergy destruction was first systematically presented by Tsatsaronis (1999), who emphasized the importance of separating losses imposed by technological limits from those that could be reduced by improved design or operation. The methodological treatment of endogenous and exogenous exergy destruction was provided in detail by Kelly et al. (2009), who compared different ways of calculating endogenous destruction and explicitly described the principle of “keeping the studied component real while assuming the others ideal.”

Later studies integrated these concepts within a single framework, giving rise to the hybrid cycle method. A landmark application was presented by Petrakopoulou et al. (2012), who analyzed a combined cycle power plant and demonstrated how both AV/UN and EN/EX distinctions could be performed within one consistent procedure. Their work also illustrated how exogenous destruction could be traced back to specific upstream or downstream components, adding diagnostic depth. Since then, the hybrid cycle method has been widely adopted, with applications in systems such as organic Rankine cycles, refrigeration, and LNG-based plants (Özen & Koçak, 2022). Recent works by Yousefizadeh Dibazar et al. (2020) and Liu et al. (2020) confirmed its practicality and reliability in modern energy system evaluations.

From a broader perspective, Morosuk and Tsatsaronis (2019) provided a comprehensive review of advanced exergy-based methods, highlighting how exergy, exergoeconomic, and exergoenvironmental extensions each address different questions. Their synthesis shows that AEA has evolved into a multidimensional framework that supports not only thermodynamic optimization but also economic and environmental decision-making. Taken together, the literature demonstrates that today’s advanced exergy analysis is the result of integrating the AV/UN and EN/EX concepts into a unified methodology, which is why it is now regarded as one of the most powerful diagnostic tools for energy system analysis.

From a broader perspective, Morosuk and Tsatsaronis (2019) provided a comprehensive overview of advanced exergy-based methods, including exergoeconomic and exergoenvironmental extensions, clarifying how each tool addresses different questions. Altogether, the literature shows that today's AEA framework is

Applications of AEA in Energy Systems

Industrial processes

AEA has found impactful applications in industrial settings, where seemingly small gains in efficiency can lead to major economic and environmental returns. For instance, in natural gas liquid (NGL) recovery plants, Jovijari et al. (2022b) conducted a detailed AEA and found that while conventional exergy analysis pointed to compressors and heat exchangers as the primary loss contributors, the advanced analysis revealed that a significant portion of the heat exchangers' losses were unavoidable helping prioritize where actual improvements should be targeted.

In ORC systems, AEA has enabled decomposition of exergy destruction into component-origin and interaction-origin categories. A recent “thermodynamic cycle” study by Wang et al. (2021) meticulously modeled the expander and heat exchanger, showing that exergy losses were not only within the expander but also significantly influenced by upstream components like the evaporator

Unconventional sectors

AEA's adaptability has also been demonstrated in non-traditional fields. For example, in a milk processing facility, both conventional and advanced exergy analyses were conducted. While the conventional analysis offered a broad overview of losses, AEA provided a detailed partitioning into avoidable and interaction-driven inefficiencies, revealing opportunities for targeted improvements (Bühler et al., 2018).

Renewable and hybrid systems

In renewable energy systems such as combined heat and power (CHP) units and solar-assisted cycles, AEA has clarified hidden inefficiencies and synergies, thus guiding the integration of renewable resources into complex systems (Jani, Kachhwaha, Nagababu, Das, & Ehyaei, 2022; Özen, 2024; Özen & Koçak, 2022).

Integration of Economic and Environmental Dimensions

Over time, AEA has expanded to include economic and environmental dimensions, offering a more comprehensive framework for evaluating and improving energy systems. These extensions allow engineers not only to understand thermodynamic inefficiencies but also to assess their economic and ecological implications.

- **Advanced exergoeconomic analysis (AECA):** This approach evaluates the

costs associated with exergy destruction, providing guidance for cost-effective system improvements. For instance, Güler (2023) applied AECA to a dual-binary geothermal power plant and demonstrated how identifying cost-intensive losses helps reduce both operating costs and CO₂ emission-related expenses.

- **Advanced exergoenvironmental analysis (AEEA):** AEEA connects irreversibilities to environmental impacts, enabling design strategies that prioritize sustainability. Benavides Gamero et al. (2023) performed AEEA on an ORC waste-heat recovery system, showing that the majority of environmental impacts were endogenous and largely avoidable.
- **Combined AECA and AEEA:** Recent studies integrate both perspectives within a single methodological framework. A notable example is the work of Özen (2024), who applied advanced exergoeconomic and exergoenvironmental analyses to a geothermal-based power system using the Modified Productive Structure Analysis (MOPSA) method. This study highlighted how combining the two approaches provides a multidimensional understanding of system performance, revealing improvement opportunities that remain hidden when only one dimension is considered.

Together, these contributions show that AEA has become not only a diagnostic tool but also a comprehensive sustainability framework, integrating thermodynamic efficiency with economic and environmental decision-making.

Educational Contributions of AEA

Including the advanced approaches of AEA in engineering education helps students develop both critical thinking and a systems-oriented perspective. In this way, they not only gain theoretical knowledge but also learn to better understand the complexities and interdependencies of real-world energy systems, preparing them to deal with these challenges in practice.

Conclusion and Future Outlook

Advanced Exergy Analysis has emerged as a powerful approach that connects the principles of thermodynamics with real engineering practice. By separating avoidable, unavoidable, endogenous, and exogenous irreversibilities, it offers a unique diagnostic capability that supports both broad system-level improvements and targeted component optimizations.

Its wide use in industrial, renewable, and even unconventional applications, together with its extensions into economic and environmental fields, demonstrates its flexibility and relevance. At the same time, its role in education helps prepare future engineers and scientists to think critically about sustainability and efficiency.

Looking ahead, AEA is expected to become a central framework for next-generation energy systems. As the global energy transition demands higher efficiency, lower

emissions, and sustainable design, AEA provides the precision and multidimensional insight needed to meet these challenges.

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