# APPLICATION OF THERMOECONOMICS TO THE DESIGN AND SYNTHESIS OF ENERGY PLANTS

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## Contents



## Summary

Thermoeconomics, as an exergy-aided cost-reduction method, provides important information for the design of cost-effective energy-conversion plants. The exergy costing principle is used to assign monetary values to all material and energy streams within a plant as well as to the exergy destruction within each plant component. The design evaluation and optimization is based on the trade-offs between exergy destruction (exergetic efficiency) and investment cost for the most important plant components. The design of an energy-conversion plant may be improved using either an exergoeconomic iterative optimization technique or approaches of mathematical optimization. Thermoeconomics provides the designer with information about the cost formation process, the interactions among thermodynamics and economics and the interactions among plant components. This information is very valuable for improving the design of energy-conversion plants.

## 1. Introduction

Engineers involved in the design of energy-conversion plants want, after they have developed a first workable design, and in order to improve this design, to know the answers to the following questions:

1. Where do thermodynamic inefficiencies in the system occur, how high are they, and what causes them?

2. What measures or alternative designs would improve the efficiency of the overall plant?
3. How high is the required total investment and the purchased equipment costs of the most important plant components?
4. How much do the thermodynamic inefficiencies cost the plant operator?
5. What measures would improve the cost effectiveness of the overall plant?.

The answer to the first two questions is provided with the aid of an exergy analysis (see *Exergy and Thermodynamic Analysis*). An economic analysis answers the third question. The last two questions can be answered with the aid of a thermoeconomic analysis. This analysis is called here exergoeconomics, which is a more precise characterization of every exergy-aided cost-reduction approach.

Exergoeconomics applied to design optimization represents a unique combination of exergy analysis and cost analysis, to provide the designer of an energy-conversion plant with information not available through conventional energy, exergy, or cost analyses, but crucial to the design of a cost-effective plant. Design optimization of an energy-conversion system means the selection of the structure and the design parameters (the decision variables) of the system to minimize the total cost of the system products (over the entire lifetime of the system) under boundary conditions associated with available materials, financial resources, environmental protection and government regulation as well as with the safety, reliability, operability, maintainability, and availability of the system. In a truly optimized system, the magnitude of every significant thermodynamic inefficiency (exergy destruction and exergy loss) is justified by considerations related to investment and operating costs or is imposed by at least one of the above boundary conditions.

A thermodynamic optimization, which aims at minimizing the thermodynamic inefficiencies, represents a subcase of the general case of design optimization. An appropriate formulation of the optimization problem is always one of the most important and sometimes the most difficult task in an optimization study.

Various names have already been given or could be given to various exergoeconomic approaches proposed in the past. These names include the following:

- Exergy Economics Approach (EEA)
- First Exergoeconomic Approach (FEA)
- Thermoeconomic Functional Analysis (TFA)
- Exergetic Cost Theory (ECT)
- Engineering Functional Analysis (EFA)
- Last-In-First-Out Approach (LIFOA)
- Structural Analysis Approach (SAA)
- SPECO Method (SPECOM)

The main differences among the approaches refer to the definition of exergetic efficiencies, the development of auxiliary costing equations and the productive structure.

## 2. Principles of Exergoeconomics Applied to Design Optimization

Exergoeconomics applied to the design and synthesis of energy-conversion plants is based on two important principles that represent the fundamental connections between thermodynamics and economics. The first principle is common to all exergoeconomic approaches and applications, whereas the second principle refers only to applications in which new investment expenditures are needed. These principles are briefly discussed in the following.

### 2.1. Exergy Costing

This principle states that exergy is the only rational basis for assigning monetary values to the interactions an energy system experiences with its surroundings and to the thermodynamic inefficiencies within the system. Mass, energy or entropy should not be used for assigning the above mentioned monetary values because their exclusive use results in misleading conclusions.

According to the exergy-costing principle, the cost stream ($\dot{C}_j$) associated with an exergy stream ($\dot{E}_j$) is given by

$$\dot{C}_j = c_j \; \dot{E}_j \qquad (1)$$

where $c_j$ represents the average cost associated with providing each exergy unit of the stream $\dot{E}_j$ in the plant being considered. Equation (1) is applied to the exergy associated with streams of matter entering or exiting a system as well as to the exergy transfers associated with the transfer of work and heat. For the cost ($C_k$) associated with the exergy ($E_k$) contained within the *k*-th component of a system we write

$$C_k = c_k \; E_k \qquad (2)$$

Here $c_k$ is the average cost per unit of exergy supplied to the *k*-th component.

Exergy costing does not necessarily imply that costs associated with streams of matter are related only to the exergy rate of each respective stream. Nonexergy related costs can also affect the total cost rate associated with material streams. Examples include the cost of (a) treated water leaving a water treatment unit, (b) oxygen and nitrogen produced in an air separation unit, (c) limestone supplied to a fluidized-bed reactor, (d) iron used in a metallurgical process, and (e) an inorganic chemical fed into chemical reactors. Therefore, when significant nonexergy-related costs occur in a system, the total cost rate associated with the material stream *j* (denoted by $\dot{C}_j^{\mathrm{TOT}}$) is given by

$$\dot{C}_j^{\mathrm{TOT}} = \dot{C}_j + \dot{C}_j^{\mathrm{NE}} \qquad (3)$$

Here $\dot{C}_j$ is the cost rate directly related to the exergy of stream *j* (see Eq. (1)) and $\dot{C}_j^{\mathrm{NE}}$ is the cost rate due to nonexergetic effects. The term $\dot{C}_j^{\mathrm{NE}}$ represents a convenient way for charging nonexergy-related costs from one component to other system components that should bear such costs.

## 2.2. Exergy Destruction Reduces Investment Cost

The exergy destruction represents in thermodynamics a major inefficiency and a quantity to be minimized when the overall plant efficiency should be maximized. In the design of a new energy-conversion plant, however, exergy destruction within a component represents not only a thermodynamic inefficiency but also an opportunity to reduce the investment cost associated with the component being considered and, thus, with the overall plant.

Figure 1 refers to a component (subscript *k*) of the overall plant and shows that the cost rate $\dot{Z}_k^{\mathrm{CI}}$ associated with capital investment (superscript CI) decreases with increasing exergy destruction rate ($\dot{E}_{\mathrm{D},k}$) within the same component. Instead of a single curve, a shaded area is presented to denote that the investment cost could vary within a given range for each given value of the exergy destruction. The effect of component size is taken into consideration in Figure 1 by relating both $\dot{Z}_k^{\mathrm{CI}}$ and ($\dot{E}_{\mathrm{D},k}$) to the exergy rate of the product generated in this component ($\dot{E}_{\mathrm{P},k}$).

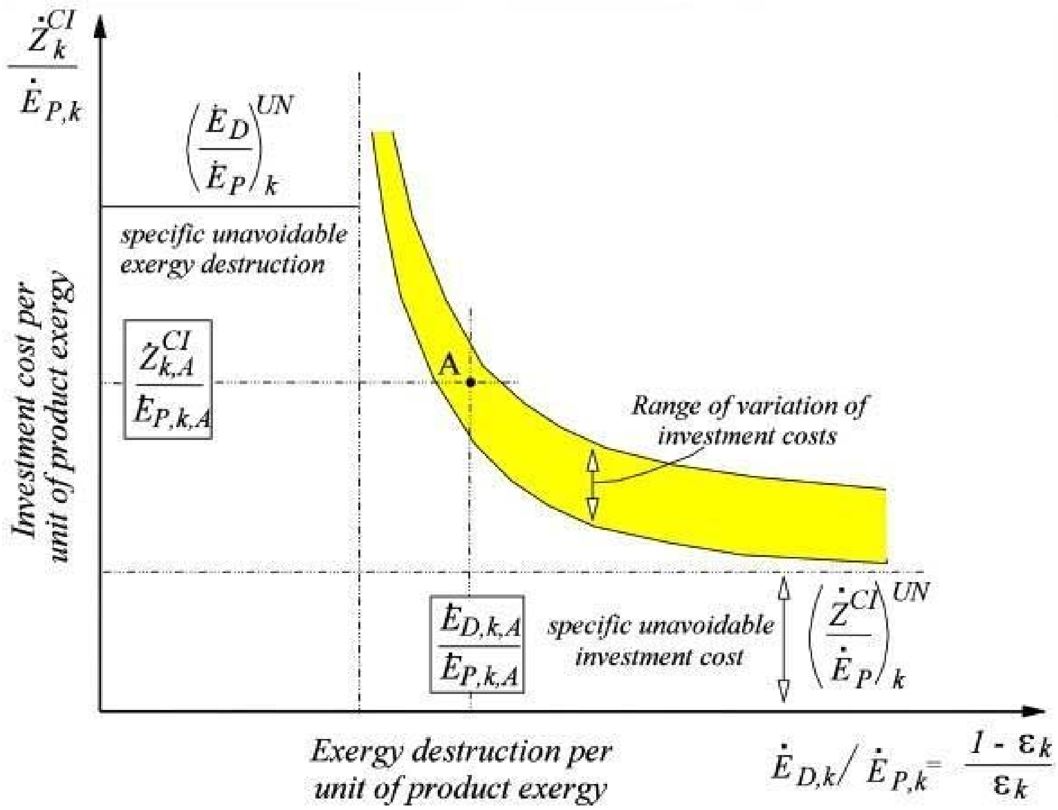

Figure 1: Expected relationship between investment cost and exergy destruction (or exergetic efficiency) for the *k*-th component of an energy conversion system.

The vast majority of components in energy-conversion plants exhibits qualitatively the behavior between $\dot{Z}_k^{\mathrm{CI}}$ and $\dot{E}_{\mathrm{D},k}$ shown in Figure 1. Should the investment cost increase or remain constant with increasing exergy destruction, then the component being considered can be excluded from optimization considerations because in these cases we would always select for this component the design point that has the lowest investment cost and, at the same time, the lowest thermodynamic inefficiencies (i.e. the highest exergetic efficiency).

The curves and the shaded area shown in Figure 1 are usually not known. However, even then we can estimate the two asymptotic lines that determine the specific unavoidable exergy destruction $\left(\frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{P},k}}\right)^{\mathrm{UN}}$ and the specific unavoidable investment cost $\left(\frac{\dot{Z}^{\mathrm{CI}}}{\dot{E}_{\mathrm{P}}}\right)_k^{\mathrm{UN}}$.

All design improvement efforts should focus only on the avoidable parts of exergy destruction and investment costs. These parts are calculated by subtracting the unavoidable value from the total value of the respective variable.

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**Biographical Sketch**

**Professor George Tsatsaronis** is the Bewag Professor of Energy Engineering and Protection of the Environment and the past Director of the Institute for Energy Engineering at the Technical University of Berlin, Germany. He studied mechanical engineering at the National Technical University of Athens, Greece, receiving the Diploma in 1972. He continued at the Technical University of Aachen, Germany, where he received a Masters Degree in business administration in 1976, a Ph.D. in combustion from the Department of Mechanical Engineering in 1977, and a Dr. Habilitatus Degree in Thermoeconomics in 1985.

In the last thirty years he has been responsible for numerous research projects and programs related to combustion, thermoeconomics (exergoeconomics), development, simulation and analysis of various energy-conversion processes (coal gasification, electricity generation, hydrogen production, cogeneration, solar energy-conversion, oil production in refineries and also from oil shales, carbon black production, refrigeration processes, etc) as well as optimization of the design and operation of energy systems with emphasis on power plants and cogeneration systems.

He is a Fellow of the American Society of Mechanical Engineers (ASME) and a member of the Greek Society of Engineers. He is a Past Chairman of the Executive Committee of the International Centre for Applied Thermodynamics.

In 1977 he received for his Ph.D. Thesis the Borchers Award from the Technical University of Aachen, Germany and in 1994 and 1999 the E.F. Obert Best Paper Award from ASME. In 1997 he became a Honorary Professor at the North China Electric Power University and in 1998 he received from ASME the James Harry Potter Gold Medal for his work in exergoeconomics. In 2002 he became a guest professor at the Zhejiang University of Technology, China, and in 2004 he received a Doctoris Honoris Causa from the Polytechnic University of Bucharest, Rumania.

He currently serves as an associate editor of *Energy - The International Journal* (since 1986), *Energy Conversion and Management* (since 1995), and *International Journal of Energy, Technology and Policy* (since 2002). He is a honorary editor of the *International Journal of Thermodynamics* (since 2003). He co-authored with A. Bejan and M. Moran the book *Thermal Design and Optimization* and published about 200 papers and scientific reports. He is the co-editor of 21 conference proceedings publications.