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A Thermorisk framework for the analysis of energy systems by combining risk and exergy analysis

G. Cassetti [a,*], E. Colombo [a], E. Zio [a,b]

[a] Department of Energy, Politecnico di Milano, Milan, Italy
[b] Chair System Science and the Energy Challenge, Fondation Electricite' de France (EDF), Centrale Supélec, Université Paris-Saclay, Chatenay-Malabry, France

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ABSTRACT

The impact of energy production, transformation and use on the environmental resources encourage to understand the mechanisms of resource degradation and to develop proper analyses to reduce the impact of the energy systems on the environment. At the technical level, most attempts for reducing the environmental impact of energy systems focus on the improvement of process efficiency. One way toward an integrated approach is that of adopting *exergy* analysis for assessing efficiency and test improving design and operation solutions. The paper presents an exergy based analysis for improving efficiency and safety of energy systems, named Thermorisk analysis.

The purpose of the Thermorisk analysis is to supply information to control, and eventually reduce, the risk of the systems (i.e. risk of accidents) by acting on the thermodynamic parameters and safety characteristics in the same frame. The proper combination of exergy and risk analysis allows monitoring the effects of efficiency improvement on the safety of the systems analyzed.

A case study is presented, showing the potential of the analysis to identify the relation between the exergy efficiency and the risk of the system analyzed, and the contribution of inefficiencies on the safety of the process. Possible modifications in the process are indicated to improve the safety of the system.

1. Introduction

Many environmental concerns are caused by or related to energy production, transformation and use [1]. International laws and organizations allocate on the energy producer the costs of pollution prevention and control measures, to encourage the rational the use of existing environmental resources [2].

It becomes increasingly important, therefore, to understand the mechanisms of resource degradation, and to develop proper analyses to reduce the impact of energy systems on environment.

Various studies [1,3] demonstrate that the impact of energy resource consumption (i.e. cumulated raw material and energy) and the achievement of improved transformation efficiency are best addressed by considering the concept of exergy [4]. A number of methodologies of analysis based on this concept have, thus, been developed [5–10].

Exergy is defined as the useful energy, or the maximum work, obtainable from a process, and its analysis allows identifying and evaluating process irreversibility.

The concept of exergy is also crucial, and hence commonly used, in cost accountings related to economic analysis [11]. This is also demonstrated by the development of the discipline of Thermoeconomics [12].

The purpose of this paper is to define a framework of analysis able to identify the relation between exergy and the impact of an energy system on health and safety, i.e. risk of accidents. In industrial sector, accidents are related to the hazardous effects shown in Table 1 [13], and their relation with exergy has been proposed in several studies.

Indeed, the relation between exergy and a toxic gas concentration has been proposed in [14], in [15] a relation between exergy and the thermal radiation from a jet of combusted gas from a turbine is identified; finally, a relation between the thermodynamic availability and the energy of explosion has been proposed in [16].

The analysis presented is a proper combination of exergy and risk analyses, for improving efficiency and safety of energy systems by reducing risk, once the influence of irreversibility is identified via a thermodynamic analysis. We refer to this new analysis as Thermorisk analysis.

The purpose of the Thermorisk analysis is, therefore, to supply information to control, and eventually reduce, the risk of the

* Corresponding author.
E-mail address: gabriele.cassetti@polimi.it (G. Cassetti).

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Nomenclature

$\dot{C}_{j,k}$	cost rate of exergy stream $\dot{E}_{j,k}$ in (€/s)
$c_{j,k}$	average costs per unit of exergy in (€/J)
$\dot{C}_F$, $\dot{C}_P$	cost rates associated to fuel and product (€/s)
$\dot{Z}_k$	capital cost of component k (€/s)
$\dot{Z}_k^{CI}$	capital investments of component k (€/s)
$\dot{Z}_k^{OM}$	operation and maintenance expenses of component k (€/s)
Θ	hazardous event
F_Θ	factor representing the hazard consequence (fatalities)
p_Θ	probability of occurrence of Θ (1/y)
x	injury factor of Θ
$\dot{R}_\Theta$	risk associated to Θ (fatalities/year)
$\dot{R}_k$	risk associated to hazards not related exergy flows in the process (fatalities/year)
$\dot{R}_P$	risk associated to hazards related to Product $\dot{E}_P$ (fatalities/year)
$\dot{R}_F$	risk associated to hazards related Fuel $\dot{E}_F$ (fatalities/year)
r_P	risk for unit of Product (fatalities/year J)
r_F	risk for unit of Fuel (fatalities/year J)
$\dot{m}$	mass flow rate (kg/s)
T	temperature (K)
p	pressure (bar)
P	nominal power (kW)
η_I	nominal energy efficiency
Q	net heat
λ	failure rate
q_i	failure probability
p_{MCS}	minimum cut set probability
t_{exp}	exposure time (s)
I	irradiance (kW/m^2)

Table 1
Hazards in industrial sector and related physical effects.

Hazard	Physical effect
Fire	Thermal radiation I (W/m^2)
Explosion	Overpressure p_0 (Pa)
	Impulse J (Pa/s)
Toxic gas	Concentration C (ppm)
	Dose Ct (ppm s)

system by acting on its thermodynamic parameters and safety characteristics in the same frame.

Hence, the proper combination of the two analyses allows monitoring the effects of efficiency optimization on the safety (i.e. risk of accidents) of the energy systems.

The Thermorisk framework is based on the theoretical structure of the Thermoeconomic analysis [7,12], and it is properly extended and modified to incorporate risk analysis [13,17–20]. The idea of adopting the framework of Thermoeconomics as starting point for the new analysis comes from the possibility of allocating the risk contributions to the different production units and, therefore, describing the risk generation in processes. In this way, it is possible to answer to the questions: Which is the component that contributes the most in the risk generation inside the process? Is the risk related to a highly efficient component or to a lowly efficient one? In the latter case, could the risk decrease by increasing the efficiency of the component?

For this reason, in Sections 2 and 3 of this paper, the framework of Thermoeconomics is briefly introduced in order to identify the common elements with the analysis presented. In Section 4, the relation between risk and exergy is proposed and explained by means of a case study that presents a simplified application of the Thermorisk analysis. In Section 5, the conclusions of the work are given.

2. Thermoeconomics as a comprehensive framework

Scientific literature on Thermoeconomics is wide and complete. In [21], Thermoeconomics is defined as a technique that combines economic and thermodynamic analyses by applying the concept of cost to exergy, in order to provide the analyst with information not available through conventional energy analysis and economic evaluation. Another relevant definition is "exergy aided cost minimization" [12]. In general, it can be defined as a theory of useful energy saving [21]. Thermoeconomics is based on the concept that all real processes in a plant or energy system are nonreversible and some exergy is therefore destroyed, consuming resources and generating a cost or loss.

The amount of resources consumed is defined as *exergy cost*, while the entity of the economic cost required is called *thermoeconomic cost*. In literature, some authors [7,22] make a distinction and call Exergoeconomics the analysis of pure exergy costs, where exergy is the quantifier, and Thermoeconomics the analysis of the economic value of these costs, where money is the quantifier. Other authors [17] use the two terms as synonyms.

The concept of exergy cost is, therefore, the cornerstone of Thermoeconomic theory and Thermoeconomics relies on the concept that exergy is the rational basis for assigning monetary costs to the different interactions that a system experiences with its surroundings and to the inefficiencies within it. This principle is called *exergy costing* [12].

2.1. Thermoeconomic analysis

Every plant has a defined productive purpose, i.e. a certain good or service. The identification of the product of the plant and the resources consumed represents the *productive structure* of the plant. A productive structure can be defined also for each plant subsystem. The definition of the productive structure of a system represents a subjective procedure, and clear criteria need to be adopted. When the product and the resources consumed by a system are measured in terms of exergy, the terms *Product* (P) and *Fuel* (F) are generally used [12,21]. Thus, the Product represents the desired result produced by the system in terms of Watts, the Fuel represents the resources expended (still expressed in Watt) to generate them. Using F and P, the Thermoeconomic analysis for a process reads:

$$\dot{C}_{j,k} = c_{j,k}\dot{E}_{j,k} \quad \text{exergy costing principle} \tag{1}$$

$$\dot{E}_F = \dot{E}_P + \dot{E}_L + \dot{E}_D \quad \text{exergy balance of component } k \tag{2}$$

$$\dot{C}_{P,k} = \dot{C}_F + \dot{Z}_k \quad \text{cost balance of component } k \tag{3}$$

$$\dot{Z}_k = \dot{Z}_j^{CI} + \dot{Z}_j^{O\&M} \quad \text{cost function of component } k \tag{4}$$