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THE IMPACT OF EXERGY ANALYSIS IN THE SYMBIOSIS OF THE ENERGY USE

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Abstract

In this work the concept of Exergy Analysis is applied to the residential and industrial sector of Greece in order to show the potential role that exergy (second – law) analysis can play to energy sustainability. Comprehensive exergy analysis is particularly valuable for evaluating energy production technologies that are energy intensive and represent a key infrastructural component. Exergy analysis is used as an analysis method for Industrial Symbiosis. It is foung that the residential energy and exergy efficiency, in 2003, came up to 22.36% and 20.92% respectively whereas the industrial energy and exergy efficiency came up to 53.72% and 51.34% respectively.

Keywords: Exergy efficiency; Residential sector; Industrial sector; Industrial symbiosis

1. Introduction

Energy constitutes an essential ingredient for social development and economic growth. The concept of Industrial symbiosis during the decade of 1990 -2010 was given key role in future industrial systems [1]. The closed energy and material loops was believed to entail a promising way in which future industrial systems could be designed so that the environmental impact from industrial operations in theory could be close to zero.

Exergy analysis has two key advantages as analysis method for Industrial Symbiosis: it provides a systemic and rigorous framework and, due to the use of exergy for flow quantification, streams of different nature are measured in the same unit. What is more the linkages between energy and exergy, exergy and the environment, energy and sustainable development as well as energy policy making and exergy have been described in detail [2]. Furthermore, the exergy of an energy form or a substance can be considered as a measure of its usefulness or quality or potential to cause change [3]. An exergy analysis is usually aimed to determine the maximum performance of a system under study and/or identify the sites of exergy destruction. The identification of the parts of the systems where exergy destruction takes place can show the road towards potential improvements [4].

During the last decades various studies have been carried out on energy and exergy utilization for many countries, for instance, USA [5], Canada [6], Japan, Finland and Sweden [7], Italy [8], Turkey [9-12], the UK [13], Norway [14-15], China [16] as well as Saudi Arabia [17-19]. In order to conduct an energy and exergy analysis for the residential and industrial sector of Greece, energy end-use quantities for the aforementioned sectors and operational data for the major procedures were used. The residential and industrial sectors are driven mainly by fossil fuels as well as electricity. As far as the residential sector is concerned, it involves as principal devices, space heaters, water heaters and cooking appliances. The industrial sector has as main tasks work production and heating and includes mines, steam generation, pulp and paper mills, cement and iron mills, petroleum refining, smelting and refining as well as other non-energy uses.

The main objective of this work is to explore how complex energy systems such as the residential and industrial sector of a country could be optimized using as analysis method of the industrial symbiosis the exergy analysis.

2. Energy and exergy analysis

The exergy approach is used to represent in a coherent way both the quantity and the quality of the different forms of energy considered. The concept of exergy presents the major advantage of efficiency definitions which are compatible with all cases of conversion of energy resources into useful energy services (heat and electricity, heat-cold-electricity, refrigeration, heat pumps, etc) and for all domains of use of energy.

The expressions of energy (**n**) and exergy (**ψ**) efficiencies for the principal types of processes considered in the present study are based on the following definitions. Energy efficiency is defined as:

$$(\mathbf{n}) = work/energy\ input \quad \textbf{(1)}$$

whereas exergy efficiency is defined as:

$$(\boldsymbol{\psi}) = work/exergy\ input \quad \textbf{(2)}$$

it is obvious that,

$$\boldsymbol{\psi} = n/\gamma \quad \textbf{(3)}$$

the exergy efficiency is equal to the conventional energy efficiency divided by the exergy factor. The weighted mean overall exergy efficiency is calculated as:

$$\boldsymbol{\psi}_{\mathbf{overall}} = \sum_{i,k} (n_i / \gamma_k) \times Fr_{ik} \quad \textbf{(4)}$$

where $\boldsymbol{\psi}_{\mathbf{overall}}$ expresses the weighted mean overall exergy efficiency, n_i stands for the energy efficiency of the *i*th sectoral mode under study (residential, industrial, tertiary, agricultural, transportation), γ_k is the exergy factor of the *k*th energy form and Fr_{ik} denotes the exergy fraction of the *k*th energy form used by the ith sectoral mode under study.

The exergy content for mechanical and electrical energy is equal to the energy content. The energy efficiencies stand for the energy of the useful streams leaving the process divided by the energy of all entering streams. The exergy efficiencies stand for the ratio of the exergy contained in the products of a process to the exergy in all input streams. It is noticed (Table 1) that the exergy efficiencies are lower than the energy efficiencies; this is attributed to the destruction of the input exergy due to irreversibilities. Thus, the exergy efficiency gives a finer understanding of performance than the energy efficiency.

Process	**Energy efficiency (%)**	**Exergy efficiency (%)**
Petroleum refining	~ 90	10
Residential heater (fuel)	60	9
Domestic water heater (fuel)	40	2-3
Coal gasification (high heat)	55	46
Steam-heated reboiler	~100	40
Blast furnace	76	46
High-pressure steam boiler	90	50

Table 1: Energy and exergy efficiencies for selected processes [3;20].

4. Results and discussion

The methodology discussed in the previous section is applied for the energy and exergy use in the residential and industrial sector of Greece. Mean energy and exergy efficiencies for each sector are calculated by multiplying the energy used in each end use by the corresponding efficiency for that end use.

The breakdown of energy in residential sector is separated into three main components, namely electrical, fossil fuel (diesel oil and natural gas) and renewable energy (biomass and solar energy). Electrical appliances consume energy from an electrical source, while non-electrical appliances use energy from fossil fuel sources.

To assess the technical performance of residential appliances, the exergy efficiency of an appliance is taken as a percentage of the work output over the exergy input. Then the exergy efficiency for the whole sector is the weighted average of the exergy efficiencies of all the appliances. Due to lack of data, ratings of the appliances used in the residential sector are based on the findings of Nakićenović et al, [21].

The overall exergy and energy efficiency for the Greek residential sector over the period 1990-2002 are presented in Fig. 1. It can be seen that exergy efficiency was lower than its corresponding energy efficiency while both energy and exergy efficiencies were reduced during the past decade. By comparison, exergy efficiencies for the residential sector are reported to be about 12% for Norway in 1995 [14], 9% for Saudi Arabia in 1990-2001 [17], 22% for Turkey in 2004-2005 [12], 23% for Brazil in 2001, 13% for Sweden in 1994, 15% for Canada in 1986, 3% for Japan in 1985 [22] and 10 % for China in 1983 [23].

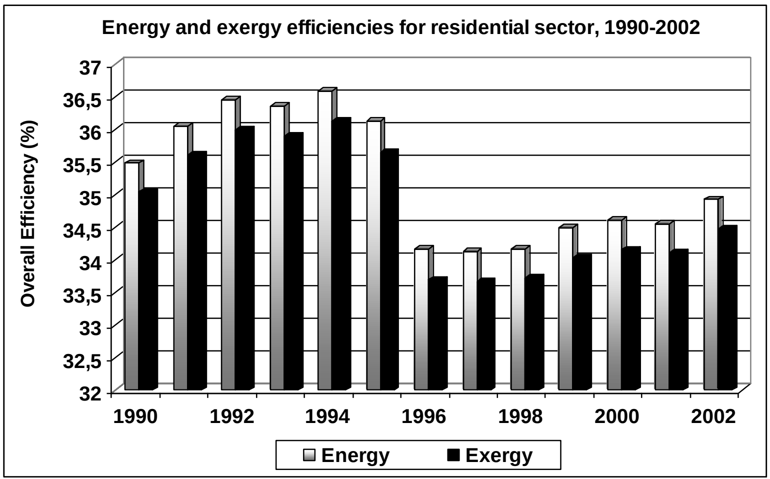

Figure 1: Overall mean energy and exergy efficiencies for the residential sector in Greece over the period 1990-2002.

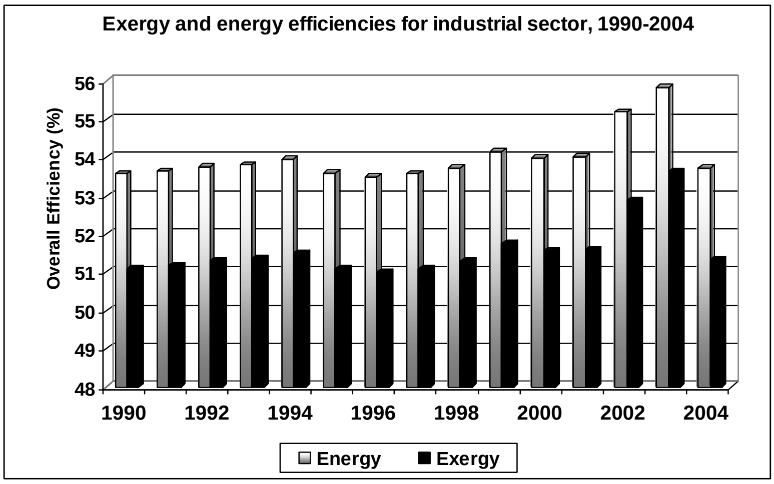

Figure 2: Overall mean energy and exergy efficiencies for the industrial sector in Greece over the period 1990-2002.

As far as the industrial sector is concerned, the breakdown of energy is also separated into three main components, namely electrical, fossil fuel (diesel oil, natural gas and coal) and renewable energy (biomass). Based on the findings of Nakićenović et al, [21] the average operation ratings of different processes used in industrial sector are calculated as shown in Table 6.

Industrial

	Coal	Ren. Fuel	Oil	Gas	Electricity	Heat	avg
Process heat, low & medium temperature	0,542	0,622	0,665	0,663	0,906		0,6796
High temperature heat, electrolysis	0,36		0,45	0,578	0,674		0,5155
Mechanical energy			0,229	0,263	0,703		0,398333
Other industrial uses	0,551	0,72	0,534	0,585	0,563		0,5906
avg	0,484333	0,671	0,4695	0,52225	0,7115		**0,546008**

divided by the exergy factor of each fuel

Industrial

	Coal	Ren. Fuel	Oil	Gas	Electricity	Heat	avg
Process heat, low & medium temperature	0,511321	0,6098039	0,621495	0,6375	0,906		0,657224
High temperature heat, electrolysis	0,339623		0,420561	0,555769	0,674		0,497488
Mechanical energy			0,214019	0,252885	0,703		0,389968
Other industrial uses	0,519811	0,7058824	0,499065	0,5625	0,563		0,570052
avg	0,456918	0,6578431	0,438785	0,502163	0,7115		**0,528683**

Table 6: Average operation ratings of the different processes of the Greek industrial sector

The overall exergy and energy efficiency of the Greek industrial sector over the period 1990-2004 is shown in Fig. 2 It is also noticed that the exergy efficiency was lower than its corresponding energy efficiency. By comparison exergy efficiencies for the industrial sector are reported to be 35.51% for Turkey in 2000 [24], 41% for Canada in 1986 [6].

The comparison of energy efficiencies of all sectors shows that the industrial sector is the most energy and exergy efficient one (Fig. 10). This can be attributed to the fuel type and the performance of the carrier.

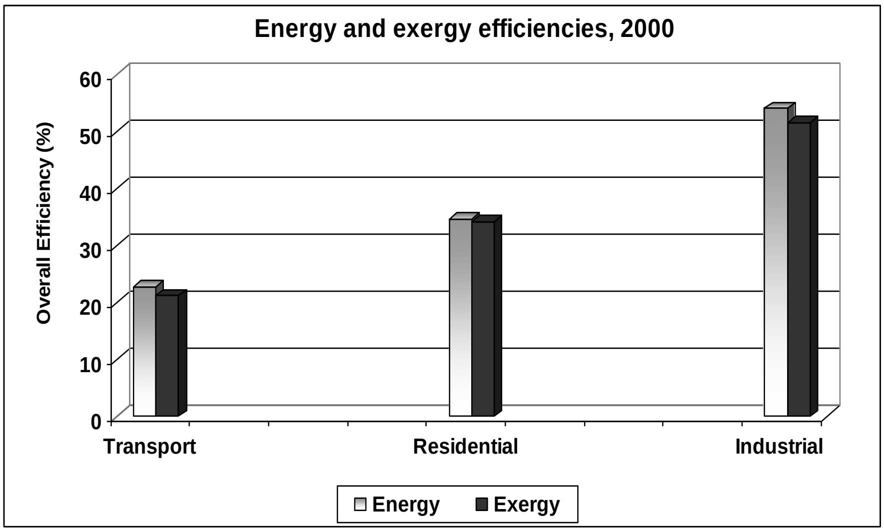

Figure 3. Overall mean energy and exergy efficiencies for the transport, residential and industrial sectors in Greece in 2000 [25]

5. Conclusions

This work analyzes energy and exergy utilization in the energy sector of Greece by considering the energy and exergy flows for the years of 1990-2004. Energy and exergy analyses and hence efficiencies for the residential and industrial sector are then obtained and compared to transport energy and exergy efficiencies. The industrial sector appears to be the most energy and exergy efficient one.

It should be noted that due to non-availability of data concerning the fuel energy consumption of the appliances as well as of industrial processes, a general methodology was employed in order to calculate the energy and exergy efficiencies.

Using exergy and entropy to measure sustainability, gives important insight into how effective material and energy are used in a system. Systems are not sustainable if they consume exergy resources at a larger rate than that at which they are renewed [26], i.e. decreasing exergy. Therefore the increase of entropy, is a meaure of the systems inherent chaos or disorder, thus moving the system away from sustainability.

It may also be concluded that the exergy analysis offers constructive suggestions for the optimization and improvement of the energy –utilization effectiveness of the sectors under study.

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