Energy Policy 39 (2011) 2475–2481

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Exergy analysis of the energy use in Greece

Christopher J. Koroneos [a,*], Evanthia A. Nanaki [b], George A. Xydis [c]

[a] Laboratory of Heat Transfer and Environmental Engineering, Aristotle University of Thessaloniki, P.O. Box 483, 54124 Thessaloniki, Greece
[b] University of Western Macedonia, Department of Mechanical Engineering, Bakola and Sialvera, 50100 Kozani, Greece
[c] Intelligent Energy Systems, Programme Risø DTU National Laboratory for Sustainable Energy, Frederiksborgvej 399, P.O. Box 49, 4000 Roskilde, Denmark

ARTICLE INFO

Article history:
Received 3 October 2010
Accepted 1 February 2011
Available online 1 March 2011

Keywords:
Exergy efficiency
Energy use
Greece

ABSTRACT

In this work, an analysis is being done on the concept of energy and exergy utilization and an application to the residential and industrial sector of Greece. The energy and exergy flows over the period from 1990 to 2004 were taken into consideration. This period was chosen based on the data reliability. The energy and exergy efficiencies are calculated for the residential and industrial sectors and compared to the findings of a previous study concerning the exergy efficiency of the Greek transport sector. The residential energy and exergy efficiencies for the year 2003 were 22.36% and 20.92%, respectively, whereas the industrial energy and exergy efficiencies for the same year were 53.72% and 51.34%, respectively. The analysis of energy and exergy utilization determines the efficiency of the economy as a whole. The results can play an important role in the establishment of efficiency standards of the energy use in various economy sectors. These standards could be utilized by energy policy makers.

1. Introduction

Energy constitutes an essential ingredient for social development and economic growth. Energy is the provider of basic needs and services (heating, cooling, lighting, cooking, and transportation) and is a critical production factor in virtually all sectors of industry.

The exergy of any energy form or a substance can be considered as the measure of its usefulness or quality or potential to cause change (Rosen and Dincer, 1997a). An exergy analysis aims 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 system where exergy destruction takes place can show the road towards potential improvements (Kanoglu et al., 2005). Recently, there has been increasing interest in using exergy analysis modeling techniques for energy-utilization assessments so as to attain energy savings. To be more specific, during the last decades, various studies have been carried out on energy and exergy utilization for many countries, such as USA (Reistad, 1975), Canada (Rosen, 1992), Japan, Finland and Sweden (Wall, 1990), Italy (Wall et al., 1994), Turkey (Ozdogan and Arikol, 1995; Rosen and Dincer, 1997b; Utlu and Hepabasli, 2003, 2005), the UK (Hammond and Stapleton, 2001), Norway (Ertesvag and Mielnik, 2000; Ertesvag, 2005), China (Xi and Chen, 2005) as well as Saudi Arabia (Dincer et al., 2004a, b, c). The approaches used to analyze energy utilization of countries or societies may be grouped into three types, namely, Reistad's approach, Wall's approach, and Sciubba's approach (Utlu and Hepbasli, 2007). Furthermore, 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 (Dincer, 2002). In this regard, it can be stressed that the potential usefulness of exergy analysis in sectoral energy utilization is substantial, and that the role of exergy in energy policy making activities is crucial (Dincer et al., 2004b).

There has been a number of studies undertaken to analyze the sectoral energy utilization of several countries; nevertheless, there has not been any study done (with the exception of a study on transport exergy analysis (Koroneos and Nanaki, 2007)) on exergy and energy utilization concerning the residential, tertiary, industrial, agricultural, and electrical utility sectors of Greece. To fill the gap, a study on the evaluation of energy utilization efficiency in the Greek residential and industrial sectors using energy and exergy analysis is carried out. In order to conduct an energy and exergy analysis for the residential and industrial sector of Greece, energy end-use quantities for these sectors and operational data of the major procedures were utilized. The energy use in the residential and industrial sectors is mainly in the form of electricity or the direct use of fossil fuels. As far as the residential sector is concerned, space heaters, water heaters, and cooking appliances are the principal energy conversion devices

---

* Corresponding author.
E-mail addresses: koroneos@aix.meng.auth.gr (C.J. Koroneos), evananaki@gmail.com (E.A. Nanaki), gexy@risoe.dtu.dk (G.A. Xydis).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.02.012

Nomenclature

E	exergy
E^{PH}	physical exergy
E^{KN}	kinetic exergy
E^{PT}	potential exergy
E^{CH}	chemical exergy
ε	total specific exergy
T_0	temperature of the environment
n_i	*i*th mole number
μ_i	chemical potential of substance *i* in its present state
μ_{io}	chemical potential of substance *i* in its environmental state
c_i	chemical concentration of substance *i* in its present state
c_{io}	chemical concentration of substance *i* in its environmental state
$\mathbf{n}$	energy efficiency
$\boldsymbol{\psi}$	exergy efficiency
$\boldsymbol{\psi}_{\text{overall}}$	weighted mean overall exergy efficiency
n_i	energy efficiency of the *i*th sectoral mode
γ_k	exergy factor of the *k*th energy form
Fr_{ik}	exergy fraction of the *k*th energy form used by the ith sectoral mode

used. The industrial sector 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 objective of this work is to apply the energy and exergy analysis to the country of Greece for its residential and industrial sector for a period of 1990–2004, with the anticipation that it will provide the policy makers with appropriate knowledge on how efficiently Greece uses its natural resources. The sectoral data used for this energy and exergy analyses were taken from the databases of the Greek Ministry of Development (Database of the Greek Ministry of Development). In addition, the exergy and energy efficiencies of the electric devices concerning the residential and industrial sectors are evaluated using the sectoral data and also taking into account the appropriate energy conversion efficiencies for the European OECD countries (Nakićenović et al., 1996). Weighted mean energy and exergy efficiencies are calculated for the overall residential, industrial, tertiary, and agricultural sectors. Data concerning the transportation sector have as origin a previous work by the authors (Koroneos and Nanaki, 2007). A comparison of the overall energy and exergy efficiencies of the Greek residential and industrial sectors with the Greek transportation sector is also presented.

2. Greece's energy profile

Greece has a total area of 13,195,740 ha and is located at the southern part of Europe. The total population of the country is approximately 10.35 million, with an increase of 6.5% during the last decades (General Secretariat of National Statistical Service of Greece, 2006). Oil is Greece's most important fuel source, accounting for approximately 63% of total energy consumption in 2003. Greece has natural gas reserves of only 35 billion cubic feet and produces negligible amounts. Greece currently consumes 2.8 billion cubic meters of gas per year of which 2.2 billion cubic meters come from Russia via pipeline, and the rest come from Algeria in liquefied form. Consumption, however, has increased significantly from 15,000.0 t of oil equivalent (toe) in 1990 to 461,000.0 toe in 2004, and is expected to continue to increase—possibly tripling over the next ten years (Fig. 1).

Lignite is Greece's only significant fossil fuel resource, with reserves reaching 4.3 billion short tons. In 1998 lignite stood up to almost 80% of inlands electricity production whereas 18% came from hydroelectric sources and 2% from crude oil. In 2004 lignite production reached 8547 thousand toe. Greece has no hard coal reserves; for this reason hard coal is imported from South Africa, Russia, Venezuela, and Colombia. As far as the electricity generation is concerned, in 2004 Greece generated 55.5 billion kW h of electricity, of which approximately 76% came from steam turbines, 20% came from hydroelectric sources, and 4% came from other renewable energy sources. The majority of the steam based electricity is of lignite-base while new plants will be gas-fired. Over the past decade electricity demand has grown nearly 50%. In addition, Law 2773/99 and its later revision, Law 3175/03, established the liberalization of the electricity market in Greece, in agreement with the provisions of the EU Directive 96/92/EC, concerning "common rules for the internal market in electricity".

In order to meet European Union mandates, renewable electricity generation projects are on the rise in Greece. The use of wind power is not particularly extensive but significant development in this direction has taken place in the last years. The wind parks in 2005 had a total installed capacity pf 573 MW. The use of solar energy is satisfactory, with its capacity reaching 1, 4 billions kW h each year.

3. Energy and exergy analysis

As a fundamental measure of the thermodynamic deviation of a considered system from its environment, exergy is equal to the maximum amount of work the system can perform when brought into thermodynamic equilibrium with its reference environment. Unlike energy, exergy is not subject to a conservation law with the exception of ideal or reversible processes. The exergy consumption during a process is proportional to the entropy created

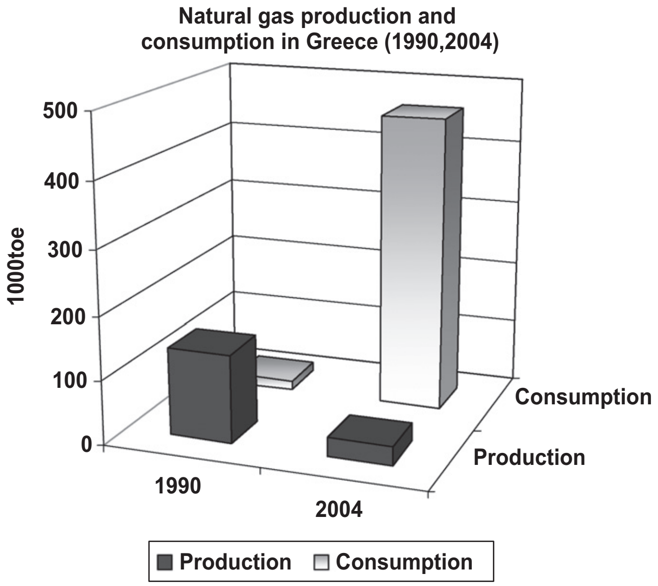

Fig. 1. Greece's Total Primary Energy Production (TPEP) and Final Energy Consumption (FEC) for the period 1990–2004 (Eurostat's database, 2006).

due to irreversibilities associated with the process. The total exergy of a system E is divided into four components: physical exergy E^{PH}, kinetic exergy E^{KN}, potential exergy E^{PT}, and chemical exergy E^{CH}

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \tag{1}$$

It is often convenient to work on a unit of mass or molar basis. The total specific exergy on a mass basis is given by

$$\varepsilon = \varepsilon^{PH} + \varepsilon^{KN} + \varepsilon^{PT} + \varepsilon^{CH} \tag{2}$$

The exergy content of different energy and material resources is presented in detail by Wall (1977, 1986). The exergy of substances and materials is given by the following equation:

$$E_x = \sum_i n_i(\mu_i - \mu_{i0}) + RT_o \sum_i n_i \ln \frac{c_i}{c_{io}} \tag{3}$$

where T_0 is the temperature of the environment; n_i is the ith mole number; μ_i is the chemical potential of substance i in its present state; μ_{io} is the chemical potential of substance i in its environmental state; c_i is the chemical concentration of substance i in its present state, and c_{io} is the chemical concentration of substance i in its environmental state.

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 ($\mathbf{n}$) and exergy (ψ) efficiencies for the principal types of processes considered in the present work are based on the following definitions: energy efficiency is defined as

$$(\mathbf{n}) = \text{work}/\text{energy input} \tag{4}$$

whereas exergy efficiency is defined as

$$(\psi) = \text{work}/\text{exergy input} \tag{5}$$

Table 1
Energy and exergy efficiencies for selected processes (Rosen and Dincer, 1997a; Gaggioli, 1980).

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 2
Exergy factors of energy carriers—exergy divided by energy (Ertesvag and Mielnik, 2000; Ertesvag, 2005).

Energy carriers	Exergy factors
Waterfall energy	1
Electrical energy	1
Oil, petroleum products	1.06
Natural gas	1.04
Coal	1.06
Coke	1.05
Fuel wood (20% humidity)	1.11

it is obvious that

$$\psi = n/\gamma \tag{6}$$

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

$$\psi_{\mathbf{overall}} = \sum_{i,k} (n_i/\gamma_k) \times \mathrm{Fr}_{ik} \tag{7}$$

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

The distinction between energy and exergy efficiencies for selected processes is highlighted in Table 1. The exergy content for mechanical and electrical energy is equal to the energy content. The exergy factors for different carries are presented in Table 2. 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.

4. Results and discussion

The time variation of total exergy consumption in the Greek residential, industrial, tertiary, agricultural, and transportation sector from 1990 to 2004 is shown in Fig. 2. There are some data missing for the tertiary sector, due to limited data sources for the years 2003 and 2004. The exergy consumption expressed by the ascending curves in Fig. 2 illuminates the increasing demand for mobility in Greece to a great extent. The transportation sector is the one with the highest exergy consumption followed by the industrial and residential sectors. This makes the transport sector to be regarded as a crucial factor for social economic development.

The analysis of energy and exergy use in the residential and industrial sector of Greece is based on the methodology presented in the previous section. 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. A breakdown of the energy used in each sector is presented in

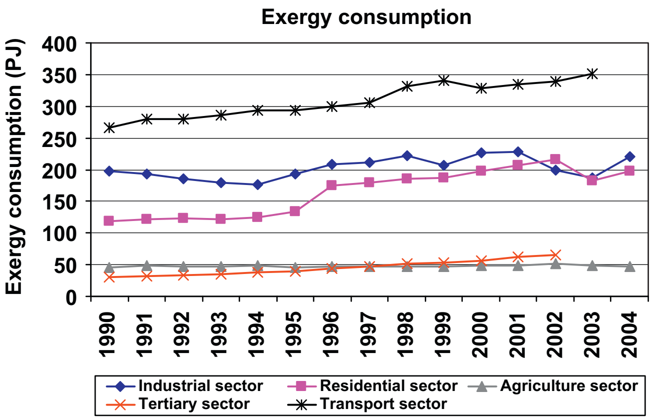

Fig. 2. Exergy consumed by each sector over the period 1990–2004.

Tables 3 and 4. A weighted mean is obtained for each sector's energy efficiencies as listed in Tables 3 and 4, where the weighting factor is the fraction of the total energy input which supplies each sector. It is noted that the exergy factors used for the calculations are 1 for electricity, 1.06 for coal, 1.07 for diesel, 1.04 for natural gas, and 1.11 for biomass.

Table 3
Energy used in the Greek *residential sector* for the period from 1990 to 2004.

Year	**1990**					**1991**					**1992**				
Main energy forms	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**
Exergy term (PJ)	32.65	67.72	0.09	15.98	2.18	36.04	67.32	0.09	15.98	2.46	38.22	66.02	0.17	15.98	2.69
Fraction	**0.28**	**0.57**	**0.00**	**0.13**	**0.02**	**0.30**	**0.55**	**0.00**	**0.13**	**0.02**	**0.31**	**0.54**	**0.00**	**0.13**	**0.02**
Year	**1993**					**1994**					**1995**				
Main energy forms	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**
Exergy term (PJ)	37.72	65.48	0.13	15.98	2.88	39.35	65.89	0.09	15.98	3.04	41.44	69.20	0.13	20.02	3.19
Fraction	**0.31**	**0.54**	**0.00**	**0.13**	**0.02**	**0.32**	**0.53**	**0.00**	**0.13**	**0.02**	**0.31**	**0.52**	**0.00**	**0.15**	**0.02**
Year	**1996**					**1997**					**1998**				
Main energy forms	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**
Exergy term (PJ)	44.12	93.97	0.13	32.62	3.31	44.71	98.23	0.13	32.62	3.47	46.05	103.20	0.57	32.62	3.62
Fraction	**0.25**	**0.54**	**0.00**	**0.19**	**0.02**	**0.25**	**0.55**	**0.00**	**0.18**	**0.02**	**0.25**	**0.55**	**0.00**	**0.18**	**0.02**
Year	**1999**					**2000**					**2001**				
Main energy forms	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**
Exergy term (PJ)	48.52	101.49	0.17	32.62	3.74	51.15	109.82	0.22	32.62	3.81	52.37	118.29	0.22	32.62	3.85
Fraction	**0.26**	**0.54**	**0.00**	**0.17**	**0.02**	**0.26**	**0.56**	**0.00**	**0.17**	**0.02**	**0.25**	**0.57**	**0.00**	**0.16**	**0.02**
Year	**2002**					**2003**					**2004**				
Main energy forms	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**	**ElEC/TY**	**DSL**	**N.G**	**Biomass**	**Solar**
Exergy term (PJ)	56.80	122.95	0.39	32.62	3.90	59.20	123.05	0.90	0.00	0.00	60.66	135.62	1.53	0.00	0.00
Fraction	**0.26**	**0.57**	**0.00**	**0.15**	**0.02**	**0.32**	**0.67**	**0.00**	**0.00**	**0.00**	**0.31**	**0.69**	**0.01**	**0.00**	**0.00**

Table 4
Energy used in the Greek *industrial sector* for the period from 1990 to 2004.

Year	**1990**					**1991**					**1992**				
Main energy forms	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**
Exergy term (PJ)	43.53	52.16	92.58	4.57	5.57	42.86	51.65	89.23	4.32	5.57	42.32	44.37	89.93	4.04	5.57
Fraction	**0.22**	**0.26**	**0.47**	**0.02**	**0.03**	**0.22**	**0.27**	**0.46**	**0.02**	**0.03**	**0.23**	**0.24**	**0.48**	**0.02**	**0.03**
Year	**1993**					**1994**					**1995**				
Main energy forms	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**
Exergy term (PJ)	40.86	45.98	83.76	2.71	5.57	41.94	44.82	84.16	0.49	5.57	43.41	44.57	98.63	0.48	5.57
Fraction	**0.23**	**0.26**	**0.47**	**0.02**	**0.03**	**0.24**	**0.25**	**0.48**	**0.00**	**0.03**	**0.23**	**0.23**	**0.51**	**0.00**	**0.03**
Year	**1996**					**1997**					**1998**				
Main energy forms	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**
Exergy term (PJ)	43.62	43.30	110.77	0.61	9.52	44.75	40.35	113.38	3.37	9.67	46.46	40.63	110.42	14.36	9.52
Fraction	**0.21**	**0.21**	**0.53**	**0.00**	**0.05**	**0.21**	**0.19**	**0.54**	**0.02**	**0.05**	**0.21**	**0.18**	**0.50**	**0.06**	**0.04**
Year	**1999**					**2000**					**2001**				
Main energy forms	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**
Exergy term (PJ)	46.42	32.62	103.51	14.67	9.67	48.81	37.94	112.96	15.85	11.20	49.56	38.61	112.78	15.76	10.82
Fraction	**0.22**	**0.16**	**0.50**	**0.07**	**0.05**	**0.22**	**0.17**	**0.50**	**0.07**	**0.05**	**0.22**	**0.17**	**0.50**	**0.07**	**0.05**
Year	**2002**					**2003**					**2004**				
Main energy forms	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**	**ElEC/TY**	**Coal**	**DSL**	**N.G**	**Biomass**
Exergy term (PJ)	50.90	30.71	89.93	16.63	11.43	50.95	27.83	74.90	21.87	11.10	42.24	74.23	74.54	19.06	11.10
Fraction	**0.26**	**0.15**	**0.45**	**0.08**	**0.06**	**0.27**	**0.15**	**0.40**	**0.12**	**0.06**	**0.19**	**0.34**	**0.34**	**0.09**	**0.05**

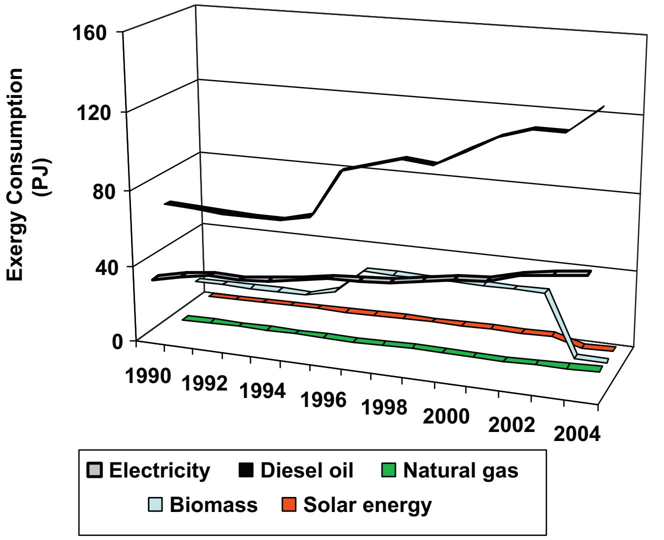

Fig. 3. Details of the exergy consumption of the Greek residential sector over the period 1990–2004.

The breakdown of energy use in the residential sector is split into three main components: electrical, fossil fuel (diesel oil and natural gas) and renewable energy (biomass and solar energy). Electrical appliances use energy from an electrical source, while non-electrical appliances use energy from fossil fuel sources. The exergy consumption of diesel oil has increased significantly over the past decade (Fig. 3). The highest exergy contributions in 2004 came from diesel oil with 135.62 PJ. Natural gas constituted 1.53 PJ of used energy in 2004. The utilization of electricity came to 60.66 PJ for the same year. In addition, utilization of renewable energy is common in the residential sector, especially the use of solar energy for water heating and also the use of biomass.

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 (Eq. (5)). 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. (1996). The average operational rating for different appliances is shown in Table 5. Based on the exergy fraction listed in Table 3, and the estimated energy efficiencies as well as the estimated average operational efficiencies listed in Table 5, the overall exergy efficiency for the residential sector, in 2000, is calculated by (Table 7)

$$\begin{aligned}\psi_{\text{overall}} = {} & (0.15533)\times 0.165072+(0.15533)\times 0.019294 \\ & +(0.3\ )\times 0.555715+(0.\ 36871)\times 0.0011 \\ & +(0.\ 5633)\times 0.25882 = 34.16\% \end{aligned} \tag{8}$$

The overall exergy and energy efficiency for the Greek residential sector over the period 1990–2002 are presented in Fig. 4. 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 (Ertesvag and Mielnik, 2000), 9% for Saudi Arabia in 1990–2001 (Dincer et al., 2004a), 22% for Turkey in 2004–2005 (Utlu and Hepabasli, 2005), 23% for Brazil in 2001, 13% for Sweden in 1994, 15% for Canada in 1986, 3% for Japan in 1985 (Ertesvag, 2001), and 10% for China in 1983 (Chen and Chen, 2006).

Table 5
Average operation ratings for the devices used in the Greek residential sector.

	Coal	Ren. fuel	Oil	Gas	Electricity	Avg.
Residential						
Cooking	0.14	0.10	0.22	0.27	0.60	0.27
Washer, dishwasher				0.76		0.76
Space heating	0.34	0.24	0.55	0.62	1.00	0.55
Hot tap water	0.18	0.12	0.44	0.45	0.67	0.37
Space cooling			0.46	0.60	0.88	0.65
Refrigeration					0.47	0.47
Mechanical energy			0.12	0.22	0.54	0.30
Lighting			0.02	0.03	0.04	0.03
EDP, TV					0.11	0.11
Other household appliances				0.39	0.56	0.47
Avg.	**0.22**	**0.16**	**0.30**	**0.37**	**0.56**	**0.40**
Residential (divided by the exergy factor of each fuel)						
Cooking	0.14	0.10	0.20	0.26	0.60	0.26
Washer, dishwasher					0.76	0.76
Space heating	0.32	0.24	0.51	0.59	1.00	0.53
Hot tap water	0.17	0.12	0.41	0.44	0.67	0.36
Space cooling			0.43	0.58	0.88	0.63
Refrigeration					0.47	0.47
Mechanical energy			0.11	0.21	0.54	0.29
Lighting			0.02	0.03	0.04	0.03
EDP, TV					0.11	0.11
Other household appliances				0.37	0.56	0.46
Avg.	0.21	0.15	0.28	0.35	0.56	**0.39**

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

	Coal	Ren. fuel	Oil	Gas	Electricity	Avg.
Industrial						
Process heat, low and medium temperature	0.54	0.62	0.67	0.66	0.91	0.68
High temperature heat, electrolysis	0.36		0.45	0.58	0.67	0.52
Mechanical energy			0.23	0.26	0.70	0.40
Other industrial uses	0.55	0.72	0.53	0.59	0.56	0.59
Avg.	0.48	0.67	0.47	0.52	0.71	**0.55**
Industrial (divided by the exergy factor of each fuel)						
Process heat, low and medium temperature	0.51	0.61	0.62	0.64	0.91	0.66
High temperature heat, electrolysis	0.34		0.42	0.56	0.67	0.50
Mechanical energy			0.21	0.25	0.70	0.39
Other industrial uses	0.52	0.71	0.50	0.56	0.56	0.57
Avg.	0.46	0.66	0.44	0.50	0.71	**0.53**

Table 7
Residential exergy efficiency in 2000.

Main energy forms	Average estimated operating (є)	Fraction	Product	ψ_{overall} (%)
Coal	0.22		0.00	
Ren. fuel (biomass)	0.16	0.17	0.03	
Ren. fuel (solar)	0.16	0.02	0.00	
Ren. fuel (geothermal)	0.16		0.00	**34.16**
Oil	0.30	0.56	0.17	
Gas	0.37	0.00	0.00	
Electricity	0.56	0.26	0.15	
			0.3416	

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). Details of the exergy use of the industrial sector for the period from 1990 to 2004 are shown clearly in Fig. 5. It is evident that the diesel exergy consumption

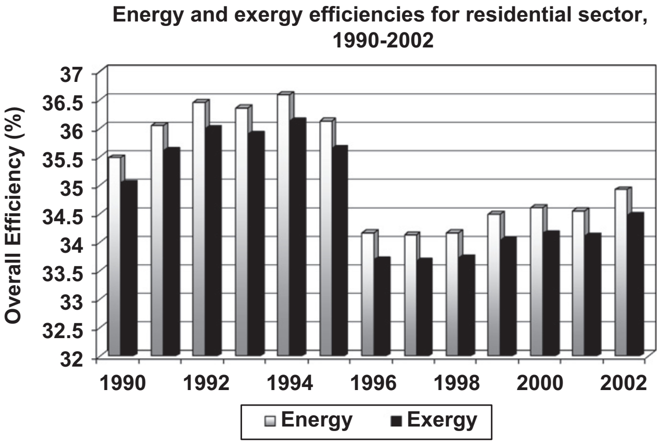

Fig. 4. Exergy consumed by each sector over the period 1990–2004.

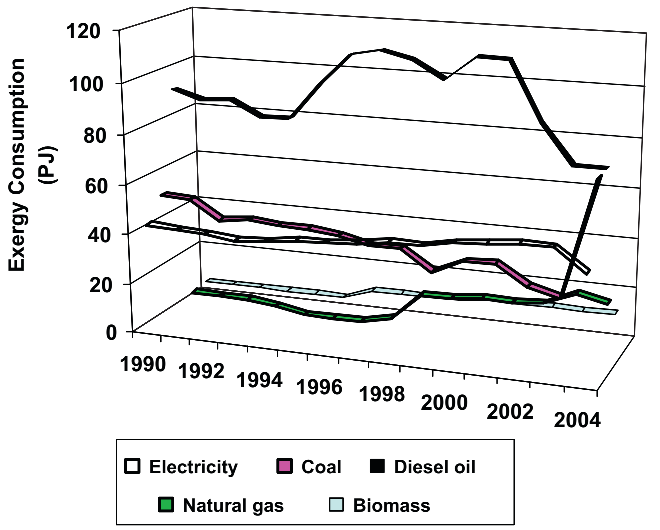

Fig. 5. Details of the exergy consumption of the Greek industrial sector over the period 1990–2004.

Table 8
Industrial exergy efficiency in 2000.

Main energy forms	Average estimated operating	Fraction	Product	ψ_{overall} (%)
Coal	0.46	0.17	0.08	**51.58**
Ren. fuel (biomass)	0.66	0.05	0.03	
Ren. fuel (solar)				
Ren. fuel (geothermal)				
Oil	0.44	0.50	0.22	
Gas	0.50	0.07	0.04	
Electricity	0.71	0.22	0.15	
			0.52	

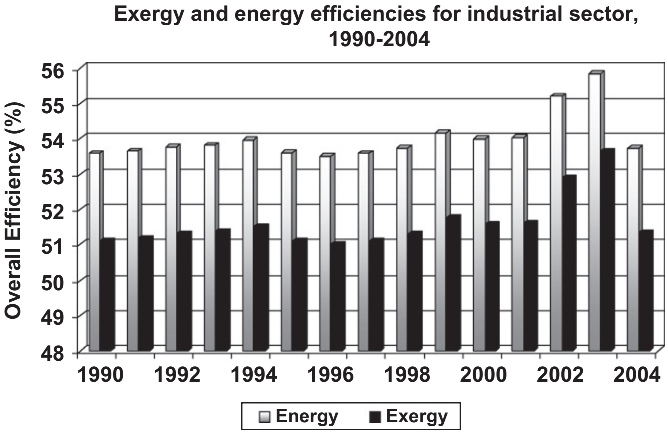

Fig. 6. Overall mean energy and exergy efficiencies for the industrial sector in Greece over the period 1990–2004.

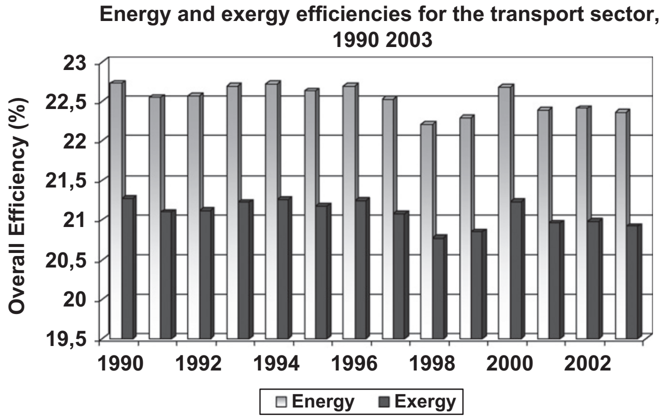

Fig. 7. Overall mean energy and exergy efficiencies for the transport sector in Greece over the period 1990–2003.

has significantly reduced over the past decade. The highest exergy contributions in 2004 came from diesel oil with 74.9 PJ and coal with 74.23 PJ, respectively. The exergy consumption of natural gas has increased over the past decade. In particular, natural gas constituted 21.87 PJ in 2004. In this sector, utilization of electricity was 42.24 PJ for the same year. Additionally, the use of renewable energy is also used in the industrial sector, especially the case of biomass (11.1 PJ in 2003). Based on the findings of Nakićenović et al. (1996) the average operation ratings of different processes used in the industrial sector are calculated and are shown in Table 6. Taking into consideration the exergy fraction listed in Table 4 and the estimated energy efficiencies, as well as the estimated average operational efficiencies listed in Table 6, the overall exergy efficiency for the industrial sector in the year 2000 is calculated as the following (Table 8):

$$\begin{aligned}\psi_{\text{overall}} &= (0.456918239)\times 0.16730+(0.657843137)\times 0.049392\\ &\quad +(0.438785047)\times 0.498154+(0.502163462)\times 0.069897\\ &\quad +(0.\,7115)\times 0.\,215253=51.58\% \end{aligned} \tag{9}$$

The overall exergy and energy efficiency of the Greek industrial sector over the period 1990–2004 is shown in Fig. 6. 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 (Utlu and Hepabasli, 2004), 41% for Canada in 1986 (Rosen, 1992).

Taking into consideration the findings of an earlier study (Koroneos and Nanaki, 2007), the energy and exergy efficiency of the Greek transportation sector is presented in Fig. 7. According to this study, the road transportation subsector is the most efficient in comparison to the other subsectors (railways, marine, and air) for the years from 1980 to 2003. The comparison of energy efficiencies of all sectors shows that the industrial sector is

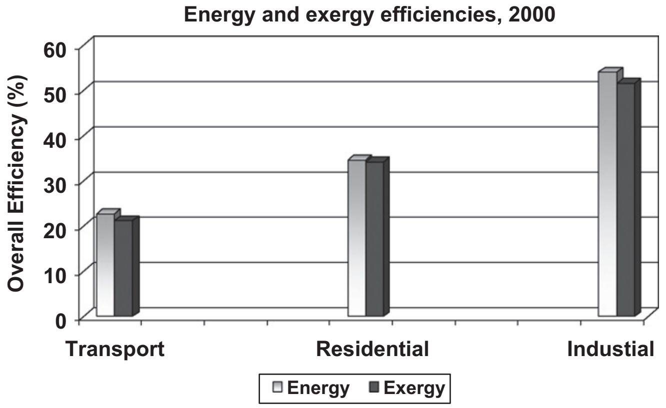

Fig. 8. Overall mean energy and exergy efficiencies for the transport, residential, and industrial sectors in Greece in 2000.

the most energy and exergy efficient one (Fig. 8). This can be attributed to the fuel type and the performance of the carrier. Such an analysis can be used as a means to increase the awareness of the notion of energy quality and degradation.

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 sectors 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 and energy use of the appliances as well as of industrial processes, a general methodology was employed in order to calculate the energy and exergy efficiencies. 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.

References

Chen, B., Chen, G.Q., 2006I. Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system. Energy Policy 31 (8–9), 1115–1150.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004a. Analysis of sectoral energy and exergy use of Saudi Arabia. International Journal of Energy Research 28, 205–243.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004b. Energy and exergy utilization in transportation sector of Saudi Arabia. Applied Thermal Engineering 24, 525–538.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004c. Energy and exergy use in public and private sector of Saudi Arabia. Elsevier—Journal of Energy Policy 32, 1615–1624.

Dincer, I., 2002. The role of exergy in energy policy making. Energy Policy 30, 137–149.

Database of the Greek Ministry of Development. 〈http://www.ypan.gr〉.

Ertesvag, I.S., Mielnik, M., 2000. Exergy analysis of the Norwegian society. Energy 25, 957–973.

Ertesvag, I.S., 2005. Energy, exergy, and extended exergy analysis of the Norwegian society 2000. Energy 30, 649–675.

Ertesvag, I.S., 2001. Society exergy analysis: a comparison of different societies. Energy 26 (3), 253–270.

General Secretariat of National Statistical Service of Greece, 2006. 〈http://www.statistics.gr〉.

Gaggioli, R.A., 1980. Second law analysis for process and energy engineering. Paper Presented at the AlChE Winter Meeting, November, 1980.

Hammond, G.P., Stapleton, A.J., 2001. Exergy analysis of the United Kingdom energy system. IMEch—Journal of Power and Energy 215, 141–162.

Kanoglu, M., Suleyman, K.I., Aysegu, A., 2005. Performance characteristics of a diesel engine power plant. Energy Conversion and Management 46, 1692–1702.

Koroneos, C., Nanaki, E., 2007. Energy and exergy utilization assessment of the Greek transport sector, Journal of Energy Policy. Elsevier.

Nakićenović, N., Gilli, P.V., Kurz, R., 1996. Regional and global exergy and energy efficiencies. Energy 21 (3), 223–237.

Ozdogan, O., Arikol, M., 1995. Energy and exergy analyses of selected Turkish Industries. Energy—The International Journal 20, 73–80.

Rosen, M.A., Dincer, I., 1997a. On exergy and environmental impact. International Journal of Energy Research 21, 643–654.

Reistad, G.M., 1975. Available energy conversion and utilization in the United States. Journal of Engineering for Power 97, 429–434.

Rosen, M.A., 1992. Evaluation of energy utilization efficiency in Canada using energy and exergy analyses. Energy—The International Journal 17, 339–350.

Rosen, M.A., Dincer, I., 1997b. Sectoral energy and exergy modeling of Turkey. ASME—Journal of Energy Resources Technology Resources Technology 119 (3), 200–204.

Utlu, Z., Hepabasli, A., 2003. A study on the evaluation of energy utilization efficiency in the Turkish residential–commercial sector using exergy analyses. Energy and Buildings 35 (11), 1145–1153.

Utlu, Z., Hepabasli, A., 2005. Analysis of energy and exergy use of the Turkish residential–commercial sector. Building and Environment 40, 641–655.

Utlu, Z., Hepbasli, A., 2007. A review on analyzing and evaluating the energy utilization efficiency of countries. Renewable and Sustainable Energy Reviews 11 (1), 1–29.

Utlu, Z., Hepabasli, A., 2004. Turkey's sectoral energy and exergy analysis between 1999 and 2000. International Journal of Energy Research 28, 1177–1196.

Wall, G., 1990. Exergy conversion in the Japanese Society. Energy—The International Journal 15, 435–444.

Wall, G., Sciubba, E., Naso, V., 1994. Exergy use in the Italian society. Energy—The International Journal 19, 1267–1274.

Wall, G., 1977. Exergy—a useful concept within resource accounting. Report no. 77-42, Institute of Theoretical Physics, Göteborg, Sweden.

Wall, G., 1986. Exergy—a useful concept. Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden.

Xi, J., Chen, G.Q., 2005. Exergy analysis of energy utilization in the transportation sector in China. Elsevier—Journal of Energy Policy 34, 1709–1719.