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Energy and exergy utilization assessment of the Greek transport sector

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Abstract

Transport is of fundamental importance to human society, providing mobility and facilitating industry and trade. Nevertheless there are also many environmental impacts; thus it is crucial that transportation planning is carried out in a sustainable manner meeting optimum travel needs, promote economic prosperity and environmental preservation. In assessing the efficiency of transportation, exergy analysis is an effective tool. This work presents an energy and exergy utilization assessment for the transportation sector of Greece taking into account the sectoral energy and exergy flows for the period over 1980–2003. Energy and exergy analyses are conducted for the four subsectors of the Greek transport sector, namely highways, railways, marine and civil aviation. The road subsector appears to be the most efficient in comparison to the other subsectors for the years between 1980 and 2003. It is believed that the exergy analysis presented here provides insights into the transport energy use and could assist in the planning of an efficient transport system.

Keywords: Energy; Exergy; Efficiency; Transportation sector; Greece

1. Introduction

The ongoing depletion of fossil fuels, which are currently being used as the major energy carries, has led to a increasing awareness that energy utilization techniques need to be more environmentally sound and efficient. The concept of exergy provides a feasible approach for efficient energy planning. Energy is defined conventionally as the capacity for doing work and overcoming resistance. Nevertheless, the concept of energy does not contain a provision for the quality of the energy and it could not be a useful tool in energy planning and policy purposes. The concept of exergy, on the other hand, incorporates the precepts of both the first and second laws of thermodynamics and thus it is considered to be suitable for energy planning and policy purposes (Schaeffer, 1990). Exergy (energy availability) is defined as "*the biggest exploitable work that could be received from a system in a given situation under concrete conditions*" (Wall, 2001).

During the past decades, there has been increasing interest, in the use of the concept of exergy. The energy utilization of a country can be assessed using exergy analysis to gain insights into its efficiency. During the last decades a large body of literature concerning the application of exergy analysis to a country's energy system has emerged. It includes, inter alia studies concerning the application of exergy analysis to the countries of USA (Reistad, 1975), Canada (Lemieux and Rosen, 1989;

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Rosen, 1992; Terkovics, 1988), Japan Finland and Sweden (Wall, 1990, 1991), Italy (Wall et al., 1994), Turkey (Ozdogan and Arikol, 1995; Rosen and Dincer, 1997), UK (Hammond and Stapleton, 2001), Brazil (Schaeffer and Wirtshafter, 1992). Additionally, exergy analyses have been applied to the industrial, transportation, public and private, utility and residential sectors of Saudi Arabia (Dincer et al., 2003, 2004a,b,c) as well as to the transport sector of China (Ji and Chen, 2006).

The transportation system of Greece consists of four subsectors, i.e. highways, railways, waterways and civil aviation. The Greek transport energy consumption increased by approximately 27% over the past decade, following an annual growth rate of 2.2%. Road dominates final energy consumption in transport in Greece. In 2001, road transport was responsible for 81% of transport energy consumption in comparison to 77% in 1991. The share of aviation energy consumption decreased from 22% in 1991 to 18% in 2001. The shares of rail are around 1% both in 1991 and 2001 and have remained stable over the past decade. It is obvious that road transport is the dominant factor regarding Greece's transport energy consumption. The transport sector in Greece is highly depended on oil products. In 2001, 1999, 5% of the energy consumed in transport derived from oil products (Koroneos and Nanaki, in press). The adaptation of a sustainable transport policy is of great significance for the Greek transport system. According to the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1997, the EU and its Member States are committed to reducing total emissions of a basket of six greenhouse gases by 8% below the 1990 level over the period 2008–2012. In this context the promotion of transport energy efficiency programs is of great significance. The key measures in the second national climate change programme, included measures for the transport sector concerning energy-efficiency improvements, which will lead to 2% reduction of specific consumption, the introduction and use of biofuels as well as improvements in the transport management (CRES, 2005).

This study aims at applying exergy analysis to the Greek transport sector for the period of 1980–2003, so as to cast light upon the status of energy utilization as well as the energy structure of this system. In the energy and exergy analyses, the actual sectoral energy data, which were taken mainly from the Database of the Greek Ministry of Development (www.ypan.gr) and the energy and exergy efficiencies in the transportation sector over the period 1980–2003 are studied. The energy efficiencies and quantities of electricity and energy inputs in Greece are listed.

Table 1
Exergy analysis related data for selected fuel forms (Kotas, 1985)

Fuel forms	LHVs (kJ/kg)	Exergy factors
Crude oil	41,816	1.08
Gasoline	43,070	1.06
Diesel oil	42,652	1.07
Kerosene	43,070	1.07
Fuel oil	41,816	1.06
LPG	50,179	1.06
Other petroleum products	42,000	1.06
Coal	26,344	1.08

2. Energy and exergy efficiency analysis

In order to evaluate the exergy flows associated with a vehicle, the standard atmosphere is considered as the reference environment (Gaggioli and Petit, 1977). The physical exergy, for fuels used in transportation devices, is negligible when compared to the chemical exergy, which is estimated as (Kotas, 1985):

$$\boldsymbol{\varepsilon} = \gamma * \text{LHV} \quad (1)$$

where $\boldsymbol{\varepsilon}$ stands for the specific exergy, γ denotes the exergy factor based on Lower Heating Value (LHV), which is the energy input for the considered process. Table 1 shows related data for selected fuel forms.

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

$$n = \frac{\text{work}}{\text{energy input}} \quad (2)$$

whereas exergy efficiency is defined as:

$$\psi = \frac{\text{work}}{\text{exergy input}} \quad (3)$$

it is obvious that,

$$\psi = \frac{n}{\gamma} \quad (4)$$

Table 2
Energy and exergy efficiencies for selected processes (Gaggioli, 1980; Kenney, 1984; Rosen and Dincer, 1997)

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

the exergy efficiency is equal to the conventional energy efficiency divided by the exergy factor. It should be mentioned that the exergy value, for the electricity used in electric locomotives, is equal to the energy value; based on this reasoning, the exergy efficiency is the same as the energy efficiency. The weighted mean overall exergy efficiency is calculated as:

$$\psi_{\text{overall}} = \sum_{i,k} \left(\frac{n_i}{\gamma_k}\right) \times \text{Fr}_{ik} \qquad (5)$$

Table 3
Energy used in the Greek transportation sector for the period from 1980 to 2003

Modes of transport	Main energy forms	Energy term (year)		Exergy term		Energy term		Exergy term	
		1980				1985			
		PJ	Fraction	PJ	Fraction	PJ	Fraction	PJ	Fraction
Highways	Gasoline	59.44	0.3521	63.0	0.3499	77.78	0.3872	82.44	0.3849
	Diesel fuel	38.39	0.2274	41.07	0.2281	51.99	0.2588	55.62	0.2597
	LPG					0.837	0.0042	0.887	0.0046
Railways	Electricity	0.335	0.0024	0.335	0.0018	0.419	0.0022	0.419	0.0019
	Diesel fuel	2.05	0.012	2.19	0.0125	2.34	0.0116	2.5	0.0116
Waterways	Crude oil	6.45	0.038	6.96	0.0386	5.69	0.0283	6.14	0.0286
	Diesel fuel	13.81	0.082	14.77	0.082	10.21	0.0508	10.92	0.0509
Civil aviation	Jet kerosene	48.3	0.2861	51.68	0.2871	51.62	0.2569	55.23	0.2578
Modes of transport	Main energy forms	Energy term (year)		Exergy term		Energy term		Exergy term	
		1990				1995			
		PJ	Fraction	PJ	Fraction			PJ	Fraction
Highways	Gasoline	106.28	0.4263	112.65	0.4239	122.02	0.4434	129.34	0.441
	Diesel fuel	59.02	0.2367	63.15	0.2376	71.92	0.2615	76.95	0.2623
	LPG	1.42	0.0057	1.5	0.0056	1.88	0.0068	1.99	0.0067
Railways	Electricity	0.46	0.0018	0.46	0.0017	0.251	0.0009	0.251	0.0008
	Diesel fuel	2.76	0.0112	2.95	0.0115	1.93	0.007	2.06	0.007
Waterways	Crude oil	9.54	0.0383	10.3	0.0387	10.76	0.0391	11.62	0.0396
	Diesel fuel	14.57	0.0584	15.58	0.0586	12.35	0.0448	13.21	0.0454
Civil aviation	Jet kerosene	55.25	0.2216	59.11	0.2224	54.08	0.1965	57.86	0.1972
Modes of transport	Main energy forms	Energy term (year)		Exergy term		Energy term		Exergy term	
		2000				2001			
		PJ	Fraction	PJ	Fraction			PJ	Fraction
Highways	Gasoline	144.67	0.4701	153.35	0.4677	149.44	0.4751	158.41	0.4727
	Diesel fuel	81.88	0.266	87.61	0.2672	82.09	0.261	87.82	0.262
	LPG	0.712	0.0028	0.75	0.0022	0.753	0.0023	0.79	
Railways	Electricity	0.335	0.001	0.335	0.0014	0.377	0.0016	0.377	0.0011
	Diesel fuel	1.72	0.0055	1.84	0.0056	1.72	0.0054	1.84	0.0054
Waterways	Crude oil	9.5	0.0308	10.26	0.0312	13.48	0.0428	14.56	0.0434
	Diesel fuel	11.39	0.037	12.19	0.0371	14.94	0.0475	15.98	0.0476
Civil aviation	Jet kerosene	57.51	0.1868	61.53	0.1876	51.7	0.1643	55.32	0.1655
Modes of transport	Main energy forms	Energy term (year)		Exergy term		Energy term		Exergy term	
		2002				2003			
		PJ	Fraction	PJ	Fraction			PJ	Fraction
Highways	Gasoline	156.47	0.4912	165.86	0.4888	160.56	0.4861	170.19	0.4835
	Diesel fuel	83.39	0.2618	89.23	0.2629	88.8	0.2688	95.02	0.2699
	LPG	0.712	0.0026	0.75	0.0025	0.65	0.002	0.69	0.0019
Railways	Electricity	0.377	0.0011	0.377	0.0011	0.382	0.0017	0.382	0.0015
	Diesel fuel	1.72	0.0054	1.84	0.0054	1.7	0.0051	1.82	0.0051
Waterways	Crude oil	11.39	0.0357	12.3	0.0362	14.99	0.0453	16.19	0.046
	Diesel fuel	14.32	0.0449	15.32	0.0451	13.02	0.0391	13.93	0.0395
Civil aviation	Jet kerosene	50.11	0.1573	53.62	0.158	50.2	0.1519	53.71	0.1526

where ψ_{overall} expresses the weighted mean overall exergy efficiency, n_i stands for the energy efficiency of the ith transportation mode, γ_k the exergy factor of the kth energy form and Fr_{ik} denotes the exergy fraction of the kth energy form used by the ith transportation mode.

Table 2 highlights the distinction between energy and exergy efficiencies for selected processes. 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 2) that the exergy efficiencies are lower than the energy efficiencies; this is attributed to the destruction of the input exergy due to irreversibilities. Out of these reasons the exergy efficiency frequently gives a finer understanding of performance than the energy efficiency.

3. Results and discussion

The application of the methodology discussed in Section 2 is presented for the energy and exergy use in the transport sector of Greece. The transportation sector of Greece consists of four main modes, namely highways railways, marine and civil aviation.

The energy and exergy efficiencies are calculated by multiplying the energy used in each end use by the corresponding efficiency for that end use. The overall efficiency of the transportation sector was obtained by adding these values. Furthermore, a weighted mean is obtained for the transportation mode energy and exergy efficiencies as listed in Table 3, where the weighting factors are the total energy and exergy inputs, which supply to each transportation mode.

Table 3 presents energy and exergy efficiencies for the four modes of transportation. The energy efficiency data for the four modes under consideration are obtained from Reistad (1975). These data are based on US devices and are assumed to be representative of the devices used in Greece. Since vehicles are not operated at full load, part load efficiencies of their devices are estimated as 22%, 28%, 15% and 28% for road, rail, marine and air, respectively. Based on the data listed in Table 3, the overall exergy efficiency for the transportation sector in the year 2000 is calculated as

$$\begin{aligned}\psi_{\text{overall}} &= \left(\frac{22\%}{1.06}\right)\times 0.4677 + \left(\frac{22\%}{1.07}\right)\times 0.2672 \\ &\quad + \left(\frac{22\%}{1.06}\right)\times 0.0022 + \left(\frac{28\%}{1.00}\right)\times 0.0014 \\ &\quad + \left(\frac{28\%}{1.07}\right)\times 0.0056 + \left(\frac{15\%}{1.08}\right)\times 0.0312 \\ &\quad + \left(\frac{15\%}{1.07}\right)\times 0.0371 + \left(\frac{28\%}{1.07}\right)\times 0.1876 \\ &= 21.23\%\end{aligned}$$

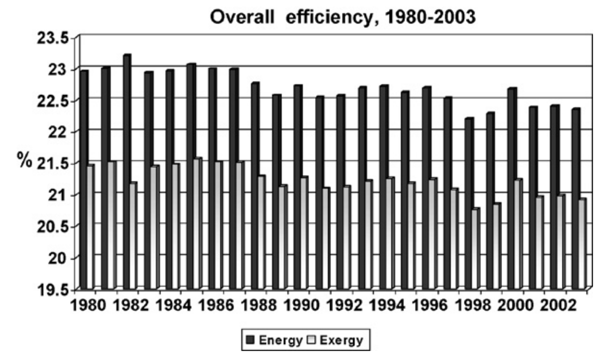

Fig. 1. Overall energy and exergy efficiencies of the transportation sector in Greece.

The overall energy and exergy efficiencies for the transportation sector for the last 23 years between 1980 and 2003 are presented in Fig. 1. The exergy efficiency of the Greek transport sector presents a slowly decreasing trend from 21.46% in 1980 to 20.92% in 2003. Since the exergy efficiencies of devices remained unchanged, the decrease of the overall exergy efficiencies could be attributed to the transition of the energy use structure in general. Furthermore, it is clearly seen that energy efficiencies are much higher than the corresponding exergy efficiencies, due to the fact that exergy considers the losses due to irreversibilities. It becomes obvious that the real overall efficiency of the Greek transportation sector is better depicted by exergy and not energy.

The time variation of total exergy consumption in the Greek transport sector for the period from 1980 to 2003 is shown in Fig. 2. Details are given in Table 3, with constructional distributions to each transportation mode and energy form, for the period from 1980 to 2003. The total exergy consumed in 2003 was 352 PJ whereas in 1980 was 180 PJ. The ascending trends of the exergy consumption in Fig. 2 illuminate the increasing demand for mobility in Greece over the past two decades. The transport sector not only plays a crucial role to socio-economic development but also is influenced both directly and indirectly by other socioeconomic factors such as fiscal policy, industry structure, etc. In particular, the growth of GDP, in Greece, during the past decade has

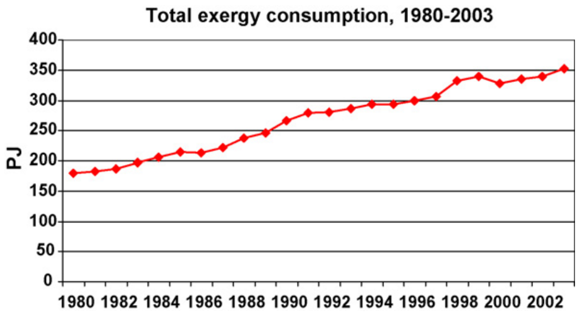

Fig. 2. Total exergy consumption of the Greek transport sector.

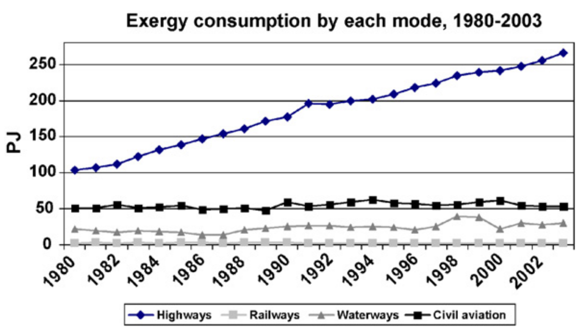

Fig. 3. Exergy consumed by each mode in the Greek transportation sector.

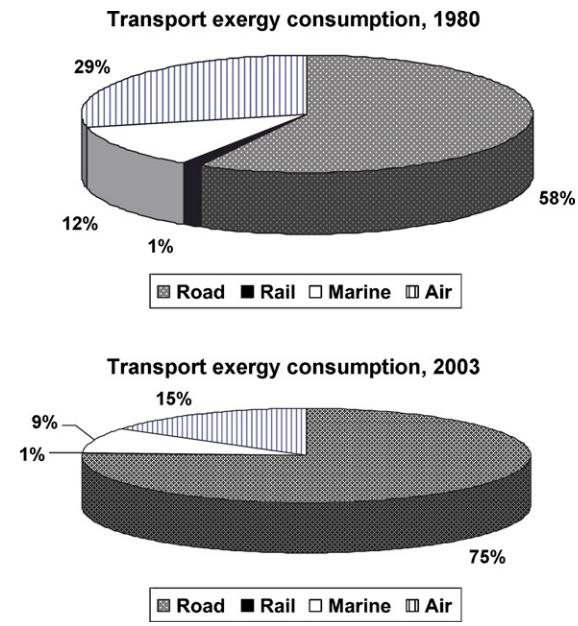

Fig. 4. Shares of transport exergy consumption by each mode in 1980 and in 2003.

led to an increase of the energy use of transport, reflecting increases in traffic and leading to increase in emissions of greenhouse gases. In addition, the fluctuations of fuel prices have affected not only the cost of driving, which is directly linked to fuel consumption, but all the sectors of the economy. It is obvious that as transport grows, it demands more energy. Therefore transport demand and energy use are closely linked (Koroneos and Nanaki, in press).

The exergy consumption of each mode for the period from 1980 to 2003 is presented in Fig. 3. In 1980, highways transport was the biggest exergy consumer with a share of 58%, and civil aviation, waterways and railways ranked second, third and fourth making up 29%, 12% and 1% of the total respectively. The same exergy consumption trends are noticed in 2003, where highways transport was the biggest exergy consumer with a share of 75%, and civil aviation, waterways and railways ranked second, third and fourth making up 15%, 9% and 1% of the total respectively (Fig. 4). It is evident that the exergy consumed by highways increased rapidly over the past two decades. The time variation of the exergy consumption of each mode reflects changes of the energy utilization structure of the Greek transportation sector, which is influenced by socio-economic factors, policies, residents' attitude as well as the very characteristics of vehicles themselves. The demand for flexibility in conjunction with the demand for convenience as well as the economic development plays a crucial role in highway transportation. Details of the exergy consumption of the highways subsector for the period from 1980 to 2003 are shown clearly in Fig. 5.

The multi-year (1980–2003) average overall energy and exergy efficiencies of each transport mode in Greece is revealed in Fig. 6. Here it is seen that the road subsector appears to be the most energy and exergy efficient one. This could be attributed to the fuel type used and the performance of the carrier. It should be pointed out, that since natural gas has the lowest exergy factor (1.04), it gives the highest energy and exergy efficiency compared to other fuels listed in Table 1. Thus, the introduction of

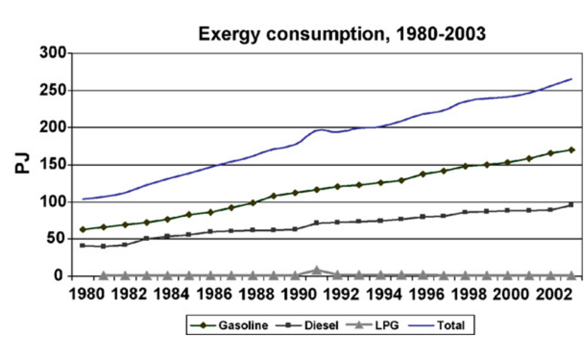

Fig. 5. Details of the exergy consumption of the Greek highways subsector.

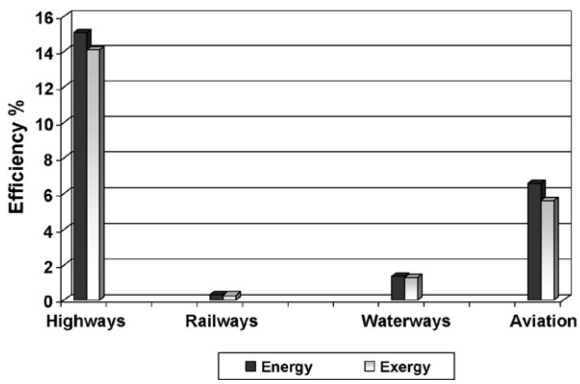

Fig. 6. The multi-year (1980–2003) averaged overall energy and exergy efficiencies of each transport mode in Greece.

natural gas in the transport sector is going to make the transportation subsectors more efficient. The latter is of great significance, as the environmental impacts will be minimized.

In this context**,** the promotion and penetration of alternative and renewable transport energy sources, such as natural gas, biofuels or electricity should be taken into consideration in the transport policy. A shift towards cleaner fuels such as unleaded petrol and low-sulphur diesel, LPG, methane and non-fossil energy sources is expected to lessen the environmental impacts of the transport sector. Greece has shown a great interest in this area as the uptake of cleaner fuels over the period 1990–1999 has increased. What is more, changes in the global energy status can have some potentially significant effects in the transport sector; therefore, the introduction of renewable fuels has one more advantage.

4. Conclusions

This work analyzes energy and exergy utilization in the transportation sector of Greece, based on actual data, by considering the energy and exergy flows for the years of 1980–2003. The variations of energy and exergy efficiencies for the transportation sector were studied for its four subsectors, namely highways, railways, marine and civil aviation. From the analysis it is shown that taking into consideration the expanding demand for mobility, the total exergy consumed by the transportation sector in 2003 increased significantly. Furthermore, highways subsector appears to be the most efficient one compared to the railways, marine and civil aviation.

The main stakeholders in a transportation system are grouped in society, economy and environment. It is of great significance that the interests of these groups are all integrated into the transportation system as they are all essential parameters in society. The lack of a holistic and flexible focus in the planning strategies will inevitably lead to an unsustainable transport system. Exergy analysis and its corresponding results offer constructive suggestions for the optimization and improvement of the transport system since it provides a linkage between the physical and engineering world and the surrounding environment. Out of this reason such an analysis can be used in a sustainable transportation planning. Finally, for a sustainable transportation system, a comprehensive analysis and further study taking into consideration each process of transportation are required.

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