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Energy and exergy utilization in transportation sector of Saudi Arabia

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Abstract

In this paper we present an analysis of energy and exergy utilization in the transportation sector of Saudi Arabia by considering the sectoral energy and exergy flows for the years of 1990–2001. Energy and exergy analyses are conducted for its three subsectors, namely road, air and marine, and hence the energy and exergy efficiencies are obtained for comparison. Road subsector appears to be the most efficient one compared to air and marine subsectors. It is found that the energy efficiencies in air and marine subsectors are found to be equal to the corresponding exergy efficiencies due to the values of exergy grade function. A comparison of the overall energy and exergy efficiencies of Saudi Arabian transportation sector with the Turkish transportation sector is also presented for the year 1993 based on the data available. Although the sectoral coverage is not same for both countries, it is still useful to illustrate the situation on how sub-sectoral energy and exergy efficiencies vary over the years. Turkish transportation sector appears to be a bit more efficient for that particular year. It is believed that the present technique is practical and useful for analyzing sectoral energy and exergy utilization to determine how efficient energy and exergy are used in transportation sector. It is also be helpful to establish standards, based on exergy, to facilitate applications in industry and in other planning processes such as energy planning.

Keywords: Efficiency; Energy; Exergy; Transportation sector; Saudi Arabia

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1. Introduction

Recently, the use of energy and other resources in the industrial world has reached levels never observed before. This leads to a decreasing supply of natural resources and an increasing amount of damage to and pollution of the natural environment. At the same time, energy resource conversion networks have become more complicated. Technical improvements are often focused towards less important resource conversions, which do not have significant potential to improve resource use. By describing the use of energy resources in society in terms of exergy, important knowledge and understanding can be gained, and areas identified where large improvements could be obtained by applying efficient technology, in the sense of more efficient energy-resource conversions.

Saudi Arabia's extensive transportation system was almost completely built in the four decades following 1950. In that year, the country had no railroads, about 200 km of paved roads, and no adequate air facilities. Most localities could be reached only by gravel roads or tracks interspersed with a few airstrips for small airplanes. By 1991 the country boasted an excellent system of expressways, paved roads, and airports that linked all the populated areas of Saudi Arabia. Gasoline makes up a larger share of the transportation fuel market in the Middle East than in other developing regions. As a result of slower growth in motorization rates, transportation demand in the region is projected to increase by about 0.6% per year from 1999 to 2020. Jet fuel is expected to show the strongest growth as air travel expands in the region. The large increase in traffic that has ensued from Saudi Arabia's economic development made it necessary to upgrade several of the nation's intercity roads to multi-lane expressways. Traffic congestion in the cities has also resulted in the development of ring roads around city centers, as well as overpasses and underpasses to keep traffic flowing. Air pollution in Saudi cities is the lowest in the Middle East and should continue to improve with the introduction of unleaded gasoline in January 2001. The switch to unleaded gasoline will result in the need for an estimated 3 million catalytic converters in order to reduce pollution from vehicle exhaust (For details, see SAMA [1]).

During the past two decades, the concept of exergy has received great attention from scientists, researchers and engineers and been applied to various industrial sectors and thermal processes. Recently, much attention has been paid to the energy and exergy modeling techniques for energy-utilization assessments in order to attain energy savings, and hence financial savings. The energy utilization of a country can be assessed using exergy analysis to gain insights into its efficiency. This approach was first introduced in a landmark paper by Reistad [2], who applied it to the USA. Since then, several other countries, e.g., Canada [3–5], Japan, Finland and Sweden [6,7], Italy [8], Turkey [9,10], and the UK [11] have been examined in such a way using modified versions of such energy approach or different modeling techniques.

Exergy appears to be a key concept, since it is a linkage between the physical and engineering world and the surrounding environment, and expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements. Therefore, it is used in the design of engineering systems and sectoral energy analysis of the countries [10].

The scarcity and undesirable side effects of careless utilization of energy resources on economics and ecology require careful analysis and planning for proper energy consumption. In this regard, exergy analysis appears to be a potential tool in:

- addressing the impact of energy resource utilization on the environment,
- furthering the goal of more efficient energy resource utilization,
- determining locations, types and true magnitudes of wastes and losses,
- revealing whether or not and how much it is possible to design more efficient energy systems by reducing the inefficiencies,
- providing a sustainable developments as a result of sustainably supply of energy resources, and
- distinguishing the high-quality and low-quality energy resources.

A brief description of energy and exergy modeling applications is given to provide a better understanding of the differences between the first and second laws of thermodynamics. To attain efficient and effective use of fuels it is essential to consider the quality and quantity of the energy used to achieve a given goal. In this regard, Table 1 shows such a situation in terms of energy and exergy efficiencies for several processes. As is well known, the first law of thermodynamics states that energy is neither produced nor destroyed. More specifically, the energy contained in all of the input streams to a process must be accounted for somewhere in the output streams from the same process or accumulated within the system in which the process is occurring. An output stream could be a loss to the atmosphere or other heat sink. The first law efficiencies given in Table 1 represent the energy of the useful streams leaving the process divided by the energy of all streams entering. The second law efficiencies listed in Table 1 represent the ratio of the exergy contained in the products of a process to the exergy in all input streams. First and second law efficiencies are often called *energy* and *exergy efficiencies*, respectively. The exergy efficiencies in Table 1 are less than the energy efficiencies, usually because the irreversibilities of the process destroy some of the input exergy. The other point that we need to highlight is that high-temperature energy resources, such as fossil fuels are used for relatively low-temperature applications, e.g., residential heating, domestic hot water. This will make exergy efficiencies much smaller than their respective energy efficiencies. Therefore, it is important to note that high-temperature energy resources should be used for high-temperature applications.

Although various studies were undertaken to analyze the sectoral energy and exergy utilization for several countries (e.g., Canada, Turkey, Japan, Italy, UK), no any study on the analysis of energy and exergy utilization in the six major economic sectors of Saudi Arabia, namely residential, public and private, industrial, transportation, agricultural and electrical utility has

Table 1
Energy (i.e., first law) and exergy (i.e., second law) efficiencies for some processes for comparison

Process	Energy efficiency (%)	Exergy efficiency (%)
Residential heater (fuel)	60	9
Domestic water heater (fuel)	40	2–3
High-pressure steam boiler	90	50
Tobacco dryer (fuel)	40	4
Coal gasification (high heat)	55	46
Petroleum refining	~90	10
Steam-heated reboiler	~100	40
Blast furnace	76	46

Source: Refs. [10,15,16].

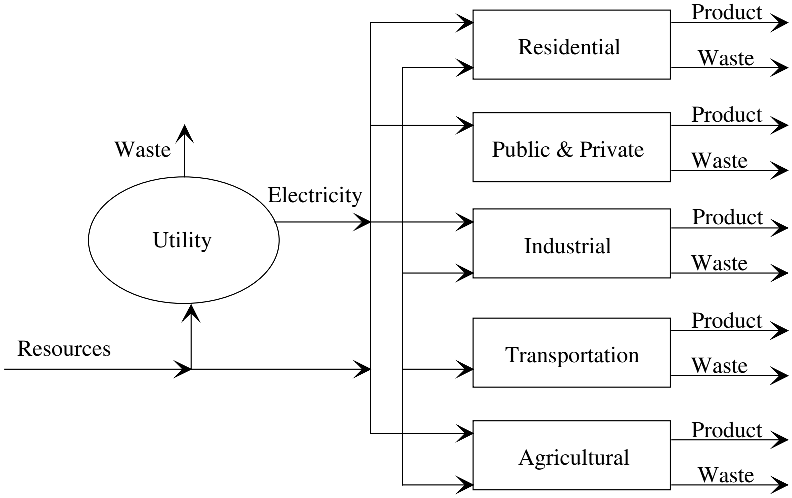

Fig. 1. An illustrative presentation of the energy flows in a macrosystem for Saudi Arabia.

appeared in the literature. The main objective of this work is to model the energy and exergy flows in a macrosystem, as stated in Fig. 1, and to apply the energy and exergy modeling technique to the transportation sector of Saudi Arabia for a period of 1990–2001. In the energy and exergy analyses, the actual sectoral energy data, which were taken from various local and international sources, are used, and the variations of energy and exergy efficiencies in the transportation sector over the years are studied. The energy efficiencies and quantities of electricity and energy inputs in Saudi Arabia are listed. The necessary energy data are taken from MIE [12], UN [13] and ENERDATA [14]. Also, the energy and exergy efficiencies obtained for Saudi Arabia are compared to the ones available for Turkey for the year 1993.

2. Energy and exergy modeling

This section presents some of the key aspects about energy and exergy modeling of sectoral energy use.

2.1. Energy and exergy balances

Energy and exergy balances for an unsteady-flow process in a system during a finite time interval can be written as:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{1}$$

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \tag{2}$$

These equations demonstrate an important difference between energy and exergy that energy is conserved, while exergy is consumed due to irreversibilities. Exergy indicates the quality of energy, and in any real process, it need not be conserved, but it is destroyed or lost.

The input and output terms in Eqs. (1) and (2) are net quantities after accounting for imports and exports whereas the accumulation terms are zero and simplifies the analysis without deviating from the accuracy of the results. With these, Eqs. (1) and (2) can be rewritten as:

$$\sum_{\text{in}}(h+ke+pe)_{\text{in}}m_{\text{in}} - \sum_{\text{ex}}(h+ke+pe)_{\text{ex}}m_{\text{ex}} + \sum_{r} Q_r - W = 0 \quad (3)$$

$$\sum_{\text{in}} \varepsilon_{\text{in}} m_{\text{in}} - \sum_{\text{ex}} \varepsilon_{\text{ex}} m_{\text{ex}} + \sum_{r} E^Q - E^W - I = 0 \quad (4)$$

where m_{in} and m_{ex} denote mass input across port 'in' and mass exiting across port 'ex' respectively; Q_r denotes the amount of heat transfer into the system across region r on the system boundary; E^Q is the exergy transfer associated with Q_r; W is the work (including shaft work, electricity, etc.) transferred out of the system; E^W is the exergy transfer associated with W; I is the system exergy consumption; and h, ke, pe, and ε denote the specific values of enthalpy, kinetic energy, potential energy, and exergy respectively.

The exergy consumption I is greater than zero for an irreversible process and equal to zero for a reversible process, namely $I > 0$ for a irreversible process, and $I = 0$ for a reversible process.

Since $m_{\text{in}} = m_{\text{ex}} = 0$, for a closed system, Eqs. (3) and (4) are simplified to:

$$\sum_{r} Q_r - W = 0 \quad (5)$$

$$\sum_{r} E^Q - E^W - I = 0 \quad (6)$$

2.2. Basic aspects for exergy analysis

The following subsection discusses some basic quantities and mathematical relations related to exergy.

2.2.1. Exergy of a flowing stream of matter

Consider a flowing stream of matter at temperature T, pressure P, chemical composition μ_j of species j, mass m, specific enthalpy h, specific entropy s, and mass fraction x_j of species j. Assuming a conceptual environment in an equilibrium state with intensive properties at T_0 , P_0 and μ_{j00}. And assuming the environment to be large enough such that its intensive properties are negligibly affected by any interactions with the system.

With the above considerations, the specific exergy of the flowing stream of matter can be expressed as:

$$\varepsilon = [ke + pe + (h - h_0) - T_0(s - s_0)] + \left[\sum_{j}(\mu_{j0} - \mu_{j00})x_j\right] \quad (7)$$

Note that the above equation can be separated into physical and chemical components (assuming $ke = 0$ and $pe = 0$). The physical exergy $[(h - h_0) - T_0(s - s_0)]$ is the maximum available work extracted from a flowing stream as it is brought to the environmental state. The chemical exergy

$[\sum_j(\mu_{j0} - \mu_{j00})x_j]$ is the maximum available work extracted from the stream as it is brought from the environmental state to the dead state.

2.2.2. Exergy of heat

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is:

$$E^Q = \left(1 - \frac{T_0}{T_r}\right)Q_r \tag{8}$$

2.2.3. Exergy of work

The exergy associated with work is:

$$E^W = W \tag{9}$$

2.2.4. Chemical exergy

One of the most common mass flows are hydrocarbon fuels at near-ambient conditions, for which the first term in the square brackets in Eq. (7) is approximately zero, and the specific exergy reduces to chemical exergy, which can be written as

$$\varepsilon_f = \gamma_f H_f \tag{10}$$

where γ_f denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy (last term in square brackets in Eq. (7)) to the fuel higher heating value H_f. Table 2 shows some typical values of H_f, ε_f, and γ_f for the fuels encountered in the present study. Usually, the specific chemical exergy ε_f of a fuel at T_0 and P_0 is approximately equal to higher heating value H_f. As given in Table 2, natural gas has the highest chemical exergy value.

2.2.5. Exergy consumption

The amount of exergy consumed due to irreversibilities during a process is:

$$I = T_0 S_{gen} \tag{11}$$

2.2.6. The reference environment

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, is a sink or source for heat and materials, and

Table 2
Properties of selected fuels (for a reference environment temperature of 25 °C, the pressure of 1 atm and chemical composition as defined in the text)

Fuel	H_f (kJ/kg)	ε_f (kJ/kg)	γ_f
Gasoline	47,849	47,394	0.99
Natural gas	55,448	51,702	0.93
Fuel oil	47,405	47,101	0.99
Kerosene	46,117	45,897	0.99

Source: Reistad [2].

experiences only internally reversible processes in which its intensive properties (i.e., temperature T_0, pressure P_0 and chemical potentials μ_{j00} for each of the j components) remains constant. With minor exceptions, Gaggioli and Petit's model [17] is used as a reference environment in which $T_0 = 10$ °C, $P_0 = 1$ atm, and the chemical composition is taken to be air saturated with water vapor, and the following condensed phases are used at 25 °C and 1 atm: water (H_2O), gypsum ($CaSO_4 \times 2H_2O$), and limestone ($CaCO_3$). It is noted that, following Gaggioli and Petit [17], gypsum and limestone are taken to be part of the reference environment so as to provide non-reactive, dead-state chemical forms for the elements such as sulphur and calcium.

2.3. Energy and exergy efficiencies for principal types of processes

The expressions of energy (η) and exergy (ψ) efficiencies for the principal types of processes considered in the present study are based on the following definitions:

$$\eta = (\text{energy in products/total energy input}) \tag{12}$$

$$\psi = (\text{exergy in products/ total exergy input}) \tag{13}$$

2.3.1. Heating

Fossil fuel heating processes are taken to generate product heat Q_p at a constant temperature T_p, from fuel mass m_f. The energy and exergy efficiencies for fuel heating are

$$\eta_{h,f} = Q_p/m_f H_f$$

and

$$\psi_{h,f} = E^{Q_p}/m_f \varepsilon_f \tag{14}$$

and hence

$$\psi_{h,f} = ((1 - T_0/T_p)Q_p)/(m_f \gamma_f H_f) \cong (1 - T_0/T_p)\eta_{h,f} \tag{15}$$

where double subscripts indicate the processes in which the quantity represented by the first subscript is produced by the quantity represented by the second, e.g., the double subscript h,e means heating with electricity.

2.3.2. Work production

Fossil-fuel work production processes produces shaft work W. The efficiencies for shaft work production from fossil fuels are

$$\eta_{m,f} = W/m_f H_f \tag{16}$$

$$\psi_{m,f} = E^W/m_f \varepsilon_f = W/m_f \gamma_f H_f = \eta_{m,f}/\gamma_f \tag{17}$$

2.3.3. Kinetic energy production

The efficiencies for the fossil fuel-driven kinetic energy production processes, which occur in some devices in the transportation sector (e.g., turbojet engines and rockets) and which produces a change in kinetic energy Δke in a stream of matter m_s, are as follows:

$$\eta_{ke,\mathrm{f}} = m_\mathrm{s}\Delta ke_\mathrm{s}/m_\mathrm{f}H_\mathrm{f} \tag{18}$$

$$\psi_{ke,\mathrm{f}} = m_\mathrm{s}\Delta ke_\mathrm{s}/m_\mathrm{f}\varepsilon_\mathrm{f} = m_\mathrm{s}\Delta ke_\mathrm{s}/m_\mathrm{f}\gamma_\mathrm{f}H_\mathrm{f} = \eta_{ke,\mathrm{f}}/\gamma_{ke,\mathrm{f}} \tag{19}$$

3. Results and discussion

Here, an application of the energy and exergy modeling technique discussed in the previous section is presented for the analysis energy and exergy use in the transportation sector of Saudi Arabia.

The transportation sector in Saudi Arabia is composed of three main modes, road, air and marine. Mean energy and exergy efficiencies are calculated by multiplying the energy used in each end use by the corresponding efficiency for that end use. Finally, adding these values to obtain the overall efficiency of the transportation sector.

A breakdown is presented in Table 3, by mode or transportation, of the energy consumed in Saudi Arabian transportation sector. In addition to an energy breakdown, Table 3 shows energy efficiencies for the three modes of transportation, obtained from Reistad [2]. These values are based on US devices and are assumed to be representative of Saudi Arabian devices. Since vehicles generally are not operated at full load, a distinction is made between rated load (full load) and operating (part load) efficiencies.

A weighted mean is obtained for the transportation mode energy efficiencies as listed in Table 3, where the weighting factor is the fraction of the total energy input which supplies to each transportation mode, as shown in Fig. 2. Here it is clearly seen that the road subsector appears to be the most energy and exergy efficient one. This is due to the fuel type used and the performance of the carrier. We should note that natural gas has the highest chemical exergy value and lowest exergy grade function, as given in Table 2, which will give the highest energy and exergy efficiency compared to other fuels listed there. This means that switching to natural gas may make the transportation subsectors more efficient if the carriers perform as good as the current ones. This may be a good opportunity for more efficient energy use with lesser environmental impact.

Based on the data listed in Table 3, the weighted mean overall energy efficiency for the transportation sector in the year 2000 is calculated as:

$$T_{\eta_0} = (0.491 \times 22) + (0.303 \times 22) + (0.118 \times 28) + (0.009 \times 28) + (0.076 \times 15) = \underline{\underline{22.24\%}}$$

Before evaluating the overall mean exergy efficiencies for the transportation sector, it is to be noted that the outputs of transportation devices appear to be in the form of kinetic energy (shaft work). The exergy associated with shaft work (W) is by definition equal to the energy, i.e.

$$E^W = W$$

Thus, for electric shaft work production, the energy and exergy efficiencies of transportation devices can be shown to be similar:

$$\eta_{m,e} = W/W_e$$

$$\psi_{m,e} = E^W/E^{W_e} = W/W_e = \eta_{m,e}$$

Table 3
Energy consumption and process data for the transportation sector in Saudi Arabia.

			Energy consumption		Energy efficiencies (%)	
Year	Mode of transport	Main fuel types	PJ	%	Rated load	Estimated operating
1990	Road	Gasoline	321.61	43.73	28	22
		Diesel	195.45	26.58	28	22
	Air	Jet kerosene	97.61	13.27	35	28
		Air fuel	8.20	1.12	35	28
	Marine	Ships Fuel	112.50	15.30	–	15
		Diesel	0.01	0.00	–	15
1991	Road	Gasoline	337.69	45.65	28	22
		Diesel	206.78	27.95	28	22
	Air	Jet kerosene	99.17	13.41	35	28
		Air fuel	8.34	1.13	35	28
	Marine	Ships fuel	87.75	11.86	–	15
		Diesel	0.01	0.00	–	15
1992	Road	Gasoline	354.57	46.29	28	22
		Diesel	218.78	28.56	28	22
	Air	Jet kerosene	100.76	13.16	35	28
		Air fuel	8.47	1.11	35	28
	Marine	Ships fuel	83.36	10.88	–	15
		Diesel	0.01	0.00	–	15
1993	Road	Gasoline	372.30	46.89	28	22
		Diesel	231.46	29.15	28	22
	Air	Jet kerosene	102.37	12.89	35	28
		Air fuel	8.60	1.08	35	28
	Marine	Ships fuel	79.19	9.97	–	15
		Diesel	0.01	0.00	–	15
1994	Road	Gasoline	390.92	47.45	28	22
		Diesel	244.89	29.73	28	22
	Air	Jet kerosene	104.01	12.63	35	28
		Air fuel	8.74	1.06	35	28
	Marine	Ships fuel	75.23	9.13	–	15
		Diesel	0.01	0.00	–	15
1995	Road	Gasoline	410.46	47.97	28	22
		Diesel	259.09	30.28	28	22
	Air	Jet kerosene	105.68	12.35	35	28
		Air fuel	8.88	1.04	35	28

(*continued on next page*)

Table 3 (*continued*)

			Energy consumption		Energy efficiencies (%)	
Year	Mode of transport	Main fuel types	PJ	%	Rated load	Estimated operating
	Marine	Ships fuel	71.47	8.35	–	15
		Diesel	0.01	0.00	–	15
1996	Road	Gasoline	430.99	48.46	28	22
		Diesel	274.12	30.82	28	22
	Air	Jet kerosene	107.37	12.07	35	28
		Air fuel	9.02	1.01	35	28
	Marine	Ships fuel	67.90	7.63	–	15
		Diesel	0.01	0.00	–	15
1997	Road	Gasoline	441.76	48.64	28	22
		Diesel	278.78	30.70	28	22
	Air	Jet kerosene	109.19	12.02	35	28
		Air fuel	9.18	1.01	35	28
	Marine	Ships fuel	69.25	7.63	–	15
		Diesel	0.01	0.00	–	15
1998	Road	Gasoline	452.81	48.83	28	22
		Diesel	283.52	30.57	28	22
	Air	Jet kerosene	111.05	11.97	35	28
		Air fuel	9.33	1.01	35	28
	Marine	Ships fuel	70.64	7.62	–	15
		Diesel	0.01	0.00	–	15
1999	Road	Gasoline	464.13	49.01	28	22
		Diesel	288.34	30.45	28	22
	Air	Jet kerosene	112.94	11.93	35	28
		Air fuel	9.49	1.00	35	28
	Marine	Ships fuel	72.05	7.61	-	15
		Diesel	0.01	0.00	–	15
2000	Road	Gasoline	475.73	49.20	28	22
		Diesel	293.24	30.33	28	22
	Air	Jet kerosene	114.86	11.88	35	28
		Air fuel	9.65	1.00	35	28
	Marine	Ships fuel	73.49	7.60	–	15
		Diesel	0.01	0.00	–	15
2001	Road	Gasoline	487.62	49.38	28	22
		Diesel	298.23	30.20	28	22

Table 3 (*continued*)

Year	Mode of transport	Main fuel types	Energy consumption PJ	%	Energy efficiencies (%) Rated load	Estimated operating
	Air	Jet kerosene	116.81	11.83	35	28
		Air fuel	9.82	0.99	35	28
	Marine	Ships fuel	74.96	7.59	–	15
		Diesel	0.01	0.00	–	15

And for fossil fuelled shaft work production in transportation devices, the exergy efficiency can be shown similar to the energy efficiency as follows:

$$\eta_{m,\mathrm{f}} = W/m_\mathrm{f}H_\mathrm{f}$$

and

$$\psi_{m,\mathrm{f}} = E^W/m_\mathrm{f}\gamma_\mathrm{f}H_\mathrm{f} \text{ and } \psi_{m,\mathrm{f}} = \eta_{ke,\mathrm{f}}/\gamma_\mathrm{f}.$$

The weighted mean overall exergy efficiency for the transportation sector in the year 2000 is calculated as:

$$T_{\psi_0} = (0.491 \times 22/1.04) + (0.303 \times 22) + (0.118 \times 28/0.99) + (0.009 \times 28) + (0.076 \times 15/0.99) = \underline{\underline{21.84\%}}$$

Furthermore, the overall mean energy and exergy efficiencies for the transportation sector for the last 12 years between 1990 and 2001 is shown in Fig. 3. As clearly seen here, energy efficiencies are much higher than the corresponding exergy efficiencies, due to fact that exergy takes into account the losses due to irreversibilities not energy. So, the real picture about overall efficiency in the

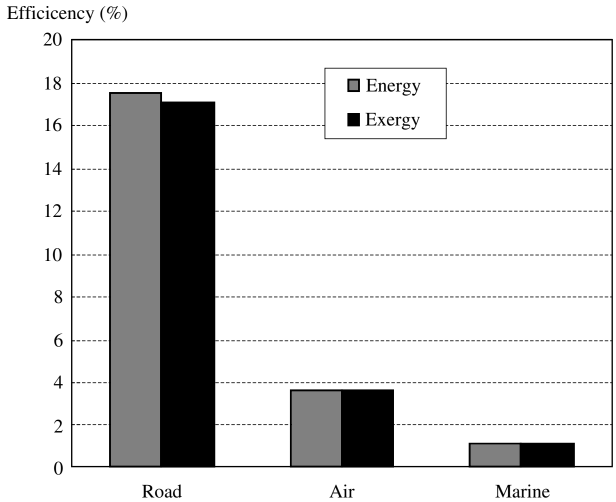

Fig. 2. Overall energy and exergy efficiencies of the subsectors of transportation sector in Saudi Arabia.

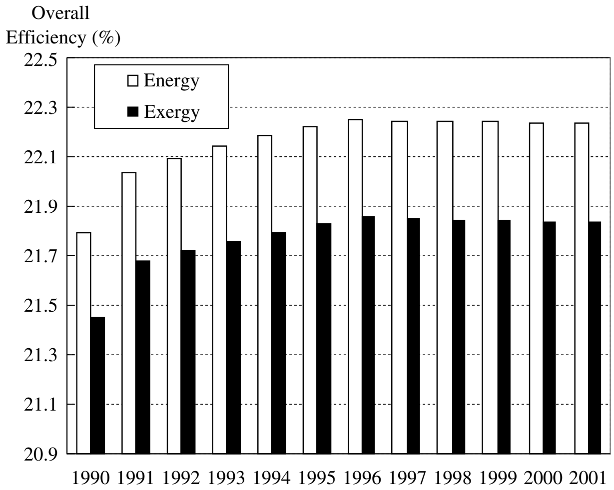

Fig. 3. Overall energy and exergy efficiencies of the transportation sector in Saudi Arabia.

transportation sector is given by exergy, not energy since it does not consider the irreversibilities due to the first law of thermodynamics which refers to the energy conservation law.

In addition, a comparison of the overall energy and exergy efficiencies of Saudi Arabian transportation sector with the Turkish transportation sector is also presented for the year 1993 since we have the sectoral data published earlier for this particular year as obtained from Rosen and Dincer [10]. The main fuel types in Turkish transportation sector were coal, diesel and electricity for rail; jet fuel for air; diesel and gasoline for marine; gasoline and diesel for road; and natural gas for pipelines. Although the sectoral coverage is slightly different for each country, it is useful to illustrate the situation on how energy and exergy efficiencies vary as shown in Fig. 4.

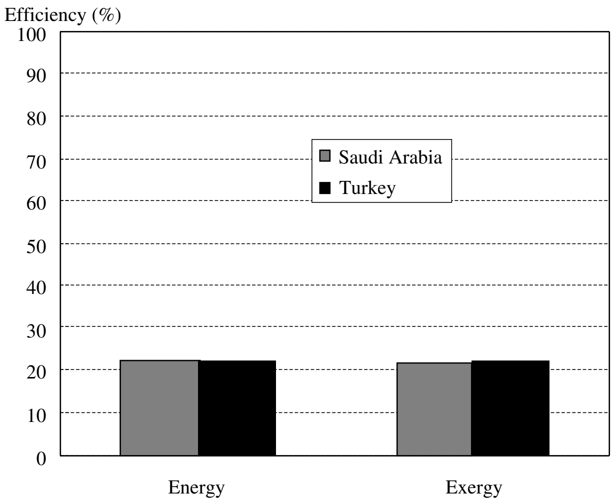

Fig. 4. Comparison of energy and exergy efficiencies of transportation sector of Saudi Arabia with Turkey.

Turkish transportation sector appears to be a bit more efficient than Saudi Arabia's transportation sector for that particular year (e.g., 22.4% for Turkey and 22.1% for Saudi Arabia).

Note that it is clearly discussed in Section 2.3 that energy and exergy efficiencies for the transportation sector are almost similar. This is due to the fact that in our analysis, we are assuming energy grade function γ_f to be unity, which is a realistic assumption for the fuels encountered here. By invoking the assumption in the definition of exergy efficiencies for the types of processes occurring in this sector, it can be found that they are almost similar to energy efficiencies. Thus energy and exergy efficiencies in this sector turns out to be almost equal as long as the assumption of energy grade function γ_f to be unity is valid, and it will not differ with other countries.

4. Conclusions

This paper presents a study undertaken to analyze the energy and exergy utilization in the transportation sector of Saudi Arabia, based on the actual data, by considering the energy and exergy flows sector for the years of 1990–2001. Then, the variations of energy and exergy efficiencies for the transportation sector are studied for its three significant subsectors, namely road, air and marine. From the analysis, road subsector appears to be the most efficient one compared to the air and marine subsectors for the entire period from 1990 to 2001. A comparison of the overall energy and exergy efficiencies of Saudi Arabian transportation sector with the Turkish transportation sector is also presented for the year 1993. It is found that Turkish transportation sector is slightly more efficient for that particular year. Such a technique presented here is beneficial for analyzing sectoral energy and exergy utilization to illustrate how efficiently the country utilizes the energy resources.

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