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Evaluating Energy and Exergy Efficiencies in Transportation Sector of Iran

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Abstract

Considering the increasing energy demands, energy has gained an important role in planning and policies of many countries. This study presented the status of overall energy consumption in the transportation sector of Iran. According to most of the recently issued statistics, the annual transportation energy consumption of Iran is more than 296×10^6 barrels of oil equivalent, which is about 25% of Iran's total annual energy consumption. So, it is logical to analyze energy consumption in transportation sector for the purpose of better planning. Statistics of energy consumption in Iran's transportation sector was presented for a period of 24 years (1988 to 2011) in this paper. Different transportation sub-sectors (highways, airways, railways, and waterways) and different energy forms were considered separately in the presented statistics. Using these data, energy and exergy efficiencies of the transportation sector were derived. Analyzing the efficiency values in the mentioned 24 year period resulted in concluding some considerable points, which could be used in Iran's transportation principle policies in the future.

Keywords: Efficiency, Energy, Exergy, Transportation

1. Introduction

Transportation as the main oil consumer has an increasing rate of energy use in the world and transportation sector provides many benefits to the society: It is indispensable, for instance, for business to link different locations and enable physical access to markets. This sector is also crucial in the global national resource use (especially, energy use) in developed and developing countries and is of special importance as one of the major sources of air pollution[1]. In Iran, transportation sector is responsible for 25% of energy consumption.

Exergy content of a natural resource characterizes "the measure for potential usefulness" (in other words, quality); i.e. its ability to perform "useful work"[1]. Concept of exergy provides a feasible approach for efficient energy planning. Energy is conventionally defined as the capacity for doing work and overcoming resistance. Nevertheless, the concept of energy does not contain a provision for the energy quality and could not be a useful tool in energy planning and policy purposes. Concept of exergy, on the other hand, incorporates the precepts of both the first and second laws of thermodynamics and thus is considered to be suitable for energy planning and policy purposes. During the past decades, there has been an increasing interest in the use of the concept of exergy. Energy utilization of a country can be assessed using exergy analysis to gain insights into its efficiency[2].

Exergy analyses have been applied to the industrial, transportation, utility, and residential sectors of some countries[2–6]. Application of exergy analysis in transportation sector is a relatively new subject[7]. Some studies have been undertaken to analyze energy and exergy utilization in transportation sector in several countries including Turkey, Saudi Arabia, Jordan, and Malaysia[2,7–10].

The aim of this study was to apply energy and exergy analyses to Iranian transport sector. The transportation system in Iran was regarded to consist of four essential sub-sectors; i.e. highways, railways, waterways, and civil aviation. Pipeline transport was excluded from this

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analysis due to its very limited scale. Historical data from 1988 to 2011 were used.

2. Energy and Exergy Efficiency Analyses

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

Where $\boldsymbol{\varepsilon}$ is fuel-specific exergy, γ denotes exergy grade function and LHV is lower heating value of the fuel. Table 1 shows the lower heating values and fuel exergy grade functions of different fuels considered in this study.

Similar to the conventional energy efficiency (the first law efficiency) as

$$\eta = \text{work / energy input} \quad (2)$$

The exergy efficiency (the second law efficiency) is defined as[8]:

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

Where work is done by the vehicle to overcome the drag force due to the ambient fluid and the friction due to the ground.
Obviously:

$$\psi = \eta / \gamma \quad (4)$$

that is, exergy efficiency simply equals the conventional energy efficiency divided by the exergy factor[8].

Table 1. Lower Heating Values (LHVs) and exergy factors for the selected fuels[8,9]

Fuel	LHV (kJ/kg)	Exergy factor
Gasoline	43070	1.07
Diesel oil	42652	1.06
Natural gas	36220	1.06
LPG	50179	1.06
Fuel oil	41816	1.06
Kerosene	43070	1.07

$$\eta_{overall} = \sum \eta_i \times Fr_{i,j} \quad (5)$$

where $\eta_{overall}$ expresses the overall weighted mean energy efficiency, η_i denotes the energy efficiency of the ith transportation sub-sector, and $Fr_{i,j}$ is the fraction of the jth energy form used by the ith transportation sub-sector.

Similar to $\eta_{overall}$, the weighted mean overall exergy efficiency is calculated as[2]:

$$\Psi_{overall} = \sum \frac{\eta_i}{\gamma_j} \times Fr_{i,j} \quad (6)$$

where $\psi_{overall}$ expresses the weighted mean overall exergy efficiency and γ_j is the exergy factor of the jth energy form.

3. Results and Discussion

3.1 Energy Consumption

Transportation sector of Iran consists of four main modes, namely highways, railways, and marine and civil aviation. Details of energy consumption in Iranian transportation sector are given in Table 2, with constructional distributions to each transportation sub-sector and energy form for the 24 year period from 1988 to 2011. The statistics were extracted from the Iranian annual energy balance sheets. According to these data, the total energy consumed in 2011 was 3.43 times of the energy consumption of transportation sector in 1988.

In all of the mentioned years, transport of highways was the biggest energy consumer with the share of 93%. It is obvious that it constituted most of Iranian transportation energy consumption.

Generally, development of transportation assures growth of economy. During this period, Iran's GDP

Table 2. Energy consumption details of Iran transportation sector (from 1988 to 2011)

Year		Highways				Waterways			Airways	Railways		Total
		Gasoline	Diesel	Natural Gas	LPG	Gasoline	Diesel	Fuel Oil	Aviation Fuel	Diesel	Electricity	
1988	PJ	218.9	238.3	0.0	0.0	0.1	2.4	8.5	16.6	5.7	0.0	490.7
	%	44.62	48.57	0.00	0.00	0.02	0.50	1.74	3.39	1.16	0.00	100
1989	PJ	237.9	242.1	0.0	0.0	0.1	4.4	7.9	16.1	5.7	0.0	514.2
	%	46.27	47.08	0.00	0.00	0.02	0.86	1.53	3.14	1.10	0.00	100
1990	PJ	255.2	264.8	0.0	0.0	0.1	6.0	3.2	20.6	7.4	0.0	557.4
	%	45.79	47.51	0.00	0.00	0.02	1.07	0.58	3.69	1.33	0.00	100
1991	PJ	271.7	302.5	0.0	0.0	0.1	7.2	8.6	23.6	5.9	0.0	619.5
	%	43.85	48.83	0.00	0.00	0.02	1.15	1.39	3.81	0.95	0.00	100
1992	PJ	300.2	315.9	0.0	0.0	0.1	6.7	9.2	26.1	5.7	0.0	663.9
	%	45.22	47.57	0.00	0.00	0.02	1.00	1.39	3.93	0.87	0.00	100
1993	PJ	327.6	373.1	0.0	0.3	0.1	5.5	7.4	24.9	5.6	0.0	744.5
	%	44.00	50.11	0.00	0.05	0.01	0.73	1.00	3.35	0.76	0.00	100
1994	PJ	353.2	370.9	0.0	0.5	0.1	7.7	18.9	27.7	5.8	0.0	784.7
	%	45.00	47.27	0.00	0.07	0.01	0.98	2.40	3.53	0.74	0.00	100
1995	PJ	353.0	371.1	0.0	1.1	0.1	7.7	9.4	27.4	6.7	0.0	776.5
	%	45.47	47.80	0.00	0.14	0.01	0.99	1.21	3.53	0.86	0.00	100
1996	PJ	366.8	419.9	0.0	2.8	0.1	5.3	6.1	30.6	7.1	0.0	838.8
	%	43.73	50.06	0.00	0.33	0.01	0.63	0.73	3.65	0.85	0.00	100
1997	PJ	382.0	421.0	0.0	4.1	0.1	5.8	12.5	35.6	7.5	0.0	868.7
	%	43.98	48.47	0.00	0.48	0.01	0.67	1.44	4.09	0.87	0.00	100
1998	PJ	424.7	411.0	0.0	5.8	0.1	6.5	24.0	34.1	6.8	0.0	913.0
	%	46.52	45.02	0.00	0.63	0.01	0.71	2.63	3.73	0.75	0.00	100
1999	PJ	441.4	433.8	0.0	9.9	0.1	8.9	28.6	34.6	7.1	0.0	964.3
	%	45.77	44.99	0.00	1.02	0.01	0.92	2.97	3.58	0.73	0.00	100
2000	PJ	481.9	464.3	0.1	13.4	0.2	9.2	25.4	37.5	7.4	0.0	1039.3
	%	46.37	44.67	0.01	1.29	0.02	0.88	2.44	3.60	0.71	0.00	100
2001	PJ	519.5	484.4	0.2	15.0	0.6	9.2	25.4	38.1	7.7	0.1	1100.2
	%	47.22	44.03	0.01	1.36	0.05	0.84	2.31	3.46	0.70	0.01	100
2002	PJ	573.6	515.9	0.2	16.0	0.8	10.7	24.1	34.9	8.0	0.0	1184.2
	%	48.44	43.57	0.02	1.35	0.07	0.90	2.03	2.95	0.68	0.00	100
2003	PJ	639.2	517.5	0.3	14.7	0.8	12.2	23.2	33.6	8.6	0.1	1250.2
	%	51.12	41.39	0.02	1.18	0.07	0.98	1.86	2.69	0.69	0.00	100
2004	PJ	689.7	538.3	3.0	13.6	0.9	13.8	22.1	34.2	8.7	0.3	1324.7
	%	52.07	40.63	0.23	1.03	0.07	1.04	1.67	2.58	0.66	0.02	100
2005	PJ	756.2	569.3	11.0	11.8	1.1	15.4	21.6	37.2	9.5	0.4	1433.4
	%	52.75	39.71	0.77	0.83	0.08	1.07	1.51	2.59	0.66	0.03	100
2006	PJ	838.5	571.5	18.9	9.7	1.2	16.9	18.3	43.5	10.8	0.5	1529.7
	%	54.82	37.36	1.24	0.63	0.08	1.10	1.19	2.84	0.70	0.03	100
2007	PJ	751.9	613.2	37.7	11.3	1.4	17.3	35.8	44.1	10.8	0.6	1524.0
	%	49.34	40.24	2.47	0.74	0.09	1.13	2.35	2.89	0.71	0.04	100
2008	PJ	762.7	642.9	66.7	8.1	1.2	22.4	33.5	44.6	11.4	0.9	1594.5
	%	47.83	40.32	4.19	0.51	0.08	1.41	2.10	2.80	0.72	0.06	100
2009	PJ	735.0	646.2	124.7	23.7	1.6	27.7	127.5	51.2	11.6	1.0	1750.4
	%	41.99	36.92	7.13	1.36	0.09	1.58	7.29	2.92	0.66	0.06	100
2010	PJ	693.0	663.0	200.8	6.6	3.5	25.2	0.7	52.6	12.2	1.1	1658.7
	%	41.78	39.97	12.10	0.40	0.21	1.52	0.04	3.17	0.73	0.07	100
2011	PJ	680.3	665.6	226.2	1.9	4.4	23.9	18.1	49.2	12.1	1.3	1683.1
	%	40.42	39.55	13.44	0.11	0.26	1.42	1.07	2.92	0.72	0.08	100

in 2011 grew by 3.09 times of the GDP in 1988. But as mentioned before, energy consumed in 2011 was 3.43 times of the energy consumption of transportation sector in 1988, representing that growth of energy consumption in transportation sector was not proportional to the development of economy in Iran.

3.2 Energy and Exergy Efficiencies

Using Tables 1 and 2 and Equations (5) and (6) and considering part load efficiencies mentioned in the previous section, the weighted mean overall energy and exergy efficiency values were calculated for 1988 to 2011. For example, based on the data listed in Table 2, the overall energy efficiency for the transportation sector in 2011 was calculated as:

$$\eta_{overall} = (22\%)\times0.4042 + (22\%)\times0.3955 + (22\%)\times0.1344 + (22\%)\times0.0011 + (15\%)\times0.0026 + (15\%)\times0.0142 + (15\%)\times0.0107 + (28\%)\times0.0292 + (28\%)\times0.0072 + (28\%)\times0.0008 = 22.03\%$$

And the overall exergy efficiency for the transportation sector in 2011 was calculated as:

$$\psi_{overall} = (22\% / 1.07)\times0.4042 + (22\% / 1.06)\times0.3955 + (22\% / 1.06)\times0.1344 + (22\% / 1.06)\times0.0011 + (15\% / 1.07)\times0.0026 + (15\% / 1.06)\times0.0142 + (15\% / 1.06)\times0.0107 + (28\% / 1.07)\times0.0292 + (28\% / 1.06)\times0.0072 + (28\% / 1)\times0.0008 = 20.7\%$$

Figure 1 presents energy and exergy efficiencies of Iranian transportation sector from 1988 to 2011. It is clearly seen that energy efficiencies were higher than the corresponding exergy efficiencies, due to the fact that exergy considers the losses due to irreversibility[2].

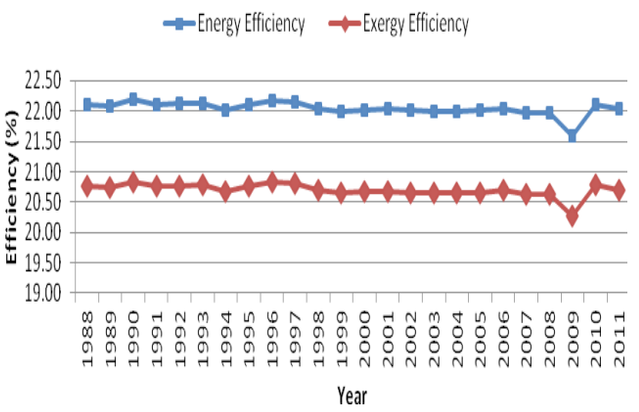

Figure 1. Energy and exergy efficiencies of Iran transportation sector.

A slight decreasing trend could be observed at both energy and exergy efficiencies, which was not desirable. Energy efficiency ranged from 21.59% (2009) to 22.18% (1990) with the mean of 22.04% and exergy efficiency ranged from 20.28% (2009) to 20.83% (1990 and 1996) with the mean of 20.70%. A reason for trough occurring in 2009 was that fuel oil consumption in waterway transportation sector increased by 3.8 times of its previous year (2008), which was because of development of bunkering centers and selling fuel oil to foreigner ships by Iran in 2009. According to the low part load efficiency of waterways (15%), the overall energy and exergy efficiencies of 2009 were affected. The reason of efficiency peaks in 1990 was that energy consumption of airways increased by 28% in this year. It was a big change compared to the 8% growth of overall transportation energy consumption. According to the high part load efficiency of airways (28%), the overall energy and exergy efficiencies of year 1990 considerably increased. A similar explanation can be mentioned for 1996: Iran had passed a destroying war (against Iraq) in 1988 and started reconstruction plans in those years.

A close look at the obtained values of energy and exergy efficiencies shows that efficiencies did not change too much. Two main reasons can be mentioned about this situation:

- Lack of well defined transportation policies in Iran could be clearly seen. According to 1988's statistics, highway transportation nominated 93% of total energy consumption in transportation sector. After 24 years in 2011, share of highway transportation was still 93%, which could represent a weak transportation policy in Iran.
- Restricted international sanctions against Iran have prevented international companies from selling new airplanes or trains to Iran. So, airway and railway transportation have remained in a limited state.

As mentioned before, part load efficiency of highways (22%) was less than that of airways or railways (28%). So, if energy consumption share of highways had decreased, energy and exergy efficiencies would have increased. Let's do a thumb nail calculation. In the mentioned period (1988 to 2011), the gasoline consumption in highway transportation increased by 461.4 PJ (from 218.9 PJ in 1988 to 680.3 PJ in 2011) and electricity consumption in railway transportation did not change too much (from 0 in 1988 to 1.3 PJ in 2011). Supposing that half of 461.4 PJ

increase happed in electricity, instead of gasoline, gasoline consumption in highways and electricity consumption in railways in 2011 would be 449.6 PJ and 232 PJ, respectively. Using these assumptions and Eqs. (5) and (6), the overall energy and exergy efficiencies of transportation sector in 2011 could be calculated as shown below:

$$\eta_{overall} = (22\%)\times0.2671 + (22\%)\times0.3955 + (22\%)\times0.1344 + (22\%)\times0.0011 + (15\%)\times0.0026 + (15\%)\times0.0142 + (15\%)\times0.0107 + (28\%)\times0.0292 + (28\%)\times0.0072 + (28\%)\times0.1378 = 22.85\%$$

$$\psi_{overall} = (22\% / 1.07)\times0.2671 + (22\% / 1.06)\times0.3955 + (22\% / 1.06)\times0.1344 + (22\% / 1.06)\times0.0011 + (15\% / 1.07)\times0.0026 + (15\% / 1.06)\times0.0142 + (15\% / 1.06)\times0.0107 + (28\% / 1.07)\times0.0292 + (28\% / 1.06)\times0.0072 + (28\% / 1)\times0.1378 = 21.72\%$$

Without any change in total transportation consumption, 0.82% and 1.02% increase in overall energy and exergy efficiencies of transportation sector in 2011 could be achieved, respectively. Considering the great amount of total transportation energy consumption in Iran (296.6×10^6 barrels of oil equivalent-BOE), it seems that a proper policy would help Iran's government to effectively decrease its energy costs. Therefore, a flexible international policy for eliminating the sanction of public transportation devices against Iran and an internal energy policy for an acceptable energy vision are required. Furthermore, it would be a world global effort for decreasing the emissions of greenhouse gases.

Overall energy and exergy efficiencies of transportation sector of some countries for the year 2000 are presented in Figure 2. According to Figure 1, the energy and exergy efficiencies of Iranian transportation sector were 22.02% and 20.68% in 2000, respectively. However, it cannot be deduced that one society is "better", or more "efficient", than another in the wider, everyday meaning of the word[12].

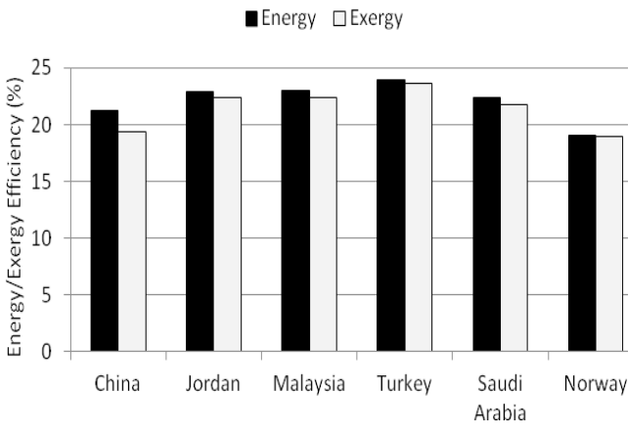

Figure 2. Energy and exergy efficiencies of the transportation sector of some countries in 2000[9].

4. Conclusion

A general view of Iran's transportation energy consumption was considered in this paper. Iran transportation sector consumed 1683.1 PJ of energy, which was 25% of its total consumed energy in 2011. So, any progress in this sector will have effective results on Iran's overall energy status. It should be also mentioned that energy consumed in 2011 was 3.43 times of the energy consumption of transportation sector in 1988. Also, Iran's GDP in 2011 grew by 3.09 times of the GDP in 1988, showing that growth of energy consumption in transportation sector was not proportional to economy development in Iran.

Detailed energy statistics of a 24 year period (from 1988 to 2011) was presented in this article. Different transportation sub-sectors (highways, airways, railways and waterways) and different energy forms were also considered. Using these data, energy and exergy efficiencies of transportation sector were annually calculated. According to the calculations, values of energy and exergy efficiencies did not significantly change in this 24 year period, which revealed the lack of a well defined transportation policy in Iran. Nevertheless, international sanctions against Iran have intensified the undesirable condition, because the government could not buy new transportation devices, such as advanced electrical locomotives.

It was represented in this study that spreading electrical railway transportation could be considered as the basic vision of government in transportation sector. On the other hand, more flexible international policy for eliminating the sanctions of public transportation devices against Iran would be a global effort for both improving energy efficiency and decreasing the emissions of greenhouse gases.

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