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An Analysis of Energy and Exergy Utilization in The Transportation Sector of India

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Abstract — A detailed analysis based on utilization aspects of energy and exergy for Indian transportation sector is presented in this paper. According to the Energy Statistics of India issued in 2017, the annual energy consumption by India's transportation sector is 6.149×10^6 tonnes which is about 7.54% of India's total annual energy consumption for the year 2015. Statistics of energy consumption in Indian highway transportation sector, as available, is presented for a period of 15 years from 2001 to 2015 in this paper. The overall mean energy as well as exergy efficiency values for the complete sub-sector are 21.45% and 20.05% respectively. On comparison with other countries such as Iran, Saudi Arabia and Cameroon, the least efficient was the transport sector of India in terms of the sectoral energetic and exergetic aspects.

Keywords — Energy, Exergy, Efficiency, Transport sector of India.

I. INTRODUCTION

Transportation is considered as the main oil consumer as it has an increasing rate of energy use in the world and it has many benefits to the society as well. India's transport sector is large having a huge diversity. It serves the needs of 1.34 billion people today. Transportation modes in India mainly consist of transport by land, water as well as air.

The share of the transportation sector in country's overall infrastructure investments is found to increase from 2% of GDP during the year 1995-1999 to an average of 2.6% of GDP between 2007 and 2011 [1]. The transport sector contributed approximately 5.89% to the country's GDP, with the maximum contribution of the highway transportation.

The motive of this study is to represent a careful analysis of the development and growth of the idea of exergy along with its related applications in the society. This report is based on a careful consultation of a number of journal articles, published books, research papers, etc. This paper deals with the study of the utilization of energy as well as exergy in Indian highway transportation sub-sector. The results obtained in this report have direct consequences on application decisions as well as on the research and development directions targeting towards energy security as the country's goal.

II. EXERGY: A THEORETICAL CONCEPT

A. *The concept of exergy*

Exergy is the energy that is obtained to be used, i.e., it can measure the maximum capability of an energy system for performing some useful work. In simple words, exergy can be defined as the capacity to generate work. The extraction of the available work from a source of energy depends on the corresponding condition of its surroundings. The more there is a difference in temperature between the surroundings and energy source, the capability for extraction of work from the system will also be greater [2].

In thermodynamics, the definition of exergy or available work of a system is based on the maximum useful work that can be obtained during a process which helps to bring equilibrium between the system and the heat reservoir or surrounding [3]. Exergy analysis is hence a way to prevail over the deficiencies of energy analysis. Exergy analysis is conceptually based on the second law of thermodynamics. It is a very useful tool for identifying the locations, causes and also the magnitudes of various process inefficiencies which energy analysis cannot reveal alone. The exergy is a quantitative estimation of its usefulness or quality. The exergy analysis takes into account that its quality can be degraded.

B. *Values of energy and exergy for commodities in macrosystems*

Energy resources are usually measured in energy units similarly as exergy resources. The exergy value of an energy resource can be simply expressed as a product of the energy content and its quality factor. A material can be quantified in terms of exergy units by multiplying its quantity by an exergy based unit factor for the respective material. The quality factor is nothing but the ratio of exergy to energy. In regional and national assessments,

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hydrocarbon fuels are encountered as the most common material flows at near ambient conditions. In this type of material flow, the physical exergy approximately turns to be zero. As a result, the specific exergy of that material converts into fuel-specific chemical exergy (ex_f), which is expressed as:

$$ex_f = \gamma \times LHV \quad (1)$$

where, γ represents the exergy grade function of the fuel and LHV represents the lower heating value of the fuel.

Table-1 lists some of the typical fuels encountered in various regional and national assessments along with their LHV and γ values.

Table-1: Properties (LHV) of selected petroleum fuels [4]

Fuel	LHV (kJ/kg)	Exergy Factor (γ)
Gasoline	43,070	1.07
Diesel	42,652	1.06
Natural Gas	36,220	1.06
LPG	50,179	1.06
Fuel Oil	41,816	1.06

III. Reference Environment

Evaluation of exergy is always made with respect to a reference environment. For the various macrosystems, the reference environment has been used in many different evaluation processes. It is based basically on the model prepared by Gaggioli and Petit in 1977 [5]. The reference model is having a temperature T_0 of 25°C, pressure P_0 of 1atm and also chemical composition consisting of air that is saturated completely with water vapor, along with the following materials at condensed phases: water (H_2O), gypsum ($CaSO_4 \cdot 2H_2O$) and limestone ($CaCO_3$). In this study, this reference environment model has been used, but by considering a temperature of 10°C [2].

IV. Methodology and Data Sources

A. *Analysis of the transportation sector*

The transport sector's energy consumption amounts to petroleum products such as gasoline, high speed diesel and fuel oil. Energy as well as exergy utilization in the transport sector is evaluated and then analyzed. The Indian transport sector is mainly composed of domestic and international aviation, pipelines transport, roadways as well as railways which uses majorly three types of fuels, namely, high speed diesel oil (HSDO), light diesel oil (LDO) and fuel oil (FO). Other types of fuels that are used in the sector are low sulphur heavy stock oil and liquefied petroleum gas. However, these fuels have not been considered as they have no/low contribution in the transportation sector.

Mean energy and exergy efficiencies are calculated by multiplying the energy used (percentage consumption) in each mode by the corresponding operating efficiency. After that, all the yearly energy and exergy values are added in order to obtain the overall efficiency of the whole sector.

B. *Data sources*

Amount of fuel consumption by different machineries used in the transportation sector activities are collected from Energy Statistics of India 2017 [6] and 2012 [7]. The energy consumption data is thus presented in Table-2. The table shows fuel consumption in '000 tonnes and the corresponding energy consumption in Peta Joule (PJ).

C. *Steps and procedures for energy and exergy analysis*

Energy and exergy efficiencies were determined using the given equations considering grade function as unity. The sectoral overall energy efficiency can be found easily by dividing the total energy produced/output by the total input energy. Then, the overall weighted mean was obtained for the energy and exergy efficiencies for the fossil fuel processes. Weighing factors are the ratio of energy input of each fuel to the total input energy of the sector. The device exergy efficiencies of the transportation sector are evaluated using data for the years 2001-2015. Energy and exergy efficiency values for each mode were then calculated to determine the overall energy and exergy efficiency of the Indian transport sector.

Table-2: Energy consumption data for the Transportation Sector of India for 15 years (2001-2015) [6], [7], [8]

Year	Petroleum product	Consumption ('000 tonnes)	Energy Consumption		Energy Efficiency (%)	
			PJ	%	Rated Load	Estimated Operating Load
2001-02	HSDO	4,161	174.18	92	28	22
	LDO	90	2.22	1.2	28	22
	FO	308	12.89	6.8	-	15
2002-03	HSDO	4,054	169.7	93	28	22
	LDO	40	1.67	1	28	22
	FO	263	11	6	-	15
2003-04	HSDO	3,838	160.66	90.7	28	22
	LDO	57	2.38	1.3	28	22
	FO	339	14.19	8	-	15
2004-05	HSDO	3,917	163.96	90.7	28	22
	LDO	49	2.05	1.1	28	22
	FO	352	14.73	8.2	-	15
2005-06	HSDO	4,264	178.49	89	28	22
	LDO	52	2.17	1	28	22

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Year	Petroleum product	Consumption ('000 tonnes)	Energy Consumption		Energy Efficiency (%)	
			PJ	%	Rated Load	Estimated Operating Load
	FO	478	20	10	-	15
2006-07	HSDO	4,316	180.66	88.6	28	22
	LDO	53	2.22	1.1	28	22
	FO	502	21.01	10.3	-	15
2007-08	HSDO	5,003	209.42	93.4	28	22
	LDO	36	1.5	0.7	28	22
	FO	315	13.18	5.9	-	15
2008-09	HSDO	5,293	221.56	91.6	28	22
	LDO	15	0.62	0.3	28	22
	FO	469	19.63	8.1	-	15
2009-10	HSDO	5,365	224.58	90.5	28	22
	LDO	6	0.25	0.1	28	22
	FO	560	23.44	9.4	-	15
2010-11	HSDO	5,417	226.75	87.3	28	22
	LDO	5	0.21	0.1	28	22
	FO	780	32.65	12.6	-	15
2011-12	HSDO	5,529	231.44	93.7	28	22
	LDO	3	0.12	0.1	28	22
	FO	371	15.53	6.2	-	15
2012-13	HSDO	5,160	216	94.8	28	22
	LDO	3	0.12	0.1	28	22
	FO	277	11.59	5.1	-	15
2013-14	HSDO	3,203	134.07	90.9	28	22
	LDO	4	0.16	0.1	28	22
	FO	315	13.18	9	-	15
2014-15	HSDO	4,617	193.26	92.9	28	22
	LDO	5	0.21	0.1	28	22
	FO	346	14.48	7	-	15
2015-16	HSDO	5,765	241.32	93.7	28	22
	LDO	4	0.16	0.1	28	22
	FO	380	15.9	6.2	-	15

V. DATA ANALYSIS

Using Table-1, Table-2 along with the following equations under this section (for energy and exergy) and considering part load efficiencies as mentioned in the previous section, the weighted mean overall energy and exergy efficiency values are calculated from 2001 to 2015. After data collection, data processing and evaluation is done in order to see how efficient the Indian highway transport sector is.

A. Energy and exergy efficiencies for principal types of processes

Energy efficiency and exergy efficiency are also known as first law efficiency and second law efficiency respectively. The expressions for energy efficiency (η) and exergy efficiency (ψ) for the principal types of processes in macrosystems are commonly based on standard definitions as shown [8]:

η = (Energy in products output) / (Total energy input) (2)

ψ = (Exergy in products output) / (Total exergy input) (3)

Exergy efficiencies can often be written as a function of the corresponding energy efficiencies by assuming the exergy grade function (exergy factor, γ) to be unity (or equal to 1), which is valid mainly for those fuels such as, gasoline, diesel oil, natural gas and fuel oil.

Obviously, $\psi = \eta / \gamma$ (4)

When exergy factor (γ) is equal to 1, exergy efficiency simply equals the conventional energy efficiency, i.e.,

$\psi = \eta$ (5)

B. Mean and overall energy efficiency analysis

Gasoline, diesel and fuel oil are utilized for the machines used in transportation activities. At first, the weighted mean energy efficiencies can be found for each type of fuel by multiplying a weighing factor (f) with the operating energy efficiency (η) for that fuel. Weighing factor is the ratio of energy input of each fuel to the total sectoral input energy. This can be expressed by,

f = (Energy input of a fuel) / (Total energy input) (6)

Weighted energy efficiency of gasoline (HSDO),

$\eta_{gasoline} = \eta \times f_{gasoline}$ (7)

Weighted energy efficiency of diesel (LDO),

$\eta_{diesel} = \eta \times f_{diesel}$ (8)

Weighted energy efficiency of fuel oil (FO),

$\eta_{fuel\ oil} = \eta \times f_{fuel\ oil}$ (9)

where $f_{gasoline}$, f_{diesel} and $f_{fuel\ oil}$ are the weighing factors of gasoline, diesel and fuel oil respectively.

Firstly, the weighing factors for each of the fuels are

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determined by the equation (6). In this problem, all the fuels have the same part loads. Using the part load efficiency, weighted mean energy efficiency of a fuel can be found.

Finally, the overall mean or weighted mean energy efficiency (η_o) for the transport sector in a particular year can be expressed by,

$$\eta_o = \eta_{gasoline} + \eta_{diesel} + \eta_{fuel\ oil} \quad (10)$$

The overall weighted mean energy efficiency can also be expressed as:

$$\eta_o = \Sigma\ \eta_i \times f_{i,j} \quad (11)$$

where, η_i denotes the operating efficiency of the *i*th fuel; and $f_{i,j}$ is the fraction of *i*th fuel used in the *j*th year.

C. Mean and overall exergy efficiency analysis

For fossil fuel driven shaft work production in transportation devices, the exergy efficiency can be shown similar to the energy efficiency. Now, the exergy efficiency for the whole sector is the weighted average of the exergy efficiencies of all devices, with the exergy consumption fraction of each form of fuels as the weighting factor.

Weighted exergy efficiency of gasoline (HSDO),

$$\psi_{gasoline} = (\eta / \gamma_{gasoline}) \times f_{gasoline} = \eta_{gasoline} / \gamma_{gasoline} \quad (12)$$

Weighted exergy efficiency of diesel (LDO),

$$\psi_{diesel} = (\eta / \gamma_{diesel}) \times f_{diesel} = \eta_{diesel} / \gamma_{diesel} \quad (13)$$

Weighted exergy efficiency of fuel oil (FO),

$$\psi_{fuel\ oil} = (\eta / \gamma_{fuel\ oil}) \times f_{fuel\ oil} = \eta_{fuel\ oil} / \gamma_{fuel\ oil} \quad (14)$$

Therefore, the overall mean or weighted mean exergy efficiency (ψ_o) for the transport sector in a particular year can be expressed by,

$$\psi_o = \psi_{gasoline} + \psi_{diesel} + \psi_{fuel\ oil} \quad (15)$$

The overall weighted mean exergy efficiency can also be expressed as:

$$\psi_o = \Sigma\ (\eta_i / \gamma_i) \times f_{i,j} \quad (16)$$

where, η_i denotes the operating efficiency of the *i*th fuel; γ_i denotes exergy factor of *i*th fuel; and $f_{i,j}$ is the fraction of *i*th fuel used in the *j*th year.

VI. Results and Discussion

Based on the data listed in Table-1 and 2 and using equations (10) and (15), the energy and exergy efficiencies are evaluated. Mean and overall energy and exergy efficiency calculations are done in the following steps:

The weighted mean energy efficiency for the transport sector in the year 2001 is calculated as:

$$\eta_o = (22\%)\times0.92 + (22\%)\times0.012 + (15\%)\times0.068$$
$$= 21.52\%$$

The weighted mean exergy efficiency for the transport sector in the year 2001 is calculated as:

$$\psi_o = (22\% / 1.07)\times0.92 + (22\% / 1.06)\times0.012 + (15\% / 1.06)\times0.068$$
$$= 20.12\%$$

The weighted mean energy and exergy efficiencies for all the remaining years of the sector are evaluated in similar way.

The results obtained are depicted in a tabular form which shows the efficiency values for a 15 year period. The results are also represented using suitable graph which shows variation of efficiency values over the years. The following Table-3 shows the yearly data analysis of the sector.

Table-3: Yearly data analysis of Indian Transportation Sector for 15 year period (2001-2015)

Year	Energy (η_o)	Exergy (ψ_o)
2001	21.52	20.12
2002	21.58	20.17
2003	21.44	20.05
2004	21.43	20.03
2005	21.30	19.92
2006	21.28	19.90
2007	21.59	20.18
2008	21.43	20.04
2009	21.34	19.96
2010	21.19	19.75
2011	21.56	20.16
2012	21.64	20.23
2013	21.37	19.98
2014	21.51	20.11
2015	21.56	20.16

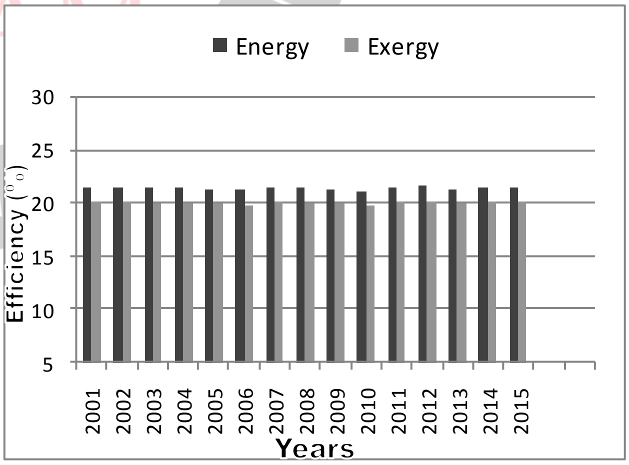

Figure-1: Overall energy and exergy efficiencies of Indian Transportation Sector from 2001-2015

From the above data analysis and corresponding yearly graph we can see that the total energy consumed in 2015 is 1.36 times of the energy consumption of transportation sector in 2001, representing that growth of energy consumption in transportation sector was not proportional to the development of economy in India.

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Decreasing trend could be observed in some of the years at both energy and exergy efficiencies, which was not desirable. Energy efficiency ranged from 21.19% in 2010 to 21.64% in 2012 with the mean of 21.45%. Exergy efficiency ranged from 19.75% in 2010 to 20.23% in 2012 with the mean of 20.05%.

VII. Comparison with Other Countries

Sectoral and overall energy and exergy efficiencies for India, Iran [4], Saudi Arabia [9] and Cameroon [10] are compared. The comparison is based on previous studies, and the data considered is for the year 2015 for India, 2011 for Iran, 2000 for Saudi Arabia and 2010 for Cameroon.

Figure-2 shows a comparison of Indian transport sector with that of other countries. It is seen that the efficiencies are slightly different from each other.

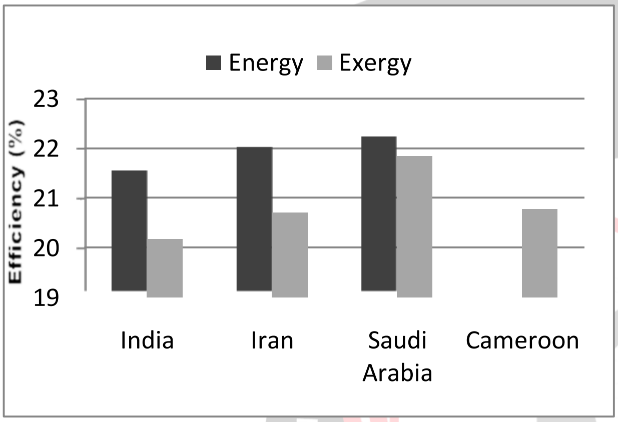

Figure-2: Comparison of overall energy and exergy efficiencies of the Transportation Sector between India, Iran, Saudi Arabia and Cameroon

The above figure shows a comparison of overall energy and exergy efficiencies of the transportation sector between India, Iran, Saudi Arabia and Cameroon. The transport sector of India is found less efficient when compared with the other countries. Such differences can be prevented due to dissimilar structure of the modes of transportation in these countries.

It can be expected that the results of this study will really be very helpful in developing highly productive planning for the future energy policies, especially for further investigation in the other sectors of the country as well.

VIII. Conclusion

In summary, it can be concluded that the exergy analysis has a much more ability and potential in its usefulness in sectoral energy utilization. This study provided a general overview of India's transportation sector and its related energy consumption. Here, we investigated the energy and exergy utilization in the transportation sector of India and conducted the analysis which was based on the actual data by considering energy and exergy use in the sector for the years 2001 to 2015. The total energy consumed by all the sectors in the year 2015 is found to be 3,413.09 PJ as mentioned in the Energy Statistics of India, 2017. India's transportation sector consumed about 257.38 PJ of energy in the same year, which is just 7.54% of the total consumed energy in 2015. So, the sector should make some progress and any progress will surely have effective results on the overall energy status of India.

Detailed energy statistics for the 15 year period (from 2001 to 2015) has been presented in this paper. By using these statistical data values, energy and exergy efficiencies of this sector were calculated annually. From the results, it should be mentioned that the energy consumed in 2015 was much higher than the energy consumption in 2001 of the transport sector. The overall exergy efficiencies in the transportation sector resulted in slightly less values than the corresponding energy efficiencies. The average overall energy and exergy efficiencies for the sector are found to be 21.45% and 20.05% respectively. Transportation in the highway sub-sector has been considered in this paper. Different energy forms were considered here. The technique presented in this paper is advantageous for analyzing the sectoral energy as well as exergy utilization and thus helps in providing the real picture of the transport sector. It helps in the establishment of energy conservation policies. According to the calculations, values of energy and exergy efficiencies did not significantly change in the 15 year period, which revealed the need of a competent transportation policy in India. Hence, suitable government policies should be actively undertaken.

The results yielding through exergy analysis are very crucial and helpful not only in the sectoral level but also in the national level. Furthermore, the results could provide important guidelines and deep insights for future research and development allocations and projects.

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