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An Application of Energy and Exergy Analysis of Transport Sector of India

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Abstract: *The present article is dedicated for evaluating the transportation sector of India in terms of energetic and exergetic aspects. In this regard, energy and exergy utilization efficiencies during the period 2005-2011 are assessed based on real data obtained from Energy statistics of India. Sectoral energy and exergy analyses are conducted to study the variations of energy and exergy efficiencies, overall energy and exergy efficiencies for the entire sub-sector are found to be in the range of 21.30 to 30.03%. When compared with other neighbouring countries, such as Saudi Arabia, Malaysia and Turkey, the Indian transport sector is the least efficient. Such difference is inevitable due to dissimilar transport structure in these countries. It is expected that that the results of this study will be helpful in developing highly useful and productive planning for future energy policies, especially for the transportation sector. This, in turn, will help achieve the 'energy-security' goal of the country.*

Keywords: *Energy, Exergy, Efficiency, Sectoral energy use, Transport sector of India.*

I. Introduction

India's transport sector is large and diverse; it caters to the needs of 1.2 billion people. In 2007, the sector contributed about 5.5 percent to the nation's GDP, with road transportation contributing the lion's share. Good physical connectivity in the urban and rural areas is essential for economic growth. Since the early 1990s, India's growing economy has witnessed a rise in demand for transport infrastructure and services. However, the sector has not been able to keep pace with rising demand and is proving to be a drag on the economy. Major improvements in the sector are required to support the country's continued economic growth and to reduce poverty. [1]

This work represents a brief critical and analytical account of the development of the concept of exergy and of its applications to the society. It is based on a careful and consultation of a very large number of published references taken from archival journals, technical reports, lecture series etc., considered first of its kind in India since there is no such study on energy and exergy utilizations for the transportation sub-sector of India. Furthermore, comparison of obtained results of energy and exergy efficiencies with other countries around the world is carried out. The results obtained are expected to yield useful data in developing 'energy-security' policy targeting towards sustainable development in the hands of energy policy makers of the country.

II. Theoretical And Mathematical Formulation Of Exergy Analysis

2.1 The concept of exergy

Exergy can be defined as a measure of maximum capacity of an energy system to perform useful work as it proceeds to a specified final state in equilibrium within the surroundings. In simple words, we can describe exergy as the ability to produce work. The available work that can be extracted from an energy source depends on the state of its surroundings. The greater the temperature differences between an energy source and its surroundings, the greater the capacity to extract work from the system.

Exergy analysis permits many of the shortcomings of energy analysis to be overcome. Exergy analysis is based on the second law of thermodynamics, and is useful in identifying the causes, locations and magnitudes of process inefficiencies which are not revealed by energy analysis alone based on first law of thermodynamics. The exergy associated with an energy quantity is a quantitative assessment of its usefulness or quality. Exergy analysis acknowledges that, although energy cannot be created or destroyed, it can be degraded in quality, eventually reaching a state in which it is in complete equilibrium with the surroundings and hence of no further use for performing tasks.

2.2 Energy and exergy values for commodities in macrosystems

The exergy of an energy resource can for simplicity often be expressed as the product of its energy content and a quality factor (the exergy-to-energy ratio) for the energy resource. This value relates to the price of the material or resource, which is also partly defined by the environment through, for instance, demand. In assessments of regions and nations, the most common material flows often are hydrocarbon fuels at near ambient conditions. The physical exergy for such material flows is approximately zero, and the specific exergy reduces to the fuel specific chemical exergy ex_f, which can be written as:

$ex_f = \gamma_f H_f$ (1)

where γ_f denotes the exergy grade function for the fuel, defined as the ratio of fuel chemical exergy to fuel higher heating value H_f . [2,3]

Table-1 lists typical values of H_f , ex_f and γ_f for fuels typically encountered in regional and national assessments. The specific chemical exergy of a fuel at T_0 and P_0 is usually approximately equal to its higher heating value H_f.

Table-1: Properties of selected fuels.*

Fuel	H_f (kJ/kg)	Chemical exergy (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
Diesel	39,500	42,265	1.07
Kerosene	46,117	45,897	0.99

* For a reference-environment temperature of 25˚C, pressure of 1 atm and chemical composition as defined in the text. *Source*: Reistad (1975). [4]

2.3 The reference environment for macrosystems

The reference environment used in many assessments of macrosystems is based on the model of Gaggioli and Petit (1977), which has a temperature T_0=25◦C, pressureP_0=1 atm and a chemical composition consisting of air saturated with water vapor, and the following condensed phases at 25◦C and 1 atm: water (H_2O), gypsum ($CaSO_4 \cdot 2H_2O$) and limestone ($CaCO_3$). This reference-environment model is used in this chapter, but with a temperature of 10◦C. [3, 5]

2.4 Efficiencies for devices in macrosystems

Energy η and exergy ψ efficiencies for the principal processes in macrosystems are usually based on standard definitions:

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

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

Exergy efficiencies can often be written as a function of the corresponding energy efficiencies by assuming the energy grade function γ_f to be unity, which is commonly valid for typically encountered fuels (kerosene, gasoline, diesel and natural gas).

Heating

Electric and fossil fuel heating processes are taken to generate product heat Q_p at a constant temperature T_p, either from electrical energy We or fuel mass m_f . The efficiencies for electrical heating are

$\eta_{h,e} = Q_p/W_e$
(4)

and

$\psi_{h,e} = E_x^{Qp}/E_x^{We} = (1 - T_0/T_p)Q_p/W_e$

Combining these expressions yields

$\psi_{h,e} = (1 - T_0/T_p)\eta_{h,e}$
(5)

For fuel heating, these efficiencies are

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

(6)
and

$\psi_{h,f} = Ex^{Qp}/m_f\, ex_f$

or

$\psi_{h,f} = (1 - T_0/T_p)Q_p / (m_f \gamma_f H_f) \approx (1 - T_0/T_p)\eta_{h,f}$
(7)

where double subscripts indicate 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.

Cooling
The efficiencies for electric cooling are

$\eta_{c,e} = Q_p / W_e$
(8)

$\psi_{c,e} = Ex^{Qp} / Ex^{We} = (1 - T_0 / T_p)\, Q_p / W_e$
(9)

or

$\psi_{c,e} = (1 - T_0 / T_p)\, \eta_{c,e}$
(10)

Work production
Electric and fossil fuel work production processes produce shaft work W. The efficiencies for shaft work production from electricity are

$\eta_{m,e} = W / W_e$
(11)

$\psi_{m,e} = Ex^{W} / Ex^{We} = W / W_e = \eta_{m,e}$
(12)
For fuel-based work production, these efficiencies are

$\eta_{m,f} = W / m_f H_f$
(13)

$\psi_{m,f} = Ex^{W} / m_f\, ex_f = W/m_f \gamma_f H_f \approx \eta_{m,f}$
(14)

Electricity generation
The efficiencies for electricity generation from fuel are

$\eta_{e,f} = W_e / m_f H_f$
(15)

$\psi_{e,f} = Ex^{We} / m_f ex_f = W_e / m_f \gamma_f H_f \approx \eta_{e,f}$
(16)

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 produce a change in kinetic energy Δke in a stream of matter m_s, are as follows:

$\eta_{ke,f} = m_s \Delta ke_s / m_f H_f$
(17)

$\psi_{ke,f} = m_s \Delta ke_s / m_f ex_f = m_s \Delta ke_s / m_f \gamma_f H_f \approx \eta_{ke,f}$
(18)

III. METHODOLOGY AND DATA SOURCES

3.1 Analysis of the Transportation Sector

Energy and exergy utilization in the transportation sector is evaluated and analyzed. The transportation sector in India is composed of mainly International aviation, Domestic aviation, Pipeline transport, Roadways and Railways which uses mainly 3 types of fuels, viz. High speed diesel oil (HSDO), Light diesel oil (LDO) and Furnace oil (FO). Another type of fuel that is used is Low sulphur heavy stock oil, however this fuel has not been considered as it has no contribution in the transportation sector.

Mean energy and exergy efficiencies are calculated by multiplying the energy used in each mode by the corresponding efficiency. Then, these values are added to obtain the overall efficiency of the transportation sector.

3.2 Energy efficiencies for the transportation sector

Table-2 provides energy efficiencies for the various types of fuels in the modes of transportation. These values are based on average U.S devices. They seem to represent the general nature of the devices and are assumed to represent the Indian devices in absence of any other more accurate data. Since, vehicles generally are not operated at full load; a distinction is made between rated load (full load) efficiencies and estimated operating load (part load) efficiencies. [4]

Table-2: Efficiencies for the Transport Sector (Process and operating data) [2]

Fuel/Petroleum product	Rated Load/Efficiency (%)	Estimated Operating Load/Efficiency (%)
High speed diesel oil	28	22
Light diesel oil	28	22
Fuel oil	-	15

3.3 Data sources

Amount of fuel consumption by different machineries used in the transportation activities are collected from Energy statistics of India 2013 and presented in Table-3.

Table-3: Energy consumption data for Transport Sector in India for 2005-2011. [1]

Year	Petroleum Product	Consumption ('000 tonnes)
2005	High speed diesel oil	4264
	Light diesel oil	52
	Fuel oil	478

2006	High speed diesel oil	4316
	Light diesel oil	53
	Fuel oil	502
2007	High speed diesel oil	5003
	Light diesel oil	35
	Fuel oil	315
2008	High speed diesel oil	5292
	Light diesel oil	15
	Fuel oil	469
2009	High speed diesel oil	5365
	Light diesel oil	6
	Fuel oil	560
2010	High speed diesel oil	5416
	Light diesel oil	5
	Fuel oil	780
2011	High speed diesel oil	5528
	Light diesel oil	3
	Fuel oil	371

3.4 Steps and procedures for energy and exergy analysis

Energy and exergy efficiencies were determined using (2) and (3) considering grade function as unity. The overall energy efficiency can be easily found by dividing total energy produced by total input energy. [3] The overall weighted mean was obtained for the energy and exergy efficiencies for the fossil fuel processes as well. Weighing factors are the ratio of energy input of each of the fuels to the total input energy of this sector. The device exergy efficiencies are evaluated using data for the years 2005– 2011. Energy and exergy efficiencies were then used to calculate the overall energy and exergy efficiencies of this sector.

Table-4: Energy consumption data for Transport Sector in India for 2005-2011. [1, 2]

Year	Petroleum Product	Consumption ('000 tonnes)	Energy Consumption		Energy Efficiency	
			PJ	%	Rated Load	Estimated Operating Load
2005	High speed diesel oil	4264	178.53	88.67	28	22
	Light diesel oil	52	2.81	1.4	28	22
	Fuel oil	478	20	9.93	-	15
2006	High speed diesel oil	4316	180.71	88.61	28	22
	Light diesel oil	53	2.22	1.09	28	22

	Fuel oil	502	21	10.3	-	15
2007	High speed diesel oil	5003	209.47	93.46	28	22
	Light diesel oil	35	1.46	0.64	28	22
	Fuel oil	315	13.19	5.9	-	15
2008	High speed diesel oil	5292	221.58	91.61	28	22
	Light diesel oil	15	0.63	0.26	28	22
	Fuel oil	469	19.64	8.13	-	15
2009	High speed diesel oil	5365	224.63	90.45	28	22
	Light diesel oil	6	0.25	0.11	28	22
	Fuel oil	560	23.45	9.44	-	15
2010	High speed diesel oil	5416	226.77	87.34	28	22
	Light diesel oil	5	0.21	0.08	28	22
	Fuel oil	780	32.66	12.58	-	15
2011	High speed diesel oil	5528	231.46	93.66	28	22
	Light diesel oil	3	0.125	0.06	28	22
	Fuel oil	371	15.53	6.28	-	15

IV. Data Analysis, Results And Discussions

4.1 Mean and overall energy efficiencies

Generally, the overall or mean weighted energy efficiency is determined by dividing the total energy produced by the total energy output. In this problem, all the fuels have the same part loads. Using the part load efficiency, weighted mean energy efficiency of every fuel can be found. Based on the data listed in Table-4, the weighted mean energy efficiency for the transport sector in the year 2010, e.g., is calculated using equation: $\eta_0 = \eta_{HSDO} + \eta_{LDO} + \eta_{FO}$.

η_0 = (0.8734 x 22) + (0.0008 x 22) + (0.1258 x 15) = 21.119% ≈ 21.12%

4.2 Mean and overall exergy efficiencies

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

i.e: $Ex^W = W$

Thus, for electrical shaft work production, the energy and exergy efficiencies of transportation devices can be shown to be identical.

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

$\psi_{m,e} = Ex^w / Ex^{We} = W / W_e = \eta_{m,e}$

$\psi_{m,e} = \eta_{m,e}$

For fossil fueled shaft work production in transportation devices, the exergy efficiency can be shown to be similar to the energy efficiency:

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

$\psi_{m,f} = Ex^w/ m_f.H_f.\gamma_f$

When γ_f is unity (as is often assumed for most fuels). [Rosen, 1992]. [6]

$\psi_{m,f} = \eta_{m,f}$

Hence, $\eta_0 = \psi_0$

Thus, the overall mean exergy efficiencies for the transportation sector are equal to the overall mean energy efficiencies.

Based on the data listed in Table-4, the weighted mean energy efficiency for the transport sector in the year 2010, e.g., is calculated using equation: $\psi_0 = \psi_{HSDO} + \psi_{LDO} + \psi_{FO}$.

$\Psi_0 = (0.8734 \times 22) + (0.0008 \times 22) + (0.1258 \times 15) = 21.119\% \approx 21.12\%$

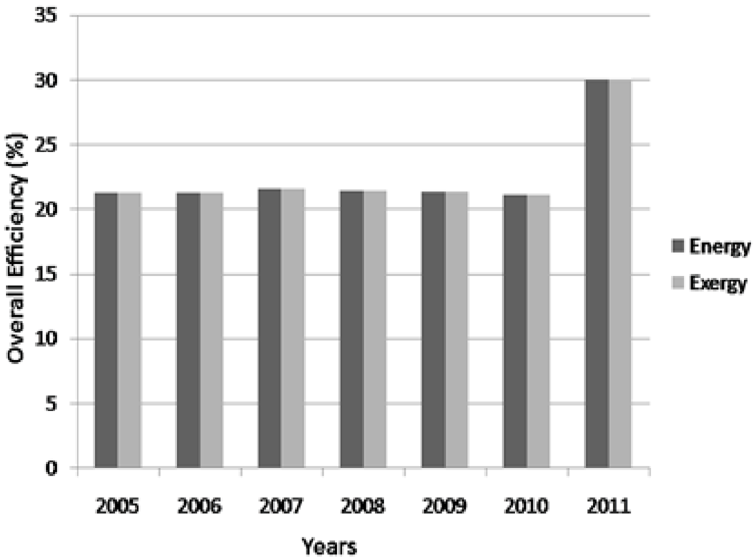

Fig. 1 Overall mean energy and exergy efficiencies for the transport sector for 2005-2011

4.3 Comparison with other countries

Sector and overall energy and exergy efficiencies for India, Saudi Arabia, Malaysia and Turkey are compared. The comparison is based on previous studies, and the data used is for the year 1993 for Saudi Arabia and Turkey and 2005 for India and Malaysia. The efficiencies differ slightly, but the main trends described earlier in this section regarding the differences between energy and exergy efficiencies are exhibited by each country.

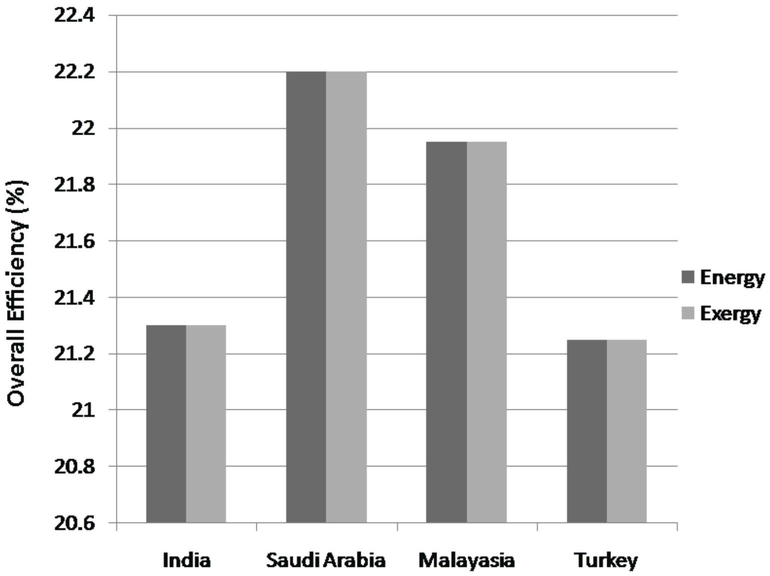

Fig. 2: Comparison of overall energy and exergy efficiencies for the industrial sector of India, Saudi Arabia, Malaysia and Turkey. [1, 2]

When compared with other neighboring countries, such as Saudi Arabia and Malaysia, the transport sector is less efficient. Such difference is inevitable due to dissimilar structure of the modes of transportation in these countries. It is expected that that the results of this study will be helpful in developing highly applicable and productive planning for future energy policies, especially for the Residential, Agricultural , Public and private and Utility sectors.

V. CONCLUSION

In summary, it can be said 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. The results of exergy analyses of processes and systems have direct implications on application decisions and on research and development (R&D) directions. Further, exergy analyses more than energy analyses provide insights into the best directions for R&D effort. The overall mean energy efficiency and the overall mean exergy efficiency in the Indian transportation sector for the period 2005-2011 is 22.55%. This study also shows that airway transportation contribution should be increased to improve the overall energy and exergy efficiencies of the Indian transport sector. It is very necessary in the light of the results of this work that Indian policy makers review the issue of mass importation of used vehicles into the country. All efforts should also be made to ease air transportation and make it affordable for Indians. The Indian railway system should also be resuscitated for cheap and affordable transportation of goods and passengers.

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