An Application of Energy and Exergy Analysis in Industrial Sector of India

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***Abstract*— The present article is dedicated for evaluating the industrial sector 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 67.23% to 77.83%. When compared with other neighbouring countries, such as Saudi Arabia, Malaysia and Turkey, the Indian industrial sector is the more efficient. Such difference is inevitable due to the proper use of fossil-fuel resources. It is concluded that the present technique and associated analysis is beneficial for analyzing sectoral energy and exergy utilization in India and provides the information on how efficiently energy is used. It is also helpful to establish standards to facilitate application in industry and in other processes for a successful energy planning towards sustainable development.**

Keywords—Energy; Exergy; Efficiency; Sectoral energy use; Industrial sector of India.

I. INTRODUCTION

The Indian industrial sector accounts for 26% of GDP and employs 22% of the total workforce. India is 11th in the world in terms of nominal factory output according to data compiled through CIA World Fact book figures. The Indian industrial sector underwent significant changes as a result of the economic liberalization started from the New Economic Policy of 1991, which removed import restrictions, brought in foreign competition, led to the privatization of certain public sector industries, liberalized the FDI regime, improved infrastructure and led to an expansion in the production of fast moving consumer goods.[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 in detail consultation of a very large number of published references taken from archival journals, conference proceedings, technical reports and lecture series., considered first of its kind in India since there is no such study on energy and exergy utilizations for the sub-sector. Furthermore, comparison of obtained results of energy and exergy efficiencies with other countries around the world is carried out.

II. THEORITICAL AND MATHEMATICAL FORMULATION OF EXERGY ANALYSIS

A. *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 from an initial state to specified final state in equilibrium within the surroundings which is called the 'dead state'. Thus evaluation of exergy is always made with respect to a reference surrounding environment. The reference environment is in stable equilibrium, acts as an infinite system, a sink or surface for heat and materials, and experiences only internal reversible processes in which its intensive properties remains constant. In simple words, we can describe exergy as the maximum ability to produce work or, maximum usefulness of the energy content of a system or, an energy resource and it may be noted that not all energy content of a system can be converted into useful work.

Exergy analysis permits to overcome many of the shortcomings of energy analysis. Exergy analysis is based on the second law of thermodynamics, and is useful in identifying the causes, locations and magnitudes of process inefficiencies which cannot be identified by the first law of thermodynamics or, simple energy efficiency alone. The exergy associated with an energy quantity is a quantitative assessment of its usefulness or quality. Exergy analysis is basically a qualitative analysis of the energy used to perform a job say, usage of exergy in industrial sector of a country. The 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.

B. *Energy and exergy values for commodities in macrosystem*

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:

$$ex_f = \gamma_f H_f \quad (1)$$

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]

C. *The reference environment for macrosystems*

The reference environment used in many assessments of macrosystems is based on the model of Gaggioli and Petit [5] which has a temperature T_0=25◦C, pressure P_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.

D. *Efficiencies for devices in macrosystems*

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

$$\eta = \text{(Energy in products) / (Total energy input)} \quad (2)$$

$$\psi = \text{(Exergy in products) / (Total exergy input)} \quad (3)$$

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:

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

and

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

Combining these expressions yields

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

For fuel heating, these efficiencies are

$$\eta_{h,f} = Q_p/m_f H_f \quad (6)$$

and

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

or

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

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

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

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

or

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

Work production

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

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

$$\psi_{m,e} = Ex^W / Ex^{We} = W / W_e = \eta_{m,e} \tag{12}$$

For fuel-based work production, these efficiencies are

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

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

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

Electricity generation

The efficiencies for electricity generation from fuel are

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

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

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:

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

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

III. METHODOLOGY AND DATA SOURCES

A. Analysis of the Industrial Sector

Energy and exergy utilization in the industrial sector is evaluated and analyzed. The industrial sector of India is composed of many industries. Few of the industries are oil and gas, chemical and petro-chemical, iron and steel, cement, power plants, etc. The hierarchical diagram for the Indian industrial sector is shown in Fig-1 and the main fuels that are being used are:

1. High speed diesel oil (HSDO)
2. Light diesel oil (LDO)
3. Furnace oil (FO)
4. Raw coal
5. Lignite

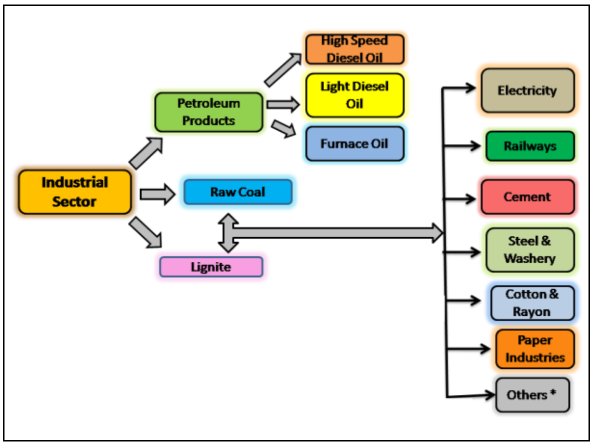

Fig.1. Hierarchy Tree for the industrial sector of India [1]

B. Energy efficiencies for the industrial sector

Table-2 provides energy efficiencies for the various types of fuels used in the industries. 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, machines 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 Industrial 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
Raw Coal	80	70
Lignite	46	40

C. Data sources

Amount of fuel consumption by different machineries used in the industrial activities are collected from Energy statistics of India 2013 [1] and presented in Table-3.

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

Year	Fuel & Petroleum Products	Consumption ('000 tonnes)
2005	HSDO	964
	LDO	325
	FO	1828
	Raw Coal	395590
	Lignite	30340
2006	HSDO	1234
	LDO	244
	FO	1830
	Raw Coal	419800
	Lignite	30800
2007	HSDO	1241
	LDO	200
	FO	1634
	Raw Coal	453570
	Lignite	34660
2008	HSDO	1310
	LDO	155
	FO	2843
	Raw Coal	489170
	Lignite	31790
2009	HSDO	1502
	LDO	143
	FO	3134
	Raw Coal	513790
	Lignite	34430
	HSDO	1440
2010	LDO	127
	FO	2774
	Raw Coal	523470
	Lignite	37690
2011	HSDO	1649
	LDO	102
	FO	2409
	Raw Coal	535730
	Lignite	41880

D. Steps and procedures taken 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 Industrial Sector in India for 2005-2011 [1, 2]

Year	Fuel & Petroleum Products	Consumptions ('000 tonnes)	Energy Consumption		Energy Efficiency	
			PJ	*%*	*Rated Load (%)*	*Estimated Operating Load (%)*
2005	HSDO	964	40.36	0.58	28	22
	LDO	325	13.60	0.19	28	22
	FO	1828	76.54	1.1	-	15
	Raw Coal	395590	6341.3	91.13	80	70
	Lignite	30340	486.35	7.0	46	40
2006	HSDO	1234	51.67	0.7	28	22
	LDO	244	10.21	0.13	28	22
	FO	1830	76.62	1.03	-	15
	Raw Coal	419800	6775.57	91.42	80	70
	Lignite	30800	497.11	6.72	46	40
2007	HSDO	1241	51.96	0.65	28	22
	LDO	200	8.37	0.10	28	22
	FO	1634	68.42	0.85	-	15
	Raw Coal	453570	7320.62	91.4	80	70
	Lignite	34660	559.41	7.0	46	40
2008	HSDO	1310	54.85	0.64	28	22
	LDO	155	6.49	0.07	28	22
	FO	2843	119.04	1.38	-	15
	Raw Coal	489170	7895.2	91.92	80	70
	Lignite	31790	513.09	6.00	46	40
2009	HSDO	1502	62.89	0.69	28	22
	LDO	143	6.00	0.06	28	22
	FO	3134	131.22	1.45	-	15
	Raw Coal	513790	8292.57	91.65	80	70
	Lignite	34430	555.7	6.15	46	40
2010	HSDO	1440	60.29	0.65	28	22
	LDO	127	5.32	0.05	28	22
	FO	2774	116.15	1.25	-	15
	Raw Coal	523470	8448.8	91.44	80	70

	Lignite	37690	608.32	6.61	46	40
2011	HSDO	1649	69.04	0.72	28	22
	LDO	102	4.27	0.04	28	22
	FO	2409	100.86	1.06	-	15
	Raw Coal	535730	8646.68	91.04	80	70
	Lignite	41880	675.94	7.14	46	40

IV. DATA ANALYSIS, RESULT AND DISCUSSION

A. 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 industrial sector in the year 2010, e.g., is calculated using equation:

$$\eta_{0} = \eta_{HSDO} + \eta_{LDO} + \eta_{FO} + \eta_{Raw\ Coal} + \eta_{Lignite}.$$

$$\eta_{o} = (0.0065x28) + (0.005x28) + (0.0125x100) + (0.944x80) + (0.0661x46) = 77.40\%$$

B. Mean and overall exergy efficiencies

Based on the process and operating data listed in Table- 2 and the estimated energy efficiencies, the overall exergy efficiency for industrial sector in the year 2010 is calculated using the equation:

$$\Psi_{0} = \Psi_{HSDO} + \Psi_{LDO} + \Psi_{FO} + \Psi_{Raw\ Coal} + \Psi_{Lignite}.$$

$$\Psi_{0} = (0.0065x22) + 0.005x22) + (0.0125x15) + (0.944x70) + (0.0661x40) = 66.993\% \approx 67\%$$

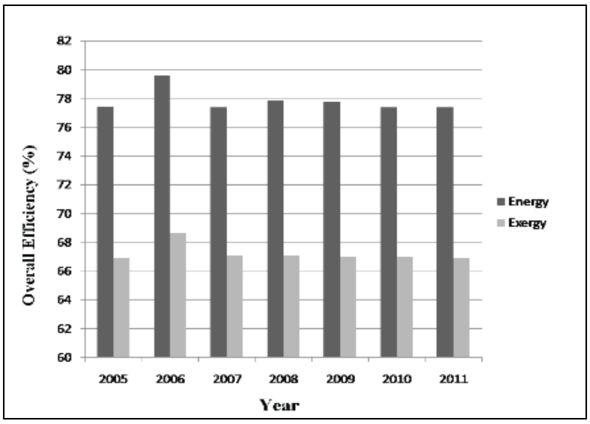

Fig. 2. Overall mean energy and exergy efficiencies for the industrial sector for 2005-2011

C. Comparison with other countries

Sector and overall energy and exergy efficiencies for India, Saudi Arabia, Malaysia and Turkey are compared and the comparison is shown in Fig.3. 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. The Indian industrial sector (including Power sector) is more efficient and such difference is inevitable due to dissimilar structure of the industries in these countries. From the above results it can be said that compared to some other Asian countries like Saudi Arabia, Malaysia and Turkey, the way energy is used in Indian industrial sector is better. Still there is a lot of scope for improvement and thereby reduction in the quantity of energy usage. Since this type of exergy analysis in industrial sector is first of this kind for India, it is expected that that the results of this study will be helpful in developing highly applicable and productive planning for future energy policies. In fact, similar analyses may be extended to cover Residential, Agricultural, Public and private and Utility sectors.

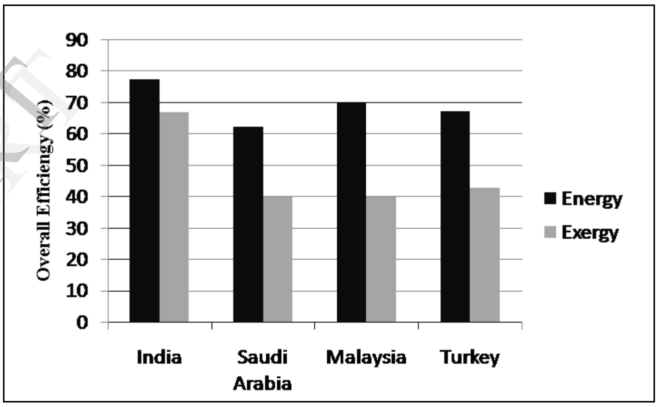

Fig. 3. Comparison of overall energy and exergy efficiencies for the industrial sector of India, Saudi Arabia, Malaysia and Turkey. [1, 2]

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 industrial sector for the period 2005-2011 is 77.8% and 67.23%. This study also shows that domestic industrial contribution should be increased to improve the overall energy and exergy efficiencies of the Indian industrial sector.

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