Resource Utilization and Destruction in Indian Industrial Sectors: An Exergy Analysis

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Section 1 Exergy

Physical exergy attributes are the temperature, pressure, potential head gradient between the system and the surrounding (end state). Thus, the physical exergy (B_{ph}) is given by,

$$B_{ph} = (h - h_0) - T_0(S - S_0) \tag{1.1}$$

Where h and S are the specific enthalpy and entropy (kJ/kgK)

T-Temperature (K)

Subscript '0' denotes conditions of the reference environment

The amount of thermal exergy (B_{th}) transfer associated with heat transfer (Qr) (across a system boundary (r) at constant temperature (Tr) is: Thermal exergy (B_{th}) transfer at constant temperature is given by

$$B_{th} = Q_r(1 - \frac{T_0}{T_r}) \quad \text{(KJ)} \tag{1.2}$$

Chemical exergy (B_{ch}) is attributed to the difference in molecular (chemical) composition between the system and the reference environment (sink). Chemical exergy is, exergy 'embodied' in any substance, it is the maximum amount of work that can be extracted from any substance as it merges or attend the equilibrium (if all possible chemical reactions are allowed to occur) with its own of the three sinks (end states such as solid, liquid and gas) at environmental temperature and pressure. On earth, the three possible end states (reference states) are atmosphere, sea water and the top layer of the earth crust and their respective compositions [1].

The chemical exergy of any compound can be calculated from the standard chemical exergy values of the elements, considering its reference reaction as follows [2,3].

$$B_{ch,k}{}^0 = \Delta G_r{}^0 + \sum_k \gamma_k b_{ch,k}{}^0 \tag{1.3}$$

where $\gamma_k and b_{ch,k}{}^0$ are the number of moles and the standard chemical exergy (KJ/mol) of the kth reference species respectively. 0 denotes that reference temperatureT_0 (298.15 K) and standard pressure p_0 (standard atmosphere or101325 Pa) of the reference system are assumed [2].

The chemical exergy of different energy and material resources are represented as follows [4].

$$B_{ch,i}{}^0 = \sum_i n_i(\mu_i - \mu_{i\,O}) + \mathrm{RT}_o \sum_i n_i \, ln \frac{C_i}{C_{i\,O}} \qquad (1.4)$$

Where T_o is the temperature of the environment, n_i is the i'th mole number, μ_i is the chemical potential of substance I in the present state, $\mu_{i\,O}$ is the chemical potential of substance I in the reference environment, C_i is the chemical concentration of substance I in the present state, $C_{i\,O}$ is the chemical concentration of substance I in the reference environment.

Standard chemical exergy of carbon is estimated using the standard chemical exergy of the reference species and the value of free energy of formation (ΔG_f) of the reaction

CO_2 generated by combustion reaction is given as follows

$$C + O_2 - - - \rightarrow CO_2$$

1 mole carbon to 1 mole carbon dioxide

12 molecular weight to 44 molecular weight

Gibbs function of formation is

$\Delta G_f = -394.3 \left(\frac{KJ}{mol}\right)$[5]

Estimating the standard chemical exergy of the CO_2 using following equation with an assumption of ideal gas behaviour and atmospheric air as a reference environment.

$$b_{ch,n} = RT_0 \ln\left(\frac{P_n}{P_{0,n}}\right) = RT_n \ln\left(\frac{1}{x_{in}}\right) \qquad (1.5)$$

where: R gas constant,

T_0 standard ambient temperature (298.16 K),

$P_{0,n}$ conventional mean ideal gas partial pressure in the atmosphere (kPa),

P_n standard atmospheric pressure (101,325 kPa),

$$b_{ch,co2} = RT_0 \ln\left(\frac{P_n}{P_{0,co2}}\right)$$

where: R gas constant (0.008314 KJ/mol K),

T_0 standard ambient temperature (298,15 K),

$P_{0,co2}$ partial pressure of CO_2 the atmosphere (0.039 kPa),

Pn standard pressure (101.325 kPa),

$$b_{ch,co2} = 0.008314 \times 298.16 \times \ln(\frac{101.325}{0.039})$$

$$b_{ch,co2} = 19.49\ (\frac{KJ}{mol})$$

Chemical exergy of carbon is estimated, using the estimated vales of the standard chemical exergy of the CO_2, O_2 and the value of free energy of formation (ΔG_f) of the reaction

$$b_{ch,c} = -\Delta G_f + (1 \times b_{ch,CO2} - 1 \times b_{ch,O2}$$

$$b_{ch,c} = 394.3 + (1 \times 19.49 - 1 \times 2.398)$$

$$b_{ch,c} = 409.82\ (\frac{KJ}{mol})$$

Chemical exergy of a gaseous mixture is given by [6]

$$B_{ch,i}{}^{0} = \sum_i n_i(\mu_i - \mu_{i\,O}) + \mathrm{RT}_o \sum_i n_i\, ln \frac{C_i}{C_{i\,O}}$$

regarding the reaction of water formation as

$$H_2 + \frac{1}{2} O_2 - -\!\!-\!\!\rightarrow H_2O$$

1 mole hydrogen to 1 mole H_2O

$$\Delta G_f = -273.2\ (\frac{KJ}{mol})$$

$$b_{ch,H_2} = -\Delta G_{f(H_2O)} + (1 \times b_{ch,H_2O} - \frac{1}{2} \times b_{ch,O2})$$

$$b_{ch,H_2} = 235.2\ kJ/mol$$

Calculation of the standard chemical exergy of methane vapour. The reaction of formation is

$$C + 2H_2 - - - \rightarrow CH_4$$

Gibbs function of formation is

$$\Delta G_f = -508.19\ (\frac{KJ}{mol})^7$$

$$b_{ch,C} = 410.53\ (\frac{KJ}{mol})$$

$$b_{ch,H_2} = 238.35(\frac{KJ}{mol})$$

$$b_{ch,H_2} = \Delta G_{f(CH_4)} + (1 \times b_{ch,C} + 2 \times b_{ch,H_2})$$

$$= -508.19 + (409.82\ + 2 \times 238.35)$$

$$b_{ch,CH_4} = 836.42 \frac{kJ}{mol}$$

Exergy factor (exergy coefficients) is the ratio of standard chemical exergy content to net calorific energy content [8]. In Table 1 exergy factors for selected energy forms are shown, that are used in this study.

Table 1: Exergy factors for fuel[8, 9, 10]

Fuel forms	Exergy factors
Coal	1.06
Coke	1.05

Crude oil	1.08
Gasoline	1.07
Diesel oil	1.06
Kerosene	1.07
Fuel oil	1.06
LPG	1.06
Other petroleum products	1.06
Natural gas	1.04
Electricity	1.0

Sample calculation of exergy factor for coal [11][12]

Exergy factor for dry organic substances contained in solid fuels consisting of C, H, O and N with mass ratio of oxygen to carbon less than 0.667 is given by following equation[11]

$$\varphi_{dry} = 1.0437 + 0.1882\frac{h}{c} + 0.0610\frac{o}{c} + 0.0404\frac{n}{c}$$

Where c, h o and n are the mass fractions of carbon, hydrogen, oxygen and nitrogen respectively.

Therefore the exergy factor for anthracite coal having net calorific value 289.40 KJ/kg and with the following composition by mass: C=0.782, H=0.024, N=0.009, S=0.010, O=-0.015, and ash=0.080 is estimated from above equation.

$$\varphi_{dry} = 1.0437 + 0.1882 \times \frac{0.024}{0.782} + 0.0610 \times \frac{0.015}{0.782} + 0.0404 \times \frac{0.009}{0.782}$$

$$\varphi_{dry} = 1.0511$$

Chemical exergy of the anthracite coal is estimated as follows[11]

$$e^{\cdot} = [(NCV) + 2.44 \times w]\varphi_{dry} + 9.417 \times s$$

Net Calorific Value $(NCV)$of anthracite coal is $u^{\cdot}$ =289.40 KJ/kg

$$e^{\cdot} = [289.40 + 2.442 \times 0.080] \times 1.0511 + 9.417 \times 0.010$$

$$e^{\cdot} = 307.18\ KJ/kg$$

Exergy Factor for anthracite coal

$$\varphi = \frac{e^{\cdot}}{u^{\cdot}}$$

$$\varphi = \frac{307.18}{289.40} = 1.061$$

Section 2 Utility Sector

Since electricity is not a material good, it is regarded as a `utility' service. Electricity being pure form of energy, has ease of convenience for many end use applications. Its demand has been observed to increase with time, economic development, industrialization, and all sorts of anthropogenic activities, and will continue to be in the future.

India has 84 0007 MW of hydroelectric potential, however, only 38.5% (or 32 300 MW) of this potential has been developed (2008)[13] Though India has a very ambitious Nuclear power Programme, its contribution to the total electricity generation is very less (3 % of total). Figure 1 shows the % share of electricity generation technologies in India over the period 1990-to-2010. The electricity generation demand is expected to shoot-up and cross 300 GW in next 10 years. With increase in consensus about the environmental emissions and its impact on the environment, there are sudden increase in opportunities for renewable energy technologies. India has been one of the strongest and abundant renewable energy (wind and Solar energy) resources. In 2010 installed renewable power generating capacity in India is 17 GW[14]. India also had installed 2767 MW of small hydro plants (size less than 25 MW), 1412 MW cogeneration from bagasse and 901 MW of biomass based power generation from agriculture residues. In spite of this electricity generation from renewable resources contributing only 1-to-2% of the annual electricity requirement of the country. India has abundant amount of solar energy. Most surface area in India receives sunlight for almost 250-300 days in a year, with 4-7 KWh of solar radiation exposed per square meter which is suitable for Solar power generation [15]. India receives solar energy equivalent to over 5000 trillion KWh/year [16]. So far 3 million square meters of solar thermal systems have been installed providing 15 million litters per day of hot water. In addition, there are 372,293 solar cookers [17]. The biggest hurdle with the adoption of solar energy is the comparative cost of electricity generation, for Solar Photo Voltaic PV it cost INR 12-20/KWh while for coal fuelled thermal power generation it is INR 1-2/KWh. Solar Photo Voltaic has slowly started some acceptance In India, so far 58MWe capacity has been installed through 750,000 systems including solar lanterns, home lightning systems, street lighting systems, water pumping systems, small power plants [16]. Because of technological or economic feasibility constraints India has been unable to tap and convert renewable resources in to useful form of energy/work, up to the capability exist in the country. Renewable energy sources like Wind, Solar and Hydro power can help to reduce the burden on the availability of fossil fuel resources in order to satisfy the energy need of the society. Despite having higher potential (600 billion kWh annually) for hydropower, only 38.5 % of this potential has been developed [18]. Though wind energy has been used in India from ancient times for applications like water pumping, it has had a very small share to the total electricity generation in the country. With increasing awareness about the environmental emissions associated with fossil fuel and international pressure due to Kyoto Protocol India has witnessed substantial growth in wind energy sector in last decade. India ranks fifth in the world after Germany, USA, Spain and Denmark with installed capacity of 300 MW Wind energy generation capacity, in the year 2007-08 [16]. An estimate shows that India has potential of wind power generation of about 45000 MW [16] Most of the coastal region in south part of the country is suitable for wind power generation. Ministry of New and Renewable energy, Government of India has one of the most ambitious programs for renewable energy in the world. Jawaharlal Nehru Solar mission has the ambitious of generation of 20000 MW electricity generation from solar energy. Because of supportive role of Ministry of New and Renewable Energy (MNRE) in the development of renewable technologies lot of private companies in India and abroad have invested in India for solar and wind power generation. In 2007, India had 174946 megawatts (175 GW) of installed electric generation capacity from utility and nonutility sector (India stat) and generated 813103 Million kWh (CMIE, Energy, March 2010, Page 112-124). Despite such huge generation, till today electrification rate is only 44% still about 404 million people in India lack access to electricity and per capita consumption of electricity is only 350 kWh per annum, which is much lower than the world average of over 2000 kWh [19]. In India transportation and distribution (T&D) losses are very high, average transportation and distribution losses are approximately 30-45 %, in some states the T&D losses reached up to 50% which is very high as compared to other developing and developed societies. For US the T&D losses are just 5 % of the total electricity generation[20]. Because of the dominance of fossil fuels in the generation mix for electricity generation in India, this sector has become the largest contributor to the environmental degradation. More than 40% of the total carbon emissions come from fossil fuelled based electricity generation [21].

Exergy values of resource consumed were further used for the estimation of exergetic efficiency of electricity generation technology. Exergy efficiency was calculated using equation 1.1 and the trend was analysed for the various technologies of electricity generation technologies in India, the trends are shown in Figure 2.1.3. For fossil fuelled thermal power generation the work done is the electricity generated while as the exergy input is the exergy of fossil fuel (Coal, Natural gas, diesel) consumed for the thermal power generation. For hydropower the work done is the electricity generated in hydropower station and the exergy input is the potential energy difference of the falling water. The exergy input of the flowing water input to hydroelectricity and nuclear power generation was estimated as the product of reciprocal of reported exergy efficiency of these technologies and the measured electrical output. Hydro power has been by far the most efficient technology for the electricity generation from second law (exergy) perspective. The reported exergy efficiency of hydroelectric station used for the calculation here in this work is 85 % [22]. There are different opinions/viewpoint/speculations among the researchers regarding the exergy of the nuclear fuel. Most generally the heat exergy (thermal exergy) of the nuclear fuel is taken for calculation [23]. For nuclear power generation in Light Water, Heavy Water and Prototype Fast Breeder Reactor, the exergy input from Uranium (radioactive element) is the exergy released when the (small atomic weight) light uranium atoms (nucleons) regroup in to heavy atom in fusion reaction or by splitting of heavy atoms in to neutrons and light atoms in fission reaction [24].

$$\text{Exergy Efficiency} = \frac{\text{Work Done}}{\text{Exergy of Input}}$$

Sample calculation for coal fuelled thermal electricity generated in India in year 2007-08.

Electricity generated= 540567.00

Exergy associated with electricity produced= 1946.04 PJ

Coal exergy consumed = 6083.65 PJ

$$\text{Exergy Efficiency for coal fuelled thermal power generation} = \frac{1946.04}{6083.65} \times 100$$

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=31.99 %

Similarly, the exergy efficiency of various electricity generation technologies in India have been estimated and the values are tabulated in following Table 2.

Table 2. Exergy efficiencies of electricity generation technologies in India

	Coal Fueled Electricity	Lignite Fueled Electricity	Natural Gas Fueled	Diesel Fueled Electricity	Nuclear Electric Power	Hydro Electricity	Total Electricity

			Electricity				
1970-71	-	-	-	-	33.00	85.00	49.30
1971-72	34.76	-	10.45	-	-	85.00	51.29
1972-73	34.71	-	12.17	-	33.00	85.00	48.56
1973-74	33.99	-	9.54	-	33.00	85.00	48.18
1974-75	36.52	-	11.80	-	33.00	85.00	44.41
1975-76	34.63	-	12.53	-	33.00	85.00	43.44
1976-77	34.25	-	12.70	-	33.00	85.00	42.40
1977-78	36.48	-	12.27	-	33.00	85.00	45.08
1978-79	38.77	-	9.05	-	33.00	85.00	48.12
1979-80	34.03	-	10.33	-	33.00	85.00	43.47
1980-81	28.90	-	11.40	-	33.00	85.00	36.36
1981-82	27.95	-	11.64	-	33.00	85.00	35.48
1982-83	29.67	-	17.41	-	33.00	85.00	35.80
1983-84	28.43	-	17.03	-	33.00	85.00	34.38
1984-85	32.11	-	13.29	-	33.00	85.00	37.15
1985-86	30.97	-	14.93	-	33.00	85.00	35.57
1986-87	30.04	-	16.21	-	33.00	85.00	34.39
1987-88	30.08	-	13.99	-	33.00	85.00	33.04
1988-89	30.49	-	17.77	-	33.00	85.00	34.50
1989-90	30.65	-	30.55	-	33.00	85.00	34.86
1990-91	33.26	-	24.62	-	33.00	85.00	37.52
1991-92	33.16	-	25.14	-	33.00	85.00	36.99
1992-93	32.45	-	29.41	-	33.00	85.00	36.23
1993-94	31.93	-	33.58	-	33.00	85.00	35.76
1994-95	32.07	-	37.61	-	33.00	85.00	36.58

1995-96	31.27	-	38.69	-	33.00	85.00	35.00
1996-97	30.43	-	41.50	24.52	33.00	85.00	33.33
1997-98	32.06	-	44.52	27.07	33.00	85.00	35.24
1998-99	31.37	-	51.23	28.16	33.00	85.00	35.52
1999-00	31.28	-	60.06	38.96	33.00	85.00	35.97
2000-01	31.27	17.42	59.30	40.66	33.00	85.00	33.72
2001-02	27.24	17.23	55.53	41.17	33.00	85.00	33.40
2002-03	32.82	17.14	53.77	50.45	33.00	85.00	34.21
2003-04	32.48	17.85	57.00	46.27	33.00	85.00	34.54
2004-05	31.37	23.64	56.88	36.13	33.00	85.00	33.79
2005-06	-	24.13	-	36.56	-	-	-
2006-07	32.87	24.18	59.62	29.63	33.00	85.00	35.75
2007-08	31.99	25.56	71.15	31.98	33.00	85.00	33.38

Section 3 Industry Sector

Sample calculation of exergy efficiency for Iron & Steel Industry in India (2007-08)

Energy utilization in the industry sector is categorized according to the energy use as follows

Table 3. Energy use in the industrial sector in India by type of Use (%)

Use Category	Electrical	All Fuels
Mechanical Drive	65	0
Heating	28	100
Others (Assumed Lighting)	7	0
TOTAL	100	100

INPUTS

Total Electric energy consumed in the Iron & Steel Industry= 75.78 PJ

Total Electric exergy consumed in the Iron & Steel Industry= 75.78 PJ

Total Fuel energy consumed in the Iron & Steel Industry= 369.21 PJ

Total Fuel exergy consumed in the Iron & Steel Industry= 391.37 PJ

[I] Mechanical Drive

Since 65 % of the electric energy is used for mechanical drive application

Energy & $exergy\ input\ for\ mechanical\ drive = 75.78 \times 0.65 = 49.26\ PJ$

Mechanical drives are assumed to be 90 % efficient

Enegy & $exergy\ output\ for\ mechanical\ drive = 49.26 \times 0.90 = 44.33\ PJ$

[II] Heating

Process heating in the industry is subdivided in to three categories based on the temperature ranges as follows. The temperature range and the efficiency values are taken from the study of Dincer et al.[25]

Table 4. Process heating temperatures and efficiencies for the industrial sector

Category	Temperature (° C)	Electrical (%)	Fuel (%)
Low	<121	100	65.5
Medium	121–399	90	60
High	>399	70	50

Breakdown of the energy used for each temperature range in the industry is referred from the Brown et al. study for 108 industrial processes.

From this study the breakdown for Iron & steel Industry is given as follows

Table 5. Breakdown of energy used for each temperature (%)

Industry	T range	T0	Mean T (°C)	Electricity	Fuel
Iron and steel	Low	25	45	4.2	0
	High	25	983	95.8	100

Exergy efficiency of low temperature electric heating = 45+273 = 318K and η= 100 %

$$\Psi_{\mathrm{e\,h\,Low}} = 1 \times \left[1 - \left(\frac{298}{318}\right)\right] = 6.28\ \%$$

Exergy efficiency of high temperature electric heating: T = 983+273 = 1256 K and η= 70 %

$$\Psi_{e\,h\,high} = 0.7 \times \left[1 - \left(\frac{298}{1256}\right)\right] = 53.39\%$$

Exergy efficiency of low temperature fuel heating: T = 45+273 = 318 K and η = 65 %

$$\Psi_{f\,h\,Low} = 0.65 \times \left[1 - \left(\frac{298}{318}\right)\right] = 4.08\ \%$$

Exergy efficiency of high temperature fuel heating: T = 983+273 = 1256 K and η = 50 %

$$\Psi_{f\,h\,high} = 0.5 \times \left[1 - \left(\frac{298}{1256}\right)\right] = 38.13\ \%$$

Energy efficiency of electric heating= efficiency × percentage of electric energy used

$$\eta_e = 100\% \times 4.2\% + 90\% \times 0\% + 70\% \times 95.8\% = 71.26\%$$

Energy efficiency of fuel heating= efficiency× percentage of fuel energy used in iron & steel industry

$\eta_{f} = 65\% \times 0\% + 60\% \times 0\% + 50\% \times 100\% = 50\%$

Exergy efficiency of electric heating= efficiency×% electric energy used in iron & steel industry

$$\Psi_e = 6.28\% \times 4.2\% + 53.39\% \times 95.8\% = 51.0\%$$

Exergy efficiency of fuel heating= efficiency×% fuel energy used in iron & steel industry

$$\Psi_f = 7.2\ \% \times 0\ \% + 38.7\ \% \times 100\ \% = 38.7\ \%$$

In Industry 28 % of the electricity is used for heating applications.

Energy Efficiency of heating

$$\eta_q = \frac{(\text{Electric energy used} \times \text{efficiency} + \text{Fuel energy used} \times \text{efficienfy})}{(\text{Electric energy} + \text{Fuel Energy input})}$$

$$\eta_q = \frac{(75.78 \times 0.28 \times 0.713 + 369.21 \times 0.50)}{(75.78 \times 0.28 + 369.21)}$$

$$\eta_q = 51.15\ \%$$

Exergy Efficiency of heating

$$\Psi_q = \frac{(\text{Electric exergy input} \times \text{efficiency} + \text{Fuel exergy input} \times \text{efficienfy})}{(\text{Electric exergy} + \text{Fuel Exergy input})}$$

$$\Psi_q = \frac{(75.78 \times 0.28 \times 0.514 + 391.37 \times 0.387)}{(75.78 \times 0.28 + 391.37)}$$

$$\Psi_q = 39.35\ \%$$

Energy Output of heating $=$ Energy Input $\times$ Energy Efficiency for heating

$$\text{Energy Output of heating} = 75.78 \times 0.28 \times 0.72 + 369.21 \times 0.50 = 199.88\ \text{PJ}$$

$$\text{Exergy Output of heating} = \text{Exergy Input} \times \text{Exergy Efficiency for heating}$$

$$\text{Exergy Output of heating} = 75.78 \times 0.28 \times 0.52 + 391.37 \times 0.387 = 162.35 \text{ PJ}$$

[III] Lighting

7 % of electricity is used for lighting application

$$\text{Energy } \& \ exergy\ input\ for\ lighting = 75.78 \times 0.07 = 5.30\ PJ$$

Lighting energy and exergy efficiencies are assumed as 18.5% and 17.1%

$$\text{Enegy output for lighting} = 5.30 \times 0.185 = 0.98 \text{ PJ}$$

$$\text{Exegy output for lighting} = 5.30 \times 0.17 = 0.90 \text{ PJ}$$

$$\text{Total Energy Input} = \text{Aggrigate energy input for heating, lightening and mechanical drive}$$

$$\text{Total Energy Input} = 369.21 + 75.78 = 444.99 \text{ PJ}$$

$$\text{Total Exergy Input} = 391.37 + 75.78 = 466.78 \text{ PJ}$$

$$\text{Total Energy output} = 199.88 + 44.33 + 0.98 = 245.19 \text{ PJ}$$

$$\text{Total exergy output} = 162.35 + 44.33 + 0.90 = 207.58 \text{ PJ}$$

$$\text{Overall energy efficiency} = \frac{\text{Total energy output}}{\text{Total energy input}} \times 100$$

$$= \frac{245.19}{444.99} \times 100 = 55.10\ \%$$

$$\text{Overall exergy efficiency} = \frac{\text{Total exergy output}}{\text{Total exergy input}} \times 100$$

$$= \frac{207.58}{466.78} \times 100 = 44.34\ \%$$

Similarly the exergy efficiency for Fertilizers, Chemical, Cement industry, etc., has been obtained using the same methodology as mentioned above for Iron and Steel industry and the corresponding values are Tabulated in Table 6. The results of exergy efficiency for various industries are compared with other studies.

Table 6. Exergy efficiency in Industry

Industry exergy efficiency						
	Cement	Chemical and petroleum	Fertilizer	Iron and steel	Sugar	Non-specified
1990-91	33.65	23.38	25.74	40.76	75.99	14.66
1991-92	33.64	21.63	25.69	40.87	75.99	14.68
1992-93	33.57	22.34	25.68	40.92	75.99	14.70
1993-94	34.07	23.71	25.72	41.05	75.99	14.73
1994-95	33.88	23.06	25.77	41.24	75.99	14.72
1995-96	34.59	22.46	25.40	41.41	75.99	15.68
1996-97	34.94	23.30	25.95	41.26	75.99	14.82
1997-98	35.28	23.40	25.42	41.71	75.99	14.98
1998-99	34.33	24.41	25.45	41.84	75.99	15.11
1999-00	35.71	24.27	25.44	42.56	75.99	15.40
2000-01	34.09	25.86	25.43	43.12	75.99	15.91
2001-02	34.38	24.32	25.77	43.20	75.99	17.36
2002-03	34.40	28.41	25.99	42.65	75.99	17.24
2003-04	34.88	30.63	25.05	45.26	75.99	15.86
2004-05	34.48	30.89	25.13	44.71	75.99	15.97
2005-06	34.80	32.15	25.18	43.55	75.99	15.51
2006-07	35.30	36.10	24.77	45.86	75.99	15.49
2007-08	35.40	-	24.47	45.21	75.99	15.60
2008-09	38.30	-	24.58	45.49	75.99	15.43

Section 4 Residential Sector

Exergy analysis has been used and it is find to suitable to evaluate the performance of the Residential and Commercial Sector in India. The exergy efficiency data for the residential sector, available in the literature was used for the calculating the exergy efficiency of residential sector. The values of the exergy efficiency of home appliance are given in Table 7.

Table 7. Exergy Input for various applications in residential sector 2007

Q2Application	Exergy	Unit
Electric Water Heater	58.67	PJ
Fans	81.81	PJ
Air cooler	29.13	PJ
Air-conditioning	8.31	PJ
Refrigerator	84.56	PJ
Washing machines	1.12	PJ
Electric Oven	1.83	PJ
Toaster	0.94	PJ
Microwave	2.22	PJ
Entertainment	6.57	PJ
CD Player	9.23	PJ
TV	53.89	PJ
DVD/VCR	0.54	PJ
Computer	0.31	PJ
Lighting	149.18	PJ
Entertainment	70.55	PJ
Kitchen Appliances	90.68	PJ
Heating/Cooling	177.91	PJ
Cooking Appliances (LPG)	546	PJ
Fuelwood/Firewood appliances	3348.00	PJ
Kerosene based cookstove	420.77	PJ
Total	**5142.2**	**PJ**

Table 8. Exergy efficiency, product and reference temperatures of different appliances

Appliance	Tp (K)	T0 (K)	Exergy eff (%)
Fluorescent light	–	–	18.5
TV	–	–	80
Fan	–	–	80
Iron	432	300	30
Refrigerator	265	300	7
Rice cooker	382	300	17.2
Washing machine	–	–	80
Bulb	–	–	25
Hi-fi	–	–	70

Blender/mixer/food processor	–	–	80
Vacuum cleaner	–	–	70
Sandwich maker/toaster	432	300	30
Kettle	341	300	10.8
Hand phone charger	–	–	70
Hair dryer	–	–	70
Air conditioner	287	308	4.09
PC	–	–	70
Microwave oven	–	–	70
Water heater	323	300	2.54
Electric stove	324	300	7.3
Electric Gate	–	–	80
Electric water filter	–	–	70
VCD/VCR/DVD player	–	–	70
Cooking appliances (LPG)	393	300	14.88

Sources: Rosen and Dincer (1997), Utlu and Hepbasli, (2003) and Dincer et.al.

Sample Calculation for Exergy Efficiency of Residential Sector 2007

Total Electric energy consumed for Electric Water Heater =16298 GWh

$$= 16298(\mathrm{GWh}) \times \frac{0.0036}{1000000}\frac{(\mathrm{PJ})}{(GWh)}$$

$$= 58.61\ (\mathrm{PJ})$$

Exergy efficieny of electric water heater= 2.54

Exergy Output of electric water heater$= 58.61\ (\mathrm{PJ}) \times 2.54$

$$= 1.49\ \mathrm{PJ}$$

Similarly the exergy output was estimated from exergy input and exergy efficiency values for various end use applications in Residential and commercial sector and the values are tabulated in Table 9.

Table 9. Exergy output from residential sector in India, for 2007-08

Exergy Output (PJ)	
Particulars	**PJ**
Electric Water Heater	58.67
Fans	81.81

Air cooler	29.13
Air-conditioning	8.31
Refrigerator	84.56
Washing machines	1.12
Electric Oven	1.83
Toaster	0.94
Microwave	2.22
Entertainment	6.57
CD Player	9.23
TV	53.89
DVD/VCR	0.54
Computer	0.31
Lighting	149.18
Entertainment	70.55
Kitchen Appliances	90.68
Heating/Cooling	177.91
Cooking appliances (LPG)	545.98
Fuel wood/ Firewood appliances	3348.00
Kerosene based cook stove	420.77
Total	719.77

From the values of exergy of resources consumed and the exergy output the exergy efficiency for residential sector has been estimated as follows.

Total exergy input in Residential & Commercial sector for 2007=5142.2 PJ

Total exergy output from Residential & Commercial sector for 2007=719.65 PJ

$$\text{Overall exergy efficiency} = \frac{\text{Total exergy output}}{\text{Total exergy input}} \times 100$$

$$= \frac{5142.2}{719.65} \times 100 = 14\ \%$$

Section 5 Transport Sector

$$\text{Exergy Efficiency} = \frac{\text{Work Done}}{\text{Exergy of Input}}$$

Sample calculation for exergy efficiency of Transport Sector of India for the year 2007-08.

Table 10: Exergy Input from various resources in Transport Sector of India for 2007-08

Resource consumed in Transport Sector for 2007-08	Exergy Consumed (PJ)
Electricity	39.99
Gasoline	480.80985
Diesel	1264.85612
Aviation Turbine fuel	221.3704
Natural Gas	1.56
Heavy Fuel Oil	13.49
Lubricants	120.3073814
Lifgt Diesel Oil	1.66
Furnance Oil	14.96
Total Exergy Input	2159.00

Table 11: Exergy efficiency for various modes of Transport.

Transport Mode	**Exergy Efficiency (%)**
International aviation	28.28
Domestic aviation	28.28
Road	22.22

Rail	28.00
Domestic navigation	15.15

Table 12: Exergy Output from various modes of Transport In India for 2007-08

Transport Mode	Exergy Output (PJ)
International aviation	62.60
Domestic aviation	0.01
Road	382.58
Rail	16.42
Domestic navigation	3.32
Total exergy output	464.93

Exergy output= 464.94 PJ

Exergy of fuel consumed = 2159 PJ

$$\text{Exergy Efficiency for transport sector} = \frac{464.94}{2159} \times 100$$

`

=21.53 %

Section 6 Agriculture Sector

Exergy conversion efficiency values for Agriculture Sector were estimated and has been evaluated over a past four decades. Figure 2.5.2 shows the trend of exergy efficiency of agriculture sector.

Sample Calculation

$$\text{Exergy Efficiency} = \frac{\text{Work Done}}{\text{Exergy of Input}}$$

Table 13: Exergy Input from various resources in Agriculture Sector of India for 2007-08

Resource consumed in Agriculture Sector for 2007-08	Exergy Consumed (PJ)
Electricity	375.06
Natural Gas	6.41
Diesel	473.40
Lifgt Diesel Oil	0.14
Total Exergy Input	855.01

Table 14: Exergy efficiency for various fuel conversion in Agriculture Sector.

Fuel	**Exergy Efficiency (%)**
Electricity	90%
Fossil Fuels	22 %

Table 15: Exergy Output from various modes of Agriculture In India for 2007-08

Transport Mode	**Exergy Output (PJ)**
Exergy output from Electricity use	337.55
Exergy output from Fossil fuel use	105.59

Total exergy output	443.14

For the year 2007-08,

Total work output (useful work obtained from fuel and electricty consumption)=443 14 PJ

Total exergy consumed =855 PJ

$$\text{Exergy efficiency for agriculture sector} = \frac{443.14}{855} \times 100 = 51.83\%$$

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