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Energy and exergy analyses of energy consumptions in the industrial sector in South Africa

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Abstract

The energy-utilization over a 10-year period (1994–2003) has been analysed for the South African industrial sector, which consumes more primary energy than any other sector of the economy. Four principal sub-sectors, namely iron and steel, chemical and petrochemical, mining and quarrying, and non-ferrous metals/non-metallic minerals were considered in this study. Primary-energy utilization data were used to calculate the weighted mean energy and exergy efficiencies for the sub-sectors and then overall values for the industrial sector were obtained. The results indicate that exergy efficiency is considerably lower than energy efficiency in all the sub-sectors, particularly in mining and quarrying processes, for which the values were approximately 83% and 16%, respectively. The performance of exergy utilization in the industrial sector can be improved by introducing various conservation strategies. Results from this study were compared with those for other countries.

Keywords: Energy; Exergy; Industrial energy-consumption; South African energy-utilization

Introduction

Up until about 1970, energy seemed abundant and cheap so that an increase in global annual energy-consumption, especially in developed economies was not a major concern. By the mid 1970s, recurrent fuel shortages, insecurity of crude-oil supplies and hiking unit

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prices altered perceptions. As the world's fossil-fuel resources are limited, energy has to be used in an economic manner to prevent the rapid depletion of fossil-fuel reserves, save costs and mitigate the production of green-house gases that cause environmental degradation. Availability of energy in the right quality, sufficient quantity and reasonable cost is now a principal requirement for sustainable development.

The First Law of Thermodynamics is conventionally used to analyse energy consumption and plant performance, but unfortunately it is unable to account for the quality of energy. This is where exergy analysis becomes relevant. Exergy is a consequence of the Second Law of Thermodynamics and it measures the quality of energy in a plant or process. Exergy investigations of the energy-consumption have been carried out for various countries, namely Canada [1], Japan [2], Saudi Arabia [3,4], Sweden [5], Turkey [6–9], UK [10] and US [11], but no similar study has been done for South Africa. However the energy industry in South Africa is well-developed and the energy-consumption per capita is comparable with those of industrialised nations, as shown in Fig. 1. Sufficient end-use data are available for meaningful energy and exergy analyses. Therefore the primary objective of this study is to use current energy and exergy modelling techniques for the industrial sector of South Africa.

South Africa is endowed with abundant reserves of coal, which are estimated at more than 55 billion tonnes and it is used to generate the bulk of grid electricity there. The country has approximately 261,000 ton of uranium. It is exploited in nuclear-power generation, which currently accounts for about 5% of the national electricity production. There is limited potential for crude-oil, natural gas and hydro resources, but the bulk of oil demand is met through importation. However the technology for the conversion of coal is well established. Together hydro, pumped storage and gas turbines generate 9% of supplied electricity (Department of Minerals and Energy [12]). Renewable-energy technology, especially solar and wind power, is attractive but its contribution to national energy-consumption

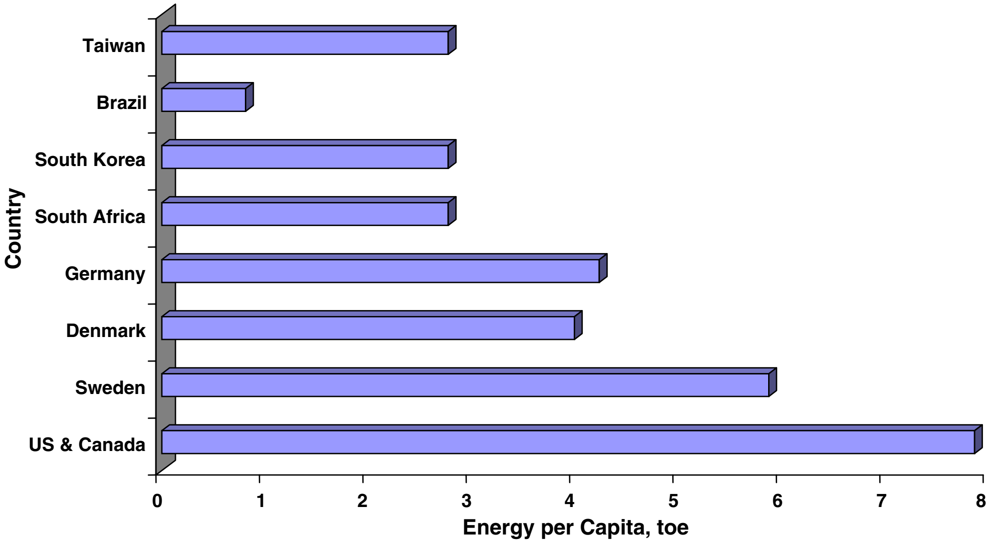
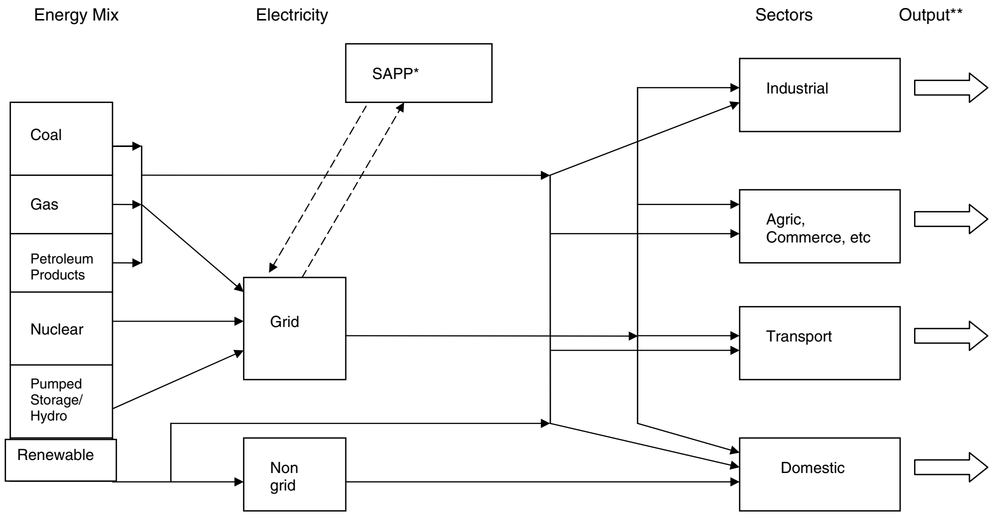


Fig. 1. Energy consumption per capita in stated countries.



**Output: products, utilities, service and wastes. *SAPP = Southern Africa Power Pool

Fig. 2. Primary-energy resources: transformation and utilization by various sectors in South Africa.

is negligible. It is certain that coal combustion and probably pebble-bed modular reactors (PBMR) will be used in the further growth of power generation.

South Africa exports energy to some of its neighbouring countries under the aegis of the Southern Africa Power Pool (SAPP) framework. Fig. 2 depicts the primary-energy sources, their transformation and utilization by various sectors of the economy. The industrial sector is considered in this study because it is the main singular energy-consumer with approximately 44% of the total national energy-use.

Fundamentals of energy and exergy efficiency for the industrial sector

Equations for exergy are analogous to those for energy: for a closed system,

$$\sum_r E^{Q^r} - E^W - I = 0 \tag{1}$$

where E^{Q^r} and E^W are the exergy values associated with the heat transfer (Q^r) and work (W) delivered by the system respectively. I is the exergy consumed or lost due to irreversibility.

When the heat transfer, Q^r takes place at a uniform temperature, T_r, then the associated thermal exergy, E^{Q^r}, is given by [1]:

$$E^{Q^r} = (1 - T_0/T_r) \cdot Q^r \tag{2}$$

The exergy, E^W associated with work is:

$$E^W = W \tag{3}$$

When both the kinetic exergy and the potential exergy are negligible, the total specific exergy of a flowing stream consists of the physical and chemical exergy which can then be written as:

$$\varepsilon = [(h - h_0) - T_0(s - s_0)] + \left[\sum_i (\mu_{i0} - \mu_{i00})\chi_i\right] \tag{4}$$

where s is the specific entropy, μ_{io}, is the species chemical potential in its reference environmental state, and χ_i is the corresponding number of moles of different chemical species i. The subscript 0 refers to the reference state when thermodynamic equilibrium is established with the reference environment.

Knowledge of the environmental conditions are required to compute the exergy of any system and a temperature (T_0) of 25 °C and a pressure (P_0) of 101.3 kPa are employed in this study. For hydrocarbon fuels flowing at near ambient conditions, the physical exergy is negligible and the specific chemical exergy in Eq. (4) can then be written as [1,5]:

$$\varepsilon_f = \gamma_f H_f \tag{5}$$

where γ_f, the fuel exergy grade function is defined as the ratio of the fuel's specific chemical-exergy ε_f, to the higher heating-value H_f of the fuel. As ε_f, and H_f are nearly equal, γ_f is assumed to be unity. Properties of some fuels are presented in Table 1.

In the industrial sector, energy is consumed primarily by heating processes and mechanical drives. The first-law efficiencies for heating by electricity and fossil-fuels are respectively given by [5]:

$$\eta_{he} = Q_p / W_e \tag{6}$$

$$\eta_{hf} = Q_p / m_f H_f \tag{7}$$

The corresponding exergy efficiencies are given by:

$$\psi_{he} = E^{Q_p} / E^{W_e} \tag{8}$$

and

$$\psi_{hf} = E^{Q_p} / m_f \varepsilon_f \tag{9}$$

Using substitutions from Eqs. (2), (3) and (6) in (8) we obtain

$$\psi_{he} = (1 - T_0/T_p)\eta_{he} \tag{10}$$

Using substitutions from Eqs. (2), (5) and (7) in (9) we obtain

$$\psi_{hf} = (1 - T_0/T_p)\eta_{hf} \tag{11}$$

Eqs. (6) and (7) can be used to determine the respective values of the first-law efficiency for electrical and fossil-fuel heating. Similarly, Eqs. (10) and (11) can be solved for the corresponding second-law efficiencies.

Table 1
Properties of some fuels at a reference temperature of 25 °C and a pressure of 1 atm[a]

Fossil-fuel	Chemical exergy, ε_f (kJ/kg)	Higher heating-value H_f (kJ/kg)	Fuel exergy grade function, γ_f
Coal	34090	32733	1.04
Fuel oil	47101	47405	0.99
Gasoline	47394	47849	0.99
Kerosene	45897	46117	0.99
Natural gas	51702	55448	0.93

[a] *Source*: Reistad [11], Rosen [1] and Dincer et al. [3].

For mechanical drives, the energy and exergy efficiencies are respectively given by:

$$\eta_{\mathrm{me}} = W_{\mathrm{out}}/W_{\mathrm{in}} \tag{12}$$

$$\psi_{\mathrm{me}} = \eta_{\mathrm{me}} \tag{13}$$

When the energy and exergy efficiencies for a process or sub-sector have been obtained, then the corresponding weighted values are given by:

$$(\eta, \psi) = \sum_{j} (\varphi_j)(\eta_j, \psi_j) \tag{14}$$

where φ_j is the weighting factor; η_j and ψ_j are the respective energy and exergy efficiencies for a process or sub-sector j. Thus once η_j and ψ_j have been evaluated, the problem reduces to obtaining the weighting factors.

Methodology

Electricity and fuel consumption data were obtained from the energy balance and Annual Reports of the Department of Minerals and Energy [13]. The fuel is the total fossil-fuel products consisting of coal, petroleum and oil, and natural gas. Renewable energy (solar and wind) was neglected because its contribution is small and relevant data are sparse. Energy consumers were categorised into industrial, transport, agriculture, commercial and public, and residential sectors. The industrial sector is the main singular energy-consumer of the total national energy use. In this sector, iron and steel, chemical and petrochemical, mining and quarrying, and non-ferrous metals/non-metallic minerals sub-sectors were analysed. Together, they represent about 75% of energy use in the sector. The other industrial consumers include construction, textiles, food, paper, pulp and wood products, but their individual energy use is small and not included in the study.

The industrial sector is diversified and complex. It is difficult to use the exact operating temperatures for consumers in each sub-sector. A pragmatic approach was used instead of a detailed definition of all the thermal processes in a sub-sector. Energy users in a particular sub-sector were assumed to operate at low, medium or high temperature-levels as defined by Rosen [1] and Dincer et al. [3]. Therefore results presented in this paper are indicative of sectoral performance.

The overall efficiencies were determined as follows (Dincer et al. [3]):

(a) The first and second-law efficiencies were calculated for each operating temperature for both electrical and fuel heating. The reference temperature was 298 K.
(b) The weighted mean-efficiencies for electrical and fuel heating for each sub-sector were calculated. The weighting factor computed from Table 2 was a fraction of energy used at each of the three temperature levels to the total energy consumed.
(c) Using the results obtained in (b), the weighted mean efficiencies for the heating processes in the sub-sectors were calculated. The weighting factor computed from Table 3 was the ratio of electrical or fuel consumed to the total energy-consumption in the sector.
(d) Overall average energy and exergy efficiencies for heating processes were calculated. The weighting factor employed was the ratio of energy-consumption by the sub-sector to the total energy-consumption in that sector.

Table 2
Process-heating data for the industrial sector[a]

Industrial sub-sector	T_p category	Mean T_p (°C)	% and type of energy used in each T_p category	
			Electricity (%)	Fuel (%)
Iron and steel	Low	45	4.2	0
	Medium	–	0	0
	High	983	95.8	100.0
Chemical and petrochemical	Low	42	62.5	0
	Medium	141	37.5	100.0
	High	494	0	0
Mining and quarrying	Low	31	91.7	0.9
	Medium	163	0	9.0
	High	1482	8.3	90.1
Non-ferrous metals and non-metallic minerals	Low	34	4.2	0
	Medium	290	0	0
	High	1035	95.8	100.0

[a] *Source*: Brown et al. [18], Rosen [1] and Dincer et al. [3].

(e) Weighted mean overall energy and exergy efficiencies for combined heating and mechanical drives were evaluated for each sub-sector. The weighting factor is the ratio of the sub-sector energy-consumption for both heating and mechanical drives to the total sectoral energy-input. It was assumed that mechanical drives consumed 20% of the energy and operated at between 80% and 95% efficiency.

Results and discussion

Although data for ten years were collected and analysed, variations of annual fuel and electricity use were not substantial over the period. Coal, petroleum products and electricity contributed 29%, 33%, and 25%, respectively to the national energy-consumption. Table 3 depicts the primary-fuel and electricity consumptions in the sub-sectors and the corresponding annual overall mean energy and exergy efficiencies for heating-processes alone. Quarrying and mining consumed the bulk of the electricity. Iron-and-steel production and chemical-and-petrochemical industries consumed more fossil-fuels than other users. Fig. 3 shows the average overall mean-efficiencies for the sub-sectors for heating only. It can be observed that exergy efficiency is significantly lower than energy efficiency in all sub-sectors and this shows there is considerable potential for improvement in these large-scale systems. In particular, mining and quarrying seem to perform best based on energy analysis (83%) but the corresponding exergy-based performance is lowest (16%). Although energy efficiencies in other sub-sectors are comparable, the exergy efficiencies vary considerably. This confirms that energy analysis alone, as practised conventionally, is not sufficient to evaluate performance of a plant or process. Also, electrical (i.e. high-grade) energy should not be used for low-temperature operations.

Exergy analysis will receive more attention because of the need to reduce energy costs (i.e. due to increasing unit oil-prices), conserve fossil fuels for future generations, limit production of deleterious green-house gases that degrade the environment and because of recent uncertainties of oil pathways. In addition, exergy considerations will assist in the implementation of the Kyoto Protocol that has been ratified by many nations. Therefore, exergy-saving opportunities must be identified in the energy chain of a production system.

Table 3
Variations of the fuel and electricity consumptions and the corresponding mean energy and exergy efficiencies for heating processes

Year	Sub-sector	Fuel (PJ)	Electricity (PJ)	Overall mean energy and exergy efficiencies (%)	
				η Mean	ψ Mean
1994	Iron and steel	212.7	52.6	54.22	40.77
	Chemical and petrochemical	177.8	11.3	55.56	26.57
	Mining and quarrying	28.4	117.6	88.47	12.95
	Non-ferrous metals and non-metallic minerals	56.1	25.2	56.59	42.73
1995	Iron and steel	209.3	58.5	54.64	41.04
	Chemical and petrochemical	247.7	13	55.35	26.44
	Mining and quarrying	34.7	119.4	87.05	13.95
	Non-ferrous metals and non-metallic minerals	53.2	29.3	57.55	43.33
1996	Iron and steel	170.9	56.3	55.27	41.43
	Chemical and petrochemical	253.7	9.5	55.07	26.26
	Mining and quarrying	34	125.4	87.60	13.56
	Non-ferrous metals and non-metallic minerals	39.3	51.1	62.02	46.12
1997	Iron and steel	142.6	64.3	56.61	42.26
	Chemical and petrochemical	245.3	9.1	55.06	26.26
	Mining and quarrying	54.7	109.4	82.02	17.46
	Non-ferrous metals and non-metallic minerals	36	56.8	63.01	46.74
1998	Iron and steel	197	67.9	55.45	41.54
	Chemical and petrochemical	265	9.5	55.04	26.24
	Mining and quarrying	61.8	105.1	80.30	18.66
	Non-ferrous metals and non-metallic minerals	41.3	57.3	62.35	46.33
1999	Iron and steel	183.8	70.3	55.88	41.81
	Chemical and petrochemical	255.2	9	55.03	26.23
	Mining and quarrying	41.44	104	84.27	15.89
	Non-ferrous metals and non-metallic minerals	42.5	57.7	62.24	46.26
2000	Iron and steel	189	75.3	56.06	41.92
	Chemical and petrochemical	265.4	9.5	55.04	26.24
	Mining and quarrying	26.2	104.5	88.19	13.14
	Non-ferrous metals and non-metallic minerals	42.6	58.3	62.28	46.29

(*continued on next page*)

Table 3 (*continued*)

Year	Sub-sector	Fuel (PJ)	Electricity (PJ)	Overall mean energy and exergy efficiencies (%)	
				η Mean	ψ Mean
2001	Iron and steel	206.2	66.8	55.20	41.39
	Chemical and petrochemical	207.6	33.9	57.21	27.62
	Mining and quarrying	68.8	114.1	80.03	18.85
	Non-ferrous metals and non-metallic minerals	38.4	62	63.13	46.82
2002	Iron and steel	208	73.2	55.53	41.59
	Chemical and petrochemical	149.5	35.1	58.23	28.27
	Mining and quarrying	67.8	115.9	80.36	18.62
	Non-ferrous metals and non-metallic minerals	38.2	63.7	63.29	46.92
2003	Iron and steel	209.4	80.4	55.90	41.82
	Chemical and petrochemical	145.9	34	58.21	28.25
	Mining and quarrying	64	110.9	80.51	18.52
	Non-ferrous metals and non-metallic minerals	46.1	64.7	62.41	46.37

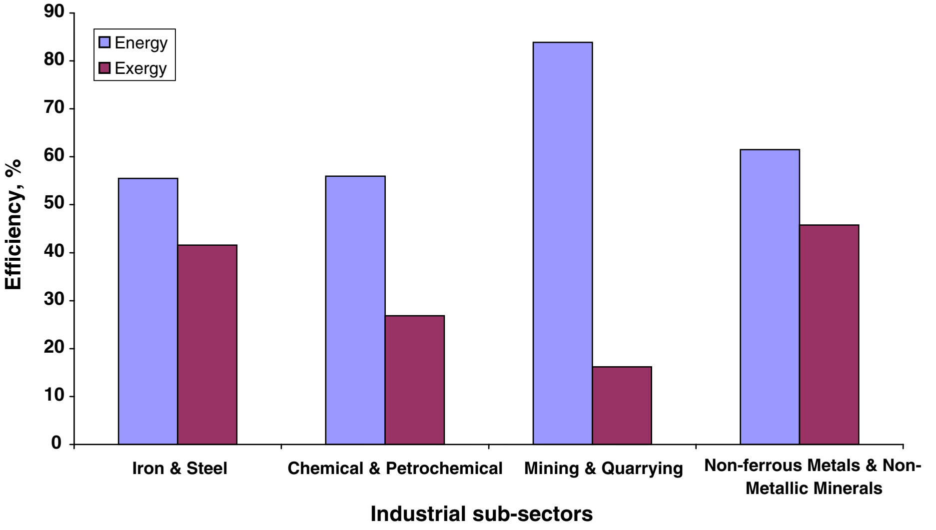


Fig. 3. Weighted mean efficiencies in the industrial sector, 1994–2003.

Annual overall weighted energy and exergy efficiencies for heating processes seem to remain constant during the 10-year period as shown in Fig. 4. These values were respectively 64% and 29%. Therefore plant performance in the industrial sector should be improved by introducing various strategies and mechanisms to monitor, control and conserve useful-energy. Strategies should be implemented to diversify the use of energy, for example, the demand for electricity may be reduced for thermal end-use applications by

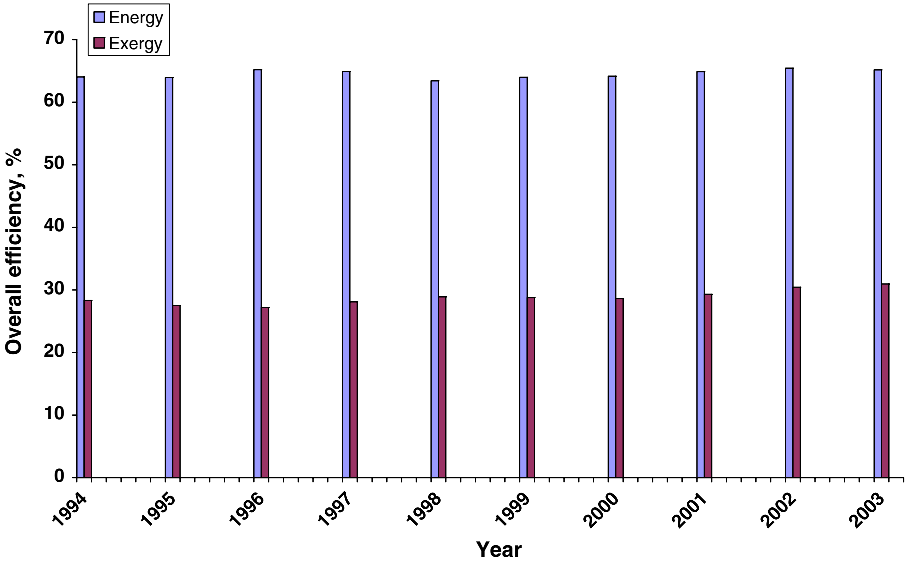


Fig. 4. Overall energy and exergy efficiencies for heating only within the industrial sector of South Africa.

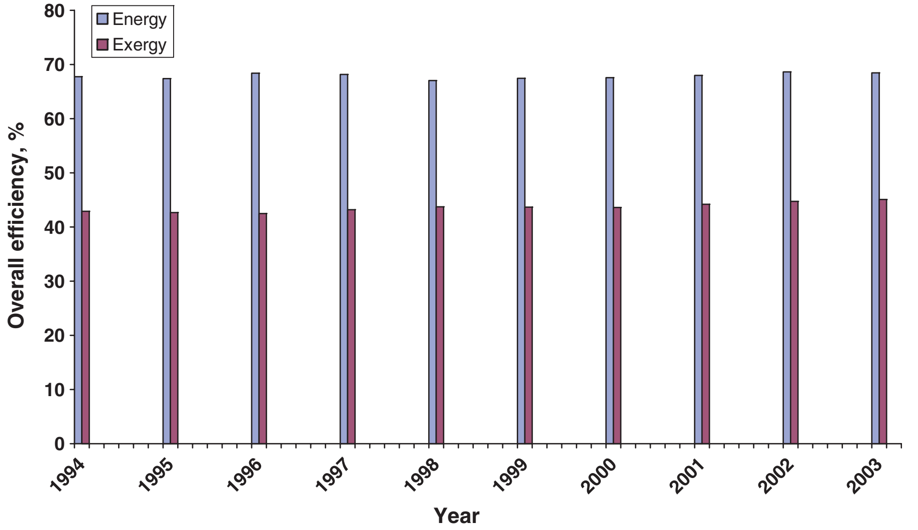


Fig. 5. Overall energy and exergy efficiencies for the industrial sector in South Africa.

switching to alternative resources. Renewable energy is abundant and can be harnessed easily for low-grade thermal applications with minimal impact on the environment. The Government has introduced policies to promote the use of renewable energy. Since the beginning of this century, the SADC industrial energy-management program has been promoting industrial energy-conservation in some SADC member countries, including South Africa. ESKOM, the electricity company, is encouraging demand-side energy management. The total effect of all these programs should improve exergy consumption in the

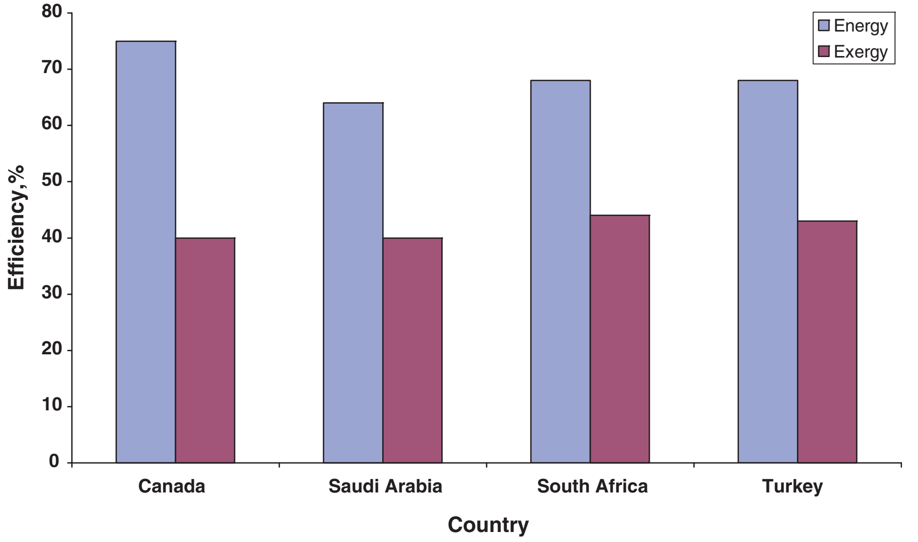


Fig. 6. Comparison of the energy and exergy efficiencies of various countries.

industrial sector. Therefore, national framework and policies will need to be introduced to monitor and control activities related to clean energy, energy conservation, plant efficiency, emission control and environmental protection.

Fig. 5 presents the overall annual energy and exergy efficiencies for both heating and mechanical drives in the industrial sector. The values also seem constant at approximately 68% and 44%, respectively. The slight increase over results for heating alone is because of the better performance of mechanical drives. However the national annual energy-balance does not reflect the real performances of the energy systems. For completeness of information and in order to effect changes, an exergy analysis will be required. However, future research should focus on detailed analyses of specific operating plants in the industrial sub-sectors to evaluate their performances by using the exergy method.

Fig. 6 compares the overall energy and exergy efficiencies from this study with results obtained by Rosen [1], Ozdogan and Arikol [6] and Dincer et al. [3] for Canada, Turkey and Saudi Arabia respectively. Although the industrial sub-sectors are not completely identical in the four studies, variations in energy and exergy efficiencies are comparable.

Conclusion

Energy and exergy efficiencies of four industrial sub-sectors, namely, iron-and-steel, chemical-and-petrochemical, mining-quarrying, and non-ferrous metals/non-metallic minerals, were determined to obtain the overall mean values for the industrial sector in South Africa. Mining and quarrying seemed to have the least exergy efficiency, though its energy efficiency was the highest. This may be due to use of electricity for low-grade thermal applications. Therefore electrical (i.e. high-grade) energy should not be used for low-temperature operations. A more rationale and efficient use of energy is required in the industrial sector. The exergy analysis for South Africa is comparable with results of previous studies for Canada, Turkey and Saudi Arabia. However an in-depth study of each industrial sub-sector will be essential to identify units or areas for systemic improvements. In conclusion, exergy needs to be used optimally to reduce the rate of depletion of fossil-fuel reserves, save costs, mitigate production of green-house gases that cause global warming and improve the overall performances of plants and processes.

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