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Energy and exergy use in the utility sector of Saudi Arabia

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Abstract

We present an analysis of energy and exergy utilization in the utility sector of Saudi Arabia by considering the sectoral energy and exergy flows for the years 1990–2001. Energy and exergy analyses were conducted for its two subsectors, namely power-only plants and power/distillation plants, and hence the energy and exergy efficiencies were obtained for comparison. The power/distillation plant subsector appeared to be more energy/exergy efficient compared to the conventional power-only plant subsector for the particular reference conditions assumed in the analysis. A comparison of the overall energy and exergy efficiencies of Saudi Arabian utility sector with the Turkish utility sector is also presented for the year 1993. Although the sectoral coverage is different for each country, it is useful to illustrate the situation of how energy and exergy efficiencies vary. The turkish utility sector appeared to be more efficient for that particular year. Power/distillation makes a significant contribution to Saudi Arabia's overall power generation in the utility sector.

Keywords: Desalination plant; Energy; Exergy; Power plant; Saudi Arabia

1. Introduction

Since seawater desalination plants require considerable energy resources, they are normally associated with the power plants, as in the case of the Arab Gulf countries where the majority of desalinated water is produced in dual-purpose plants. The profitability of dual-purpose plants from an economic point of view is usually dependent upon its impact on power system expenditures throughout the lifetime of the plant [1]. For this reason, dual-purpose desalination plants appear to be an optimal option for both seawater desalination and electricity generation as commonly done in various countries, e.g., Saudi Arabia.

Recently, the use of energy and other resources in the industrial world has reached levels

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never observed before. This leads to a decreasing supply of natural resources and an increasing amount of damage to and pollution of the natural environment. At the same time, energy resource conversion networks have become more complicated. Technical improvements are often focused towards less important resource conversions that do not have significant potential to improve resource use. By describing the use of energy resources in society in terms of exergy, important knowledge and understanding can be gained and areas identified for great improvement by applying efficient technology including more efficient energy-resource conversions.

Note that Saudi Arabia is one of the biggest crude oil producers with the largest crude oil reserves in the world, and that with one-fourth of the world's proven oil reserves, Saudi Arabia will likely remain the world's largest oil producer for the foreseeable future. In the country, the electricity generation sector (the "utility" sector), therefore, plays a crucial role. The Saudi Arabia's five-year development plan (1990–1994) targeted the electrification of the country as a top priority. The plan emphasized improving the efficiency, planning and conservation of electric power, and coordinating the electricity sector policy, particularly on pricing of electricity, with that for other sources of energy. At present, electricity produced at Saudi Arabia's 25 desalination plants accounts for about 10% of the total annual electricity production capacity. A long-term goal is to increase the capacity of steam stations and desalination plants to enable them to generate half of the electricity output. With the rapid growth in population and industrialization, domestic electricity consumption has climbed steadily during the past two decades [2,3].

During the past two decades, the concept of exergy has received great attention from scientists, researchers and engineers and been applied to various utility sectors and thermal processes. Recently, much attention has been paid to the energy and exergy modeling techniques for energy-utilization assessments in order to attain energy savings, and hence financial savings. The energy utilization of a country can be assessed using exergy analysis to gain insights into its efficiency. This approach was first introduced in a landmark paper by Reistad [4], who applied it in the US. Since then, several other countries, e.g., Canada [5–7]; Japan, Finland and Sweden [8,9]; Italy [10]; Turkey [11–13]; the UK [14]; and Norway [15,16] have been examined in such a way using modified versions of this approach or different modeling techniques.

More recently, Dincer et al. [17,18] investigated the energy and exergy utilization in industrial and transportation sectors only out of six major economic sectors of Saudi Arabia, namely residential, public and private, industrial, transportation, agricultural and electrical utility, as shown in detail in Fig. 1 as a macrosystem. In the current investigation, the authors extended the study with power generation data to cover the utility sector. Therefore, the primary objective of this paper is to model the sectoral energy and exergy flows in a macrosystem and to apply the energy and exergy modeling technique to the utility sector of Saudi Arabia for the period of 1990 to 2001. In the energy and exergy analyses, the actual sectoral energy data, which were taken from various local and international sources, were used, and the variations of energy and exergy efficiencies in the utility sector over the years were studied. The energy efficiencies and quantities of electricity and energy input in Saudi Arabia are listed. The necessary energy data are taken from MIE [19], UN [20] and ENERDATA [21]. Also, the energy and exergy efficiencies obtained for Saudi Arabia were compared to the ones available for Turkey for the year 1993.

2. Saudi Arabian utility sector: an outlook

The development of the power sector in Saudi Arabia has been instrumental to the country's

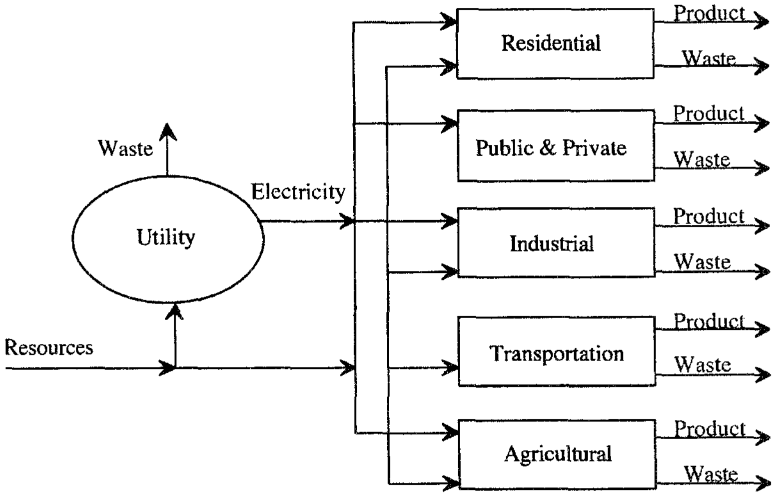

Fig. 1. An illustrative presentation of the energy flows in a macro-system for Saudi Arabia.

economic prosperity. With one of the highest per capita electricity consumption rates in the world, Saudi Arabia's next challenge is to expand its power capacity and network to meet the needs of a growing population and to support the country's ambitious industrialization plan. Several power projects have been launched to achieve this expansion, including upgrading existing power plants and building new power facilities. The government has also taken concrete steps towards restructuring and privatizing the power sector in order to make it more efficient and economically viable.

Saudi Arabia's ten regional power companies have recently been consolidated into a single joint-stock company, the Saudi Electricity Company (SEC), in order to expedite the streamlining of the sector's operations. Capitalized at about $9 billion, the new power company is to be self-supported, independent from the government, and in charge of bringing about the necessary capacity increase planned for the year 2020. A strategy to unbundle the power sector into transmission, generation, and distribution is also under review by the Saudi government. This tremendous potential for growth makes the country one of the world's most attractive markets for power generation, as well as for power transmission and distribution equipment.

Saudi Arabia's total installed electricity capacity and its net electricity generation have witnessed dramatic growth since the mid-1970s. From 1975 to 1996, the generation capacity of all the power companies in the country increased 16 times, from 1,173 to 18,780 MW, not including power generated by desalination plants. Desalination makes a significant contribution to Saudi Arabia's overall power generation. Nine of the country's 25 desalination plants are dual-system plants, generating 3,214 MW of electricity, and accounting for 33% of the country's total capacity. While part of the power generated by the desalination plants is used to operate the facilities themselves, the significant excess production is transmitted to the Saudi Consolidated Electricity Companies. In 1997 alone, the excess power transmitted to these companies was 3,224 MW. It is estimated that once the projects currently under way are completed, Saudi Arabia's desalination plants will be producing over 5,087 MW of electricity.

According to the government's 25-year electricity plan, the growth in electricity demand in the country's five regions between 1995 and 2020 will average 4.5%. Demand growth in the last few years has been assessed at 15% per year. Several factors have contributed to this demand surge. The country's 16% annual industrial growth has played a major role in boosting the demand for power. Between 1975 and 1996, the electricity consumption of Saudi industries increased 10 times, from 2.17 million MWh to 22.5 million MWh. In the Eastern Province, where 725 of the country's operating factories are located, peak demand for power grew by 17% in 1997 alone. As Saudi Arabia's economic diversification intensifies, industrialization is expected to exert further pressure on the power sector. The industrial sector already accounts for approximately 60% of electricity demand in the country, while the residential and commercial sectors account for approximately 25% and 15% of demand, respectively.

Detailed information on the above topics is available elsewhere [20–22].

3. Energy and exergy modeling

This section presents some of the key aspects of thermodynamics, in terms of energy and exergy, relevant to the current study.

3.1. Energy and exergy balances

Energy and exergy balances for an unsteady-flow process in a system during a finite time interval can be written as:

Energy input − energy output = energy accumulation (1)

Exergy input − exergy output − exergy consumption = exergy accumulation (2)

The above equations demonstrate an important difference between energy and exergy: energy is conserved, while exergy is consumed due to irreversibilities. Exergy indicates the quality of energy, and in any real process, it need not be conserved, but it is destroyed or lost. Then, Eqs. (1) and (2) can be formulated as:

$$\sum_{in} (h + ke + pe)_{in} m_{in} - \sum_{ex} (h + ke + pe)_{ex} + \sum_{r} Q_r - W = 0 \quad (3)$$

$$\sum_{in} \varepsilon_{in} m_{in} - \sum_{ex} \varepsilon_{ex} m_{ex} + \sum_{r} E^{Q} - E^{W} - I = 0 \quad (4)$$

where m_{in} and m_{ex} denote mass input across port *in* and mass exiting across port *ex*, respectively; Q_r denotes the amount of heat transfer into the system across region r on the system boundary; Q^E is the exergy transfer associated with Q_r; W is the work (including shaft work, electricity, etc.) transferred out of the system; E^W is the exergy transfer associated with W; I is the system exergy consumption; and h, ke, pe, and ε denote the specific values of enthalpy, kinetic energy, potential energy, and exergy, respectively. Note that the exergy consumption I is greater than zero for an irreversible process and equal to zero for a reversible process.

Since $m_{in} = m_{ex} = 0$, for a closed system, Eqs. (3) and (4) are simplified to:

$$\sum_{r} Q_r - W = 0 \quad (5)$$

$$\sum_{r} E^{Q} - E^{W} - I = 0 \quad (6)$$

3.2. Basic quantities for exergy analysis

Here we discuss some basic quantities and mathematical relations related to exergy.

3.2.1. Exergy of a flowing stream of matter

Consider a flowing stream of matter at temperature T, pressure P, a chemical composition μ_j of species j, mass m, specific enthalpy h, specific entropy s, and mass fraction x_j of species j. Assume a conceptual environment in an equilibrium state with intensive properties at T_0, P_0 and μ_{j00}, and assume the environment to be large enough such that its intensive properties are negligibly affected by any interactions with the system. With the above considerations, the specific exergy of the flowing stream of matter can be expressed as:

$$\varepsilon = \left[ke + pe + (h - h_0) - T_0(s - s_0) \right] + \left[\sum_j (\mu_{j0} - \mu_{j00}) x_j \right] \quad (7)$$

Note that the above equation can be separated into physical and chemical components (assuming $ke = 0$ and $pe = 0$). The physical exergy $\left[(h-h_0) - T_0(s-s_0)\right]$ is the maximum available work extracted from a flowing stream as it is brought to the environmental state. The chemical exergy $\left[\sum_j (\mu_{j0}-\mu_{j00})x_j\right]$ is the maximum available work extracted from the stream as it is brought from the environmental state to the dead state.

3.2.2. Exergy of heat

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is:

$$E^Q = \left(1 - \frac{T_0}{T_r}\right) Q_r \quad (8)$$

3.2.3. Exergy of work

The exergy associated with work is:

$$E^W = W \quad (9)$$

3.2.4. Chemical exergy

One of the most common mass flows are hydrocarbon fuels at near-ambient conditions, for which the first term in the square brackets in Eq. (7) is approximately zero, and the specific exergy reduces to chemical exergy, which can be written as

$$\varepsilon_f = \gamma_f H_f \quad (10)$$

where γ_f denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy [last term in square brackets in Eq. (7)] to the fuel higher heating value H_f. Table 1 shows typical values of H_f, ε_f, and γ_f for the fuels encountered in the present study. Usually, the specific chemical exergy ε_f of a fuel at T_0 and P_0 is approximately equal to higher heating value H_f.

3.2.5. Exergy consumption

The amount of exergy consumed due to irreversibilities during a process is:

$$I = T_0 S_{gen} \quad (11)$$

3.2.6. Reference environment

Exergy is always evaluated with respect to a reference environment, which is at stable equilibrium, acts as an infinite system, is a sink or source for heat and materials, and experiences only internally reversible processes in which its intensive properties (i.e., temperature T_0, pressure P_0 and chemical potentials μ_{j00} for each of the j components) remain constant. With minor exceptions, Gaggioli and Petit's model [23] was used as a reference environment in which $T_0 = 10°C$, $P_0 =$

Table 1
Properties of selected fuels (for a reference environment temperature of 25°C, pressure of 1 atm and chemical composition as defined in the text)

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

Adapted from Reistad [4].

1 atm, and the chemical composition is taken to be air saturated with water vapor, and the following condensed phases are used at 25°C and 1 atm: water (H_2O), gypsum ($CaSO_4{\cdot}2H_2O$), and limestone ($CaCO_3$). It is noted that, following Gaggioli and Petit [23], gypsum and limestone are taken to be part of the reference environment so as to provide nonreactive, dead-state chemical forms for the elements such as sulphur and calcium.

3.3. Energy and exergy efficiencies for principal types of processes

The expressions of energy (η) and exergy (ψ) efficiencies for the principal types of processes considered in the present study are based on the following definitions:

$$\eta = (\text{energy in products/total energy input}) \quad (12)$$

$$\psi = (\text{exergy in products/total exergy input}) \quad (13)$$

Here, 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 the essential fuels (e.g., kerosene, gasoline, diesel and natural gas).

Note that the exergy efficiency frequently gives a finer understanding of performance than the energy efficiency. In calculating the energy efficiency, the same weight is assigned to energy whether it becomes shaft work or a stream of low temperature fluid. Also, it centers attention on reducing "losses" to improve efficiency. The exergy efficiency weights energy flows by accounting for each in terms of availability. It stresses that both losses and internal irreversibilities need to be dealt with to improve performance. In many cases it is the irreversibilities that are more significant and the more difficult to deal with. Furthermore, exergy efficiency contains several implications, including: (1) the quality, or inherent capacity to cause change, of energy and matter streams is important, and (2) the quality of such streams is degraded or destroyed due to irreversibilities in practical processes (and conserved only for the limiting case of ideal, or reversible, processes).

3.3.1. 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 W_e or fuel mass m_f. The efficiencies for electrical heating are:

$$\eta_{h,e} = Q_p / W_e \quad (14)$$

$$\psi_{h,e} = E^{Q_p} / E^{W_e} = \left[\left(1 - T_0/T_p\right)Q_p\right] / \left(W_e\right) \quad \text{and}$$
$$\psi_{h,e} = \left(1 - T_0/T_p\right)\eta_{h,e} \quad (15)$$

For fuel heating, these efficiencies are

$$\eta_{h,f} = Q_p / m_f H_f \quad (16)$$

$$\psi_{h,f} = E^{Q_p} / m_f \varepsilon_f \quad \text{and}$$
$$\psi_{h,f} = \left[\left(1 - T_0/T_p\right)Q_p\right] / \left(m_f \gamma_f H_f\right) \cong \left(1 - T_0/T_p\right)\eta_{h,f} \quad (17)$$

where double subscripts indicate the 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.

3.3.2. Cooling

The efficiencies for electric cooling are

$$\eta_{c,e} = W_p / W_e \quad (18)$$

$$\psi_{c,e} = E^{Q_p}/E^{W_e} = \left[\left(1 - T_0/T_p\right)Q_p\right]/\left(W_e\right)$$
$$\psi_{c,e} = \left(1 - T_0/T_p\right)\eta_{c,e} \tag{19}$$

3.3.3. Work production

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

$$\eta_{m,e} = W/W_e \tag{20}$$

$$\psi_{m,e} = E^{W}/E^{W_e} = W/W_e = \eta_{m,e} \tag{21}$$

For fuel, these efficiencies are

$$\eta_{m,f} = W/m_f H_f \tag{22}$$

$$\psi_f = E^{W}/m_f \varepsilon_f = W/m_f \gamma_f H_f \cong \eta_{m,f} \tag{23}$$

3.3.4. Electricity generation

The efficiencies for electricity generation from fossil fuel are

$$\eta_{e,f} = W_e/m_f H_f \tag{24}$$

$$\psi_{e,f} = E^{W_e}/m_f \varepsilon_f = W_e/m_f \gamma_f H_f \cong \eta_{e,f} \tag{25}$$

Therefore, the exergy efficiencies for electricity generation process can be taken as equivalent to the corresponding energy efficiencies.

3.4.5. Kinetic energy production

The efficiencies for the fossil fuel-driven kinetic energy production processes, which produce a change in kinetic energy Δke in a stream of matter m_s, are as follows:

$$\eta_{ke,f} = m_s \,\Delta ke_s/m_f H_f \tag{26}$$

$$\psi_{ke,f} = m_s \,\Delta ke_s/m_f \varepsilon_f = m_s \,\Delta ke_s/m_f \gamma_f H_f \cong \eta_{ke,f} \tag{27}$$

4. Results and discussion

Here, an application of the energy and exergy modeling technique discussed in the previous section is presented for the energy and exergy use in the utility sector of Saudi Arabia.

The main electricity generation resource in Saudi Arabia is fossil-fuels, particularly diesel, oil, fuel oil and natural gas, and the electricity is therefore generated by both power-only plants and power/distillation plants. The power-only plants and power/distillation plants are taken into consideration as subsectors in the utility sector of Saudi Arabia. The electricity generation from thermal renewables (e.g., solar, solid biomass and animal products) is negligibly small. The energy efficiencies and quantities of electricity and energy inputs in Saudi Arabia are listed. The energy efficiencies in this sector are equal to the exergy efficiencies due to the values of energy grade function (e.g., $\gamma \cong 1$), as outlined in Eqs. (24) and (25).

Table 2 lists the energy inputs to both power-only plants and power/distillation plants for the 12 years between 1990 and 2001. In addition, the electricity generated in power-only plants and power/distillation plants for those 12 years is given in Table 3. The overall efficiency can easily be found by dividing total electrical energy produced by the total input energy.

Furthermore, using the data given in Tables 2 and 3, we can find energy efficiencies of both power-only plants and power/distillation plants. We can also calculate the overall mean energy efficiencies of the utility sector. The sample calculations for the year 2000 are shown as follows:

Table 2
Energy consumption data for the utility sector in Saudi Arabia

Year	Energy consumed, PJ	
	Power-only plants	Power/distillation plants
1990	591.24	141.28
1991	648.12	139.82
1992	694.36	148.43
1993	779.78	142.99
1994	893.05	156.12
1995	912.21	159.50
1996	958.95	153.36
1997	1011.98	179.88
1998	1095.59	172.77
1999	1195.56	171.12
2000	1231.38	167.10
2001	1298.81	179.22

Table 3
Energy generation data for the utility sector in Saudi Arabia

Year	Electricity generated, PJ	
Year	Power-only plants	Power/distillation plants
1990	162.96	70.68
1991	179.51	69.64
1992	194.76	71.68
1993	222.26	73.63
1994	251.86	75.88
1995	259.01	79.11
1996	273.40	78.84
1997	291.89	72.12
1998	311.74	75.42
1999	337.31	75.33
2000	350.25	78.20
2001	371.14	78.50

- For power plants:

$\eta_{e,P}$ = (electrical energy output)/(fuel energy input in power plants)
= 350.25 PJ/1231.38 PJ = 28.44%

- For desalination plants:

$\eta_{e,d}$ = (electrical energy output)/(fuel energy input in desalination plants)
= 78.2 PJ/167.09 PJ = 46.8%

- Overall mean energy efficiency:

U_{η_o} = (0.817×28.44) + (0.182×46.8) = 31.75%

Since for the fossil fuel energy we assume $\gamma_f = 1$ (see Table 1), the exergy efficiencies of electricity generation from both power-only plants and power/distillation plants are the same as the energy efficiencies. This equivalence was shown earlier in Table 1 through Eq. (10).

Thus, the mean overall exergy efficiency is considered to be equal to the mean overall energy efficiency. That is,

$$U_{\eta_o} = U_{\psi_o} = 31.75\% \quad \text{(for the year 2000)}$$

The graphical representation of the overall mean energy and exergy efficiencies of the utility sector for the 12 years between 1990 and 2001 is shown in Figs. 2 and 3. It can be seen in the figures that, as a relative comparison for the same reference conditions, for over all the years, energy and exergy efficiencies of the power/distillation plants are much higher than the corresponding efficiencies of the power-only plants for the same reference conditions. This means that for the same reference conditions the energy and exergy losses in power-only plants are greater than the losses occurring in power/distillation plants. It should be noted that in the efficiency calculation certain reference conditions are taken into consideration. Sometimes these conditions may be different from design and

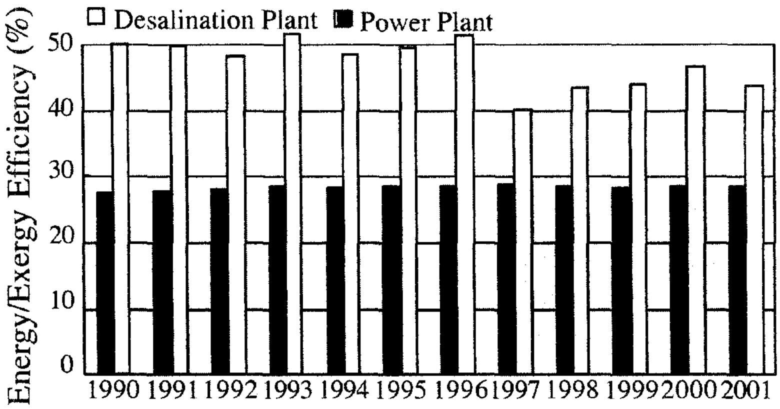

Fig. 2. Yearly energy/exergy efficiencies of power/desalination plants and conventional power-only plants of the utility sector, based on input and output energies and exergies in Saudi Arabia.

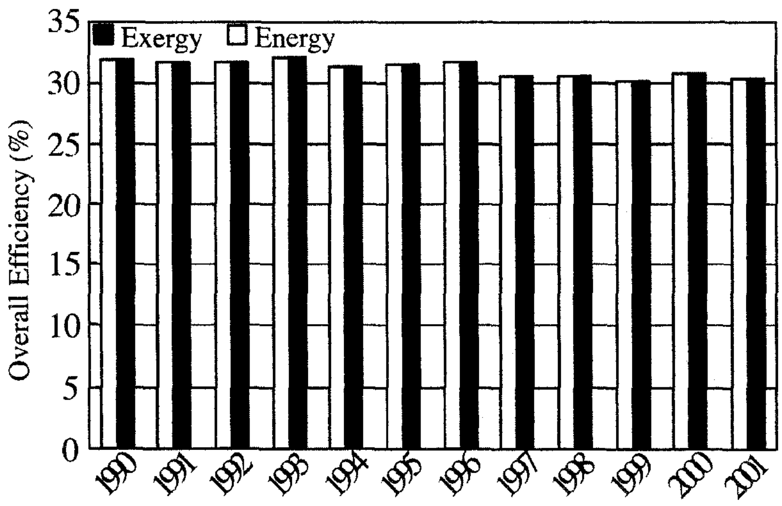

Fig. 3. Overall energy and exergy efficiencies of the utility sector in Saudi Arabia vs. year.

operating conditions. Furthermore, operation management and strategies may play a key role on how efficiently the systems or processes are operated.

In general, for the utility sector, several investigators [e.g., 4–13] have come up with the same result that the energy and exergy efficiencies for similar activities are almost identical for the utility sectors. This result indicates that inefficiencies in these sectors are not caused by mismatch in the input–output quality levels but rather by the presently available techniques used for conversion processes. Substantial improvements in these sectors are expected to be difficult to obtain and will involve major changes in the conversion methods.

In addition, a comparison of the overall energy and exergy efficiencies of the Saudi Arabian utility sector with the Turkish utility sector is also presented for the year 1993 since we have the sectoral data published earlier for this particular year [12]. In the Turkish utility sector the two main electricity generation sources are from hydro and fossil fuels (including coal, petroleum,

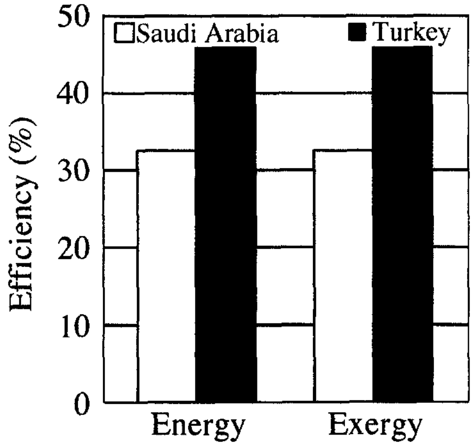

Fig. 4. Comparison of energy and exergy efficiencies of the utility sector of Saudi Arabia with Turkey.

and natural gas). The electricity generation from thermal renewables (e.g., geothermal and solid biomass and animal products) was 0.5 PJ, which was negligible compared to hydro. Although the sectoral coverage is different for each country, it is useful to illustrate the situation on how energy and exergy efficiencies vary as a rough overall comparison, and this is shown in Fig. 4. The Turkish utility sector appears to be more efficient than Saudi Arabia's utility sector for that particular year due to fact that in Turkey the essential electricity generation source is hydro, which is more efficient than fuel-driven power plants.

5. Conclusions

We investigated energy and exergy use in the utility sector of Saudi Arabia and conducted an analysis, based on actual data, by considering the energy and exergy flows sector for the years of 1990 to 2001. Then, the variations of energy and exergy efficiencies for the utility sector were studied for their two significant subsectors, namely power-only plants and power/distillation plants. From the analysis, power/distillation plants appear to be more efficient than the power-only plants for the entire period from 1990–2001 for the particular reference conditions assumed in the study. A comparison of the overall energy and exergy efficiencies of Saudi Arabian utility sector with the Turkish utility sector is also presented for the year 1993. It was found that the Turkish utility sector was more efficient for that particular year. It is concluded that the present technique is beneficial for analyzing sectoral energy and exergy utilization and that the results give a rough picture on Saudi Arabia's energy and exergy use in utility sector although it is a simple analysis.

For more precise results of the efficiencies, a comprehensive analysis of each component or each process is required for more definitive conclusions. Further study will be undertaken to include the exergy contents of freshwater and/or salty water in the exergy analysis and to determine the irreversibilies occurring in each component of the plant. It is also important to conduct an exergoeconomic analysis of the power plants which will consider the cost accounting of exergy losses.

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