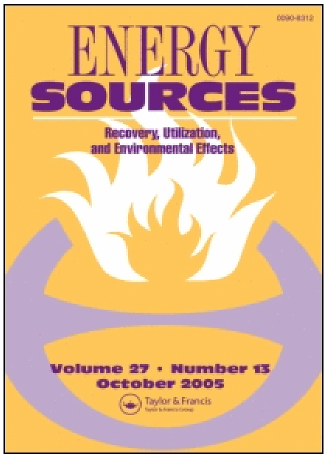

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Optimization of Fossil Fuel Sources: An Exergy Approach

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Optimization of Fossil Fuel Sources: An Exergy Approach

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Abstract *We performed linear programming for optimization of fossil fuel supply in 2000 in Turkey. For this, an exergy analysis is made because the second law of thermodynamics takes into account the quality of energy as well as quantity of energy. Our analyses showed that the interfuel substitution between different fossil fuels will lead to a best energy mix of the country. The total retail price of fossil fuels can be lowered to 11.349 billion US$ from 13.012 billion US$ by increasing the domestic production of oil, lignite, and hard coal and by decreasing imports. The remaining demand can be met by natural gas imports. In conclusion, our analysis showed that a reduction of 1.663 billion US$ in fossil fuel cost can be made possible by giving more emphasis on domestic production, particularly of oil, lignite and hard coal.*

Keywords exergy, fossil fuels, optimization, Turkey

Introduction

Turkey has been one of the most successful emerging countries in developing energy consumption capacity for two decades and its performance is expected to be higher in the future than at present (Ediger and Tatlıdil, 2002; Ediger, 2003). The future accomplishment of the country, however, will depend on its efforts towards finding solutions to energy problems that the country has already been dealing with.

One of the most significant problems of the Turkish energy system is its dependency on imports. Turkey consumed 81.251 million toe (tons-of-oil-equivalent) primary energy while it produced only 26.855 million toe in 2000, indicating that only 33.1% of its consumption is met by domestic production and the remaining 66.9% is imported (Table 1). The historical data clearly show that the percentage of primary energy production in

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Table 1
Production and consumption in fossil fuels and in total primary energy during 1970–2000

X1000 toe	1970	1975	1980	1985	1990	1995	2000
Hard coal							
Production	2,790	2,936	2,195	2,199	2,080	1,319	1,159
Consumption	2,883	3,025	2,824	3,775	6,150	5,905	9,983
%	96.8	97.1	77.7	58.3	33.8	22.3	11.6
Lignite							
Production	1,735	2,745	3,738	8,212	9,524	10,735	12,128
Consumption	1,732	2,692	3,970	7,933	9,765	10,605	13,219
%	100.2	102.0	94.2	103.5	97.5	101.2	91.7
Oil							
Production	3,719	3,250	2,447	2,216	3,903	3,692	2,886
Consumption	7,958	14,178	16,074	18,134	23,901	29,324	32,297
%	46.7	22.9	15.2	12.2	16.3	12.6	8.9
Natural gas							
Production	0	0	21	62	193	166	581
Consumption	0	0	21	62	3,110	6,313	13,729
%	0.0	0.0	100.0	100.0	6.2	2.6	4.2
Total fossil fuel							
Production	8,244	8,931	8,401	12,689	15,700	15,912	16,754
Consumption	12,573	19,895	22,889	29,904	42,926	52,147	69,228
%	65.6	44.9	36.7	42.4	36.6	30.5	24.2
Total primary energy							
Production	14,516	16,473	17,358	21,935	25,478	26,719	26,855
Consumption	18,872	27,437	31,973	39,399	52,987	63,679	81,251
%	76.9	60.0	54.3	55.7	48.1	42.0	33.1

Source: WEC TNC, 2002.

consumption decreased persistently from 76.9% in 1970 to 33.1% in 2000. WEC TNC (1997, 2002) estimated this figure to decrease down to 25% by 2020.

Secondly, the energy consumption is dominated by fossil fuels, although a considerable amount of renewable energy potential exists in the country (Ediger and Tuna, 1993; Ediger and Kentel, 1999). These fuels consist of 62.4% of total primary energy production and 85.2% of total primary energy consumption in 2000. However, the dependency on foreign sources is the highest in fossil fuels reaching 75.8% in 2000 from 34.4% in 1970 (Table 1). Among the fossil fuels, lignite has the biggest share in primary energy production consisting 45.2% of total and oil has the biggest share in primary energy consumption consisting 39.7% of total in 2000. They are followed by oil (10.7%), hard coal (4.3%), and natural gas (2.2%) in production and by natural gas (16.9%), lignite (16.3%), and hard coal (12.3%) in consumption.

Finally, the energy efficiency is low compared to the similar countries. İleri and Gürer (1998) found out that the energy efficiencies in Turkish sectors are about 15% for transportation, 45% for thermal and hydropower plants, 55% for residential and commercial uses, and 58% for industrial application with an average of 35%. The Turkish industrial sector has an annual energy saving potential of approximately 30% to increase the efficient use of energy, which is suggested to have improved for a sustainable development of the country (İleri and Gürer, 1998; Ediger, 2001, 2002, 2004; Hepbaşlı and Özalp, 2003).

One of the most effective solutions to solve these problems appears to be interfuel substitution between different fossil fuels leading to a best energy mix of the country. This can be achieved by employing more useful energy forms than used at present because the energy efficiency of a country is mostly related to the amount of useful energy used in its energy system as noted by several authors previously (e.g., Schurr, 1984; Patterson, 1996, etc.).

A number of studies starting from the pioneer study of Adams and Miovic (1968) showed clearly that a move from a less efficient fuel to a more efficient one implies that more energy services or useful energy are being achieved. The useful energy, which is defined as "*the energy really available as output of the energy-using devices*" by Percebois (1979, p. 149) is dependent on the relative efficiency in converting energy to useful work and a distinction should be made between useful energy and primary and secondary energy (e.g., Adams and Miovic, 1968; Brookes, 1972; O'Toole, 1976; Häfele, 1977; Percebois, 1979; Eden et al., 1981; Phylipsen et al., 1997; Sheffield, 1998).

The aim of this study is, therefore, to optimize the fossil fuels used in Turkey in 2000 by minimizing their costs. This is done by means of second law of thermodynamics, also known as exergy analysis because the first law of thermodynamics is related to the quantity of energy whereas the second law of thermodynamics takes into account the quality of energy as well as quantity of energy (Çamdali et al., 2001; Rosen and Dinçer, 2004).

Exergy, a thermodynamic property of a system, is simply a measure for the maximum useful work produced by that system. It is the amount of work obtainable when the system is brought to a state of unrestricted equilibrium (thermal, mechanical, and chemical) with the environment by means of reversible processes involving thermal and chemical interaction only with the environment (Kotas, 1980; Rivero et al., 2004 and the references therein). It is also defined as a flow of matter or energy as it comes to equilibrium with a specified reference environment (Caton, 2000; Rosen and Dinçer, 2004).

Unfortunately, there are only a few studies on exergy analyses in Turkey. Performing the energy and exergy analyses of selected Turkish industries, Özdoğan and Arıkol (1995) found a current annual exergy loss of about 2.84 million toe. Rosen and Dinçer (1997) performed sectorial energy and exergy modeling of Turkey and İleri and Gürer (1998) studied the exergy efficiencies in Turkish sectors.

The data used in this study, including the total sales amounts and total retail prices of hard coal, lignite, oil, and natural gas in 2000, is obtained from the World Energy Council Turkish National Committee (WEC TNC), Ministry of Energy and Natural Resources of Turkey (ETKB), Turkish Coal Enterprises (TKI), Turkey Hard Coal Enterprise (TTK), General Directorate of Petroleum Affairs (PIGM), and Petroleum Pipeline Corporation (BOTAS). The domestic productions in hard coal, lignite, and oil are done by the state-owned TTK (hc-ttk), by the state-owned TKI (lig-tki) and private sector (lig-ps), and by several state-owned and private companies (co-do), respectively. The domestic natural gas production is not included since it is negligible. Imports are in the form of hard coal (hc-imp), crude oil (co-imp), petroleum products (pp-imp), and natural gas (ng-pp).

Chemical Exergy and Fuel Quality Factor

Three types of exergy transfer across the control surface are taken into consideration in the models: exergy of work transfer, exergy of heat transfer, and exergy associated with steady stream of matter (Kotas, 1980). If mass flows are combustible fuels at ambient conditions, the specific exergy (ε) reduces to chemical exergy neglecting kinetic and

Table 2
Specific chemical exergy values

Energy carrier	Fuel exergy grade function[a] (γ_f)	Maximum heating values[b] (h_f)	Specific chemical exergy values (ε)
Hard coal			
TTK (hc-ttk)	1.04	4,113 kCal/kg	4,277.52 kCal/kg
Import (hc-imp)	1.04	6,500 kCal/kg	6,760.00 kCal/kg
Lignite			
TKI (lig-tki)	1.04	2,311 kCal/kg	2,403.44 kCal/kg
Private sector (lig-ps)	1.04	2,500 kCal/kg	2,600.00 kCal/kg
Crude oil (co-do, co-imp) and petroleum product (pp-imp)	0.99	10,500 kCal/kg	10,395.00 kCal/kg
Natural gas (ng-pp)	0.92	9,100 kCal/scm[c]	8,372.00 kCal/scm

[a] *Source:* Schaeffert and Wirtshafter, 1992; Dinçer et al., 2004a, 2004b.
[b] *Source:* ETKB, TKI, TTK, PIGM, BOTAŞ, and WEC TNC, 2002.
[c] Standard cubic meter.

potential exergies. In this case, the chemical exergy is defined by the following formula:

$$\varepsilon = \sum_i (\mu_{i0} - \mu_{i00}) \tag{1}$$

where μ_{i0} and μ_{i00} are the chemical exergy potentials at ambient conditions and dead states, respectively. Formula (1) is expressed as follows by Dinçer et al. (2004b):

$$\varepsilon = \gamma_f h_f \tag{2}$$

where γ_f denotes the fuel exergy grade function and h_f is the maximum heating value. Therefore, the specific chemical exergy of each energy carrier can be calculated by multiplying fuel exergy grade function by calorific value of that fuel, as given in Table 2.

Linear Programming for Optimization

Linear programming is an optimization method applicable where both the objective function and the constraints can be expressed as linear combinations of the variables (Kuester and Mize, 1973; Stoecker, 1989). The objective function F is the sum of multiplications of C_n (constant) and X_n (decision variables) as expressed by the following formula:

$$F = C_1 X_1 + C_2 X_2 + \cdots + C_n X_n \tag{3}$$

In this study, the objective function, which is to be minimized, is the total exergy cost (C), the formula of which is given below (Tunç et al., 2006):

$$\begin{aligned} C = {} & \Omega_{hc\text{-}ttk}\Xi_{hc\text{-}ttk} + \Omega_{hc\text{-}imp}\Xi_{hc\text{-}imp} + \Omega_{lig\text{-}tki}\Xi_{lig\text{-}tki} + \Omega_{lig\text{-}ps}\Xi_{lig\text{-}ps} \\ & + \Omega_{co\text{-}do}\Xi_{co\text{-}do} + \Omega_{co\text{-}imp}\Xi_{co\text{-}imp} + \Omega_{pp\text{-}imp}\Xi_{pp\text{-}imp} + \Omega_{ng\text{-}imp}\Xi_{ng\text{-}imp} \end{aligned} \tag{4}$$

Table 3
Unit exergy prices

Fossil fuels	Total sales	Total retail prices (US$)	Total chemical exergy (toe)	Unit exergy prices (US$/toe)
hc-ttk	2,163,000 ton	90,846,000	925,228	98
hc-imp	12,155,000 ton	1,640,925,000	8,216,780	200
lig-tki	39,990,000 ton	839,790,000	9,611,357	87
lig-ps	25,214,000 ton	579,922,000	6,555,640	88
co-do	2,679,597 ton	163,401,825	2,785,441	59
co-imp	21,671,150 ton	4,788,023,881	22,527,160	213
pp-imp	8,622,152 ton	2,575,781,688	8,962,727	287
ng-imp	14,247,871,606 scm	2,333,801,369	11,928,318	196
Overall		13,012,491,764	71,512,651	182

where Ω is cost constant and Ξ is exergy functions of fossil fuels. The cost constant, which is the price per unit exergy, are calculated for each fuels by dividing total price in US$ to total chemical exergy in toe (Table 3). Total chemical exergy values are obtained by multiplication of sales amounts and specific chemical exergy values given in Table 2.

The following function is obtained by using the unit exergy prices given in Table 3:

$$\begin{aligned} C = {} & 98 * \Xi_{hc\text{-}ttk} + 200 * \Xi_{hc\text{-}imp} + 87 * \Xi_{lig\text{-}tki} + 88 * \Xi_{lig\text{-}ps} + 59 * \Xi_{co\text{-}do} \\ & + 213 * \Xi_{co\text{-}imp} + 287 * \Xi_{pp\text{-}imp} + 196 * \Xi_{ng\text{-}imp} \end{aligned} \tag{5}$$

The next step is to determine the constraints. The general formula for constraints is as follows:

$$A_{i1}X_1 + A_{i2}X_2 + \cdots + A_{in}X_n \leq, =, \geq B_i, \qquad i = 1, 2, \ldots, m \tag{6}$$

where A_{in} and B_i are given constants and X_n are the decision variables. The values of A may be positive, negative, or zero, whereas B is always positive in our case.

The constraints are taken as minimum and maximum values of domestic productions and imports for each fossil fuels obtained during the last 30 years (Table 4). The maximum value of natural gas gives, however, the total of all existing contracting amounts.

Results and Conclusions

As a result of linear programming for optimization, we obtained the optimum exergy amounts and minimum costs for each fossil fuel. The results are given in Table 5. The optimum exergy amounts in toe are then converted into the optimum mass amounts in tons or sm^3 by using the specific exergy values given in Table 2. The differences between the optimum and actual amounts are also calculated in Table 6.

As clearly seen in Tables 3 and 5, the total retail price of fossil fuels can be lowered to 11.349 billion US$ from 13.012 billion US$ by increasing hard coal (TTK), lignite (TKİ and private sector), crude oil (domestic), and natural gas (import) and by decreasing hard coal (import), crude oil (import), and petroleum product (import). The new mix in fossil fuels allows a saving capacity of about 1.663 billion US$.

Table 4
Minimum and maximum values of each fossil fuel from 1970 to 2000 (the years are given in parentheses)

	Minimums			Maximums		
Fossil fuels	Original values	Energy (toe)	Exergy (toe)	Original values	Energy (toe)	Exergy (toe)
hc-ttk	1,990,000 ton (1999)	818,487	851,226	4,965,000 ton (1974)	2,042,105	2,123,789
hc-imp	0 ton (1970–72)	0	0	12,155,000 ton (2000)	7,900,750	8,216,780
lig-tki	3,993,000 ton (1970)	922,782	959,693	42,184,000 ton (1992)	9,748,722	10,138,671
lig-ps	1,389,000 ton (1980)	347,250	361,140	28,710,000 ton (1999)	7,177,500	7,464,600
co-do	2,087,000 ton (1984)	2,191,350	2,169,437	4,451,000 ton (1991)	4,673,550	4,626,815
co-imp	3,845,000 ton (1970)	4,037,250	3,996,878	23,735,000 ton (1998)	24,921,750	24,672,533
pp-imp	179,000 ton (1973)	187,950	186,071	9,246,000 ton (2000)	9,708,300	9,611,217
ng-imp	14,247,871,606 scm (2000)	12,965,563	11,928,318	51,058,000,000 scm	46,462,780	42,745,758

Table 5
Results

Fossil fuels	Optimum exergy amounts (toe)	Minimum costs (US$)
hc-ttk	2,123,789	208,131,300
hc-imp	230,059	46,011,800
lig-tki	10,138,671	882,064,400
lig-ps	7,464,600	656,884,800
co-do	4,626,815	272,982,100
co-imp	3,996,878	851,335,000
pp-imp	186,071	53,402,380
ng-imp	42,745,758	8,378,169,000
Total	71,512,651	11,348,980,000

The highest increases are recorded in natural gas (import), hard coal (TTK), and crude oil (domestic) as 258.4%, 129.5%, and 66.1%, respectively (Table 6). On the other hand, the highest decreases are recorded in petroleum product (import) as 97.9%, in hard coal (import) as 97.2%, and in crude oil (import) as 82.3%. The reason why all imports except natural gas have negative values is because the unit exergy price of natural gas is the lowest among others (see Table 3). The unit exergy price is 196 US$ per toe for natural gas while varies between 200 and 287 US$ per toe for the others.

Finally, it should also be noted that the optimum amounts for domestic productions can be achieved only if maximum capacities are used, which is a matter of investment. In cases where limited investments are available, priority should be given to the fossil fuel, which has small exergy prices. The unit exergy prices are, from lowest to highest, 59 US$ per toe for domestic oil, 87 US$ per toe for lignite production by TKİ, 88 US$ per toe for lignite production by private companies, and 98 US$ per toe for hard coal production by TTK.

Table 6
Actual and optimum amounts and differences
(the rate of changes is given in parenthesis)

Sources	Actual amount	Optimum amount	Difference
Hard coal			
TTK	2,163,000 ton	4,965,000 ton	+2,801,998 ton (+129.5%)
Import	12,155,000 ton	340,324 ton	−11,814,676 ton (−97.2%)
Lignite			
TKI	39,990,000 ton	42,184,000 ton	+2,193,993 ton (+5.5%)
Private sector	25,214,000 ton	28,710,000 ton	+3,496,000 ton (+13.9%)
Crude oil			
Domestic	2,679,597 ton	4,451,000 ton	+1,771,403 ton (+66.1%)
Import	21,671,150 ton	3,845,000 ton	−17,826,150 ton (−82.3%)
Petroleum products (imp.)	8,622,152 ton	179,000 ton	−8,443,152 ton (−97.9%)
Natural gas (imp.)	14,247,871,606 scm	51,058,000,000 scm	+36,810,128,394 m^3 (+258.4%)

In conclusion, our analysis showed that a reduction of 1.663 billion US$ in fossil fuel cost can be made possible by giving more emphasis on domestic production of oil, lignite or hard coal. Among the imports, priority should be given to natural gas.

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