# AN ANALYSIS ON THE UTILIZATION OF ENERGY AND EXERGY IN TURKEY

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# ABSTRACT

AN ANALYSIS ON THE UTILIZATION OF ENERGY AND EXERGY IN TURKEY

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Today, energy has become one of the most indispensable necessities in the world. Most of the wars and the disputes between the countries have been arising because of the increasing scarcity of energy resources. Therefore, like most country, Turkey has also started to develop new energy policies for more efficient production and utilization of energy. In order to help the understanding of more efficient energy utilization, so far there have been some researches made about energy and exergy (available energy) utilization efficiencies of Turkey with the viewpoint of the quality of energy.

In this study, it is aimed to examine energy system of Turkey by computing energy and exergy utilization efficiencies between 1990 and 2006 using the first and the second laws of thermodynamics.

The utility sector energy efficiencies are found to range from 41% to 47% and the exergy efficiencies to range from 42% and 48% between 1990 and 2006. The energy efficiencies of the end use sectors of Turkey , namely Industrial, Transportation, Agricultural and Residential-Commercial sectors, are respectively 62%, 22%, 27% and 55% on the average with respect to years. On the other hand, their average exergy efficiencies are 33%, 23%, 27% and 7% between the examined years. The total end use energy and exergy efficiencies are 49% and 21% on the average. Overall energy efficiencies of Turkey range between 37% and 41%, whereas overall exergy efficiencies range between 16% and 17%.

Within all the sectors, Residential–Commercial sector is found as the sector having the highest exergetic improvement potential.

Keywords: Energy, Exergy, Efficiency, Exergetic Improvement Potential

# ÖZ

TÜRKİYE'DEKİ ENERJİ VE EKSERJİ KULLANIMI ÜZERİNE BİR ANALİZ

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Günümüzde, enerji dünyadaki en vazgeçilmez ihtiyaçlardan biri haline gelmiştir. Çoğu savaşlar ve ülkeler arası anlaşmazlıklar enerji kaynaklarının kıtlığındaki artıştan kaynaklanmaktadır. Bu yüzden, çoğu ülke gibi Türkiye de enerjiyi daha verimli bir şekilde üretmek ve kullanmak için yeni enerji politikaları geliştirmeye başlamıştır. Enerjinin daha etkin kullanımını anlamaya yardımcı olmak amacıyla, günümüze kadar enerji kalitesine yönelik bir bakış açısıyla Türkiye'nin enerji ve ekserji (kullanılabilir enerji) kullanım verimlilikleri üzerine bir takım araştırmalar yapılmıştır.

Bu çalışmada; termodinamiğin birinci ve ikinci kanunları kullanılarak, 1990 ve 2006 yılları arasındaki enerji ve ekserji kullanım verimlilikleri hesaplanarak Türkiye'nin enerji sisteminin irdelenmesi amaçlanmıştır.

1990 ve 2006 yılları arasında, elektrik üretim sektörünün enerji verimliliklerinin %41 ile %47 arasında ve ekserji verimlerinin %42 ve %48 arasında değişmekte olduğu bulunmuştur. Türkiye'nin son kullanım sektörleri olan, Endüstriyel, Ulaşım, Tarım ve Evsel-Ticari sektörlerinin enerji verimlikleri yıllar bazında ortalaması sırasıyla %62, %22, %27 ve %55'tir. Diğer taraftan, bu sektörlerin ortalama ekseji verimlilikleri sırasıyla %33, %23, %27 ve %7'dir. Toplam son kullanım enerji ve ekserji verimlilikleri ise ortalama olarak %49 ve %21'dir. Türkiye'nin toplam enerji verimlilikleri %37 ve %41 arasında iken, toplam ekserji verimlilikleri %16 ve %17 arasında seyretmektedir.

Tüm sektörler arasında, Evsel-Ticari sektörünün en fazla ekserjetik gelişim potansiyeli olan sektör olduğu bulunmuştur.

Anahtar Kelimeler: Enerji, Ekserji, Verimlilik, Ekserjetik Gelişim Potansiyeli

To My Wife

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**TABLE OF CONTENTS**

## LIST OF TABLES

TABLES

## LIST OF FIGURES

FIGURES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| T | Temperature |
| m | Mass |
| E | Energy |
| $Q$ | The amount of heat energy added to system |
| $W$ | The work performed by the system on the surroundings |
| ke | Kinetic energy |
| pe | Potential energy |
| X | Exergy |
| $H$ | Heating value (Enthalpy) |
| IP | Exergetic improvement potential |
| COP | Coefficient of performance |
| WEC-TNC | World Energy Council-Turkish National Committee |
| EÜAŞ | Turkish Electricity Generation Company |
| RCS | Residential-commercial sector |

**Greek Letters**

| | |
|---|---|
| $\psi$ | Exergy efficiency |
| $\eta$ | Energy Efficiency |

**Indices**

| | |
|---|---|
| 0 | Dead state |
| 1 | Initial state |
| 2 | Final state |

| | |
|---|---|
| ch | Chemical |
| ph | Physical |
| w | work |
| q | heat |
| f | fuel |
| e | electric |
| r | renewable |
| in | input |
| out | output |
| geo | geothermal |
| env. | environment |

# CHAPTER 1

# INTRODUCTION

Today, energy has become one of the most indispensable necessities in the world. Most of the wars and the disputes between the countries have been arising because of the increasing scarcity of energy resources.

Especially, starting from the 1973 and 1979 oil crisis, most of the countries have commenced to expand their energy resources. Some countries have made this by searching new resources in their country or in the other countries to take a share from them. And some powerful countries have created and have been creating artificial wars (e.g. Gulf wars) to obtain more energy resources under the claim of promising democracy and human rights.

On the other hand, with the high acceleration in the increasing scarcity of energy resources, many scientists have been warning that the efficient utilization of resources is coming to be the only choice for all of the countries. So that most of the peaceable countries, including Turkey have started to develop new energy policies to produce and utilize energy in a more efficient manner.

Energy itself gives information about the quantity of the resource. It does not give any information about the quality of the energy carrying resource. For example, atmosphere and sea water have lots of energy, but no work can be produced from them. So that, together with energy analysis, exergy (available energy) analysis have been used to find more efficient utilization methods not only on quantity base but also on quality base.

In order to help the understanding of more efficient energy utilization, so far there have been some researches made about energy and exergy utilization efficiencies of Turkey with the viewpoint of the quality of energy.

The common recommendation made by the former researches is to use high quality energy carriers for high quality processes, and to use low quality energy carriers for low quality processes. Since a great deal of the energy is obtained by burning high quality energy carriers (fossil fuels) at very high temperatures, obviously the use of this energy for low quality processes like space and water heating is very inefficient.

## 1.1 THE OBJECTIVES OF THE THESIS

In this study, it is aimed to examine energy system of Turkey by computing energy and exergy utilization values with the most recent available data of the years from 1990 to 2006 using the first and the second laws of thermodynamics.

An analysis of the acquired values on a comparison basis with the former values of Turkey and some other countries is considered to be beneficial to understand our energy system efficiencies more clearly. Thus, the improvements in the efficiency of basic sectors in Turkey can be seen and necessary recommendations on the low efficient sectors of the country are able to be proposed using the conclusions of this analysis.

## 1.2 LITERATURE SURVEY

The first scientists who dealt with establishing and formulating the second law of thermodynamics were Carnot and Clausius in 1824 and 1867 respectively. So that thermodynamical background of exergy concept dates back to 1850s.

Exergy was first named by Rant [1] in 1956 as “technical available work” and has been widely adopted by many researchers and scientists.

Availability (exergy) analysis has been used for efficient use of energy in many areas like industrial equipments and power plants since 1850s [e.g. 2, 3, and 4].

However, the energy and exergy analysis of a country has not been performed until 1975. The first analysis was applied by Reistad to US for the year 1970, published in 1975 [5]. In his paper, utility sector with oil refining and electricity generation and distribution was examined separately from end use and end use of energy was parted into three sectors: industry, transportation and residential–commercial. Each sector was divided into energy utilization components according to energy carrier they use. After making necessary assumptions and calculations for each component, the overall energy and exergy utilization efficiency of the country could be computed by finding mean efficiencies from components to sectors.

Wall [6] adapted a new technique, which contributes towards a deeper understanding of the concept of exergy and increases the area of its use. The report was primarily intended for persons directly connected with energy and materials processing within business and industry. However, it was written in such a way that persons with a different back-ground can without difficulty partake in the study and its conclusions. Detailed information such as tables and computer programs were presented in the appendices. The objective was not to describe the calculation methods in exhaustive detail, but to more concisely point out the value of this method and provide new insights and conclusions. [7]

A relatively a new approach, Extended-exergy accounting method (EEA) was introduced by Sciubba was applied to the Italian society in 1996 by Milia and Sciubba [8] and recently to Norway with the figures of 2000 by Ertaswag [9]. The EEA gives exergetic values to labor and to monetary flows within the system (country). Furthermore, the society EEA includes cross-flows of exergy associated with products and services transferred in the different sectors of the society. In this approach, the system is subdivided into seven sectors: extraction, conversion, agriculture, industry, transportation, tertiary and domestic.

Reistad's approach was applied by most of the researchers [5,12,18-31] in such a way using same or modified versions of the approach. On the other hand, Wall's approach was applied to 4 different countries [11,12,13,14,15,16] by Wall and others. It was only applied by Ertesvag and Mielnik [17] to Norway until recently. Chen et al. [41] used also Wall's approach for China in 2006 to calculate exergy efficiencies of China in 1993. On the other hand, as stated above, Sciubba's approach was also followed by Erteswag [9] only.

The most evident difference in these three approaches is the subdivision into sectors. In Reistad's approach three sectors and utility sector are evaluated separately, whereas in the Scuibba's approach there are seven sectors. On the other hand, in Wall's approach there is no significant sectoral subdivision, it deals rather with resource accounting of the country observed specifically.

The other difference is the conversions in the sectors. In Wall's approach, useful output is accounted for whenever produced. For example, transportation, lighting, and space heating within the households contribute to the exergy output or utilization of that sector. Therefore, emphasis is put on the conversion rather than on the use and transfer of the product. In the Scuibbia's approach, however, only services and products that are transferred to another sector are accounted for as output or useful products. So, the analysis of the exergy conversion provides different results in the two approaches. [10]

It is thought that because of the complexity of the other two methods, the Reistad's approach has been proved to be the most applicable method for Turkey since it has been the only approach used by the researchers to find the energy exergy efficiencies of Turkey up to now. The studies that have been made for Turkey are summarized below. In addition, the studies of Dincer et al. [7,21-24] for Saudi Arabia which help as an example to the recent studies of Turkey are also summarized below.

Exergy analysis of Turkey was first performed by Unal [26] under the supervision of Ileri in 1995. In his thesis, energy and exergy balance for Turkey in 1991 was formed and the efficiency values of Utility, Industry, Transportation and Residential-Commercial Sectors were found to find the overall energy and exergy efficiencies of Turkey. The utility sector was examined separately in the thesis just like Reistad's approach.

After Unal's thesis, the first study on the energy and exergy utilization of Turkey was performed by Rosen and Dincer [27]. In their article, the energy and exergy analyses of the four main economic sectors (Utility, Industry, Transportation and Residential-Commercial Sectors) of Turkey were performed to find the sectoral efficiencies and overall efficiency of Turkish energy system.

In 1998, Ileri and Gurer [28] performed the review of Unal's analysis for the year 1995 in a more compact way with minor differences.

Energy and exergy modeling technique used for Turkey [27] was applied to Saudi Arabia by Dincer et al. [7,21-24] for the period of 1990–2001 with minor differences. In their analysis, residential, public and private, industrial, transportation, agricultural, and utility sectors of Saudi Arabia have been investigated. Energy and exergy efficiencies of Saudi Arabian sectors were found to see how efficiently energy and exergy were used in these sectors. After some sectoral analyses, the energy and exergy efficiencies obtained for Saudi Arabia were compared to those available for Turkey for 1993.

The most of the studies on the energy and exergy utilization efficiencies of Turkey have been performed by Utlu and Hepbasli. They applied sectoral energy and exergy modeling to Turkey for the years 1999, 2000 and 2001 [29,30]. In addition, Utlu estimated Turkey's sectoral energy and exergy utilization efficiency by 2023 under the supervision of Hepbasli [31]. Moreover, they have made a lot of studies [32-40] on the energy and exergy efficiencies of Turkish energy sectors separately.

## 1.3 METHODOLOGY

The present study uses Reistad's approach which was also used by Unal for the year 1991 in 1995.

In modeling sectoral energy and exergy utilization efficiencies of Turkey between 1990 and 2006, the present study proposes the following procedure.

1- Subgroup Turkey into five main sectors, namely utility, industrial, transportation, commercial-residential and agricultural. The industrial, transportation, commercial-residential and agricultural sectors can also be called as end use sectors.
2- Make necessary assumptions and estimations for the efficiencies to find out the missing or unreliable input or output values.
3- List energy and exergy inputs and outputs in terms of sectoral values using energy and exergy balance equations for each year.
4- Split each sector into its energy utilization components or subsectors, such as space heating, cooking or petrochemical industry etc.
5- Calculate energy and exergy utilization efficiencies for each subsector or component using the relations given in the next chapter and the assumptions made during the calculations.
6- Find the overall efficiency of the each sector by simply dividing the total output values to input values of the sector.

7- Draw the subsectoral efficiencies together with the related sectors efficiency on a 17-year scale to identify the changes in the efficiencies of subsectors better.

8- Draw the sectoral efficiencies together with the overall efficiency of Turkey on a 17-year scale.

9- Find the exergetic improvement potential (defined in the next chapter) of the subsectors and sectors and draw on a 17-year scale.

10- Analyze the energy and exergy efficiency changes between the analyzed years for saving opportunities.

11- Find the overall end use efficiencies of Turkey. Find the exergetic improvement potentials of overall end use and show them together with the exergetic improvement potentials of the industrial, transportation, commercial-residential and agricultural sectors. Analyze the energy and exergy efficiency changes between the analyzed years for saving opportunities.

## 1.4 OUTLINE OF THE THESIS

The following chapter gives the theoretical background of this study. Starting from the overview of the first and second laws of thermodynamics and general exergy analysis, energy and exergy efficiency equations are handled in this chapter.

The third chapter constitutes the main application part of this study. In this chapter, firstly the reference environment is estimated since exergy can be defined with respect to a reference environment. Using the stated methodology above, all the subsectoral and sectoral efficiencies of Turkey are calculated to find the sectoral efficiencies and overall end use efficiency of Turkey respectively. All these calculations are made for all the years between 1990 and 2006. Using the values evaluated, the change in the efficiencies during this period can be seen from the graphs drawn for sectoral efficiency improvements. Also, exergetic improvement potential of the sectors and Turkey are shown graphically to clarify the improvements between the analyzed years and to understand which sectors need more improvement in the exergy utilization.

The final chapter is devoted for conclusions and recommendations which are based on the efficiencies obtained and the graphs drawn in the preceding chapter. Also the previously found efficiencies of Turkey and other countries are compared with this study in the end of the conclusion part.

# CHAPTER 2

# THEORETICAL ANALYSIS

## 2.1 THE FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is an expression of the universal law of conservation of energy, and identifies heat transfer and work as a form of energy transfer. It asserts that, both work and heat can be converted reciprocally to each other. From the view point of quality of energy, there is no difference between heat and work according to the first law. So that, the amount of heat energy added to a thermodynamic system minus the work done by the system on the surroundings must be equivalent to the energy change in the system. The mathematical statement of the first law is given by:

$$\Delta E = Q - W$$

Where ; $\Delta E$ = Energy change

$Q$ = The amount of heat energy added to system

$W$ = The work performed by the system on the surroundings

## 2.2 THE SECOND LAW OF THERMODYNAMICS

The second law says that temperature differences between systems in contact with each other tend to even out and that work can be obtained from these non-equilibrium differences, but that loss of heat occurs, in the form of entropy, when work is done. This means that an isolated system will eventually come to have a uniform temperature.

For example, a heat engine is a mechanical device that provides useful work from the difference in temperature of two bodies as shown in Figure 1. But it can not covert all the heat to work. Always, some of the heat is wasted.

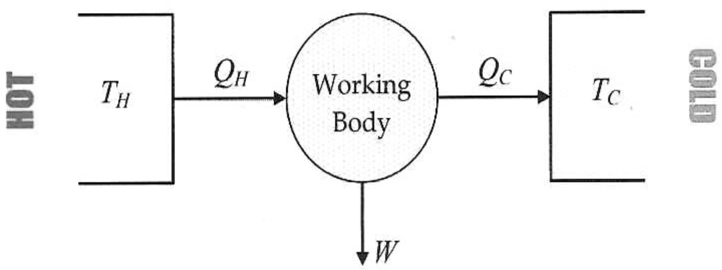


**Figure 1:** Illustration of a heat engine

Since any thermodynamic engine requires such a temperature difference, it follows that no useful work can be derived from an isolated system in equilibrium; there must always be an external energy source and a cold sink. (This is why perpetual motion machines cannot exist.)

## 2.3 EXERGY ANALYSIS

Exergy is defined as the maximum theoretical useful work obtainable as the system interacts with its surroundings and comes to equilibrium. Since the definition of the reversible work is maximum useful work between two states, when the final state of the system has equilibrium with surroundings, exergy becomes the reversible work.

In order to quantify the exergy of a system, we must specify both the system and the surroundings. The exergy reference environment is used to standardize the quantification of exergy. In the analysis, firstly the exergy reference environment or simply the environment is assumed to be a large, simple compressible system (nonflowing close system). The temperature of the environment is assumed to be uniform at To and the pressure is assumed to be uniform at Po. Also, it is assumed that the intensive properties of the environment are not significantly changed by any process. Therefore, the environment is modeled as a thermal reservoir at To.

Consider a closed system that is undergoing a process in which it interacts with the exergy reference environment. Applying the 1st law gives:

$$\Delta E = Q - W \tag{1}$$

Since the environment is a thermal reservoir at To, an entropy balance gives:

$$S_{gen} = \Delta S - \frac{Q}{T_O} \tag{2}$$

Combining the equations (1) and (2) and solving for the work gives:

$$W = -\Delta E + T_O \cdot \Delta S - T_O \cdot S_{gen} \tag{3}$$

The useful work is found by subtracting out the environment work.

$$W_{env.} = P_0 \cdot (V_2 - V_1) \tag{4}$$

$$W_u = -\Delta E + T_O \cdot \Delta S - T_O \cdot S_{gen} - P_0 \cdot (V_2 - V_1) \tag{5}$$

$$W_u = (E_1 - E_2) + P_0 \cdot (V_1 - V_2) - T_O \cdot (S_1 - S_2) - T_O \cdot S_{gen} \tag{6}$$

As stated above assuming no chemical or other reactions and interactions, if the final state of the system is in equilibrium with the environment, that is $E_2 = E_0$, $V_2 = V_0$, $S_2 = S_0$, $ke_2 = ke_0 = 0$, $pe_2 = pe_0 = 0$ then the useful work is given by:

$$W_u = ke_1 + pe_1 + (U_1 - U_0) + P_0 \cdot (V_1 - V_0) - T_O \cdot (S_1 - S_0) - T_O \cdot S_{gen} \tag{7}$$

Clearly, the useful work will be a maximum when the process is reversible and $S_{gen} = 0$. The maximum useful work that can be obtained from a system that is interacting with the exergy reference environment is the exergy (X) of the system:

$$X = ke_1 + pe_1 + (U_1 - U_0) + P_0 \cdot (V_1 - V_0) - T_O \cdot (S_1 - S_0) \tag{8}$$

Assuming an imaginary piston (Figure 2) for the fluid downstream, the equations above may be adapted for a flowing fluid as done in the following relations.

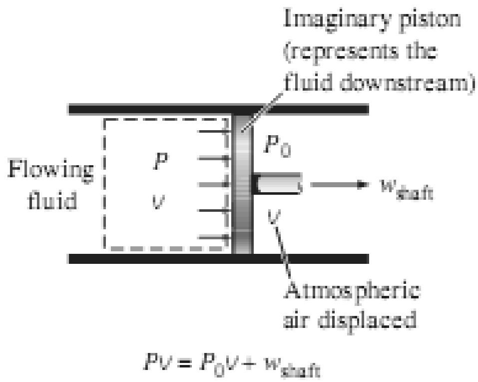


**Figure 2:** Illustration of an imaginary piston in the flow section of a flowing fluid to find the exergy associated with flow energy [47]

The flow work is expressed as $P \cdot V$ and the work done against the atmosphere is $P_0 \cdot V$, the exergy associated with flow energy can be expressed as [47]:

$$X_{flow} = P_1 \cdot V - P_0 \cdot V = (P_1 - P_0) \cdot V \tag{9}$$

Since $X_{flowingfluid} = X_{nonflowingfluid} + X_{flow}$,

$$X_{flowingfluid} = ke_1 + pe_1 + (U_1 - U_0) + P_0 \cdot (V_1 - V_0) - T_O \cdot (S_1 - S_0) + (P_1 - P_0) \cdot V \tag{10}$$

Collecting the $U + P \cdot V$ terms in (10):

$$X_{flowingfluid} = ke_1 + pe_1 + (U_1 + P_1 \cdot V) + (U_0 + P_0 \cdot V) - T_O \cdot (S_1 - S_0) \tag{11}$$

Using the relation of $H = U + P \cdot V$, the exergy term for a flowing stream of matter becomes:

$$X = ke_1 + pe_1 + (H_1 - H_0) - T_O \cdot (S_1 - S_0) \tag{12}$$

When analyzing energy systems, combustion of fossil fuels constitutes a great deal of energy consumption in most countries. So that, some scientists [e.g. 42,43,44,45] added a chemical exergy term to the exergy equation above when chemical reactions concerned. This chemical exergy term is calculated with direct proportionality, called quality factor (q) or exergy grade function, to the heating value ($H_f$) of the energy carrier used.  The chemical exergy is given by:

$$X_{ch} = q \cdot m_f \cdot H_f \tag{13}$$

Average quality factor of some energy carriers are listed in Appendix A. Adding the chemical exergy term, the exergy equation for a flowing steam of matter can be expressed as:

$$X = ke_1 + pe_1 + (H_1 - H_0) - T_O \cdot (S_1 - S_0) + q \cdot m_f \cdot H_f \tag{14}$$

Assuming there is no kinetic and potential energies and no chemical exergy, the remaining term $(H_1 - H_0) - T_O \cdot (S_1 - S_0)$ is defined as physical exergy which is maximum available work extracted from a flowing stream as it is brought to the environmental state.

Since the most common mass flows are hydrocarbon fuels at near-ambient conditions, for which the term in the square brackets (potential, kinetic and physical exergies) in Equation (14) is approximately zero, and exergy reduces to chemical exergy, which can be written as

$$X = q \cdot m_f \cdot H_f \tag{15}$$

On the other hand, when hydroelectric and wind power plants concerned, the physical and chemical exergies are approximately zero because of the near ambient conditions for the flowing particles without any chemical reaction. Thus, for hydroelectric and wind power plants, exergy reduces to potential and kinetic energies respectively. So that, it can be said that potential and kinetic energy values are equivalent to the potential and kinetic exergies respectively.

Nevertheless, when there is a heat transfer concerned across a system boundary at constant temperature T, there is no need for complex calculations to find the exergy of the heat transfer. Applying the definition of exergy, maximum theoretical useful work, exergy of a heat transfer can easily be found from the well known reversible heat engine relation:

$$X_q = (1 - \frac{T_0}{T}) \cdot Q \tag{16}$$

Likewise, exergy of work (which may be in the form of electricity or mechanical energy) is the work itself from the definition of exergy.

$$X_w = W \tag{17}$$

After the exergy analysis, it is thought to be beneficial to show the basic differences between energy and exergy concepts by tabulating below.

**Table 1:** Basic Differences between Energy and Exergy [48,26,47]

| Energy | Exergy |
|---|---|
| 1- may be defined as motion or ability to produce motion | 1- may be defined as work or ability to produce work. |
| 2- is always conserved in a process, so can neither be destroyed | 2- is always conserved in a reversible process, but is always consumed in irreversible process. |

**Table 1 (Continued)**

| | |
|---|---|
| 3- is dependent on the parameters of matter or energy flow only, and independent of the environment parameters. | 3- is dependent both on the parameters of matter or energy flow and on the environment parameters. |
| 4- has values different from zero | 4- is equal to zero (in a dead state by equilibrium with the environment). |
| 5- is guided by the first law of thermodynamics for all the processes**.** | 5- is guided by the first law of thermodynamics for reversible processes only (in irreversible processes it is destroyed partly or completely). |
| 6- is a measure of quantity. | 6- is a measure of not only quantity but also quality due to entropy. |
| 7- is limited by the second law of thermodynamics for all processes | 7- is not limited for reversible processes due to the second law of thermodynamics. |
| 8- increases with the rise of temperature | 8- for constant pressure processes reaches minimum at the temperature of the environment; at temperature lower than that, it increase as the temperature drops (Since a cold medium can serve as the heat sink to a heat engine that absorbs heat from the environment). |

## 2.4 ENERGY AND EXERGY EFFICIENCIES

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:

$$\eta = (\text{energy output} / \text{energy input}) \quad (18)$$

$$\psi = (\text{exergy output} / \text{exergy input}) \quad (19)$$

For example, both input (fuel) and output (electricity) values may easily be found to calculate the efficiencies for electricity generation from fossil fuels.

In most of the processes, energy and exergy inputs to a system can easily be found, since the input values are the consumption values (like electricity and fuel consumption). But the output values, which change according to the efficiency and effectiveness of the equipment used for the process, are very hard to determine. So that the energy efficiencies are estimated for huge systems and the exergy efficiencies are found by thermodynamic relations between these two efficiencies for most of the processes.

Likewise, for electricity generation from the renewable resources (hydraulic, wind, solar, biomass etc.), energy input values are very difficult to find especially in a macro system like a country which has a lot of power plants. Therefore, to find the energy and exergy efficiencies of renewable power plants, some estimations must be performed too.

In the following part, the efficiency equations for principle types of processes [22] are explained which are used for further calculations of this study.

### 2.4.1 Efficiencies for Principle Types of Processes

#### 2.4.1.1 Heating

Electric and fossil fuel heating processes are taken to generate product heat Q at a constant temperature T; either from electrical energy W or fuel mass $m_f$. The energy and exergy efficiencies for electric and fuel heating are respectively:

$$\eta_e = Q/W \tag{20}$$

$$\psi_e = X_q / X_W = (1-\frac{T_0}{T}) \cdot Q/W = \eta \cdot (1-\frac{T_0}{T}) \tag{21}$$

$$\eta_f = Q / m_f \cdot H_f \tag{22}$$

$$\psi_f = X_q / X_f$$

Using the chemical exergy relation (15) for $X_f$ :

$$\psi_f = (1 - \frac{T_0}{T}) \cdot Q / (q \cdot m_f \cdot H_f) = \frac{\eta}{q} \cdot (1 - \frac{T_0}{T}) \tag{23}$$

Note that, for quality factor (q) = 1, exergy relations (21) and (23) are the same which verifies the quality factor of electricity to be unity.

On the other hand, for space and water heating processes, heat is not directly used. It is rather used by convectional heat transfer. For a desired supply temperature T for space and water heating equipment, the exergy efficiency for electric and fuel heating may be calculated from the equation: [42, 34]

$$\psi = \frac{\eta}{q} \cdot \left( 1 - \left[ \frac{T_0}{T - T_0} \right] \cdot \ln\left( \frac{T}{T_O} \right) \right) \tag{24}$$

### 2.4.1.2 Cooling

Energy and exergy efficiencies of cooling devices may be calculated from the following equations, where heat (Q) is extracted from cool reservoir at temperature T and COP denotes the coefficient of performance (efficiency multiplied by 100) :

$$\eta = \frac{COP}{100} = Q / W \tag{25}$$

$$\psi = \eta \cdot (\frac{T_0}{T} - 1) \tag{26}$$

### 2.4.1.3 Electricity Generation

The energy and exergy efficiencies for generating electricity from fossil fuels are respectively:

$$\eta = W / m_f \cdot H_f \quad (27)$$

$$\psi = X_w / X_f = W / (m_f \cdot q \cdot H_f) = \eta / q \quad (28)$$

Since for most of the fuels used in electricity generation, quality factor is approximately equivalent to unity, exergy and energy efficiencies for electricity generation through fossil fuels are almost the same.

On the other hand, as stated before, for hydroelectricity and wind power plants the exergy and energy values are equivalent to potential and kinetic energies. So the efficiencies of a hydroelectric power plant may be found from:

$$\eta = \psi = W / X_{in} = W / E_{in} = W / pe \quad (29)$$

Likely, the efficiencies of wind power plant are:

$$\eta = \psi = W / X_{in} = W / E_{in} = W / ke \quad (30)$$

### 2.4.1.3 Work Production for Mechanical Drives

Electric or fossil fuel driven work production processes produce shaft work W for mechanical drives which are used in the industrial sectors. The energy and exergy efficiencies for electric and fossil fuel driven shaft work production processes are:

$$\eta_e = W / W_e \quad (31)$$

$$\psi_e = X_w / X_{w_e} = W / W_e = \eta_e \tag{32}$$

$$\eta_f = W / (m_f \cdot H_f) \tag{33}$$

$$\psi_f = X_w / (m_f \cdot q \cdot H_f) = W / (m_f \cdot q \cdot H_f) = \frac{\eta_f}{q} \approx \eta_f \tag{34}$$

Since most of the fossil fuels have a quality factor of approximately unity, it can be said that the exergy and energy efficiencies for mechanical drives are approximately equivalent.

### 2.4.2 Exergetic Improvement Potential

Van Gool [46] has also noted that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic ‘improvement potential when analyzing different processes or sectors of the economy. This improvement potential, denoted IP, is given by [25,40].

$$IP = (1-\psi) \cdot (X_{in} - X_{out}) \tag{35}$$

Since; $\psi = \frac{X_{out}}{X_{in}} \Rightarrow X_{out} = \psi \cdot X_{in}$

Exergetic Improvement Potential is also simplified as:

$$IP = (1-\psi)^2 \cdot X_{in} \tag{36}$$

Or using $X_{out} = \psi \cdot X_{in}$ relation

Exergetic Improvement Potential may also be shown as:

$$IP = \frac{(1-\psi)^2}{\psi} \cdot X_{out}$$

### 2.4.3 Average Efficiency Calculations

When the utilization ratio of a subsector or component is multiplied by the total utilization and the efficiency of the component, the output of that subsector or component is found. So that using equations (18) and (19), total utilization value (input) is simplified. Therefore the general efficiency equations (18) and (19) are simplified as shown below.

$$\eta = (a_1 \cdot \eta_1 + a_2 \cdot \eta_2 + ...... + a_n \cdot \eta_n)/100 \quad (37)$$

$$\psi = (a_1 \cdot \psi_1 + a_2 \cdot \psi_2 + ...... + a_n \cdot \psi_n)/100 \quad (38)$$

Where; $a_1$, $a_2$ and $a_n$ denote the utilization percentages of components or subsectors.

$\eta_1$, $\eta_2$ and $\eta_n$ denote the exergy efficiencies of components or subsectors.

$\psi_1$, $\psi_2$ and $\psi_n$ denote the exergy efficiencies of components or subsectors.

# CHAPTER 3

# ENERGY AND EXERGY UTILIZATION IN TURKEY

## 3.1 Reference Environment

As stated in the theoretical analysis, energy does not depend on the reference environment. However exergy is always evaluated with respect to a reference environment. So that reference environment must be clearly stated for exergy calculations before starting the analysis. The reference environment is assumed to be in 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, pressure and chemical composition of the environment) remains constant [7].

According to Turkish Meteorological Institute [49], the average temperature of Turkey is around 13 °C between the years 1971 and 2005. In the analyses of Dincer et al. [7,21-24] for Saudi Arabia, the environment temperature is assumed to be 10 °C. Likewise, reference environment may be adopted as 10 °C at 1 atm pressure just as in the case of Dincer et al.'s studies.

After defining the reference environment, let's start to analyze the Turkish energy sectors to find the sectoral and overall efficiencies of Turkey between the years 1990 and 2006.

### 3.2 Utility Sector

The utility sector in Turkey produces more than half of the electricity from fossil fuels, particularly lignite, natural gas, hard coal and petroleum products (diesel oil, fuel oil, gasoline). Almost all the rest of the electricity is generated from hydroelectric power plants.

The data of the inputs and the outputs of the utility sector of Turkey (also the other sectors) are available in WEC-TNC reports and statistics from 1990 to 2006 [51-53]. However when the recent assessment of Utlu and Hepbasli [38], who used WEC-TNC reports to evaluate the efficiencies of Turkish utility sector between 1990 an 2004, is carefully examined, it is obviously seen that wind and hydroelectric power plants were assumed to be about 100 % efficient in the reports. In addition, geothermal electricity generation was assumed to be around 10 % energy and exergy efficient which contradicts with the literature [50,54] on the geothermal power plants. So that, before analyzing the input values of the sector totally, the efficiencies of these power plants should be estimated. Thus, the input values for these three power plants in the WEC-TNC reports are corrected firstly to obtain more reasonable results.

In addition, there are no values for biomass inputs and some biomass outputs are missing in the reports. So that the biomass values between 1990 and 2004 are adopted from the article of Utlu and Hepbasli [38] in this study. On the other hand, biomass output values for the years 2005 and 2006 are taken from the WEC-TNC reports and the input values are computed with 10 % efficiency which is the average efficiency between 1990 and 2004.

### 3.2.1 Estimations of the efficiencies for Hydroelectric, Geothermal and Wind Power plants

#### 3.2.1.1 Hydroelectric Power Plants

Most of the hydroelectric power plants have been and being operated by Turkish Electricity Generation Company (EÜAŞ) in Turkey. According to the data for most of the state owned power plants which performed 83 % of the hydroelectric production in 2006 given in Appendix B, average turbine efficiency of the plants is calculated as 92.6%. On the other hand, including the generator efficiencies, the average efficiency of the hydroelectric power plants is found to be 88.5% as explained in Appendix B.

Because the most of the hydroelectric power plants operated in 2006 were also being operated during 1990s, the average efficiency value found in 2006 may also be used for all the years between 1990 and 2006. Thus, using equation (29) in chapter 2, the energy and exergy efficiencies of hydroelectric power plants are assumed as 0.8845 for all the years examined.

#### 3.2.1.2 Geothermal Power Plants

The only geothermal power plant of Turkey was the Kızıldere plant until 2006. In 2006, Salavatlı plant started to produce electricity, but it only produced 5.7 % percent of the geothermal electricity in 2006 [56]. So that, finding the efficiencies of Kızıldere plant is thought to be adequate for the analysis of geothermal plants in Turkey. As stated in the article of Utlu and Hepbasli [50], there have been several researches [54,57-59] made for the energy and exergy analysis of the Kızıldere Geothermal Power plant. In these researches, the exergy efficiencies of the plant were found between 19.8% and 20.8 %. On the other hand energy efficiency of the plant was found as 4.6 % [54].

Thus, the energy efficiency of the geothermal electricity generation is estimated as 4.6 % from Dagdas's study [54]. Since there has been a consensus on the exergy efficiency of the power plant to be around 20 %, the exergy efficiency of geothermal power plant is adopted as 20 %.

#### 3.2.1.3 Wind Power Plants

As proven in Appendix C, Betz's law states that the power output of a wind turbine is at maximum when the wind is slowed to one-third of its initial velocity. Therefore, the highest efficiency of a wind turbine can be 59.26 percent without any other losses. In practice, the actual efficiency ranges between 20 and 40 percent and is about 35 percent for many wind turbines [47].

Like in the case of most power plants, energy and exergy efficiencies may be estimated as 35 % percent for the wind power plants in Turkey.

### 3.2.2 Input and Output Configuration in the Utility Sector

Output configuration (electricity generation) of Turkey can easily be found by converting GWh units in WEC-TNC reports [51-53] into PJ units.

**Table 2 :** Electricity produced (PJ) in the utility sector of Turkey 1990-2006 [51-53]

| Years | Hard coal | Lignite | Petroleum | Natural gas | Biomass | Hydro | Geothermal | Wind |
|---|---|---|---|---|---|---|---|---|
| 1990 | 2.2 | 70.4 | 14.2 | 36.7 | 0 | 83.3 | 0.29 | 0 |
| 1991 | 3.6 | 74.1 | 11.9 | 45.3 | 0.14 | 81.7 | 0.29 | 0 |
| 1992 | 6.5 | 81.9 | 19.0 | 38.9 | 0.17 | 95.6 | 0.25 | 0 |
| 1993 | 6.5 | 79.1 | 18.6 | 38.8 | 0.20 | 122.2 | 0.28 | 0 |
| 1994 | 7.1 | 94.5 | 20.0 | 49.8 | 0.18 | 110.1 | 0.28 | 0 |
| 1995 | 8.0 | 92.9 | 20.8 | 59.7 | 0.08 | 128.0 | 0.31 | 0 |
| 1996 | 9.3 | 100.2 | 23.5 | 61.8 | 0.63 | 145.7 | 0.30 | 0 |
| 1997 | 11.8 | 110.1 | 25.8 | 79.5 | 1.06 | 143.3 | 0.30 | 0 |
| 1998 | 10.7 | 117.8 | 28.5 | 89.4 | 0.92 | 152.0 | 0.31 | 0.02 |
| 1999 | 11.2 | 122.1 | 29.1 | 130.9 | 0.74 | 124.8 | 0.29 | 0.08 |

**Table 2 (Continued)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2000 | 13.8 | 123.7 | 33.5 | 166.4 | 0.79 | 111.2 | 0.27 | 0.12 |
| 2001 | 14.6 | 123.7 | 37.3 | 178.4 | 0.83 | 86.4 | 0.32 | 0.22 |
| 2002 | 14.7 | 101.0 | 38.7 | 189.0 | 0.63 | 121.3 | 0.38 | 0.17 |
| 2003 | 31.2 | 84.9 | 33.1 | 228.7 | 0.42 | 127.2 | 0.32 | 0.22 |
| 2004 | 43.2 | 80.8 | 27.6 | 224.1 | 0.37 | 165.9 | 0.33 | 0.21 |
| 2005 | 47.7 | 107.8 | 19.7 | 264.4 | 0.44 | 142.4 | 0.34 | 0.21 |
| 2006 | 51.2 | 116.8 | 15.6 | 290.5 | 0.55 | 159.3 | 0.34 | 0.46 |

Likewise, the energy input values of the utility sector (except biomass as stated in the beginning of this chapter) are also taken from WEC-TNC reports by converting toe units into PJ units. However, for the hydraulic, geothermal, and wind inputs are found by dividing the output values into the efficiency estimations made in part 3.2.1 for hydroelectric, geothermal and wind power plants.

**Table 3 :** Energy inputs (PJ) for the utility sector in Turkey 1990-2006 [50-53]

| Years | Hard coal | Lignite | Petroleum | Natural gas | Biomass | Hydro | Geothermal | Wind |
|---|---|---|---|---|---|---|---|---|
| 1990 | 9.2 | 208.3 | 46.5 | 97.4 | 0 | 94.2 | 6.3 | 0 |
| 1991 | 14.8 | 235.3 | 30.7 | 109.3 | 1.3 | 92.3 | 6.4 | 0 |
| 1992 | 25.5 | 257.8 | 61.9 | 99.2 | 1.7 | 108.1 | 5.5 | 0 |
| 1993 | 24.7 | 238.0 | 66.7 | 96.4 | 2.0 | 138.2 | 6.2 | 0 |
| 1994 | 27.5 | 288.8 | 69.5 | 111.5 | 1.8 | 124.5 | 6.2 | 0 |
| 1995 | 23.8 | 286.4 | 75.5 | 137.2 | 0.8 | 144.7 | 6.8 | 0 |
| 1996 | 28.2 | 311.5 | 78.8 | 144.4 | 6.3 | 164.7 | 6.6 | 0 |
| 1997 | 35.0 | 343.2 | 85.9 | 174.1 | 10.6 | 162.1 | 6.6 | 0 |
| 1998 | 35.9 | 373.8 | 94.1 | 209.0 | 9.2 | 171.9 | 6.7 | 0.06 |
| 1999 | 33.2 | 386.7 | 96.4 | 288.6 | 7.4 | 141.1 | 6.4 | 0.22 |
| 2000 | 33.0 | 385.3 | 149.4 | 357.9 | 8.0 | 125.7 | 6.0 | 0.34 |
| 2001 | 38.4 | 383.5 | 145.1 | 401.0 | 8.3 | 97.7 | 7.1 | 0.64 |
| 2002 | 36.2 | 318.5 | 142.4 | 421.6 | 6.3 | 137.1 | 8.3 | 0.49 |
| 2003 | 78.4 | 264.7 | 127.7 | 469.0 | 4.2 | 143.8 | 7.0 | 0.63 |
| 2004 | 105.1 | 256.9 | 107.9 | 491.8 | 3.8 | 187.6 | 7.3 | 0.59 |
| 2005 | 111.1 | 286.8 | 86.3 | 587.5 | 4.4 | 161.0 | 7.4 | 0.61 |
| 2006 | 128.1 | 351.3 | 73.5 | 630.3 | 5.5 | 180.1 | 7.4 | 1.31 |

Exergy inputs to the sector are simply found by multiplying each energy carrier's energy utilization with its quality factor except geothermal exergy input. Geothermal exergy inputs are found by dividing the output values into the estimated exergy efficiency (20 %).

**Table 4:** Exergy inputs (PJ) for the utility sector in Turkey 1990-2006 [50-53]

| Years | Hard coal | Lignite | Petroleum | Natural gas | Biomass | Hydro | Geothermal | Wind |
|---|---|---|---|---|---|---|---|---|
| 1990 | 9.4 | 216.7 | 46.1 | 89.6 | 0 | 94.2 | 1.4 | 0 |
| 1991 | 15.3 | 244.7 | 30.3 | 100.5 | 1.4 | 92.3 | 1.5 | 0 |
| 1992 | 26.3 | 268.1 | 61.3 | 91.3 | 1.8 | 108.1 | 1.3 | 0 |
| 1993 | 25.5 | 247.5 | 66.0 | 88.7 | 2.1 | 138.2 | 1.4 | 0 |
| 1994 | 28.3 | 300.3 | 68.9 | 102.6 | 1.9 | 124.5 | 1.4 | 0 |
| 1995 | 24.5 | 297.9 | 74.7 | 126.3 | 0.8 | 144.7 | 1.6 | 0 |
| 1996 | 29.0 | 324.0 | 78.0 | 132.9 | 6.6 | 164.7 | 1.5 | 0 |
| 1997 | 36.1 | 356.9 | 85.1 | 160.2 | 11.1 | 162.1 | 1.5 | 0 |
| 1998 | 37.0 | 388.7 | 93.1 | 192.3 | 9.7 | 171.9 | 1.5 | 0.06 |
| 1999 | 34.2 | 402.1 | 95.5 | 265.5 | 7.8 | 141.1 | 1.5 | 0.22 |
| 2000 | 33.9 | 400.7 | 147.9 | 329.2 | 8.4 | 125.7 | 1.4 | 0.34 |
| 2001 | 39.5 | 398.9 | 143.7 | 369.0 | 8.7 | 97.7 | 1.6 | 0.64 |
| 2002 | 37.2 | 331.3 | 141.0 | 387.9 | 6.7 | 137.1 | 1.9 | 0.49 |
| 2003 | 80.8 | 275.3 | 126.4 | 431.5 | 4.4 | 143.8 | 1.6 | 0.63 |
| 2004 | 108.2 | 267.2 | 106.8 | 452.4 | 3.9 | 187.6 | 1.7 | 0.59 |
| 2005 | 114.4 | 298.3 | 85.4 | 540.5 | 4.6 | 161.0 | 1.7 | 0.61 |
| 2006 | 132.0 | 365.4 | 72.7 | 579.9 | 5.8 | 180.1 | 1.7 | 1.31 |

### 3.2.3 Energy and Exergy Efficiencies of the Utility Sector

Energy and exergy efficiencies of power plants according to each energy carrier they use may easily be found by dividing output values into input values.

**Table 5:** Energy efficiencies of power plants between 1990 and 2006 (%)

| Years | Hard coal | Lignite | Petroleum | Natural gas | Biomass | Hydro | Geothermal | Wind |
|---|---|---|---|---|---|---|---|---|
| 1990 | 24.4 | 33.8 | 30.5 | 37.7 | - | 88.5 | 4.6 | - |
| 1991 | 24.2 | 31.5 | 38.7 | 41.5 | 10.8 | 88.5 | 4.6 | - |
| 1992 | 25.6 | 31.8 | 30.7 | 39.3 | 10.0 | 88.5 | 4.6 | - |
| 1993 | 26.1 | 33.2 | 28.0 | 40.3 | 9.8 | 88.5 | 4.6 | - |
| 1994 | 25.9 | 32.7 | 28.7 | 44.6 | 9.8 | 88.5 | 4.6 | - |
| 1995 | 33.8 | 32.5 | 27.5 | 43.5 | 10.0 | 88.5 | 4.6 | - |
| 1996 | 32.9 | 32.2 | 29.9 | 42.8 | 10.0 | 88.5 | 4.6 | - |
| 1997 | 33.7 | 32.1 | 30.0 | 45.7 | 10.0 | 88.5 | 4.6 | - |
| 1998 | 29.9 | 31.5 | 30.3 | 42.8 | 10.0 | 88.5 | 4.6 | 35 |
| 1999 | 33.8 | 31.6 | 30.2 | 45.3 | 10.0 | 88.5 | 4.6 | 35 |
| 2000 | 41.7 | 32.1 | 22.4 | 46.5 | 9.9 | 88.5 | 4.6 | 35 |
| 2001 | 38.0 | 32.3 | 25.7 | 44.5 | 10.0 | 88.5 | 4.6 | 35 |
| 2002 | 40.8 | 31.7 | 27.2 | 44.8 | 10.0 | 88.5 | 4.6 | 35 |
| 2003 | 39.8 | 32.1 | 25.9 | 48.8 | 10.1 | 88.5 | 4.6 | 35 |
| 2004 | 41.1 | 31.5 | 25.6 | 45.6 | 9.9 | 88.5 | 4.6 | 35 |
| 2005 | 42.9 | 37.6 | 22.9 | 45.0 | 10.0 | 88.5 | 4.6 | 35 |
| 2006 | 40.0 | 33.2 | 21.3 | 46.1 | 10.1 | 88.5 | 4.6 | 35 |

**Table 6:** Exergy efficiencies of power plants between 1990 and 2006 (%)

| Years | Hard coal | Lignite | Petroleum | Natural gas | Biomass | Hydro | Geothermal | Wind |
|---|---|---|---|---|---|---|---|---|
| 1990 | 23.7 | 32.5 | 30.8 | 41.0 | - | 88.5 | 20 | - |
| 1991 | 23.5 | 30.3 | 39.1 | 45.1 | 10.3 | 88.5 | 20 | - |
| 1992 | 24.9 | 30.6 | 31.0 | 42.7 | 9.5 | 88.5 | 20 | - |
| 1993 | 25.4 | 31.9 | 28.2 | 43.8 | 9.3 | 88.5 | 20 | - |
| 1994 | 25.2 | 31.5 | 29.0 | 48.5 | 9.3 | 88.5 | 20 | - |
| 1995 | 32.8 | 31.2 | 27.8 | 47.3 | 9.5 | 88.5 | 20 | - |
| 1996 | 31.9 | 30.9 | 30.2 | 46.5 | 9.5 | 88.5 | 20 | - |
| 1997 | 32.7 | 30.9 | 30.3 | 49.6 | 9.5 | 88.5 | 20 | - |
| 1998 | 29.0 | 30.3 | 30.6 | 46.5 | 9.5 | 88.5 | 20 | 35 |
| 1999 | 32.8 | 30.4 | 30.5 | 49.3 | 9.5 | 88.5 | 20 | 35 |
| 2000 | 40.5 | 30.9 | 22.7 | 50.5 | 9.5 | 88.5 | 20 | 35 |
| 2001 | 36.8 | 31.0 | 26.0 | 48.4 | 9.5 | 88.5 | 20 | 35 |
| 2002 | 39.6 | 30.5 | 27.4 | 48.7 | 9.5 | 88.5 | 20 | 35 |

**Table 6 (Continued)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2003 | 38.61 | 30.84 | 26.19 | 53.01 | 9.5 | 88.5 | 20 | 35 |
| 2004 | 39.92 | 30.25 | 25.86 | 49.53 | 9.4 | 88.5 | 20 | 35 |
| 2005 | 41.68 | 36.15 | 23.11 | 48.92 | 9.5 | 88.5 | 20 | 35 |
| 2006 | 38.78 | 31.96 | 21.49 | 50.09 | 9.6 | 88.5 | 20 | 35 |

In order to find the overall efficiencies of the utility sector, the total outputs are divided into total inputs for each year (As done in Table 7). However, electricity produced in power plants does not totally come to the end-users. When in-plant usage, transmission and other losses and electricity supply to oil refineries are discarded from the total electricity produced, the net electricity supply to end-users is found. By dividing the net electricity supply to end-users into the input values (enlarging the control volume up to the end users), net electricity supply efficiencies are found (See Table 8).

**Table 7:** Total Inputs and Outputs in the Utility Sector together with in-plant usage, transmission and other losses, electricity supply to oil refineries and the net electricity supply to end-users (PJ)

| Years | Total Energy Input | Total Exergy Input | Total Electricity Produced | In-plant usage, transmission and other losses | Electricity supply to oil refineries | Net electricity supply to end-users |
|---|---|---|---|---|---|---|
| 1990 | 461.9 | 457.4 | 207.2 | 36.0 | 4.1 | 167.1 |
| 1991 | 490.1 | 486.0 | 217.0 | 40.4 | 5.2 | 171.3 |
| 1992 | 559.7 | 558.1 | 242.4 | 47.7 | 5.5 | 189.3 |
| 1993 | 572.2 | 569.4 | 265.7 | 51.1 | 6.0 | 208.6 |
| 1994 | 629.9 | 627.9 | 282.0 | 59.0 | 6.0 | 216.9 |
| 1995 | 675.2 | 670.4 | 309.8 | 65.4 | 6.0 | 238.3 |
| 1996 | 740.6 | 736.8 | 341.5 | 74.3 | 6.0 | 261.2 |
| 1997 | 817.4 | 812.8 | 371.9 | 85.1 | 7.1 | 279.7 |
| 1998 | 900.6 | 894.2 | 399.7 | 94.8 | 7.6 | 297.3 |
| 1999 | 960.1 | 947.9 | 419.2 | 98.2 | 6.7 | 314.3 |
| 2000 | 1065.5 | 1047.5 | 449.7 | 107.9 | 7.8 | 334.0 |
| 2001 | 1081.8 | 1059.7 | 441.8 | 107.3 | 5.9 | 328.6 |
| 2002 | 1070.9 | 1043.5 | 465.9 | 106.6 | 6.0 | 353.3 |
| 2003 | 1095.4 | 1064.4 | 506.1 | 105.8 | 3.7 | 396.6 |

**Table 7 (Continued)**

| | | | | | | |
|---|---|---|---|---|---|---|
| 2004 | 1160.9 | 1128.4 | 542.5 | 104.0 | 3.0 | 435.5 |
| 2005 | 1245.1 | 1206.5 | 583.0 | 109.9 | 3.1 | 470.1 |
| 2006 | 1377.5 | 1338.8 | 634.7 | 113.6 | 3.1 | 518.0 |

After finding all the overall efficiencies of the utility sector in Table 8, it is time to draw the efficiencies of power plants and the overall efficiency of Turkey together in Figure 3 and Figure 4.

**Table 8:** Overall and exergy efficiencies of Utility Sector, Net Supply Energy Energy and Exergy efficiencies, percent of losses after generation (%)

| Years | Overall Energy Efficiency | Overall Exergy Efficiency | Net Supply Energy Efficiency | Net Supply Exergy Efficiency | Percent of Losses after Generation |
|---|---|---|---|---|---|
| 1990 | 44.9 | 45.3 | 36.2 | 36.5 | 17.4 |
| 1991 | 44.3 | 44.6 | 35.0 | 35.3 | 18.6 |
| 1992 | 43.3 | 43.4 | 33.8 | 33.9 | 19.7 |
| 1993 | 46.4 | 46.7 | 36.5 | 36.6 | 19.2 |
| 1994 | 44.8 | 44.9 | 34.4 | 34.6 | 20.9 |
| 1995 | 45.9 | 46.2 | 35.3 | 35.6 | 21.1 |
| 1996 | 46.1 | 46.4 | 35.3 | 35.5 | 21.8 |
| 1997 | 45.5 | 45.8 | 34.2 | 34.4 | 22.9 |
| 1998 | 44.4 | 44.7 | 33.0 | 33.3 | 23.7 |
| 1999 | 43.7 | 44.2 | 32.7 | 33.2 | 23.4 |
| 2000 | 42.2 | 42.9 | 31.4 | 31.9 | 24.0 |
| 2001 | 40.8 | 41.7 | 30.4 | 31.0 | 24.3 |
| 2002 | 43.5 | 44.6 | 33.0 | 33.9 | 22.9 |
| 2003 | 46.2 | 47.6 | 36.2 | 37.3 | 20.9 |
| 2004 | 46.7 | 48.1 | 37.5 | 38.6 | 19.2 |
| 2005 | 46.8 | 48.3 | 37.8 | 39.0 | 18.9 |
| 2006 | 46.1 | 47.4 | 37.6 | 38.7 | 17.9 |

According to Table 8, about 18 to 24 % energy loss occurs after the generation of electricity which is thought to be very much for transmission and other losses.

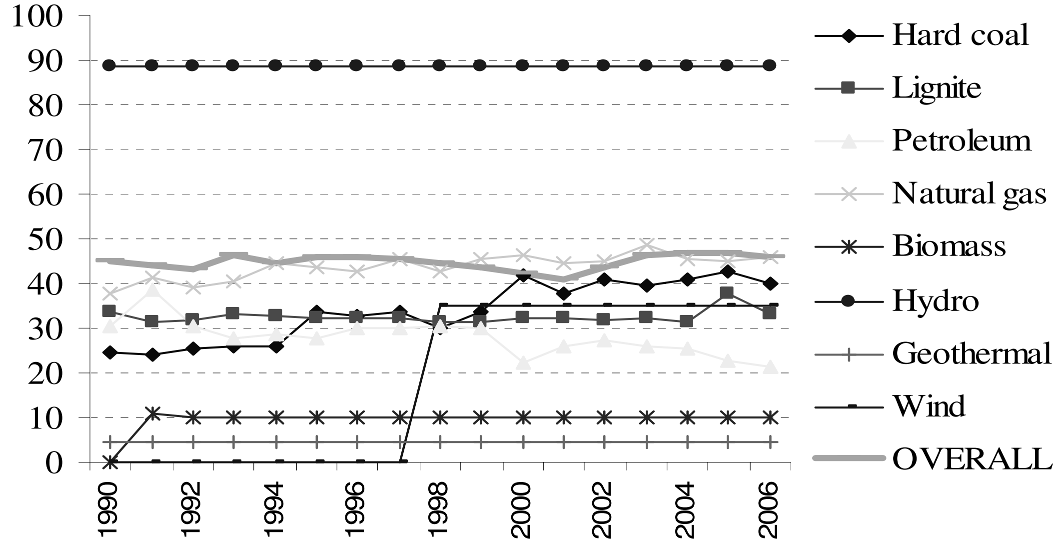


**Figure 3:** Energy Efficiency of Power Plants between 1990 and 2006 (%)

The energy and exergy efficiencies of the fossil fuelled power plants are nearly same, as expected because of the fuels' quality factors being nearly unity.

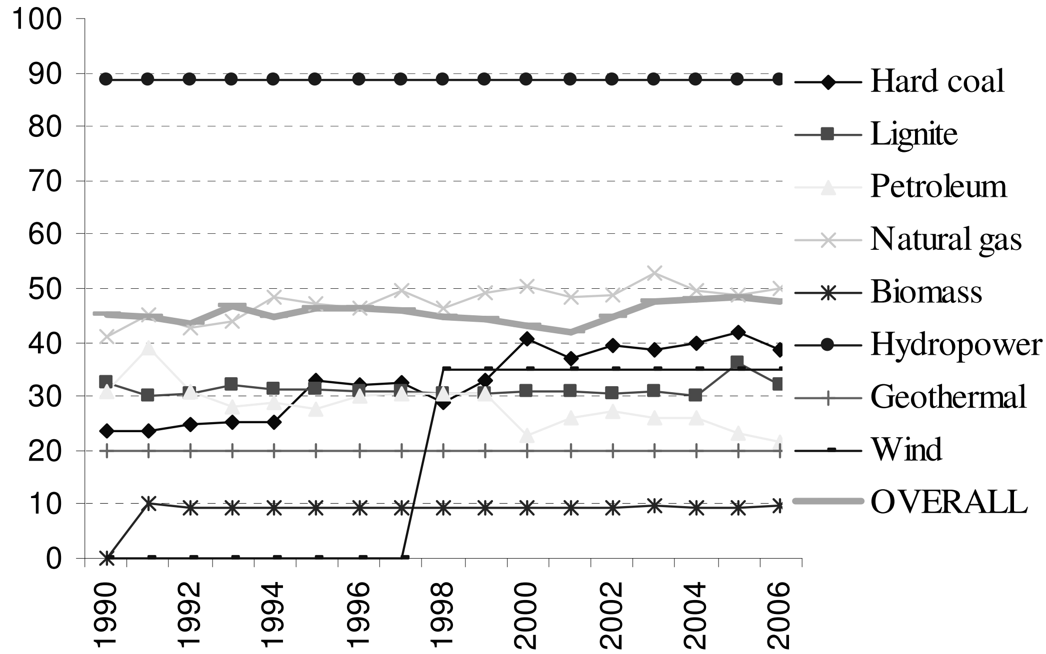


**Figure 4:** Exergy Efficiency of Power Plants between 1990 and 2006 (%)

Using Equation (35), the exergetic improvement potentials of the power plants are calculated and shown in Figure 5.

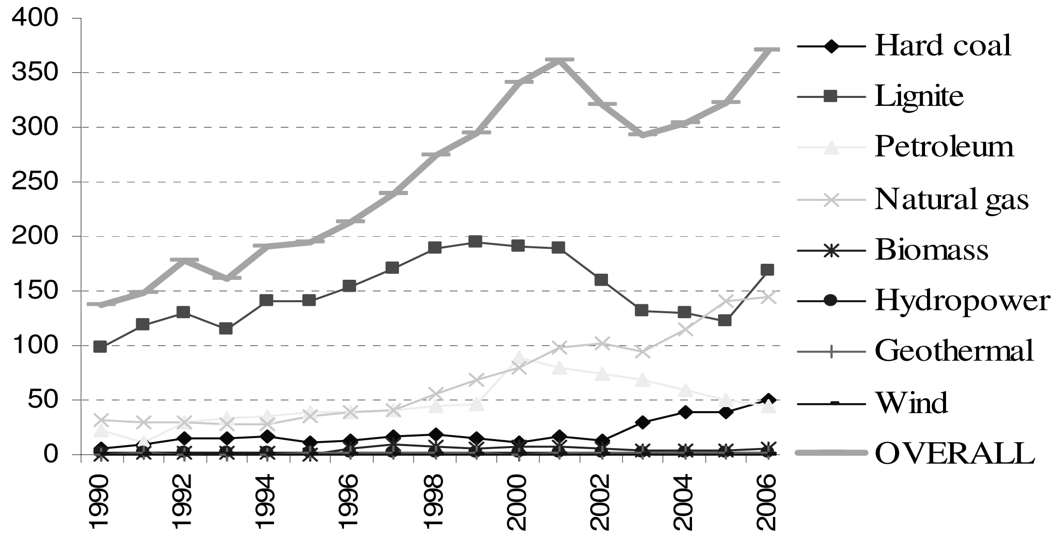


**Figure 5:** Exergetic Improvement Potentials of the Power Plants (PJ)

Although they produced less than half electricity with respect to natural gas power plants in most years, the lignite power plants have the highest exergetic improvement potential. This is primarily because of their inefficiencies.

In fact, petroleum fuelled power plants have the lowest efficiencies within the fossil fuelled power plants, so that their improvement potentials are the third highest one in the average. However, they produce less energy with respect to lignite power plants. So that their improvement potential is lower than lignite power plants.

Despite having the highest efficiencies within the fossil fuels, the exergetic improvement potential of the natural gas power plants increases a lot. This is because of the higher utilization of natural gas for electricity production occurs year by year.

### 3.3 Industrial Sector

Industrial sector of Turkey consists of many industries most of which consumes less energy with respect to the total consumption of the sector. In fact, when gathered together, they consume most of the energy in Turkey. However, according to the most energy consuming sectors, Turkish industry may be defined in 7 sectors: iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, and non-metal industry. As a complementary industry, the eighth industry is defined as other industries. This division of the industrial sector in Turkey is adopted from the WEC-TNC reports [51,52,53] which provide the necessary data in this analysis.

Energy utilization of the industrial sector according to the use categories is listed in Table 1 which is made for the industrial sector in 1991. However, according a recent publication [40] which tells 82 % of industrial consumption is performed for heating applications in Turkey, the same proportions in Table 9 may assumed to be used for all the years between 1990 and 2006.

**Table 9:** Energy use in the industrial sector in Turkey by type of Use (%) [26,61]

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

In the analysis of Turkish Industrial sector, it is preferred to use Dincer et al.'s [7] method which is applied by Utlu and Hepbasli [40] to Turkey between the years 1990 and 2003, for only the heating efficiency calculations with minor differences.

In the Dincer et al.'s study, first all the consumption in the industrial sector is assumed to occur for heating processes. Process heating temperatures and efficiencies used in their studies for the industrial sector is given in Table 10. By preparing the breakdown of energy used for each temperature in the industries using Brown et al.'s study for 108 industrial processes [62], weighted mean efficiencies for electrical heating and fuel heating are evaluated for each industry. Using the fuel and electricity consumption of each industry, the overall heating efficiencies of the industries are evaluated. Thus, the overall heating efficiency of the sector is found by dividing the total outputs (evaluated from the efficiency of each industry multiplied by the input of industry) into total inputs (consumption values). After finding the overall heating efficiency of the sector, they took into account the mechanical drives with 90 % efficiency considering their percentage in total consumption.

**Table 10:** Process heating temperatures and efficiencies for the industrial sector [7,55]

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

In this study, overall heating efficiency of the sector is found by the same way with an exception. All the consumption in the industrial sector is not assumed to occur for heating processes. Calculations for heating efficiencies are performed by using the consumption of heating found by using the percentages given in Table 9. So that, mechanical drives are not taken into account with respect to total consumption, their efficiencies are rather used with only the electricity consumption they realized, to find the mechanical drive outputs.

### 3.3.1 Estimations for the efficiencies in the Industrial Sector

Mechanical drives are assumed to be 90 % efficient like most of the studies [7, 22, 40, 63]. Lighting is assumed to be used as 10 % incandescent and 90 % fluorescent with first and second law efficiencies of about 5 % and 4.5 % and 20 % and 18.5 % respectively [5,26]. Averaging the efficiencies of lighting with respect to utilization ratios, average energy and exergy efficiencies of lighting are found as 18.5 % and 17.1 % respectively.

Utlu and Hepbasli listed the breakdown of energy used for each temperature in the industries of Turkey by using Brown et al.'s study. Table 10 gives the energy efficiencies for each temperature. Using the energy efficiencies and the equations (21) and (23), exergy efficiencies are computed for each temperature.

**Table 11** : Process heating data and energy–exergy efficiency data for the industrial sector for all categories of heating temperature (T ) in the industrial sector [40,62]

| Industry | T range | Breakdown of energy used for each temperature (%) | | | Breakdown of energy and exergy efficiencies for each temperature category for $T_0$=10 ˚C | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Electrical heating | | Fuel heating | |
| | | Mean T (˚C) | Electricity | Fuel | η (%) | ψ (%) | η (%) | ψ (%) |
| Iron and steel | Low | 45 | 4.2 | 0 | 100 | 11.0 | 65 | 7.2 |
| | Medium | - | 0 | 0 | 90 | - | 60 | - |
| | High | 983 | 95.8 | 100 | 70 | 54.2 | 50 | 38.7 |
| Chemical and petrochemical | Low | 42 | 62.5 | 0 | 100 | 10.2 | 65 | 6.6 |
| | Medium | 141 | 37.5 | 100 | 90 | 28.5 | 60 | 19.0 |
| | High | 494 | 0 | 0 | 70 | 44.2 | 50 | 31.6 |
| Petrochemical – Feedstock | Low | 57 | 0 | 0 | 100 | 14.2 | 65 | 9.3 |
| | Medium | 227 | 0 | 0 | 90 | 39.1 | 60 | 26.0 |
| | High | 494 | 0 | 100 | 70 | 44.2 | 50 | 31.6 |
| Fertilizer | Low | 57 | 10 | 30 | 100 | 14.2 | 65 | 9.3 |
| | Medium | 350 | 80 | 30 | 90 | 49.1 | 60 | 32.7 |
| | High | 900 | 10 | 40 | 70 | 53.1 | 50 | 37.9 |

**Table 11 (continued)**

| Industry | T range | Breakdown of energy used for each temperature (%) | | | Breakdown of energy and exergy efficiencies for each temperature category for $T_0$=10 ˚C | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Electrical heating | | Fuel heating | |
| | | Mean T (˚C) | Electricity | Fuel | η (%) | ψ (%) | η (%) | ψ (%) |
| Cement | Low | 42 | 91.7 | 0.9 | 100 | 10.2 | 65 | 6.6 |
| | Medium | 141 | 0 | 9 | 90 | 28.5 | 60 | 19.0 |
| | High | 586 | 8.3 | 90.1 | 70 | 46.9 | 50 | 33.5 |
| Sugar | Low | 83 | 100 | 59 | 100 | 20.5 | 65 | 13.3 |
| | Medium | 315 | 0 | 9 | 90 | 46.7 | 60 | 31.1 |
| | High | 400 | 0 | 32 | 70 | 40.6 | 50 | 29.0 |
| Non-iron metals | Low | 61 | 10 | 13.8 | 100 | 15.3 | 65 | 9.9 |
| | Medium | 132 | 9.4 | 22.6 | 90 | 27.1 | 60 | 18.1 |
| | High | 401 | 80.4 | 63.6 | 70 | 40.6 | 50 | 29.0 |
| Other Industry | Low | 57 | 10.6 | 13.8 | 100 | 14.2 | 65 | 9.3 |
| | Medium | 132 | 89.4 | 86.2 | 90 | 27.1 | 60 | 18.1 |
| | High | 400 | 0.1 | 0.1 | 70 | 40.6 | 50 | 29.0 |

Equations (21) and (23) for electrical heating and fuel heating are equivalent to each other when the quality factor (q) is 1. Since mostly fossil fuels whose quality factors are around 1 are used in the industrial sector, Quality factors are assumed to be 1 for fuel heating exergy efficiency calculations. So that, Equations (21) and (23) becomes:

$$\psi = \eta \cdot (1 - \frac{T_0}{T})$$

The sample calculation for energy and exergy efficiencies of Iron and steel industry is given below:

Low temperature electric heating: T = 45+273 = 318 ˚K and η = 100 %

$$\psi = 100\% \cdot (1 - \frac{283}{318}) = 11.0\%$$

High temperature electric heating: T = 45+273 = 1256 °K and η = 70 %

$$\psi = 70\% \cdot (1 - \frac{283}{1256}) = 54.2\%$$

Low temperature fuel heating: T = 45+273 = 318 °K and η = 65 %

$$\psi = 65\% \cdot (1 - \frac{283}{318}) = 7.2\%$$

High temperature fuel heating: T = 983+273 = 1256 °K and η = 50 %

$$\psi = 50\% \cdot (1 - \frac{283}{1256}) = 38.7\%$$

Mean Energy and Exergy Efficiencies of Iron and Steel industry for electric and fuel heating are found by multiplying the efficiencies by their fractions of utilization and addding the results.

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

$$\eta_f = 65\% \times 0\% + 50\% \times 100\% = 50\%$$

$$\psi_e = 11.0\% \times 4.2\% + 54.2\% \times 95.8\% = 52.4\%$$

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

Likewise the other industrial heating efficiencies are also calculated and tabulated in Table 12 .

**Table 12:** Mean Electricity and Fuel Heating Efficiencies of Industries

| Industries | Electricity η (%) | Fuel η (%) | Electricity ψ (%) | Fuel ψ (%) |
|---|---|---|---|---|
| Iron and steel | 71.3 | 50 | 52.4 | 38.7 |
| Chemical and Petrochemical | 96.3 | 60 | 17.0 | 19.0 |
| Petrochemical–Feedstock | 0 | 50 | 0.00 | 31.6 |
| Fertilizer | 89 | 57.5 | 46.0 | 27.8 |
| Cement | 97.5 | 51.0 | 13.2 | 32.0 |
| Sugar | 100.0 | 59.8 | 20.5 | 19.9 |
| Non-iron metals | 74.7 | 54.3 | 36.7 | 23.9 |
| Other Industry | 91.1 | 60.7 | 25.8 | 16.9 |

By looking at the mean efficiencies, it is obviously seen that electricity use is much more energy and exergy efficient than fuel use.

### 3.3.2 Input Configuration of the Industrial Sector

Table 13 shows the energy consumption (Fuel and Electricity) data in the Turkish industrial sector from 1990 to 2006 which is obtained from WEC-TNC reports assuming the consumption other than electricity is totally fuel consumption. The exergy consumptions (input) are simply found by multiplying each energy carrier's energy utilization in the WEC-TNC reports with their quality factors and adding all the fuel exergy consumptions together.

**Table 13:** Energy consumption (Fuel and Electricity) data in the Turkish industrial sector from 1990 to 2006 in PJ [40,51-53]

| Years | Iron–steel | | Chemical-Petrochemical | | Petrochemical - feedstock | | Fertilizer | | Cement | | Sugar | | Non iron metals | | Other industry | | Industrial | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity |
| 1990 | 108.6 | 17.4 | 35.2 | 14.5 | 61.8 | 0 | 31.7 | 4.1 | 81.1 | 14.4 | 27.5 | 1.4 | 13.9 | 9.2 | 149.6 | 39.9 | 509.3 | 100.9 |
| 1991 | 112.0 | 18.0 | 36.8 | 11.6 | 54.0 | 0 | 29.8 | 3.6 | 91.6 | 15.3 | 27.6 | 1.4 | 13.4 | 8.7 | 176.7 | 38.7 | 541.9 | 97.3 |
| 1992 | 112.4 | 21.5 | 38.5 | 12.6 | 56.4 | 0 | 37.5 | 1.5 | 78.2 | 17.0 | 22.6 | 1.4 | 13.9 | 9.5 | 182.7 | 44.4 | 542.3 | 107.9 |
| 1993 | 110.6 | 24.2 | 43.1 | 17.2 | 60.9 | 0 | 33.7 | 1.6 | 77.5 | 17.6 | 21.0 | 2.0 | 12.7 | 9.6 | 210.4 | 44.9 | 569.8 | 117.2 |
| 1994 | 107.9 | 23.5 | 38.2 | 14.9 | 64.1 | 0 | 28.6 | 1.4 | 87.1 | 15.3 | 15.6 | 1.1 | 16.6 | 7.6 | 166.8 | 53.1 | 524.7 | 116.7 |
| 1995 | 111.6 | 25.0 | 42.0 | 15.7 | 69.4 | 0 | 36.2 | 1.4 | 80.6 | 10.4 | 17.4 | 1.3 | 24.1 | 7.8 | 220.6 | 69.1 | 601.4 | 130.6 |
| 1996 | 123.5 | 28.6 | 40.3 | 18.9 | 63.3 | 0 | 36.9 | 1.5 | 92.7 | 9.8 | 20.8 | 1.2 | 19.7 | 7.0 | 291.9 | 73.1 | 691.7 | 140.1 |
| 1997 | 123.2 | 31.1 | 46.3 | 22.2 | 64.0 | 0 | 33.4 | 3.0 | 85.0 | 16.4 | 23.0 | 1.2 | 16.9 | 7.0 | 360.3 | 76.5 | 752.2 | 157.5 |
| 1998 | 111.7 | 31.3 | 36.1 | 23.8 | 71.6 | 0 | 25.0 | 2.7 | 73.5 | 10.1 | 26.1 | 1.2 | 14.9 | 7.0 | 372.5 | 90.3 | 731.3 | 166.5 |
| 1999 | 109.6 | 27.8 | 46.0 | 22.1 | 63.4 | 0 | 7.8 | 1.3 | 93.5 | 8.9 | 25.4 | 1.2 | 25.7 | 7.0 | 287.3 | 100.3 | 658.6 | 168.7 |
| 2000 | 115.3 | 30.2 | 47.0 | 22.9 | 62.9 | 0 | 9.2 | 1.8 | 85.7 | 14.4 | 20.7 | 1.2 | 27.4 | 7.0 | 442.2 | 98.5 | 810.5 | 176.1 |
| 2001 | 107.3 | 30.1 | 49.5 | 20.0 | 62.8 | 0 | 63.2 | 1.8 | 80.5 | 11.6 | 46.8 | 1.2 | 27.8 | 7.0 | 292.4 | 149.7 | 692.8 | 221.5 |
| 2002 | 101.8 | 29.8 | 48.8 | 7.6 | 66.6 | 0 | 23.0 | 1.8 | 106.7 | 11.8 | 46.8 | 1.2 | 32.7 | 9.2 | 443.1 | 112.1 | 841.7 | 173.6 |
| 2003 | 109.0 | 31.6 | 51.1 | 7.6 | 59.6 | 0 | 21.9 | 1.8 | 89.4 | 12.4 | 30.5 | 1.2 | 30.4 | 9.2 | 537.8 | 122.6 | 929.6 | 186.4 |
| 2004 | 114.0 | 39.4 | 46.4 | 13.4 | 58.0 | 0 | 55.8 | 1.8 | 137.0 | 14.0 | 26.9 | 0.0 | 34.9 | 9.7 | 523.3 | 130.6 | 996.2 | 209.0 |
| 2005 | 116.6 | 42.0 | 96.3 | 17.7 | 66.4 | 0 | 29.5 | 1.8 | 158.6 | 15.6 | 26.9 | 0.0 | 47.4 | 8.9 | 517.1 | 125.4 | 974.7 | 221.3 |
| 2006 | 110.4 | 48.2 | 67.2 | 14.8 | 44.8 | 0 | 9.3 | 1.8 | 154.6 | 16.5 | 23.3 | 0.0 | 42.0 | 10.0 | 603.6 | 150.4 | 1055.2 | 241.8 |

**Table 14:** Exergy consumption (Fuel and Electricity) data in the Turkish industrial sector from 1990 to 2006 in PJ [40, 51-53]

| Years | Iron–steel | | Chemical-Petrochemical | | Petrochemical - feedstock | | Fertilizer | | Cement | | Sugar | | Non iron metals | | Other industry | | Industrial | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity | Fuel | Electricity |
| 1990 | 112.5 | 17.4 | 35.1 | 14.5 | 61.1 | 0 | 30.4 | 4.1 | 83.1 | 14.4 | 28.3 | 1.4 | 13.9 | 9.2 | 150.6 | 39.9 | 514.9 | 100.9 |
| 1991 | 115.7 | 18.0 | 35.9 | 11.6 | 53.5 | 0 | 28.5 | 3.6 | 93.4 | 15.3 | 28.5 | 1.4 | 13.4 | 8.7 | 178.5 | 38.7 | 547.3 | 97.3 |
| 1992 | 115.9 | 21.5 | 37.6 | 12.6 | 55.9 | 0 | 35.6 | 1.5 | 80.0 | 17.0 | 23.2 | 1.4 | 13.9 | 9.5 | 183.1 | 44.4 | 545.2 | 107.9 |
| 1993 | 114.2 | 24.2 | 42.2 | 17.2 | 60.3 | 0 | 31.3 | 1.6 | 79.8 | 17.6 | 21.5 | 2.0 | 12.7 | 9.6 | 209.8 | 44.9 | 571.7 | 117.2 |
| 1994 | 111.5 | 23.5 | 37.5 | 14.9 | 63.4 | 0 | 26.6 | 1.4 | 90.3 | 15.3 | 15.9 | 1.1 | 16.6 | 7.6 | 165.2 | 53.1 | 527.1 | 116.7 |
| 1995 | 115.6 | 25.0 | 41.2 | 15.7 | 68.7 | 0 | 34.0 | 1.4 | 83.6 | 10.4 | 17.7 | 1.3 | 23.7 | 7.8 | 217.9 | 69.1 | 602.3 | 130.6 |
| 1996 | 127.9 | 28.6 | 39.6 | 18.9 | 62.7 | 0 | 34.5 | 1.5 | 96.3 | 9.8 | 21.2 | 1.2 | 19.2 | 7.0 | 291.9 | 73.1 | 693.3 | 140.1 |
| 1997 | 127.7 | 31.1 | 45.2 | 22.2 | 63.4 | 0 | 31.1 | 3.0 | 88.0 | 16.4 | 23.3 | 1.2 | 16.7 | 7.0 | 360.4 | 76.5 | 755.7 | 157.5 |
| 1998 | 115.7 | 31.3 | 35.8 | 23.8 | 70.9 | 0 | 23.5 | 2.7 | 76.6 | 10.1 | 26.7 | 1.2 | 14.8 | 7.0 | 371.9 | 90.3 | 736.0 | 166.5 |
| 1999 | 113.7 | 27.8 | 44.9 | 22.1 | 62.7 | 0 | 7.4 | 1.3 | 97.2 | 8.9 | 26.0 | 1.2 | 24.8 | 7.0 | 285.7 | 100.3 | 662.5 | 168.7 |
| 2000 | 119.6 | 30.2 | 45.9 | 22.9 | 62.2 | 0 | 8.8 | 1.8 | 89.1 | 14.4 | 21.3 | 1.2 | 26.8 | 7.0 | 444.2 | 98.5 | 817.9 | 176.1 |
| 2001 | 111.4 | 30.1 | 48.1 | 20.0 | 62.2 | 0 | 62.5 | 1.8 | 83.7 | 11.6 | 47.0 | 1.2 | 27.1 | 7.0 | 289.2 | 149.7 | 731.2 | 221.5 |
| 2002 | 105.6 | 29.8 | 47.6 | 7.6 | 66.0 | 0 | 21.5 | 1.8 | 110.8 | 11.8 | 47.0 | 1.2 | 31.7 | 9.2 | 440.7 | 112.1 | 870.8 | 173.6 |
| 2003 | 113.2 | 31.6 | 49.8 | 7.6 | 59.0 | 0 | 20.5 | 1.8 | 92.9 | 12.4 | 30.7 | 1.2 | 29.2 | 9.2 | 534.5 | 122.6 | 929.8 | 186.4 |
| 2004 | 110.8 | 39.4 | 45.1 | 13.4 | 57.4 | 0 | 54.0 | 1.8 | 138.7 | 14.0 | 26.9 | 0.0 | 33.5 | 9.7 | 463.0 | 130.6 | 929.4 | 209.0 |
| 2005 | 108.2 | 40.3 | 60.2 | 14.8 | 32.9 | 0 | 24.2 | 1.8 | 154.6 | 15.6 | 22.1 | 0.0 | 35.1 | 9.9 | 462.5 | 138.9 | 899.7 | 221.3 |
| 2006 | 107.7 | 48.2 | 64.3 | 14.8 | 44.4 | 0 | 8.8 | 1.8 | 156.5 | 16.5 | 23.2 | 0.0 | 40.0 | 10.0 | 537.8 | 150.4 | 982.8 | 241.8 |

### 3.3.3 Heating Efficiencies in the Industrial Sector

Since efficiencies times inputs gives outputs, the energy and exergy consumptions of the industries are used to find the outputs and the efficiencies accordingly. Because 28% percent of electricity consumption is used for heating only, electrical heating output values are found accordingly to find the heating efficiencies of the industries by simple output over input equations.

Sample calculation for Iron and Steel Industry in 2006:

$$\eta_q = (E_f \times \eta_f + E_e \times 0.28 \times \eta_e)/(E_f + E_e \times 0.28)$$

$$\eta_q = (110.4 \times 50\% + 48.2 \times 0.28 \times 71.3\%)/(110.4 + 48.2 \times 0.28) = 52.3\%$$

$$\psi_q = (X_f \times \psi_f + X_e \times 0.28 \times \psi_e)/(X_f + X_e \times 0.28)$$

$$\psi_q = (107.7 \times 38.8\% + 48.2 \times 0.28 \times 52.4\%)/(107.7 + 48.2 \times 0.28) = 40.3\%$$

By making the above calculations for all the industries for the related years, the heating energy and exergy efficiencies of industries are found and tabulated in Table 15 and Table 16 respectively.

**Table 15:** Heating Energy Efficiencies of Industries from 1990 to 2006 (%)

| Years | Iron–steel | Chemical-Petrochem. | Petrochem.-feedstock | Fertilizer | Cement | Sugar | Noniron metals | Other industry |
|---|---|---|---|---|---|---|---|---|
| 1990 | 50.9 | 63.8 | 50.0 | 58.6 | 53.2 | 60.3 | 57.5 | 62.9 |
| 1991 | 50.9 | 62.9 | 50.0 | 58.5 | 53.1 | 60.3 | 57.5 | 62.5 |
| 1992 | 51.1 | 63.0 | 50.0 | 57.8 | 53.7 | 60.5 | 57.6 | 62.7 |
| 1993 | 51.2 | 63.7 | 50.0 | 57.9 | 53.8 | 60.8 | 57.9 | 62.5 |
| 1994 | 51.2 | 63.6 | 50.0 | 57.9 | 53.2 | 60.5 | 56.6 | 63.2 |
| 1995 | 51.3 | 63.4 | 50.0 | 57.8 | 52.7 | 60.6 | 56.0 | 63.2 |
| 1996 | 51.3 | 64.2 | 50.0 | 57.8 | 52.4 | 60.4 | 56.2 | 62.7 |
| 1997 | 51.4 | 64.3 | 50.0 | 58.3 | 53.4 | 60.3 | 56.5 | 62.5 |
| 1998 | 51.6 | 65.7 | 50.0 | 58.4 | 52.8 | 60.3 | 56.7 | 62.7 |
| 1999 | 51.4 | 64.3 | 50.0 | 58.9 | 52.3 | 60.3 | 55.8 | 63.5 |

**Table 15 (continued)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2000 | 51.5 | 64.4 | 50.0 | 59.1 | 53.1 | 60.4 | 55.7 | 62.5 |
| 2001 | 51.6 | 63.7 | 50.0 | 57.7 | 52.8 | 60.0 | 55.7 | 64.6 |
| 2002 | 51.6 | 61.5 | 50.0 | 58.2 | 52.4 | 60.0 | 55.8 | 62.8 |
| 2003 | 51.6 | 61.5 | 50.0 | 58.2 | 52.8 | 60.2 | 55.9 | 62.6 |
| 2004 | 51.9 | 62.7 | 50.0 | 57.8 | 52.3 | 59.8 | 55.8 | 62.7 |
| 2005 | 52.0 | 61.8 | 50.0 | 58.0 | 52.3 | 59.8 | 55.4 | 62.7 |
| 2006 | 52.3 | 62.1 | 50.0 | 59.2 | 52.4 | 59.8 | 55.6 | 62.7 |

**Table 16:** Heating Exergy Efficiencies of Industries from 1990 to 2006 (%)

| Years | Iron–steel | Chemical-Petrochem. | Petrochem.-feedstock | Fertilizer | Cement | Sugar | Noniron metals | Other industry |
|---|---|---|---|---|---|---|---|---|
| 1990 | 39.3 | 18.8 | 31.6 | 28.5 | 31.1 | 19.9 | 25.9 | 17.5 |
| 1991 | 39.3 | 18.8 | 31.6 | 28.4 | 31.2 | 19.9 | 25.9 | 17.4 |
| 1992 | 39.4 | 18.8 | 31.6 | 28.0 | 30.9 | 20.0 | 26.0 | 17.5 |
| 1993 | 39.5 | 18.8 | 31.6 | 28.0 | 30.9 | 20.0 | 26.2 | 17.4 |
| 1994 | 39.5 | 18.8 | 31.6 | 28.0 | 31.1 | 20.0 | 25.4 | 17.6 |
| 1995 | 39.5 | 18.8 | 31.6 | 28.0 | 31.4 | 20.0 | 25.0 | 17.6 |
| 1996 | 39.5 | 18.8 | 31.6 | 28.0 | 31.5 | 20.0 | 25.1 | 17.5 |
| 1997 | 39.6 | 18.8 | 31.6 | 28.3 | 31.1 | 20.0 | 25.3 | 17.4 |
| 1998 | 39.7 | 18.7 | 31.6 | 28.3 | 31.3 | 19.9 | 25.4 | 17.5 |
| 1999 | 39.6 | 18.8 | 31.6 | 28.6 | 31.5 | 19.9 | 24.9 | 17.7 |
| 2000 | 39.6 | 18.8 | 31.6 | 28.8 | 31.2 | 20.0 | 24.8 | 17.4 |
| 2001 | 39.7 | 18.8 | 31.6 | 27.9 | 31.3 | 19.9 | 24.8 | 18.0 |
| 2002 | 39.7 | 18.9 | 31.6 | 28.2 | 31.4 | 19.9 | 24.9 | 17.5 |
| 2003 | 39.7 | 18.9 | 31.6 | 28.2 | 31.3 | 19.9 | 24.9 | 17.4 |
| 2004 | 40.0 | 18.8 | 31.6 | 28.0 | 31.5 | 19.9 | 24.9 | 17.5 |
| 2005 | 40.0 | 18.9 | 31.6 | 28.2 | 31.5 | 19.9 | 24.8 | 17.6 |
| 2006 | 40.3 | 18.9 | 31.6 | 28.8 | 31.4 | 19.9 | 24.7 | 17.5 |

By multiplying the efficiencies of the sectors with their corresponding consumptions and adding the results, the overall output of the industrial sector and thus the overall heating efficiency of the industrial sector are easily be found. Namely the same calculations made for each industry above, are performed for the overall industry too.

After calculating the outputs, total heating inputs, outputs and overall heating energy and exergy efficiencies of the industrial sector are tabulated in Table 17. In order to understand the changes in the energy and exergy heating efficiencies of the industries, it is better to draw the efficiencies of the industries and the overall energy and exergy efficiencies of the industrial sector together in Figures 6 and 7 respectively.

**Table 17:** Heating Inputs, outputs and overall heating energy and exergy efficiencies of the industrial sector (PJ)

| Years | Energy input | Energy output | Exergy input | Exergy output | $\eta_q$ (%) | $\psi_q$ (%) |
|---|---|---|---|---|---|---|
| 1990 | 537.6 | 305.5 | 543.2 | 147.1 | 56.8 | 27.1 |
| 1991 | 569.1 | 323.9 | 574.5 | 153.3 | 56.9 | 26.7 |
| 1992 | 572.5 | 327.4 | 575.5 | 152.9 | 57.2 | 26.6 |
| 1993 | 602.6 | 346.4 | 604.5 | 157.8 | 57.5 | 26.1 |
| 1994 | 557.4 | 318.0 | 559.8 | 151.2 | 57.1 | 27.0 |
| 1995 | 638.0 | 367.1 | 638.8 | 167.2 | 57.5 | 26.2 |
| 1996 | 730.9 | 420.8 | 732.5 | 187.0 | 57.6 | 25.5 |
| 1997 | 796.3 | 464.5 | 799.8 | 197.2 | 58.3 | 24.7 |
| 1998 | 777.9 | 456.1 | 782.6 | 190.4 | 58.6 | 24.3 |
| 1999 | 705.9 | 411.6 | 709.7 | 178.5 | 58.3 | 25.2 |
| 2000 | 859.8 | 505.7 | 867.2 | 205.5 | 58.8 | 23.7 |
| 2001 | 754.8 | 467.8 | 793.2 | 198.3 | 62.0 | 25.0 |
| 2002 | 890.3 | 538.6 | 919.4 | 218.0 | 60.5 | 23.7 |
| 2003 | 981.8 | 580.3 | 982.0 | 226.2 | 59.1 | 23.0 |
| 2004 | 1054.7 | 619.8 | 987.9 | 238.1 | 58.8 | 24.1 |
| 2005 | 1036.7 | 654.8 | 961.6 | 229.2 | 63.2 | 23.8 |
| 2006 | 1122.9 | 664.6 | 1050.5 | 246.0 | 59.2 | 23.4 |

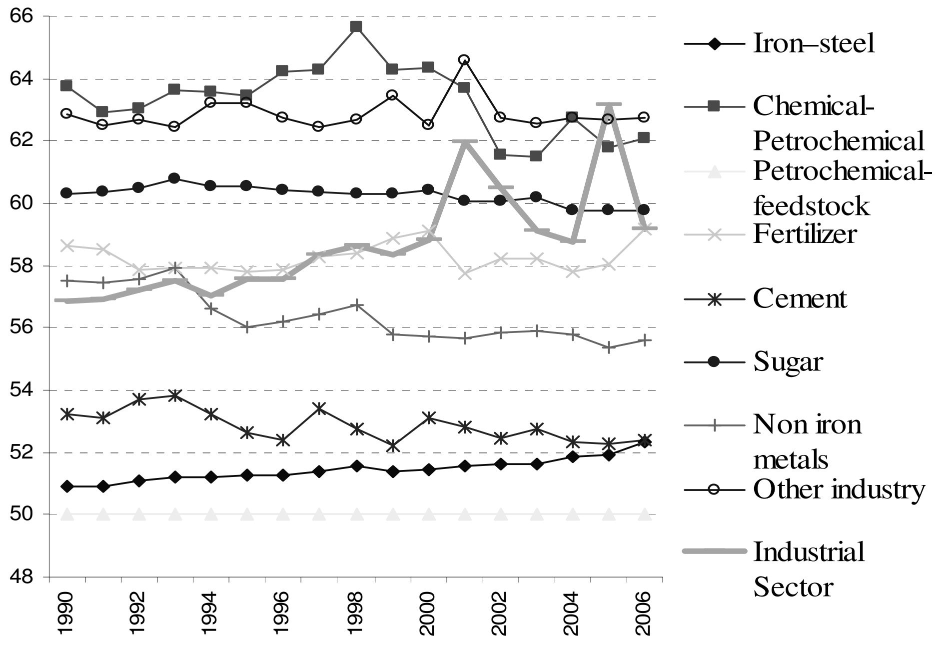


**Figure 6:** Heating Energy efficiencies of industries between 1990 and 2006 (%)

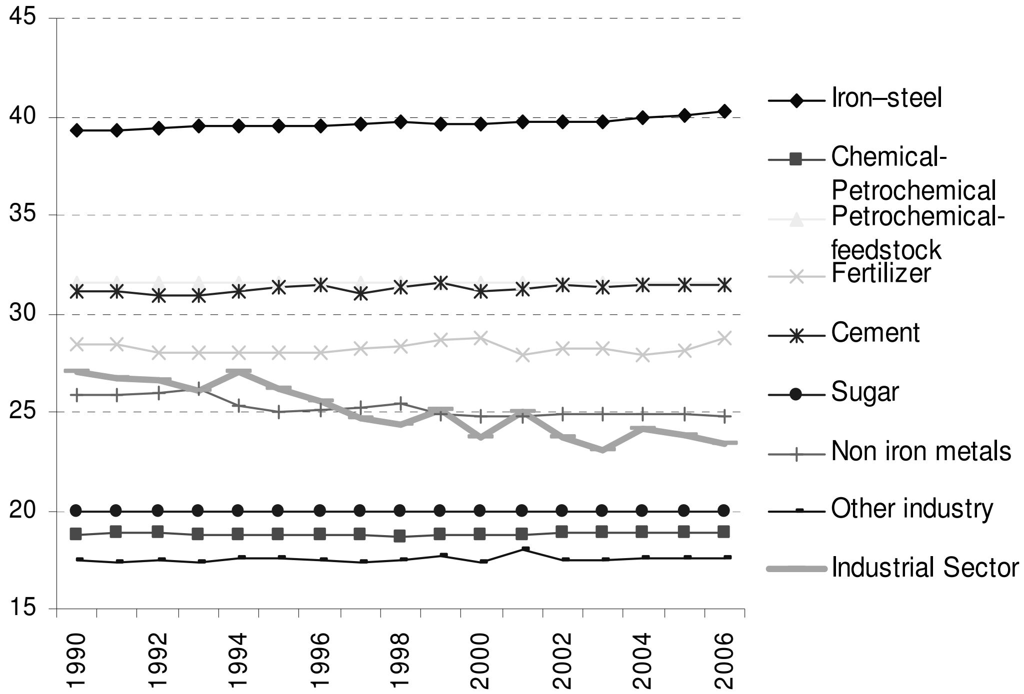


**Figure 7:** Heating Exergy efficiencies of industries between 1990 and 2006 (%)

### 3.3.4 Overall Efficiencies of the Industrial Sector

The outputs for mechanical drives and lighting are evaluated by multiplying the efficiencies with the consumption values (inputs). By means of adding all the outputs and inputs, and then dividing the total outputs into inputs, overall efficiencies of the industries and industrial sector are found for the related year.

The method of calculating the overall efficiency of an industry is the same as the calculation of the overall efficiency of the industrial sector. So that, only the overall efficiency calculation of the Industrial Sector in 2006 is given below as an example:

Electricity input to the Industrial Sector is 241.82 from Tables 13 and 14 (Same for energy and exergy).

Using the proportions in Table 9, mechanical drive and lighting inputs are as follows:

Mechanical Drive input: $241.8 \times 0.65 = 157.2$ PJ

Lighting Input: $241.8 \times 0.07 = 16.9$ PJ

Lighting energy and exergy efficiencies are estimated as 18.5% and 17.1% in part 3.3.1. Likewise Mechanical Drives are assumed to be 90% energy and exergy efficient. Using the general equations (18 and 19) of the efficiencies, the outputs are calculates:

Lighting Energy Output: $16.9 \times 18.5\% = 3.13$ PJ

Lighting Exergy Output: $16.9 \times 17.1\% = 2.90$ PJ

Mechanical Drive Energy and Exergy Output: $157.2 \times 0.9 = 141.5$ PJ

Taking the Heating inputs and outputs from Table 17, total industrial energy and exergy outputs in 2006 are calculated as follows:

Total Energy Output = 664.6+3.1+141.5 = 809.2

Total Exergy Output = 246+3+141.5 = 390.5

From Table 13; Total Energy Input = 1055.2+241.8 = 1297 PJ

From Table 13; Total Energy Input = 982.8+241.8 = 1224.6 PJ

Then the overall energy and exergy efficiencies of the industrial sector in 2006 are calculated the general equations (18 and 19) as follows:

$\eta = 809.2/1297 = 62.4\%$

$$\psi = 390.5/1224.6 = 31.9\%$$

Applying these calculations for the other years, the output values and thus the overall efficiencies of the industrial sector are found between 1990 and 2006. Likewise, the same relations are applied for the subsectors also, to find the overall efficiencies of subsectors.

**Table 18:** Inputs, outputs and overall energy and exergy efficiencies of the industrial sector between 1990 and 2006 (PJ)

| Years | Energy input | Energy output | Exergy input | Exergy output | η (%) | ψ (%) |
|---|---|---|---|---|---|---|
| 1990 | 610.2 | 365.9 | 615.8 | 207.3 | 60.0 | 33.7 |
| 1991 | 639.2 | 382.1 | 644.5 | 211.3 | 59.8 | 32.8 |
| 1992 | 650.2 | 392.0 | 653.1 | 217.3 | 60.3 | 33.3 |
| 1993 | 686.9 | 416.5 | 688.8 | 227.7 | 60.6 | 33.1 |
| 1994 | 641.5 | 387.8 | 643.9 | 220.9 | 60.5 | 34.3 |
| 1995 | 732.1 | 445.2 | 732.9 | 245.2 | 60.8 | 33.5 |
| 1996 | 831.7 | 504.6 | 833.4 | 270.7 | 60.7 | 32.5 |
| 1997 | 909.7 | 558.7 | 913.2 | 291.3 | 61.4 | 31.9 |
| 1998 | 897.8 | 555.7 | 902.5 | 289.8 | 61.9 | 32.1 |
| 1999 | 827.3 | 512.4 | 831.2 | 279.2 | 61.9 | 33.6 |
| 2000 | 986.6 | 611.0 | 994.0 | 310.6 | 61.9 | 31.3 |
| 2001 | 914.3 | 600.2 | 952.7 | 330.5 | 65.7 | 34.7 |
| 2002 | 1015.2 | 642.4 | 1044.4 | 321.6 | 63.3 | 30.8 |
| 2003 | 1116.0 | 691.7 | 1116.2 | 337.5 | 62.0 | 30.2 |
| 2004 | 1205.1 | 744.7 | 1138.3 | 362.8 | 61.8 | 31.9 |
| 2005 | 1196.0 | 787.1 | 1120.9 | 361.3 | 65.8 | 32.2 |
| 2006 | 1297.0 | 809.2 | 1224.6 | 390.3 | 62.4 | 31.9 |

The overall energy and exergy efficiencies of the industries and the industrial sector are tabulated together in tables 19 and 20, and graphed in figures 8 and 9 respectively. In figure 20, there is also electricity consumption percentage included for further discussion to be performed.

**Table 19:** Overall Energy and Exergy Efficiencies of the Industries and the Industrial Sector between 1990 and 2006 (%)

| Years | Iron–steel | Chemical-Petrochem. | Petrochem.-feedstock | Fertilizer | Cement | Sugar | Non iron metals | Other industry | Industrial Sector |
|---|---|---|---|---|---|---|---|---|---|
| 1990 | 54.1 | 67.8 | 50.0 | 60.6 | 56.5 | 61.1 | 64.8 | 65.9 | 60.0 |
| 1991 | 54.1 | 66.4 | 50.0 | 60.4 | 56.2 | 61.1 | 64.7 | 65.2 | 59.8 |
| 1992 | 54.8 | 66.6 | 50.0 | 58.5 | 57.5 | 61.4 | 65.0 | 65.5 | 60.3 |
| 1993 | 55.3 | 67.6 | 50.0 | 58.7 | 57.7 | 62.2 | 65.7 | 65.1 | 60.6 |
| 1994 | 55.3 | 67.5 | 50.0 | 58.7 | 56.4 | 61.6 | 62.6 | 66.7 | 60.5 |
| 1995 | 55.4 | 67.3 | 50.0 | 58.5 | 55.1 | 61.7 | 60.8 | 66.6 | 60.8 |
| 1996 | 55.6 | 68.5 | 50.0 | 58.5 | 54.5 | 61.3 | 61.3 | 65.7 | 60.7 |
| 1997 | 56.0 | 68.7 | 50.0 | 59.7 | 56.9 | 61.2 | 62.1 | 65.0 | 61.4 |
| 1998 | 56.5 | 70.6 | 50.0 | 60.1 | 55.4 | 61.0 | 62.8 | 65.5 | 61.9 |
| 1999 | 56.0 | 68.7 | 50.0 | 61.3 | 54.2 | 61.0 | 60.0 | 67.1 | 61.9 |
| 2000 | 56.2 | 68.8 | 50.0 | 62.0 | 56.2 | 61.3 | 59.7 | 65.2 | 61.9 |
| 2001 | 56.5 | 67.7 | 50.0 | 58.2 | 55.6 | 60.5 | 59.7 | 69.1 | 65.6 |
| 2002 | 56.7 | 63.6 | 50.0 | 59.5 | 54.6 | 60.5 | 60.1 | 65.7 | 63.3 |
| 2003 | 56.7 | 63.5 | 50.0 | 59.6 | 55.4 | 60.8 | 60.5 | 65.3 | 62.0 |
| 2004 | 57.6 | 66.0 | 50.0 | 58.4 | 54.4 | 59.8 | 60.1 | 65.6 | 61.8 |
| 2005 | 57.9 | 64.2 | 50.0 | 59.1 | 54.3 | 59.8 | 58.5 | 65.5 | 65.8 |
| 2006 | 59.0 | 64.8 | 50.0 | 62.0 | 54.5 | 59.8 | 59.4 | 65.6 | 62.4 |

**Table 20:** Overall Energy and Exergy Efficiencies of the Industries and the Industrial Sector between 1990 and 2006 (%)

| Years | Iron–steel | Chemical-Petrochem. | Petrochem.-feedstock | Fertilizer | Cement | Sugar | Non iron metals | Other industry | Industrial Sector |
|---|---|---|---|---|---|---|---|---|---|
| 1990 | 43.5 | 32.3 | 31.6 | 33.2 | 36.6 | 22.0 | 42.2 | 27.4 | 33.7 |
| 1991 | 43.5 | 30.1 | 31.6 | 32.8 | 36.4 | 22.1 | 42.1 | 25.8 | 32.8 |
| 1992 | 44.3 | 30.4 | 31.6 | 29.6 | 37.5 | 22.6 | 42.6 | 26.7 | 33.3 |
| 1993 | 45.0 | 32.2 | 31.6 | 29.9 | 37.7 | 23.8 | 43.8 | 25.7 | 33.1 |
| 1994 | 44.9 | 31.9 | 31.6 | 30.0 | 36.5 | 22.8 | 38.3 | 29.0 | 34.3 |
| 1995 | 45.1 | 31.6 | 31.6 | 29.5 | 35.4 | 23.0 | 35.3 | 28.9 | 33.5 |
| 1996 | 45.3 | 33.6 | 31.6 | 29.6 | 34.9 | 22.4 | 36.3 | 26.9 | 32.5 |
| 1997 | 45.7 | 34.0 | 31.6 | 31.7 | 36.9 | 22.2 | 37.6 | 25.6 | 31.9 |
| 1998 | 46.3 | 37.1 | 31.6 | 32.4 | 35.6 | 21.9 | 38.7 | 26.7 | 32.1 |
| 1999 | 45.7 | 34.0 | 31.6 | 34.4 | 34.6 | 22.0 | 34.1 | 29.9 | 33.6 |
| 2000 | 45.9 | 34.1 | 31.6 | 35.4 | 36.3 | 22.4 | 33.5 | 26.0 | 31.2 |
| 2001 | 46.3 | 32.3 | 31.6 | 29.0 | 35.8 | 21.1 | 33.4 | 34.0 | 34.7 |
| 2002 | 46.6 | 25.3 | 31.6 | 31.3 | 35.0 | 21.1 | 34.2 | 27.0 | 30.8 |
| 2003 | 46.5 | 25.0 | 31.6 | 31.4 | 35.7 | 21.7 | 34.9 | 26.2 | 30.2 |
| 2004 | 48.1 | 29.4 | 31.6 | 29.2 | 34.9 | 19.9 | 34.3 | 27.9 | 31.9 |
| 2005 | 48.4 | 28.0 | 31.6 | 30.9 | 34.9 | 19.9 | 34.1 | 28.4 | 32.2 |
| 2006 | 49.8 | 27.5 | 31.6 | 35.5 | 35.0 | 19.9 | 33.1 | 27.8 | 31.9 |

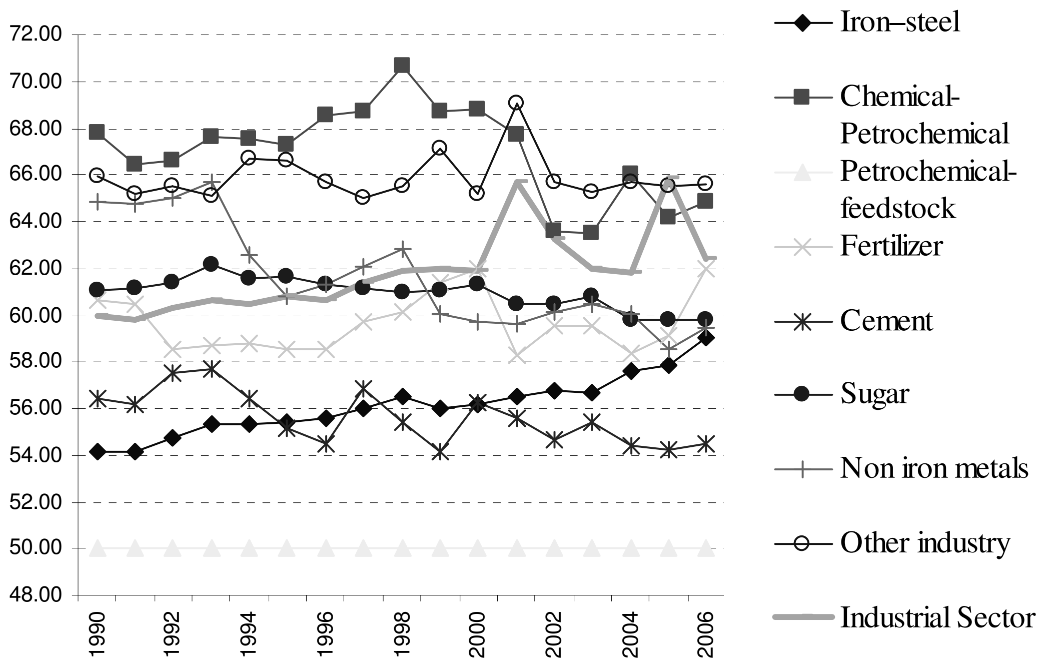


**Figure 8:** Overall Energy Efficiencies of the Industries (%)

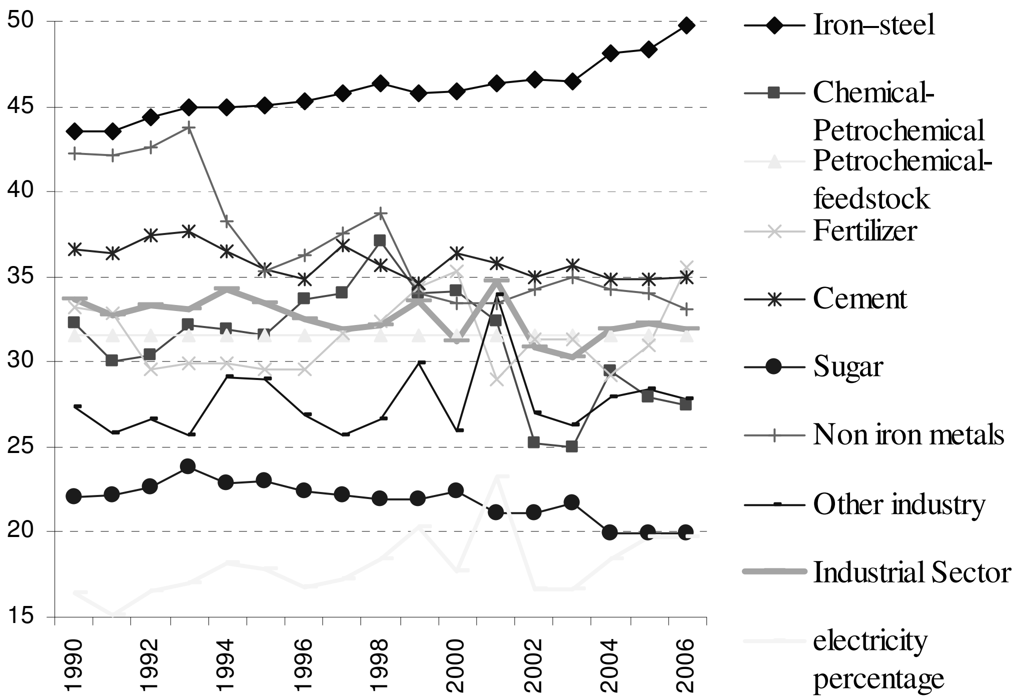


**Figure 9:** Overall Exergy Efficiencies of the Industries and electricity consumption percentage (%)

The similarity between the shape of the overall exergy efficiency and the electricity use percentage shows that the increasing electricity consumption for high quality works results more efficient industry.

Using Equation (36), exergetic improvement potentials of all the industries are calculated and shown in Figure 10.

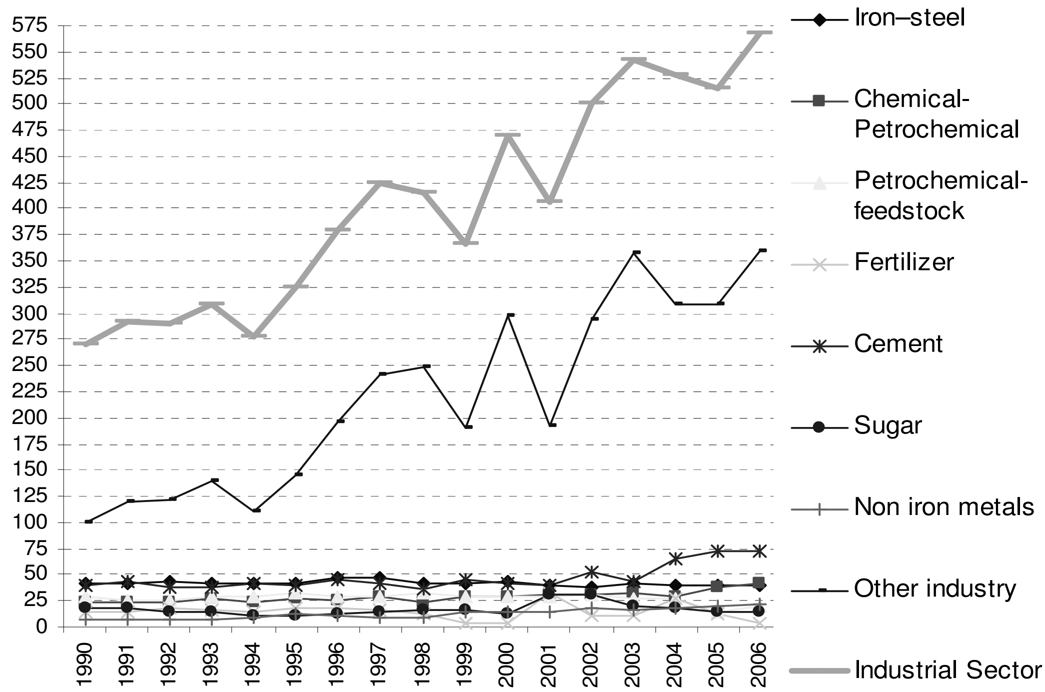


**Figure 10:** Exergetic Improvement Potentials of All Industries (PJ)

The other industries have the highest exergetic improvement potentials. This is because, they consume more fuel and electricity for low heating temperatures as seen in Table 11 of part 3.3.1.

Because of the dominance of the Other industry in Figure 10, the exergetic improvement potentials of the remaining seven known industry are shown also in Figure 11 separately.

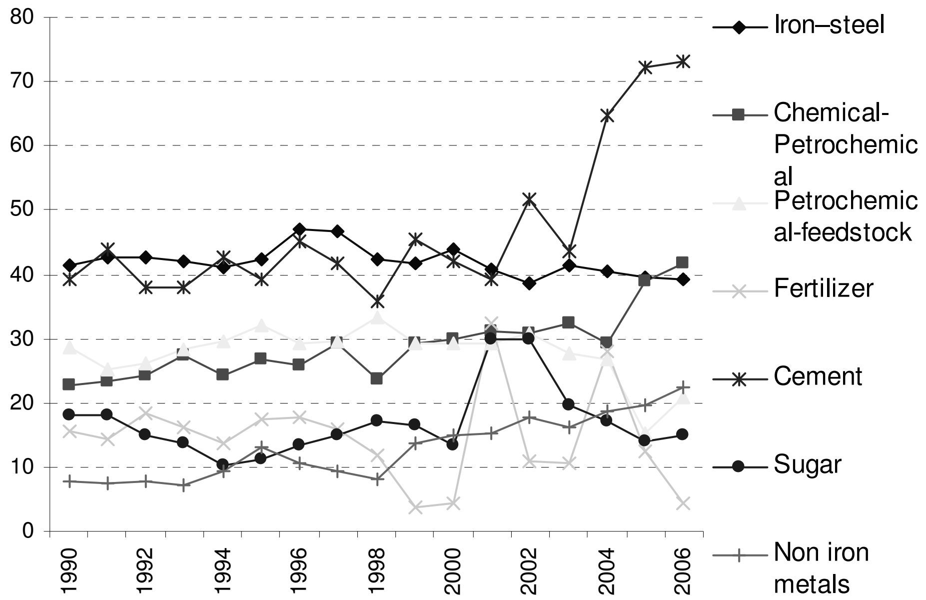


**Figure 11:** Exergetic Improvement Potentials of Seven Known Industries (PJ)

Cement industry has the highest exergetic improvement potential. This is primarily because of the increase in their consumption in the last few years. In addition they consume most of the electricity for low heating temperatures as seen in Table 11 of part 3.3.1 and their high temperatures are even very low with respect to iron-steel industry.

The greatest improvement has occurred in the fertilizer industry, because its improvement potential decreased a lot. This is because of the decrease of fuel consumption in the industry. In addition, the electricity is more efficiently used with respect to fuel according to Table 12 in part 3.3.1.

## 3.4 Transportation Sector

Turkish transportation sector's energy consumption is highly dominated by highway fossil fuel, mostly oil consumption. Railways, Marine and Airways subsectors constitute the other parts of the sector.

Railways subsector mainly utilizes oil and electricity. Since 2000 railways subsector consumes only oil and electricity. Before 2000, there were small amount hard Coal consumptions. And the lignite operated trains has not been working since 1992.

Because of the general technological restrictions, the only consumption of Marine and Airways subsectors is oil.

Highways subsector started to use natural gas since 1994. The LPG consumption of Highways subsector is thought to be included in the oil consumption in the WEC-TNC reports [51-53].

### 3.4.1 Estimations for the efficiencies in the Transportation Sector

Many studies [21,22,27,64,65,66] on the utilization on energy and exergy efficiencies assume the same efficiencies in the Transportation Sector which are tabulated below. So that energy efficiencies of Turkish Transportation Subsectors are assumed to be the same as in Table 21.

**Table 21:** Energy Efficiencies of the Transportation Subsectors (%)

| Railways | Marine | Airways | Highways |
|---|---|---|---|
| 28 | 15 | 28 | 22 |

The exergy efficiency for Work Production of Mechanical Drives is defined in equation (34) as the energy efficiency divided by the quality factor of the energy carrier used. Since the transportation devices are the work producing devices, the exergy efficiencies are found accordingly, using the value of quality factors in Appendix A and tabulated below according to the energy carriers used in the subsectors of transportation.

**Table 22:** Exergy efficiencies of Transportation Subsectors (%)

| Railways | | | | Marine | Airways | Highways | |
|---|---|---|---|---|---|---|---|
| Hard coal | Lignite | Oil | Electricity | Oil | Oil | Oil | Natural gas |
| 27.18 | 26.92 | 28.28 | 28.00 | 15.15 | 28.28 | 22.22 | 23.91 |

### 3.4.2 Input and Output Configuration of the Transportation Sector

Table 23 shows the energy consumption data in the Turkish Transportation sector from 1990 to 2006 which are obtained from WEC-TNC reports and converted into PJ unit.

**Table 23:** Energy consumption data in the Turkish Transportation sector (PJ)

| Years | Railways | | | | Marine | Airways | Highways | |
|---|---|---|---|---|---|---|---|---|
| | Hard coal | Lignite | Oil | Electricity | Oil | Oil | Oil | Natural gas |
| 1990 | 0.42 | 0.29 | 8.04 | 1.26 | 6.61 | 13.02 | 335.51 | 0 |
| 1991 | 0.29 | 0.25 | 8.37 | 1.42 | 7.07 | 14.73 | 315.50 | 0 |
| 1992 | 0.46 | 0.04 | 7.95 | 1.59 | 8.29 | 15.66 | 323.75 | 0 |
| 1993 | 0.46 | 0 | 8.83 | 1.72 | 8.62 | 20.89 | 395.62 | 0 |
| 1994 | 0.21 | 0 | 9.17 | 1.76 | 8.12 | 23.27 | 372.06 | 0.13 |
| 1995 | 0.08 | 0 | 9.25 | 1.76 | 9.46 | 38.68 | 404.00 | 0.04 |
| 1996 | 0.29 | 0 | 9.50 | 1.93 | 9.08 | 42.61 | 429.40 | 0.13 |
| 1997 | 0.21 | 0 | 9.59 | 2.18 | 9.08 | 45.00 | 408.43 | 0.13 |
| 1998 | 0.21 | 0 | 8.87 | 2.34 | 9.46 | 46.30 | 383.11 | 0.17 |
| 1999 | 0.17 | 0 | 8.67 | 2.39 | 8.62 | 40.10 | 415.05 | 0.17 |
| 2000 | 0.04 | 0 | 8.67 | 2.60 | 8.16 | 43.28 | 439.70 | 0.17 |

**Table 23 (Continued)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2001 | 0.00 | 0 | 7.16 | 2.97 | 10.55 | 47.05 | 434.47 | 0.17 |
| 2002 | 0.00 | 0 | 7.45 | 2.97 | 10.80 | 15.20 | 440.79 | 0.17 |
| 2003 | 0.00 | 0 | 7.66 | 3.22 | 11.72 | 37.93 | 458.20 | 0.17 |
| 2004 | 0.00 | 0 | 7.66 | 2.64 | 16.28 | 68.07 | 481.81 | 0.17 |
| 2005 | 0.00 | 0 | 9.21 | 2.70 | 17.20 | 57.27 | 488.22 | 0.18 |
| 2006 | 0.00 | 0 | 9.27 | 2.84 | 19.43 | 63.18 | 528.13 | 0.20 |

Using Equation (15), exergy consumptions in the Turkish Transportation sector are easily evaluated by multiplying the energy inputs with the related quality factors in Appendix A.

**Table 24:** Exergy consumption in the Turkish Transportation sector (PJ)

| Years | Railways | | | | Marine | Airways | Highways | |
|---|---|---|---|---|---|---|---|---|
| | Hard coal | Lignite | Oil | Electricity | Oil | Oil | Oil | Natural gas |
| 1990 | 0.43 | 0.30 | 7.96 | 1.26 | 6.55 | 12.89 | 332.16 | 0 |
| 1991 | 0.30 | 0.26 | 8.29 | 1.42 | 7.00 | 14.59 | 312.35 | 0 |
| 1992 | 0.47 | 0.04 | 7.87 | 1.59 | 8.21 | 15.50 | 320.51 | 0 |
| 1993 | 0.47 | 0 | 8.74 | 1.72 | 8.54 | 20.68 | 391.67 | 0 |
| 1994 | 0.22 | 0 | 9.08 | 1.76 | 8.04 | 23.04 | 368.34 | 0.12 |
| 1995 | 0.09 | 0 | 9.16 | 1.76 | 9.37 | 38.29 | 399.96 | 0.04 |
| 1996 | 0.30 | 0 | 9.41 | 1.93 | 8.99 | 42.19 | 425.11 | 0.12 |
| 1997 | 0.22 | 0 | 9.49 | 2.18 | 8.99 | 44.55 | 404.35 | 0.12 |
| 1998 | 0.22 | 0 | 8.79 | 2.34 | 9.37 | 45.83 | 379.28 | 0.15 |
| 1999 | 0.17 | 0 | 8.58 | 2.39 | 8.54 | 39.70 | 410.90 | 0.15 |
| 2000 | 0.04 | 0 | 8.58 | 2.60 | 8.08 | 42.85 | 435.31 | 0.15 |
| 2001 | 0.00 | 0 | 7.09 | 2.97 | 10.44 | 46.58 | 430.13 | 0.15 |
| 2002 | 0.00 | 0 | 7.38 | 2.97 | 10.69 | 15.04 | 436.38 | 0.15 |
| 2003 | 0.00 | 0 | 7.58 | 3.22 | 11.60 | 37.55 | 453.62 | 0.15 |
| 2004 | 0.00 | 0 | 7.58 | 2.64 | 16.12 | 67.38 | 477.00 | 0.15 |
| 2005 | 0.00 | 0 | 9.12 | 2.70 | 17.03 | 56.69 | 483.34 | 0.17 |
| 2006 | 0.00 | 0 | 9.18 | 2.84 | 19.24 | 62.55 | 522.85 | 0.18 |

Energy and exergy outputs are found by simply multiplying the inputs with the related efficiencies and tabulated in Table 25. Since exergy efficiencies are found by dividing the energy efficiencies by quality factors, and exergy outputs are calculated by multiplying the exergy efficiencies with exergy inputs which are computed by multiplying the quality factors with energy inputs, exergy outputs are exactly same as energy outputs.

**Table 25:** Energy or Exergy outputs in the Turkish Transportation sector (PJ)

| Years | Railways | | | | Marine | Airways | Highways | |
|---|---|---|---|---|---|---|---|---|
| | Hard coal | Lignite | Oil | Electric. | Oil | Oil | Oil | Natural gas |
| 1990 | 0.12 | 0.08 | 2.25 | 0.35 | 0.99 | 3.65 | 73.81 | 0.00 |
| 1991 | 0.08 | 0.07 | 2.34 | 0.40 | 1.06 | 4.13 | 69.41 | 0.00 |
| 1992 | 0.13 | 0.01 | 2.23 | 0.45 | 1.24 | 4.38 | 71.22 | 0.00 |
| 1993 | 0.13 | 0.00 | 2.47 | 0.48 | 1.29 | 5.85 | 87.04 | 0.00 |
| 1994 | 0.06 | 0.00 | 2.57 | 0.49 | 1.22 | 6.52 | 81.85 | 0.03 |
| 1995 | 0.02 | 0.00 | 2.59 | 0.49 | 1.42 | 10.83 | 88.88 | 0.01 |
| 1996 | 0.08 | 0.00 | 2.66 | 0.54 | 1.36 | 11.93 | 94.47 | 0.03 |
| 1997 | 0.06 | 0.00 | 2.68 | 0.61 | 1.36 | 12.60 | 89.86 | 0.03 |
| 1998 | 0.06 | 0.00 | 2.48 | 0.66 | 1.42 | 12.96 | 84.28 | 0.04 |
| 1999 | 0.05 | 0.00 | 2.43 | 0.67 | 1.29 | 11.23 | 91.31 | 0.04 |
| 2000 | 0.01 | 0.00 | 2.43 | 0.73 | 1.22 | 12.12 | 96.73 | 0.04 |
| 2001 | 0.00 | 0.00 | 2.00 | 0.83 | 1.58 | 13.17 | 95.58 | 0.04 |
| 2002 | 0.00 | 0.00 | 2.09 | 0.83 | 1.62 | 4.25 | 96.97 | 0.04 |
| 2003 | 0.00 | 0.00 | 2.14 | 0.90 | 1.76 | 10.62 | 100.81 | 0.04 |
| 2004 | 0.00 | 0.00 | 2.14 | 0.74 | 2.44 | 19.06 | 106.00 | 0.04 |
| 2005 | 0.00 | 0.00 | 2.58 | 0.75 | 2.58 | 16.03 | 107.41 | 0.04 |
| 2006 | 0.00 | 0.00 | 2.60 | 0.80 | 2.91 | 17.69 | 116.19 | 0.04 |

### 3.4.2 Efficiencies of the Transportation Sector

For every subsector, total outputs are divided by total inputs to find the efficiencies of the subsector. Likewise overall efficiency of the transportation sector is calculated accordingly. Since the energy efficiencies are assumed in Table 21, only the overall efficiencies of Transportation Sector need to be calculated. So that, the computed values for the overall efficiencies are given near the exergy efficiencies of subsectors and the sector itself.

**Table 26:** Overall Exergy Efficiencies of the Transportation Subsectors and the Transportation Sector together with the overall energy efficiencies of Transportation Sector (%)

| Years | Railways | Marine | Airways | Highways | Transportation Sector (exergy) | Transportation Sector (energy) |
|---|---|---|---|---|---|---|
| 1990 | 28.2 | 15.2 | 28.3 | 22.2 | 22.5 | 22.3 |
| 1991 | 28.2 | 15.2 | 28.3 | 22.2 | 22.5 | 22.3 |
| 1992 | 28.2 | 15.2 | 28.3 | 22.2 | 22.5 | 22.3 |
| 1993 | 28.2 | 15.2 | 28.3 | 22.2 | 22.5 | 22.3 |
| 1994 | 28.2 | 15.2 | 28.3 | 22.2 | 22.6 | 22.4 |
| 1995 | 28.2 | 15.2 | 28.3 | 22.2 | 22.7 | 22.5 |
| 1996 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.5 |
| 1997 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.6 |
| 1998 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.6 |
| 1999 | 28.2 | 15.2 | 28.3 | 22.2 | 22.7 | 22.5 |
| 2000 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.5 |
| 2001 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.5 |
| 2002 | 28.2 | 15.2 | 28.3 | 22.2 | 22.4 | 22.2 |
| 2003 | 28.2 | 15.2 | 28.3 | 22.2 | 22.6 | 22.4 |
| 2004 | 28.2 | 15.2 | 28.3 | 22.2 | 22.8 | 22.6 |
| 2005 | 28.2 | 15.2 | 28.3 | 22.2 | 22.7 | 22.5 |
| 2006 | 28.2 | 15.2 | 28.3 | 22.2 | 22.7 | 22.5 |

The calculated exergy efficiencies are graphed on a 17-year scale in Figure 12 to see the overall sector better.

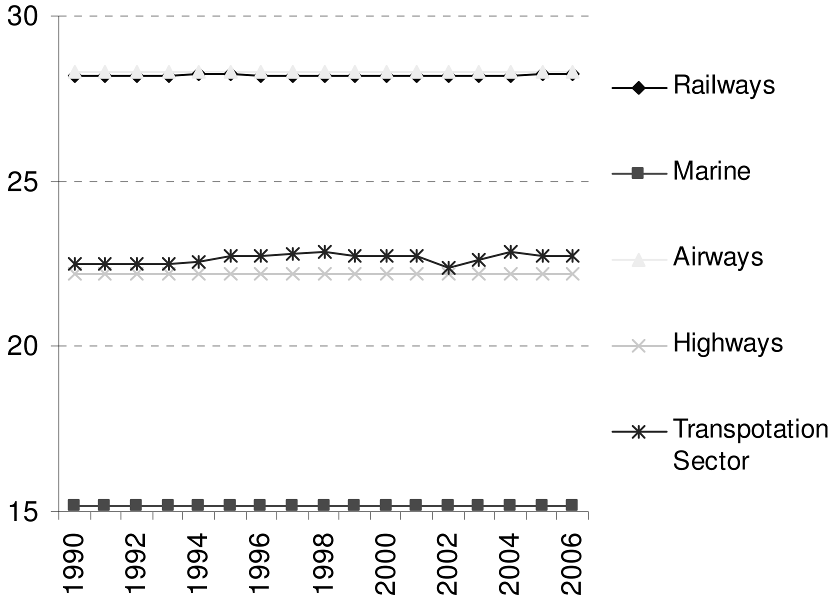


**Figure 12:** Exergy Efficiencies of Transportation Sector (%)

Using Equation (36), exergetic improvement potentials of transportation sector are calculated and shown in Figure 13.

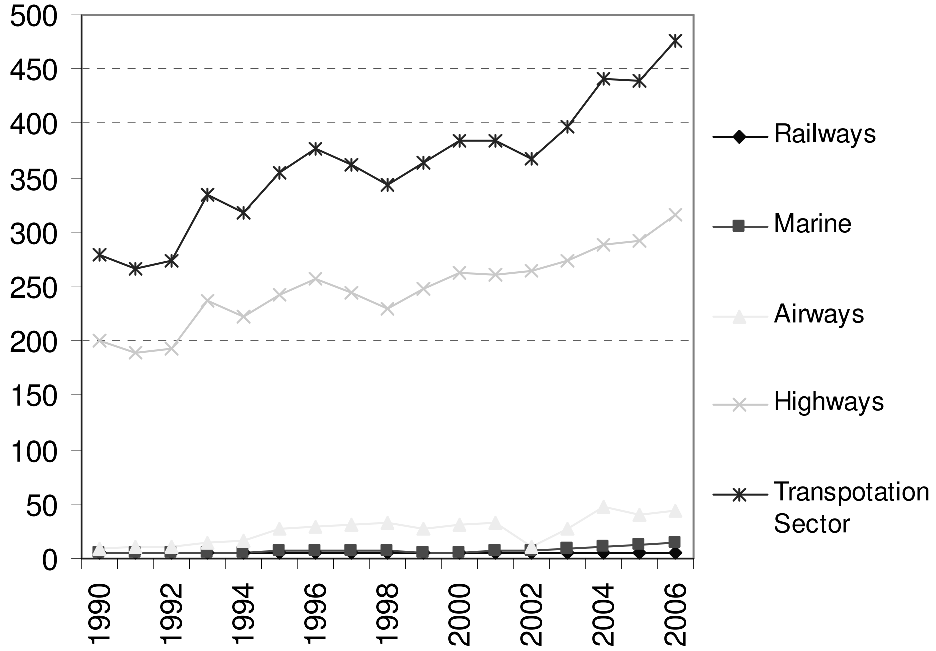


**Figure 13:** Exergetic Improvement Potentials of Transportation Sector (PJ)

Because of the dominance of highways, the efficiency of this sector almost only depends on the efficient use of cars, busses and trucks.

### 3.5 Agricultural Sector

Agricultural sector of Turkey consumes oil and electricity. The electricity consumption is performed by the pumps which are driven by an electric motor, whereas oil consumption is realized by a lot of different devices. However, the main agricultural devices are seen to be as the tractors and combine-harvesters. According to the statistical data of Turkish Statistics Institute [67], the number of combine harvesters is not changed significantly, whereas the number of tractors is increased 50 % since 1990. When compared with the 69% oil consumption increase of agricultural sector in Turkey since 1990 [68], the tractors can be admitted as the representative device for oil consumption.

#### 3.5.1 Estimations for the efficiencies in the Agricultural Sector

The agricultural sector analysis of a country using Reistad's approach has only been performed by Dincer et al. [10,22,24] for Saudi Arabia. In their articles, firstly the first and second law efficiencies of tractors and pumps were assumed, and then using the related energy consumptions of the sector the overall energy and exergy efficiencies were calculated.

The two analyses on Saudi Arabia are very different from each other. In the first analysis [22], tractors and pumps are assumed to be 22 and 90 percent efficient respectively, whereas they are assumed to be 75% and 70% efficient in the second analysis. In addition, the second law efficiency of the pumps was calculated like heat pumps in both studies.

In this analysis, the energy efficiency of tractors and the pumps are assumed to be 22% and 90% respectively as done in the first article of Dincer et al. [22].

However, the exergy efficiencies of the pumps are assumed differently. In the agricultural sector of Turkey, pumps are mostly used for pumping water. They are operated as electric motors producing mechanical energy to elevate the water from the wells. Since mechanical energy production from electricity has the same energy and exergy efficiencies as shown in equation (32), exergy efficiency of pumps are found as 90% from the energy efficiency assumption.

The exergy efficiency for energy production from fuel is defined in equation (34) as the energy efficiency divided by the quality factor of the energy carrier used. Since the agricultural devices are the work producing devices, the exergy efficiency of the devices (tractors as representative) is found accordingly, using the value of quality factor of oil that is 0.99.

The estimated and the calculated values for the efficiencies of the devices in the Turkish Agricultural Sector are tabulated below.

**Table 27:** Energy and Exergy Efficiencies of Tractors and Pumps (%)

| | Tractors | Pumps |
|---|---|---|
| $\eta$ | 22 | 90 |
| $\psi$ | 22.22 | 90 |

### 3.5.2 Input and Output Configuration of the Agricultural Sector

The energy consumption data in the Turkish Agricultural Sector from 1990 to 2006 are obtained from the energy statistics [68] and converted into PJ unit. They are also available in the WEC-TNC reports [51-53]. The exergy inputs for electricity are the same as energy the energy inputs, whereas the exergy outputs for oil are computed by simply multiplying the energy values with the quality factor of oil, using Equation (15). The energy and exergy inputs in the Agricultural Sector are tabulated in Table 28.

**Table 28:** Energy and Exergy Inputs in the Agricultural Sector (PJ)

| | ENERGY INPUTS | | | EXERGY INPUTS | | |
|---|---|---|---|---|---|---|
| Years | Electricity | Oil | TOTAL | Electricity | Oil | TOTAL |
| 1990 | 2.07 | 79.82 | 81.89 | 2.07 | 79.02 | 81.09 |
| 1991 | 2.56 | 80.15 | 82.72 | 2.56 | 79.35 | 81.91 |
| 1992 | 3.09 | 80.37 | 83.46 | 3.09 | 79.57 | 82.66 |
| 1993 | 3.56 | 99.00 | 102.56 | 3.56 | 98.01 | 101.57 |
| 1994 | 4.30 | 99.52 | 103.82 | 4.30 | 98.52 | 102.82 |
| 1995 | 5.45 | 101.51 | 106.96 | 5.45 | 100.50 | 105.94 |
| 1996 | 6.57 | 107.01 | 113.58 | 6.57 | 105.94 | 112.51 |
| 1997 | 7.24 | 110.93 | 118.17 | 7.24 | 109.82 | 117.06 |
| 1998 | 8.45 | 109.89 | 118.34 | 8.45 | 108.79 | 117.24 |
| 1999 | 9.45 | 112.91 | 122.35 | 9.45 | 111.78 | 121.22 |
| 2000 | 11.05 | 117.59 | 128.64 | 11.05 | 116.41 | 127.46 |
| 2001 | 11.53 | 112.53 | 124.06 | 11.53 | 111.41 | 122.94 |
| 2002 | 12.56 | 114.27 | 126.83 | 12.56 | 113.12 | 125.69 |
| 2003 | 13.17 | 116.00 | 129.17 | 13.17 | 114.84 | 128.01 |
| 2004 | 14.02 | 124.69 | 138.71 | 14.02 | 123.44 | 137.47 |
| 2005 | 14.81 | 125.82 | 140.62 | 14.81 | 124.56 | 139.37 |
| 2006 | 15.99 | 135.13 | 151.12 | 15.99 | 133.78 | 149.77 |

Using the input values above, energy and exergy outputs are found by simply multiplying the inputs with the related efficiencies.

Since exergy efficiencies for oil consumption (tractors) are found by dividing the energy efficiencies by quality factors, and exergy outputs are calculated by multiplying the exergy efficiencies with exergy inputs which are computed by multiplying the quality factors with energy inputs, exergy outputs are exactly same as energy outputs. Likewise, electricity outputs are the same, because both energy and exergy inputs and efficiencies are equivalent.

The calculated data for energy and exergy outputs are tabulated below.

**Table 29:** Energy and Exergy Outputs in the Agricultural Sector (PJ)

| | ENERGY OUTPUTS | | | EXERGY OUTPUTS | | |
|---|---|---|---|---|---|---|
| Years | Electricity | Oil | TOTAL | Electricity | Oil | TOTAL |
| 1990 | 1.86 | 17.56 | 19.42 | 1.86 | 17.56 | 19.42 |
| 1991 | 2.31 | 17.63 | 19.94 | 2.31 | 17.63 | 19.94 |
| 1992 | 2.78 | 17.68 | 20.46 | 2.78 | 17.68 | 20.46 |
| 1993 | 3.20 | 21.78 | 24.98 | 3.20 | 21.78 | 24.98 |
| 1994 | 3.87 | 21.89 | 25.76 | 3.87 | 21.89 | 25.76 |
| 1995 | 4.90 | 22.33 | 27.23 | 4.90 | 22.33 | 27.23 |
| 1996 | 5.91 | 23.54 | 29.46 | 5.91 | 23.54 | 29.45 |
| 1997 | 6.52 | 24.40 | 30.92 | 6.52 | 24.40 | 30.92 |
| 1998 | 7.61 | 24.18 | 31.78 | 7.61 | 24.17 | 31.78 |
| 1999 | 8.50 | 24.84 | 33.34 | 8.50 | 24.84 | 33.34 |
| 2000 | 9.95 | 25.87 | 35.82 | 9.95 | 25.87 | 35.81 |
| 2001 | 10.38 | 24.76 | 35.14 | 10.38 | 24.75 | 35.13 |
| 2002 | 11.31 | 25.14 | 36.45 | 11.31 | 25.14 | 36.44 |
| 2003 | 11.85 | 25.52 | 37.37 | 11.85 | 25.52 | 37.37 |
| 2004 | 12.62 | 27.43 | 40.05 | 12.62 | 27.43 | 40.05 |
| 2005 | 13.33 | 27.68 | 41.01 | 13.33 | 27.68 | 41.00 |
| 2006 | 14.39 | 29.73 | 44.12 | 14.39 | 29.73 | 44.12 |

### 3.4.2 Energy and Exergy Efficiencies of the Agricultural Sector

The energy and exergy efficiencies are computed by dividing total output values given in Table 29 into total input values given in Table 28. The resulting efficiencies are tabulated in Table 30 and graphed on Figure 14.

**Table 30:** Energy and Exergy efficiencies of Agricultural Sector

| Years | η (%) | ψ (%) |
|---|---|---|
| 1990 | 23.7 | 24.0 |
| 1991 | 24.1 | 24.3 |
| 1992 | 24.5 | 24.8 |
| 1993 | 24.4 | 24.6 |
| 1994 | 24.8 | 25.1 |
| 1995 | 25.5 | 25.7 |
| 1996 | 25.9 | 26.2 |
| 1997 | 26.2 | 26.4 |
| 1998 | 26.9 | 27.1 |
| 1999 | 27.3 | 27.5 |
| 2000 | 27.8 | 28.1 |
| 2001 | 28.3 | 28.6 |
| 2002 | 28.7 | 29.0 |
| 2003 | 28.9 | 29.2 |
| 2004 | 28.9 | 29.1 |
| 2005 | 29.2 | 29.4 |
| 2006 | 29.2 | 29.5 |

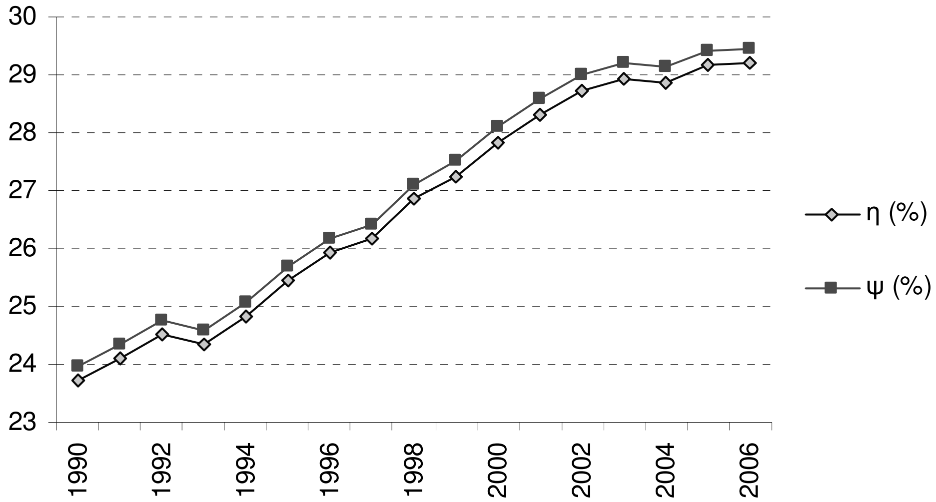


**Figure 14:** Energy and Exergy efficiencies of Agricultural Sector (PJ)

Since electricity consumption increases every year Agricultural Sector, the efficiency of the sector is automatically increases.

Using Equation (36), exergetic improvement potentials of Agricultural Sector are calculated and shown on Figure 15.

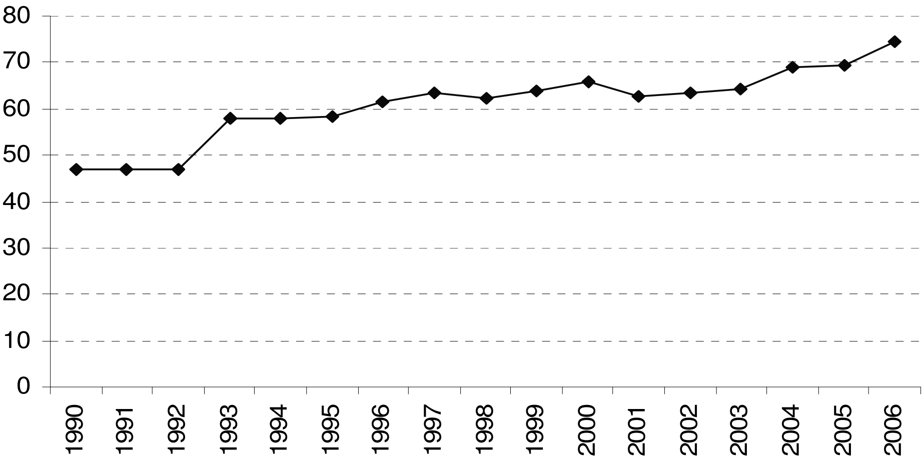


**Figure 15:** Exergetic Improvement Potential of Agricultural Sector (PJ)

Although there is increase in the efficiency of the sector, because of higher consumptions year by year, improvement potential increases.

### 3.6 Residential-Commercial Sector

Turkish residential-commercial sector (RCS) utilizes energy for lighting, space heating, water heating, cooking and electrical appliances. The energy used can be classified as electricity, fossil fuels and renewables (includes biomass, wood, geothermal and solar) [36]. The only detailed data for the Turkish residential-commercial sector were prepared for the year 1998 by State Institute of Statistics in 2002 [69]. So that, for a long term analysis of the sector, there should be some assumptions to be made.

First of all, the energy (electricity, fuels and renewable) utilization percentages of the energy consuming appliances and activities should be estimated.

According to the study of Utlu and Hepbasli [36] on residential-commercial sector for the estimations of 2000 and 2020 using the 1998 data, the electricity consumption for lighting is expected to increase from 35% to 38% with %2 transformation ratio from incandescent to fluorescent for every year, the electricity consumption for refrigeration is expected to decrease from 40% to 35% and the electricity consumption of other appliances is expected to increase or decrease around 1 to 2 percent in 20 years. Likewise, the consumption of fuels is expected, to decrease from 37% to 32% for water heating, to decrease from 20% to 18% and to increase from 43% to 50% for space heating. On the other hand, their estimations suggest that renewable use, for water heating will increase from %30 to %54, whereas renewable use will decrease from 68% to 46% for space heating.

When the estimations of Utlu and Hepbasli are totally examined, it is seen that the fuel and electricity consumptions does not change significantly for every year. The only significant change occurs in the type of lighting that is transforming into fluorescent %2 every year.

However, according to their estimations on renewables, the renewable use changes about 24% from space heating to water heating because of the expected natural gas utilization increase in space heating application. However this estimation is thought to anticipate according to the ongoing infrastructure studies on further gas utilization in other cities of Turkey in the following years. Thus, the assumption of no change in the utilization type for renewables for the former years is not thought to be unreasonable.

In this study, the consumption ratios according to energy carriers used are assumed to be same as the ratios of 2000 [36], for every year. However, only change is assumed to occur in the type of lighting that is transforming into fluorescent %2 every year. These estimations are seen to be consistent with the estimations mentioned above, because the small changes were assumed to occur during 20 years period for most of the applications.

According to Unal's thesis [26], 90% of lighting was incandescent in the residential-commercial sector in 1991. Using %2 decrease assumption for every year, the incandescent use is found as 72% for 2002 which is 70% in the estimations of Utlu and Hepbasli. So the lighting estimation also seems to be reasonable.

The percentages of energy utilization values of the Turkish residential-commercial sector by components are given in Table 31.

**Table 31:** Energy utilization values of the Turkish residential-commercial sector by components (%) [36]

| | Electricity | Fuel | Renewables* |
|---|---|---|---|
| Lighting | 35 | | |
| Refrigeration | 40 | | |
| Water heating | 4 | 37 | 30 |
| Cooking | 3 | 20 | 2 |
| Space heating | 2 | 43 | 68 |
| Washing machine | 2 | | |
| Vacuum cleaner | 1 | | |
| Air conditioning | 2 | | |
| Television | 6 | | |
| Iron | 1 | | |
| Miscellaneous | 4 | | |
| TOTAL | 100 | 100 | 100 |

* Renewables include biomass, wood, geothermal and solar.

### 3.6.1 Estimations for the efficiencies in the Residential-Commercial sector

#### 3.6.1.1 Lighting

Lighting is assumed just as done in the industrial sector analysis. Assuming 90% incandescent use in 1991 and %2 decrease every year, the incandescent use decreases from 92 % to 60% between 1990 and 2006.

**Table 32:** Lighting efficiencies (%) [5,26]

| | Fluorescent | Incandescent |
|---|---|---|
| **η** | 20 | 5 |
| **ψ** | 18.5 | 4.5 |

Overall energy and exergy efficiencies of lighting in the Residential-Commercial sector (RCS) are found by averaging the efficiencies with respect to the utilization ratios and tabulated below.

**Table 33:** Energy and exergy efficiencies of lighting in the RCS (%)

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|---|---|---|---|
| η | 6.2 | 6.5 | 6.8 | 7.1 | 7.4 | 7.7 | 8.0 | 8.3 | 8.6 | 8.9 |
| ψ | 5.6 | 5.9 | 6.2 | 6.5 | 6.7 | 7.0 | 7.3 | 7.6 | 7.9 | 8.1 |

**Table 33** (continued)

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|
| η | 9.2 | 9.5 | 9.8 | 10.1 | 10.4 | 10.7 | 11.0 |
| ψ | 8.4 | 8.7 | 9.0 | 9.3 | 9.5 | 9.8 | 10.1 |

### 3.6.1.2 Cooking

Energy efficiency for cooking by fuel and renewable (wood) consumption is assumed to be 40 % [26,36]. On the other hand, cooking by electricity is assumed to be 80 % efficient [22,26].

The temperature for cooking is assumed to be 120 °C [26,36]. Therefore, the exergy efficiencies for cooking can be calculated by using the equations (22) and (23) from Chapter 2. The quality factor is assumed to be 0.99 for cooking and 1.05 for renewables, because wood is used for cooking within the renewables.

$$\psi_e = \eta \cdot (1 - \frac{T_0}{T}) \qquad \psi_f = \frac{\eta}{q} \cdot (1 - \frac{T_0}{T})$$

$$\psi_e = 80\% \cdot (1 - \frac{283}{393}) = 22.4\%$$

$$\psi_f = \frac{40\%}{0.99} \cdot (1 - \frac{283}{393}) = 11.3\%$$

$$\psi_r = \frac{40\%}{1.05} \cdot (1 - \frac{283}{393}) = 10.7\%$$

#### 3.6.1.2 Water Heating

Energy efficiency for water heating by fuel and renewable consumption is assumed to be 60 % [26,36]. On the other hand, water heating by electricity is assumed to be 90 % efficient [26,36].

The temperature for water heating is assumed to be 60 °C [26,36]. Therefore, the exergy efficiencies for water heating can be calculated by using the equations (22) and (23) from Chapter 2 given below. The quality factor is assumed to be 0.99 for cooking by fuels and renewables, since mostly LPG is used mostly used within the fuels, and wood and solar energy carriers are mostly used within the renewables.

$$\psi = \frac{\eta}{q} \cdot \left( 1 - \left[ \frac{T_0}{T - T_0} \right] \cdot \ln\left( \frac{T}{T_O} \right) \right)$$

$$\psi_e = \frac{90\%}{1} \cdot \left( 1 - \left[ \frac{283}{333 - 283} \right] \cdot \ln\left( \frac{333}{283} \right) \right) = 7.1\%$$

$$\psi_f = \psi_r = \frac{60\%}{0.99} \cdot \left( 1 - \left[ \frac{283}{333 - 283} \right] \cdot \ln\left( \frac{333}{283} \right) \right) = 4.8\%$$

Although it is used at very low levels with respect to wood and solar within the renewables, for further discussion, the calculation of geothermal water heating is given below, for an average efficiency 54% [36].

$$\psi_{geo} = \frac{54\%}{0.29} \cdot \left(1 - \left[\frac{283}{333 - 283}\right] \cdot \ln\left(\frac{333}{283}\right)\right) = 14.7\%$$

#### 3.6.1.3 Space Heating

Energy efficiency for space heating by fuel and renewable consumption is assumed to be 50 % [26,36]. On the other hand, space heating by electricity is assumed to be 98 % efficient [36].

The temperature for water heating is assumed to be 50 °C [26,36]. Therefore, the exergy efficiencies for space heating can also be calculated by using the equations (22) and (23) from Chapter 2 given below. The quality factor is assumed to be 0.99 for cooking by fuels and renewables, since mostly LPG is used mostly used within the fuels, and wood (mostly) and geothermal energy carriers are mostly used within the renewables.

$$\psi = \frac{\eta}{q} \cdot \left(1 - \left[\frac{T_0}{T - T_0}\right] \cdot \ln\left(\frac{T}{T_O}\right)\right)$$

$$\psi_e = \frac{98\%}{1} \cdot \left(1 - \left[\frac{283}{323 - 283}\right] \cdot \ln\left(\frac{323}{283}\right)\right) = 6.3\%$$

$$\psi_f = \psi_r = \frac{50\%}{0.99} \cdot \left(1 - \left[\frac{283}{323 - 283}\right] \cdot \ln\left(\frac{323}{283}\right)\right) = 3.3\%$$

Although it is used at low levels with respect to wood within the renewables, for further discussion, the calculation of geothermal space heating is given below, for an average efficiency 54% [36].

$$\psi_{geo} = \frac{54\%}{0.29} \cdot \left(1 - \left[\frac{283}{323-283}\right] \cdot \ln\left(\frac{323}{283}\right)\right) = 12.0\%$$

### 3.6.1.5 Refrigeration

It is assumed that the temperatures inside freezers and refrigerators are approximately - 8 °C, the coefficient of performance (COP) is 1.0 [26,36]. Therefore, the exergy efficiencies for refrigeration can be calculated by using the equation (26) from Chapter 2 given below.

$$\psi = \eta \cdot \left[\frac{T_0}{T} - 1\right]$$

$$\psi = 100\% \cdot \left[\frac{283}{265} - 1\right] = 6.8\%$$

### 3.6.1.6 Air Conditioning

It is assumed that the COP value of the electric air conditioning unit is 2 and it extracts heat from air at 14 °C and the outside temperature is 35 °C [36]. So, the exergy efficiencies for refrigeration can be calculated by using the equation (26) from Chapter 2 given below.

$$\psi = \eta \cdot \left[\frac{T_0}{T} - 1\right]$$

$$\psi = 200\% \cdot \left[\frac{308}{287} - 1\right] = 14.6\%$$

### 3.6.1.7 Electrical Appliances

Efficiencies of the other electrical appliances are taken from the estimations made bay Utlu and Hepbasli [36]. The efficiencies of the all the electrical appliances except lighting are tabulated below.

**Table 34:** Efficiencies of the other electrical appliances (%)

| | η | ψ |
|---|---|---|
| Cooking | 80 | 22.3 |
| Water Heating | 90 | 7.12 |
| Space Heating | 98 | 6.34 |
| Refrigeration | 100 | 6.79 |
| Air conditioning | 200 | 14.63 |
| Washing machine | 80 | 80 |
| Vacuum cleaner | 70 | 70 |
| Television | 80 | 80 |
| Iron | 98 | 30 |
| Miscellaneous | 70 | 65 |

### 3.6.2 Input Configuration of the Residential-Commercial Sector

Energy consumption (Fuel, Electricity and Renewables) data for the Turkish Residential-Commercial sector from 1990 to 2006 are obtained from WEC-TNC reports, assuming the renewables as biomass, wood, geothermal and solar. The exergy consumptions (input) are simply found by multiplying each energy carrier's energy utilization in the WEC-TNC reports with its quality factor and adding all the exergy consumptions together. The energy and exergy consumptions of the Residential-Commercial sector are tabulated together in Table 35.

**Table 35:** Energy and Exergy Inputs in the Residential-Commercial sector [51-53]

| | Energy Consumption (PJ) | | | | Exergy Consumption(PJ) | | | |
|---|---|---|---|---|---|---|---|---|
| Years | Fuel | Electricity | Renewables | Total | Fuel | Electricity | Renewables | Total |
| 1990 | 265.01 | 60.08 | 317.80 | 642.89 | 268.53 | 60.08 | 322.01 | 650.62 |
| 1991 | 277.07 | 70.79 | 318.35 | 666.21 | 280.24 | 70.79 | 322.52 | 673.55 |
| 1992 | 303.73 | 76.15 | 319.80 | 699.67 | 306.56 | 76.15 | 323.23 | 705.93 |
| 1993 | 305.37 | 84.68 | 318.81 | 708.86 | 307.18 | 84.68 | 321.68 | 713.55 |
| 1994 | 272.51 | 92.08 | 319.13 | 683.73 | 272.50 | 92.08 | 321.38 | 685.97 |
| 1995 | 319.43 | 98.58 | 318.56 | 736.58 | 319.06 | 98.58 | 320.06 | 737.71 |
| 1996 | 341.45 | 112.16 | 319.37 | 772.98 | 338.25 | 112.16 | 319.79 | 770.20 |
| 1997 | 374.68 | 128.80 | 321.34 | 824.82 | 370.25 | 128.80 | 319.91 | 818.95 |
| 1998 | 345.55 | 138.84 | 322.59 | 806.98 | 339.55 | 138.84 | 319.49 | 797.88 |
| 1999 | 331.60 | 149.16 | 313.66 | 794.41 | 324.42 | 149.16 | 308.88 | 782.46 |
| 2000 | 370.92 | 164.39 | 304.33 | 839.63 | 361.75 | 164.39 | 298.10 | 824.24 |
| 2001 | 297.00 | 165.81 | 295.81 | 758.62 | 288.30 | 165.81 | 287.90 | 742.00 |
| 2002 | 309.88 | 174.01 | 288.97 | 772.86 | 301.59 | 174.01 | 279.20 | 754.79 |
| 2003 | 351.14 | 187.63 | 283.11 | 821.89 | 340.81 | 187.63 | 271.17 | 799.61 |
| 2004 | 393.43 | 207.49 | 276.15 | 877.07 | 381.86 | 207.49 | 262.88 | 852.23 |
| 2005 | 579.41 | 251.81 | 272.72 | 1103.93 | 562.26 | 251.81 | 255.57 | 1069.63 |
| 2006 | 470.22 | 251.33 | 271.62 | 993.16 | 450.34 | 251.33 | 249.40 | 951.07 |

### 3.6.3 Energy and Exergy Efficiencies of the Residential-Commercial Sector

Since there are a lot of components in this sector, It is thought to be easier to calculate the efficiencies by averaging method, rather than finding the outputs one by one. Using the equations (37) and (38) with the related efficiencies given in part 3.6.1 the efficiencies of fuel, electricity, and renewable consumptions are found for each year. Using the average efficiencies together with the data in Table 35, the overall efficiencies of the Residential-Commercial Sector are easily found.

$$\eta = (a_1 \cdot \eta_1 + a_2 \cdot \eta_2 + \ldots\ldots + a_n \cdot \eta_n)/100$$

$$\psi = (a_1 \cdot \psi_1 + a_2 \cdot \psi_2 + ...... + a_n \cdot \psi_n)/100$$

The calculation for fuel consumption efficiencies by using Table (31) and the related efficiencies given in part 3.6.1, is given below:

$$\eta_f = (37 \cdot 60\% + 20 \cdot 40\% + 43 \cdot 50\%)/100 = 51.7\%$$

$$\psi_f = (37 \cdot 4.8\% + 20 \cdot 11.3\% + 43 \cdot 3.3\%)/100 = 5.4\%$$

Likewise, the calculation for renewable consumption efficiencies by using Table (31) and the related efficiencies given in part 3.6.1, is given below:

$$\eta_r = (30 \cdot 60\% + 2 \cdot 40\% + 68 \cdot 50\%)/100 = 52.8\%$$

$$\psi_r = (30 \cdot 4.8\% + 2 \cdot 10.7\% + 68 \cdot 3.3\%)/100 = 5.4\%$$

On the other hand, since lighting efficiency is defined differently for every year, only the calculation for electricity consumption efficiencies for the year 2006 is given as an example for the other years.

For the year 2006:

$$\eta_e = (35 \cdot 11\% + 40 \cdot 100\% + 4 \cdot 90\% + 3 \cdot 80\% + 2 \cdot 98\% + 2 \cdot 80\% + 1 \cdot 70\% + 2 \cdot 200\% + 6 \cdot 80\% + 1 \cdot 98\% + 4 \cdot 70\%)/100 = 66.7\%$$

$$\psi_e = (35 \cdot 10.1\% + 40 \cdot 6.8\% + 4 \cdot 7.1\% + 3 \cdot 22.3\% + 2 \cdot 6.3\% + 2 \cdot 80\% + 1 \cdot 70\% + 2 \cdot 14.6\% + 6 \cdot 80\% + 1 \cdot 30\% + 4 \cdot 65\%)/100 = 17.6\%$$

The computed efficiency values are for electricity, fuel and renewable consumption are listed below.

**Table 36:** Efficiencies of electricity, fuel and renewable consumption (%)

| Years | ENERGY EFFICIENCIES | | | EXERGY EFFICIENCIES | | |
|---|---|---|---|---|---|---|
| | Fuel | Electricity | Renewables | Fuel | Electricity | Renewables |
| 1990 | 51.7 | 65.0 | 52.8 | 5.4 | 16.1 | 3.9 |
| 1991 | 51.7 | 65.1 | 52.8 | 5.4 | 16.2 | 3.9 |
| 1992 | 51.7 | 65.2 | 52.8 | 5.4 | 16.3 | 3.9 |
| 1993 | 51.7 | 65.3 | 52.8 | 5.4 | 16.4 | 3.9 |
| 1994 | 51.7 | 65.4 | 52.8 | 5.4 | 16.5 | 3.9 |
| 1995 | 51.7 | 65.5 | 52.8 | 5.4 | 16.6 | 3.9 |
| 1996 | 51.7 | 65.6 | 52.8 | 5.4 | 16.6 | 3.9 |
| 1997 | 51.7 | 65.8 | 52.8 | 5.4 | 16.7 | 3.9 |
| 1998 | 51.7 | 65.9 | 52.8 | 5.4 | 16.8 | 3.9 |
| 1999 | 51.7 | 66.0 | 52.8 | 5.4 | 16.9 | 3.9 |
| 2000 | 51.7 | 66.1 | 52.8 | 5.4 | 17.0 | 3.9 |
| 2001 | 51.7 | 66.2 | 52.8 | 5.4 | 17.1 | 3.9 |
| 2002 | 51.7 | 66.3 | 52.8 | 5.4 | 17.2 | 3.9 |
| 2003 | 51.7 | 66.4 | 52.8 | 5.4 | 17.3 | 3.9 |
| 2004 | 51.7 | 66.5 | 52.8 | 5.4 | 17.4 | 3.9 |
| 2005 | 51.7 | 66.6 | 52.8 | 5.4 | 17.5 | 3.9 |
| 2006 | 51.7 | 66.7 | 52.8 | 5.4 | 17.6 | 3.9 |

Using Table 35 and Table 36 together, the energy and exergy outputs of the sector are easily found by multiplying the inputs with the related efficiencies. The resulting energy and exergy outputs in the Residential-Commercial sector are tabulated in Table 37.

**Table 37:** Energy and Exergy Outputs in the Residential-Commercial sector (PJ)

| Years | ENERGY OUPUTS | | | | EXERGY OUTPUTS | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel | Electricity | Renewables | Total | Fuel | Electricity | Renewables | Total |
| 1990 | 137.0 | 39.1 | 167.8 | 343.9 | 14.6 | 9.7 | 137.0 | 39.1 |
| 1991 | 143.2 | 46.1 | 168.1 | 357.4 | 15.2 | 11.4 | 143.2 | 46.1 |
| 1992 | 157.0 | 49.7 | 168.9 | 375.5 | 16.7 | 12.4 | 157.0 | 49.7 |
| 1993 | 157.9 | 55.3 | 168.3 | 381.5 | 16.7 | 13.9 | 157.9 | 55.3 |
| 1994 | 140.9 | 60.3 | 168.5 | 369.6 | 14.8 | 15.2 | 140.9 | 60.3 |
| 1995 | 165.1 | 64.6 | 168.2 | 398.0 | 17.4 | 16.3 | 165.1 | 64.6 |
| 1996 | 176.5 | 73.6 | 168.6 | 418.8 | 18.4 | 18.7 | 176.5 | 73.6 |
| 1997 | 193.7 | 84.7 | 169.7 | 448.1 | 20.1 | 21.6 | 193.7 | 84.7 |
| 1998 | 178.7 | 91.4 | 170.3 | 440.4 | 18.5 | 23.4 | 178.7 | 91.4 |
| 1999 | 171.4 | 98.4 | 165.6 | 435.4 | 17.7 | 25.3 | 171.4 | 98.4 |
| 2000 | 191.8 | 108.6 | 160.7 | 461.0 | 19.7 | 28.0 | 191.8 | 108.6 |
| 2001 | 153.6 | 109.7 | 156.2 | 419.4 | 15.7 | 28.4 | 153.6 | 109.7 |
| 2002 | 160.2 | 115.3 | 152.6 | 428.1 | 16.4 | 30.0 | 160.2 | 115.3 |
| 2003 | 181.5 | 124.5 | 149.5 | 455.6 | 18.5 | 32.5 | 181.5 | 124.5 |
| 2004 | 203.4 | 137.9 | 145.8 | 487.2 | 20.8 | 36.2 | 203.4 | 137.9 |
| 2005 | 299.6 | 167.7 | 144.0 | 611.2 | 30.6 | 44.1 | 299.6 | 167.7 |
| 2006 | 243.1 | 167.6 | 143.4 | 554.1 | 24.5 | 44.3 | 243.1 | 167.6 |

By simply dividing total outputs of the sector into the inputs, the overall energy and exergy efficiencies of the Residential-Commercial sector are calculated and tabulated in Table 38. In addition, all the energy and exergy efficiency values for consumption types and Residential-Commercial Sector (RCS) graphed on figures 16 and 17.

**Table 38:** The Overall Energy and Exergy Efficiencies of the Residential-Commercial Sector (%)

| Years | η | ψ |
|---|---|---|
| 1990 | 53.5 | 5.6 |
| 1991 | 53.7 | 5.8 |
| 1992 | 53.7 | 5.9 |
| 1993 | 53.8 | 6.0 |
| 1994 | 54.1 | 6.2 |
| 1995 | 54.0 | 6.2 |
| 1996 | 54.2 | 6.4 |
| 1997 | 54.3 | 6.6 |
| 1998 | 54.6 | 6.8 |
| 1999 | 54.8 | 7.0 |
| 2000 | 54.9 | 7.2 |
| 2001 | 55.3 | 7.4 |
| 2002 | 55.4 | 7.6 |
| 2003 | 55.4 | 7.7 |
| 2004 | 55.5 | 7.9 |
| 2005 | 55.4 | 7.9 |
| 2006 | 55.8 | 8.3 |

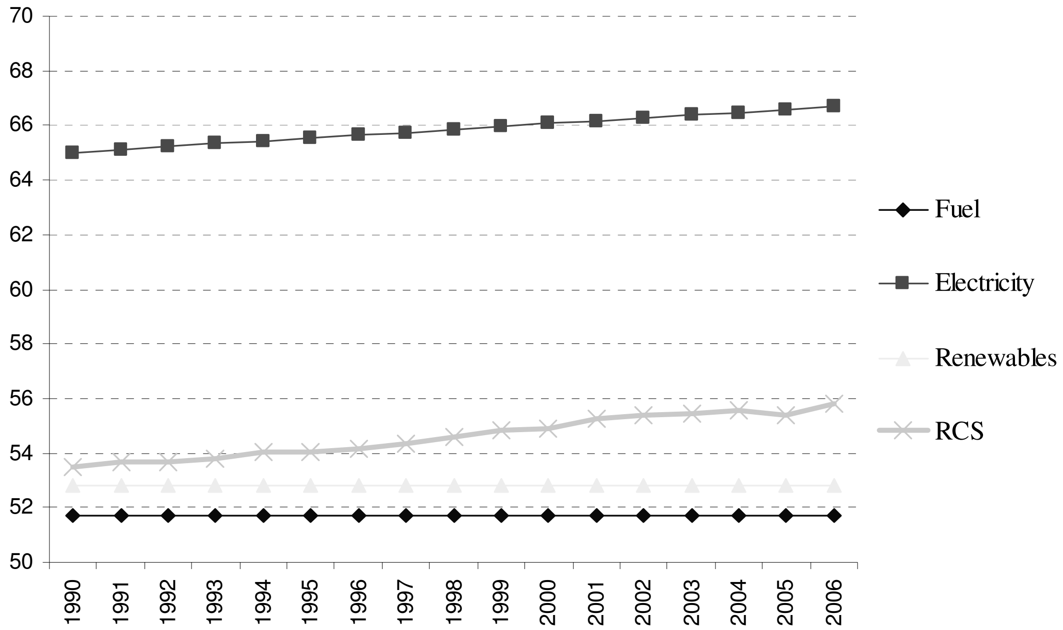


**Figure 16:** Energy efficiencies in the Residential-Commercial Sector (%)

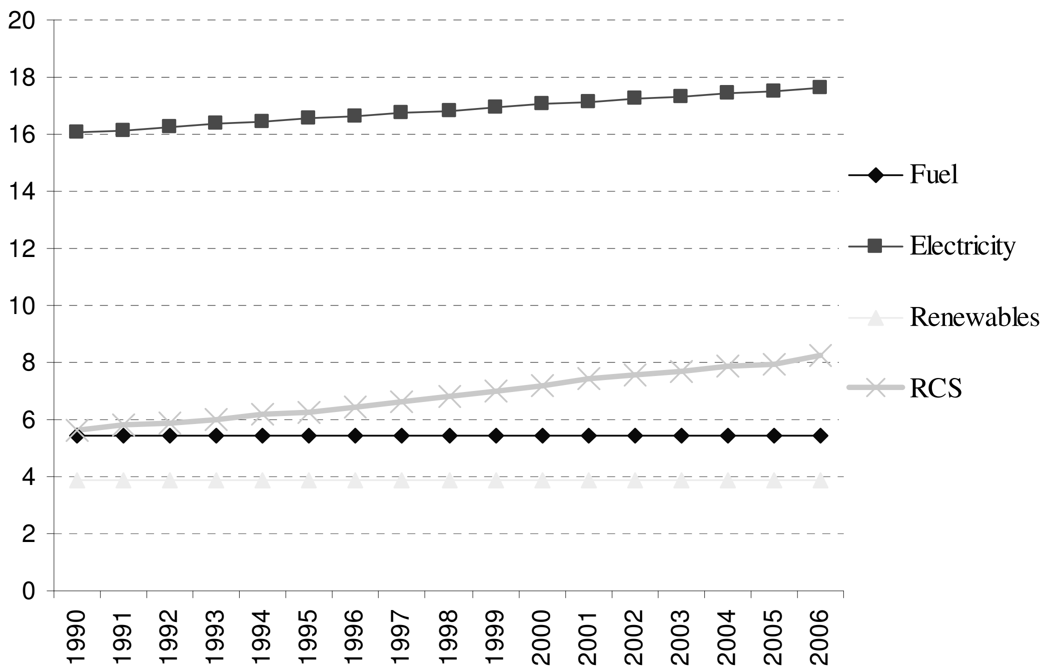


**Figure 17:** Exergy efficiencies in the Residential-Commercial Sector (%)

Using Equation (36), exergetic improvement potentials of residential-commercial sector are calculated and shown in Figure 18.

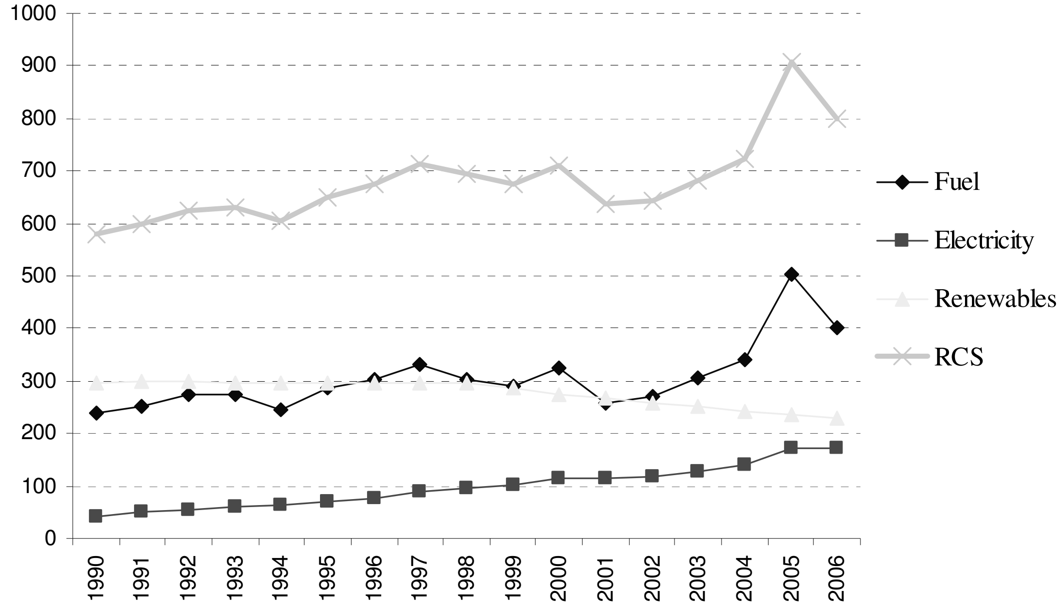


**Figure 18:** Exergetic improvement potentials of residential-commercial sector (PJ)

### 3.7 Overall End Use Energy and Exergy Efficiencies of Turkey

Overall efficiencies of the utility sector and net supply efficiencies are defined in Part 3.2. The overall efficiencies of end use sectors called industrial, transportation, commercial-residential and agricultural sectors are found here to understand the total picture on the final consumptions of energy carriers in Turkey.

To evaluate the overall end use consumptions and efficiencies, it is better to show all the inputs and outputs together to find the total inputs and outputs. The end use sectoral and total energy inputs and outputs are given in Tables 39 and 40.

**Table 39:** End Use Energy Inputs (PJ)

| Years | Industrial | Transportation | Agricultural | Residential-Commercial | Total |
|---|---|---|---|---|---|
| 1990 | 610.2 | 365.2 | 81.9 | 642.9 | 1700.1 |
| 1991 | 639.2 | 347.7 | 82.7 | 666.2 | 1735.7 |
| 1992 | 650.2 | 357.7 | 83.5 | 699.7 | 1791.0 |
| 1993 | 686.9 | 436.1 | 102.6 | 708.9 | 1934.5 |
| 1994 | 641.5 | 414.7 | 103.8 | 683.7 | 1843.7 |
| 1995 | 732.1 | 463.3 | 107.0 | 736.6 | 2038.9 |
| 1996 | 831.7 | 493.0 | 113.6 | 773.0 | 2211.2 |
| 1997 | 909.7 | 474.6 | 118.2 | 824.8 | 2327.3 |
| 1998 | 897.8 | 450.5 | 118.3 | 807.0 | 2273.6 |
| 1999 | 827.3 | 475.2 | 122.4 | 794.4 | 2219.2 |
| 2000 | 986.6 | 502.6 | 128.6 | 839.6 | 2457.5 |
| 2001 | 914.3 | 502.4 | 124.1 | 758.6 | 2299.3 |
| 2002 | 1015.2 | 477.4 | 126.8 | 772.9 | 2392.3 |
| 2003 | 1116.0 | 518.9 | 129.2 | 821.9 | 2586.0 |
| 2004 | 1205.1 | 576.6 | 138.7 | 877.1 | 2797.6 |
| 2005 | 1196.0 | 574.8 | 140.6 | 1103.9 | 3015.3 |
| 2006 | 1297.0 | 623.1 | 151.1 | 993.2 | 3064.3 |

As seen from Table 39, the most of the end use consumption has been performed by industrial sector since 1996. Before, the Residential-Commercial sector consumed the most of the energy. Industrial consumption increased 113%, whereas Residential-Commercial increased 55% between 1990 and 2006. On the other hand, the Transportation and the Agricultural consumptions increased 71% and 85% respectively.

By adding all the outputs of the four sectors and dividing the results into the inputs, the overall and use energy efficiencies are calculated and tabulated below and graphed on Figure 19 together with the beforehand calculated sectoral efficiencies.

**Table 40:** Energy End Use Efficiencies (%)

| | Industrial | Transportation | Agricultural | Residential-Commercial | Overall End Use |
|---|---|---|---|---|---|
| 1990 | 60.0 | 22.3 | 23.7 | 53.5 | 47.7 |
| 1991 | 59.8 | 22.3 | 24.1 | 53.7 | 48.2 |
| 1992 | 60.3 | 22.3 | 24.5 | 53.7 | 48.4 |
| 1993 | 60.6 | 22.3 | 24.4 | 53.8 | 47.6 |
| 1994 | 60.5 | 22.4 | 24.8 | 54.1 | 47.5 |
| 1995 | 60.8 | 22.5 | 25.5 | 54.0 | 47.8 |
| 1996 | 60.7 | 22.5 | 25.9 | 54.2 | 48.1 |
| 1997 | 61.4 | 22.6 | 26.2 | 54.3 | 49.2 |
| 1998 | 61.9 | 22.6 | 26.9 | 54.6 | 49.7 |
| 1999 | 61.9 | 22.5 | 27.3 | 54.8 | 49.0 |
| 2000 | 61.9 | 22.5 | 27.8 | 54.9 | 49.7 |
| 2001 | 65.7 | 22.5 | 28.3 | 55.3 | 50.8 |
| 2002 | 63.3 | 22.2 | 28.7 | 55.4 | 50.7 |
| 2003 | 62.0 | 22.4 | 28.9 | 55.4 | 50.3 |
| 2004 | 61.8 | 22.6 | 28.9 | 55.5 | 50.1 |
| 2005 | 65.8 | 22.5 | 29.2 | 55.4 | 52.0 |
| 2006 | 62.4 | 22.5 | 29.2 | 55.8 | 50.5 |

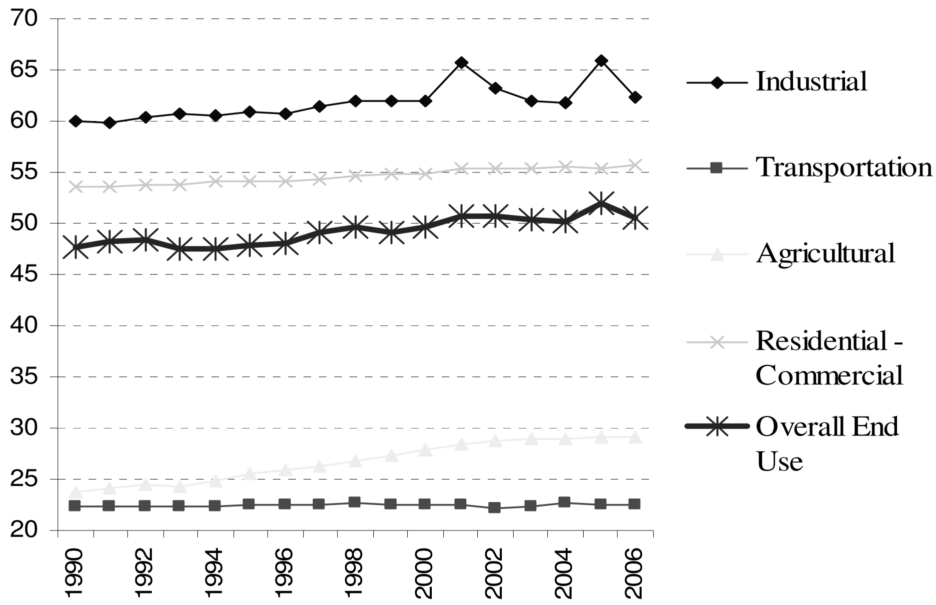


**Figure 19:** Energy End Use Efficiencies (%)

Energy end use efficiencies do not change significantly between 1990 and 2006. Therefore, energy efficiencies do not give significant idea about the improvements, as expected. To understand the improvements better, the exergy efficiencies and improvement potentials should be calculated. Therefore, the overall end use exergy efficiencies are calculated and tabulated below and graphed on Figure 20 together with the beforehand calculated sectoral efficiencies.

**Table 41:** End Use Exergy Efficiencies (%)

| | Industrial | Transportation | Agricultural | Residential-Commercial | Overall End Use |
|---|---|---|---|---|---|
| 1990 | 33.7 | 22.5 | 24.0 | 5.6 | 20.2 |
| 1991 | 32.8 | 22.5 | 24.3 | 5.8 | 20.0 |
| 1992 | 33.3 | 22.5 | 24.8 | 5.9 | 20.0 |
| 1993 | 33.1 | 22.5 | 24.6 | 6.0 | 20.3 |
| 1994 | 34.3 | 22.6 | 25.1 | 6.2 | 20.7 |
| 1995 | 33.5 | 22.7 | 25.7 | 6.2 | 20.8 |
| 1996 | 32.5 | 22.8 | 26.2 | 6.4 | 20.9 |
| 1997 | 31.9 | 22.8 | 26.4 | 6.6 | 20.9 |
| 1998 | 32.1 | 22.9 | 27.1 | 6.8 | 21.1 |

**Table 41 (Continued)**

| | | | | | |
|---|---|---|---|---|---|
| 1999 | 33.6 | 22.8 | 27.5 | 7.0 | 21.5 |
| 2000 | 31.3 | 22.8 | 28.1 | 7.2 | 21.2 |
| 2001 | 34.7 | 22.8 | 28.6 | 7.4 | 23.1 |
| 2002 | 30.8 | 22.4 | 29.0 | 7.6 | 21.7 |
| 2003 | 30.2 | 22.6 | 29.2 | 7.7 | 21.6 |
| 2004 | 31.9 | 22.9 | 29.1 | 7.9 | 22.3 |
| 2005 | 32.2 | 22.7 | 29.4 | 7.9 | 21.3 |
| 2006 | 31.9 | 22.7 | 29.5 | 8.3 | 22.2 |

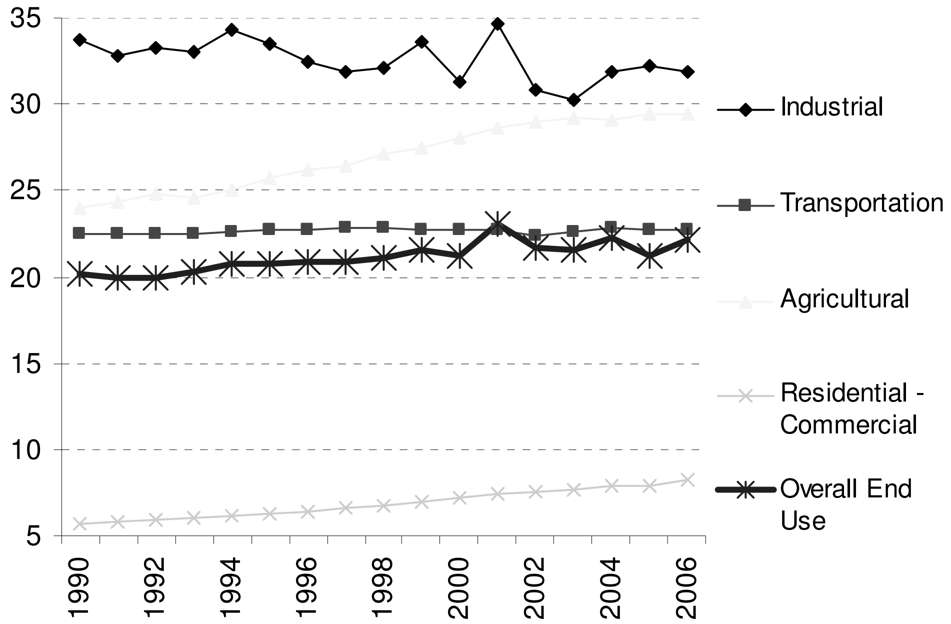


**Figure 20:** End Use Exergy Efficiencies (%)

When compared with efficiencies of the other sectors and its own energy efficiency, the exergy efficiency of the Residential-Commercial sector is the poorest one. This is expected because low quality processes like space heating and water heating are performed mostly by high quality fossil fuels in Turkey.

To see the exergetic improvement potentials of the end use sectors directly, it is better to calculate using Equation (36) and draw on figure as done below.

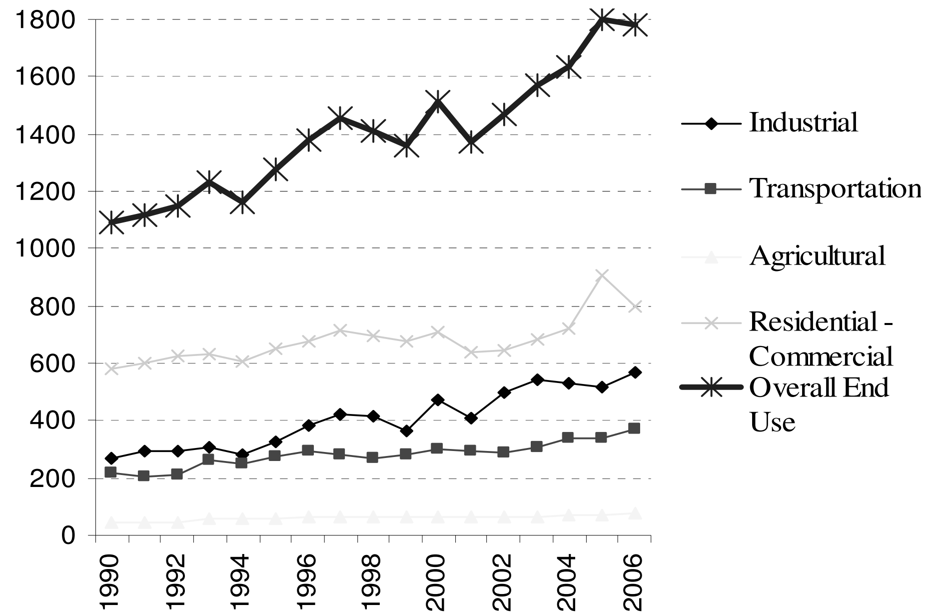


**Figure 21:** Exergetic Improvement Potentials of End Use Sectors (PJ)

The Figure 21 makes easier to compare the necessary improvements for the end use sectors. Having the lowest exergy efficiencies, as stated above, Residential-Commercial sector has the highest exergetic improvement potential. Although Residential-Commercial sector consumes about equal or less energy in the years examined, because of the very low exergy efficiency values, its improvement potential becomes nearly 2 times the improvement potential of the industrial sector in most years.

The industrial sector has the second most improvement potential, due to low temperature heating applications made by electricity or fossil fuels in some subsectors. The low temperature heating applications is not common in the industrial sector. This is why, despite having the highest consumption the industrial sector has less improvement potential with respect to Residential-Commercial sector.

## 3.8 Overall Energy and Exergy Efficiencies of Turkey

Since the end use sectors use the electricity produced by the utility sector, when the total inputs of the end use sectors are added with the losses in the utility sector including all losses up to end users, the overall input is found if there is no import and export. By subtracting the export values (or adding the import values), which are found by the difference between the produced electricity minus the electricity inputs of the end use sectors to match the results, the overall energy input values of Turkey are found. Likewise exergy input values can also be found. By subtracting net supply efficiencies (given in Table 8) from one and multiplying the results with the energy inputs to the utility sector, total losses in the utility sector up to end users are found.

To understand the procedure better, let's show the related data on a figure with letters corresponding to each data and show the procedure with the letters.

**Table 42:** Overal Input calculation data (PJ)

| Years | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| | End Use Energy Inputs | End Use Exergy Inputs | Utility Energy Loss | Utility Exergy Loss | Utility Net Electricity Supply | End Use Electricty Inputs |
| 1990 | 1700.1 | 1709.1 | 294.9 | 290.4 | 167.1 | 164.3 |
| 1991 | 1735.7 | 1744.2 | 318.7 | 314.7 | 171.3 | 172.0 |
| 1992 | 1791.0 | 1795.9 | 370.4 | 368.7 | 189.3 | 188.7 |
| 1993 | 1934.5 | 1935.7 | 363.6 | 360.8 | 208.6 | 207.1 |
| 1994 | 1843.7 | 1843.2 | 413.0 | 411.0 | 216.9 | 214.9 |
| 1995 | 2038.9 | 2035.2 | 436.8 | 432.1 | 238.3 | 236.4 |
| 1996 | 2211.2 | 2204.1 | 479.4 | 475.6 | 261.2 | 260.7 |
| 1997 | 2327.3 | 2319.1 | 537.7 | 533.2 | 279.7 | 295.7 |
| 1998 | 2273.6 | 2263.6 | 603.2 | 596.9 | 297.3 | 316.1 |
| 1999 | 2219.2 | 2205.3 | 645.8 | 633.6 | 314.3 | 329.7 |
| 2000 | 2457.5 | 2443.3 | 731.4 | 713.5 | 334.0 | 354.1 |
| 2001 | 2299.3 | 2315.0 | 753.2 | 731.1 | 328.6 | 401.8 |
| 2002 | 2392.3 | 2397.5 | 717.6 | 690.2 | 353.3 | 363.1 |
| 2003 | 2586.0 | 2557.5 | 698.8 | 667.7 | 396.6 | 390.4 |
| 2004 | 2797.6 | 2698.9 | 725.3 | 692.9 | 435.5 | 433.1 |
| 2005 | 3015.3 | 2899.0 | 775.0 | 736.4 | 470.1 | 490.6 |
| 2006 | 3064.3 | 2942.3 | 859.6 | 820.9 | 518.0 | 512.0 |

Overall Energy Input = A + C – (E –F)

Overall Exergy Input = B + D – (E –F)

Since the end use output values are also the overall output values, the resulting input values are tabulated with the output values together with the accordingly computed the efficiencies.

**Table 43:** Overall Energy and Exergy Inputs, Outputs and Efficiencies of Turkey

| Years | Energy Inputs (PJ) | Exergy Inputs (PJ) | Energy Outputs (PJ) | Exergy Outputs (PJ) | η (%) | ψ (%) |
|---|---|---|---|---|---|---|
| 1990 | 1992.2 | 2001.2 | 810.4 | 344.7 | 40.7 | 17.2 |
| 1991 | 2055.2 | 2063.6 | 836.9 | 347.9 | 40.7 | 16.9 |
| 1992 | 2160.9 | 2165.7 | 867.6 | 359.0 | 40.2 | 16.6 |
| 1993 | 2296.6 | 2297.8 | 920.3 | 393.0 | 40.1 | 17.1 |
| 1994 | 2254.6 | 2254.1 | 875.9 | 381.8 | 38.9 | 16.9 |
| 1995 | 2473.8 | 2470.1 | 974.6 | 422.8 | 39.4 | 17.1 |
| 1996 | 2690.1 | 2683.0 | 1063.9 | 460.6 | 39.6 | 17.2 |
| 1997 | 2881.0 | 2872.9 | 1144.9 | 483.5 | 39.7 | 16.8 |
| 1998 | 2895.7 | 2885.6 | 1129.7 | 477.7 | 39.0 | 16.6 |
| 1999 | 2880.4 | 2866.4 | 1088.2 | 474.4 | 37.8 | 16.6 |
| 2000 | 3209.0 | 3194.8 | 1221.1 | 518.9 | 38.1 | 16.2 |
| 2001 | 3125.6 | 3141.3 | 1168.0 | 534.1 | 37.4 | 17.0 |
| 2002 | 3119.7 | 3124.9 | 1212.7 | 521.1 | 38.9 | 16.7 |
| 2003 | 3278.5 | 3250.1 | 1300.9 | 552.7 | 39.7 | 17.0 |
| 2004 | 3520.5 | 3421.8 | 1402.3 | 600.4 | 39.8 | 17.6 |
| 2005 | 3810.8 | 3694.5 | 1568.7 | 616.3 | 41.2 | 16.7 |
| 2006 | 3917.9 | 3795.9 | 1547.6 | 653.1 | 39.5 | 17.2 |

Overall efficiencies are expected to decrease with respect to decrease with respect to end use efficiencies, since the outputs are the same but overall inputs are higher.

To understand the overall efficiency picture of Turkey, let's show all the energy and exergy efficiencies together as tabulated in tables below.

**Table 44:** Sectoral and Overall Energy Efficiencies of Turkey (%)

| | Industrial | Transportation | Agricultural | Residential - Commercial | Utility | Utility & supply | Turkey |
|---|---|---|---|---|---|---|---|
| 1990 | 60.0 | 22.3 | 23.7 | 53.5 | 44.9 | 36.2 | 40.7 |
| 1991 | 59.8 | 22.3 | 24.1 | 53.7 | 44.3 | 35.0 | 40.7 |
| 1992 | 60.3 | 22.3 | 24.5 | 53.7 | 43.3 | 33.8 | 40.2 |
| 1993 | 60.6 | 22.3 | 24.4 | 53.8 | 46.4 | 36.5 | 40.1 |
| 1994 | 60.5 | 22.4 | 24.8 | 54.1 | 44.8 | 34.4 | 38.9 |
| 1995 | 60.8 | 22.5 | 25.5 | 54.0 | 45.9 | 35.3 | 39.4 |
| 1996 | 60.7 | 22.5 | 25.9 | 54.2 | 46.1 | 35.3 | 39.6 |
| 1997 | 61.4 | 22.6 | 26.2 | 54.3 | 45.5 | 34.2 | 39.7 |
| 1998 | 61.9 | 22.6 | 26.9 | 54.6 | 44.4 | 33.0 | 39.0 |
| 1999 | 61.9 | 22.5 | 27.3 | 54.8 | 43.7 | 32.7 | 37.8 |
| 2000 | 61.9 | 22.5 | 27.8 | 54.9 | 42.2 | 31.4 | 38.1 |
| 2001 | 65.7 | 22.5 | 28.3 | 55.3 | 40.8 | 30.4 | 37.4 |
| 2002 | 63.3 | 22.2 | 28.7 | 55.4 | 43.5 | 33.0 | 38.9 |
| 2003 | 62.0 | 22.4 | 28.9 | 55.4 | 46.2 | 36.2 | 39.7 |
| 2004 | 61.8 | 22.6 | 28.9 | 55.5 | 46.7 | 37.5 | 39.8 |
| 2005 | 65.8 | 22.5 | 29.2 | 55.4 | 46.8 | 37.8 | 41.2 |
| 2006 | 62.4 | 22.5 | 29.2 | 55.8 | 46.1 | 37.6 | 39.5 |

**Table 45:** Sectoral and Overall Exergy Efficiencies of Turkey (%)

| | Industrial | Transportation | Agricultural | Residential - Commercial | Utility | Utility & supply | Turkey |
|---|---|---|---|---|---|---|---|
| 1990 | 33.7 | 22.5 | 24.0 | 5.6 | 45.3 | 36.5 | 17.2 |
| 1991 | 32.8 | 22.5 | 24.3 | 5.8 | 44.6 | 35.3 | 16.9 |
| 1992 | 33.3 | 22.5 | 24.8 | 5.9 | 43.4 | 33.9 | 16.6 |
| 1993 | 33.1 | 22.5 | 24.6 | 6.0 | 46.7 | 36.6 | 17.1 |
| 1994 | 34.3 | 22.6 | 25.1 | 6.2 | 44.9 | 34.6 | 16.9 |
| 1995 | 33.5 | 22.7 | 25.7 | 6.2 | 46.2 | 35.6 | 17.1 |

**Table 45** (Continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1996 | 32.5 | 22.8 | 26.2 | 6.4 | 46.4 | 35.5 | 17.2 |
| 1997 | 31.9 | 22.8 | 26.4 | 6.6 | 45.8 | 34.4 | 16.8 |
| 1998 | 32.1 | 22.9 | 27.1 | 6.8 | 44.7 | 33.3 | 16.6 |
| 1999 | 33.6 | 22.8 | 27.5 | 7.0 | 44.2 | 33.2 | 16.6 |
| 2000 | 31.3 | 22.8 | 28.1 | 7.2 | 42.9 | 31.9 | 16.2 |
| 2001 | 34.7 | 22.8 | 28.6 | 7.4 | 41.7 | 31.0 | 17.0 |
| 2002 | 30.8 | 22.4 | 29.0 | 7.6 | 44.6 | 33.9 | 16.7 |
| 2003 | 30.2 | 22.6 | 29.2 | 7.7 | 47.6 | 37.3 | 17.0 |
| 2004 | 31.9 | 22.9 | 29.1 | 7.9 | 48.1 | 38.6 | 17.6 |
| 2005 | 32.2 | 22.7 | 29.4 | 7.9 | 48.3 | 39.0 | 16.7 |
| 2006 | 31.9 | 22.7 | 29.5 | 8.3 | 47.4 | 38.7 | 17.2 |

In order to see the exergetic improvement potentials of all sectors with the overall potential of Turkey, it is better to calculate the overall exergetic improvement potential using Equation (36) and draw on figure with all sectoral improvement potentials. In addition the exergetic improvement potentials of the utility sector with supply losses are shown according to the net supply exergy efficiencies.

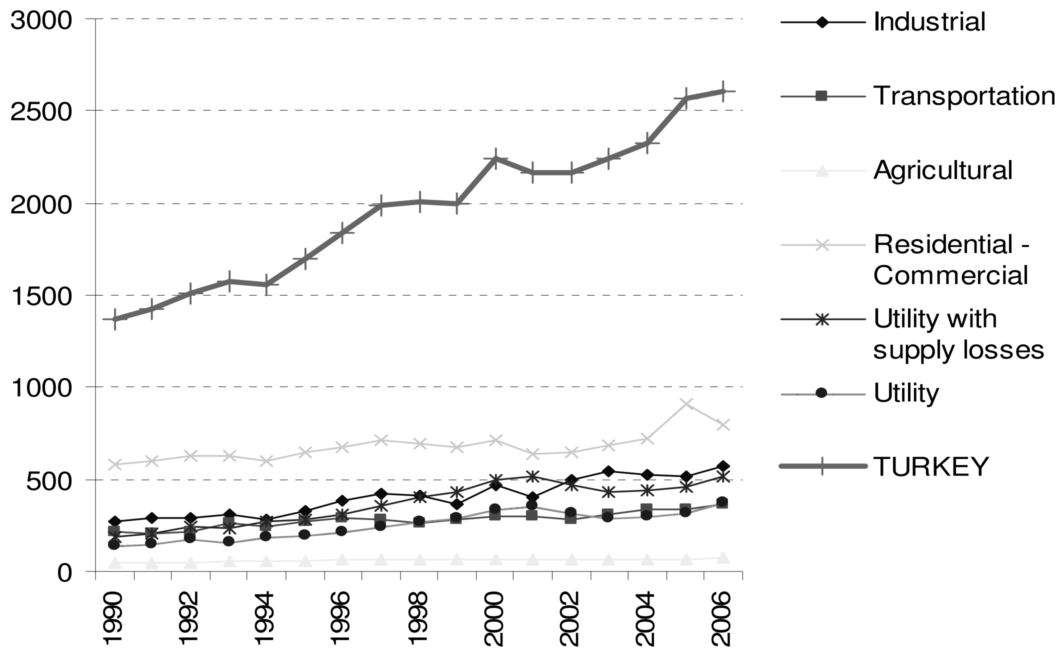


**Figure 22:** Sectoral and Overall Exergetic Improvement Potentials of Turkey (PJ)

Although the utility sector itself has the lowest exergetic improvement potential in the average, together with the very high supply losses after generation it has second highest improvement potentials in some years.

Primarily because of its lowest exergy efficiencies, Residential-Commercial sector has the highest exegetic improvement potential within all the sectors.

# CHAPTER 4

# CONCLUSIONS AND RECOMENDATIONS

The energy and exergy analysis of a country is a very a sophisticated process, especially because of the lack of the information and mismatches within the information which should cover all the country. To overcome the lack of the information, a lot of estimations have been made using the literature. With the reasonable assumptions made during the study, the following sectoral conclusions have been found.

Although the efficiencies of lignite power plants are very low between 1990 and 2006, overall energy and exergy efficiencies of utility sector becomes nearly the same which is thought to be because of the increase in the operations of the high efficient gas power plants and the rise of the efficiencies of coal power plants. The efficiency increase of coal power plants is expected because of the privatization of the state owned plants and private enterprises have been made in coal power plants since 1990s. So that the privatization of lignite power plants should also put into force to overcome their low efficiencies which affect the utility sector a lot. In addition, net supply efficiencies of this sector are very low because of the very high transmission and other losses which must be put in order by the government.

Although most of experts say that hydraulic power plants have around 100% efficiencies in Turkey, the plants in Turkey have around 88% efficiencies because of the inefficiency of both turbines and generators. EUAŞ has started for the rehabilitations on turbines [56], but low efficiency generators should also be handled.

The industrial sector of Turkey is composed of many subsectors. However, there is information about only 7 sectors, namely iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, and non-metal industry. The other sectors are modeled as the Other Industry which consumes less individual energy with low temperatures but most in total. Therefore, the highest improvement is expected to be made in the Other Industry by the utilization of low quality energy carriers (like geothermal energy) for low temperature works.  If the Other Industry could be classified into subsectors according to their fuel and electricity consumptions, this study would be more beneficial to understand the other subsectoral exergetic improvement potentials as well.

The Transportation and the Agricultural sectors are very similar in energy consumption, because of the high oil use and low electricity use in both sectors. However, because of the dominance of oil in transportation, the efficiency of the Transportation sector does not change significantly. On the other hand, with the increase of electricity use for irrigation, the efficiency of energy and exergy consumption increases in the Agricultural Sector.

The Residential-Commercial Sector (RCS) in Turkey shows the difference between energy and exergy analysis very significantly. Because of the high quality fossil fuel utilization for the low temperature processes like water and space heating which constitute 80% of fuel consumption in the sector, the exergy efficiencies of the RCS are around 6% to 8 % between 1990 and 2006, whereas the energy efficiencies of this sector are about %55 percent within the examined years. So that, the RCS has the highest exergetic improvement potentials and the lowest efficiencies in all the years with respect to other sectors. The low efficiency of this sector also decreases the exergy efficiency of the overall end use sectors mentioned above.

In order to increase the efficiencies of both Residential-Commercial Sector and the overall end use sectors, geothermal heating must be used widespread for low temperature processes like water and space heating, because it has the highest exergy efficiencies for water and space heating as calculated in parts 3.6.1.2 and 3.6.1.3.

The efficiencies of several countries together with Turkey are given below for further discussions with the present study.

**Table 46:** Efficiencies of Countries (%) [10]

| Countries | Year analyzed | Investigators | Approach used | Total energy efficiency | Total exergy efficiency |
|---|---|---|---|---|---|
| Sweden | 1920 | Wall [11] | Wall's | | 25 |
| Ghana | 1975 | Wall [12] | Wall's | | 28 |
| Sweden | 1980 | Wall [13] | Wall's | | 22 |
| Japan | 1985 | Wall [14] | Wall's | | 19 |
| Italy | 1990 | Wall et al. [15] | Wall's | | 17 |
| Sweden | 1994 | Wall [16] | Wall's | | 17 |
| Norway | 1995 | Ertesvag & Mielnik [17] | Wall's | | 24 |
| USA | 1970 | Reistad [5] | Reistad's | 50 | 21 |
| Finland | 1985 | Wall [12] | Reistad's | | 13 |
| Canada | 1986 | Rosen [18] | Reistad's | 50 | 24 |
| Brazil | 1987 | Schaeffer&Wirtschafter[19] | Reistad's | 32 | 24 |
| OECD | 1990 | Nakicenovic et al. [20] | Reistad's | | 12 |
| World | 1990 | Nakicenovic et al. [20] | Reistad's | | 10 |
| Non-OECD | 1990 | Nakicenovic et al. [20] | Reistad's | | 9 |
| S. Arabia | 1990-2001 | Dincer et al. [7,21-24] | Reistad's | 43-60 | 26-39 |
| UK | 1965-1997 | Hammond & Stapleton [25] | Reistad's | 69-71 | 18-25 |
| Turkey | 1991 | Unal [26] | Reistad's | 45 | 24 |
| Turkey | 1993 | Rosen and Dincer [27] | Reistad's | 41 | 27 |
| Turkey | 1995 | İleri & Gürer [28 ] | Reistad's | 35 | 13 |
| Turkey | 1999 | Utlu & Hepbasli [29 ] | Reistad's | 43 | 24 |

**Table 46 (continued)**

| | | | | | |
|---|---|---|---|---|---|
| Turkey | 2000 | Utlu & Hepbasli [29] | Reistad's | 45 | 25 |
| Turkey | 2001 | Utlu & Hepbasli [ 30] | Reistad's | 45 | 25 |
| Turkey | 2023 | Utlu & Hepbasli [31] | Reistad's | 57 | 31 |
| Norway | 2000 | Ertesvag [9] | Sciubba's | 47 | 33 |
| Turkey | 1990-2006 | Present Study | Reistad's | 37 - 41 | 16 -17 |

In the other studies of Turkey are somewhat different from this study, because of the different assumptions are taken into account. For the calculations of overall energy and exergy, the method in this study is very similar to the İleri and Gürer's study [27]. Therefore, the energy efficiencies are similar. However exergy efficiencies of this study are higher than İleri and Gürer's study, which is thought to be because of the lower ambient temperature assumption of this study. There are also a lot of similarities between this study and Unal's study [26]. However, in the overall energy and exergy efficiency calculations, Unal's study takes the utility sector separately from the other sectors, which increases the overall efficiencies.

Despite different assumptions taken between the studies, when compared to the other countries, exergy efficiencies of Turkey are smaller with respect to most of the countries. However, they seem to be higher with respect to OECD, World and Non-OECD exergy efficiencies. Although the previous studies were mostly done for the years 1970s, 1980s and 1990s, most of the exergy efficiencies of them are higher than those of Turkey. This should encourage Turkey to make improvements on the efficient use of resources.

## APPENDIX A

## AVERAGE RAW DATA FOR ENERGY CARRIERS

**Table 47:** Average Values for Enthalpy, Chemical Exergy and Quality factor of energy carriers [7, 26,45,51]

| Energy carriers | Enthalpy (kJ/kg) | Chemical Exergy (kJ/kg) | Quality Factor (q) |
|---|---|---|---|
| Gasoline | 47849 | 47394 | 0.99 |
| Natural gas (KJ/m³) | 55448 | 51702 | 0.92 |
| Hard coal | 25552 | 26319 | 1.03 |
| Wood | 12252 | 12865 | 1.05 |
| Asphaltite | 17991 | 18531 | 1.03 |
| Lignite (For industry and household) | 12252 | 12742 | 1.04 |
| Lignite (For Electricity Generation) | 8368 | 8703 | 1.04 |
| Fuel oil | 47405 | 47101 | 0.99 |
| LPG (KJ/m³) | 45460 | 45005 | 0.99 |
| Other Petroleum by Products | 43932 | 43493 | 0.99 |
| Biowaste | 9623 | 10104 | 1.05 |
| Geothermal (Heat) | 36006 | 10442 | 0.29 |
| Solar | 36006 | 33486 | 0.93 |
| Electricity (KJ/KWh) | 3600 | 3600 | 1 |
| Mechanical energy | | | 1 |

## APPENDIX B

## HYDOELECTRIC POWER PLANTS

**Table 48:** Efficiencies and Electricity Generation Values for most of the State owned hydroelectric power plants [55,56]

| PLANT NAME | TURBINE EFFICIENCY (%) | GENERATOR EFFICIENCY (%) | ELECTRICITY GENERATION IN 2006 (MWh) |
|---|---|---|---|
| ADIGÜZEL | 93.5 | 85.0 | 67,718 |
| ALMUS | 86.0 | 90.0* | 93,086 |
| ALTINKAYA | 94.8 | 98.3 | 720,855 |
| ASLANTAŞ | 90.0 | 97.9 | 599,280 |
| ATATÜRK | 96.0 | 98.7 | 8,881,082 |
| BERKE | 93.9 | 98.8 | 1,591,879 |
| ÇAMLIGÖZE | 93.0 | 97.1 | 121,970 |
| ÇATALAN | 94.5 | 96.0 | 418,240 |
| DEMİRKÖPRÜ | 91.5 | 96.6 | 128,207 |
| DERBENT | 96.0 | 90.0 | 165,827 |
| DİCLE | 93.2 | 98.0 | 212,282 |
| GEZENDE | 91.0 | 98.5 | 404,421 |
| GÖKÇEKAYA | 94.5 | 98.1 | 407,153 |
| H.UĞURLU | 93.5 | 97.6 | 1,200,780 |
| HİRFANLI | 91.6 | 97.0 | 144,341 |

**Table 48 (continued)**

| | | | |
|---|---|---|---|
| KADINCIK | 88.8 | 98.0 | 353,245 |
| KAPULUKAYA | 91.2 | 96.4 | 93,880 |
| KARACAÖREN 1 | 94.0 | 98.5 | 82,961 |
| KARACAÖREN 2 | 93.8 | 96.8 | 126,545 |
| KARAKAYA | 94.5 | 98.8 | 8,597,681 |
| KARKAMIŞ | 95.2 | 95.0 * | 461,758 |
| KEBAN | 90.0 | 90.0 | 7,280,758 |
| KEMER | 92.5 | 98.0 | 68,907 |
| KESİKKÖPRÜ | 91.7 | 97.5 | 93,554 |
| KILIÇKAYA | 84.0 | 90.0 | 443,719 |
| KOÇKÖPRÜ | 68.0 | 68.0 | 443,719 |
| KÖKLÜCE | 94.0 | 84.1 | 417,900 |
| KRALKIZI | 95.0 | 98.5 | 118,695 |
| MANAVGAT | 90.0 | 98.4 | 151,275 |
| MENZELET | 90.0 | 90.0 | 485,121 |
| ÖZLÜCE | 95.0 | 98.5 | 582,882 |
| S. UĞURLU | 93.8 | 95.4 | 343,711 |
| SARIYAR | 85.0 | 87.0 | 290,515 |
| SEYHAN | 91.8 | 96.5 | 247,040 |
| SIR | 95.9 | 98.6 | 686,875 |
| ZERNEK (HOŞAP) | 58.0 | 58.0 | 8,461 |
| TOTAL GENERATION OF PLANTS : | | | 36,536,323 |
| TOTAL HYROELECTRICITY GENERATION : | | | 44,244,400 |

* Estimated from the efficiency of the plants having the same generator brand [55].

**Table 49:** Overall Plant and Turbine Efficiencies Calculated for most of the State Owned Hydroelectric Power Plants.

| PLANT NAME | OVERALL EFFICIENCY [a] (%) | HYDRAULIC ENERGY INPUT [b] (MWh) | TURBINE OUTPUT [c] (MWh) |
|---|---|---|---|
| ADIGÜZEL | 79.5 | 85,207 | 79,668 |
| ALMUS | 77.4 | 120,266 | 103,429 |
| ALTINKAYA | 93.2 | 773,625 | 733,396 |
| ASLANTAŞ | 88.1 | 680,289 | 612,260 |
| ATATÜRK | 94.8 | 9,364,112 | 8,993,005 |
| BERKE | 92.8 | 1,715,371 | 1,610,562 |
| ÇAMLIGÖZE | 90.3 | 135,040 | 125,587 |
| ÇATALAN | 90.7 | 461,023 | 435,667 |
| DEMİRKÖPRÜ | 88.4 | 145,049 | 132,719 |
| DERBENT | 86.4 | 191,929 | 184,252 |
| DİCLE | 91.3 | 232,419 | 216,614 |
| GEZENDE | 89.6 | 451,186 | 410,580 |
| GÖKÇEKAYA | 92.7 | 439,150 | 414,996 |
| H.UĞURLU | 91.3 | 1,315,837 | 1,230,307 |
| HİRFANLI | 88.9 | 162,451 | 148,805 |
| KADINCIK | 87.0 | 405,924 | 360,454 |
| KAPULUKAYA | 87.9 | 106,783 | 97,386 |
| KARACAÖREN 1 | 92.6 | 89,600 | 84,224 |
| KARACAÖREN 2 | 90.8 | 139,444 | 130,728 |
| KARAKAYA | 93.3 | 9,210,443 | 8,703,868 |
| KARKAMIŞ | 90.4 | 510,568 | 486,061 |
| KEBAN | 81.0 | 8,988,590 | 8,089,731 |
| KEMER | 90.7 | 76,014 | 70,313 |
| KESİKKÖPRÜ | 89.4 | 104,638 | 95,953 |

**Table 49 (continued)**

| | | | |
|---|---|---|---|
| KILIÇKAYA | 75.6 | 586,930 | 493,021 |
| KOÇKÖPRÜ | 46.2 | 959,600 | 652,528 |
| KÖKLÜCE | 79.1 | 528,500 | 496,790 |
| KRALKIZI | 93.6 | 126,845 | 120,503 |
| MANAVGAT | 88.6 | 170,816 | 153,735 |
| MENZELET | 81.0 | 598,915 | 539,023 |
| ÖZLÜCE | 93.6 | 622,904 | 591,758 |
| S. UĞURLU | 89.5 | 384,098 | 360,284 |
| SARIYAR | 74.0 | 392,853 | 333,925 |
| SEYHAN | 88.6 | 278,856 | 255,993 |
| SIR | 94.6 | 726,411 | 696,628 |
| ZERNEK (HOŞAP) | 33.6 | 25,152 | 14,588 |
| TOTAL | | 41,306,835 | 38,259,343 |
| AVERAGE OVERALL EFFICIENCY [d]: | | 88.5% | |
| AVERAGE TURBINE EFFICIENCY [e]: | | 92.6% | |

Notes;

a; Overall efficiencies are calculated by multiplying the generator efficiencies with the turbine efficiencies.

b; Hydraulic energy inputs are calculated by dividing electricity generated into the overall efficiencies.

c; Turbine outputs are calculated by multiplying turbine inputs (hydraulic energy inputs) with the turbine efficiencies.

d; Average efficiency of a power plant is found by dividing the total electricity produced, into the total hydraulic energy input.

e; Average turbine efficiency of a power plant is found by dividing total turbine output, into the total turbine input (hydraulic energy input).

## APPENDIX C

## PROOF OF BETZ'S LAW [60]

Assume; there is a higher pressure right upstream the turbine ($p_b$) than the surrounding atmospheric pressure and a lower pressure right downstream the turbine ($p_a$) than the surrounding atmospheric pressure,

Since the velocity is theoretically the same both upstream and downstream the turbine, the energy potential lies in the differential pressure. The cross sections 1 and 2 are so far away from the turbine that the pressures are the same.

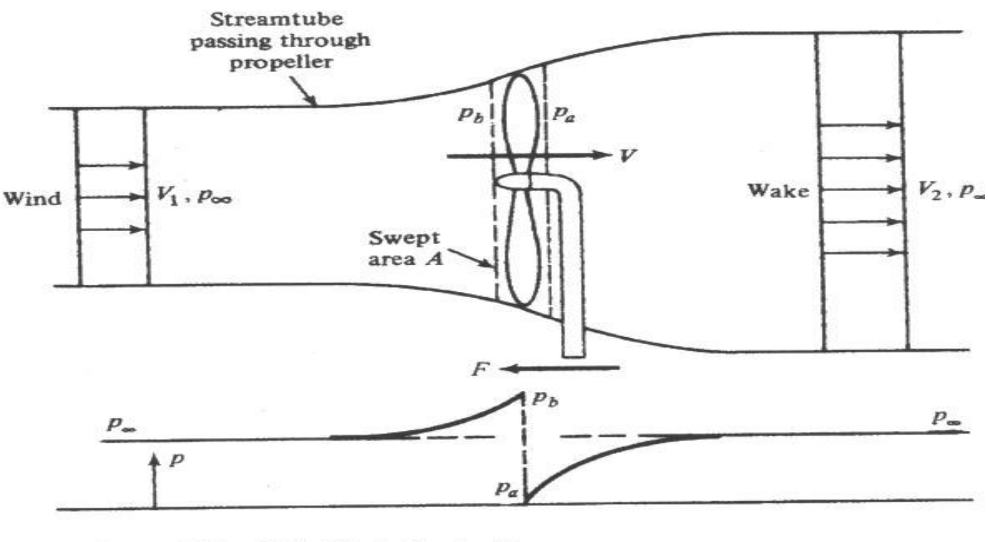


**Figure 23 :** Illustration of a wind turbine.

Continuity : $V_1 \cdot A_1 = V_2 \cdot A_2 = V \cdot A$

Balance of forces: $\rho \cdot V_1 \cdot A_1 \cdot V_1 - (p_b - p_a) \cdot A = \rho \cdot V_2 \cdot A_2 \cdot V_2$

Energy flux: $P_{turbine} = \frac{1}{2} \cdot \rho \cdot V_1^2 \cdot V_1 \cdot A_1 - \frac{1}{2} \cdot \rho \cdot V_2^2 \cdot V_2 \cdot A_2 = V \cdot A \cdot (p_b - p_a)$

Substitute the pressure term; *$(p_b$-$p_a)$* from the equation for the balance of forces in to the equation for the energy flux, and at the same time use the continuity equation to change the area terms; $A_1$ and $A_2$ with $A$, the velocity V can be found as the average of the two velocities:

$$\frac{1}{2} \cdot \rho \cdot V_1^2 \cdot V_1 \cdot A_1 - \frac{1}{2} \cdot \rho \cdot V_2^2 \cdot V_2 \cdot A_2 = V \cdot \left(\rho \cdot V_1^2 \cdot A_1 - \rho \cdot V_2^2 \cdot A_2\right)$$

$$\Downarrow$$

$$\frac{1}{2} \cdot \rho \cdot V_1^2 \cdot V \cdot A - \frac{1}{2} \cdot \rho \cdot V_2^2 \cdot V \cdot A = \rho \cdot V^2 \cdot A \cdot (V_1 - V_2)$$

$$\Downarrow$$

$$\frac{1}{2} \cdot \left(V_1^2 - V_2^2\right) = V \cdot (V_1 - V_2)$$

$$\Downarrow$$

$$\frac{1}{2} \cdot \left(V_1^2 - V_2^2\right) = \frac{1}{2} \cdot (V_1 - V_2) \cdot (V_1 + V_2) = V \cdot (V_1 - V_2)$$

$$\Downarrow$$

$$V = \frac{V_1 + V_2}{2}$$

Define the efficiency, η:

$$\eta = \frac{\frac{1}{2} \cdot \rho \cdot V_1^2 \cdot V_1 \cdot A_1 - \frac{1}{2} \cdot \rho \cdot V_2^2 \cdot V_2 \cdot A_2}{\frac{1}{2} \cdot \rho \cdot V_1^2 \cdot V_1 \cdot A_1}$$

In the following, assume that the velocity $V_2$ can be expressed as $V_2 = a \cdot V_1$, where $a$ is a constant.

From continuity: $A_1 = V \cdot A/V_1 = 0{,}5 \cdot (1+a)$

$A_2 = V \cdot A/V_2 = 0{,}5 \cdot (1+a)/a$

Substitute the relations of $A_1$ and $A_2$ into the efficiency equation and simplify the equation:

$$\eta = \frac{(1+a) - a^2 \cdot (1+a)}{2} = \frac{\left(-a^3 - a^2 + a + 1\right)}{2}$$

Maximum efficiency:

$$\frac{\partial \eta}{\partial a} = 0 = \frac{\left(-3 \cdot a^2 - 2 \cdot a + 1\right)}{2}$$

$$\Downarrow$$

$$a = \frac{V_2}{V_1} = 1/3$$

$$\eta_{\max} = \frac{\left(-1/3^3 - 1/3^2 + 1/3 + 1\right)}{2} = \frac{1}{2}\left(-\frac{1}{27} - \frac{1}{9} + \frac{1}{3} + 1\right) = \frac{1}{2}\left(-\frac{1}{27} - \frac{3}{27} + \frac{9}{27} + \frac{27}{27}\right) = \frac{16}{27}$$

$$\eta_{\max} = 0{,}5926$$

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