

AN ABSTRACT OF THE THESIS OF

Mingyuan Zhang for the degree of Doctor of Philosophy
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With the rapid increase of the world energy demand and consumption, the method and techniques to analyze, improve and optimize energy conversion systems have to deal not only with direct fuel exergy (energy) consumption, but also with other resources, which have associated exergy consumptions, and with environmental impacts, such as global warming.

A general method for energy conversion system analysis is presented in this thesis. This method uses exergy as a measure to compare and analyze the natural resource consumption (both fuels and materials) and the global warming impact of different energy conversion systems for their life-time. The method, which adds the fuel production exergy and material exergy into consideration, allows more complete exergy analyses to be conducted. The global warming impact due to the chemical emissions and impact associated with direct exergy consumption (fuel consumption) as well as

system equipment materials consumption of the energy conversion system are considered together in this thesis.

Based on the concept of exergy, the Total Equivalent Resource Exergy (TERE), which includes both direct resource exergy consumption and resource exergy needed to recover the total equivalent global warming gases of the energy conversion system, is proposed in this thesis. TERE uses exergy as a criterion to compare the energy conversion systems and providing information of how effective a system is regarding the use of natural resources. The calculation of TERE values for the selected energy conversion systems indicates that the resource exergy and the environmental impact exergy are both substantial impacts and should be compared together. This concept of TERE can be used as the objective function for energy system design and optimization.

Analysis of Energy Conversion Systems, Including
Material and Global Warming aspects

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ANALYSIS OF ENERGY CONVERSION SYSTEMS, INCLUDING MATERIAL AND GLOBAL WARMING ASPECTS

CHAPTER 1.

INTRODUCTION

1.1 GENERAL

With the rapid growth in population and industrialization and the associated increase of the world energy demand and consumption, the development of techniques for designing efficient energy conversion systems continues to be a very important worldwide issue. In addition to the energy problem, which has not been solved, other issues which have had a strong impact in the last few years are the scarcity of other natural resources (e.g., materials) and environmental damage.

Figure 1.1 shows the primary energy consumption in the world from 1950 to 1980. During these 30 years, the world primary energy consumption grew from 73.25 MTJ ($73.25 \times 10^{18} \text{ J}$) to 287.2 MTJ (M. Grathwohl, 1982), an increase of four times. Around the year 2000, the world primary energy consumption is expected to be from 439.5 MTJ to 559.6 MTJ. Figure 1.2 gives the 1991 global primary energy consumption by different sources (British Petroleum, 1992). It can be seen that over 90 percent of the world consumption of primary energy comes from fossil fuels such as oil (40.2%),

coal (28%), and natural gas (22.7%). Since fossil fuels represent a nonrenewable source of energy, it is important to ask: "what are the remaining amounts of fossil fuels and how long will they last?" At the rates the above three fossil fuels were used in 1991, British Petroleum Company estimated that coal could last for 240 years, oil for 44 years and natural gas 55 years. We cannot be sure that these estimates are accurate; however within the last few decades

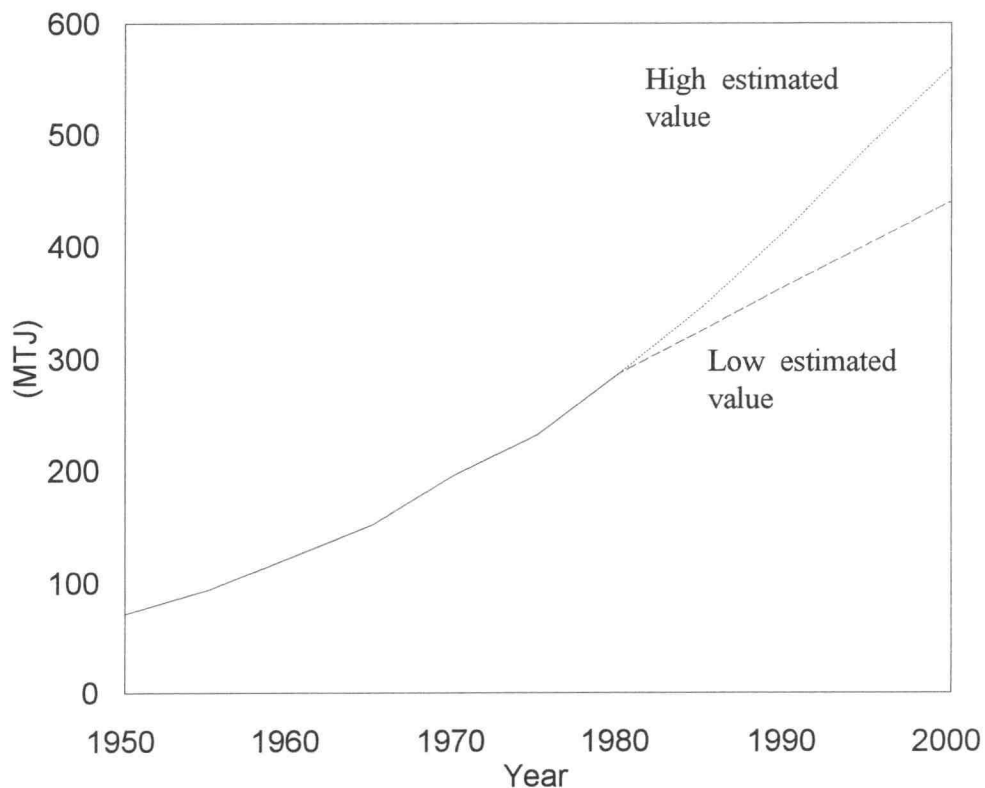


Figure 1.1 World primary energy consumption from 1950 to 1980 and the predicted primary energy demanded for 2000 (M. Grathwohl, 1982)

it appears that most people agree the nominal lifetime is a few hundred years at most. So, even though the estimates may not be precise, it is prudent to conclude that fossil fuels will become economically very restricted during the next century.

As with the fossil fuels, the consumption of the other natural resources (metals, timber, etc.) are also increasing rapidly. Since the 1940's, the production of aluminum has

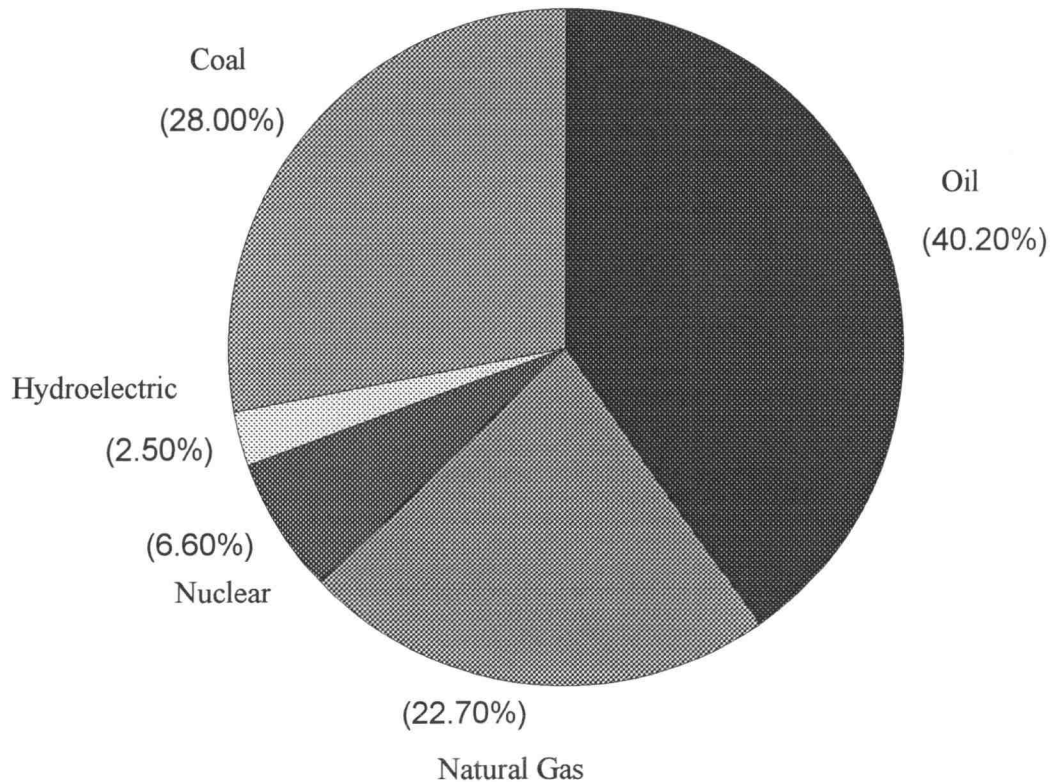


Figure 1.2 World primary energy consumption in 1991 by different sources (British Petroleum, 1992)

continued to grow 12% annually across the world. Even though we have not found any grounds for fearing that the world will "run out" of metals or timber, after years and years of mining the materials, it has caused the decline in the grade of ores for many materials. This decline of the ore's grade results in much more energy consumed in the mining and extraction of the useful materials from the ground. As much as 65% of total energy needed for producing copper is consumed in mining and concentrating processes (Frost, 1979).

The heavy consumption of the natural resources causes another serious problem, global warming. Since the advent of the Industrial Revolution, human activity has been contributing significant amounts of gases to the atmosphere. These gaseous emissions change the concentrations of certain gases in the atmosphere which in turn may influence the global climate. The predominant influence now appears to be global warming. Global warming, with the effects of lower rainfall, decreasing soil moisture, increasing sea level, etc., has been the subject of worldwide attention. Research has shown that the global temperature has increased by about 0.6°C over the last 100 years due to the change of concentrations of these gases. The gases which are emitted and contribute to global warming are termed greenhouse gases. The primary greenhouse gases in decreasing order of present influence are carbon dioxide (CO_2), chlorofluorocarbons (also known as CFCs), methane (CH_4) and nitrous

oxide(N_2O). Table 1.1 presents a summary of how concentrations of these key greenhouse gases have changed over the years and an estimate of their atmospheric lifetime. It is clear that some of these gases stay in the atmosphere for a very long time and that the concentrations have increased substantially over the past 200 years. Table 1.2 gives the relative contributions of these key greenhouse gases as presented by recent research efforts. As the figures indicate, CO_2 and CFCs contribute over 75% of the global warming contributions, with values of 55 percent and 24 percent respectively.

Table 1.1 Summary of key greenhouse gases influenced by human activities¹

	CO_2	CH_4	CFC-11	CFC-12	N_2O
Pre-industrial atmospheric concentration (1750-1800)	280 ppmv ²	0.8 ppmv	0	0	288 ppbv ²
Current atmospheric concentration (1990)	353 ppmv	1.72 ppmv	280 pptv ²	484 pptv	310 ppbv
Current rate of annual atmospheric accumulation	1.8 ppmv (0.5%)	0.015 ppmv (0.9%)	9.5 pptv (4%)	17 pptv (4%)	0.8 ppbv (0.25%)
Atmospheric lifetime (years)	(50-200)	10	65	130	150

1 Source: Houghton et al., 1990.

2 ppmv = parts per million by volume;
 ppbv = parts per billion by volume;
 pptv = parts per trillion by volume.

The human activity that principally contributes to the increase of the concentration of CO₂ in the atmosphere is the burning of fossil fuels. Whenever fossil fuels are burned, there are associated CO₂ emissions. For the world as a whole, the burning of fossil fuels produced about 22 billion tons of CO₂ emission in 1990. (Krause et al., 1990) Table 1.3 gives the emission rate of different fossil fuels on both unit mass and unit energy bases.

The CFCs have chlorine, fluorine and carbon atoms as part of their structure, and were invented in the early 1930s. Since then, they have become very useful chemical

Table 1.2 Relative global warming contribution of greenhouse gases (percent)

CO ₂	CFC-11 & CFC-12	Other CFCs	N ₂ O	CH ₄
55%	17%	7%	6%	15%

Source: Houghton et al., 1990.

Table 1.3 CO₂ emission associated with burning of fossil fuels¹

Fuel	CO ₂ emission (kg/kg fuel)	CO ₂ emission (kg/kJ fuel)
Coal	3.15	0.089
Natural gas	2.48	0.053
Oil	3.12	0.069

1: See Appendix B for detail.

compounds. They are used as working fluids in refrigeration and air conditioning, as cleaning agents in the metal working and electronics industries, and in many other uses. CFCs used as refrigerants have very desirable qualities: they are efficient, nonflammable, non-explosive, low in toxicity, odorless, and inexpensive. This makes them the backbone of the modern air conditioning and refrigeration equipment. The average annual growth rate in production of CFCs from 1960 through 1976 was 6.9 percent for the United States and 16.9 percent outside the United States. Table 1.4 shows the estimated world and the United States production of CFCs in 1973. From Table 1.1, it can be seen that the concentration of CFCs in the atmosphere is much less than that of CO_2 . However, since CFCs are much more potent for global warming, on a per molecule basis, than CO_2 and other trace gases, they play an important role in the total global warming impact. Because of the potential impact of CFCs on the ozone layer and global warming, in Sept. 1987, in Montreal, the United Nations Environment Program (UNEP) completed negotiations over a global protocol on limits for CFCs. Now, the challenge facing energy conversion system designers and producers is to develop the system with same or better efficiency but using less or no CFCs.

Therefore, methods and techniques to analyze, improve and optimize the energy conversion system have to deal not only with direct fuel exergy (energy) consumption, but also with other resources, which have associated exergy

consumptions, and with environmental impacts, such as global warming.

The second law of thermodynamics, through the exergy concept, is recognized as a very powerful tool for systematic study of efficiency, optimization and simulation of energy conversion systems. Exergy is specifically defined as the maximum work which can be obtained from the system. The exergy values of the fuel and material which also can be quantified in exergy are the physical value of resource. So, comparison of exergy consumption informs us about the thermodynamic imperfection of the utilization of the natural resources, and provides us with knowledge of how effective a system is regarding the utilization of natural resources. Exergy analysis also offers a theoretical measure of environmental impact. Since environmental impact results

Table 1.4 Estimated world and U.S. production and atmospheric emissions of CFCs in 1973¹

CFCs	World production (k tons)	U.S. production (k tons)	World emissions (k tons)	U.S. emissions (k tons)
CFC-11	930	150	700	140
CFC-12		220		170
CFC-22	120	60	60	28
Subtotal	1,050	430	760	338
Other CFCs	1,370	720	360	220
Total	2,420	1,150	1,120	558

1 Source: Cumberland, 1982.

from the aspect that a specific stream (pollutant) is out of balance (equilibrium) with the environment, and exergy is precisely a measure of the departure of a specific thermodynamic state from the dead state (environment), it appears that exergy may readily serve as an appropriate measure of environmental impact.

The work presented in this thesis focuses on the use of the exergy concept for the analysis of energy conversion systems, including material and selected global environment impacts. The global environmental impact which will be focused upon is global warming.

The following section will present a literature review on the main topics of interest in this thesis. The final section of this chapter gives a precise statement of the problems studied in this thesis.

1.2 LITERATURE REVIEW

This section presents a brief literature overview on the analysis of energy conversion systems, with emphasis on the research that addresses the CO₂ emissions associated with the fossil burning, energy consumption and the environmental impact of global warming from the energy conversion system, and/or studies on the energy consumption associated with material production.

Prior studies by Rotty (1979) and Marland and Rotty (1983) documented a procedure to estimate carbon dioxide

(CO₂) emission from fossil fuels. The method they used considers the carbon content and fraction oxidized for each fuel group. Using similar methods and combining the national fuel consumption for electricity generation and transportation, Fischer et al.(1991) and Yau et al.(1991) presented some results of CO₂ emission associated with electricity generation. San Martin (1989) also presented some results on CO₂ emission associated with electricity generation. The difference between his study and the others is that the total fuel consumption for the electricity production includes fuels for both electricity generation and the power plant construction.

Traditional analyses of energy conversion systems, both energy and exergy, have typically considered the direct primary fuel (coal, oil and natural gas) consumption as well as outputs at the system boundary. The recent study by Michael L'Ecuyer et al. (1993) is this kind of research. This study compared the primary energy consumption and CO₂ emission associated with primary energy consumption of several energy conversion systems (different types of heat pumps, electric heat resistance and oil and gas furnaces) for six locations in the U.S.. Since all comparisons of their study were based on direct primary fuel consumption, (for electricity, they considered the primary fuel used for electricity generation and transmission) their results show that the system which has high end-use efficiency will save energy and reduce the global environmental impact (global

warming impact due to CO₂ emission only). The CO₂ emission associated with the primary fuel consumption in their work is based on the EPA's (Environment Protection Agency, 1990) estimation.

Since the CO₂ emission associated with fossil fuel or electricity consumption is not the only source of environment impact of the energy conversion system, the concept of TEWI (Total Equivalent Warming Impact) was proposed by Fischer et al. (1991,1994). In these studies, they considered the total global warming impact of an energy conversion system to consist of two parts. One is the impact associated with fuel consumption, called indirect impact, and the other is the impact due to the refrigerant emission, called direct impact. The GWP (Global Warming Potential) value developed by Houghton et al. (1990) is used to convert the refrigerant emissions to equivalent CO₂ emissions. The direct and indirect global warming impacts of several different energy conversion systems (e.g. household refrigerators, commercial chillers, automobile air conditioning) were compared. Fischer's work was widely cited. Similar studies were done by Calm (1993), who used the concept of TEWI to analyze air conditioners and chillers; Turiel and Levine (1989) discussed the relations between energy efficiency and CFC emission of refrigerator and freezer; Steadman (1993), and Alefeld et al. (1993) analyzed the possible global warming impact of heat pump systems.

Boustead and Hancock (1979) attempted to analyze the industrial system by means of the method they called "process energy analysis". Using this method, the energy consumption of ancillary operations (that is those which do not contribute directly to the actual production process) and capital energy associated with the manufacture of the system itself are combined to result in a total production energy or gross energy requirement. In their study, several industrial systems and processes were analyzed as examples, and a table reporting energy required for several different fuels and materials was developed. The same kind of method was used by Chapman and Robert (1979), and Frost et al. (1979) for metal production.

Szargut et al. (1988,1990) proposed an analysis method of cumulative exergy consumption (CExC). Unlike the cumulative energy consumption (proposed by Boustead, 1979 and Chapman, 1983), cumulative exergy consumption is more informative as it takes into account the exergy of the non-fuel materials extracted from the environment. The analysis of CExC can be regarded as a further development of the industrial energy analysis considering cumulative energy consumption. This idea was used by Frangopoulos and Spakovsky (1991,1992,1993). They used methodologies method, which considered the cost of energy consumption, the material consumption and pollution, during their energy system analysis.

Considering the concept of material exergy, Aceves-Saborio, Ranasinghe and Reistad (1989) applied the irreversibility minimization analysis to the design and optimization of heat exchangers. The irreversibility minimization method they presented in their work, which adds an irreversibility term due to the material of construction of the heat exchanger in the overall irreversibility minimization equation for heat exchanger optimization, allows physically realistic optimization to be conducted. Exergetic efficiency expressions that similarly include an irreversibility term due to the material of construction of the heat exchanger show physically more realistic values than the usual expressions that do not include such a term.

The high energy consumption of the material industries has drawn increasing attention in recent years. Choosing materials which require less energy and are easy to be recycled has been a major concern in civil construction and automobile industries [(Fussler and Krummenacher, 1991) and (Ashby, 1992)].

1.3 PROBLEM STATEMENT

Most of the analyses on the energy conversion system summarized in the previous section concentrated on the direct energy (primary fuel) consumption of the system. Some analyses consider some of the environmental impacts of the system. However, the focus is still on the impact due to direct primary fuel consumption and the refrigerant

emission. Although the exergy (energy) consumed by material production is accepted and used in some studies, these studies have been restricted to the components of the system or the theoretical analysis. Therefore, a method which can evaluate both the total resource exergy consumption and the associated environment impact of the system is needed and specific analyses for different energy conversion systems should be conducted.

The purpose of this thesis is to search the general method which can be used to analyze, design and optimize energy conversion systems. The method will use exergy as a measure to compare the natural resources (both fuel and material) consumption and impact of different energy conversion systems. The objectives to be accomplished include:

- (a): Taking the material exergy consumption into consideration in the system analysis.
- (b): Using resource exergy instead of local chemical exergy of fuel and material in the analysis.
- (c): Considering both resource exergy consumption and the global environmental impact of global warming in the analysis.
- (d): Developing a method which combines both the resource exergy and global warming impact into a single criterion for evaluation of an energy system.
- (e): Analyzing and comparing different energy conversion systems with the method developed in (d).

(f): Discussing the possibility of the system materials including refrigerants recycling and associated exergy saving.

This thesis has seven chapters. Chapter 2 includes the basic exergy concept and exergy calculations for some species. The total resource exergy requirement for energy conversion systems will be discussed in Chapter 3. Chapter 4 presents the calculation of global warming impact, which includes both chemical emission and exergy related impact, and the development of the overall combined criterion for resource exergy and global warming impact. Chapter 5 presents the calculation and comparison of total resource exergy consumption, global warming impact and the combined criterion of the selected energy conversion systems for their lifetime. Chapter 6 considers material and refrigerant recycle and possible exergy savings. The conclusions and potential future work are presented in Chapter 7.

CHAPTER 2.

EXERGY: CONCEPT AND CALCULATION

2.1 INTRODUCTION

One of the main applications of engineering thermodynamics is the study of process (or system) efficiency. A traditional technique is the use of an energy balance on the system, usually to determine energy transfer between system and environment. This balance is based on the first law of thermodynamics, a conservation principle. Information within the balance is used in any attempt to reduce heat loss or enhance heat recovery. However, energy balances provide no information on the degradation of energy that occurs in the system, nor do they quantify the usefulness of the energy content in the various streams leaving the system as product or waste. An energy balance for an adiabatic system, such as a heat exchanger, could lead one to believe that these systems are free of losses of any kind. The exergy method of analysis overcomes these limitations of the first law of thermodynamics. The concept of exergy is based on the first and second laws. Its application indicates clearly the locations of energy degradation in a process that may lead to improved operation or technology. It is also believed that wider application of the exergy method of analysis can lead to substantially reduced rates in the use of natural resources and impacts on the environment. In this chapter, the concept of exergy and dead state will be discussed, the

method and equations for calculating physical and chemical exergy will be presented.

2.2 CONCEPT OF EXERGY

Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural environment (dead state) by means of reversible processes, involving interaction only with the above mentioned components (Szargut, 1988).

Thermodynamic equilibrium means thermal equilibrium, mechanical equilibrium, and chemical equilibrium. That is the temperature (T), pressure (P) and chemical potentials (μ_i) of the system are equal to the environment temperature (T_0), the pressure (P_0) and chemical potentials ($\mu_{0,i}$) respectively.

In order to calculate exergy, the environment (dead state) must be specified. It is important to distinguish between the environment and the system surroundings. The surroundings comprise everything not included in the system. The dead state is considered to be an environment that is in stable equilibrium and has associated with it a unique temperature (T_0), a unique pressure (P_0), and unique chemical potentials ($\mu_{0,i}$) for the components making it up. These values do not change as a result of any of the processes under consideration. All substances of interest should be formable from the substances making up the dead state. Since

the dead state serves as a reference state, when an absolute value of the exergy is required, the dead state and composition of the dead state must be defined and specified. For different dead states, there will be different results. As one example, consider the influence when calculating the efficiency of a system; let EX_{in} and EX_{out} be the exergies into and out of the system respectively. The system exergy efficiency may be expressed as:

$$\eta = EX_{out}/EX_{in}$$

For a constant difference $EX_{in} - EX_{out}$, the efficiency tends to become unity if the level of exergy is increased, and tends to zero if it is decreased. So selecting an appropriate dead state is important. There are many researchers who have contributed in this area [(Szargut et al., 1967,1988), (Reistad,1970), (Gaggioli and Petit, 1976), (Sussman, 1979) and (Ahrendts, 1980)]. Actually, there is no one specification of dead state that suffices for all applications. However for the general exergy calculation, there are no big differences for the results by using any of the primary dead states proposed by these researchers. In this work, the dead state proposed by Szargut et al. is used, since it is most convenient and well accepted. Szargut et al.(1988) gave three rules for the choice of dead states for calculating exergy values of open systems:

- (1) As reference species for the calculation of exergy, the common components of the environment should be adopted.

- (2) The mean parameters of the conventionally adopted common components of the environment, in the location under consideration (ambient temperature, partial pressure in the air, or the concentration in seawater or in external layer of the earth's crust) should be taken as the zero level for the calculation of chemical exergy.
- (3) If an exact calculation of the chemical exergy of a particular element is impossible because of the lack of sufficiently exact thermal data, the calculation should be made with currently available data and the result should be accepted as a conventional standard value of the chemical exergy of the element under consideration.

Based on these rules, they proposed the following dead states:

- (1) For substances including: O_2 , N_2 , CO_2 , H_2O , D_2O , Ar, He, Ne, Kr, Xe, a gaseous dead state equivalent to their composition in a "standard atmosphere", as specified in Table 2.1, can be used.
- (2) For substances including: Al, Co, Cr, Fe, Mg, Mn, P, Sb, Si, Sn, Ti, U, V, a solid dead state containing the elements as existing in a "standard representation" of the earth's land surface is adopted. (See Table 2.2)
- (3) For other substances, the composition of the ions or compounds as existing in a "standard seawater" is adopted. (See Table 2.3)

Table 2.1 The composition of a gaseous reference substances in the "standard atmosphere"

Substances	Conventional mean pressure in the environment (kPa*)
Ar	0.906
CO ₂	0.0335
D ₂ O (g)	0.000342
H ₂ O (g)	2.2
He	0.000485
Kr	0.000097
N ₂	75.78
Ne	0.00177
O ₂	20.39
Xe	0.0000087

*: Mean atmospheric pressure is 99.31(kPa).

Source: Szargut, 1988.

Table 2.2 Conventional average concentration of selected solid reference species in the external layer of the earth crust.

Chemical element	Reference species	
	Formula	Mole fraction
Al (s)	Al ₂ SiO ₅	2×10^{-3}
Co (s)	Co ₃ O ₄	2×10^{-7}
Cr (s)	Cr ₂ O ₃	4×10^{-7}
Fe (s)	Fe ₂ O ₃	1.3×10^{-3}
Mg (s)	CaCO ₃ •MgCO ₃	2.3×10^{-3}
Mn (s)	MnO ₂	2×10^{-4}
P (s)	Ca ₃ (PO ₄) ₂	4×10^{-4}

Source: Szargut, 1988.

Table 2.3 Selected reference species
dissolved in seawater

Chemical element	Reference species	
	Chemical formula	Average molarity (mol/kg H ₂ O)
Ca (s)	Ca ²⁺	9.6×10 ⁻³
Cl ₂ (g)	Cl ⁻¹	0.5657
Cu (s)	Cu ²⁺	7.3×10 ⁻¹⁰
F ₂ (g)	F ⁻¹	3.87×10 ⁻⁵
Na (s)	Na ⁺	0.474

Source: Szargut, 1988.

The exergy or total exergy can be divided into two parts: physical exergy (thermomechanical exergy) and chemical exergy.

Physical exergy EX_{ph} , is the maximum work obtainable by taking the substance through reversible physical processes from its initial state (temperature T , pressure P) to the state determined by the dead state (temperature T_0 and pressure P_0).

Chemical exergy EX_{ch} , is the maximum work that can be obtained by taking a substance having the parameters (T_0 , P_0 , μ_i) to the state of thermodynamic equilibrium with the datum level components of the dead state (P_0 , T_0 , $\mu_{0,i}$).

Figure 2.1 illustrates the relationship between the total, physical and chemical exergies. From the above discussion, it can be seen that the greater the deviation of the state (temperature pressure and composition) of the given system (fluids) from the thermodynamic equilibrium

with the natural environment, the greater the exergy value (the ability to perform maximum work) it has.

2.3 EXERGY CALCULATION

In principle, the total exergy of a control stream could be determined by letting it be brought to equilibrium with the environment by one idealized device where the stream would undergo physical and chemical processes while interacting with the environment. However, it is convenient to separate physical exergy and chemical exergy, enabling calculation of exergy values using standard chemical exergy tables. The general equation to calculate the physical exergy of a stream is given by equation (2.1):

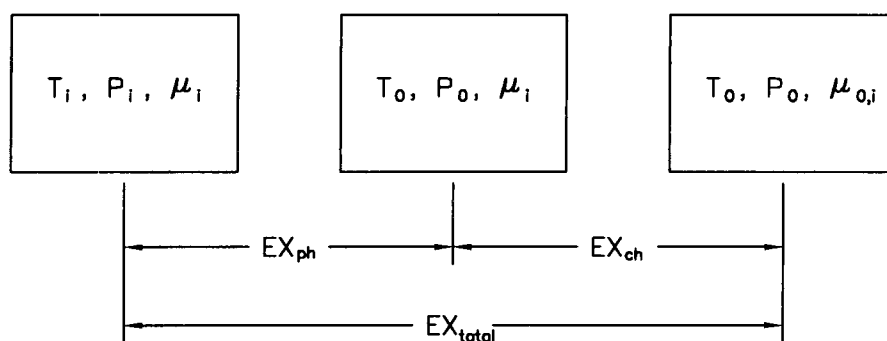


Figure 2.1 The relationship between total exergy, physical exergy and chemical exergy.

$$EX_{ph} = H - H_0 - T_0(S - S_0) \quad (2.1)$$

where: H , S represent the enthalpy and entropy of the specific stream at the state (temperature T and pressure P) of consideration.

H_0 , S_0 represent the enthalpy and entropy of the same specific stream at the dead state (temperature T_0 and pressure P_0).

If the stream under consideration is ideal gas, the ideal gas relations can be used. Substituting the ideal gas relation into Eq. (2.1) and assuming the ideal gas has a constant heat capacity gives an expression for the specific physical exergy as follows:

$$EX_{ph} = c_p \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] + RT_0 \ln \frac{P}{P_0} \quad (2.2)$$

where: c_p is the specific isobaric heat capacity of the gas under consideration.

R is the ideal gas constant.

Eq. (2.2) shows the physical exergy is comprised of two parts, one depending on temperature, the other depending on pressure. In determining physical exergy, the final state of the stream is the state defined by P_0 , T_0 , μ_i (as shown in Figure 2.1). This state will now be the initial state in the reversible processes which will determine the chemical exergy of the stream of substance. The final state to which the substance will be reduced according to the definition of exergy is equilibrium with the dead state (P_0 , T_0 , $\mu_{0,i}$).

Based on the dead states discussed above, the following equations can be used to calculate the chemical exergy of different substances:

If the substances under consideration contain only the reference species in the atmospheric air, and since the gaseous species under consideration can be treated as ideal gases, chemical exergy is given by:

$$EX_{ch,i} = RT_0 \ln \frac{P_i}{P_{0,i}} \quad (2.3)$$

where: $P_i, P_{0,i}$ are the partial pressures of component i in the stream under consideration and in the dead state respectively.

The atmosphere can serve as an appropriate dead state for only 10 chemical elements. For other elements, the earth surface and sea water can serve as the dead state. For these elements and chemical compounds, the chemical exergy can be calculated by the following equation:

$$EX_{ch} = \Delta_f G^0 + \sum_i n_i \times EX_{ch,i} \quad (2.4)$$

where: $\Delta_f G^0$ is the standard normal free energy of formation.

n_i is the number of moles of element i in the compound under consideration.

$EX_{ch,i}$ is the chemical exergy of element i of the compound.

The following examples will show some exergy calculation using these equations. Only chemical exergy values will be evaluated. The results will be used in this thesis.

Assumptions:

(1) The streams under consideration in this work are at the standard state. That is the temperature T and pressure P of the stream are equal to those of the dead state, i.e. T_0 and P_0 ; and $P_0 = 1 \text{ atm}$ and $T_0 = 298.15 \text{ K}$.

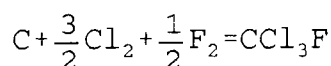
(2) All gases under consideration are treated as ideal gases. Since under the condition of the assumption (1), the maximum error for using ideal gas model is less than 3%.

First considering CO_2 , which is a reference species in the atmospheric air, Eq.(2.3) may be used. Introducing that the partial pressure of CO_2 in dry air is 0.0335, therefore Eq.(2.3) yields:

$$\begin{aligned} \text{EX}_{\text{ch},\text{CO}_2} &= RT_0 \ln \frac{P_{\text{CO}_2}}{P_{0,\text{CO}_2}} = 8.314 \times 298.15 \times \ln \frac{0.0335}{99.31} \\ &= 19,817 \text{ (kJ/kmol)} = 450.4 \text{ (kJ/kg)} \end{aligned}$$

where: $R = 8.314 \text{ (kJ/kmol)}$

Now considering CFCs, which are neither reference species in the atmosphere, nor in the standard chemical exergy table, thus Eq.(2.4) must be used. The reaction of formation of CFC-11 is:



The exergy balance of the reaction of formation of CFC-11 then can be shown as:

$$EX_{ch,CFC-11} = EX_{ch,C} + \frac{3}{2} EX_{ch,Cl_2} + \frac{1}{2} EX_{ch,F_2} + \Delta_f G_{CFC-11}$$

using exergy values from standard exergy table (Szargut, et al., 1988) and the value of standard Gibbs Free Energy of formation (Reid, et al., 1987):

$$\Delta_f G_{CFC-11} = -245.5 \text{ (kJ/mol)}$$

$$EX_{ch,C} = 410.3 \text{ (kJ/mol)}$$

$$EX_{ch,Cl_2} = 123.6 \text{ (kJ/mol)}$$

$$EX_{ch,F_2} = 466.3 \text{ (kJ/mol)}$$

Substituting these values into the above equation:

$$\begin{aligned} EX_{ch,CFC-11} &= -245.5 + 410.3 + 1.5 \times 123.6 + 0.5 \times 466.3 \\ &= 583.3 \text{ (kJ/mol)} \end{aligned}$$

Using the same method, the chemical exergy of CFCs and other substances can be calculated. The results are given in Table 2.4.

Table 2.4 Standard chemical exergy of selected substances*

Substance	Molecular mass	Standard chemical exergy (MJ/kmol)	Standard chemical exergy (MJ/kg)
C	12	410.3	34.2
H ₂	2	236.1	118.1
CO ₂	44	19.8	0.45
Cl ₂	70.9	123.6	1.74
CFC-11 (CCl ₃ F)	137.4	583.3	4.25
CFC-12 (CCl ₂ F ₂)	120.9	557.7	4.61
HCFC-22 (CHClF ₂)	86.5	585.5	6.77
Fe	55.9	376.4	6.73
Cu	63.5	134.2	2.11
Al	27	888.4	32.9

*: See appendix A for detailed calculation.

2.4 DISCUSSION

From the definition of exergy, we know that the more exergy a substance has, the greater the deviation of its state and composition from the thermodynamic equilibrium with the environment (dead state). In other words, the more exergy a substance has, the more potential it has to impact the environment. Based on this, the idea arises that the exergy of streams leaving the system could serve as a measure of their environmental impact. The above exergy

values (Table 2.4) allow this to be examined for several substances. Considering Cl_2 and CO_2 , Cl_2 has higher chemical exergy than CO_2 and it is also known to have a higher environmental impact; this indicates that exergy may serve as a measure. However, when CFC-12 and HCFC-22 are considered, the result is quite different: CFC-12 and HCFC-22 have nearly the same level of chemical exergy, but their environmental impacts are known to be substantially different. CFC-12 has an ozone depletion potential (ODP) of 0.93 and an equivalent global warming impact (EWI) of 7,300 whereas HCFC-22 only has an ODP of 0.049 and an EWI of 1,500 (Fischer, 1991). Thus, it is apparent that the usual exergy with the presently accepted dead states can not adequately directly measure the environmental impact as they are presently perceived. There are several issues that relate to this which have been identified:

(1) The dead state used to calculate the chemical exergy value is based on the general composition of the common component in a specified natural environment. This dead state can satisfy the general thermodynamic analysis; however, when the environmental problem is considered other specific environments may be most important, such as ones considered most suitable to humans, specific plants, animals etc.. So the dead state selection which is most appropriate for environmental impact is not clear.

(2) Environmental impact may be separated into local and global impacts. Many of the local impacts are caused by

significant departure of the state of the streams from the environment (dead state) and the impact results from immediate reaction caused by the departure. When streams coming out of the system have high physical exergy values (such as high pressure or temperature) they will have high potential ability to perform work on the local environment, or high potential for impact on the local environment. If the streams do not have high physical exergy value, the reaction between the streams and environment will depend on the chemical properties and chemical exergy of the streams. The chemical exergy value of the streams is based on the dead state which is discussed above. For some substances that are quite reactive, their departure from the local environment (dead state) will correlate nicely with the local environmental impact. On the other hand, for some substances, such as CFCs and CO_2 , that are not chemically active substances, they will not react with the local environment rapidly, and thus have little local environmental impact. Since significant amounts of these substances are released over a long time period and they do not react in the local environment, the natural environment can not recycle all of these substances and they accumulate in the atmosphere. Over a long period, this accumulation makes the concentration of these substances in the global environment change such that there is a global impact that can change the overall environment, in which we are living, and the

dead state, which would be used as the reference to calculate the exergy.

The above discussions illustrate:

- ▶ Exergy is a measure of the departure of the states of a substance to the environment (dead state).
- ▶ The chemical exergy value calculated by using presently accepted dead states can not directly serve as a measure of the local or global environment impacts.

With this as a basis, in the following chapters of this thesis the exergy will be used as:

- 1: A measure of the natural resource use. Traditionally natural resources are divided into fuel and other (such as material) resources. This separation is often arbitrary, e.g., oil is usually considered as fuel resource and wood as a construction material. However, oil can be used for producing useful material and wood can be used as a fuel. So it would be more appropriate to treat these resources together and the exergy values which are used to make these materials (fuels) from the environment (production exergy and chemical exergy) would be an adequate resource measure.
- 2: A measure of the resources needed to alleviate a global environmental impact (global warming impact). Since global environmental impacts are due to the change of the concentrations of some specific substances in the environment (dead state). The exergy required in a process to remove the amount of the substances which

are released by a system can be considered as the measure of the environmental impact caused by this system.

- 3: A comparison criterion combining the two above uses to measure how effective and environmentally friendly a system is regarding natural resources.

CHAPTER 3.

EXERGY REQUIREMENT OF ENERGY CONVERSION SYSTEM

3.1 INTRODUCTION

A general energy conversion system is illustrated in Figure 3.1. It has streams flowing in and out of the system boundary, one or more specific processes (energy conversion techniques) within the system and equipment to accomplish each process. As discussed in Chapter 1, traditional analyses of such systems, both energy and exergy, have typically considered the direct fuel consumption [(L'Ecuyer and Zoi, 1993) and (Steadman, 1993) et al.]. Some analyses, for simple components have considered also the exergy

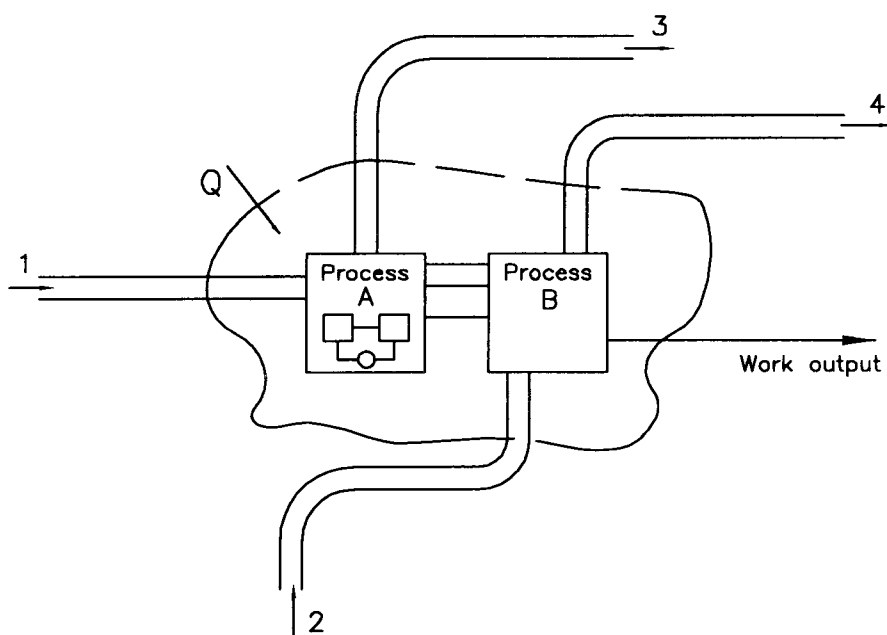


Figure 3.1 Scheme of a general energy conversion system

required for the materials of the component [(Boustead and Hancock, 1979) and (Aceves-Saborio, Ranasinghe and Reistad, 1989)]. However as shown in Figure 3.1, an energy conversion system in general includes three major parts: the energy conversion technique, materials which make up the equipment, and input/output streams which include the fuel consumption (direct exergy consumption). The equipment requires materials and in turn the extraction and production of useful materials requires exergy. Figure 3.2 illustrates this important relationship between materials and fuels. Therefore, when an energy conversion system is analyzed

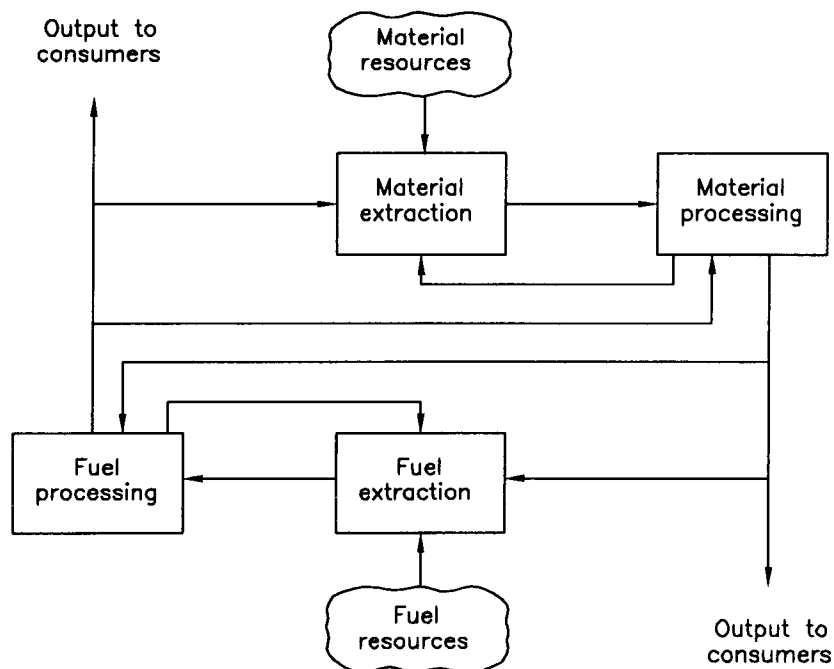


Figure 3.2 Diagram of fuel and material production

completely, it is necessary to consider the direct exergy consumption, the fuel production exergy, and the material exergy. Another important point of this work is how to choose the system boundary. Usually when a system boundary is selected, it only considers the system itself and streams directly related to the system, as boundary A in Figure 3.3. However from Figure 3.2, it can be seen that to extract and produce fuel and material from ground (dead state), additional exergy is needed. So, the system boundary should include fuels and materials production processes (as boundary B in Figure 3.3) and the total exergy used by the system should include fuel and material production exergy.

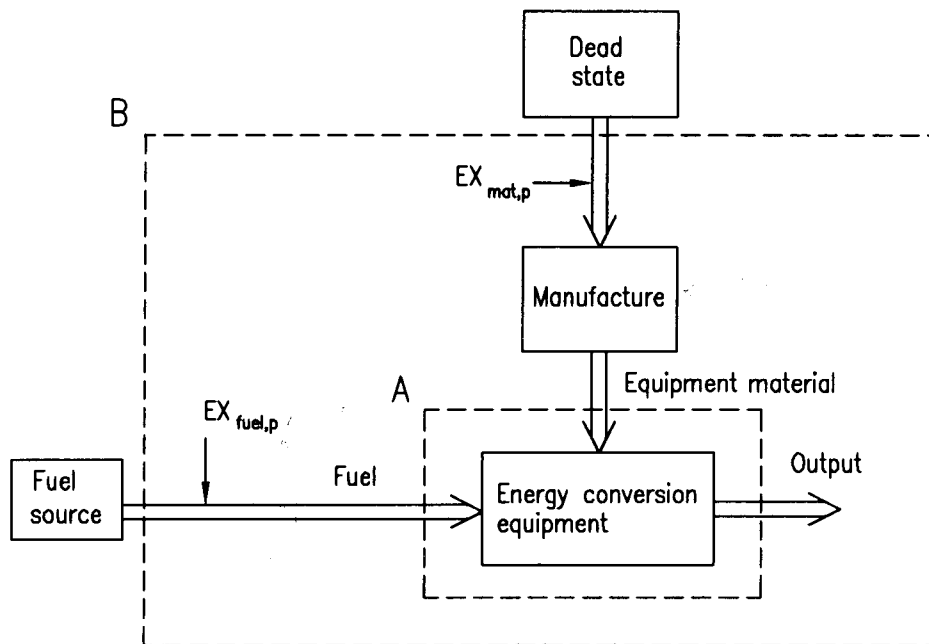


Figure 3.3 Energy conversion system and its boundary

This work focuses on an overall evaluation that considers the direct exergy, the exergy for the material which constitutes the equipment in the system (including working fluids etc.), and the exergy required to obtain the direct exergy fuel from its source.

3.2 FUEL EXERGY

The specifics of the procedure for calculating the exergy requirement of any energy conversion system are key to the extent of the exergy analysis. The required exergy comes from fuel. The fuel can be divided into two groups: primary fuel and secondary fuel. A primary fuel is a naturally occurring raw material which can be used as a technologically useful source of energy without modification of its chemical structure. Examples of this type of fuel are coal, crude oil and natural gas. A secondary fuel is a source of energy which has been derived from a primary fuel, such as electricity, gasoline etc.

To analyze the exergy of fuel, it is necessary to obtain the exergy content of the fuel ($EX_{\text{fuel},C}$), which is the work obtainable when the fuel is brought from its current state to the dead state. For electricity, this is exactly equal to the electrical energy, while for a pure chemical fuel, this may be calculated by the equations presented in Chapter 2:

$$(EX_{\text{fuel},C}) = \Delta_f G^0 + \sum n_i \times (EX_{\text{ch}})_i \quad (2.4)$$

Equation (2.4) applies when the fuel under consideration is at the standard state; that is the temperature T of the fuel equals the dead state temperature T_0 , and the pressure P of the fuel equals the dead state pressure P_0 , $T_0 = 298.15$ K, and $P_0 = 1$ atm.

For fuels such as coal or liquid fuels, which are multicomponent mixtures, various models have been proposed [(Rant, 1960), (Szargut and Styrylska, 1964), (Reistad, 1970), (Shieh and Fan, 1982)]. The calculation for the exergy content of such fuels in this work uses the method proposed by J.H. Shieh and L.T. Fan (1982):

$$\begin{aligned} (EX_{\text{fuel},C}) = & 8177.79 [C] + 5.25 [N] + 27892.63 [H] + 4364.33 [S] - \\ & 3173.66 [O] + 5763.41 [F] + 2810.57 [Cl] + 1204.3 [Br] + \\ & 692.5 [I] - T^0 (S_{\text{ash}}^0) (W_{\text{ash}}) + 0.15 [O] \{ 7837.67 [C] + \\ & 33888.89 [H] - 4236.1 [O] + 3828.75 [S] + 4447.37 [F] + \\ & 1790.9 [Cl] + 681.97 [Br] + 334.86 [I] \} \quad (\text{kcal/kg}) \quad (3.1) \end{aligned}$$

where: $[C], [H], [X], [N], [S]$ and $[O]$ are the mass fractions of C, H_2 , halogen, N_2 , S and O_2 respectively.

$S_{\text{ash}}^0, W_{\text{ash}}$ are standard entropy and molecular mass of ash respectively.

This equation can be used to calculate the exergy content (chemical exergy) for a variety of fuels when the chemical composition of the fuel is known.

The exergy content of the fuel is the exergy in the fuel at its specific sampling point. When an energy conversion system uses a primary or secondary fuel as the source of exergy, the consumption of the exergy contained in the fuel at the system boundary is here referred to as the direct exergy consumption. However, as referred to previously, in order to produce fuels in a usable form and deliver them to the system, additional exergy is expended. Figure 3.4 represents a schematic of the fuel production process. Thus, the exergy that can be linked with the use of any fuel includes the exergy content of the fuel and the exergy used throughout the processing sequence from extraction of the fuel in the fuel reservoir to the delivery to the system. This second part of exergy is here termed the production exergy of the fuel denoted by $EX_{\text{fuel,P}}$. The total exergy linked to the fuel is termed the resource exergy of the fuel, $EX_{\text{fuel,R}}$, defined as:

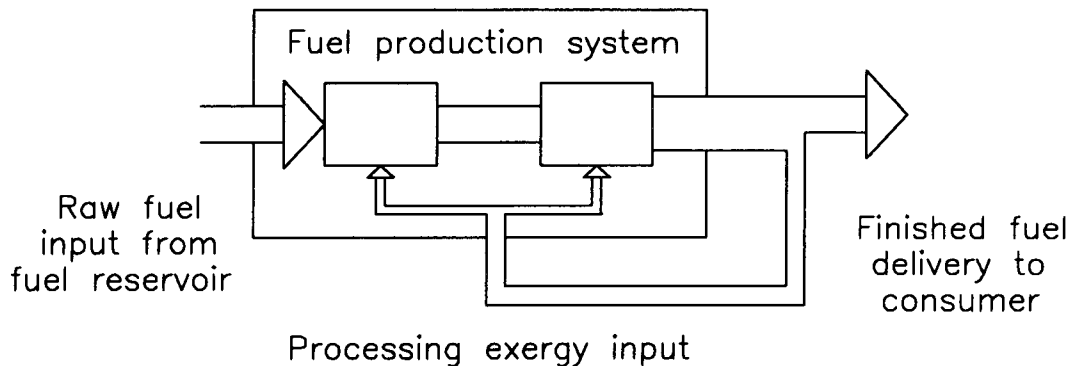


Figure 3.4 Diagram of fuel production process.

$$EX_{\text{fuel},R} = EX_{\text{fuel},C} + EX_{\text{fuel},P} \quad (3.2)$$

For evaluation of fuel exergy streams, the exergy efficiency can be useful. The general definition of exergy efficiency is given by:

$$\eta_{EX} = \frac{\text{Exergy available in the final product}}{\text{Total input exergy}} \quad (3.3)$$

Thus, for a primary fuel, the exergy efficiency is:

$$\eta_{EX} = \frac{EX_{\text{fuel},C}}{EX_{\text{fuel},R}} = \frac{EX_{\text{fuel},C}}{[EX_{\text{fuel},C} + EX_{\text{fuel},P}]} \quad (3.4)$$

For a secondary fuel, there may be several distinct segments in the fuel production process. In such instances, it is useful to show the production exergy of the fuel as being composed of several terms:

$$EX_{\text{fuel},P} = \Sigma (EX_{\text{fuel},P_i}) = EX_{P1} + EX_{P2} + \dots \quad (3.5)$$

and the exergy efficiency becomes:

$$\eta_{EX} = \frac{EX_{\text{fuel},C}}{[EX_{\text{fuel},C} + EX_{\text{fuel},P1} + EX_{\text{fuel},P2} + \dots]} \quad (3.6)$$

Due to the differences in fuel producing industries and the production methods used, it is clear that no single precise production exergy value can be determined for each type of fuel. Also, with the introduction of new production

techniques and the effort to improve the production efficiency, the exergy efficiencies change with time. In spite of these problems, values for production exergy are needed in order to carry out an appropriate overall system exergy analysis. Table 3.1 presents one set of values for resource exergies associated with selected fuels. Table 3.1 was developed with the method prescribed above and using data values compiled from various sources.

Table 3.1 Typical values for the resource exergy associated with fuel

Fuel	Production & delivery exergy ^{2,3} (MJ)	Exergy content of fuel ¹ (MJ)	Resource exergy of fuel ¹ (MJ)	Exergy production efficiency ¹ (%)
Coal (1kg)	1.39	35.39	36.78	96.2
Electricity (1 kWh)	7.72	3.6	11.32	31.8
Natural gas (1kg) (68% of CH ₄)	7.16	46.77	53.93	86.7
Gasoline (C ₈ H ₁₈) (1kg)	9.74	47.48	57.22	83.0
Diesel (C ₁₂ H ₂₆) (1kg)	8.89	47.23	56.12	84.2

1: See Appendix A for detailed calculation.

2: Data source: I. Boustead and G. Hancock, 1979.

3: Data source: J. Szargut et al., 1988.

3.3. MATERIAL EXERGY

As discussed above, besides the direct exergy consumption and fuel production exergy, it is important to consider the material exergy. There are several reasons why considering material exergy is of great interest:

- First, the materials production industries are very exergy intensive industries. In 1977, material production industries accounted for over 20% of world fuel consumption (J. Thomas, 1977). In the U.S.A., production of primary metals consumed 15% of total industrial energy consumption in 1990 (Union of Concerned Scientists et al., 1990).
- Second, during the designing of energy conversion systems, it is important to consider both the efficiency and the physical system size for a specified energy conversion rate. If consideration is only given to improving the efficiency, the system can be designed with excessively large equipment sizes and is not practical. This is particularly true as attempts are made to increase performance of already quite efficient systems.
- Third, with the growing interest in reducing environmental damage, the choice of less exergy intensive, easier to recycle materials must be injected into the design process of energy conversion systems.

As was the case for the resource exergy of the fuel, the total exergy (resource exergy) of a material can also be divided into two parts: exergy content of material $EX_{mat,C}$ and

production exergy of material $EX_{mat,P}$. To evaluate the exergy content of material, Eq.(2.4) can be used. The exergy content value of each material depends on the concentration of this material in the environment (dead state). The evaluation of the production exergy of a material is not as easy as the evaluation of the exergy content. The production exergy of the material is the exergy used to mine, refine and shape the material to the final equipment parts of the thermal system. The fundamental principle of finding the production exergy of material is to calculate the total exergy consumed by the material production process. There are two major methods to estimate the production exergy of materials:

(1) Statistical analysis:

When the supply of exergy to various industries is available, this information, in combination with data on industrial output, allows an estimate to be made of the exergy consumed per unit output. For example, in 1973, the U.S.A. reports the energy supplied to the primary aluminum industry as 1.166×10^{15} (KJ) and the output of primary aluminum as 4.53×10^9 (kg). This yields a value of 257 (MJ/kg) aluminum. However, the result is not exactly the value we seek, because it does not include either the exergy consumed in generating the fuel (the production and delivery exergy of the fuel as discussed above) or the exergy associated with the consumption of raw material, that is, the exergy for mining and delivery. In general, data from statistical

sources such as this do not take into account all the subsidiary production exergy values, but the data can provide an order of magnitude estimate of the production exergy of material.

(2) Process analysis:

Process analysis involves three stages. The first is to identify the network of processes which contribute to the final product, such as represented in Figure 3.5. Next each process within the network has to be analyzed to identify the inputs, in the form of equipment, material and exergy. Finally an exergy value has to be assigned to each input. The total production exergy of the material will be the sum of these exergy inputs:

$$EX_{mat,P} = \sum (EX_{mat,Pi}) \quad (3.7)$$

This is not a simple calculation to accomplish this since it is difficult to define and quantify all the steps of the process from extraction of basic raw material to their final products. For values representative of a country or region, this calculation can only be carried out by using broad-based primary data of each process. However, the published data related to the performance of any industrial process is unfortunately scattered throughout the literature and a search for specific values can be very time-consuming. Here, for the production exergy of selected materials, results which have appeared in various publications are used. Since the values are from a wide variety of published

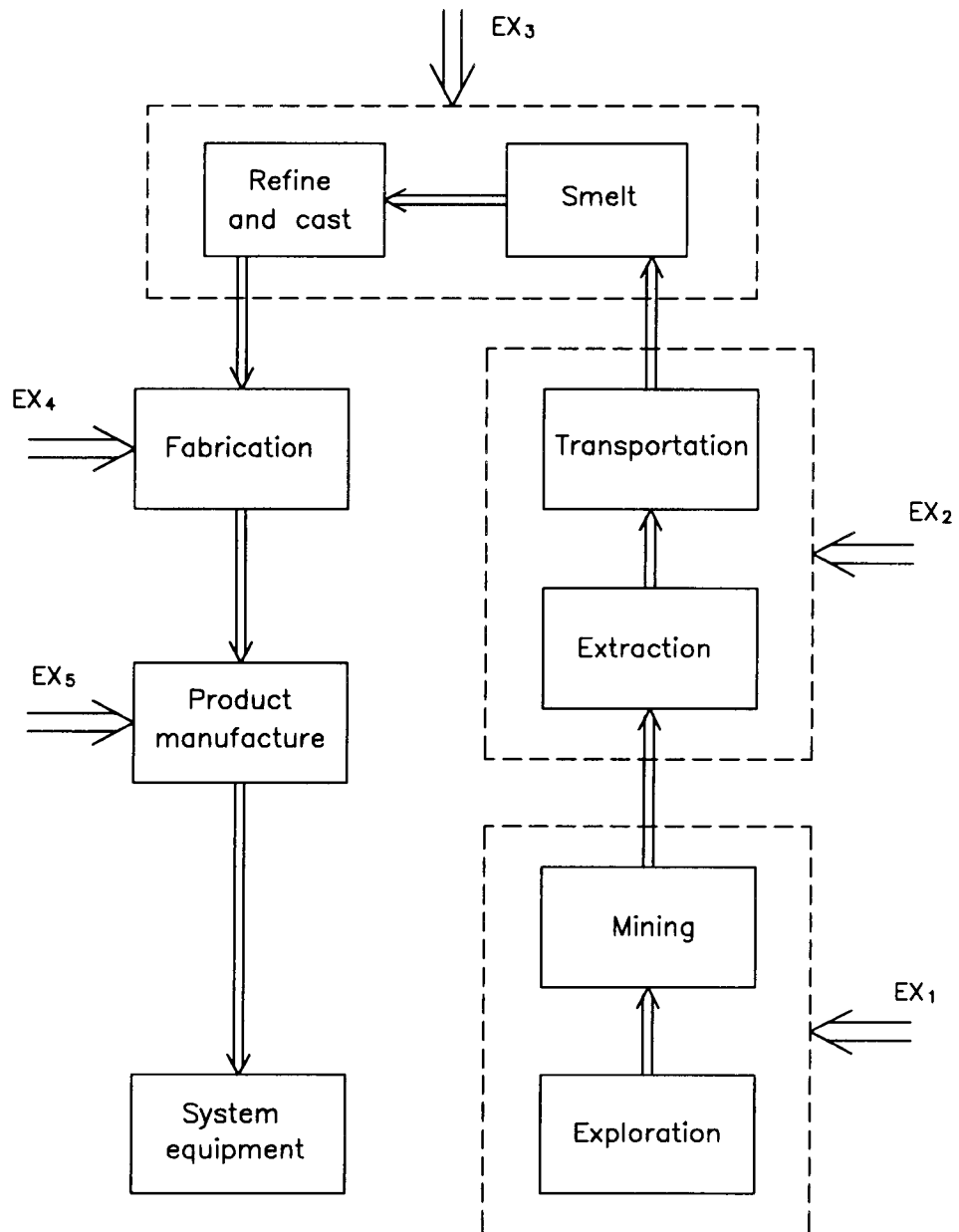


Figure 3.5 Material production processes

sources, "the rounded values" are used in this work. Table 3.2 summarizes exergy content, production exergy and total exergy of some selected materials.

Table 3.2 Exergy content and total resource exergy for selected material and their products

Material	Exergy content of material ¹ (MJ/kg)	Production & delivery exergy ^{2,3,4,5} (MJ/kg)	Total exergy of material used in this work (MJ/kg)
Carbon steel (general product)	6.74	40-50	50
Stainless steel (general product)	6.74	100-110	110
Steel pipe	6.74	40-55	55
Steel sheet & strip	6.74	40-55	55
Copper (general product)	2.11	90-120	110
Aluminum (general product)	32.93	260-300	300
Polyethylene	47.55	50-90	110

1: See Appendix A for exergy content of material calculation.

2: C.Fussler and B. Krummenacher, 1991.

3: M. Ashby, 1992.

4: P. Frost and R. Hale, 1979.

5: I. Boustead and F. Hancock, 1979.

3.4. DISCUSSION

Most of the human activity can be developed by consuming the natural resources. The consumption of the natural resources appears from raw material extraction to the final stage of production. So a measure which can include all these resource consumptions should be introduced enabling the evaluation of the exhaustion of these natural resources. The method presented in this chapter, which uses resource exergy as a measure and adds the fuel production exergy and material exergy into the consideration, allows more complete exergy analyses to be conducted. The method developed here is designed to include concerns about the natural resources, where, the assessment of environmental friendliness is based not only on the direct exergy consumption, but also on the overall system and life-cycle view of the energy conversion system including materials for equipment, working fluids etc. It is apparent that material exergy and fuel production exergy will be factored into energy conversion system specification and design as well as equipment and substance selection.

CHAPTER 4.

GLOBAL WARMING ENVIRONMENTAL IMPACT
CONSIDERATION OF ENERGY CONVERSION SYSTEM

4.1 INTRODUCTION

As indicated in Chapter 1, global warming, with the effects of lower rainfall, decreasing soil moisture and increasing temperature, has been the subject of worldwide attention and research indicates that carbon dioxide and CFCs are the major contribution (about 79%). In 1987, space conditioning in the U.S.A. (the overall energy conversion system) used 5.4 quadrillion Btu of energy (not including material exergy and fuel production exergy); this represents 9% of the total U.S.A. end-use energy. This energy consumption results in about 433 million metric tons of carbon dioxide emission. When combined with the emissions of CFCs, which are used as refrigerants in the energy conversion systems, the space conditioning overall energy conversion system contributes more greenhouse gases to total U.S.A. emission than most other activities. So "concern about environment friendliness" must be injected into energy conversion system analysis and design. In this chapter, the global warming environmental impacts of energy conversion systems will be examined. This will include not only the impact of refrigerant emission on the environment, but also the global warming impact associated with direct exergy consumption (fuel consumption) as well as equipment material

exergy consumption of the energy conversion system. Based on this evaluation, a concept of total equivalent resource exergy (TERE) of an energy conversion system will be introduced, which will consider both resource exergy consumption of the energy conversion system and the exergy required to recover the greenhouse gases equivalent to the emission of the system.

4.2 TOTAL EQUIVALENT GLOBAL WARMING IMPACT

In the last several years, in the energy conversion industry, much attention has focused on the replacement of working fluids (CFC's) due to their role in ozone depletion and the global warming potential. However as Figure 4.1 shows, the emission of working fluids into the atmosphere is only one part of the global warming impact, this will be termed the chemical emission effect. Another global warming impact from the energy conversion system is the CO₂ emission associated with the exergy consumption of the whole energy conversion system, it is called the exergy-related effect. The chemical emission and exergy-related effects of the energy conversion system cannot be considered separately; they are influenced by each other. Several recent researchers [(Turiel and Levine 1989), (Fischer et al., 1991) and (Calm et al., 1993)] combined these two effects on the environment when they analyzed the energy conversion system. However, during their analysis, for the exergy-related

effect of the system they only considered direct exergy consumption (fuel consumption) of the system and the associated CO₂ emission. There is another exergy-related effect which is the CO₂ emission associated with exergy consumption for the fuel and the system equipment material production. The previous chapter has discussed the fuel and equipment material production and their associated exergy consumption, which will then have a global warming impact.

The total equivalent warming impact, TEWI, can be used to consider both the chemical emission and exergy-related effects. The TEWI is defined as the equivalent amount of CO₂

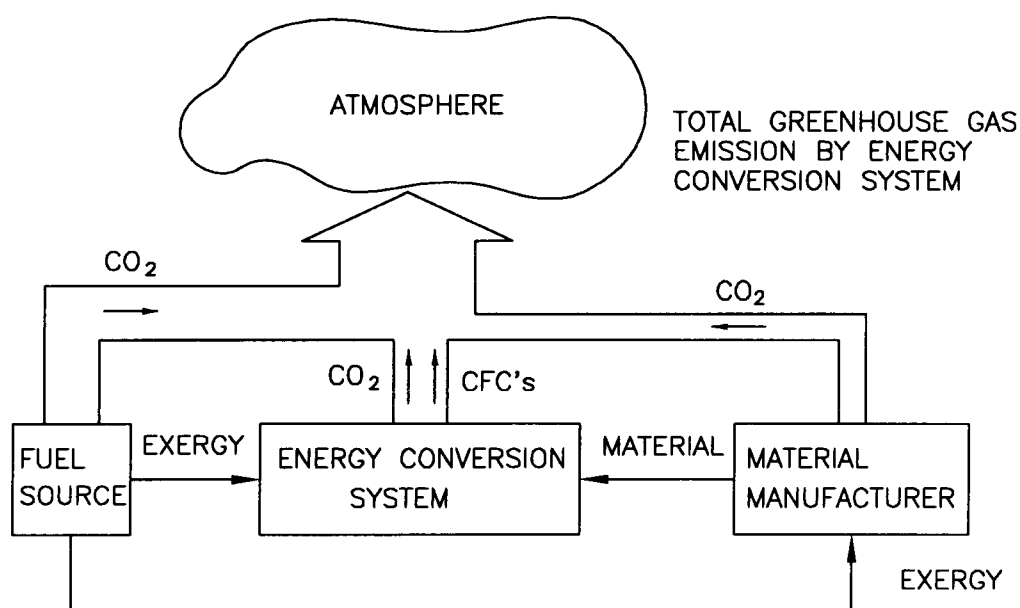


Figure 4.1 Total global warming impact of energy conversion system

that would give approximately the same integrated radiative forcing over a particular integrating time due to the CFCs and CO₂ of the complete system (Fischer et al., 1991). For the energy conversion system, the TEWI is given as:

$$TEWI = EWI_{CH} + EWI_{EX} \quad (4.1)$$

where: TEWI : Total equivalent global warming impact of the system.

EWI_{CH} : Chemical emission global warming impact of the system.

EWI_{EX} : Exergy-related global warming impact of the system.

For EWI_{EX} , here it is proposed that it includes the CO₂ emission impacts due to the direct fuel exergy consumption of the system and also the exergy which is used to produce the materials (equipment and refrigerants). So, EWI_{EX} can be written as:

$$EWI_{EX} = EWI_{EX,fuel} + EWI_{EX,mat} \quad (4.2)$$

where: $EWI_{EX,fuel}$: Exergy-related impact due to direct fuel consumption of the system.

$EWI_{EX,mat}$: Exergy-related impact due to material exergy consumption.

The chemical emission impact and the exergy-related impact which includes the total exergy consumption of the system associated with environment impact will be combined in this work and the result will be used to analyze various

energy conversion systems. In the next section, the direct emission of CFCs is related to equivalent CO₂ emission.

4.3 REFRIGERANT EMISSION AND GLOBAL WARMING IMPACT (CHEMICAL EMISSION IMPACT)

To evaluate the global warming impact due to the system chemical emissions, a relative measure, referred to as the global warming potential index (GWP) developed by the Intergovernmental Panel on Climate Change (IPCC) 1990, that uses carbon dioxide as a reference gas will be used. The GWP of the emission of a greenhouse gas is the time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide:

$$\text{GWP} = \frac{\int_0^{\text{ITH}} a_i \cdot c_i \cdot dt}{\int_0^{\text{ITH}} a_{\text{co}_2} \cdot c_{\text{co}_2} \cdot dt} \quad (4.3)$$

where: a_i : is the instantaneous radiative forcing due to a unit increasing in the concentration of greenhouse gas i .

c_i : is concentration of the greenhouse gas i remaining at time t after its release.

a_{co_2} , c_{co_2} : are corresponding values for carbon dioxide.

ITH: is the number of years over which the calculation is performed (integrating time horizon).

The GWP index provides a simplified means of estimating the relative strength or potency of each CFC on the basis of equivalent CO₂ emission. For some environment impacts, it is important to evaluate the cumulative warming over an extended period after the release of greenhouse gas, so the calculation of the GWP value takes into account both the impact and atmospheric lifetime of the greenhouse gas. Table 4.1 gives the GWP values for different greenhouse gases for different ITH. From Table 4.1, it is easy to see that the GWP is time dependent and that different rates of decay must be considered in viewing GWPs. For example: one kg of CFC-22 would have the same impact on global warming as 4100 kg of CO₂ during the first 20 years; this represents about 58% of the impact of one kg CFC-12. However, the impact of one kg

Table 4.1 GWP values of CFCs for different ITH*
(kg of CO₂ emission equivalent to one kg CFC)

ITH (years)	CFC-11	CFC-12	HCFC-22	HFC-134 _a
20	4,500	7,100	4,100	3,200
100	3,500	7,300	1,500	1,200
500	1,500	4,500	510	420

* Source: S. Fischer, et al. 1992.

of CFC-22 would be comparable to only 1500 kg CO₂ over 100 years, representing an equivalent impact that is only 21% of that for one kg of CFC-12.

4.4 EXERGY CONSUMPTION AND GLOBAL WARMING IMPACT (EXERGY-RELATED IMPACT)

As discussed above, the exergy consumed by the system also has an associated CO₂ emission, which comes from the fossil fuel used in the power plant and material production. To evaluate this part of the environment effect, it is essential to relate the exergy consumption to the carbon dioxide emission. This evaluation will involve consideration of the direct use of fossil fuel, such as coal, natural gas and oil; and the electricity generated by these fossil fuels. Actually, the evaluation requires a consideration of many factors, including: the exact nature and grade of fuel used and the efficiency of electricity generation, transportation and distribution. Table 4.2 gives the average industrial energy consumption from all sources in the United States. These values will be the assumed material resource mix for this work. The average electricity generation associated with fuel consumption to be used in this work is given in Table 4.3. Using these two tables and considering the CO₂ content of the fossil fuel, the CO₂ emission for the average material resource exergy consumption and average electricity generation can be evaluated; the results are presented in Table 4.4.

Table 4.2 Industrial Energy Consumption by Source*

Fuel	Percent
Coal	8.76
Natural gas	29.5
Petroleum	27.2
Electricity	34.4
Hydro	0.1

*Source: Energy Information Abstract Annual 1992.

Table 4.3 Fuel Consumption for Electricity Generation* in the U.S.

Fuel	Percent
Coal	53.7
Natural gas	9.6
Petroleum	4.0
Nuclear	21.9
Hydro and other	10.8

* Source: Energy Information Abstract Annual 1992.

Table 4.4 CO₂ Emissions Associated with Exergy Consumption*

Exergy	CO ₂ emission (kg)
Material resource	
1 MJ	0.103
1 kWh	0.372
Electricity generation	
1 MJ	0.178
1 kWh	0.64

* See Appendix B for detailed evaluation.

4.5 TOTAL EQUIVALENT GLOBAL WARMING IMPACT OF THE ENERGY CONVERSION SYSTEM

Using the definitions and method discussed above, the total equivalent global warming impact of the energy conversion systems for their lifetime can be evaluated. Using Eq.(4.1), the TEWI of the energy conversion system is expressed as:

$$TEWI_{sys} = EWI_{CH} + EWI_{EX}$$

For the energy conversion system,

► EWI_{CH} can be expressed as:

$$EWI_{CH} = (\alpha_1 \times Y + \alpha_2) \times M_{CH} \times GWP_{CH} \quad (4.4)$$

where: M_{CH} : Refrigerant charge mass(kg).

α_1 : Refrigerant average annual loss rate
(fraction of charge/year).

α_2 : Disposal loss of refrigerant after life
time(fraction of charge).

Y : Energy conversion system life time (year).

► EWI_{EX} can be expressed by using Eq.(4.2):

$$EWI_{EX} = EWI_{EX,fuel} + EWI_{EX,mat}$$

where:

• $EWI_{EX,fuel}$ may be evaluated by the following equation:

$$EWI_{EX,fuel} = Q \div \eta \times Y \times \beta_{fuel} \quad (4.5)$$

where: Q : Total energy required for the energy conversion system in one year (MJ/year).
 η : Energy conversion system end use efficiency.
 β_{fuel} : Carbon dioxide emission associated with specific fuel consumption ($\text{kg CO}_2/\text{MJ}_{\text{fuel}}$).
 (See Table 4.4 and Table B3).

- $\text{EWI}_{\text{EX,mat}}$ may be calculated by this equation:

$$\text{EWI}_{\text{EX,mat}} = \sum (1 + \gamma_{\text{mat}} \times Y) \times M_{\text{mat},i} \times \text{EX}_{\text{mat},R,i} \times \beta_{\text{mat},i} \quad (4.6)$$

where: γ_{mat} : Material replace rate (fraction of total material/year).
 $M_{\text{mat},i}$: Mass of material (kg).
 $\text{EX}_{\text{mat},R,i}$: Material resource exergy (MJ/kg).
 $\beta_{\text{mat},i}$: Carbon dioxide emission associated with material resource exergy consumption (kg/MJ_R). (See Table 4.4).

The evaluation of total equivalent global warming impact for the energy conversion system based on the method discussed above is illustrated by the following example.
 Example: For the total space heating requirement in the selected building is 45,260 (MJ/year), determine the TEWI for two electric air-source heat pump systems one which uses CFC-12 and one that uses HCFC-22 and for an electric resistance heating system. Table 4.5 gives the design data of these selected systems.

Table 4.5 Design and performance data of selected systems*

	Electric heat resistance	Air-source heat pump (1)	Air-source heat pump (2)
Refrigerant type		CFC-12	HCFC-22
Refrigerant (charge kg)		3.5	3.5
End use efficiency	1.0	2.44	2.44
Life-time (year)	15	15	15
Steel (kg)	200	350	350
Copper (kg)		45	45
Aluminum (kg)		30	30
Material replace rate (γ)	3.33%	3.33%	3.33%
Refrigerant annual loss rate (α_1)		4%	4%
Refrigerant disposal loss (α_2)		50%	50%

*: See Chapter 5 for detailed assumptions.

Using the above method, related equations and tables, the TEWI values for these selected systems will be:

► Electric resistance:

$$EWI_{CH} = 0$$

$$EWI_{EX} = EWI_{EX,fuel} + EWI_{EX,mat}$$

$$\begin{aligned} EWI_{EX,fuel} &= (Q/\eta) \times Y \times \beta_{fuel} \\ &= (45,260/1) \times 15 \times 0.178 = 120,800 \text{ (kg CO}_2\text{)} \end{aligned}$$

$$\begin{aligned} EWI_{EX,mat} &= \Sigma (1+Y \times \gamma) \times M_{mat,i} \times EX_{mat,Ri} \times \beta_{mat,i} \\ &= (1+0.033 \times 15) \times (200 \times 74^*) \times 0.103 = 2,300 \text{ (kg CO}_2\text{)} \end{aligned}$$

$$\begin{aligned} TEWI &= EWI_{EX,fuel} + EWI_{EX,mat} + EWI_{CH} \\ &= 123,100 \text{ (kg CO}_2\text{)} \end{aligned}$$

(*: Considering 40% of steel is stainless steel.)

► Heat pump system:

System (1): (Using CFC-12 as refrigerant)

$$\begin{aligned} EWI_{CH} &= (\alpha_1 \times Y + \alpha_2) \times M_{CH} \times GWP_{CH} \\ &= (0.04 \times 15 + 0.5) \times 3.5 \times 7,300^* = 28,300 \text{ (kg CO}_2\text{)} \end{aligned}$$

$$EWI_{EX} = EWI_{EX,fuel} + EWI_{EX,mat}$$

$$\begin{aligned} EWI_{EX,fuel} &= (Q/\eta) \times Y_{fuel} \times \beta_{fuel} \\ &= 45,260 \div 2.44 \times 15 \times 0.178 = 49,500 \text{ (kg CO}_2\text{)} \end{aligned}$$

$$\begin{aligned} EWI_{EX,mat} &= \Sigma (1+\gamma \times Y) \times M_{mat,i} \times EX_{mat,Ri} \times \beta_{mat,i} \\ &= (1+0.033 \times 15) \times [(350 \times 74 + 45 \times 110 + 30 \times 300) \times 0.103 \\ &\quad + (0.04 \times 15 \times 0.5) \times 3.5 \times 57] = 6,200 \text{ (kg CO}_2\text{)} \end{aligned}$$

$$\begin{aligned}
 TEWI &= EWI_{CH} + EWI_{EX,fuel} + EWI_{EX,mat} \\
 &= 84,000 \text{ (kg CO}_2\text{)}
 \end{aligned}$$

System (2): (Using HCFC-22 as refrigerant)

$$EWI_{CH} = (0.5 + 0.04 \times 15) \times 3.5 \times 1,500^* = 5,800 \text{ (kg CO}_2\text{)}$$

$$\begin{aligned}
 TEWI &= EWI_{CH} + EWI_{EX,fuel} + EWI_{EX,mat} \\
 &= 61,500 \text{ (kg CO}_2\text{)}
 \end{aligned}$$

Table 4.6 summarizes the calculation results and Figure 4.3 shows the comparison of these results.

(*: Based on 100 year ITH.)

Table 4.6 Global warming impact of selected energy conversion systems

	Electric heat resistance	Air-source heat pump (1) (CFC-12)	Air-source heat pump (2) (HCFC-22)
EWI _{CH} (kg CO ₂)	0.0	28,300	5,800
		(34%)	(9%)
EWI _{EX,fuel} (kg CO ₂)	120,800	49,500	49,500
	(98%)	(59%)	(81%)
EWI _{EX,mat} (kg CO ₂)	2,300	6,200	6,200
	(2%)	(7%)	(10%)
TEWI (kg CO ₂)	123,100	84,000	61,500

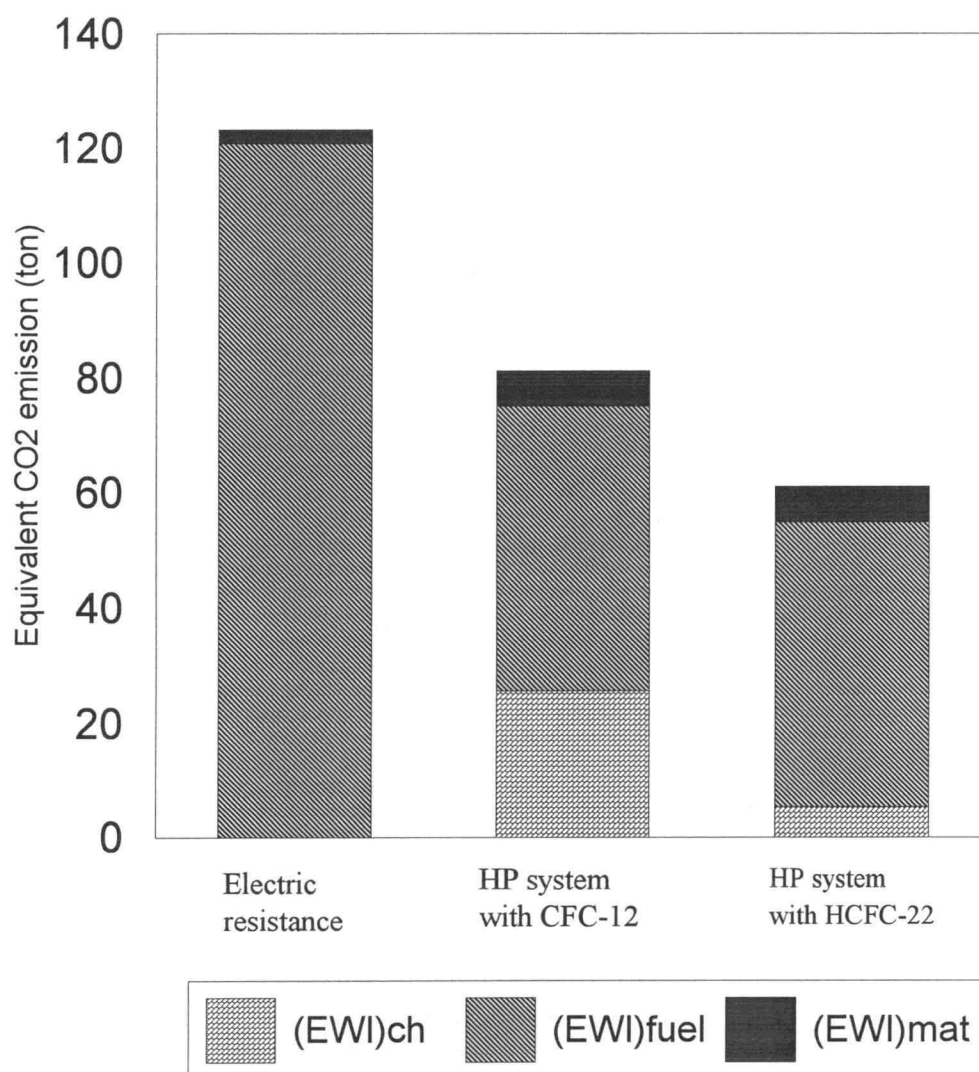


Fig. 4.2 Global warming impact (TEWI) of selected energy conversion systems

4.6 THE TOTAL EQUIVALENT RESOURCE EXERGY OF ENERGY CONVERSION SYSTEM

The above discussions and evaluation, lead to the following results:

- 1: Resource exergy consumption and environment impact are two key subjects of energy conversion system analysis. So to optimize an energy conversion system, it is necessary to consider both resource exergy consumption and environment impact.
- 2: There is a strong relationship between exergy consumption and environment impact.

Based on these results and some recent studies [(Blok, et al., 1992), (T. Suda, et al., 1992) and (E.I. Yantovskii, et al., 1992, 1993, 1994)] which present several different carbon dioxide recovery techniques, the concept of Total Equivalent Resource Exergy (TERE) of energy conversion systems is introduced. The TERE considers not only the total resource exergy consumed by the energy conversion system, but also the resource exergy needed to recover the greenhouse gases equal to the total equivalent CO_2 released by the system. Figure 4.3 shows a combined system which includes a general energy conversion system and a CO_2 recovery system. From Figure 4.3, it can be seen that the total resource exergy consumed by the combined system is the sum of the resource exergy used by the two subsystems. This total resource exergy is defined as the total equivalent resource exergy (TERE) of the energy conversion system:

$$T_{RE} = (EX_{fuel,R})_{EC} + (EX_{mat,R})_{EC} + (EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE} \quad (4.7)$$

where: $(EX_{fuel,R})_{EC}$, $(EX_{mat,R})_{EC}$: Fuel resource exergy and material resource exergy of the energy conversion system respectively.

$(EX_{fuel,R})_{RE}$, $(EX_{mat,R})_{RE}$: Fuel resource exergy and material resource exergy of the carbon dioxide recovery system respectively.

The sum of $(EX_{fuel,R})_{RE}$ and $(EX_{mat,R})_{RE}$ is called total resource exergy of the CO₂ recovery system and described as:

$$(EX_{total})_{RE} = (EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE} \quad (4.8)$$

For a special CO₂ recovery technique, which the exergy required to recover one kilogram carbon dioxide is constant, the value of $(EX_{total})_{RE}$ depends on the chemical emission

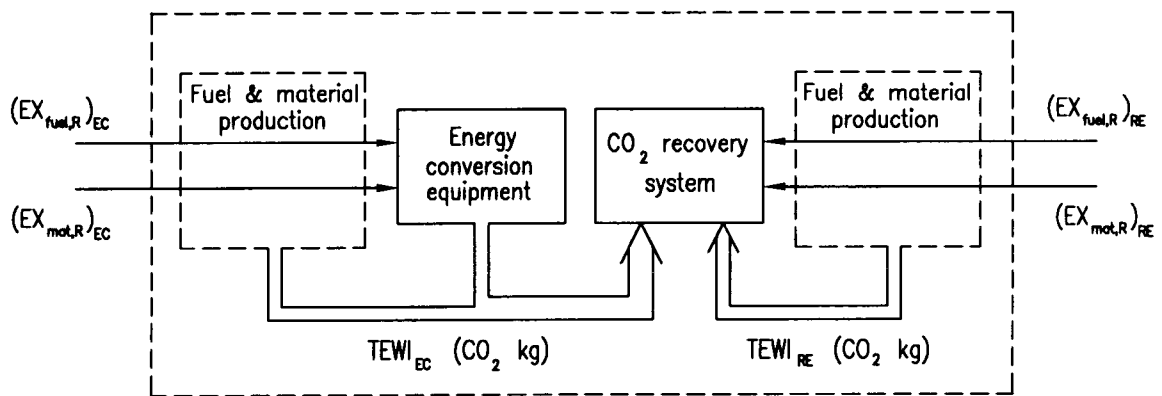


Figure 4.3 A general energy conversion system and a carbon dioxide recovery system

(M_{CH}) , fuel resource exergy $(EX_{fuel,R})$ and material resource exergy $(EX_{mat,R})$ consumption of the energy conversion system. It can be written as:

$$\begin{aligned} (EX_{total})_{RE} &= (EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE} \\ &= F_1 \{ (M_{CH})_{EC}, (EX_{fuel,R})_{EC}, (EX_{mat,R})_{EC} \} \end{aligned} \quad (4.9)$$

and TERE is given as:

$$\begin{aligned} TERE &= (EX_{fuel,R})_{EC} + (EX_{mat,R})_{EC} + \\ &\quad + F_1 \{ (M_{CH})_{EC}, (EX_{fuel,R})_{EC}, (EX_{mat,R})_{EC} \} \\ &= F \{ (M_{CH})_{EC}, (EX_{fuel,R})_{EC}, (EX_{mat,R})_{EC} \} \end{aligned} \quad (4.10)$$

The total equivalent CO_2 emission of the combined system is:

$$(TEWI)_{total} = (TEWI)_{EC} + (TEWI)_{RE} \quad (4.11)$$

where: $(TEWI)_{total}$, $(TEWI)_{EC}$ and $(TEWI)_{RE}$ are total equivalent warming impacts of combined system, energy conversion system and CO_2 recovery system respectively.

Defining the exergy required to reduce the CO_2 in the atmosphere by one kilogram as:

$$(ex_{CO_2})_{RE} = \frac{(EX_{total})_{RE}}{(TEWI)_{total}} = \frac{(EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE}}{(TEWI)_{EC} + (TEWI)_{RE}} \quad (4.12)$$

So, Eq.(4.9) can be rewritten as:

$$\begin{aligned} (EX_{total})_{RE} &= (ex_{CO_2}) \times (TEWI)_{total} \\ &= (ex_{CO_2}) \times [(TEWI)_{EC} + (TEWI)_{RE}] \end{aligned} \quad (4.13)$$

where:

$$(TEWI)_{EC} = (EWI_{CH})_{EC} + (EWI_{EX,fuel})_{EC} + (EWI_{EX,mat})_{EC}$$

$$(TEWI)_{RE} = (EWI_{CH})_{RE} + (EWI_{EX,fuel})_{RE} + (EWI_{EX,mat})_{RE}$$

Considering for a specific CO₂ recovery system, the material resource exergy and fuel resource exergy consumption have a linear relationship, that is:

$$(EX_{mat,R})_{RE} = A \times (EX_{fuel,R})_{RE} \quad (4.14)$$

where: A is a constant for a specific CO₂ recovery system.

Introducing Eq.(4.5) and Eq.(4.6):

$$EWI_{EX,fuel} = (EX_{fuel,R}) \times \beta_{fuel} \quad (4.5)$$

$$EWI_{EX,mat} = (EX_{mat,R}) \times \beta_{mat} \quad (4.6)$$

Substituting Eq.(4.5), Eq.(4.6) and Eq.(4.14) into Eq.(4.13):

$$\begin{aligned} (EX_{total})_{RE} &= (ex_{CO_2}) \times [(TEWI)_{EC} + (TEWI)_{RE}] \\ &= (ex_{CO_2}) \times \{ (TEWI)_{EC} + [EWI_{CH} + (EX_{fuel,R}) \times \beta_{fuel} + (EX_{mat,R}) \times \beta_{mat}]_{RE} \} \\ &= (ex_{CO_2}) \times \{ (TEWI)_{EC} + [EWI_{CH} + (EX_{fuel,R}) \times \beta_{fuel} + A \times (EX_{fuel,R}) \times \beta_{mat}]_{RE} \} \end{aligned} \quad (4.15)$$

Combining Eq.(4.15) with Eq.(4.9) gives :

$$\begin{aligned} (EX_{total})_{RE} &= (EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE} = (1+A) \times (EX_{fuel,R})_{RE} \\ &= (ex_{CO_2}) \times \{ (TEWI)_{EC} + (EWI_{CH})_{RE} + (EX_{fuel,R})_{RE} \times \beta_{fuel} + A \times (EX_{fuel,R})_{RE} \times \beta_{mat} \} \end{aligned} \quad (4.16)$$

The above equation can be rewritten as:

$$(EX_{\text{fuel},R})_{RE} = (ex_{\text{CO}_2})_{RE} \times \frac{TEWI_{EC} + (EWI_{CH})_{RE}}{(1+A) - (ex_{\text{CO}_2})_{RE} \times [\beta_{\text{fuel}} + A \times \beta_{\text{mat}}]} \quad (4.17)$$

$$(EX_{\text{mat},R})_{RE} = A \times (ex_{\text{CO}_2})_{RE} \times \frac{TEWI_{EC} + (EWI_{CH})_{RE}}{(1+A) - (ex_{\text{CO}_2})_{RE} \times [\beta_{\text{fuel}} + A \times \beta_{\text{mat}}]} \quad (4.18)$$

Finally, the TERE is given as:

$$TERE = (EX_{\text{fuel},R})_{EC} + (EX_{\text{mat},R})_{EC} + (EX_{\text{fuel},R})_{RE} + (EX_{\text{mat},R})_{RE} \quad (4.7)$$

where: $(EX_{\text{fuel},R})_{RE}$: is defined by Eq.(4.17).

$(EX_{\text{mat},R})_{RE}$: is defined by Eq.(4.18).

$(ex_{\text{CO}_2})_{RE}$: is defined by Eq.(4.12).

$TEWI_{EC}$: is defined by Eq.(4.1)

$(EWI_{CH})_{RE}$: is defined by Eq.(4.4).

A : is defined by Eq.(4.14).

From Eq.(4.7), it is easy to see that TERE is function of

$(EX_{\text{fuel},R})_{EC}$, $(EX_{\text{mat},R})_{EC}$, $(EX_{\text{fuel},R})_{RE}$ and $(EX_{\text{mat},R})_{RE}$:

$$TERE = G_1 \{ (EX_{\text{fuel},R})_{EC}, (EX_{\text{mat},R})_{EC}, (EX_{\text{fuel},R})_{RE}, (EX_{\text{mat},R})_{RE} \}$$

since $(EX_{\text{fuel},R})_{RE}$ and $(EX_{\text{mat},R})_{RE}$ are function of A , $(ex_{\text{CO}_2})_{RE}$,

$(EWI_{CH})_{EC}$, $(EWI_{CH})_{RE}$, $(EX_{\text{fuel},R})_{EC}$, $(EX_{\text{mat},R})_{EC}$, β_{fuel} and β_{mat} . If

considering A , $(ex_{\text{CO}_2})_{RE}$, $(EWI_{CH})_{RE}$, β_{fuel} and β_{mat} are constant

numbers, then TERE will only be the function of $(EX_{\text{fuel},R})_{EC}$,

$(EX_{\text{mat},R})_{EC}$ and $(M_{CH})_{EC}$, that is:

$$TERE = G \{ (EX_{\text{fuel},R})_{EC}, (EX_{\text{mat},R})_{EC}, (M_{CH})_{EC} \} \quad (4.19)$$

The objective function which is to minimize the TERE of an energy conversion system can be expressed as:

$$\text{Minimize } \{\text{TERE}\} = G\{(\text{EX}_{\text{fuel,R}})_{\text{EC}}, (\text{EX}_{\text{mat,R}})_{\text{EC}}, (\text{M}_{\text{CH}})_{\text{EC}}\} \quad (4.20)$$

This equation considers both the system resource exergy consumption and the system environment impact, it will make energy conversion system analysis, optimization and design more reasonable.

In recent years, many different approaches to the CO₂ recovery problem have been shown in the literature. In most cases, the removal technologies are for power plants. Generally there are three main methods for removal of CO₂ from power plant flue gases:

- ▶ Chemical absorption, using amines as absorbing agent to absorb carbon dioxide from flue gases [(Suda, et al. 1992) and (Bolland, et al. 1992)]. CO₂ is absorbed by a solvent at low temperature and/or high pressure and released at high temperature and/or low pressure. In Bolland's study, for one kilogram of CO₂ recovery, about 6 MJ resource exergy is consumed.
- ▶ Membrane separation, using membranes to remove carbon dioxide from flues gases [(Feron, et al. 1992), (Hendriks, et al. 1992), (Saha, et al. 1992) and (Jansen, et al. 1992)]. This method relies on differences in solubility and diffusion of gases in polymers or other type of membranes materials. Hendriks' work shows that about 4 MJ resource exergy is

required to recover one net kilogram CO₂. Some other results show that using membrane method will increase electricity cost by 20% to 40%.

- Modifying the power plant in such a way that uses oxygen as the combustion medium instead of air. Then the excess flue gas (most is CO₂) is compressed and liquified [(Allam, et al. 1992), (Ruyck, 1992) and (Yantovskii, et al. 1992,1993)]. Estimates vary widely, with the more conservative indicating the overall power plant efficiency will be reduced by up to 30% with this method of recovery.

Present schemes for keeping the CO₂ out of the atmosphere are to dispose of it at high pressure into abandoned oil wells or deep into the ocean.

Although there are different options for recovery of the CO₂ emissions from the atmosphere, most of these approaches are either theoretical work (computer simulation), or laboratory test. Thus, the estimation of a precise value for the CO₂ recovery exergy of a real system is not feasible. This work will use a value of 5 MJ of resource exergy to recover one net kilogram of CO₂. It is developed from the power plant CO₂ removal technologies reported by (Hendriks, 1992), (Suda, 1992), and (Bolland, 1992) and represents a nominal value within the approximate range of 4 MJ to 6 MJ per kg CO₂. The value selected above is not to be considered a precise value and serves here for the purpose of demonstration. This work also assumes that the material

resource exergy for CO₂ recovery systems represents about eight percent of the total resource exergy, similar to what has been observed in energy conversion system. Combining these assumptions with the equations proposed in this chapter, the exergy required to recover the total equivalent CO₂ emission and the TERE values for the energy conversion systems in the previous section's example can be evaluated. Eq.(4.12) is set equal to the 5 (MJ/kg.CO₂) value.

$$(ex_{CO_2})_{EX} = \frac{(EX_{fuel,R})_{RE} + (EX_{mat,R})_{RE}}{(EWI)_{EC} + (TEWI)_{RE}} = 5 \text{ (MJ/kgCO}_2\text{)}$$

Combining the above result with Eqs.(4.17) and (4.18), and considering:

$$A = 0.08$$

$$\beta_{mat} = 0.103 \text{ (kg CO}_2\text{/MJ) (Table 4.4)}$$

$$\beta_{fuel} = 0.103 \text{ (kg CO}_2\text{/MJ) (Table 4.4)}$$

the exergy required to recover CO₂ and the TERE value for electric resistance heater are:

$$\begin{aligned} (EX_{fuel,R})_{RE} &= (ex_{CO_2})_{RE} \times \frac{TEWI_{EC} + (EWI_{CH})_{RE}}{(1+A) - (ex_{CO_2})_{RE} \times [\beta_{fuel} + A \times \beta_{mat}]} \\ &= 5 \times \frac{123,130 \times 10^{-3}}{(1+0.08) - 5 \times (0.103 + 0.08 \times 0.103)} = 1,200 \text{ (GJ)} \end{aligned}$$

$$(EX_{mat,R})_{RE} = A \times (ex_{CO_2})_{RE} \times \frac{TEWI_{RE} + (EWI_{CH})_{RE}}{(1+A) - (ex_{CO_2})_{RE} [\beta_{fuel} + A \times \beta_{mat}]}$$

$$= 1,200 \times 0.08 = 100 \text{ (GJ)}$$

$$TERE = 2,200 + 1,200 + 100 = 3,500 \text{ (GJ)}$$

Using the same procedures, the TERE values of the two heat pump systems can be calculated. The results are presented in Table 4.7. The comparison of the total CO₂ recovery exergy and TERE values of the selected energy conversion systems are shown in Figures 4.5 and 4.6.

Table 4.7 The TERE values and CO₂ recovery exergy of selected energy conversion systems

	Electric heat resistance	Air-source heat pump (1) CFC-12	Air-source heat pump (2) HCFC-22
Fuel resource exergy of CO ₂ recovery (GJ)	1,200	800	600
	34%	44%	37%
Material resource exergy of CO ₂ recovery (GJ)	100	70	50
	3%	4%	3%
Total resource exergy of energy conversion system (GJ)	2,200	950	950
	63%	52%	60%
Total equivalent resource exergy (TERE) (GJ)	3,500	1,820	1,600

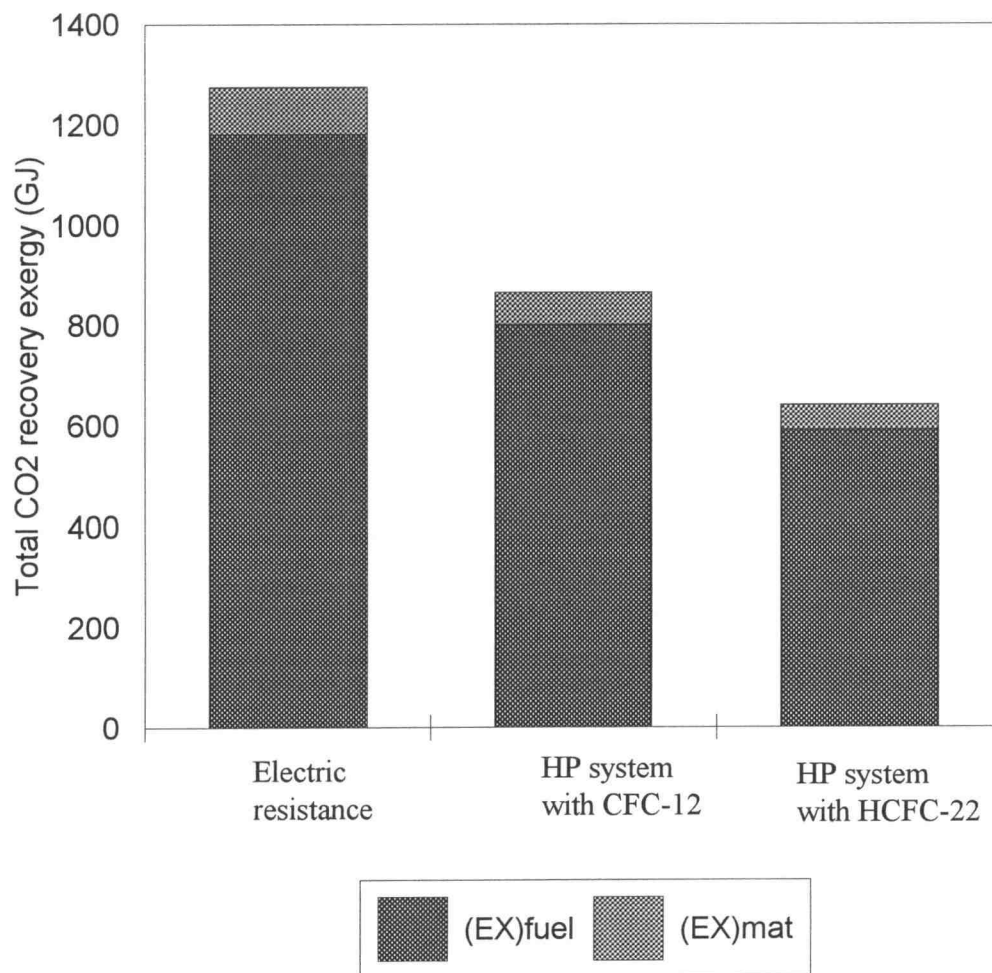
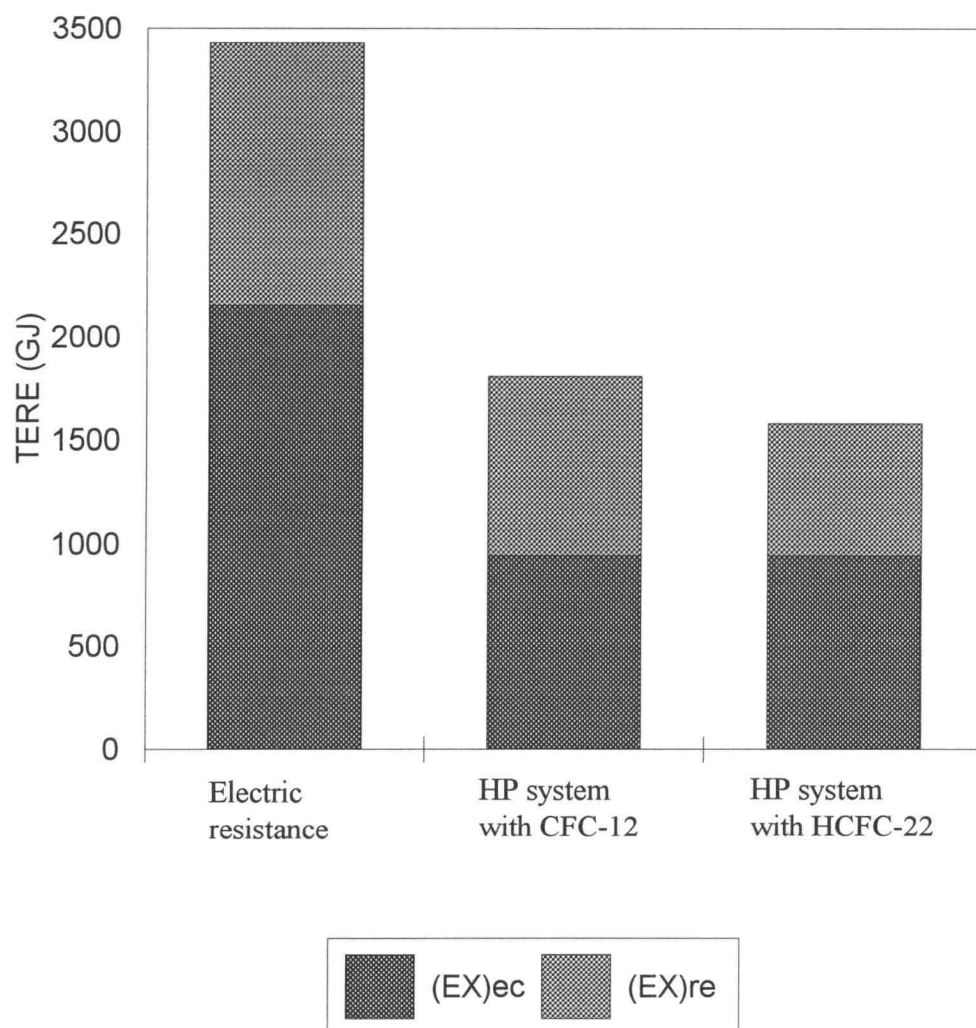


Figure 4.4 The total CO₂ recovery exergy for selected energy conversion systems



Figures 4.5 The total equivalent resource exergy (TERE) for selected energy conversion systems

4.7 CONCLUSION

In the energy conversion industry, when people consider the global warming impact of the system, most put their attention on either alternative refrigerants or reducing the direct exergy consumption (fuel consumption) of the system. In this work, the global warming impact due to the chemical emission and impact associated with direct exergy consumption (fuel consumption) as well as system equipment materials consumption of the energy conversion system are considered together. The TERE method presented in this chapter indicates that the resource exergy of the energy conversion system and environmental impact exergy are both substantial impacts and should be compared together.

In this work, 5 MJ of resource exergy $[(ex_{CO_2})_{RE}]$ is used for the calculation of recovering one net kilogram of carbon dioxide from the atmosphere. The specific value of this impacts the comparison. The question arises: what is the minimum resource exergy required to recover CO_2 from the atmosphere and what is the maximum this could be and still allow a net CO_2 recovery. From the exergy calculation it can be seen that the exergy difference between CO_2 at the state of atmosphere (P_0 , T_0 , and $X_{CO_2,i}$) and the state ($P=100$ atm, T_0 , and $X_{CO_2}=1$), which the CO_2 is recovered and compressed from atmosphere, is about 0.5 MJ. So the minimum exergy required to recovery CO_2 from atmosphere should be no less than 0.5 MJ. From Eq.(4.17) it can be seen that the maximum

value of $(ex_{CO_2})_{RE}$ would be that which would satisfy the following equation:

$$1+A \geq (ex_{CO_2})_{RE} \times [\beta_{fuel} + A \times \beta_{mat}] \quad (4.21)$$

or:

$$(ex_{CO_2})_{RE} \leq \frac{1+A}{\beta_{fuel} + A \times \beta_{mat}} \quad (4.22)$$

For the fuel consumption model used in this thesis, the maximum value of $(ex_{CO_2})_{RE}$ will be:

$$(ex_{CO_2})_{RE,Max} = \frac{1+0.08}{0.103+0.08 \times 0.103} = 9.7 \text{ (MJ/kgCO}_2\text{)}$$

For a specific CO₂ recovery method, if the value of $(ex_{CO_2})_{RE}$ is greater than the value of $(ex_{CO_2})_{RE,Max}$, that means the CO₂ emission associated with CO₂ recovery exergy would be greater than the CO₂ to be recovered and hence such a CO₂ recovery method would not work.

For comparison, it is noted that the theoretical minimum for the exergy of recovering CO₂ from the atmosphere and disposed of it at 100 atm pressure is about 0.5 (MJ/kgCO₂). Thus the nominal value of 5 (MJ/kgCO₂) used in this work not only lies midway in the nominal range for systems presented in the literatures (4 to 6 MJ/kgCO₂), but also roughly midway between the minimum value of 0.5 (MJ/kgCO₂) and the maximum value of 9.7 (MJ/kgCO₂).

The Total Equivalent Resource Exergy (TERE) proposed in this chapter, which considers both resource exergy

consumption and the global warming impact of the energy conversion system, is based on the exergy concept. The TERE value uses the exergy as a measure to compare the energy conversion systems the utilization of natural resources (both fuel and material resources). Even though the calculation equation (Eq.4.7) proposed in this chapter only considers the global warming impact, it appears it could readily be extended to evaluate other global environmental impacts. Rewriting Eq.4.7 in a general form yields:

$$\text{TERE} = (\text{EX}_{\text{fuel,R}})_{\text{EC}} + (\text{EX}_{\text{mat,R}})_{\text{EC}} + \sum (\text{EX}_{\text{fuel,R}})_{\text{Re,i}} + \sum (\text{EX}_{\text{mat,R}})_{\text{Re,i}} \quad (4.23)$$

where: $(\text{EX}_{\text{fuel,R}})_{\text{Re,i}}$: is fuel resource exergy of recovery
global environmental impact gas i.

$(\text{EX}_{\text{mat,R}})_{\text{Re,i}}$: is material resource exergy of recovery
global environmental impact gas i.

The general TERE calculation equation (Eq.4.23) can then be used for the situation where any other global environment impact is considered during the energy conversion analysis. The concept of TERE makes the analysis more reasonable and more complete and can be used as the objective function for energy conversion system design and optimization.

CHAPTER 5.

A COMPARISON OF TOTAL EXERGY CONSUMPTION AND GLOBAL WARMING
IMPACTS OF ENERGY CONVERSION SYSTEMS IN THEIR LIFETIME

5.1 INTRODUCTION

As discussed in previous chapters, to analyze an energy conversion system completely, it is necessary to consider both the total resource exergy consumption and the total equivalent environment impact of the system. For the system resource exergy consumption, it includes direct fuel exergy, system material exergy and exergy required to obtain fuel and material from its source. For the total equivalent environment impact of the system, it includes the impact due to the chemical material emission, impact associated with direct fuel consumption as well as impact associated with system material production and transportation. In this chapter, the total resource exergy and total equivalent environment impact of three different types of energy conversion systems will be evaluated for a single family home of load in a specific climate by using the method discussed in previous chapters. The total equivalent resource exergy consumption of selected energy conversion systems will also be evaluated and compared.

5.2 TOTAL EXERGY CONSUMPTION OF ALTERNATIVE ENERGY CONVERSION SYSTEMS

A "typical" single family home, located in the Portland Oregon area, that would require a three-ton heat pump system, is used for the basis of this analysis. For this system the design heat load is 25.83(MJ/hr) with a design temperature of -5°C and total space heating requirement in the selected area is 45,260(MJ/year). These specific values are taken from L'Ecuyer et al. (1993). The three chosen energy conversion systems are:

- ▶ High efficiency air-source heat pump
- ▶ Direct-expansion ground-source heat pump
- ▶ Vertical ground-coupled heat pump

Table 5.1 provides a comparison of the design data of these three heat pump systems.

Estimates of equipment materials consumed by each system in this study are summarized in Table 5.2. Although little data is reported in the literature, the materials used by the different systems varies quite widely. The specific numbers used in this study (Tables 5.1 and 5.2) are based on limited data available to the author [(Lennox Industries Inc, 1994), (Lenarduzzi,1991), (Kavanaugh, 1992) and (Bose, 1983)] and the author's assumptions and are used here for illustrative purposes only. They do not represent actual values based on an extensive investigation.

The following assumptions are used in this analysis:

1: The systems have an application life-time of 15 years, and during that life-time, 50% of the equipment material will be replaced (equivalent to an annual material replace rate of 3.33%). The replacement of material during the life-time and the estimated 15 years life-time are due to a combination of equipment failure (e.g., compressor and some auxiliary system replacement after 10 years, etc.) and remodelling.

2: Since no reliable data are found on refrigerant annual loss rate in unitary heat pump systems for recent years and considering extreme annual loss is about eight percent (Fisher et al., 1991), an average four percent annual loss rate is used in this work. In recent years,

Table 5.1 Design and performance data of the selected heat pump systems

Three-ton heat pump system	Air-source heat pump ²	Direct-expansion ground-source heat pump ¹	Vertical ground-coupled heat pump ^{2,3}
Refrigerant	HCFC-22	HCFC-22	HCFC-22
Refrigerant (Charged kg)	3.5	12.7	2.0
End-use efficiency (heating)	2.44	2.85	3.1
Life-time (year)	15	15	15

1: Lenarduzzi, 1991.

2: L'Ecuyer, 1993.

3: Bose, 1983.

Table 5.2 Material consumption of the selected systems

Heat pump	Subsystem	Material	Mass (kg)
Air-source heat pump	Outdoor units (compressor, fan unit, exchanger, and auxiliary duct)	Copper Steel Aluminum	25 95 15
	Indoor units (fan unit, exchanger, and auxiliary duct)	Copper Steel Aluminum	20 55 15
	Heat resistance and duct system	Steel	200
	Total	Copper Steel Aluminum	45 350 30
Direct-expansion ground-source heat pump ¹	Indoor units (compressor, fan unit, exchanger and duct)	Copper Steel Aluminum	25 95 15
	Ground coil	Copper Steel	340 15
	Heat resistance and duct system	Steel	200
	Total	Copper Steel Aluminum	365 310 15

1: Lenarduzzi, 1991.

Table 5.2 continued

Heat pump	Subsystem	Material	Mass (kg)
Vertical ground-coupled heat pump ^{2,3}	Indoor units (compressor, fan unit, exchanger and duct)	Copper Steel Aluminum	25 95 15
	Outdoor units (exchanger, fan unit and auxiliary duct)	Copper Steel Aluminum	15 50 10
	Ground pipe	Propylene	200
	Heat resistance and duct system	Steel	200
	Total	Copper Steel Aluminum Propylene	40 345 25 200

2: Bose, 1983.

3: Kavanaugh, 1992.

after the system's life-time, most refrigerant can be recovered. However, the unitary equipment technician skill levels may nonetheless prevent complete recovery and for some systems, due to part of the system equipment or piping being broken, the total refrigerant may be released to the atmosphere. Based on these considerations, it is assumed that 50% of the total refrigerant (working fluid) will be released to the atmosphere at the end of the system life-time.

3: The values in Table 5.2 for the vertical ground-coupled heat pump are based on using water as the working

fluid in the ground; if an antifreeze is used in the system, account must also be taken of this fluid.

4: The GWP values of CFCs are based on a 100 year ITH.

Based on the above assumptions and using the method discussed in previous chapters, the direct fuel exergy requirement and resource exergy consumption of the heat pump system for its life-time can be written as Eq.(5.1) and Eq.(5.2) respectively:

$$\Sigma (EX_{\text{fuel, req}}^i) = (Q/\eta) \times Y \quad (5.1)$$

$$EX_{\text{fuel, rec}}^i = EX_{\text{fuel, req}}^i / \eta_{\text{EX, fuel}}^i \quad (5.2)$$

where: $\eta_{\text{EX, fuel}}^i$: Fuel exergy production efficiency of fuel i.

$EX_{\text{fuel, req}}^i$, $EX_{\text{fuel, rec}}^i$: Fuel exergy requirement and resource exergy consumption of fuel i respectively.

Using these equations and data from Tables 3.1 and 5.1, the total fuel resource exergy consumption of the selected heat pump systems for their life-time will be:

► Air-source heat pump:

$$\begin{aligned} EX_{\text{fuel, rec}} &= (Q/\eta/\eta_{\text{EX, ele}}) \times Y \\ &= 45,260 \div 2.44 \div 0.318 \times 15 = 875,000 \text{ (MJ)} \end{aligned}$$

► Direct-expansion ground-source heat pump:

$$EX_{\text{fuel, rec}} = 45,260 \times 15 \div 0.318 \div 2.85 = 749,100 \text{ (MJ)}$$

► Vertical ground-coupled heat pump:

$$EX_{\text{fuel, rec}} = 45,260 \times 15 \div 0.318 \div 3.1 = 688,700 \text{ (MJ)}$$

For the material resource exergy of the systems, the following equation can be used:

$$EX_{mat,sys} = \sum (\gamma_{1,i} \times Y + \gamma_{2,i}) \times M_i \times EX_{mat,Ri} \quad (5.3)$$

where: M_i : Mass of material i (kg).

$EX_{mat,Ri}$: Resource exergy of material i (MJ/kg).

$\gamma_{1,i}$: Replace rate of material i (fraction of total mass/year).

$\gamma_{2,i}$: Material i disposal loss after its life-time (fraction of total mass).

Using this equation with the data in Tables 5.2 and 3.2, material resource exergy for these three systems are:

► Air-source heat pump:

$$\begin{aligned} \text{Copper:} \quad (EX_{mat,R})_{Co} &= (\gamma_{1,Co} \times Y + \gamma_{2,Co}) \times M_{Co} \times EX_{Co,Ri} \\ &= (0.033 \times 15 + 1) \times 45 \times 110 = 7,430 \text{ (MJ)} \end{aligned}$$

$$\text{Steel:} \quad (EX_{mat,R})_{St} = (0. \times 5 + 1) \times 350 \times 75^{**} = 39,370 \text{ (MJ)}$$

$$\text{Aluminum:} \quad (EX_{mat,R})_{Al} = (0.1 \times 5 + 1) \times 30 \times 300 = 13,500 \text{ (MJ)}$$

$$\text{Refrigerant:} \quad (EX_{mat,R})_{Ref} = (0.04 \times 15 + 0.5) \times 3.5 \times 57^* = 220 \text{ (MJ)}$$

Total material resource exergy:

$$\begin{aligned} (EX_{mat,R})_{Total} &= (EX_{mat,R})_{Co} + (EX_{mat,R})_{St} + (EX_{mat,R})_{Al} + (EX_{mat,R})_{Ref} \\ &= 7,430 + 39,370 + 13,500 + 220 = 60,520 \text{ (MJ)} \end{aligned}$$

*: Due to lack of information of production exergy of refrigerant, comparison with some chemical products, 50 (MJ/kg) material production exergy for all refrigerants is assumed in this work.

** : Considering 40% of steel is stainless steel.

The same method can be used to evaluate the ground-source heat pumps. The results are summarized in Table 5.3. The total resource exergy consumed by these three heat pump systems should be the summation of the fuel resource exergy and material resource exergy. This summation is given in Table 5.4. Figures 5.1, 5.2 and 5.3 give the comparisons the resource exergy consumptions of the heat pump systems.

Table 5.3 Material resource exergy consumption of selected systems (MJ)

	Air-source heat pump	Direct-expansion ground-source heat pump	Vertical ground-coupled heat pump
Refrigerant	220	800	130
Copper	7,430	60,200	6,600
Steel	39,370	34,900	38,800
Aluminum	13,500	6,800	11,250
Propylene	0	0	33,000
Total	60,520	102,700	89,800

Table 5.4 The total resource exergy consumption of selected systems

	Air-source heat pump	Direct-expansion ground-source heat pump	Vertical ground-coupled heat pump
Fuel resource exergy (GJ)	875	750	690
	94%	88%	88%
Material resource exergy (GJ)	60	103	90
	6%	12%	12%
Total resource exergy (GJ)	935	853	780

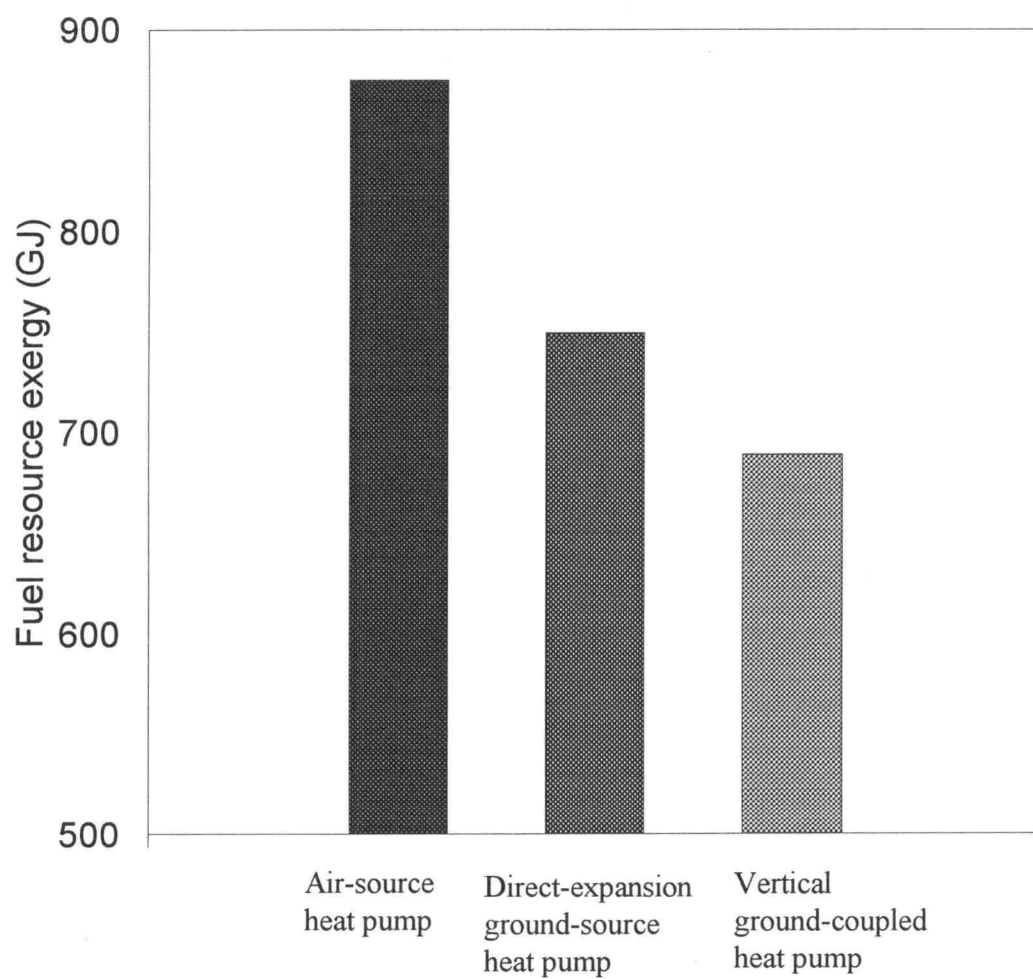


Figure 5.1 Fuel resource exergy consumption of selected systems during their life-time

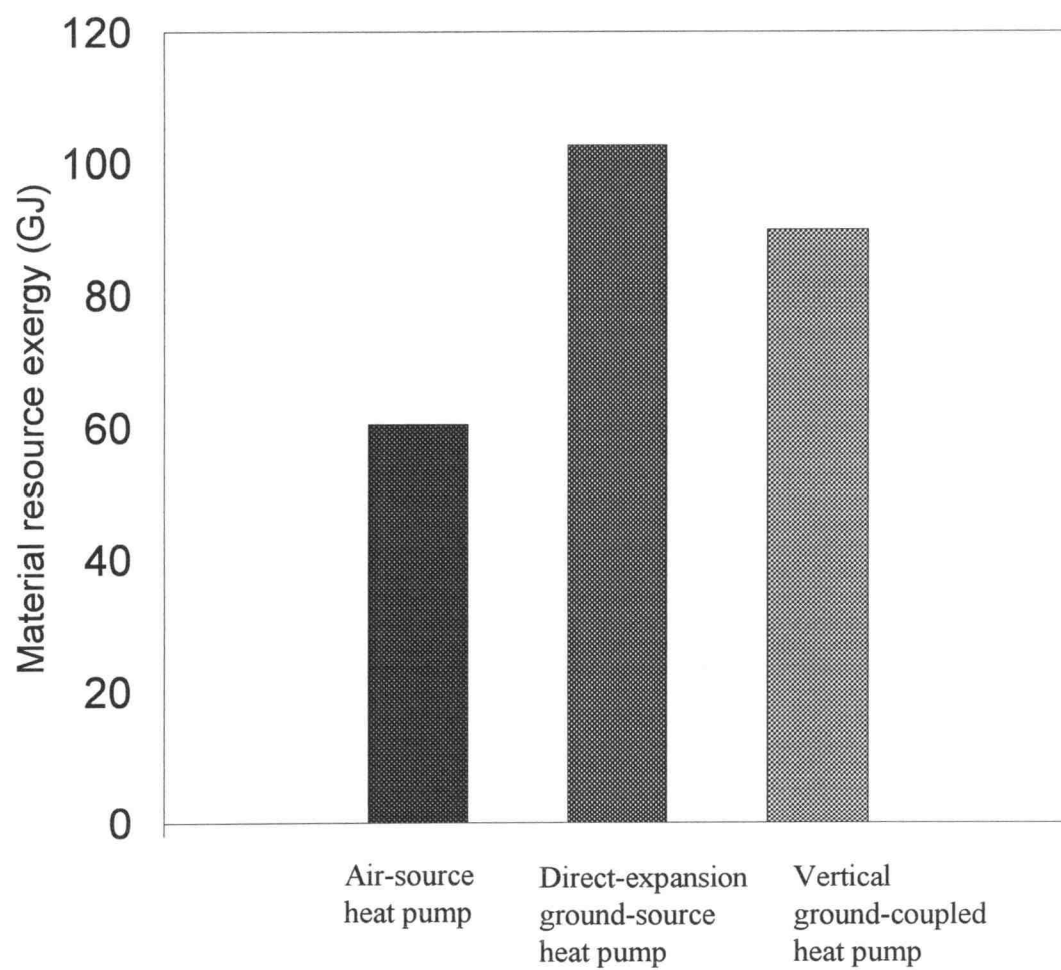


Figure 5.2 Material resource exergy consumption of selected systems during their life-time.

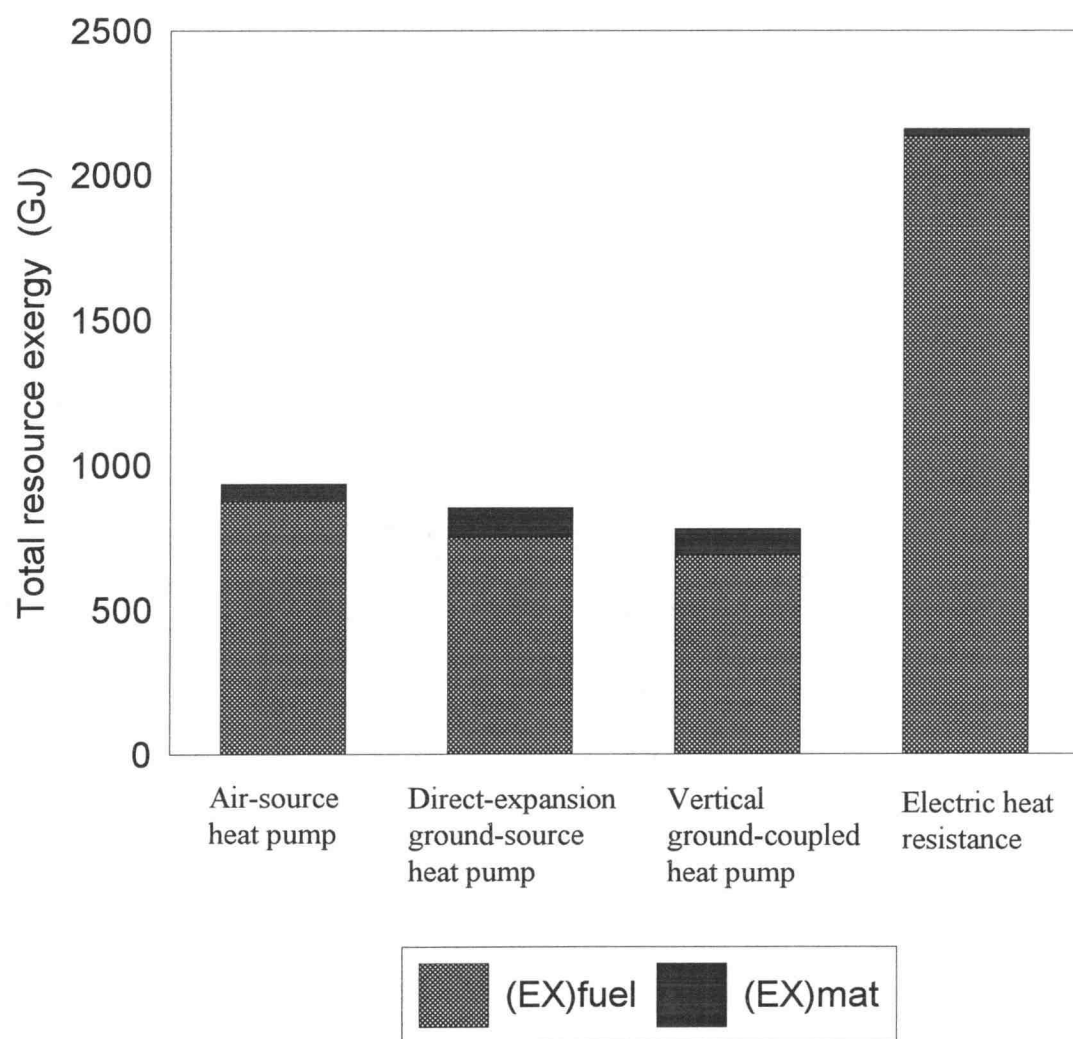


Figure 5.3 The total resource exergy consumption of selected systems during their life-time

5.3 TOTAL GLOBAL WARMING IMPACT OF THE ALTERNATIVE ENERGY CONVERSION SYSTEMS

Combining the method proposed in Chapter 4 with the results obtained in the previous part of this Chapter, the total global warming impact of the three selected heat pump systems will be analyzed in this part.

Using Eq.(4.4) and the data from Tables 5.1 and 4.1, the chemical emission global warming impact of the selected heat pump systems are:

- Air-source heat pump:

$$\begin{aligned} EWI_{CH} &= (\alpha_1 \times Y + \alpha_2) \times M_{CH} \times GWP_{CH} \\ &= (0.04 \times 15 + 0.5) \times 3.5 \times 1500 = 5,780 \text{ (kg CO}_2\text{)} \end{aligned}$$

- Direct-expansion ground-source heat pump:

$$EWI_{CH} = (0.04 \times 15 + 0.5) \times 12.7 \times 1500 = 20,960 \text{ (kg CO}_2\text{)}$$

- Vertical ground-coupled heat pump:

$$EWI_{CH} = (0.04 \times 15 + 0.5) \times 2 \times 1500 = 3,300 \text{ (kg CO}_2\text{)}$$

The global warming impact associated with fuel resource exergy and material resource exergy consumption of these heat pump systems can be evaluated by means of Eqs.(4.5) and (5.3) with Tables 4.4, 5.3 and 5.4:

- Air-source heat pump:

$$\begin{aligned} EWI_{EX, fuel} &= Q \times Y \div \eta \times \beta_{ele} \\ &= 45,260 \times 15 \div 2.44 \times 0.178 = 49,530 \text{ (kg CO}_2\text{)} \\ EWI_{EX, mat} &= \sum (\gamma_{2,i} + \gamma_{1,i} \times Y) \times M_i \times EX_{mat,i} \times \beta_{mat} \\ &= 0.103 \times \{ (0.033 \times 15 + 1) \times (45 \times 110 + 350 \times 75 + 30 \times 300) \\ &\quad + (0.04 \times 15 + 0.5) \times 3.5 \times 57 \} = 6,240 \text{ (kg CO}_2\text{)} \end{aligned}$$

Combining the above results, the total equivalent warming impact (TEWI) of the heat pump system is:

$$\begin{aligned} \text{TEWI} &= \text{EWI}_{\text{CH}} + \text{EWI}_{\text{EX,fuel}} + \text{EWI}_{\text{EX,mat}} \\ &= 5,780 + 49,530 + 6,240 = 61,550 \text{ (kg CO}_2\text{)} \end{aligned}$$

Using the same method, the greenhouse effect associated with exergy consumption and the total equivalent warming impact (TEWI) of the ground-source heat pumps are calculated and the results are given in Table 5.5. The comparisons of global warming impact due to the different sources of these heat pump systems are shown in Figures 5.4, 5.5 and 5.6. The total equivalent warming impact (TEWI) of selected systems are also compared with the electric heat resistance system which works at same condition. Figure 5.7 shows this comparison.

Table 5.5 The total global warming impact of selected heat pump systems

Global warming impact	Air-source heat pump	Direct-expansion ground-source heat pump	Vertical ground-coupled heat pump
Chemical emission (EWI_{CH}) (CO_2 kg)	5,800	21,000	3,300
	10%	28%	6%
Direct fuel consumption ($EWI_{EX,fuel}$) (CO_2 kg)	49,500	42,400	39,000
	80%	57%	76%
Material consumption ($EWI_{EX,mat}$) (CO_2 kg)	6,200	10,600	9,300
	10%	15%	18%
Total equivalent Warming impact (TEWI) (CO_2 kg)	61,500	73,930	51,600

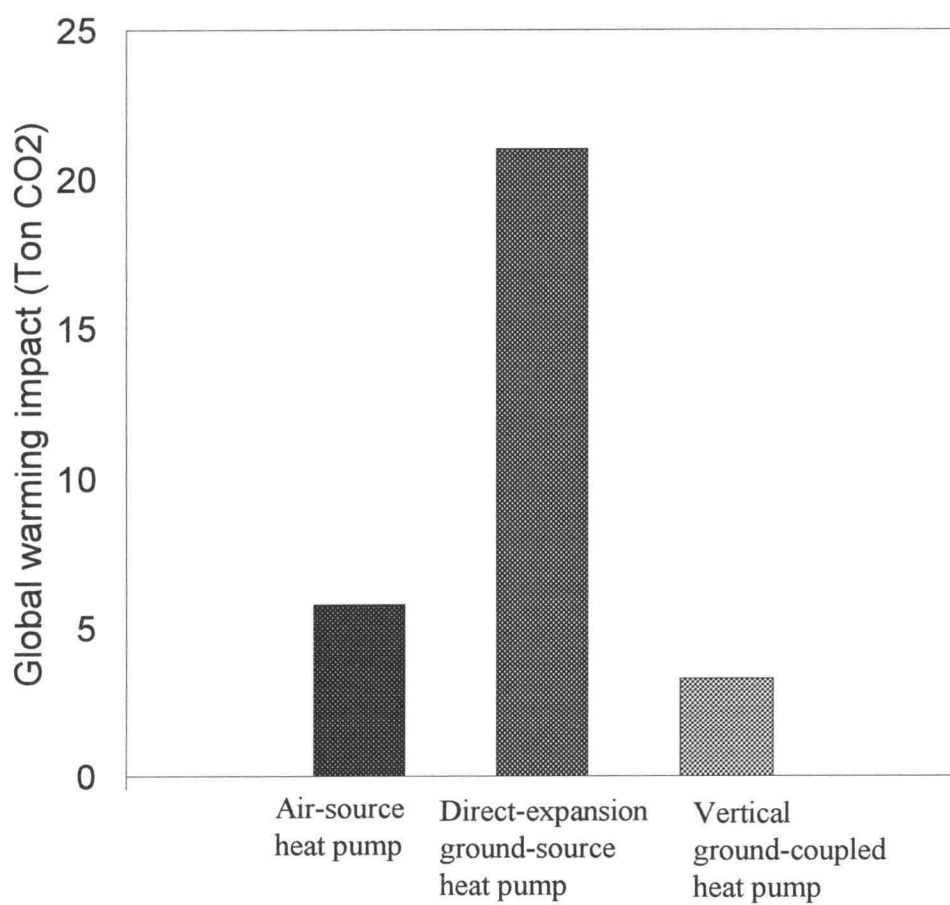


Figure 5.4 Global warming impact associated with chemical emission of selected systems during their life-time

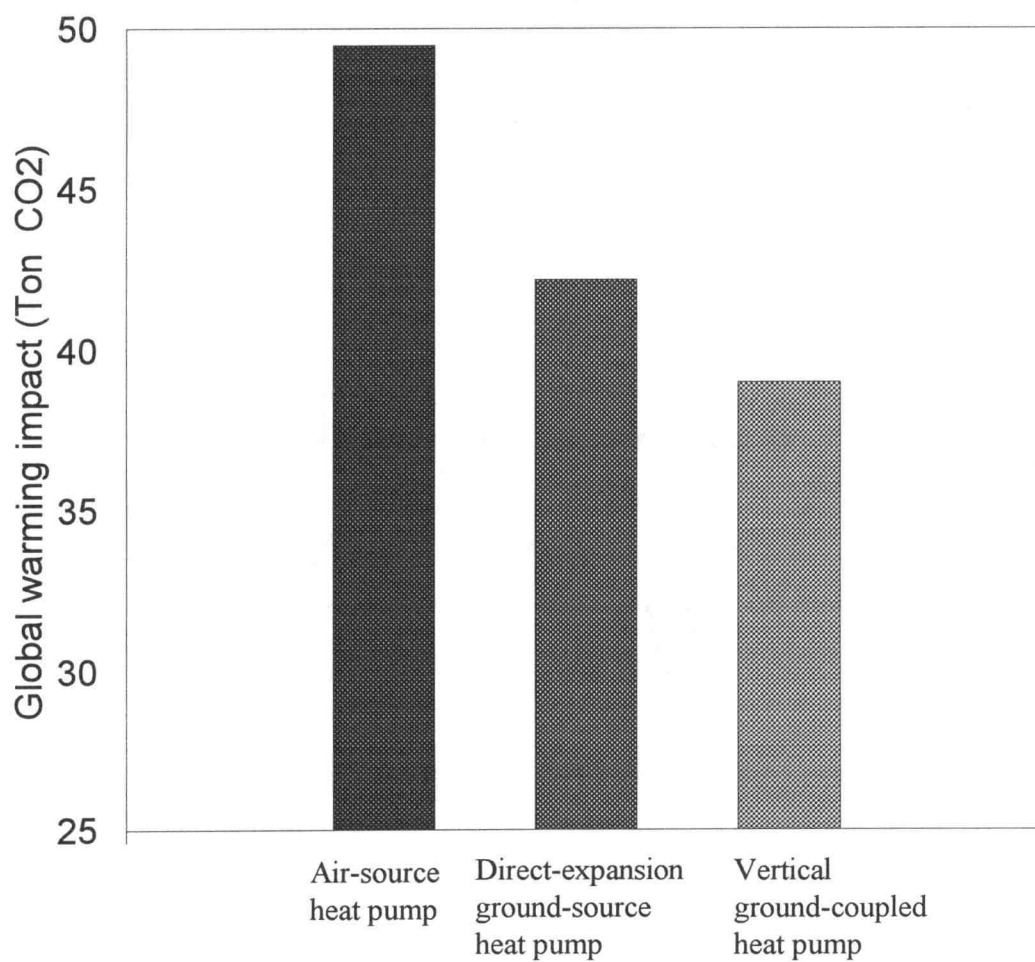


Figure 5.5 Global warming impact associated with direct fuel consumption of selected systems during their life-time

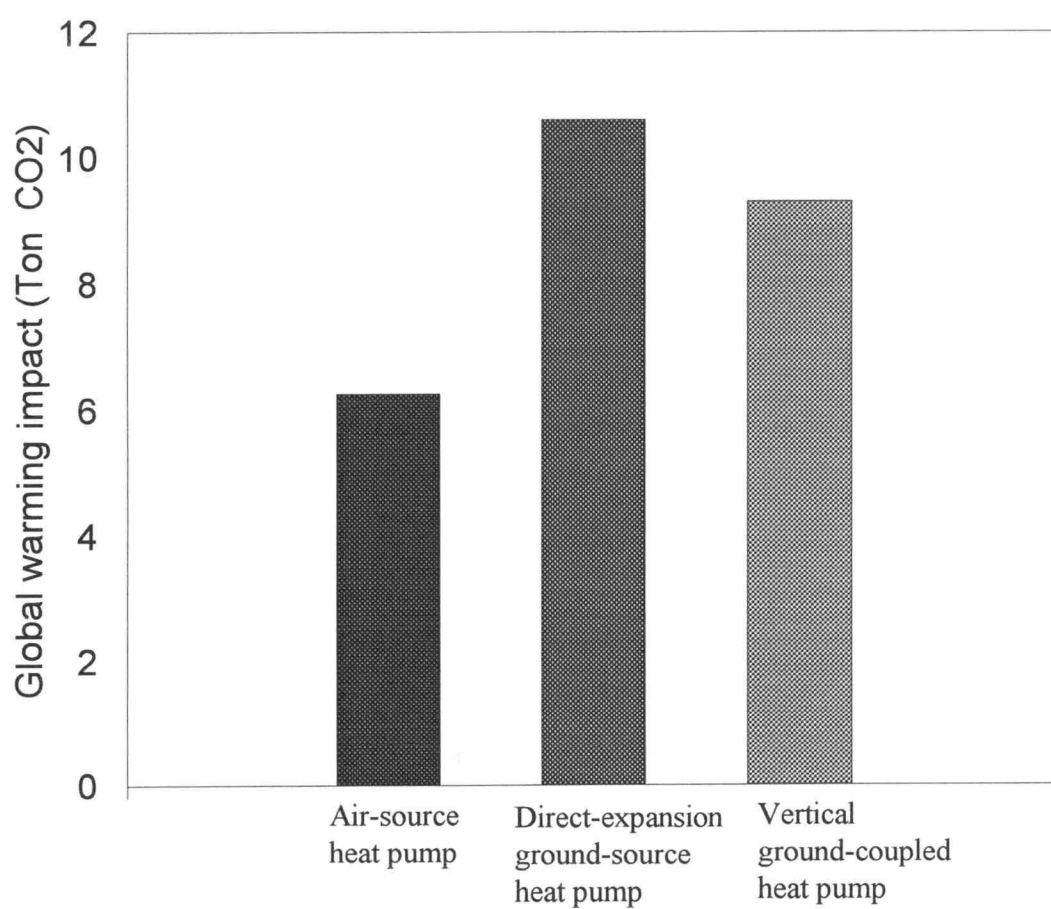


Figure 5.6 Global warming impact associated with material consumption of selected systems during their life-time

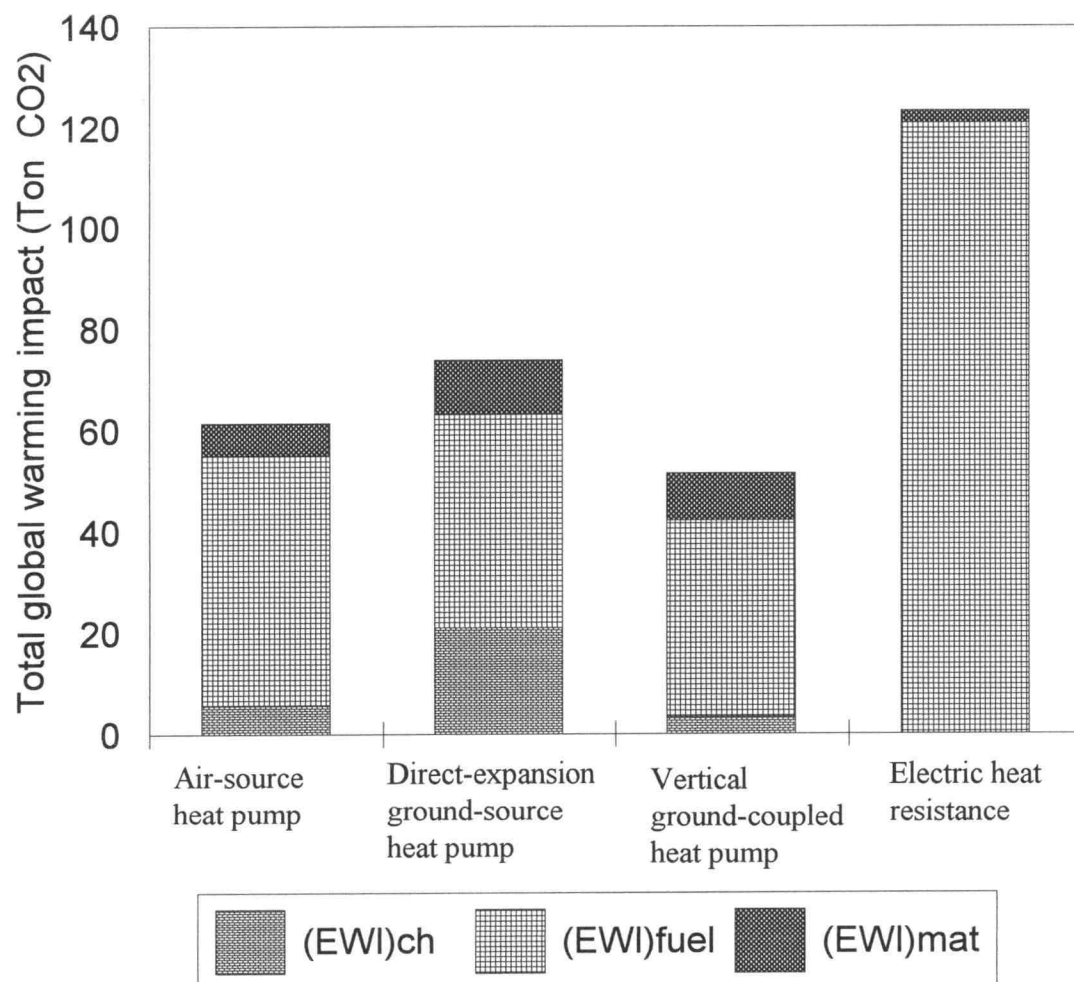


Figure 5.7 Total global warming impact (TEWI) of selected systems during their life-time

5.4 THE TOTAL EQUIVALENT RESOURCE EXERGY OF ALTERNATIVE ENERGY CONVERSION SYSTEMS

From the above discussions and comparisons, for the selected heat pump systems, it has shown two different results. If only considering the total resource exergy, the air-source heat pump has the highest exergy consumption; if considering global warming impact, the direct-expansion ground source heat pump has the most global warming impact. In this part, the concept and calculation method of total equivalent resource exergy (TERE) will be used to calculate and compare the selected heat pump systems.

Considering:

$$A = 0.08,$$

$$\beta_{\text{fuel}} = 0.103 \text{ (kg CO}_2\text{/MJ)}$$

$$\beta_{\text{mat}} = 0.103 \text{ (kg CO}_2\text{/MJ)}$$

$$(EX_{\text{CO}_2})_{\text{RE}} = 5 \text{ (MJ/kg CO}_2\text{)}$$

Combining these data and results obtained in previous part of this chapter with Eqs.(4.17) and (4.18), the exergy needed to recover equivalent CO₂ emission and the TERE values for selected heat pump systems are:

► Air-source heat pump:

$$\begin{aligned} (EX_{\text{fuel,R}})_{\text{RE}} &= (ex_{\text{CO}_2})_{\text{EC}} \times \frac{TEWI_{\text{EC}} + (EWI_{\text{CH}})_{\text{RE}}}{(1+A) - (ex_{\text{CO}_2})_{\text{RE}} \times [\beta_{\text{fuel}} + A \times \beta_{\text{mat}}]} \\ &= 5 \times \frac{61,550 \times 10^{-3}}{(1+0.08) - 5 \times (0.103 + 0.08 \times 0.103)} = 590 \text{ (GJ)} \end{aligned}$$

$$(EX_{\text{mat},R})_{RE} = A \times (ex_{CO_2})_{RE} \times \frac{TEWI_{EC} + (EWI_{CH})_{RE}}{(1+A) - (ex_{CO_2})_{RE} \times [\beta_{\text{fuel}} + A \times \beta_{\text{mat}}]}$$

$$= 590 \times 0.08 = 50 \text{ (GJ)}$$

$$TERE = 940 + 590 + 50 = 1,580 \text{ (GJ)}$$

The TERE values of ground-source heat pumps can be calculated by using the same method, and the results are given in Table 5.6. Comparison of TERE of the selected heat pump systems are shown in Figures 5.8 and 5.9.

Table 5.6 The TERE values and CO₂ recovery exergy of selected energy conversion systems

	Air-source heat pump	Direct- expansion ground-source heat pump	Vertical ground- coupled heat pump
Fuel resource exergy of CO ₂ recovery (GJ)	590	710	500
	37%	44%	38%
Material resource exergy of CO ₂ recovery (GJ)	50	60	40
	3%	4%	3%
Total resource exergy of CO ₂ recovery (GJ)	640	770	540
	40%	48%	41%
Total resource exergy of energy conversion system (GJ)	940	850	780
	60%	52%	59%
Total equivalent resource exergy (TERE) (GJ)	1,580	1,620	1,320

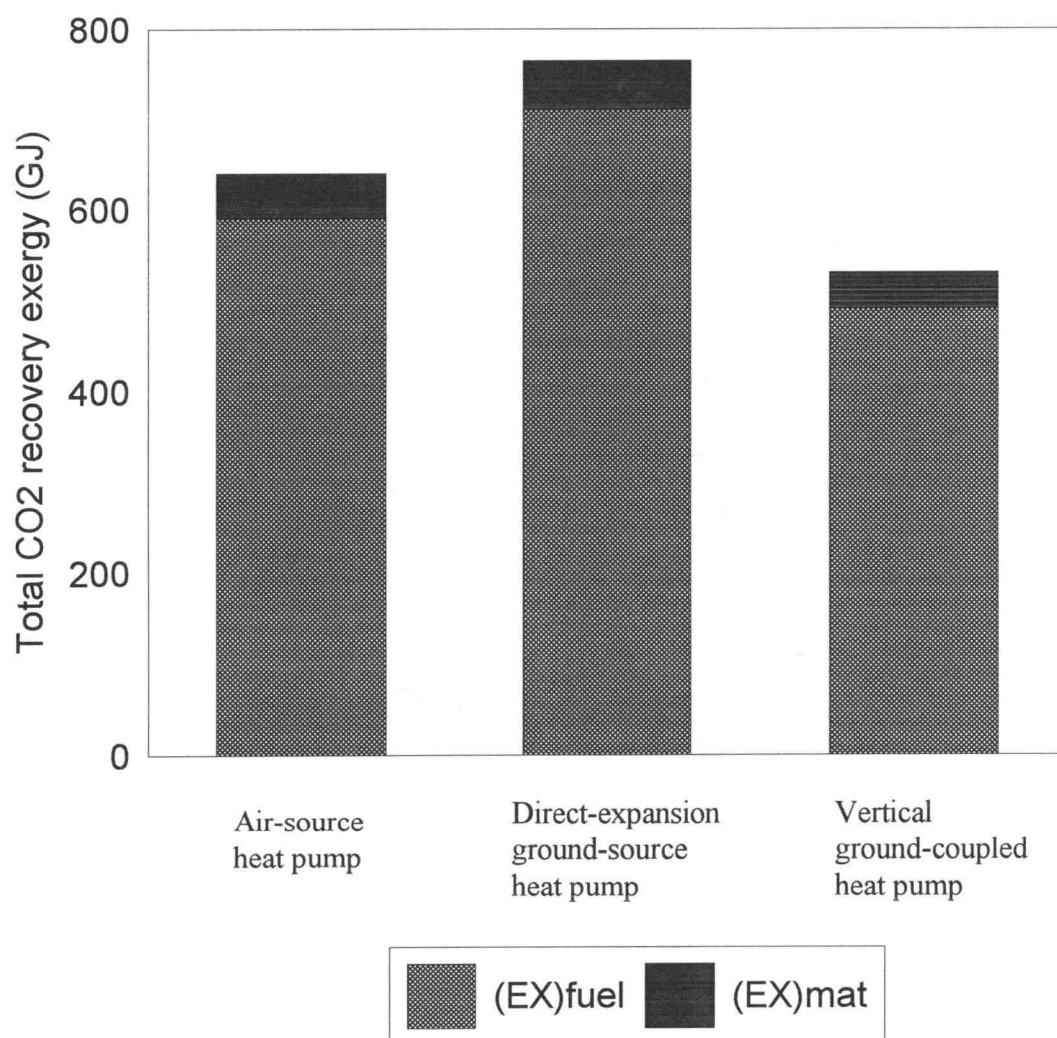


Figure 5.8 The total CO₂ recovery exergy for selected heat pump systems

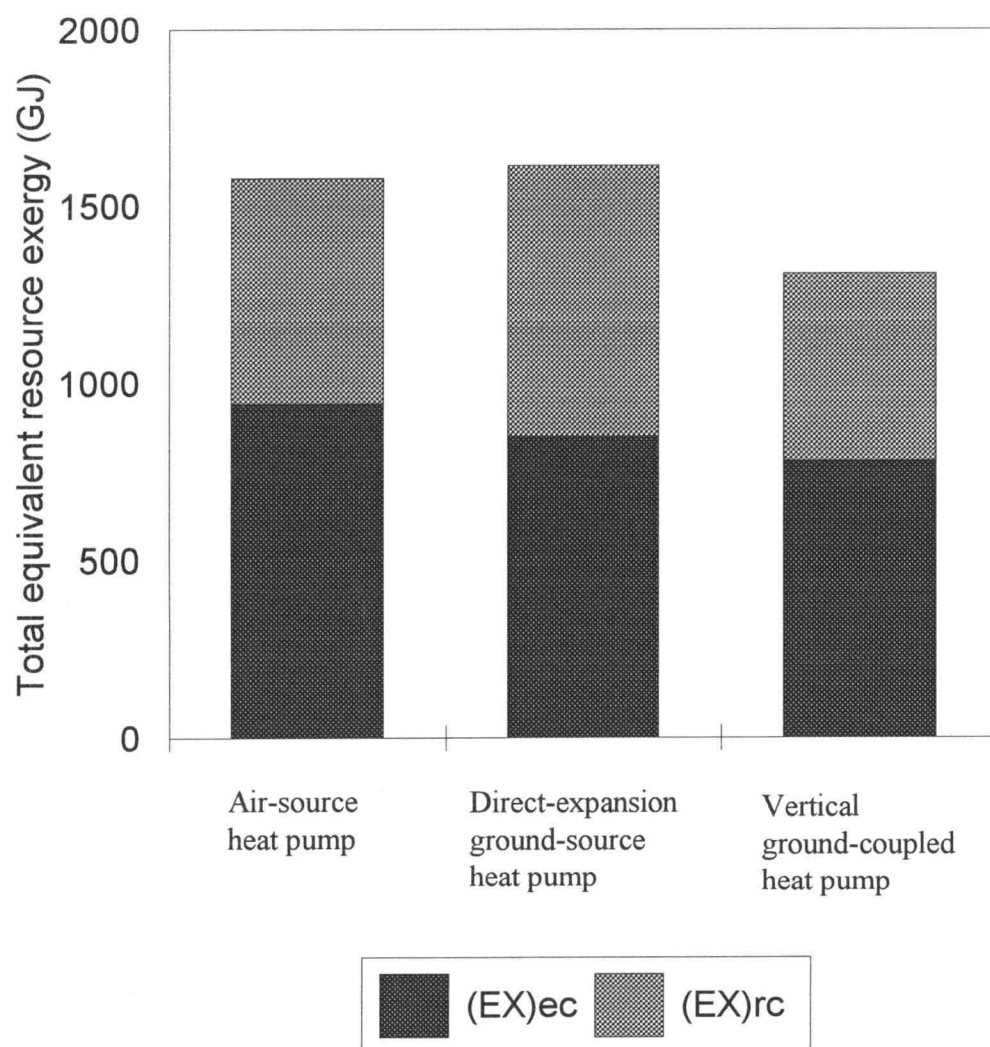


Figure 5.9. The Total Equivalent Resource Exergy (TERE) for selected heat pump systems

5.5 CONCLUSION

The work presented in this chapter illustrates the calculation procedure of the total resource exergy, total equivalent global warming impact (TEWI) and total equivalent resource exergy (TERE) for the general energy conversion systems. The calculation results and the comparison of selected heat pump systems for the specific case are shown. The major conclusions drawn from the calculation are:

- ▶ The total equivalent resource exergy (TERE) proposed in the previous chapter, which includes the resource exergy consumed by the energy conversion system and exergy needed to recover the global warming gases, allows an overall comparison of energy conversion systems. From the calculation results, it can be seen that if only system exergy consumption is considered, the direct-expansion heat pump uses less resource exergy than the of air-source heat pump. However, using TERE as a criterion to analyze and compare these energy conversion systems during their life-time, the air-source heat pump system is better than direct-expansion ground source heat pump system considered here. The concept of TERE, which makes the analysis more complete, thus can be used effectively as the objective function for energy conversion system optimization.
- ▶ The calculation results have shown that the system material exergy and associated environment impact are important factors when an energy conversion system is

analyzed completely. Tables 5.4 and 5.5 show that the material resource exergy amounts to about 6% to 12% total resource exergy consumption of the selected heat pump system; and the global warming impact associated with this material exergy consumption amounts to about 10% to 18% of total system global warming impact.

CHAPTER 6.

MATERIAL AND REFRIGERANT RECYCLING

6.1 INTRODUCTION

In the previous chapters, material resource exergy and associated environmental impact have been discussed. In this chapter, the focus of the study will shift to the secondary production of materials and refrigerants (recycling of materials and refrigerants), which are made from waste materials. The role of refrigerants and materials recycling will be examined and the potential for reduction of the resource exergy, material resources and the associated global environmental impacts will be evaluated.

6.2 MATERIAL AND REFRIGERANT RECYCLING

The calculation and discussion in previous chapters are based on the following two assumptions:

- (1) All materials are produced from the dead state (natural environment).
- (2) All materials will go to waste and become irrecoverable at the end of system equipment lifetime.

The evaluation has shown all materials contain exergy (chemical exergy and primary production exergy). Exergy is used to produce materials from the natural environment (dead state). So when materials are used, exergy is used, and with

the consumption of materials and exergy, there is associated with environmental impacts. When the energy conversion system equipment reaches the end of its life-time, the exergy within the materials as well as the material itself (one of the natural resources) is still useful. These used materials can be recycled and served as "ores" of new material. Figure 6.1 shows this recycle process. In Chapter 3, the calculation equation for the resource exergy of material has been discussed and been given by Eq.(3.2):

$$EX_{mat,R} = EX_{mat,C} + \Sigma(EX_{mat,P_i}) \quad (3.2)$$

For the recycling materials, the resource exergy can be expressed as:

$$(EX_{mat,R})^{Recycle} = EX_{mat,C} + \Sigma(EX_{mat,P_i})^{Recycle} \quad (6.1)$$

Comparing Figure 6.1 and Figure 3.5 and these two equations, it can be found that for the material recycling process, there are used material collection and pre-treat sub-processes instead of raw material ore exploration, mining and extraction sub-processes; the difference between the material resource exergy, $EX_{mat,R}$, and the recycled material resource exergy, $(EX_{mat,R})^{Recycle}$, will depend on the difference of the exergy input in these two different processes.

Previous researchers [(P.F. Chapman and F.Roberts, 1983) and C.R.Fussler and Krummenacher, 1991)] have shown that for

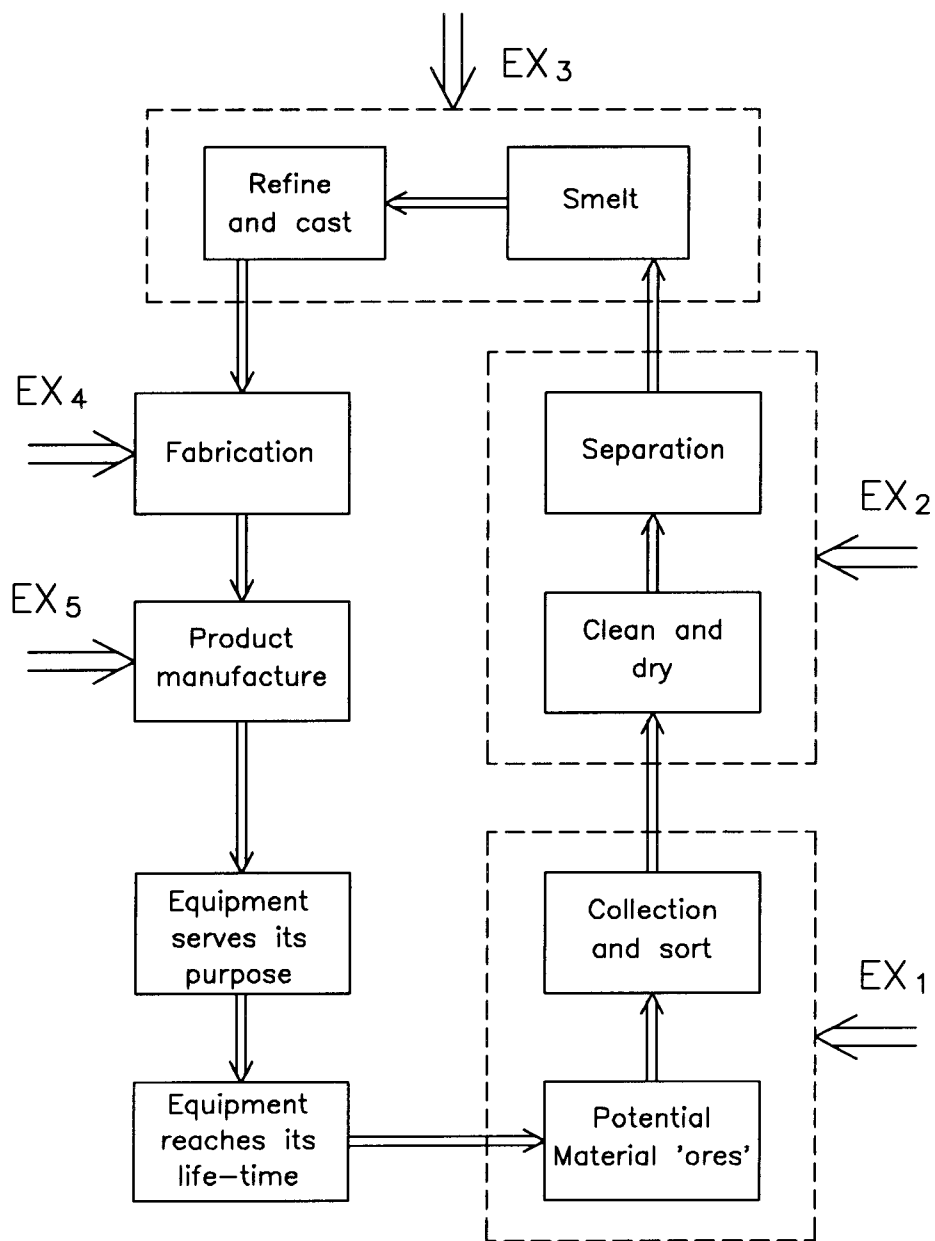


Figure 6.1 Material recycling processes

some materials, the production exergy required for the material recycling process is much less than that of new material production process. That is:

$$\Sigma (EX_{mat,Pi})^{Recycle} \ll \Sigma (EX_{mat,Pi})$$

Or, it can be said that for these materials, the material recycling exergy efficiency $(\eta_{EX,mat})^{Recycle}$ is much larger than new material production efficiency $(\eta_{EX,mat})$:

$$(\eta_{EX,mat})^{Recycle} \gg (\eta_{EX,mat})$$

Table 6.1 gives the some exergy requirements for material production from natural environment (primary production) and from recycling material (secondary production).

Table 6.1 Comparison of the exergy requirement for primary and secondary material production

Material	Primary (MJ/kg)	Secondary ^a (MJ/kg)
Steel	40	9
Thermoplastic polymers ^b	14.2	5.7
Copper	100	20
Aluminum	270	17

a: Excludes the pre-treat exergy.

b: Excludes hydrocarbon chain exergy value.

Source:

(1) Chapman et al., 1983.

(2) Fussler et al., 1991.

Since recycled materials (secondary production materials) consume less exergy than the primary production materials, so the more used materials to be recycled, the more exergy and natural resource to be saved and less environmental impact. Currently, the recycled materials are usually mixed with primary production materials to new make material products. Figure 5.2 shows this production process. For this mixed material production process, the total resource exergy of the mixed material is given as:

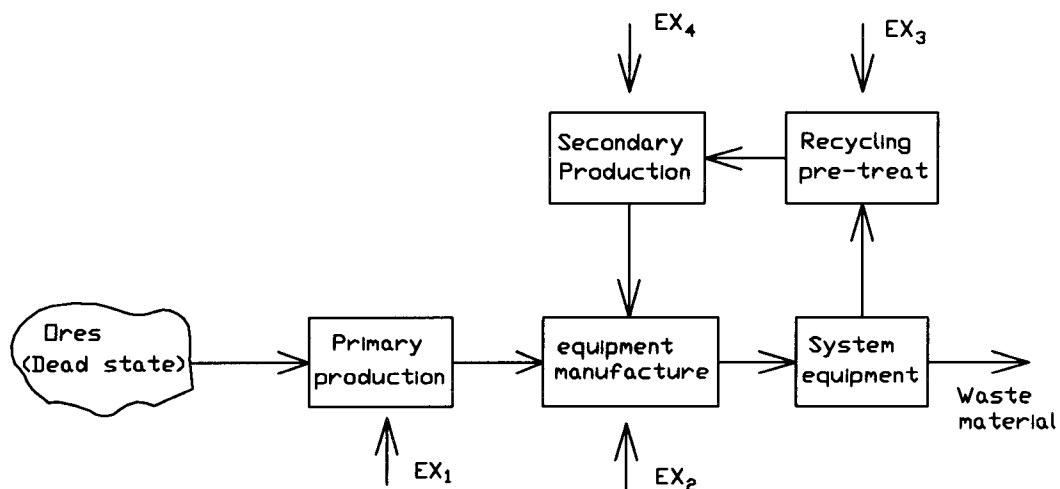


Figure 6.2 Material production processes with part of recycling material

$$(EX_{mat,R})_{mix} = EX_{mat,C} + \delta_1 \times \Sigma (EX_{mat,P_i}) + \delta_2 \times \Sigma (EX_{mat,P_i})^{Recycle} \quad (6.2)$$

where: δ_1 , δ_2 are mass fraction of raw material and recycled material in the material production product respectively.

Then, the material production efficiency is given as:

$$\eta_{EX} = \frac{EX_{mat,C}}{EX_{mat,C} + \delta_1 \times \Sigma (EX_{mat,P_i}) + \delta_2 \times \Sigma (EX_{mat,P_i})^{Recycle}} \quad (6.3)$$

From Table 4.1 in Chapter 4, it can be seen that the global warming potential indexes of refrigerants (CFCs) can be quite high. Thus, global warming impact caused by one kilogram of refrigerant (CFCs) released to the atmosphere will be equal to the impact by releasing thousands of kilograms of CO₂. So it has become important to reduce refrigerant leakage and recycle the refrigerant at the end of the system life-time. This is evident in Eq.4.4:

$$EWI_{CH} = (\alpha_1 \times Y + \alpha_2) \times M_{CH} \times GWP_{CH} \quad (4.4)$$

where it is important to reduce the annual loss rate (α_1) and disposal loss (α_2) to as small of value as possible.

The following example will show how recycling materials influences the total resource exergy consumption and associated global warming impact. Considering an air-source heat pump system and a direct-expansion ground-source heat pump system, the design data are given in Table 6.2. For

Case 1, the design data of the two systems are exactly same as discussed in Chapter 5; for Case 2, the systems will have less annual refrigerant leakage, less disposal loss and use some recycled materials. Determining the total resource exergy consumption and global warming impact for their life-time. Using the results in Table 6.1 and obtained in Chapter 5, the total resource exergy consumption, associated with global warming impact and total equivalent resource exergy for these system are given in Figures 6.3, 6.4 and 6.5.

Table 6.2 Design and performance data of selected heat pump systems

	Air-source heat pump		Direct-expansion ground-source heat pump	
	Case 1	Case 2	Case 1	Case 2
Refrigerant type	HCFC-22	HCFC-22	HCFC-22	HCFC-22
Refrigerant (charge kg)	2.44	2.44	12.7	12.7
End use efficiency	2.44	2.44	2.85	2.85
Life-time (year)	15	15	15	15
Refrigerant annual loss rate (α_1)	4%	2%	4%	2%
Refrigerant disposal loss (α_2)	50%	20%	50%	20%
Recycled materials (%)	0	40%	0	40%
Steel (kg)	350	350	310	310
Copper (kg)	45	45	365	365
Aluminum (kg)	30	30	15	15

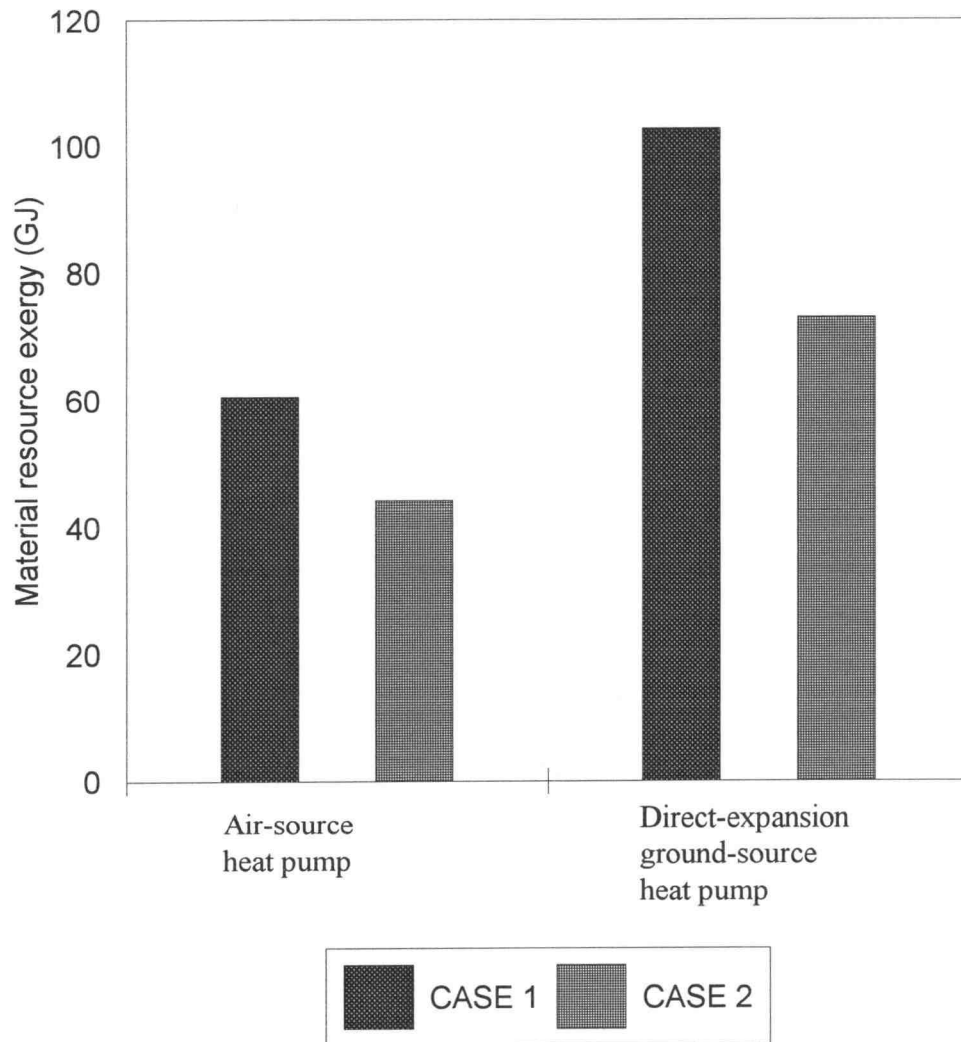


Figure 6.3 Comparison of material resource exergy consumption of two heat pump systems for two different working conditions

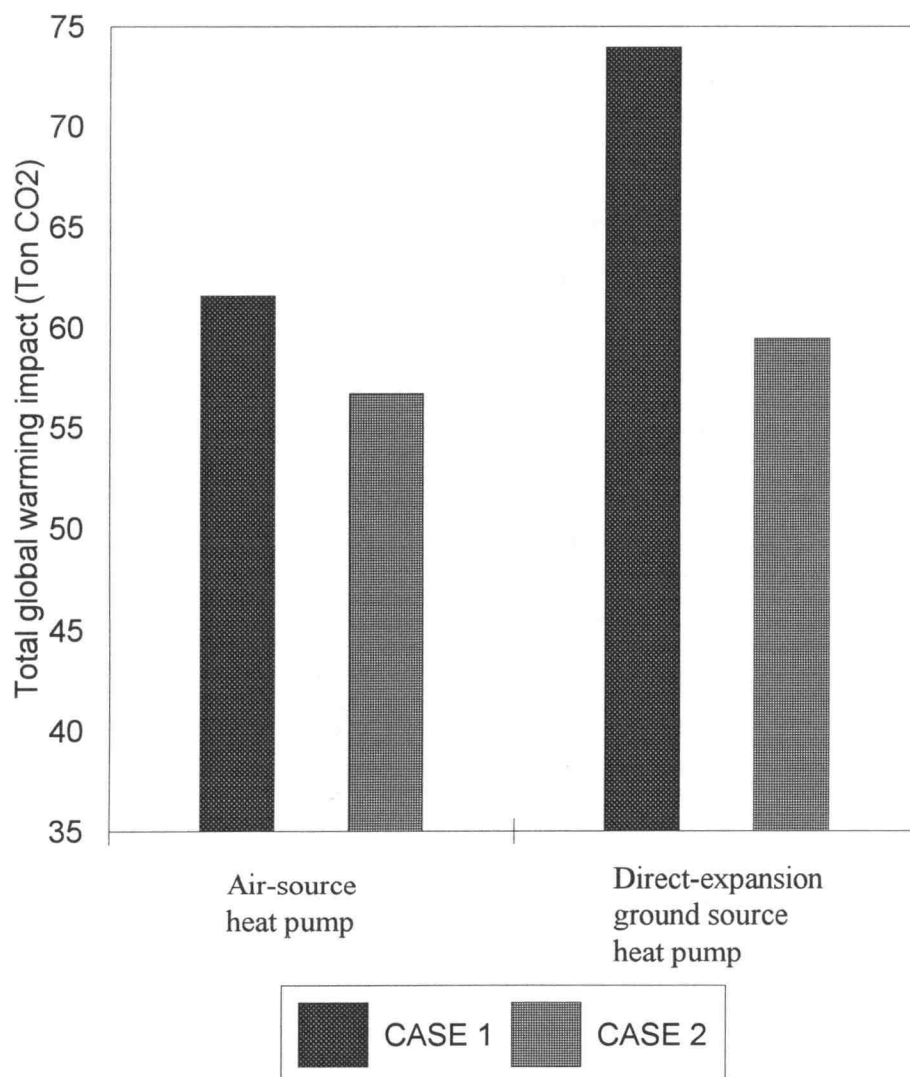


Figure 6.4 Comparison of the total global warming impact (TEWI) of two heat pump systems for two different working conditions

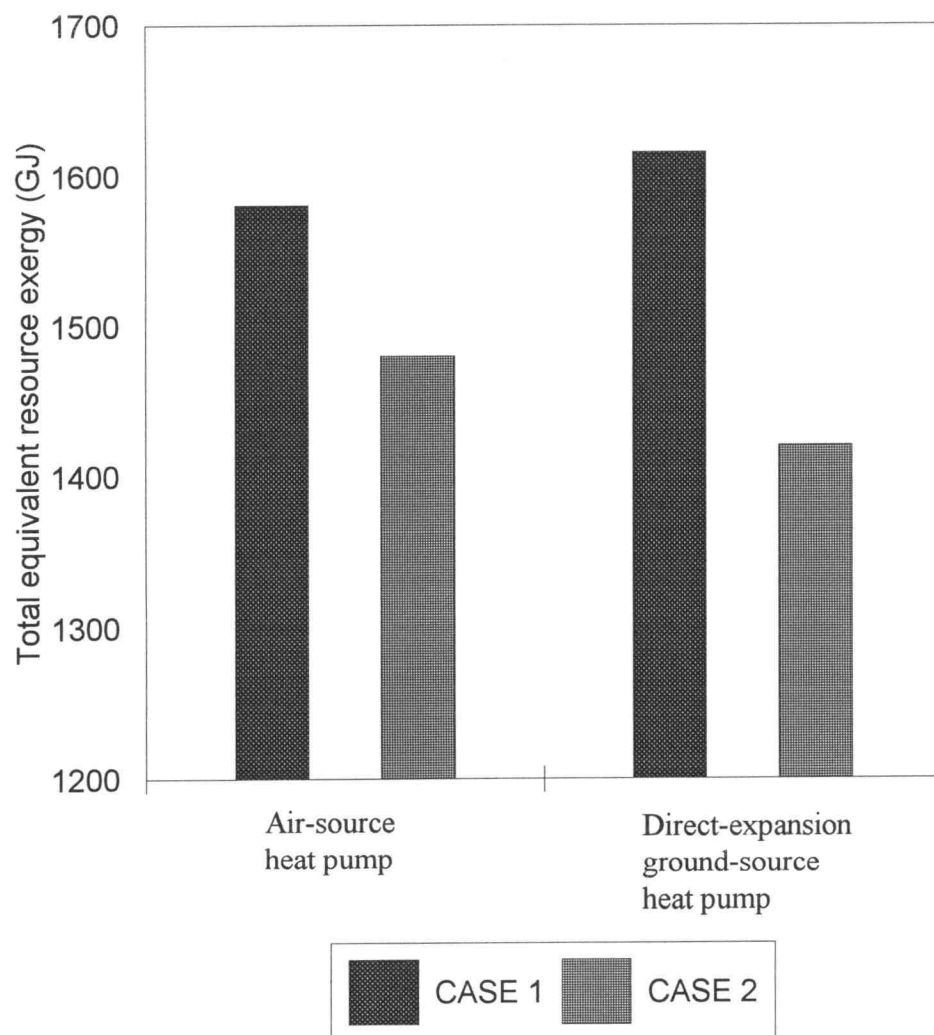


Figure 6.5 Comparison of the total equivalent resource exergy (TERE) consumption of two heat pump systems for two different working conditions

6.3 DISCUSSION

A discussion and an evaluation of the potential exergy saving by recycling materials and refrigerants were presented in this chapter. Although the evaluation is preliminary, it still shows that recycling old materials and refrigerants after the end of system life-time is a positive way to reduce system resource exergy consumption and associated environmental impact and influence system selection. From the calculation and discussion of selected heat pump systems in Chapter 5, it concludes that using TERE as a criterion, the air-source heat pump system, which has TERE value 1,580 GJ, is better than the direct-expansion ground-source heat pump system (TERE value of 1,620 GJ). However, the results in Figure 6.5 shows that if the systems using some recycled materials, reduce refrigerant leakage and recycle more refrigerant at the end of the system life-time, the direct-expansion heat pump system with a TERE value of 1,420 GJ will save more resource exergy than the air-source heat pump system with a TERE value of 1,480 GJ. This result shows that during the heat pump design and optimization, material and refrigerant recycle may be the trade-off between one system and another. It also should be noted that after years of mining and extraction ores in the natural environment have declined. Thus, more exergy will be consumed in extracting and hauling waste rock, and in crushing of the ores. So recycling will not only save resource exergy, but also the limited material resources.

Traditionally, whether the system is easy to recycle or not is not an important consideration for an energy conversion system designer. But if one takes a life-cycle view, it must be recognized that the principles of increasing recyclability (using easily recycled materials, ease of system disassembly, etc.) should be of concern to the energy conversion system designer.

CHAPTER 7.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The major conclusions drawn from this work and recommendation for potential future research work are presented in this chapter.

7.1 CONCLUSIONS

A general method for energy conversion system analysis is presented in this thesis. This method uses exergy as a measure to compare and analyze the natural resource consumption (both fuels and materials) and the global warming impact of different energy conversion systems for their life-time. The method, which makes the analysis more complete, can be used for energy conversion system design and optimization.

The process analysis method, which adds the fuel production exergy and material exergy into the consideration, allows more complete exergy analyses to be conducted. The method developed in this thesis is designed to include concerns about the natural resources, where, the assessment of environmental friendliness is based not only on the direct exergy consumption, but also on the overall system and life-cycle view of the energy conversion system including materials for equipment, working fluids etc.

The global warming impact due to the chemical emissions and impact associated with direct exergy consumption (fuel

consumption) as well as system equipment materials consumption of the energy conversion system are considered together in this thesis.

Based on the concept of exergy, the total equivalent resource exergy (TERE), which includes both direct resource exergy consumption and resource exergy needed to recover the total equivalent global warming gases of the energy conversion system, is proposed in this thesis. TERE uses exergy as a criterion to compare the energy conversion systems and providing information of how effective a system is regarding the use of natural resources (both fuels and materials). The calculation of TERE values for the selected energy conversion systems indicates that the resource exergy of the energy conversion system and environmental impact exergy are both substantial impacts and should be compared together. This concept of TERE which combines these can be used as the objective function for the system design and optimization.

Even though the application equation of TERE presented in this thesis is only for the global warming impact. It appears that it can be extended for many other global environmental impacts to be considered during the energy conversion system analysis.

A general application using the method and associated equations proposed in the thesis shows that the system material exergy and its associated global warming impact are important factors when the energy conversion system is

analyzed completely. The results shows that for the systems selected, material resource exergy amounts to about 7% to 12% total system resource exergy; and the global warming impact associated with this material exergy consumption amounts to about 10% to 18% total system global warming impact.

A discussion and an evaluation of the potential exergy saving by recycling materials and refrigerants are presented in this thesis. The preliminary evaluation shows that the recycling is a positive way to reduce system resource exergy, and natural resources (material) consumption as well as associated global warming impact. The calculation results also shows that during the energy conversion system design and optimization, material and refrigerant recycling may be significant trade-off options between one system and another.

7.2 RECOMMENDATIONS FOR FUTURE WORK

Some areas of potential future work that needs to be accomplished are:

- ▶ Material production exergy is one of the key factors for the energy conversion system analysis. However, existing data about material production exergy (especially for the recycling production exergy) is limited. Accurate material production exergy needs to be evaluated; this would assist more precise system analysis.
- ▶ The application of TERE in this thesis only includes the

global warming environmental impact. Work extending the TERE to other global environmental impacts is recommended. This would allow the method proposed in this thesis to be more complete.

- The analysis method and concept of TERE developed in this thesis make the system analysis more complete. The use of TERE as the objective function for energy conversion system design and optimal is recommended for optimization and evaluation of potential candidate energy conversion systems being developed.

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APPENDICES

APPENDIX A.

CALCULATION OF EXERGY CONTENT OF FUELS AND MATERIALS
AND THE FUEL PRODUCTION AND DELIVERY EXERGIES

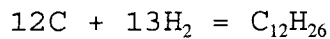
The calculations in this work are based the following assumption:

The fuels or materials under the consideration are at the standard state. That is the temperature T and pressure P of the fuels or materials are equal to those of the dead state, i.e. T_0 and P_0 ; and $T_0 = 298.15 \text{ K}$, $P_0 = 1 \text{ atm}$.

For a pure fuel or material, the exergy content of the fuel or material can be evaluated by using Eq.(2.4):

$$EX_{\text{fuel,C}} = \Delta_f G^0 + \sum n_i \times EX_{\text{ch,i}} \quad (2.4)$$

For example: diesel ($\text{C}_{12}\text{H}_{26}$), the reaction of formation can be expressed as:



The exergy balance of reaction of formation of diesel is:

$$12 \times EX_{\text{ch,C}} + 13 \times EX_{\text{ch,H}_2} + \Delta_f G^0_{\text{C}_{12}\text{H}_{26}} = EX_{\text{ch,C}_{12}\text{H}_{26}}$$

Introducing:

$$\Delta_f G^0_{\text{C}_{12}\text{H}_{26}} = 50.1 \text{ (kJ/mol)}$$

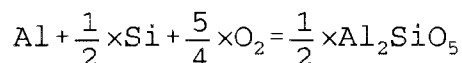
$$EX_{\text{ch,C}} = 410.26 \text{ (kJ/mol)}$$

$$EX_{\text{ch,H}_2} = 236.1 \text{ (kJ/mol)}$$

[(Szargut. 1988) and (Reid. 1987)],

$$\begin{aligned} EX_{ch,C12H26} &= 12 \times 410.26 + 13 \times 236.1 + 50.1 = \\ &= 8,042.5 \text{ (kJ/mol)} = 47.3 \text{ (MJ/kg)} \end{aligned}$$

This method can also be used to calculate the exergy content of a specific material, such as aluminum (Al). The exergy balance of reaction of formation of Al is:



$$EX_{ch,Al} = -\frac{1}{2} \times \Delta_f G^0_{Al_2SiO_5} - \frac{1}{2} \times EX_{ch,Si} - \frac{5}{4} \times EX_{ch,O_2} + \frac{1}{2} \times EX_{ch,Al_2SiO_5}$$

Introducing free energy of formation and chemical exergy of the elements, the exergy content of Al is:

$$\begin{aligned} EX_{ch,Al} &= \frac{1}{2} \times 2,625.8 - \frac{1}{2} \times 854.6 - \frac{5}{4} \times 3.97 + \frac{1}{2} \times 15.4 \\ &= 888.4 \text{ (kJ/mol)} = 32.93 \text{ (MJ/kg)} \end{aligned}$$

For a multicomponent fuel such as coal, Eq.(3.1) can be used to evaluate the exergy content. Considering the mass fraction of coal is: 86% of C, 5.5% of H₂, 2.5% of N₂ and 6% of O₂. Eq.(3.1) gives:

$$\begin{aligned} (EX)_{coal,C} &= 8177.79 \times 0.86 + 5.25 \times 0.025 + 27892.63 \times 0.055 - \\ &\quad 3173.66 \times 0.06 + 0.15 \times 0.06 \times \{7,837.67 \times 0.86 + \\ &\quad 33,888.89 \times 0.055 - 4,236.1 \times 0.06\} \\ &= 8,451.9 \text{ (kcal/kg)} = 35.39 \text{ (MJ/kg)} \end{aligned}$$

Using the same procedure, the exergy content of multicomponent fuels (such as natural gas, which the mass

fraction is 67.8% of C, 3.5% of H_2 and 9.9% of N_2) can be calculated.

As discussed above, it is not easy to calculate the production and delivery exergy of fuel and material. Here electricity is used as an example to describe how to calculate the production and delivery exergy. Figure A1 is the electricity production process. The production exergy of electricity can be calculated by using process analysis. The fuel production efficiency η_1 and fuel delivery efficiency η_2 are given as:

$$(\eta_1 \times \eta_2)_{\text{coal}} = 0.945$$

$$(\eta_1 \times \eta_2)_{\text{oil}} = 0.827$$

$$(\eta_1 \times \eta_2)_{\text{natural gas}} = 0.875$$

electricity generation efficiencies η_3 :

$$\text{thermal efficiency: } \eta_3 = 0.35$$

$$\text{hydro efficiency: } \eta_3 = 0.83$$

$$\text{nuclear efficiency: } \eta_3 = 0.30$$

and delivery of electricity efficiency η_4 :

$$\eta_4 = 0.864.$$

The exergy input at electric utilities in U.S.A. in 1991 is given at Table A1. (Energy Information Abstracts Annual 1992) Assuming primary fuel production and delivery efficiencies of hydro, nuclear and other are 100%, the values for the U.S.A. in 1991 are:

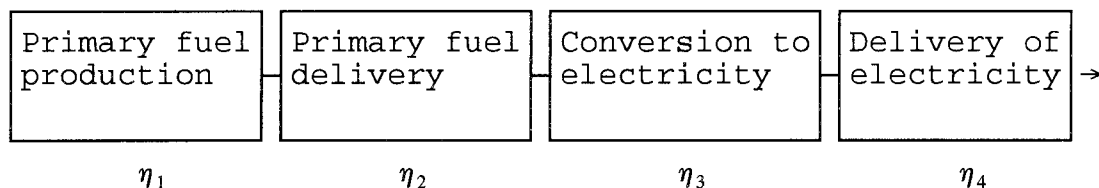


Figure A1 Production sequence of electricity.

Table A1 Exergy input at electric utilities. (1991)
(Quadrillion Btu)

Coal	Natural gas	Oil	Nuclear electric power	Hydro electric power	Other	total
16.1	2.883	1.178	6.542	3.05	0.192	29.91
53.74%	9.64%	3.94%	21.9%	10.2%	0.644%	100%

$$\begin{aligned}
 (\eta_1 \times \eta_2)_{\text{ave}} &= 0.5372 \times 0.945 + 0.0394 \times 0.827 + 0.0964 \times 0.875 \\
 &\quad + (0.2187 + 0.102 + 0.00644) = 0.9517 = 95.17\%
 \end{aligned}$$

$$\begin{aligned}
 (\eta_3)_{\text{ave}} &= (0.5372 + 0.0964 + 0.0394) \times 0.35 + 0.102 \times 0.83 + \\
 &\quad (0.2187 + 0.00644) \times 0.30 = 0.387 = 38.7\%
 \end{aligned}$$

thus, the total efficiency of electricity production and delivery in the U.S.A. in 1991 is:

$$(\eta_{\text{EX}})_{\text{total}} = \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 = 0.9517 \times 0.387 \times 0.864 = 0.318 = 31.8\%$$

Knowing the production exergy efficiency, the production exergy can be evaluated. Using Eq.(3.4), the production exergy of electricity in the U.S.A. in 1991 is:

$$\begin{aligned}
 EX_{\text{ele,P}} &= EX_{\text{ele,C}} \div \eta_{\text{EX}} - EX_{\text{ele,C}} \\
 &= 3.6 \div 0.318 - 3.6 = 7.72 \text{ (MJ)}
 \end{aligned}$$

$$EX_{\text{ele,R}} = EX_{\text{ele,C}} + EX_{\text{ele,P}} = 7.72 + 3.6 = 11.32 \text{ (MJ)}$$

APPENDIX B.

CO₂ EMISSION FROM MATERIAL RESOURCE EXERGY
CONSUMPTION AND ELECTRICITY GENERATION

Several different sources of information are used in this work to estimate the CO₂ emission from material resource exergy consumption and from electricity generation. This appendix provides the details of the estimating procedure and some comparisons with values from others.

► 1. CO₂ emission from electricity generation:

Table B1 presents typical compositions of fuels and Table B2 lists fuel resource exergy values. Using the data of these two tables, the CO₂ emission associated with different fuels for one MJ material resource exergy are as presented in Table B3.

Table B1 Mass Fractions of the Elements of Fuels

Fuel	C	H ₂	N ₂	CO ₂ (kg/kg Fuel ¹)
Coal	0.86	0.055	0.025	3.15
Natural gas	0.678	0.035	0.099	2.48
Fuel oil	0.85	0.14	0.01	3.12

Source: Szargut, 1988.

1: Assuming complete combustion.

Table B2 Resource Exergy of Fuel

Fuel	Exergy content (MJ)	Resource exergy (MJ)
Coal	35.39	36.78
Natural gas	46.77	53.93
Fuel oil	45.45	54.34
Electricity (1 kWh)	3.6	11.32

Table B3 CO₂ Emission Associated with One MJ Resource Exergy

Fuel	CO ₂ emission (kg)
Coal	0.089
Natural gas	0.053
Fuel oil	0.069

Using Table B2 and Table B3, the CO₂ emission associated with one kWh electricity generation from any specific fuel source can be evaluated; these are presented in Table B4. Combining Table B4 with Table 4.3, the CO₂ emission associated with one kWh of electricity generation in the United States is:

CO₂ emission of one kWh electricity

$$\begin{aligned}
 &= 0.537 \times 1.01 + 0.096 \times 0.60 + 0.04 \times 0.78 + 0.219 \times \\
 &\quad \times 0.008 + 0.108 \times 0.007 = 0.64 \text{ (kg CO}_2\text{)}
 \end{aligned}$$

Table B4 CO₂ Emission Associated with
1 kWh Electricity Generation

Fuel	CO ₂ emission (kg/kWh)
Coal	1.01
Natural gas	0.60
Fuel oil	0.78
Nuclear	0.008 ¹
Hydro and other	0.007 ¹

1: Source: San Martin, 1989.

► 2. CO₂ emission from material resource exergy:

Combining the above data with the industrial energy consumption by source in the United States (see Table 4.2), on average, the CO₂ emission associated with one MJ of resource exergy is:

$$\begin{aligned}
 &\text{CO}_2 \text{ emission of one MJ resource exergy} \\
 &= 0.0876 \times 0.089 + 0.295 \times 0.053 + 0.272 \times 0.069 + \\
 &\quad + 0.344 \times 0.178 = 0.103 \text{ (kg)}
 \end{aligned}$$

► 3. Comparison of results with values from others:

Prior studies by Marland et al.(1983), San Martin (1989), Fischer et al.(1991) and Yau et al. (1991) presented some results and procedure of estimating carbon dioxide emissions associated with fossil fuel consumption and electricity generation. Tables B5 and B6 present results from these prior studies and the values of this work.

Table B5 Comparison of Carbon Dioxide Emission
from Electric End-uses of Energy (kg/1kWh)

Fuel	Fischer (1991)	Yau (1991)	Robert (1989)	This work
Coal	1.14	1.082	0.964	1.01
Fuel oil	0.96	0.875	0.726	0.78
Natural gas	0.58	0.61	0.484	0.60
Nuclear	0.0	0.0	0.008	0.008
Hydro and other	0.0	0.0	0.007	0.007
Average	0.672	0.73		0.64

notes:

Fischer's data are based on the results of Marland and using the combined efficiency 0.297 for electricity generation and transmission; the average value is for North America.

Yau's results are for the years 2000: assumptions are based on EPRI Technical Assessment Guide Assumptions.

Table B6 Fuel Consumption at Electric Generation

Fuel	Fischer (1991)	Yau (1991)	This work
Coal	37%	53%	53.7%
Fuel oil	19%	8.9%	4.0%
Natural gas	12%	12.9%	9.6%
Nuclear	13%	17.5%	21.9%
Hydro and other	19%	7.5%	10.8%

Notes:

Fischer's data are based on the North America electric power generation.

Yau's data are based on EPRI Regional System and EPRI Technical Assessment Guide Assumptions.

This work's data are based on "Energy Information Abstracts Annual" 1992.