ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

EXTENDED EXERGY ACCOUNTING (EEA) ANALYSIS OF TURKISH SOCIETY- DETERMINATION OF ENVIRONMENTAL REMEDIATION COSTS

Ph.D. THESIS

Candeniz SEÇKİN

Department of Energy Science and Technology

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

GENİŞLETİLMİŞ EKSERJİ ANALİZİ METODUNUN TURKİYE UYGULAMASI – CEVRESEL ETKİ MALİYETLERİNİN BELİRLENMESİ

DOKTARA TEZİ

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ŞUBAT 2013

Candeniz Seçkin, a **Ph.D.** student of ITU **Institute of Energy/ Graduate School of Energy Science and Technology** student ID 301052004, successfully defended the **thesis/dissertation** entitled "**Extended Exergy Accounting (EEA) Analysis of Turkish Society- Determination of Environmental Remediation Cost**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my beloved father İnal SEÇKİN,

FOREWORD

In the long period of time that passed between the beginning and the delivery of this Ph.D. thesis, there have been many people who have strongly influenced the destiny of this work. I have learnt a lot from all of them, both personally and professionally. In this Foreword, I would like to mention some of these people and express my gratitude for each and every of them.

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I have had problems in this thesis and every time they dealt with my problems as if they were their own. I am really lucky to have friends like them.

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August 2012

Candeniz SEÇKİN
(Mechanical Engineer, M.Sc.)

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ABBREVIATIONS

A	: Abroad
AC	: Annual cost
AD	: Anaerobic digestion
AG	: Agricultural Sector
BOI_5	: Biochemical oxygen demand
C	: Celsius degree
CAA	: Canadian Automobile Association
CDP	: Cumulative degree of perfection
CEENE	: Cumulative exergy extraction from the natural environment
CExC	: Cumulative exergy consumption
CExD	: Cumulative exergy demand
CHP	: Combined heat and power plant
CO	: Conversion Sector
COD	: Chemical oxygen demand
Dancee	: The Danish Cooperation for Environment in Eastern Europe
DM	: Dry matter
DO	: Domestic Sector
ECN	: Energy Research Center for Netherlands
EDANA	: European Disposables and Nonwovens Association
EEA	: Extended exergy accounting
EIA	: U.S. Energy Information Administration
ELCA	: Exergetic life cycle analysis
ELV	: End of Life Vehicle
ENV	: Environment
EPA	: European Environment Agency
Eurostat	: European Union Statistical Department
EX	: Extraction Sector
FAO	: Food and Agriculture Organization of United Nations
FCC	: Fluid catalytic cracking
GJ	: Giga Joule (10^9 J)
HHV	: High heating value
IC	: Investment cost
IEA	: International Energy Agency
IGCC	: Integrated gasification combined cycle
IN	: Industrial Sector
Ind.	: Industry
IUV	: In use vehicles
J	: Joule
K	: Kelvin
KJ	: Kilo Joule (10^3 J)
KW	: Kilo-watt
kWh	: Kilo-what-hour (3600 KJ)

l	**:** liter
LASDER	**:** Turkish Tire Industrialists Association
LCA	**:** Life cycle assessment
LCEA	**:** Life cycle exergy analysis
LHV	**:** Low heating value
LPG	**:** Liquefied petroleum gas
LULUCF	**:** Land-use, land use change and forestry
MJ	**:** Mega Joule (10^6 J)
MREC	**:** Midwest Rural Energy Council
MRF	**:** Materials Reprocessing Facility
MSW	**:** Municipal solid waste
NACE	**:**Statistical classification of economic activities in the European Community
ODM	**:** Organic dry matter
OM	**:** Organic matter
OP	**:** Fixed and varying operation costs
ORC	**:** Organic Rankine Cycle
SWAP	**:** Save Waste & Prosper
tDM	**:** Ton dry matter
TE	**:** Tertiary Sector
TEP	**:** Tons equivalent of petroleum (41,868 GJ)
TJ	**:** Tera Joule (10^{12} J)
TL	**:** Turkish Lira
TN	**:** Total nitrogen
TP	**:** Total phosphorus
TR	**:** Transportation Sector
TRP	**:** Transportation line
TSS	**:** Total suspended solids
TUGEM	**:** Republic of Turkey, General Directorate of Agricultural Production and Development
TUKDER	**:** Union of Turkish Brick and Tile Producers
TUPRAS	**:** Turkish Petroleum Refineries Corporation
Turkstat	**:** Turkish Statistical Institute
Tusiad	**:** Turkish Industry and Business Association
UNDP	**:** United Nations Development Programme
UNEP	**:** United Nations Environment Programme
W	**:** Watt
YEM	**:** Construction Industry Center of Turkey

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LIST OF SYMBOLS

ar	: As received
C	: Capital
c	: Chemical concentration
$\mathbf{c_P}$	: Specific heat capacity at constant pressure
E	: Exergy
e	: Specific exergy
EE	: Extended exergy
ee	: Specific extended exergy
$\mathbf{EEA_{eff}}$	: EEA efficiency
$\mathbf{ee_C}$	: Exergetic equivalent of capital
$\mathbf{ee_L}$	: Exergetic equivalent of labour
$\mathbf{E_{in}}$	: Global exergy input into the society
En	: Energy
ENV	: Environment
$\mathbf{e_{surv}}$	: Minimum pro-capite exergy requirement for survival
$\mathbf{E_{used}}$	: Exergy consumed by the entire population
f	: Exergy consumption amplification factor
G	: Gibbs Free Energy
g	: Gravity
h	: Specific enthalpy
HDI	: Human development index
$\mathbf{HDI_0}$	: Conventional reference HDI (HDI of a primitive society)
$\mathbf{h_{fg}}$	: Enthalpy of the evaporation of water
I	: Solar radiation
L	: Labour, cumulative workhours
m	: Mass
$\mathbf{M_2}$	: Total monetary circulation in the country
n	: Mole number
$\mathbf{N_C}$	: Number of carbon atoms
$\mathbf{N_h}$	: Population numerosity
$\mathbf{N_{wh}}$	: Total number of work-hours generated in the society
P	: Pressure
P	: Product
Q	: Heat
r	: Reaction
R	: Universal gas constant
S	: Global wages in a Country, system
s	: Specific entropy
T	: Temperature
u	: Specific internal energy
V	: Velocity
V	: Volume

W	: Work
x	: Number of molecule group
X_H	: Mass friction of hydrogen
y	: Molar fraction
z	: Element mass fraction
z	: Height
ζ	: Exergy coefficient of solar energy
η_I	: First law efficiency
η_{II}	: Second law efficiency
μ	: Chemical potential
α	: Fraction of the primary exergy embodied into labour
β	: An amplification factor that accounts for the creation of wealth due to exclusively financial activities
β_{HHV}	: Exergy coefficient in terms of HHV
β_{LHV}	: Exergy coefficient in terms of LHV
$	: Dollar
€	: Euro

Subscripts

A	: Area
a	: Atomic ratio
ar	: As received
C	: Capital
ch	: Chemical
d	: Discharge heat
dry	: Dry material
el	: Electrical
ENV	: Environmental remediation
f	: Fuel
f	: Formation
fu	: Sample
g	: Gas (emissions)
geo	: Geothermal
h	: Heat
h+el	: heat and electric
i	: Substance i
input	: input
k	: Kinetic
L	: Labour
lq	: Liquid (wastewater)
M	: Material
output	: Output
p	: Potential
P	: Product
ph	: Physical
PHYS	: Energy carrier
s	: Solid waste
sector	: Sector
shaft	: Shaft
sl	: sludge

solar	**:** Solar
t	**:** Treatment system (remediation system)
total	**:** Total
w	**:** Untreated wastewater
W	**:** Waste
0	**:** Reference environment

Superscripts

0	**:** standard (at reference conditions)

EXTENDED EXERGY ACCOUNTING (EEA) ANALYSIS OF TURKISH SOCIETY- DETERMINATION OF ENVIRONMENTAL REMEDIATION COSTS

SUMMARY

The fact that *source of all activities on earth is the availability of energy and its conversion into different forms* is the motivation of the use of thermodynamic methods in resource use and sustainability analysis. Exergy, by definition, does not identify the ability of humankind to exploit a resource (it is the maximum limit of utulization from the resource but impossible to realize), but is a path-independent property, serving as a metric to measure the theoretically extractable work contained in a resource. As a result, the most promising approach to adequately describe the resource potential and consumption of this potential so far has been addressed as exergy analysis in which exergy (available energy, maximum work generation limit of the resource) is regarded as *utility potential of the resource* and resource depletion is the lost of this potential in the course of material and energy transformations. Application of an exergy based analysis to a society and determining the use of resources in terms of exergy enable to gain a more comprehensive and deeper insight from sustainability point of view, to identify areas where large improvements are needed by applying more efficient technologies. In this thesis, a completely resource-based method of analysis, the Extended Exergy Accounting (EEA) technique, has been applied to the specific case of the Turkish society (on the basis of a 2006 database), to disclose the present situation of the resource use efficiency within the society. EEA is an exergy based method but clearly has some "extended" abilities: EEA enables to convert the so-called "externalities", i.e., the immaterial/non-energetic fluxes of labour, capital and environmental remediation, into their exergetic equivalents. Hence, EEA provides a more comprehensive and deeper insight of the resource consumption and of the environmental impact. This present thesis is intended to provide support for possible structural interventions aimed at the improvement of the degree of resource consumption quality within the country. Following the routine of EEA applications, the Turkish society has been modeled as an open thermodynamic system, interacting with two "external" systems, namely "Environment" and "Abroad", and consisting itself of seven internal subsystems: Extraction-, Conversion-, Transportation-, Agricultural-, Industrial-, Tertiary- and Domestic sector. Furthermore in this thesis, the environmental remediation costs of sectoral solid waste, liquid waste, gas emissions and discharge heat are obtained in accordance with the original calculation procedure proposed by EEA, i.e., without recurring the conversion of monetary equivalent of the environmental remediation (treatment) processes into its exergetic equivalent as it has been applied so far in the literature. As a result, this thesis provides the environmental remediation cost equivalent of considered pollutants for the first time in the literature and the results have the corresponding importance. In the analysis of gas emissions, considering the wide variety of emission gases and due to lack of sufficiently disaggregated data for all types of emissions, three types of greenhouse gases (CO_2, CH_4, N_2O) are

undertaken. Thereby, computed sectoral resource consumption efficiencies are more realistic than those of societal EEA analysis applications which have been performed and presented to date in the literature.

GENİŞLETİLMİŞ EKSERJİ ANALİZİ METODUNUN TURKİYE UYGULAMASI – CEVRESEL ETKİ MALİYETLERİNİN BELİRLENMESİ

ÖZET

Bu tez çalışmasında, kaynak kullanım verimliliği yönünden incelenmek üzere Turkiye örneği ele alınmış, motod olarak Extended Exergy Accounting (EEA, Genişletilmiş Ekserji Analizi) metodu uygulanış ve ulaşılan sonuçlar sunulmuştur. İlk olarak Dr. Enrico Sciubba tarafından geliştirilerek literatüre katılan ve ekserji bazlı bir kaynak kullanım analizi metodu olan EEA metodu, bugüne kadar literatüre katılmış hiçbir metodolojinin yapısında barındırmadığı bir yenilik sunularak, ele alınan sistemin, enerji yada ağırlık birimleri ile ifade edilebilen girdilerin yanında (enerji akışları ve materyal dışında), sisteme olan "diğer" girişlerin - kapital, iş gücü ve çevresel etki - ekserji biriminde ifade edilmesi için yeni bir hesaplama metodu sunulmuştur. Metodun arkasındaki zihniyet, sistemin tükettiği kapital, işgücü ve çevresel etkinin giderilmesi için harcanan ekserjinin üretiminde kaynak kullanıldığı ve adı geçen ekserji tüketimlerinin de sistemin toplam kaynak kullanımı içerisinde ele alınması gerektiğidir. İş gücü ve kapitalin ekserji karşılıkları olarak, bunları yaratmak için gerekli olan kaynak tüketiminin ekserji değeri belirlenmektedir. Çevresel etki olarak ise, sistemden çıkan atığın temizlenmesi için gerekli kaynak kullanımının ekserji karşılığı hesaplanır. Sonuç olarak EEA, sistemin hertürlü kaynak tüketimini tek bir birimle (ekserji) ifade ederek birim bütünlüğünün sağlanmasının yanında, bugüne kadar hiç ele alınmamış olan ek akışların da sistem ekserji dengesi içerisine katılması ile "genişletilmiş ekserji dengesi (extended exergetic balance)" kurulmasını sağlamakta ve adından da anlaşılır şekilde, şu anda literatürde olan en "gelişmiş" ekserji bazlı kaynak kullanım analizi metodunu sunmaktadır. Özetle, EEA metodu ile yapılan analizlerde, sistemin her safhasında kullanılan *malzeme, enerji, kapital, işçilik ve çevresel etki (ele alınan sisteminin atık ve emisyonlarının izin verilen sınırlar dahilinde tutulması için yapılacak işlemler)* gibi faktörlerin hepsi analize katılarak ekserji biriminde ifade edilmiş ve sistemin kaynak kullanımı değerlendirmesine katılmıştır.

Bu çalışmada, sistem olarak ele alınan Türkiye, EEA metodu ile incelenmiştir. Çalışmanın amacı: eylem yapıcı birimlere, ülke içerisinde kaynak kullanım kalitesinin değerlendirilmesi ve ülkenin daha kararlı ve sürdürülebilir çizgide varlığını devam ettirmesi için en mantıklı ve faydalı müdehale noktalarının bildirilmesidir. Çalışmada yapılan uygulama özetlenecek olursa: EEA ile yapılan ülke analizlerinde mutat olduğu üzere, ele alınan ülke 7 sektörel bölüme ayrılmakta ve birbiri arasındaki ekserji alışverişleri analiz edilmektedir. Bu sektörlerin kendi içindeki ekserji akışlarının yanında çevre ile (Environment, ENV) ve diğer ülkeler (Abroad, A) ile etkileşimi de hesaplamalara dahil edilmektedir. Söz konusu 7 sektörel bölüm ve kapsadığı faliyetler şunlardır:

EX (Madencilik Sektörü): Hammadde çıkarma ve işleme (Petrol ve doğal gaz çıkarma ve rafineri işlemleri dahil)

CO (Dönüşüm Sektörü): Enerji üretim tesisleri (rafineriler, ısı ve elektrik üretimi)

AG (Tarım Sektörü): Tarım ve hayvancılık faliyetleri

IN (Endüstri Sektörü): Endüstriyel faliyet kolları (rafineriler hariç)

TR (Ulaştırma Sektörü): Ulaştırma faliyetleri

TE (Servis sektörü): Servis faliyetleri (otel, eğitim, danışmanlık vs. hizmetleri)

DO (Hanehalkı): Ev içi kullanım ve üretime dayalı faliyetler

Yukarıda özetlenen EEA metodolojisinin Türkiye uygulamasının tez içinde sunulmasının yanısıra, bugüne kadar literatürde ilk defa görülür şekilde, sektörel katı, sıvı ve gaz atıkların çevresel etki maliyetleri, EEA metodu içerinde sunulan orjinal tanım ve teori doğrultusunda hesaplanmıştır. Diğer bir değişle, bugüne kadar literatürde uygulanan: atık temizleme faliyetlerinin gerektirdiği parasal yatırımın ekserji karşılığını "çevresel etki maliyeti" olarak kabul eden pratik fakat sentetik ve metodun doğasını yansıtmayan yaklaşımın dışına çıkarak, çevresel etki maliyetleri, gerçek sistemler ele alınarak, EEA içerisinde sunulan orjinal tanımına uygun olarak hesaplanmıştır.

Çevresel etkinin ekserjetik maliyetinin hesaplanmasında ele alınan sistemlerin ticari olarak aktif, teknik olarak bilinen ve yaygınlıkla kullanılan sistemler olmasına dikkat edilmiştir. Bu amaçla,

1) günümüzde atık su ve katı atık islahı için sıklıkla kullanılan ve atıktan, yaklaşık 98% saflıkta metan oranına sahip olan -bir nevi doğal gaz alternatifi- bir tür yakıt (biyogaz) ürtilmesini sağlayan anaerobik çürütme (anaerobic digestion) prosesi

2) dönüştürülebilir atıklar için geridönüşüm

tabanlı sistem seçimleri yapılmış ve bu çalışma dahilinde analiz edilmiştir.

Katı atık söz konusu olduğunda, atık türlerinin atık kompozisyonu içindeki oranları değişmekle beraber, DO, IN ve TE Sektörlerin katı atık bileşiminin ayni maddelerden oluştuğu göz önüne alınarak aynı proses zinciri içinde atık giderimi incelenmiştir. Özetle: atığın organik kısmı anaerobik çürütme prosesine tabi tutularak elde edilen biyogaz bir kojenerasyon tesisinde yakıt olarak kullanılmış ve elektrik ve ısı üretilmiştir. Inorganik kısım ise olabilecek maksimum oranda geridönüşüme uğradıktan sonra, geridönüşümsüz kısım yakma tesinde yakılarak ısı ve elektrik üretilmiştir. Geridönüsüm işlemleri sırasında oluşan artık kısım, düzenli depolama yapılmıştır. EX Sektör atığı, doğadan gelip tekrar depolama yolu ile doğaya terk edildiğinden incelenmemiştir. CO Sektör atığı içerisinde de yukarıda sayılan sektörlerin atık bileşiminde bulunan maddeler olduğundan yukarıda özetlenen atık giderimi sistemlerine ek olarak, rafineri atıkları için IGCC (integrated gasification combined cycle, entegre gazlaştırma kombine çevrim) sistemi ile enerji üretimi yapılmıştır. AG Sectör katı atığı olarak ele alınan hayvan ve bitki artıkları, anaerobik çürütme prosesinden geçirilmiş, oluşan biyogaz enerji üretiminde kullanılmıştır. TR Sektör atığı, tamamen farklı bir bileşime sahip olduğundan, sektöre özel bir yaklaşımla, taşıtların parçalanmasından sonra geri dönüşüm prosesi yapılmış, atık lastikler ise yakılarak ısı ve elektrik üretiminde değerlendirilmiştir. Geri dönüşüm işlemi artıkları ve yanmadan arta kalan kül, düzenli depolama ile yok edilmiştir. TR Sektör atığı olarak, sadece kara yolu atıkları incelemeye alınmıştır. Türkiyedeki ulaştırma sisteminin ne derece kara yoluna dayandığı dikkate alınırsa atığın büyük kısmının kara yolu taşıtlarından üretilmesini beklemek mantıklıdır. Ayrıca diğer ulaştırma motlarının ürettiği atık üzerine veri yoktur.

Gaz emisyonlar için, güvenli ve düzenli bir veri analizinin ulaşılabilir olduğu CO_2, CH_4 ve N_2O gazları ve bunların giderilmesi ele alınmıştır. Zaten kendisi bir yakıt olarak kullanılabilir olan CH_4 enerji üretiminde değerlendirilerek, bu sistemin EEA analizi sunulmuştur. CO_2 giderimi için CO_2'nun Ca ile reaksiyonu sonucu $CaCO_3$ üretimine dayanan bir sistemden faydalanılmıştır. N_2O için ise N_2O'nun yüksek sıcaklıkta dekompozisyonuna dayanan bir sistem incelenmiştir.

Sıvı atıklar için ise, Türkiye'nin DO Sektörü tarafından üretilen evsel sıvı atık ele alınmıştır. Türkiye'ye özgü datalar incilendiğinde, atığın bir kısmının hiç işlem görmediği, bir kısmının ise çeşitli kademelerde arıtma proseslerine uğradıktan sonra "arıtma çamuru" oluştuğu ve bu çamurun düzenli depolama ile gömüldüğü bilinmektedir. Bu çalışmada hem hiç proses görmemiş atık suyun hem de üretilen çamurun anaerobik çürütülmesi yolu ile bertarafının çevresel etki maliyetleri bulunmuştur. Diğer sektörel atıklar için de, çevresel etki maliyetinin evsel sıvı atık ile aynı olduğu kabul edilerek diğer sektörler için işlem yapılmıştır. Bu yaklaşımın gerekliliği, her sektörlerün atık su bileşimlerine ait bir veri kaynağının Türkiye için olmaması ve bu derece ayrıntılı bir analizin zaman ve hacim olarak sınırlı böylesi bir tez çalışması içinde mümkün olmadığı göz önüne alınarak açıklanabilir.

Diğer bir çevresel etki ekserji maliyeti araştırması, sektörlerden atmosfere deşarj edilen ısının giderimi için yapılmıştır. Söz konusu ısı, en büyük oranda ve en yüksek sıcaklıkda baca gazları yolu ile atmosfere verildiği için baca gazları ele alınmış ve ortalama baca gazı bileşimlerinden yola çıkarak, atık gazların çevre ile aynı sıcaklığa getirilmesi için kullanılan ORC (Organic Rankine Cycle) sisteminden elektrik üretilminin EEA analizi sunulmuştur.

Yukarıda anlatılan çevresel etki ekserji maliyetleri ve sektörel verimler sonuç bölümünde özetlenerek sunulmuştur. Bulunan sonuçların ayrıntılı incelemesi de sonuç bölümünde görülmektedir. Sonuçlara göre EX, CO, AG, IN, TR, TE ve DO Sektörlerin EEA analizi verimleri 91%, 43%, 0,13%, 57%, 48%, 87% ve 99% olarak belirlenmiştir.

1. INTRODUCTION

1.1 Resource Use and Exergy Analysis

In the 1970's, it became clear that the extensive use of natural resources would lead to the depletion of these resources irreversibly. Later on, environmental problems-especially resulting from industrial activities of developed and developing countries- and also the increase in population of the world cause extensive use of natural sources which is seen as one of the major problems of mankind. The concepts of *sustainability* and *sustainable development* are proposed to define and to search the possible solutions. Sustainable development is described by the United Nation Committee as "“development that meets the needs of the present without compromising the ability of future generations to meet their own needs”" (Brundtland et al., 1987, Chapter 2).

One of the main fields of research within sustainability/sustainable development/ ecology is the measurement of the metabolism of regions, societies, industrial systems, production processes etc. Resource consumption is obviously an important aspect of the human society's metabolism, and low resource consumption is a necessary concern for sustainable way of living. However, still, available methodologies in the literature do not (or only inadequately) provide a way for determination of resource use since the term "resource" is very broad and versatile in meaning (Gößling-Reisemann, 2008, p. 13). A good definition of resource is: "“Resources are the flows and reservoirs of matter and energy that can sustain or benefit living systems”" (Gößling-Reisemann, 2008, p. 15). Another definition which is available on internet is: "“Any asset used in the production of products and/or services”" (Url-2). According to Gößling (2001):

> The term living system has to be understood in a broader sense, including our economic system as a whole, since it is composed of humans and their technological extensions. This definition also includes purely energetic components, like the radiation field of the sun, and distinguishes between the living system and its environment. (p. 30)

As it is seen in the above definitions of the term "resource", it includes natural and manmade objects. Utility potential of resources is also implied in the definition. It must be noticed that the answer of the question: "can a material (physical) object (for example: raw material, fuels etc.) or immaterial object (labour etc.) be viewed as a resource?" is dependent upon whether it can be utilized by a living system or not (Gößling, 2001, p. 13; Gößling-Reisemann, 2008, p. 30). Although in some of the studies in the literature, the difference between resource use, resource consumption and resource depletion are highlighted and they are defined as related but different concepts (Gößling-Reisemann, 2008), mostly they are used in the same meaning in the literature and also in this thesis.

The fact that source of all activities on earth is the availability of energy and its conversion into different forms is the motivation for the use of thermodynamic methods in resource use and sustainability analysis. Odum and Barett (1971) clarified that all progress is due to special power subsidies, and progress evaporates whenever and wherever they are removed. Odum and Barett (1971) and Odum (1996) states that the ultimate thing which supports and guarantees the survival of societies is the availability of energy (exergy). Ayres (1994) and Szargut et al. (1988) concluded that *available energy* or *exergy* is the only source of all planetary activities on the earth. The first law of thermodynamics declares that energy is never destroyed or created, but merely transformed. In any physical or chemical process, it is possible to change the form (state) of energy or matter, but not the quantity. Energy analysis does not give any idea about the maximum utilization potential of resources (by definition, exergy) and loss of this potential in processes. Although mass and energy are conserved properties, exergy is an extensive property, with the same unit as energy but not conserved. In all transformations of matter or energy, there is always *exergy loss* (Szargut et al., 1988). Exergy, by definition, does not identify the ability of humankind to exploit a resource (it is the maximum limit of utilization from the resource but impossible to realize), but is a path-independent property, serving as a metric to measure the theoretically extractable work contained in a resource. Therefore, exergy can be regarded as a useful tool for comparing the magnitudes of resources regardless of current technical ability and experience (Wall, 1977). Hence, exergy based analysis of systems and/or processes addresses the most resource consuming (exergy depleting) points and revealing how much it is possible to design more efficient systems in terms of “resource consumption”, it is a key component in obtaining sustainable development (Utlu and Hepbasli, 2007b, p. 5; Hermann, 2006, p. 2). As a result, the most promising approach to adequately describe the resource potential and consumption of this potential so far has been exergy analysis (Gößling-Reisemann, 2008, p. 11) in which exergy (available energy, maximum work generation limit of the resource) is regarded as utility potential of the resource and resource depletion is the loss of this potential in the course of material and energy transformations (in other words, exergy of natural resources is regarded as a measure of the resource quality). Hence, exergy is capable of functioning as a unified measure to quantify all types of resources and their utility potential and also to map the resource consumption correctly. Together with energy analysis, exergy analysis has been used to examine the ways of utilization from resources not only on quantity base but also on quality base. Thereby, exergy depletion, which occurs in all kind of processes, is regarded as a well defined candidate for the sought measure of resource use. Application of a exergy based analyses to a society and describing the use of resources in terms of exergy enables to gain a more comprehensive and deeper insight from sustainability point of view, to identify areas where large improvements (in the sense of resource depletion) are needed by applying more efficient technologies (Dincer et al, 2004, p. 526) and facilitates to determine the priority of these areas to tackle.

1.2 LCA Approach in Exergy Analysis and Extended Exergy Accounting (EEA)

Exergy analysis, originally used as a “one-dimensional‟ analysis focusing solely on the use of energy carriers in a system, was later expanded into a “Life Cycle” dimension. Life Cycle Assessment (LCA) is a “cradle to grave” method in which all energy flows from extraction to end use (including final disposal of the product) are accounted for (Davidsson, 2001, Chapter 2). LCA based methods analyze the entire supply and demand chains of a product or process, and enables to evaluate the impact of emissions (Azapagic, 1999; Burgess and Brennan, 2001). Inserting the exergy concept into Life Cycle Assessment methodology has been discussed and suggested by many different researchers since the late 1990s (Cornelissen, 1997; Finnveden and Östlund, 1997; Gong and Wall, 1997; Ayres et al., 1998; Dewulf and Van Langenhove, 2002). Authors concluded that the use of exergy in life cycle analysis has many benefits. Ayres et al. (1998) elucidated some important and beneficial concerns: using a single unit (exergy) makes it possible to compute the consumption and wasting of *nature's utility capital* over the physical life of a product, using a single unit enables to compare environmental impacts of different processes. However, Ayres et al. (1998) also pointed out that exergy counting is not an appropriate way of environmental damage assessment since it does not provide a measure of (for example) toxicity but it is the best possible available alternative. Cornelissen and Hirs (2002) states that exergetic content of the considered waste stream can not be viewed as an exact indicator for the potential of environmental damage.

Different methods that combine the concepts of exergy and LCA with many similarities but also some important differences have been introduced and performed in the literature. Brief descriptions of a few of the most known exergy analysis methods with life cycle approach are presented below, based on Davidsson (2011) and Rubio Rodríguez et al. (2011).

1.2.1 Cumulative exergy consumption (CExC)

The method is proposed by Szargut et al. (1988) in which the sum of exergy of energy carriers and material flows, from the extraction of natural resources to the final product, is accounted for. Unlike cumulative energy consumption method, non-energetic raw materials exergy is taken into account.

Dewulf et al. (2010) proposed Cumulative Degree of Perfection (CDP) as an indicator based on CExC which is defined as the ratio of the exergy of the final product(s) to the cumulative exergy consumed to make the product(s) (Hau and Bakshi, 2005).

Another notation, cumulative exergy demand (CExD) is introduced by Bösch et al. (2007) but CExD is equivalent to the definition of CExC, both quantifying the total exergy requirement in the course of fabrication and/or processing of a product (Bösch et al., 2007; Rubio Rodríguez et al., 2011).

1.2.2 Exergetic life cycle analysis (ELCA)

ELCA is a method developed by Cornelissen (1997) which is determining the depletion of natural resources by obtaining the life cycle irreversibility, i.e., the exergy loss (De Meester, 2009; Cornelissen and Hirs, 2002). Zero- ELCA, which is also a method by Cornelissen (1997), characterizes the “exergetic cost” of the pollutants by determining the cumulative exergy need for treatment of the pollutants. A zero environmental impact (zero exergy emission) is reached by bringing the pollutants to complete equilibrium with the surroundings, which can be technically achieved by application of different amendment techniques (Cornelissen, 1997; Rubio Rodríguez et al., 2011). At first, ELCA did not separate renewable and non-renewable natural sources. Cornelissen and Hirs (2002) later split the resources as renewable and non renewable resources and underlined the depletion of exergy via consumption of these different resource types.

1.2.3 Cumulative exergy extraction from the natural environment (CEENE)

CEENE is introduced by Dewulf et al. (2007) as an impact assessment method. The method scientifically enables to quantify the consumed resources that are deprived from the natural ecosystem based on consistent exergy data on fossil and nuclear sources, metal ores, minerals, air, water, land occupation and renewable energy sources. Cumulative amount of consumed exergy is called the “cumulative exergy extraction from the natural environment (CEENE)”. In CExC and CExD (mentioned above) is accounting for all kind of resource consumptions but not land use. In CEENE, land use is also included.

1.2.4 Life cycle exergy analysis (LCEA)

The essence of LCEA is outlined fundamentally by Gong and Wall (1997, 2001). The LCEA splits the life of a system into three stages: construction stage, operational stage and clean up (destruction) stage. In the stage of construction, the input exergy accumulates in the materials that compose the system (from the moment 0 to the moment of the start of system operation). The second stage is the operating stage, from the moment of start to the moment of closing of the plant, in which the exergy is provided to the system for the maintenance and operation of the plant. The third stage is destruction of the plant. In the case of exergy input from renewable energy sources, this exergy is not accounted for (free resources). A plant or a system is accepted as “sustainable” if “exergy of output” from the system is greater than the sum of exergy introduced to the system, directly and indirectly, in the first, second and third stages (Wall, 2011; Rodio Rodríguez et al. 2011; Davidsson, 2011; Mengoli, 2010). Wall (1997, 2011) points out that utilizing from renewable energy in operational phase does not make a system sustainable since in one of the aforementioned three stages, exergy of non-renewable sources might be used more than utilized renewable energy.

1.2.5 Extended exergy accounting (EEA)

Finally, another holistic method, Extended Exergy Accounting (EEA) methodology was proposed by Sciubba (1999) in which exergetic equivalent of five different production factors to obtain a commodity are accounted for. To do this, all materials and energy flows' exergy are taken into account (like CExC method). But, the novelty of EEA is that non-energetic and immaterial fluxes (capital, labor and environmental impact, totally called "externalities") are quantified in exergy (in a homogeneous unit - Joules) and internalized in the analysis by their exergetic equivalent (in other words, "resource value equivalent"). Exergetic equivalent of externalities are computed based on local econometric and social data. Therefore, method has special solutions of geographical area and economic structure under study (Sciubba et al., 2008) Labour and capital are quantified by the exergy expenditures necessary to generate them. Environmental remediation cost is quantified as cumulative exergy consumption of a treatment system for the pollutant which is used to bring the pollutants to both thermal- and chemical equilibrium with the surroundings (Sciubba et al., 2008; Corrado et al., 2006). Detailed explanation of Extended Exergy Accounting (EEA) methodology and computing of exergetic equivalent of labour, capital and environmental remediation are presented in relevant sections of this present thesis.

EEA can be considered as a synthesis of above mentioned pre-existing theories. Like it is in Life- Cycle Analysis (LCA), the time span in EEA covers the entire life of the plant, starting from the extraction of primary sources and ending with the treatment of system effluents. Exactly like CExC analysis, all inputs fluxes of the production chain are tracked and all of the exergy inputs and outputs are accounted for. Like Zero-ELCA (i.e., in line with *zero exergy emission* concept), assessment of environmental impact is characterized as the cumulative exergy consumption of a treatment system which brings the effluents to complete equilibrium with reference environment (Sciubba, 2003b)., EEA contains the concept of attributing a resources-based cost to "external" production and this approach is also available in Emergy Analysis (Sciubba et al., 2008). Thermoeconomic methods (which are not mentioned above) are other exergy based methods in which economic factors have been combined with exergy analysis. Theormoeconomics builds a single objective function by using an “exergy to money” conversion factor. (Bejan et al., 1996; Moran and Sciubba, 1994). In thermoeconomics, efficiencies are calculated via an exergy analysis and monetary costs are expressed as a function of technical and thermodynamic parameters of the process. An optimization determining the design and the operative conditions that minimize the total monetary cost is performed counting financial, environmental and technical constraints of the considered process. EEA aims to go further than thermoeconomics, and introduces a costing methodology purely in exergetic metric including conversion of capital into exergy (Sciubba, 2003b). But, like Thermoeconomics, EEA builds “exergy cost balance” to quantify the “resource based value” of every flow of matter and energy (Sciubba, 2003a).

Extended Exergy Accounting (EEA) includes the “extended exergy balance” of all material, energy carriers and also immaterial/non-energetic production factors (externalities) and provides a good measure of resource which are irreversibly consumed in the life cycle of a material or immaterial commodity. Thus, the global problem of resource depletion and environment damage can be monitored by EEA, which is in essence a carefully and rigorously defined extension not of the concept of exergy but of its application to measure different fluxes (Sciubba, 2004). Once the numeraire of *extended exergy* (which is a strictly thermodynamic quantity that expresses the amount of equivalent primary exergy “embodied” in a commodity) is employed as the sole measure of resource consumption, it automatically follows with minimization of exergy use and destruction which are essential for improving the degree of sustainability. In spite of the limitations posed by many assumptions required to close the model (which are documented in following chapters), comparison of heterogeneous resource quantities and also comparison of different socio-economic scenarios by referring them to a common base (extended exergy) are possible by means of EEA Analysis. Hence, EEA offers more insight than other exergy based methods in the literature (Sciubba et al., 2008).

1.3 Scope and Structure of the Dissertation

This thesis focuses on the analysis of the Turkish Society for the year 2006 by means of the EEA methodology and showing the state of resource depletion due to 1) human actions within the societal system and 2) interactions with environment (biosphere as a whole) and other countries. It is intended to provide support for possible structural interventions aimed at the improvement of the degree of sustainability of the Country. To attain these goals, the following steps were necessary:

- Searching and gathering necessary data for the "System $Turkey_{2006}$"

- Accounting for the exergy rates transferred via material and energy carriers between environment, other Societies and sectors of the Turkish economy in the year 2006.

- Performing an EEA Assessment including the non-energetic and immaterial fluxes of labour and capital which are transferred between abroad and Turkish sectors in the year 2006.

- Computing environmental remediation cost for considered wastes and emissions.

The dissertation is organized in chapters: Chapter 2 contains the theoretical background of exergy concept and description of EEA (Extended Exergy Accounting) theory. In Chapter 3, exergy transfers via material and energy carrier flows from Environment to the society are presented. Chapter 4 aims to determine the exergy transfers via material and energy carrier flows between seven sectors of Turkey, namely: Extraction, Conversion, Agricultural, Industrial, Transportation, Tertiary and Domestic Sectors. Chapter 5 focuses on externalities: labour, capital and environmental remediation cost. The chapter contains determination of exergetic equivalent of labour and capital, exergy input and output of the sectors via labour and capital transfers and introduction of some state-of-the-art technological systems to determine "environmental remediation cost" of gas, liquid and solid effluents as well as discharged heat from above listed Turkish sectors. As for sectoral gas emissions, only CO_2, CH_4 and N_2O are considered due to scarcity of data. Chapter 6 contains the general conclusions, evaluation of results and future work.

1.4 Summary of Contributions

The main contributions of this dissertation to the literature are briefly listed as:

➢ Extended Exergy Accounting (EEA) of the Turkish Society (system) and determination of resource use efficiency of Turkish sectors.

➢ Application of a structure of mass flow map which is different from earlier EEA studies in the literature.

- A comprehensive EEA analysis of environmental remediation (treatment) systems and determination of real "environmental remediation cost" of pollutants in line with original structure of EEA methodology.

1.5 Literature Review

The exergy concept has its roots in "Classical Thermodynamics". The first appearance of the exergy concept (but not under the name of "exergy") emerged very early in the history, first by Carnot in the year 1824. He stated that "the work that can be extracted of a heat engine is proportional to the temperature difference between the hot and the cold reservoir". The term "exergy" was introduced at a scientific meeting in 1953 by Zoran Rant and was defined as "technical working capacity" (see Sciubba and Wall (2007) for an extensive review of the literature and a historical perspective).

Assessment of systems by use of exergy analysis has been developed quite slowly. The aim of performing an exergy analysis is to have a measure of the thermodynamic perfection degree within the limit of nature. With this regard, to date, abundant amount of studies have been performed on exergy analyses of different fields (especially industrial plants) which are available in the literature. Exergy analysis has been applied mostly to chemical processes and heat exchangers. Based on data presented in Sciubba and Wall (2007), Rant (1947) performed the first "exergy analysis" (under the name of "available energy") to a chemical process: soda production. Other initial studies which introduce the concept of "exergy analysis" to the literature are: Glaser (1949) and Obert and Birnie (1949).

In recent years, "exergy" has started to be used for assessment of resource use and to measure environmental impact of wastes and emissions. Wall (1977) states that waste and emissions have effects on environment and advocates that the effects are related to the exergy of produced waste. Since exergy indicates the thermodynamic distance of the state of a subject from the reference environment, this distance is assumed to be a measure of potential (of the subject) to cause change or impact on nature (Gasparatos et al., 2009b; Gong and Wall, 2001). Researchers also agreed that exergy is useful as a measure in environmental assessment of wastes and emissions together with its advantage of characterizing resource depletion. (Szargut et al., 2002; Szargut, 2005; Gong and Wall, 2001; Rosen, 2002a; Dincer, I., 2000; Sciubba, 2003a, Ayres et al., 1998). It must be noticed that, exergy is not a completely acceptable indicator for environmental impact since it is not capable of providing information about -for example- toxicity related chemical pollution phenomena (Ayres et al., 1998; Cornelissen and Hirs, 2002; Sciubba, 2009).

As for resource consumption, exergy represents the useful energy (maximum limit of utilization) in the resource. Then, the consumption of this useful energy identifies the "resource consumption" (Sciubba, 2009). Hence, exergy is a well-defined concept that offers a unitary and objective measure and a better understanding of resource use as well as the waste emissions, with essential implications to sustainability (Szargut, 2005; Rosen et al., 2008). For those reasons, increasing number of scientists have performed exergy based analyses in resource accounting studies (Reistad, 1975; Wall, 1977; Szargut et al, 1988; Cornelissen, 1997; Ayres et al., 1998; Valero, 2008; Cornelissen and Hirs, 2002; Rosen, 2002b; Rosen, 2002c; Szargut et al., 2002; Sciubba, 2003a).

Studies on exergy analysis of Turkey started with Unlu et al. (1987), who examined the Turkish textile industry by using energy and exergy methods. Applications of societal (Ileri and Gurer, 1998; Rosen and Dincer, 1997; Unal, 1994; Utlu and Hepbasli, 2004b, Utlu and Hepbasli, 2007b) and sectoral (Ozdogan and Arikol, 1995; Utlu and Hepbasli,2003; Utlu and Hepbasli, 2004a; Utlu and Hepbasli, 2004c; Ertay, 1997; Camdali and Ediger, 2007; Utlu and Hepbasli, 2006a; Utlu and Hepbasli, 2006b; Utlu and Hepbasli, 2007a, Utlu and Hepbasli, 2009; Hepbasli, 2008) exergy analysis to the "system Turkey" abundant in the literature but the present thesis is the first EEA application to Turkish society.

EEA has been applied to different societies in the literature: Norway (Ertesvag, 2005), Italy (Milia and Sciubba,2006), Siena region of Italy (Sciubba et al., 2008), UK (Gasparatos et al.,2009c), the Dutch energy sector (Ptasinski et al.,2006), China (Chen and Chen, 2009; Dai et al., 2008) and Nova Scotia province of Canada (Bligh and Ugursal, 2012). There are also applications of EEA for particular industrial processes (Sciubba, 2003a; Talens Peiró et al., 2010; Tijani et al., 2007; Balocco et al., 2004)

2. EXERGY CONCEPT AND EEA METHODOLOGY

2.1 Definition of Exergy

"Exergy" (available energy) defines the maximum work which can be obtained from a system in the course of bringing it to a state of complete equilibrium with the reference environment (synonym: dead state, which emphasizes the impossibility of obtaining further work from a system which is in equilibrium with the reference environment) by means of ideally reversible processes in which the system interacts only with its reference environment. Conversely, the exergy of a substance at its initial state represents the theoretical minimum amount of work required to bring the substance from the dead state to its initial state. (Szargut et al.,1988; Szargut, 2005; Wall, 1977, Sciubba et al.,2008; Kotas, 1995). Exergy content of resources characterizes "the measure of potential usefulness", i.e., ability to perform "useful work" (Ayres and Ayres, 1999). This definition brings about the result of regarding the exergy content of a resource as an indicator of "resource quality". Szargut et al. (1988) and Bejan et al. (1996) presented the properties of the aforementioned processes between initial state of the substance and dead state (reference state, reference environment state) which are:

- reversible
- take place in an open system with stationary flow
- exchange heat only with the environment
- the substance is in equilibrium with the dead state at the end of the processes.

When the nuclear, magnetic, electrical and surface tension effects are ignored, exergy (E), has four components which are listed as: kinetic (E_k), potential (E_p), physical (E_{ph}), and chemical exergy (E_{ch}) (Dunbar et al., 1992; Ayres et al., 2006; Szargut et al., 1988; Bejan et al.,1996). The equation of E is seen in equation (2.1). The unit of E is the same as that of energy (J).

$$E = E_k + E_p + E_{ph} + E_{ch} \quad \textbf{(2.1)}$$

“Specific exergy” is the expression of exergy on a mass (or molar) basis (Kotas, 1995; Szargut et al., 1988; Szargut, 2005). Similarly, equation of specific exergy on a mass basis (e) is presented in equation (2.2) with identical sub-indexes used in equation (2.1). The term “specific” denotes “on a mass basis” in the further parts of this thesis. Hence, the unit of e is J/kg.

$$e = e_k + e_p + e_{ph} + e_{ch} \quad \textbf{(2.2)}$$

Equation of each exergy component is presented in Table 2.1 where V and V_0 (m^2/s) are velocity of the substance and the reference environment; g (m^2/s) is gravitational acceleration, z and z_0 (m) are the height of the substance and the reference environment, h and h_0 (J/kg) are specific enthalpy of the substance at initial state and at the state of reference environment; T_0 (K) is the temperature of the reference environment; s and s_0 (J/kg.K) are specific entropy of the substance at its initial state and at the state of reference environment, respectively; μ_i (J/kg) is the chemical potential of substance i at its the initial state; $\mu_{i,0}$ (J/kg) is the chemical potential of substance i in the reference environment; R (J/kgK) is universal gas constant; c_i (kg/m^3) is the chemical concentration of substance i at its initial state and $c_{i,0}$ (kg/m^3) is the chemical concentration of substance i in the reference environment (Wall, 1977).

Table 2.1: Specific exergy equations.

Exergy	Specific exergy	Equation number
Kinetic	$e_k=(V^2-V_0^2)/2$	**(2.3)**
Potential	$e_p= g(z-z_0)$	**(2.4)**
Physical	$e_{ph}= h-h_0-T_0(s-s_0)$	**(2.5)**
Chemical	$e_{ch} = \sum_i \mu_i - \mu_{i,0} + RT_0 \sum_i \left(\frac{c_i}{c_{i,0}} \right)$	**(2.6)**

Kinetic exergy is the exergy of a substance which is described in terms of velocity of the substance relative to velocity of the reference environment. To put it in another way, it is the amount of work needed to accelerate a mass body to a selected velocity from the velocity of the reference environment. Potential exergy is originated from the substance’s location above the reference environmental level. Since kinetic and potential energy are entirely convertible to work, equations of kinetic and potential energy and exergy are identical as it is seen in Table 2.1. Physical exergy is the theoretical maximum limit of work which is obtained as a substance passes from its initial state (temperature and pressure are T and P, respectively) to the state of reference environment (temperature and pressure are T_0 and P_0, respectively) (Szargut et al., 1988; Szargut, 2005). Equation (2.5) clearly expresses that the amount of useful work which can be extracted from a certain system is not measured by enthalpic content, because even in reversible processes, a portion of that energy is devaluated by the unavoidable entropic degradation which is equal to $[T_0(s-s_0)]$ (Szargut et al., 1988; Wall, 1977; Sciubba et al., 2008). Derivation of physical exergy is presented in Appendix J. The chemical exergy of a substance is the amount of maximum work obtained from reversible processes to bring the substance to the chemical equilibrium with the reference environment at constant temperature and pressure (T_0 and P_0). Substance composition is converted into the composition of the reference environment with the same concentration (Rivero and Garfias, 2006; Szargut et al., 1988) As it is seen in equation (2.6), the chemical exergy has two contributions: "reactional exergy" and "concentrational exergy". Reactional exergy part originated by the necessary chemical reactions to produce stable components (species) existing in the reference environment (reaction products) from the initial composition of the substance. Concentrational exergy is the exergy resulting from the reversible processes to match the chemical concentration of the reaction products with the chemical concentration of the consisting species of the reference environment (Rivero and Garfias, 2006; Wall, 1977; Szargut et al., 1988).

In previous studies (Szargut et al.,1988; Szargut, 1989; Szargut, 2005; Kotas, 1995; Morris and Szargut, 1986; Bejan et al., 1996) the concept of exergy and its calculation have been extensively discussed. Szargut et al.(1988) proposed a route for the calculation of standard chemical exergy which is chemical exergy of substances under pressure and temperature associated with the reference environment at global scale. In this thesis, Szargut's exergy calculation route or (for some substances) tabulated standard chemical exergy in Szargut et al. (1988) are used. Defined standard exergies of substances facilitate the calculation of exergy under different conditions (Chen and Qi, 2007). Details are presented in Section 2.3.

2.2 Reference Environment

In exergy analysis, all input or output fluxes (mechanical power, electrical energy, heat, nuclear energy, any type of materials, etc.), are directly assigned to corresponding exergy content. Exergy is always quantified with respect to a reference environment to address the question: how much work potential does a resource contain?. For consistency, exergy calculations must be with respect to the same set of reference conditions. The reference environment has a stable equilibrium and acts as an infinite system (sink, source) for heat and materials. Since the reference environment is stable, intensive properties (i.e., temperature T_0 , pressure P_0, chemical potentials and concentrations) remain constant (Szargut et al., 1988; Sciubba, 2003a).

There are two different approaches in the literature to address a reference environment. The first one is “partial reference environment” and the second is “comprehensive reference environments” approaches (Valero, 2008). In the first approach, a specific reference environment is defined for the analyzed processes. The rationale behind this approach is: exergy analysis is done to point out the possible improvements for the system, but some of these improvements are not attainable due to some limitations and restrictions of the system. With a specific reference environment, only possibilities for practically applicable system evolutions are analyzed. Bosjankovic (1963), Gaggioli and Petit (1976) and Sussman (1979) applied this reference environment approach in their studies. As for the second approach, reference environment consists of 3 sinks: gaseous components of the atmospheric air, solid components of the earth’s crust external layer and ions and molecular components of seawater (Szargut et al., 1988) However, there are differences in reference environment proposal of different authors: Ahrendts (1980), Kameyama et al. (1982), Ranz (1999), Szargut, et al. (1988), etc. One of the most known and widely applied reference environment system is Szargut’s approach in which criterion is abundance of species in the environment (Szargut, et al., 1988; Szargut, 2005). Szargut’s reference environment is defined at reference temperature (298,15 K) and pressure (1atm) and average composition of the Earth’s litho-,hydro- and atmo- sphere. It is assumed that the reference environment is thermodynamically dead. For a society exergy account study like this thesis, to select a global standard environment which includes the atmosphere, the ocean and the top layer of the earth’s crust (like Szargut’s approach) is reasonable. Following the procedure by

Szargut et al. (1988), the proper reference state for a substance is estimated by selecting one of the above listed environmental platforms which the element is likely to end up after undergoing a serious of reactions to reach the entire equilibrium with the reference environment. The determination of appropriate environmental platform is based on substance's volatility (atmospheric sink), solubility (oceanic sink) and non solubility (earth's crust sink) (Szargut et al.1988; Szargut, 2005; Ayres and Ayres, 1999)

Standard chemical exergy of some elements and compounds (the term "standard" signifies "at reference temperature and pressure") are determined by applying the defined procedure in Szargut et al. (1988). Tabulated values for standard chemical exergy of substances and reference environment model which are available in Szargut et al. (1988) are used in the present thesis.

2.3 Computation of Exergy and Exergy Transfer

2.3.1 Calculation of standard chemical exergy

There are four ways of computing the standard chemical exergy of compounds (Szargut et al., 1988):

1) If standard reference reactions (reactions which have inputs and outputs as species exist in reference environment) are known for the compound under study, standard chemical exergy of the compound is computed as (Szargut, 1988):

$$e^0_{ch} = -\Delta_r G^0 + \sum_k n_k \, e^0_{ch,k} - \sum_j n_j \, e^0_{ch,j} \qquad \textbf{(2.7)}$$

where e^0_{ch} (J/kg) is standard chemical exergy of the compound, $-\Delta_r G^0$(J/kg) is standard Gibbs free energy of the reference reaction, n_k and n_j are the mole numbers of output and input reference species, $e^0_{ch,k}$ and $e^0_{ch,j}$ (J/kg) are standard chemical exergies of the output and input reference species, respectively.

2) If the standard chemical exergies of consisting elements of the substance are known, standard chemical exergy of the compound can be computed as (Szargut et al., 1988):

$$e_{ch}^{0} = \Delta_f G^0 + \sum_i n_i \, e_{ch,i}^{0} \qquad \textbf{(2.8)}$$

where $\Delta_f G^0$ (J/kg) is standard Gibbs free energy of formation (for the compound), n_i is the mole number of element i in the compound, $e_{ch,i}^{0}$ (J/kg) is the standard chemical exergy of the element i.

In equation (2.8), the chemical exergy depends on the Gibbs free energy of formation of the compound, elements consisting the compound and elements' mole numbers. It must be noticed that the elemental composition can be the same for different compounds but Gibbs free energy of formations are different due to the different bounding structure in the compound.

3) If the groups of molecules in the compound are known, Szargut et al. (1988) tabulated standard chemical exergy of molecule groups. The chemical exergy of the compound is the sum of consisting molecule groups' chemical exergy and formulated in equation (2.9).

$$e_{ch}^{0} = \sum_i x_i \, e_{ch,i}^{0} \qquad \textbf{(2.9)}$$

where e_{ch}^{0} (J/kg) is standard chemical exergy of the compound, x_i is the number of molecule group i in the compound, $e_{ch,i}^{0}$ (J/kg) is the standard chemical exergy of the molecule group i.

4) An approximate standard chemical exergy equation is presented by Szargut et al. (1988) for organic substances. The general forms of equations are seen in equations (2.10) and (2.11).

$$e_{ch}^{0} = \beta_{LHV} \text{ x } LHV \qquad \textbf{(2.10)}$$

$$e_{ch}^{0} = \beta_{HHV} \text{ x } HHV \qquad \textbf{(2.11)}$$

where e^0_{ch} (J/kg) is standard chemical exergy of the organic substance; LHV and HHV (J/kg) are low heating value and high heating value of the substance, respectively; β_{LHV} and β_{HHV} are relating coefficients between e^0_{ch} and LHV and HHV, respectively.

β_{LHV} is defined as a function of the atomic ratio of the elements carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) in the substance (compound). Table 2.2 presents some of the often used β_{LHV} equations for organic compounds (Szargut et al., 1988). β_{LHV} and β_{HHV} are called "LHV exergy coefficient" and "HHV exergy coefficient" respectively, in further parts of this thesis.

Table 2.2: β_{LHV} equations for organic compounds.

Substance	β_{LHV}	Range of application	Equ. number
Gaseous hydrocarbons	$1{,}0334+0{,}0183\left(\frac{H}{C}\right)_a-0{,}0694\left(\frac{1}{N_C}\right)$		**(2.12)**
Liquid hydrocarbons	$1{,}0406+0{,}0144\left(\frac{H}{C}\right)_a$		**(2.13)**
Solid C,H,O compounds	$1{,}0438+0{,}0158\left(\frac{H}{C}\right)_a+0{,}0813\left(\frac{O}{C}\right)_a$	$\left(\frac{O}{C}\right)_a\leq 0{,}5$	**(2.14)**
Solid C,H,O compounds	$\dfrac{1{,}0414+0{,}0177\left(\frac{H}{C}\right)_a-0{,}3328\left(\frac{O}{C}\right)_a\left[1+0{,}0537\left(\frac{H}{C}\right)_a\right]}{1-0{,}4021\left(\frac{O}{C}\right)_a}$	$\left(\frac{O}{C}\right)_a\leq 2$	**(2.15)**
Solid C,H,O,N compounds	$1{,}0437+0{,}014\left(\frac{H}{C}\right)_a+0{,}0968\left(\frac{O}{C}\right)_a+0{,}0467\left(\frac{N}{C}\right)_a$	$\left(\frac{O}{C}\right)_a\leq 0{,}5$	**(2.16)**
Solid C,H,O,N compounds	$\dfrac{1{,}044+0{,}016\left(\frac{H}{C}\right)_a-0{,}3493\left(\frac{O}{C}\right)_a\left[1+0{,}0531\left(\frac{H}{C}\right)_a\right]+0{,}0493\left(\frac{N}{C}\right)_a}{1-0{,}4124\left(\frac{O}{C}\right)_a}$	$\left(\frac{O}{C}\right)_a\leq 2$	**(2.17)**
Coal, lignite, coke, peat	$1{,}0437+0{,}01896\left(\frac{z_{H_2}}{z_C}\right)+0{,}0617\left(\frac{z_{O_2}}{z_C}\right)+0{,}0428\left(\frac{z_{N_2}}{z_C}\right)$	$\frac{z_{O_2}}{z_C}\leq 0{,}67$	**(2.18)**
Wood, biomass	$\dfrac{1{,}0412+0{,}216\left(\frac{z_{H_2}}{z_C}\right)-0{,}2499\left(\frac{z_{O_2}}{z_C}\right)\left[1+0{,}7884\left(\frac{z_{H_2}}{z_C}\right)\right]+0{,}045\left(\frac{z_{N_2}}{z_C}\right)}{1-0{,}3035\left(\frac{z_{O_2}}{z_C}\right)}$	$\frac{z_{O_2}}{z_C}\leq 2{,}67$	**(2.19)**

In Table 2.2, $\left(\frac{H}{C}\right)_a$, $\left(\frac{O}{C}\right)_a$, $\left(\frac{N}{C}\right)_a$ are atomic ratio of the elements composing the considered compound; N_C is the number of carbon atoms in the molecule; z_{H2}, z_C, z_{O2}, z_{N2} are hydrogen, carbon, oxygen and nitrogen mass fractions in the compound, respectively (Szargut et al., 1988).

2.3.2 Exergy transferred via heat transfer

Equation of transferred exergy via heat transfer is seen in equation (2.20) where $\dot{E}$ (W) is the exergy transfer rate, A(m^2) is the heat transfer area, $\dot{Q}_A$ (W/m^2) is heat transfer flux rate through A, T_0 is the temperature of the reference environment, T is the temperature at which the heat transfer takes place (Cornelissen, 1997, Wall, 1977; Szargut et al. 1988).

$$\dot{E} = \int_A \left(\frac{T - T_0}{T}\right) \dot{Q}_A dA \tag{2.20}$$

If the temperature is homogeneous through the heat transfer area,

$$\dot{Q} = \int_A \dot{Q}_A dA \tag{2.21}$$

Hence, $\dot{E}$ becomes:

$$\dot{E} = \left(\frac{T - T_0}{T}\right) \dot{Q} \tag{2.22}$$

2.3.3 Exergy transfer with work interaction

As stated above, exergy is defined as the maximum work potential. Hence, transferred exergy via work interaction is totally equal to exergy transfer.

2.3.4 Exergy of electricity

By the definition of exergy, electricity is identical to the physical work (totally exergy). It is formulated in equation (2.23).

$$En_{el} = E_{el} \tag{2.23}$$

where En_{el} is the electrical energy and E_{el} is the exergy of En_{el}.

2.4 Extendend Exergy Accounting (EEA)

As it is explained in Chapter 1, for sustainable development, the depletion of exergy reservoirs and system effluent disposed directly to the environment must be minimized. Some of the widely known and used exergy based methods are briefly introduced in Chapter 1. Before EEA was proposed by Sciubba (1999), the CExC method had been introduced by Szargut in which exergy influxes of “materials” and “energy carriers” are accounted for in the analysis of the considered system. EEA method can be regarded as a further development of CExC method. EEA provides a coherent and consistent framework for expanding the CExC method which enables to include non-energetic quantities: capital, labour and environmental impact (totally named externalities) in the resource use analysis. Hence, the novelty of EEA is internalizing these three non-energetic/immaterial “production factors” (externalities) into the analysis (expressed in purely exergy unit). The idea of inclusion of externalities into the methodology stems from the fact that consumed and/or produced labour and capital also represents a “resource equivalent value” which is the corresponding resource consumption to generate them. Since EEA is a “resource use” analysis method, input and output fluxes of capital and labour quantified in exergy and included in the analysis as additional resource consumption factors (Sciubba et al., 2008; Sciubba, 2003a). In EEA theory, total generated labour within a society is the product of DO Sector which devotes DO Sector a “producer” characteristic (totally different from earlier methods) such that: DO Sector is not a pure dissipator of resources but the producer of labour within the society.

Environmental impact is also included in EEA as an important parameter of sustainability assessment researches. Environmental impact is quantified by cumulative exergy consumption of above mentioned production factors to remedy (treat) the system effluents. It is named “environmental remediation cost (EE_{ENV})” and seen in Figure 2.1. Details of the environmental remediation cost concept in EEA are explained in Section 5.3. Above mentioned constituent fluxes of EEA methodology are seen in Figure 2.1.

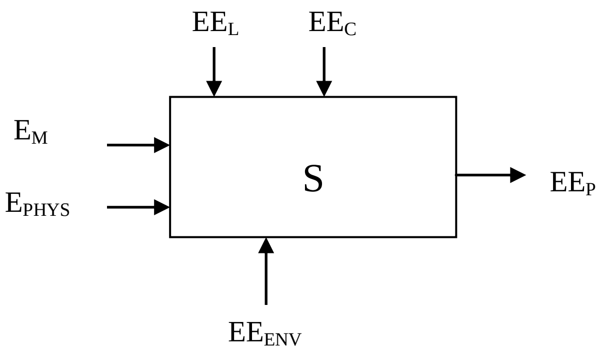

Figure 2.1 : Constituent fluxes of EEA methodology.

In Figure 2.1., S is the considered system; E_M, E_{PHYS} are exergy of materials and energy carriers, respectively; EE_L and EE_C are exergetic equivalent of labour and capital, respectively; EE_{ENV} is the environmental remediation cost; EE_P is the extended exergy of the system product P. For the system S, extended exergy of product P (EE_P) is:

$$EE_P = E_M + E_{PHYS} + EE_L + EE_C + EE_{ENV} \tag{2.24}$$

2.4.1 Exergetic equivalent of labour

The rationale behind assigning a “resource based value” for labour fluxes is: human labour is generated via consuming resources by human population in the considered control volume which is Turkey_{2006} in this thesis. Exergy equivalent of one work-hour (specific exergetic equivalent of labour, ee_L) is calculated as presented in equation (2.25) which is the ratio of the exergy consumed for labour generation (EE_L) to the total number of work-hours generated in the society (N_{wh}) (Sciubba, 2011). EE_L is a part of global exergy input into the society (E_{in}) and α is a numerical factor expressing the ratio of EE_L to the E_{in} (Sciubba, 2011). In other words, α □is a fraction of the incoming exergy flux (E_{in}) that is used to generate the cumulative work hours in the society (Sciubba, 2011, Talens Peiró et al, 2010). Since computing an exact number for EE_L is not possible, another term, E_{used} is introduced as an approximated proxy of EE_L ($EE_L \cong E_{used}$).

$$ee_L = \frac{EE_L}{N_{wh}} \cong \frac{E_{used}}{N_{wh}} = \frac{\alpha E_{in}}{N_{wh}} \tag{2.25}$$

In equation (2.25), E_{used} (J/year) is the approximated amount of exergy consumed by the entire population; N_{wh} (hours/year) is the total number of work-hours generated in the society; E_{in} (J/year) is global exergy input to the society; α is the fraction of the primary exergy embodied into labour (the ratio of E_{used}/E_{in}).

By an assumption, E_{used} is calculated as presented in equation (2.26) which is actually the equation of approximated exergy consumption by the whole population (Sciubba, 2011).

$$E_{used} = 365\,f\;e_{surv}\;N_h \tag{2.26}$$

In equation (2.26), e_{surv} (J/person.day) is the minimum exergy requirement for survival; f is an appropriate amplification factor that accounts for the fact that modern life standards require an exergy use much higher than e_{surv}; N_h (persons) is the global population of the society (Sciubba, 2011).

The rationale behind assuming that $EE_L \cong E_{used}$ is that in an industrialized and complex modern society:

1) the average exergy consumption of an inhabitant is much higher than exergy necessary for survival,
2) total number of workers (N_w) are "sustained" by this average exergy consumption.

A possible approximation for f is seen in equation (2.27):

$$f = \frac{HDI}{HDI_0} \tag{2.27}$$

where HDI is the human development index; HDI_0 is a conventional reference HDI (HDI of a primitive society).

HDI is a composite measure of life expectancy, literacy, wealth, education and standards of living for countries worldwide and tabulated for each Country on a yearly basis by the United Nations Development Programme (UNDP). Analyses show that there is a correlation between HDI of a country and pro-capite minimum energy (therefore exergy) consumption (Tsatsaronis and Lin, 1990, Sciubba, 2011). Thus, in equation (2.27), the factor f is a kind of adaptation factor which provides a useful correlation for the calculation of minimum pro-capite exergy consumption. In other words, the average pro-capite consumption pattern can be in fact directly computed as ($f\ e_{surv}$) (J/person-day).

2.4.2 Exergetic equivalent of capital

As it is explained in Section 2.4.1, in a society, labour generation takes resource consumption. Assigning an exergy equivalent to capital fluxes is conceptually based on relating the payment for labour (cost of labour in monetary sense) with resource consumption for labour generation (EE_L). The "payment" therefore denotes: wages, salaries, etc. The relation is seen in equation (2.28).

$$ee_C \ x S = EE_L = \alpha E_{in} \qquad \textbf{(2.28)}$$

ee_C (J/$) is exergy equivalent of one monetary unit; S($/year) is the global monetary amount of wages, salaries, etc.

ee_C is deriven from equation (2.28), as:

$$ee_C = \frac{\alpha E_{in}}{S} \qquad \textbf{(2.29)}$$

On the other hand, derivation of a different equation for ee_C is possible by means of β which is an amplification factor that accounts for the creation of wealth due to exclusively financial activities (Sciubba, 2011). Factor β can be calculated as:

$$\beta = \frac{M_2 - S}{S} \qquad \textbf{(2.30)}$$

where M_2 ($/year) is the total monetary circulation in the country (Sciubba, 2011). Obviously, non-labour related (i.e., purely financial) monetary circulation in the society is (M_2-S) which is created by non-labour consuming activities (financial activities, money transfer to the Government from foreign financial foundations, etc.).

From equation (2.29), S can be rewritten as:

$$S = \frac{\alpha E_{in}}{ee_C} \qquad \textbf{(2.31)}$$

Inserting equation (2.31) into equation (2.30), equation (2.30) can be rewritten as:

$$M_2 - S = \beta\ S = \beta\ \frac{\alpha E_{in}}{ee_C} \tag{2.32}$$

As a result, the equation of ee_C can be written as:

$$ee_C = \frac{\alpha \beta E_{in}}{M_2 - S} \tag{2.33}$$

2.4.3 Environmental remediation cost (EE_{ENV})

As for computing of "environmental remediation cost (EE_{ENV})", EEA follows a similar route to Zero-Exergetic Life Cycle Analysis (Zero-ELCA) methodology which is briefly explained in Chapter 1. The essence of this idea is: the potential environmental impact of an effluent is represented by the cumulative amount of exergetic resources that must be consumed by the whole treatment process to attain an ideal, zero-impact disposal of the effluent. "Environmental remediation cost (EE_{ENV})" is computed by inserting a (real or virtual) effluent treatment system (a set of processes and systems, totally named "environmental remediation (treatment) system" which is system S_t in Figure 2.2) for each type of effluents. In each environmental remediation system, physical exergy of each single effluent must be brought down to zero. In theoretical framework of EEA, each discharge into the environment must be at reference conditions, in other words, its environmental impact must be equal to zero. Since these environmental treatment systems also consume material, energy, labour and capital inputs, also they have environmental remediation costs (which are represented as E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, EE_{ENV-t} in Figure 2.2) and resource exergy use equivalent of all these fluxes must be completely and correctly charged to embedded global primary exergy consumption of P. Representation of the system S_t and above mentioned fluxes are seen in Figure 2.2, details of EE_{ENV} computing and formulations are presented in Section 5.4.

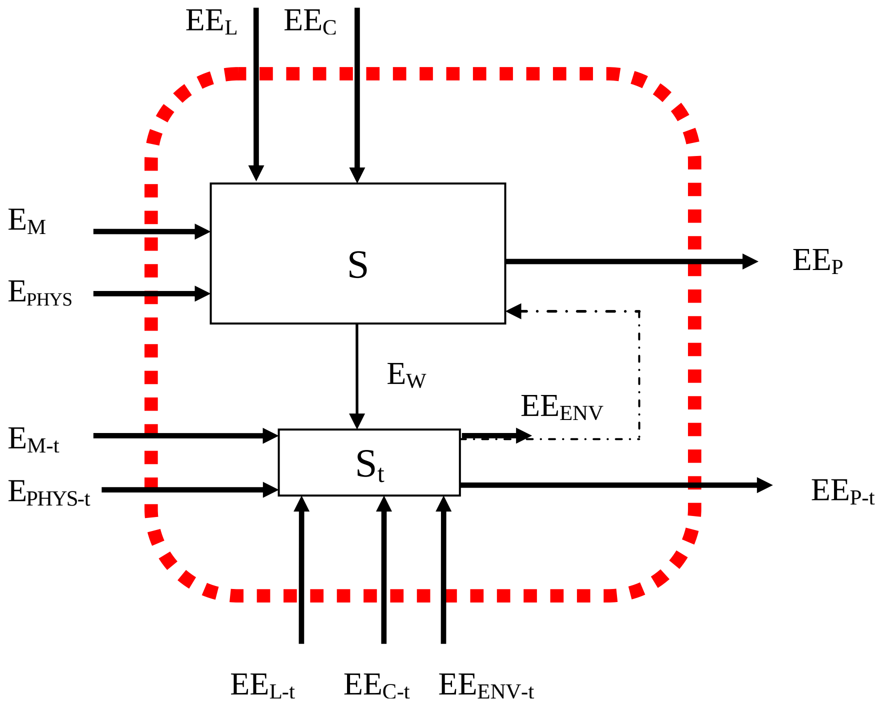

Figure 2.2 : Representation of system (S) and treatment system (S_t).

2.5 Framework of Societal EEA Application (Choice of Control Volume and Divisions)

In this study, Turkish society is chosen as the control volume which is undergone an EEA analysis. As usual in EEA analyses, the Turkish society has been modeled as an open thermodynamic system interacting with two external systems, namely "Environment" (ENV) and "Abroad" (A), and consisting itself of seven internal subsystems (sectors) which are listed below:

- Extraction sector (EX): mining and quarrying activities
- Conversion sector (CO): heat and electricity generation, all refinery activities, coal processing
- Agricultural sector (AG): agriculture, harvest, forestry, animal husbandry and fishery
- Industrial sector (IN): all manufacturing industry including construction except refineries
- Transportation sector (TR): commercial and private transportation services of passenger& goods
- Tertiary sector (TE): service activities (finance, wholesale, hotels, etc.,) but except transportation.

* Domestic sector (DO): households

Matters which are directly extracted (minerals, ores, natural gas, crude oil, water, etc.) or received (solar radiation, geothermal heat, etc.) from nature are transfers between Environment (ENV) and the Country. Abroad (A) is the “other countries except Turkey” and there are possible material and capital transfers between the Society and Abroad (Figure 2.3). Abroad and Environment are totally named “surroundings” in EEA methodology.

Details of the sectors and exergy flows between sectors are presented in following chapters.

Since TE Sector includes all commercial and financial activities of the country, in our model, TE is considered as the storage-and-distribution hub for the system: most products of all other sectors are first transferred to TE and then distributed to consuming sectors (including exports) as it is seen in Figure 2.3.

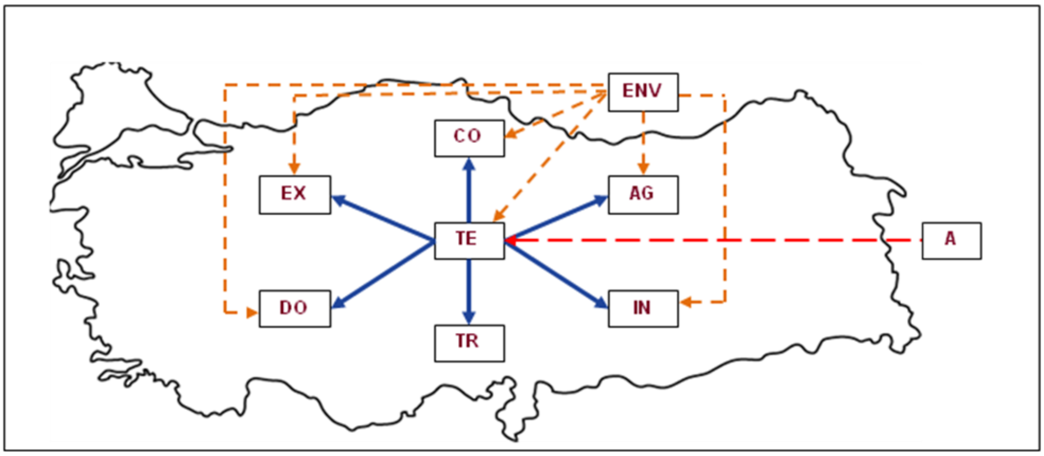

Figure 2.3 : Schematic outline of the sectors and surroundings.

3. EXERGY TRANSFERS FROM ENVIRONMENT

As it is seen in Figure 2.3., the system (Turkey) and Environment (ENV) are interacting via materials, energy carriers and water fluxes. The sectors which receive fluxes from ENV are: EX, CO, AG, IN, TE and DO. In this section, all types of transfers between the sectors and ENV and also accompanying exergy fluxes are discussed.

3.1 Exergy Fluxes from ENV to the Sectors via Energy Carriers and Materials

3.1.1 Exergy transfer from ENV to EX

As stated in Chapter 2, EX sector is in charge of mining and quarrying activities in which extraction of raw (unrefined) fossil fuels, ores and minerals are involved. Data for inland extraction of fossil fuels are retrieved from IEA (2008) and Republic of Turkey-Ministry of Energy and Natural Resources (n.d.), those for minerals and ores from Republic of Turkey-Ministry of Energy and Natural Resources-General Directorate of Mining Affairs (n.d.). For ease of accounting, it was stipulated that all extracted products are transferred to TE Sector and from TE to the consuming sectors[1]. Amounts and exergetic content of extracted fossil fuels by EX Sector are presented in Table 3.1.

Table 3.1 : Extracted fossil fuels and exergy content.

	Amount (Ton, TJ [2])	Specific Exergy (MJ/Ton) (β_{HHV}[3])	Total Exergy (TJ)
Hard Coal	2319×10^3	27860,36	64608,18
Asphaltite	452×10^3	18604,40	8409,19
Lignite	61484×10^3	8259,27	507813,13
Crude Oil	2160×10^3	43506,45	93973,93
Natural Gas	33707 [2]	0,92 [3]	31010,44
Total			705814,87

[1] This distorts the relative exergy intensity of the sectors. Exergy input of TE Sector is artificially higher than that of other sectors.
[2] Unit is TJ.
[3] For natural gas β_{HHV} is used.

In Table 3.2 and 3.3, amount and exergetic content of extracted ores and minerals are presented, respectively. Specific exergy and exergy coefficient calculations are presented in Appendix B for Table 3.1. and in Appendix A for Table 3.2 and 3.3.

Table 3.2 : Extracted ores and exergy content.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Total Exergy (TJ)
Iron ore	$3{,}78\times10^{6}$	79,77	301,96
Gold ore	8,04	0,0046	$3{,}7 \times10^{-8}$
Antimony ore	25316	831,10	21,04
Copper ore	$4{,}29 \times10^{6}$	523,09	2245,90
Bauxite ore	$8{,}79\times10^{5}$	1114,16	979,58
Zinc ore	$5{,}54 \times10^{5}$	1237,83	686,28
Silver ore	167	0,05	$0{,}9 \times10^{-5}$
Cadmium ore	141	3,38	$4{,}7 \times10^{-4}$
Chromium ore	$1{,}85 \times10^{6}$	496,58	918,60
Lead ore	$2{,}8 \times10^{5}$	540,20	151,11
Manganese ore	32144	133,29	4,28
Nickel ore	20000	214,14	4,28
Pyrite ore	63674	7674,99	488,70
Total			5801,74

Table 3.3 : Extracted minerals and exergy content.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Total Exergy (TJ)
Alunite	6683	2433,65	16,26
Barite	$1{,}62 \times10^{5}$	14,57	2,36
Bentonite	$1{,}13 \times10^{6}$	909,34	1031,42
Boron	$3{,}96 \times10^{6}$	58135,23	229958,20
Chert (Flint)	34606	131,49	4,55
Diatomite	45420	340,62	15,47
Dolomite	$4{,}69 \times10^{5}$	81,88	38,41
Feldspar	$5{,}77 \times10^{6}$	358,92	2071,63
Phosphate	1300	62,54	0,08
Illite	27898	814,16	22,71
Chalcedony	4706	31,62	0,15
Kaolinite	$1{,}06 \times10^{6}$	766,19	815,31
Ceramic clay	$3{,}03 \times10^{6}$	747,29	2267,69
Quartz	$4{,}09 \times10^{5}$	31,62	12,93
Quartz sand	$2{,}61 \times10^{6}$	131,49	342,96
Quartzite	$1{,}46 \times10^{6}$	131,49	192,39
Magnesite	$4{,}66 \times10^{5}$	449,53	209,57
Calcite	$5{,}88 \times10^{6}$	9,99	58,70
Montmorillonite	$4{,}29 \times10^{5}$	514,63	220,65
Olivine	$1{,}91 \times10^{5}$	1079,97	206,60
Perlite	$4{,}75 \times10^{5}$	754,83	358,52
Rottenstone (Pumice)	$3{,}52 \times10^{6}$	862,56	3032,45
Sepiolite	19242	521,18	10,03
Silex (Flintstone)	7228	131,49	0,95
Sodium Chloride	$1{,}34 \times10^{6}$	244,70	328,30

Table 3.3 (continued): Extracted minerals and exergy content.

Sodium Sulfate	8,26 x10^5	150,66	124,48
Talc	4969	96,23	0,48
Trona	2184	439,91	0,96
Peat	1,86 x10^5	20117,05	3740,65
Salt	2,22 x10^6	244,70	544,00
Grindstone	13899	1312,94	18,25
Carbonmonoxide	43963	451,49	19,85
Limestone	1,76 x10^8	9,99	1761,93
Greywacke	2,51 x10^6	131,49	329,50
Marl	1,08 x10^7	521,53	5649,14
Clay	4,52 x10^6	697,99	3152,02
Pyrophyllite	37955	646,43	24,54
Trass	2,22 x10^6	687,03	1526,61
Dolomite	1,42 x10^7	81,88	1165,96
Clay for brick and roof tile	4,79 x10^6	747,29	3575,85
Serpentine (Crysolite)	5763	221,21	1,27
Gypsum	4,37 x10^6	49,95	218,27
Ignimbrite	47207,16	914,73	43,18
Marble	5,01 x10^6	9,99	50,06
Onyx	6960,6	9,99	0,07
Travertine	2,54 x10^6	9,99	25,42
Andesite	2,49 x10^6	601,79	1496,02
Basalt	2,91 x10^6	977,06	2842,31
Granite	3,2 x10^5	820,96	262,76
Dressing stone+Mosaic+Slate	3,82 x10^5	9,99	3,82
Total			267795,70

3.1.2. Exergy transfer from ENV to CO

Since all heat and power plants are included in CO Sector, heat and power generation from renewable energy sources are also subsumed in CO Sector. Thereby, renewable energy utilized in energy generation is a flux from ENV to CO and these are: hydropower and wind energy (used in electricity production) and geothermal energy (used in heat and electricity production). In Table 3.4., utilized wind energy, geothermal energy for direct use (heat generation) and hydraulic energy are presented.

Table 3.4 : Exergy of utilized renewable energy sources.

	Amount (TJ)	Exergy coefficient	Total Exergy (TJ)
Wind	1151,37	1	1151,37
Geothermal Heat For Direct Use	45259,31	0,132	5980,20
Hydropower	252822,86	1	252822,86
Total			259954,43

Electricity generation is reported as 11000 TEP (460,548 TJ) and 44244 GWh (159278,4 TJ) from wind and hydraulic energy (IEA, 2008; Republic of Turkey-Ministry of Energy and Natural Resources, n.d.). The efficiency of power generation (η_I) is taken as 0,4 for wind (Nurbay and Cinar, 2005). For hydropower plants, η_I is taken as (0,9x0,7 = 0,63) in which 0,9 is assumed to be the efficiency of turbine and 0,7 is the other electrical and mechanical equipments. Hence, utilized energy (En) from wind and hydraulic energy is calculated as presented in equation (3.1) and seen in Table 3.4. Data for direct use of geothermal energy is extracted from World Energy Council-Turkish National Committee (2007) and Turkish Geothermal Energy Association (n.d.) and presented in Table 3.4.

$$\mathrm{En} = \frac{\text{Generated power}}{\eta_I} \qquad \textbf{(3.1)}$$

Exergy coefficient of wind and hydraulic energy is 1 (energy is equal to exergy since wind and hydraulic energy totally consists of potential and kinetic energy). Exergy coefficient calculation of geothermal heat (for direct use of geothermal energy) is presented in Appendix B.

Geothermal electricity generation is reported as 94 GWh (338,4 TJ) for 2006 (IEA, 2008). Dagdas et al. (2005) obtained the exergetic efficiency (η_{II}) of electricity generation for Kızıldere Geothermal Power Plant of Turkey as 0,1997 (Kızıldere Geothermal Power Plant was the only geothermal plant in 2006). The equation of exergetic efficiency and the exergy of utilized geothermal energy (E_{geo}) in electricity generation are presented in equation (3.2).

$$\eta_{II} = \frac{\text{Generated electricity}}{E_{geo}} \qquad \textbf{(3.2a)}$$

$$E_{geo} = \frac{\text{Generated electricity}}{\eta_{II}} = \frac{338{,}4}{0{,}1997} = 1694{,}54 \text{ TJ} \qquad \textbf{(3.2b)}$$

In conclusion, sum of presented exergy flows in Table 3.4 and exergy consumption in geothermal power plants (E_{geo}) is the exergy flux from ENV to CO Sector which amounts to 261648,97 TJ.

3.1.3. Exergy transfer from ENV to AG

In EEA methodology, solar energy which is received by the whole agricultural area of the country is taken as solar exergy input of AG Sector from ENV. AG sector has 358050 km^2 of agricultural (excluding fallow land) and 211890 km^2 of forest area (Turkstat, 2009a; Turkstat, 2009g). Although a portion of the forests contributes to wood production which is a AG Sector activity, this portion is so little relative to the whole forest covered area and the corresponding impinging solar exergy is neglected in this study.

Annually received solar radiation of AG Sector ($E_{solar,AG}$) is:

$$E_{solar,AG} = 365\, I_d\, A_{AG}\, \zeta \tag{3.3}$$

where I_d (kJ/ m^2day) is the average solar radiation on horizontal surface, A_{AG} (m^2) is the agricultural area, ζ is the exergy coefficient of solar energy (ratio of E_{solar}/En_{solar}). Numerical data is presented in Table 3.5.

Table 3.5 : I_d, A_{AG}, ζ and $E_{solar,AG}$.

		Reference
I_d	3,7 kWh/m^2day = 13320 kJ/ m^2day	Ozturk et al, 2006
A_{AG}	358050 km^2	Turkstat, 2009a; Turkstat, 2009g
ζ	0,93	Szargut et al, 1988
$E_{solar,AG}$	1,62x10^9 TJ	

3.1.4. Exergy transfer from ENV to IN

IN sector utilizes solar energy for heat and electricity generation. Annually received solar energy is reported as 122000 TEP (5107,9 TJ) (Republic of Turkey- Ministry of Energy and Natural Resources, n.d.). Corresponding exergy flux is computed via eqation (3.4) and obtained as 4750,34 TJ.

$$E_{solar} = En_{solar}\, \zeta \tag{3.4}$$

3.1.5. Exergy transfer from ENV to TE and DO

In Republic of Turkey-Ministry of Energy and Natural Resources (n.d.), total amount of solar use is reported for DO and TE Sectors. It is assumed that solar energy utilization is divided evenly between these sectors. Solar energy flux to one of these sectors is 140500 TEP (5882,45 TJ). E_{solar} is computed by equation (3.4) and obtained as 5470,68 TJ.

3.2. Water Transfer between ENV and the Sectors

Water transferred from ENV to AG Sector is estimated on the basis of net water content of AG products. For all other sectors, water received directly from ENV is obtained from (Tusiad, 2008). Water fluxes and corresponding exergy content are presented in Table 3.6. Exergy of water is taken as 0,9 kJ/mol (50 MJ/m^3) (Szargut et al., 1988).

Table 3.6 : Exergy of water received from ENV.

Sector	Water (10^4x m^3)	Exergy (TJ)
EX	17800	8900
CO	2304	1152
AG	9444,14	4722
IN	114675	57337,5
TE	516400	258200

3.3. Summary of Fluxes Received from ENV

As a conclusion, total exergy inputs from ENV to the sectors are seen in Table 3.7.

Table 3.7 : Summary of fluxes received from ENV.

Sector	Flux	Exergy (TJ)
EX	Fuels	705814,87
	Ores	5801,74
	Minerals	267795,71
	Water	8900
	Total	988312,32
CO	Wind	1151,37
	Geothermal Heat For Direct Use	5980,20
	Hydropower	252822,86
	Geothermal Heat For Electricity Generation	1694
	Water	1152
	Total	262800,43
AG	Solar Energy	$1,62x10^9$
	Water	4722
	Total	$1,62x10^9$
IN	Solar Energy	4750,34
	Water	57337,50
	Total	62087,84
TE	Solar Energy	5470,68
	Water	258200
	Total	263670,68
DO	Solar Energy	5470,68
	Total	5470,68

In the applied model in this thesis, TE Sector is considered as the storage-and-distribution hub. Hence, EX Sector transfers all the extracted material (fossil fuels, minerals and ores) to TE Sector. As a result, exergy content of fluxes from ENV to EX and from EX to TE is presented in Table 3.8 based on Table 3.7.

Table 3.8 : EX Sector products.

Product	Exergy (TJ)
Fuels	705814,87
Ores	5801,74
Minerals	267795,71
Total	979412,32

4. EXERGY CONTENT OF SECTORAL PRODUCTS

In this Chapter, sectoral products and their exergy content are presented. Since exergy of EX Sector products are already seen in Table 3.8, the other sectors (CO, AG, IN, TR, TE and DO) are analyzed in the following sections.

4.1 Conversion Sector (CO)

All power and heat plants and refineries (petroleum refining & processing, production of other refinery products) fall within Conversion (CO) Sector. Outputs of this sector are seen in Table 4.1 and 4.2. Data for CO products are extracted from IEA (2008), Republic of Turkey-Ministry of Energy and Natural Resources (n.d.) and Turkish Geothermal Energy Association (n.d.). Since processes in coke factories represents conversion of coal into coke, coke production is also comprised in this sector. In the model applied in this thesis, distribution losses are assigned to the producing sectors for all kind of products. Thus, losses occurring in electrical lines and pipelines are assigned to CO Sector which are seen in Table 4.2 with negative sign depicting that distribution losses are regarded as sectoral losses.

Table 4.1 : CO Sector Products – 1.

Fuel	Amount ($Ton x 10^3$)	Specific Exergy (MJ/Ton)	Total Exergy (TJ)
Coke	3213	30430,40	97772,88
Briquette	155	16121,02	2498,76
Refinery Gas	600	33819,29	20291,58
LPG	808	46837,75	37844,91
Motor gasoline	3659	44350,77	162279,48
Aviation fuel	1644	44589,42	73305,01
Karosene	32	43314,54	1386,07
Diesel	7549	46366,72	350022,34
Heavy fuel oil	7281	39791,35	289720,81
Naphtha	1488	45008,10	66972,05
Other petroleum products	3184	40193,28	127975,40
Liquid biomass	2	43961,40	87,92
Total			1230157,19

Table 4.2 : CO Sector Products – 2.

Fuel	Amount (TJ)	Exergy Coefficient (β_{HHV})	Total Exergy (TJ)
Biogas	331	1,05	347,55
Electricity	634676,4	1,00	634676,4
Coke oven gas	22165	0,89	19726,85
CHP Heat	40109,54	0,67	26873,39
Geothermal Heat	45259,31	0,132	5980,21
Distribution losses			
Coke Oven Gas	-36	0,89	-32,04
Electricity	-89316	1,00	-89316
Total			598256,36

In Table 4.1, "refinery gas" is defined as non-condensable gas obtained during distillation of crude oil or treatment of oil products (e.g. cracking) in refineries (IEA, 2008). In Table 4.2, "coke oven gas" is a combustible gas mixture which is produced as a by-product of coke plants (IEA, 2008; Modesto and Nebra, 2009). Hence, both of these by-products are used in energy generation and accounted for as CO Sector products.

Since refineries are included in CO, their products are sectoral outflow of CO. Due to lack of sufficiently disaggregated data, it was necessary to construct an approximate database that includes only a simplified sample of the great variety of CO products. The approximation is based on the data in TUPRAS (2007), which makes clear that the majority of these by-products are asphalt (bitumen) and engine oil. These byproducts are presented in Table 4.3. In Table 4.3, "others" include, for instance: waxes, solvents, clarified oil, sulfur, heavy vacuum gas oil etc. (Republic of Turkey-State Planning Organization, 2000) and in the table, all the "others" are assumed to be paraffine wax.

Table 4.3 : Refinery by products.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Asphalt (Bitumen)	3,11 x10^6	38029,11	118390,05
Engine Oil	436857,14	44350,77	19374,95
Others (Paraffine Wax)	279571,43	45303,60	12665,59
Total			150430,60

Details of sources or computing of specific chemical exergy and exergy coefficients - which are presented in Table 4.1, 4.2 and 4.3 - are obtainable in Appendix B.

As a conclusion, output of Turkish CO sector is the sum of Table 4.1, 4.2 and 4.3 which represents 1978844 TJ exergy.

4.2 Agricultural Sector (AG)

This sector comprises harvesting, forestry, animal husbandry, and fishery. Natural resources made available by the environment are the main inputs to the sector as it is seen in Table 3.7. Products of the AG sector are split into three groups:

- Group 1: AG products for industrial use, energy production and consumption by DO Sector which are all transferred to TE.
- Group 2: AG products which are transferred from AG directly to DO and consumed by people in rural areas (in the model applied in this thesis, this is the only direct transfer of materials between two sectors by-passing TE sector)
- Group 3: exported AG Sector products

As for Group 1, AG sends products to TE for use in food processing industry, chemical industry, textile industry, fodder industry, seed industry and other industrial processes. In the available data for AG sector products (Turkstat, 2009f), total country own consumption of produced AG products is available but there is no data for industrial consumption and DO sector consumption share in total country consumption amount. An assumption was necessary such as: 20% of total comestible AG sector products (vegetables, fruit, leguminous seeds, honey, egg, olive, milk, soybean, tea and potato) consumption is assumed to be consumed directly by people in rural area (Group 2) and the left is transferred to TE sector to be sold to IN sector (industrial use) and DO sector. All the country consumption of cereals, meat, poultry products, fishery products, bee wax, tobacco, sunflower, rape, cotton, sugar beet is assumed to be transferred to IN sector for further processing (no direct transfer to DO sector). The allocation of AG sector products for comestible goods is presented in Table 4.4. Details of the AG products exergy content are presented in Appendix C.

Table 4.4 : AG Sector products transfer to TE and DO.

	Total Country Consumption (Ton)	Transferred to TE (Ton)	Transferred to DO (Ton)	Specific Exergy (MJ/Ton)	Exergy transferred to TE (TJ)	Exergy transferred to DO (TJ)
Fruit						
Total fruit consumption	8,33 x10^6	6,66 x10^6	1,66 x10^6	1900	12661,30	3165,32
Pistachio	97741	78192,80	19548,20			
Pear	268681	214944,80	53736,20			
Quince	78064	62451,20	15612,80			
Almond	45858	36686,40	9171,60			
Walnut	136992	109593,60	27398,40			
Strawberry	158576	126860,80	31715,20			
Mulberry	43238	34590,40	8647,60			
Apple	1,6 x10^6	1,25 x10^6	313793,20			
Plum	162362	129889,60	32472,40			
Hazelnut	38934	31147,20	7786,80			
Grape fruit	17575	14060,00	3515,00			
Fig	13354	10683,20	2670,80			
Apricot	83062	66449,60	16612,40			
Chestnut	50355	40284,00	10071,00			
Cherry	209828	167862,40	41965,60			
Lemon	356358	285086,40	71271,60			
Mandarin	425477	340381,60	85095,40			
Banana	343441	274752,80	68688,20			
Pomegranate	71156	56924,80	14231,20			
Orange	1,31 x10^6	1,05 x10^6	263366,80			
Peach	454204	363363,20	90840,80			
Sour orange	2566	2052,80	513,20			
Grape	2,22 x10^6	1,78 x10^6	445518,20			
Sour cherry	158588	126870,40	31717,60			
Cereals						
Total cereal consumption	18165220	18165220				
Barley	89800	89800		14800	1329,04	
Wheat (Total)	16,49 x10^6	16,49 x10^6		17400	286936,44	
Maize	1029500	1029500		16400	16883,80	
Rice	555320	555320,00		15200	8440,86	
Leguminous seeds						
Total Leguminous seeds consumption	891104	712883,20	178220,80	16900	12047,73	3011,93
Dry bean	208432	166745,60	41686,40			
Red lentil	268659	214927,20	53731,80			
Chickpea	365481	292384,80	73096,20			
Green lentil	48532	38825,60	9706,40			
Vegetables						
Total vegetables consumption	20,33 x10^6	16,26 x10^6	40,67 x10^5	1900	30910,97	7727,74
Broad bean	38096,26	30477,01	7619,25			
Okra	32305,56	25844,45	6461,11			
Green pea	78623	62898,40	15724,60			
Paprica	1,43 x10^6	1,14 x10^6	286792,40			
Tomato	7,69 x10^6	6,15 x10^6	1,53 x10^6			
Carrot	316546	253236,80	63309,20			

Table 4.4 (continued): AG Sector products transfer to TE and DO.

	Total Country Consumption (Ton)	Transferred to TE (Ton)	Transferred to DO (Ton)	Specific Exergy (MJ/Ton)	Exergy transferred to TE (TJ)	Exergy transferred to DO (TJ)
Cucumber	1489832	1191865,60	297966,40			
Spinach	203663,87	162931,09	40732,77			
Squash	232807,39	186245,91	46561,48			
Watermelon	3313821	2651056,80	662764,20			
Melon	1,44 x10^6	1,16 x10^6	289602,27			
Onion	1,38 x10^6	1,10 x10^6	276127,80			
Cabbage	490996	392796,80	98199,20			
Lettuce	373320,31	298656,25	74664,06			
Eggplant	750172,12	600137,69	150034,42			
Leek	214977,30	171981,84	42995,46			
Garlic	51540	41232,00	10308,00			
Purslane	2949,20	2359,36	589,84			
Green bean	494975	395980,00	98995,00			
Green onion	146557,60	117246,08	29311,52			
Radish	149457	119565,60	29891,40			
Meat	438530	438530,00		10000	4385,30	
Poultry	934731,97	934731,97		4500	4206,29	
Fish products	661991	661991,00		5750	3806,45	
Milk	11,95 x10^6	9,56 x10^6	2,39 x10^6	4900	46852,23	11713,06
Egg	733348	586678,40	146669,60	7000	4106,75	1026,69
Honey	83842	67073,60	16768,40	15200	1019,52	254,88
Beewax	3483,65	3483,65		15200	52,95	
Others						
Olive	1,76 x10^6	1,41 x10^6	353349,80	19000	26854,58	6713,65
Tobacco	98137	98137,00		10700	1050,07	
Sunflower	1,90 x10^6	1,90 x10^6		19000	36153,30	
Rape	229958	229958		37000	8508,45	
Cotton	1,36 x10^6	1,36 x10^6		16700	22731,46	
Soybean	1,28 x10^6	1,03 x10^6	256718,20	16600	17046,09	4261,52
Sugar beet	13,74 x10^6	13,74 x10^6		4200	57724,01	
Tea	927307	741845,60	185461,40	10700	7937,75	1984,44
Potato	3,69 x10^6	2,95 x10^6	738176,80	4200	12401,37	3100,34
Total exergy transfer (TJ)					*624046,69*	*42959,57*

Except comestible goods, wood for industrial purposes and biomass for energy production (including agricultural waste and wood scraps) are also products of AG Sector and sent to TE Sector for further transfer to consuming sectors. Products such as poppy, lupin, hop etc. for chemical industry; silk cocoons, wool, cotton, flax etc. and also hide for textile industry; sainfoin, wild vetches, maize etc. for mixed fodder and other fodder production; seeds for industrial seed production and agricultural product consumption for other industrial processes are also transferred to TE. These products are reported in Table 4.5 and Table 4.6. It must be noticed that information of type and amounts for industrial use of AG products are limited by the available data in Turkstat (2009f). In Table 4.5, "solid biomass" comprises fuel wood and animal manure use in energy production. As seen in Appendix B, β_{HHV} of fuel wood and animal manure is the same and seen in

Table 4.5. The presented amounts are production (not country consumption) and it is assumed that produced amount of the materials are totally consumed in the country or transferred to abroad. In other words, exported amounts of the presented AG products are included in Table 4.5 and Table 4.6. Data for produced industrial wood is retrieved from Kaplan (2007) and for solid biomass from IEA (2008). Exergy of wood is presented in Appendix B. Products transferred to seed industry are derived from TUGEM (n.d.a). The remaining data is retrieved from Turkstat (2009f). In calculation of hide production, since only the number of produced hide is available, one hide is assumed to be 10 kg on average and resulting mass of produced hide is seen in Table 4.6.

Table 4.5 : Exergy of remaining AG products which is transferred to TE -1.

	Amount	Unit	Specific Exergy (MJ/Unit)	Exergy (TJ)
Industrial Wood	14221	(m^3x10^3)	8676,44	123387,71
Manure for biogas production	447255,93	Ton	15985,77	7149,73
			β_{HHV}	
Solid Biomass	214924	TJ	1,05	225670,20
Total				356207,64

Table 4.6 : Exergy of remaining AG products which is transferred to TE -2.

		Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Chemical Industry	Poppy (capsule)	27443	15300	419,88
	Lupin	482	15300	7,37
	Hop	1384	15300	21,18
	Cow vetches	175522	16700	2931,22
Fodder Industry	Sainfoin	23084,33	16700	385,51
	Wild vetches	5540	16700	92,52
	Maize	6713312	16700	112112,31
	Fodder beet	105847,33	16700	1767,65
	Cow vetches	807078,67	16700	13478,21
	Clover	7226	16700	120,67
	Alfalfa	1880150	16700	31398,51
	Barley	7695200	14800	113888,96
	Wheat	427400	17400	7436,76
	Maize	2967000	16400	48658,80
	Soybean	730761	16600	12130,63
Textile Industry	Silk cocoons	127	4500	0,57
	Wool	46751	8000	374,01
	Hair	2728	3700	10,09
	Mohair	274	3700	1,01
	Cotton (raw)	2550000	16700	42585,00
	Cotton (lint)	976540	16700	16308,22
	Flax (fibre)	8	16400	0,13
	Hemp (fibre)	60	16400	0,98
	Hide	79335,04	20848	1653,95

Table 4.6 (continued): Exergy of remaining AG products which is transferred to TE -2

		Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Seed Industry	Wheat	225493	17400	3923,58
	Barley	26667	14800	394,67
	Maize	27319	16400	448,03
	Paddy	4685	16700	78,24
	Sunflower	5465	19000	103,84
	Soybean	419	16600	6,96
	Groundnut	101	4240	0,43
	Sugar beet	2855	4200	11,99
	Potato	93377	4200	392,18
	Cotton	18195	16700	303,86
	Chickpea	206	16900	3,48
	Dry bean	36	16900	0,61
	Lentil	1060	16900	17,91
	Rape	56	37000	2,07
	Vegetable	2524	1900	4,80
	Sesame	1,20	29000	0,03
	Alfalfa	802	16700	13,39
	Sainfoin	1089	16700	18,19
	Cow vetches	2552	16700	42,62
	Sorghum	227	16700	3,79
	Sudan grass	23	16700	0,38
	Fodder beet	120	16700	2,00
	Knotgrass	743	15300	11,37
Other Industrial Use	Barley	220000	14800	3256
	Maize	151000	16400	2476,40
	Grape	317613	1900	603,46
	Sunflower	99999	19000	1899,98
Total				419804,41

In Table 4.6, “other industrial use” stands for the amount of consumption by several industry branches, which are neither for human consumption nor for animal feed. The quantities used by food industry do not appear in this item (Tukstat, 2009f).

In Table 4.5, computed amount of manure for biogas production is presented. Landfill gas, sludge gas and other biogas such as biogas produced from the anaerobic digestion of animal slurries and of wastes in abattoirs, breweries and other agro-food industries are used for production (IEA, 2008). In the present thesis, waste for biogas production is assumed to be animal manure and provided totally by AG sector. Added to this, anaerobic digestion process is assumed to be used in the production. In Republic of Turkey, almost all of the sectors’ waste is used in biogas production and there is a board range of technologies used in biogas plants (Turker, 2008). Detailed data is not available for allocation of waste (which is used in biogas production) through waste generating sectors and employed technologies. It can be estimated that this assumption is not able to commit a serious change in EEA analysis results of AG or other sectors considering that only 331 TJ energy containing biogas is produced and consumed in Turkey.

Principally, biogas is produced from the anaerobic digestion of biomass and solid wastes and combusted to produce heat and/or power. In the case of Turkey, it follows the same line and produced biogas is utilized in heat and power generation (IEA, 2008). Non-upgraded biogas contains sulfur and other chemical compounds (together with high amount of CO_2, ~ 40%) and these compounds must be removed from biogas to protect the energy generation plant from possible resulting damage. That is because, in this study, the composition of biogas consumed in the country is assumed to be upgraded (~98% CH_4+~2% CO_2).

In Section 5.4.2.4, biogas production from AG sector solid waste is explained with details. Heating value of CO_2 is assumed to be zero. HHV of upgraded biogas is seen in Table 4.7. Computation route of biogas production is presented in Table 4.8, below. In Table 4.8, upgraded biogas obtained from manure is extracted from calculations presented in Section 5.4.2.4.

Table 4.7 : HHV of biogas.

CH_4 HHV (MJ/m^3)	37,11
CO_2 HHV (MJ/m^3)	0
HHV of biogas (MJ/m^3)	36,37

Table 4.8 : Exergy of manure for biogas production.

HHV of produced biogas (TJ)	331
HHV of upgraded biogas sample (MJ/m^3)	36,37
Produced upgraded biogas (10^{3}xm^3)	9101,66
Upgraded biogas obtained from manure (m^3 biogas/Ton manure) (wet)	20,35
Manure for biogas production (Ton) (wet)	447255,93
Specific exergy of manure (MJ/kg)	15,99
Exergy of manure for total biogas production (TJ)	7149,73

Exported AG sector products (Group 3) and their exergetic equivalent are presented in Table 4.9. As it is stated above, for the group of products seen in Table 4.5 and Table 4.6, exported amounts (if any) are already included. But for the products presented in Table 4.4, exported amounts must be taken into account as another transfer from AG to TE. Exported amounts of these products are presented in Table

4.9. For imported and exported materials and their monetary equivalent, an aggregated data is used to keep consistency through the thesis. The data is obtained from Turkstat (personal communication, December 20, 2009e). Since products such as meat, poultry products, fishery products and milk are processed in food processing industry, their export is considered under "export of industrial sector products".

Table 4.9 : Exergy of exported AG products.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Livestock	2108,31	10000	21,08
Plants (alive)	19746,67	15300	302,12
Knitable hays and others	43305,27	15300	662,57
Eggs	2694,92	7000	18,86
Honey	9300,11	15200	141,36
Other animal products	3280,24	10000	32,80
Vegetable	$1{,}19 \times 10^6$	1900	2266,41
Fruit	$2{,}62 \times 10^6$	1900	4972,63
Cereal	$1{,}74 \times 10^6$	15930	27726,86
Tobacco	154420,36	10700	1652,30
Total			37797,01

In conclusion, exergy transfer via material flux from the AG to TE Sector (Group 1) is the sum of Table 4.5 and Table 4.6 and relevant column of Table 4.4 which amounts to $1{,}4 \times 10^6$ (1400058) TJ. Added to this, Group 3 also represents an exergy flux between AG and TE Sectors with 37797 TJ exergy content (Table 4.9). Sum of Group 1 and Group 3 is the total transfer from AG to TE which amounts to $1{,}44 \times 10^6$ (1437856) TJ.

The exergy of agricultural products directly transferred to DO (Group 2) is shown in the relevant column of Table 4.4 which amounts to 42960 TJ.

4.3 Industrial Sector (IN)

Industrial sector includes all manufacturing activities including construction. Since fuel processing and energy generation are covered by CO Sector, refinery products (refined petroleum products, refinery by-products) and domestically produced electricity and heat are not included in IN Sector products.

The sector includes a large number of sub-sectors. The European Union adopted the criterion of economic origin for its development, with NACE (Statistical classification of economic activities in the European Community) as the reference framework. Industrial sector is examined according to NACE Revision 2 classification of industrial sector divisions (sub-industries, sub-sectors) and the list of the sectoral divisions is presented below (Eurostat, 2008). As it is reasoned above, the division of "Manufacture of coke and refined petroleum products" is excluded from the list of the industrial sector divisions.

- Manufacture of food products
- Manufacture of beverages
- Manufacture of tobacco products
- Manufacture of textiles
- Manufacture of wearing apparel
- Manufacture of leather and related products
- Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
- Manufacture of paper and paper products
- Printing and reproduction of recorded media
- Manufacture of chemicals and chemical products
- Manufacture of basic pharmaceutical products and pharmaceutical preparations
- Manufacture of rubber and plastic products
- Manufacture of other non-metallic mineral products
- Manufacture of basic metals
- Manufacture of fabricated metal products, except machinery and equipment
- Manufacture of computer, electronic and optical products
- Manufacture of electrical equipment
- Manufacture of machinery and equipment
- Manufacture of motor vehicles, trailers and semi-trailers
- Manufacture of other transport equipment
- Manufacture of furniture

- Other manufacturing
- Repair and installation of machinery and equipment

IN includes a large spectrum of manufacturing activities generating a broad range of products. The largest industries are: food processing, textile, wood, paper, iron and steel, nonferrous metal and chemical industries. To avoid double accounting, consumed raw materials (which are further over and over processed and convert into products of IN Sector) are regarded as the output of IN. In order to do this, within the limits of national data, "domestic production+import-export" of the raw materials are computed or -if data is available- directly published raw material consumption is used.

In this thesis, "food processing industry" (also named "food industry") covers manufacturing of food products, beverages and tobacco products, seed industry is also comprised in food industry. According to NACE Revision 2, manufacture of prepared animal feeds is also included in this division of industrial activity.

As for food industry and textile industry, because sufficiently disaggregated data about the products of the sector were not available, the exergy input in a single technological line is assumed to be equal to the exergy of the products of that line. It is tantamount to taking into account only the mass-flow rate losses (material waste) of the processes, and additionally assuming that the processes employed in production lines urge no physical or chemical conversion which substantially modifies chemical or physical exergy of the inputs (raw materials entering the processes). As a special example to explain this approach, assume that X ton/year of cotton is delivered to the textile industry: the total input exergy will be [$X.E_{cotton}$] (J/year). If the cumulative mass flow rate of cotton apparel (shirts, jeans, cloth, skirts, towels, etc.) is [$\gamma.X$], [$(1-\gamma)X$] is being the wasted material, then the total exergy assigned to the output is [$\gamma.X.E_{cotton}$]. In this study, the γ factor for food processing and textile industries is estimated to be equal to 0,9 (Ertesvag, 2005). In other words, 10% of the input mass flow is assumed not to be incorporated in the final form of the sub-sectoral products and included in the IN sector solid waste.

As it is stated earlier, TE sector is the collection and distribution hub of the model and transfers raw materials to IN sector to be used as the feedstock in industrial production. Details are presented later in the Section dedicated to TE sector (Section 4.6). In accordance with the estimated amounts of raw material for food processing and textile industry production (Table E.2), exergy of products computed in line with the above mentioned calculation route ($\gamma = 0{,}9$). For food processing industry, resulting exergy content of the products are presented in Table 4.10, 4.11 and 4.12. Presented specific exergy quantities in following tables are detailed in Appendix C.

Table 4.10 : Production of food processing industry and corresponding exergy.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Fruit			
Total fruit consumption	581749,12	1900	1105,32
Pistachio	3518,68		
Pear	9672,52		
Quince	2810,30		
Almond	1650,89		
Walnut	4931,71		
Strawberry	5708,74		
Mulberry	1556,57		
Apple	56482,78		
Plum	5845,03		
Hazelnut	1401,62		
Grape fruit	632,70		
Fig	480,74		
Apricot	2990,23		
Chestnut	1812,78		
Cherry	7553,81		
Lemon	12828,89		
Mandarin	15317,17		
Banana	12363,88		
Pomegranate	2561,62		
Orange	47406,02		
Peach	16351,34		
Sour orange	92,38		
Grape	80193,28		
Sour cherry	5709,17		
Canned fruit	281876,29		
Cereals			
Total cereal consumption	16348698		
Barley	80820	14800	1196,14
Wheat (Total)	$1{,}48 \times 10^{7}$	17400	258242,80
Maize	926550	16400	15195,42
Rice	499788	15200	7596,78
Leguminous seeds			
Total Leguminous seeds consumption	35644,16	16900	602,39
Dry bean	8337,28		
Red lentil	10746,36		

Table 4.10 (continued): Production of food processing industry and corresponding exergy.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Chickpea	14619,24		
Green lentil	1941,28		
Vegetables			
Total vegetables consumption	3,49 x10^6	1900	6630,05
Broad bean	1371,47		
Okra	1163,00		
Green pea	2830,43		
Paprika	51622,63		
Tomato	2,91 x10^6		
Carrot	11395,66		
Cucumber	53633,95		
Spinach	7331,90		
Squash	8381,07		
Watermelon	119297,56		
Melon	52128,41		
Onion	49703,00		
Cabbage	17675,86		
Lettuce	13439,53		
Eggplant	27006,20		
Leek	7739,18		
Garlic	1855,44		
Purslane	106,17		
Green bean	17819,10		
Green onion	5276,07		
Radish	5380,45		
Canned vegetable	116907,22		
Meat	394677	10000	3946,77
Poultry	841258,78	4500	3785,66
Fish products	57000	5750	327,75
Milk	6454134	4900	31625,26
Egg	26400,53	7000	184,80
Honey	30183,12	15200	458,78
Bee wax	3135,28	15200	47,66
Others			
Olive	1,06 x 10^6	19000	20224,16
Tobacco	88323,30	10700	945,06
Sunflower	1,22 x 10^6	19000	23264,65
Rape	206962,20	37000	7657,60
Cotton	1,23 x 10^6	16700	20458,31
Soybean	924185,52	16600	15341,48
Sugar beet	1,23 x 10^7	4200	51951,61
Tea	667661,04	10700	7143,97
Potato	132871,82	4200	558,06
Total exergy (TJ)			478490,48

Table 4.11 : Fodder production.

	Amount (10^3 x Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Mixed fodder	7467,08	16400	122460,13
Other fodder			
Barley	6925,68	14800	102500,06
Wheat	384,66	17400	6693,08
Maize	2670,3	16400	43792,92
Soybean	657,68	16600	10917,57
Total exergy (TJ)			286363,77

Mixed fodder is composed of several cereals (mainly maize), straws, vitamins, minerals, etc. (Kutlu, 2009). Exergy of mixed fodder is taken as the same as maize in Table 4.11. Data is retrieved from Kutlu (2009) and (Turkstat, 2009f). In Table 4.12, data is retrived from TUGEM (n.d.a).

Table 4.12 : Seed production and corresponding exergy.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Wheat	225493	17400	3923,58
Barley	26667	14800	394,67
Maize	27319	16400	448,03
Paddy	4685	16700	78,24
Sunflower	5465	19000	103,84
Soybean	419	16600	6,96
Groundnut	101	4240	0,43
Sugar beet	2855	4200	11,99
Potato	93377	4200	392,18
Cotton	18195	16700	303,86
Chickpea	206	16900	3,48
Dry bean	36	16900	0,61
Lentil	1060	16900	17,91
Rape	56	37000	2,07
Vegetable	2524	1900	4,80
Sesame	1,20	29000	0,03
Alfalfa	802	16700	13,39
Sainfoin	1089	16700	18,19
Cow vetches	2552	16700	42,62
Sorghum	227	16700	3,79
Sudan grass	23	16700	0,38
Fodder beet	120	16700	2,00
Knotgrass	743	15300	11,37
Total	414015		5784,42

As a result, exergy content of food processing industry is estimated as the sum of Table 4.10, Table 4.11 and Table 4.12 which totals to 770639 TJ.

As for textile industry (covering manufacture of textiles, manufacture of wearing apparel, manufacture of leather and related products), consumed AG products are presented in Table 4.6 and 90% of these materials are seen in Table 4.13 which are assumed to be comprised in the content of the textile industry products. All chemical fibres used by the textile industry are considered as a product of the chemical industry, so that this is an internal flow in IN. A non-negligible amount of raw materials for textile industry was imported and exported in 2006. The difference between import and export is assumed to constitute the sectoral consumption and is reported in Table 4.14. Data for "import-export" materials are retrieved from Turkstat (personal communication, December 20, 2009e).

Table 4.13 : Exergy content of textile industry products – 1.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Silk cocoons	114,30	4500	0,51
Wool	42075,90	8000	336,61
Hair	2455,20	3700	9,08
Mohair	246,60	3700	0,91
Cotton (raw)	$2{,}29 \times 10^{6}$	16700	38326,50
Cotton (lint)	878886	16700	14677,40
Flax (fibre)	7,20	16400	0,12
Hemp (fibre)	54,00	16400	0,89
Hide	71401,53	20847,63	1488,55
Synthetic fibre	1146150	18484,54	21186,05
Total			76026,62

Table 4.14 : Exergy content of textile industry products – 2.

	Import (Ton)	Export (Ton)	Import-Export (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Silk	540,71	111,71	429	4560	1,96
Wool, animal hair, yarns	57782,44	26778,68	31003,76	5850	248,03
Cotton, cotton yarn and cotton fabric	991140,04	363955,40	627184,63	16700	10473,98
Natural fibre	139189,53	9700,95	129488,58	4,93	0,64
Synthetic fibre	852042,04	505847,02	346195,02	18484,54	6399,25
Other fabric	63384,10	59148,78	4235,32	4,16	0,02
Hide	186997,39	37845	149152,73	20847,63	3109,48
Total					20233,36

In conclusion, exergy content of textile industry products are estimated as the sum of Table 4.13 and Table 4.14 which amounts to 96260 TJ.

Industrial wood consumption of IN sector is seen in Table 4.15 (Kaplan,2007). It is thought that, industrial wood is the raw material of all wood products, hence the exergy of the consumed industrial wood is assumed as the exergy of produced wood and wood products which is seen in Table 4.15. As for manufacture of paper and paper products, produced paper and cupboard in IN Sector is also seen in Table 4.15 (Sonmez, 2009).

Table 4.15 : Exergy of wood and paper products.

	Amount	Specific Exergy (MJ/Unit)	Exergy (TJ)
Industrial wood (m^3)	$14{,}85 \times 10^6$	8676,44	128879,90
Paper and cupboard (Ton)	$2{,}12 \times 10^6$	17000	36006

Following the same approach presented above, as for manufacture of chemicals and chemical products, consumed basic chemicals by the sector are accounted for since the other products of the sector are derived from these materials. In NACE Revision 2 classification, the first division of the chemical industry is associated with production of sectoral feedstock and presented below.

- Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics and synthetic rubber in primary forms
  - Manufacture of industrial gases
  - Manufacture of dyes and pigments
  - Manufacture of other inorganic basic chemicals
  - Manufacture of other organic basic chemicals
  - Manufacture of fertilizers
  - Manufacture of plastics in primary forms
  - Manufacture of synthetic rubber in primary forms

As for the last three items of the above list: manufacture of fertilizers, plastics in primary forms and synthetic rubber in primary forms, estimated product exergy contents are presented in Table 4.16. With regard to fertilizer production, production of the sector is directly used. Since fertilizer is not a raw material of any process in the sector, import and export transfers are not taken into account (they are not consumed within the sector and not comprised in sectoral products). Exergy of fertilizers is computed based on chemical content of the fertilizers and is inserted into

Table 4.16. Data for fertilizer production is retrieved from TUGEM (n.d.b). Data of primary plastic and synthetic rubber are extracted from Demirci (2008).

Table 4.16 : Exergy content of produced fertilizers and consumed plastic and rubber.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Fertilizer production			
Nitrogen-N	699525	25,71	17,99
Phosphate-P_2O_5	384832	2899,08	1115,66
Potash - K_2O	65965	4385,21	289,27
Primary plastic			
Domestic production	638000		
Import-Export	$3{,}17 \times 10^6$		
Domestic production+Import-Export	$3{,}81 \times 10^6$	32502,16	123898,25
Synthetic rubber			
Domestic production	40000		
Import-Export	110000		
Domestic production+Import-Export	150000	32502,16	4875,32
Total			130196,49

When computing the exergy of the first 4 items of manufactured basic chemicals (manufacture of industrial gases, of dyes and pigments, of other inorganic basic chemicals and of other organic basic chemicals), due to the wide variety in products and chemical compositions, it was not possible to use the standard procedures of exergy computing described in Szargut et al. (1988). As an admittedly somewhat inaccurate alternative, their production cost is converted into an exergetic equivalent by means of the capital conversion factor (ee_C). Theoretical background of “capital to exergy” conversion is discussed in Chapter 5.

Monetary equivalent of the first 4 items is extracted from Republic of Turkey-Ministry of Science, Industry and Technology (personal communication, September 28, 2008) and presented in Table 4.17.

Table 4.17 : Exergetic equivalent of other chemical industry products.

Monetary equivalent of the products (10^8 TL)	38,19
Monetary equivalent of the products (10^8 \$)	26,69
ee_C (MJ/\$)	25,50
Exergetic equivalent (TJ)	68053,64

As a result, estimated exergy of the chemical industry products (computed by means of the assumptions detailed above) is the sum of Table 4.16 and Table 4.17 which totals to 198250 TJ.

As for other non-metallic mineral products and basic metals, the same approach (presented above) is followed and sectoral consumption is seen in Table 4.18 and Table 4.19, respectively.

Table 4.18 : Exergy content of sectorally consumed non-metallic mineral products.

	Amount	Specific Exergy (MJ/Ton)	Exergy (TJ)
Cement			
Production (Ton)	$47,4 \times 10^6$		
Import-Export (Ton)	$-4,76 \times 10^6$		
Total consumption	$42,63 \times 10^6$	1500	63957,58
Glass			
Production (Ton)	$2,5 \times 10^6$		
Import-Export (Ton)	53004,79		
Total consumption	$25,53 \times 10^6$	31,62	80,74
Ready Concrete			
Production (m^3;Ton)	$74,4 \times 10^6$; $148,8 \times 10^6$		
Import-Export			
Total consumption (Ton)	$148,8 \times 10^6$	1500	223200,00
Brick			
Production (Ton)	$12,78 \times 10^6$		
Import-Export (Ton)	-30341		
Total consumption	$12,75 \times 10^6$	1079,97	13774,54
Tile			
Production (Ton)	$1,3 \times 10^6$		
Import-Export (Ton)	-32647,48		
Total consumption	$1,3 \times 10^6$	1079,97	1444,57
Lime			
Production (Ton)	$3,66 \times 10^6$		
Import-Export (Ton)	-56681,07		
Total consumption	$3,61 \times 10^6$	9,99	36,05
Plaster			
Production (Ton)	$2,5 \times 10^6$		
Import-Export (Ton)	-109386,96		
Total consumption	$2,39 \times 10^6$	49,95	119,41
Total			302612,89

In Table 4.18, data for amount of imported and exported materials (except brick and tile) are retrieved from Turkstat (personal communication, December 20, 2009e). Domestic production of cement, glass, ready concrete and plaster is retrieved from YEM (2009). Data for production, import and export of brick and tile is derived from TUKDER (2008). Production data of lime is retrieved from Foundation of Turkish Lime Manufacturers (2009). Exergy of the products are detailed in Appendix C.

Metal content of the IN Sector products (in any type of production including construction) is assumed to be the total metal consumption of the country (based on the assumption of almost all of the metal and metal containing products are used within the IN Sector) and presented in Table 4.19. In this way, all the produced, imported and exported amounts of metals are directly taken into account without a detailed analysis and included in IN Sector products. The consumed amount of steel, aluminium and copper is derived from Republic of Turkey Prime Ministry - Investment Support and Promotion Agency (2010b). The remaining of the metals are derived from Chamber of Turkish Geology Engineers (n.d.). Specific exergy of metals are obtained from Szargut et al. (1988).

Table 4.19 : Exergy content of sectorally consumed metal products.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Steel	21,22 x 10^6	6800	144309,60
Aluminium	886000	32903,70	29152,68
Copper	360000	2111,72	760,22
Lead	35000	1124,64	39,36
Zinc	60000	5178,63	310,72
Tin	3000	4589,72	13,77
Nickel	2000	3944,07	7,89
Wolfram (Tungsten)	50	4497,28	0,22
Molybdenum	20	7607,29	0,15
Magnesium	5000	26082,30	130,41
Cobalt	66	4491,53	0,30
Cadmium	50	2600,00	0,13
Titanium	117	18972,80	2,22
Chrome	500000	10467,31	5233,65
Manganese	8500	8769,09	74,54
Gold	278	78,17	0,022
Silver	161	650,78	0,105
Total			180035,99

Products of other industries (manufacture of fabricated metal products, of computer, electronic and optical products, of machinery and equipment, etc.) are produced (or assembled) from the above mentioned basic sectoral products and largely “consumed” internally to the IN sector: thus, their exergy content is not counted in final products of IN to avoid double accounting.

As the details are seen in Appendix G, in IN Sector, some of recyclable constituents of domestically generated MSW are recycled and a part of organic waste is composed to produce a fertilizer- like- material (used as a substitute of fertilizer and named “fertilizer” in Table 4.20). Resulting products from these processes are IN Sector products and summarized in Table 4.20 (Republic of Turkey-Ministry of Environment and Forests, 2009). Specific exergy contents of presented materials in Table 4.20 are detailed in Appendix C.

Table 4.20 : Products of the recycling processes.

Material	Consumed waste material (Ton)	Recycled product (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Material recycling				
Plastic & rubber	125339,7	91874	32502,16	2986,10
Metal	91660,22	85244	19834,39	1690,76
Paper & cupboard	1075365	1075365	17000	18281,21
Glass	90770	90770	31,62	2,87
Composite material	3813,33	3432	16691,76	57,29
Composting				
Organic waste	104807	24648	18373,31	452,87
Total	1491755,25	1371333		23471,09

Added to this, by-products of the sector which are used as fuel or feedstock in different industrial processes are also sectoral products. Within this content, blast furnace gas (which is a combustible gas produced as a by-product from iron and steel industry during the combustion of coke in blast furnaces (IEA, 2008; Modesto and Nebra, 2009)) and produced scrap are presented in Table 4.21 and Table 4.22, respectively. It must be noticed that data for re-used scrap is very limited for Turkey and presented amount of scrap materials is only the available data. As for blast furnace gas, energy content and exergy coefficient (β_{HHV}) are retrieved from IEA (2008) and Szargut et al. (1988), respectively. As stated earlier, in the model applied in this thesis, distribution losses are assigned to relevant sectors for all kind of products. Thus, gas loss occurring through the distribution of blast furnace gas is assigned to IN Sector which is seen in Table 4.22 with negative sign depicting that distribution losses are regarded as sectoral losses.

Table 4.21 : Exergy of produced scrap (Szargut et al., 1988).

Material	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Steel	2400000	6800	16320
Zinc	20000	5178,63	103,57
Copper	78000	2111,72	164,71
Lead	10000	1124,64	11,25
Aluminium	75890,70	32903,70	2497,09
Total			19096,62

Table 4.22 : Produced blast furnace gas and exergy content.

Material	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Blast furnace gas			
Production	37970	0,97	36830,90
Distribution losses	-1322	0,97	-1282,34
Total	36648		35548,56

Estimated exergy content of IN Sector products are summarized in Table 4.23.

Table 4.23 : Exergy content of IN sector products.

	Exergy of products (TJ)
Food processing	770639
Textile products	96260
Wood products	128880
Paper and cupboard	36006
Chemical products	198250
Non-metallic mineral	302613
Metal	180036
Waste recycling	23471
Scrap	19097
Blast furnace gas	35549
Total	1790801

4.4 Transportation Sector (TR)

The transportation sector (TR) includes transportation of passengers and goods (both public and private) in all transportation modes: rail, road, air, marine and also material-carrying activities (pipelines, escalators, cableways, etc.). In EEA methodology, internal movimentation of materials and goods in the sectors is named "secondary transportation" and corresponding energy use is assigned to the relevant sectors. According to this definition, for example, diesel energy use of AG sector (by tractors) is charged to AG sector. In documents of national energy budgets for Turkey (IEA, 2008; Republic of Turkey - Ministry of Energy and Natural Resources, n.d.), energy use for secondary transportation of the sectors is assigned to sectoral consumption. As such, no extra data and/or estimations are needed.

In energy budget of Turkey, transportation sector is documented under 6 divisions: rail, marine, air, road transportation, pipeline transport and non-specified transportation (cableway, tram, escalators, etc.). The calculation of energy use in each transportation mode is quite straightforward, and can be conducted on the basis of above referenced available national energy budgets. However, there is no available data on allocation of fuel consumption in TR sector services (sectoral output, sectoral product) to other sectors. Hence, some preliminary approximations were necessary. Assumptions and resulting apportionment of fuel consumption through transportation service receiving sectors are presented in Appendix D.

In Table D.1 (Appendix D), total transferred energy carriers consumed by TR sector and total energy and exergy consumptions are reported. As it is seen in the Table D.1, sum of exergy consumptions via energy carriers amounts to 663682,24 TJ which also refers to E_{PHYS} flow received by TR sector.

In transportation sector, the goal of electricity and fossil fuel consumption is production of shaft work. Produced shaft power is work output of the transportation system and by definition, equal to exergy. For electrically and fossil fuel propelled vehicles, shaft work output is calculated by equations (4.1) and (4.2), respectively (Saidur, 2007; Ediger and Camdali, 2007; Ji and Chen, 2006; Jaber et al., 2008).

For electrically propelled vehicles:

$$W_{shaft} = \eta_I \text{ x } En_{el} \tag{4.1}$$

For fossil fuel propelled vehicles:

$$W_{shaft} = \eta_I \text{ x } En_f \text{ x } m_f \tag{4.2}$$

where, W_{shaft} (J) is the shaft work; η_I is the first law efficiency of considered transportation mode; En_{el} (J) is the electrical energy; En_f (J/Ton) is low heating value (LHV) of fuel; m_f (Ton/year) is fuel consumption.

The first law efficiency (η_I) of road (Nakicenovic et al., 1996; CAA, 2009), marine, air and rail (Nakicenovic et al., 1996) transportation modes are reported in Table 4.24. For non-specified transportation, the prevailing energy carrier is electricity and the efficiency is assumed to be 75% based on Nakicenovic et al. (1996). Efficiency of pipeline transportation (operation of pipelines transporting of gases, liquids and other commodities; pumping stations) is computed based on data presented in Johnson (2010). Details are seen in equations (4.3) and (4.4).

Table 4.24 : Efficiency of transportation modes.

Transportation mode	Traction	Efficiency (%)
Rail		
	Electricity	75,8
	Diesel	25
Air		26
Marine		31
Road		12
Pipeline transport		
	Electricity	90
	Natural Gas	29
Non specified		75

As for the efficiency of natural gas consumption in pipeline transport (Johnson, 2010):

- Efficiency of transmission pipeline (transport) = 95-98%
- Efficiency of gas fired compressor station = 30-40 %

$$\text{Overal efficiency} = 0{,}95 \text{ x } 0{,}3 \cong 0{,}29 \tag{4.3}$$

As for the efficiency of electricity consumption in pipeline transport (Johnson, 2010):

- Efficiency of transmission pipeline (transport) = 95-98%
- Efficiency of electrical motor = 95-98%

$$\text{Overal efficiency} = 0{,}95 \text{ x } 0{,}95 \cong 0{,}90 \tag{4.4}$$

LHV of fuels which are used in sectoral transportation activities are seen in Table 4.25.

Table 4.25 : Low heating value (LHV) of fuels.

Fuel	LHV (MJ/Ton)
LPG	46607
Motor Gasoline	42863,45
Aviation Fuel	44031,32
Diesel	42791
Heavy Fuel Oil	38456
Liquid Biomass	40059,3

In Appendix D, sectoral fuel and electricity consumption (used in order to serve to the other sectors) are presented. As a result, inserting necessary data into equations

(4.1) and (4.2), exergetic output from the sector and dissipation of the output through the service receiving sectors are computed and reported in Table 4.26.

It must be noticed that, in Appendix D, natural gas consumption is quantified by corresponding HHV equivalent. In equation (4.2), LHV of natural gas is needed which is computed by means of the ratio LHV/HHV=0,91 for natural gas.

Table 4.26 : Exergetic output of TR Sector and its distribution through the sectors (TJ).

	EX	CO	AG	IN	TR	TE	DO	Total
Rail	322,08	25,33	3,96	317,31			2234,62	2903,30
Air	8871,41	698,67	162,42	8785,01	19,47	92,43	1095,75	19725,15
Marine	2708,59	213,01	33,34	2668,46			288,30	5911,69
Road	16241,00	1281,07	403,56	16172,70	74,51	1675,68	26196,54	62045,06
Pipeline transport	264,17	264,17	264,17	264,17	264,17	264,17	264,17	1849,21
Non specified							1134	1134
Total	28407,25	2482,25	867,45	28207,64	358,16	2032,28	31213,37	93568,40

4.5 Domestic Sector (DO)

As stated earlier, through the traditional exergy analysis and other exergy based exergoeconomic or thermoeconomic analysis methods, the peculiar novelty of EEA is inclusion of additional production factors into the system balance: human labour, capital and environmental remediation cost. One of the consequences is that the domestic sector is considered as the producer of working hours, i.e., domestic sector output is the labour consumed through the country and it is expressed in terms of exergy by following the methodology presented in Section 2.4.1 and Section 5.1.2. Sectorally consumed labour (and its exergetic equivalent) is a direct flux from DO Sector to the relevant sectors. Computation and distribution of labour exergy fluxes through the sectors are detailed in Section 5.2, hence, computation is not repeated in this section. Exergetic equivalent of the produced labour by DO Sector is 4,35 x 10^6 (4351692) TJ.

As mentioned in Section 5.4.2.1 and detailed in Appendix G, materials used in recycling processes (material recycling, composting and incineration for energy generation) are assumed to be provided by MSW (municipal solid waste) produced by DO Sector. In the available database for Turkey, sectoral source of recycled materials is not available. As a result, it is assumed that all the recyled waste is generated by DO Sector and these waste materials are additional products of the sector. These products are transferred to TE and then dispatched to CO and IN Sector to be recycled accordingly. Products of incineration are included in the CO Sector electricity generation (Table 4.2); compost and recycled materials are seen as IN Sector products in Table 4.20.

In Appendix G, amount of incinerated MSW is presented. Exergy of MSW which is allocated for incineration process is presented in Table 4.27. Specific exergy of the MSW consisting materials are detailed in Appendix C.

Table 4.27 : Exergy of incinerated MSW.

	% wt.	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Organic	50,22%	300994,61	19922,34	5996,52
Paper & cupboard	13,30%	79713,83	17000	1355,14
Textile	5,28%	31645,79	13904,76	440,03
Plastic	14,39%	86246,76	32502,16	2803,21
Diaper	3,90%	23374,73	18975,58	443,55
Tetra-pak	0,64%	3835,85	17000	65,21
Glass	5,82%	34882,29	131,48	4,59
Metal (Al)	0,68%	4075,59	32928,09	134,20
Metal (Fe)	0,88%	5274,30	6740,69	35,55
Other metals (Cu)	0,07%	419,55	2086,61	0,88
Wood	0,51%	3056,70	20658,24	63,15
Other combustibles	2,10%	12586,39	35503,40	446,86
Ash	2,21%	13245,68	0	0
Total	100%	599352,08	19669,35	11788,87

In the year 2006, 104807 Ton organic waste is composted (Turkstat, 2008a). The list of materials which underwent material recycling processes is presented in Appendix G. The consumed raw materials for these recycling processes and corresponding exergy content are seen in Table 4.28. In Table 4.28, recycled metal is assumed to be half aluminium and half iron which are the most recycling materials in Turkey. Data of exergy is presented in Appendix C.

Table 4.28 : Exergy of consumed materials in material recycling and composting.

Material	Consumed waste material (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Material recycling			
Plastic & rubber	125339,7	32502,16	4073,81
Metal	91660,22	19834,39	1818,02
Paper & cupboard	$1,07 \times 10^6$	17000	18281,21
Glass	90770	31,62	2,87
Composite material	3813,33	16691,76	63,65
Composting			
Organic waste	104807	19922,34	2088
Total	$1,49 \times 10^6$		26327,56

As a result, DO Sector output fluxes are summarized in Table 4.29, below.

Table 4.29 : DO Sector products (output).

Product	Exergy (TJ)
Labour	4351692
Incinerated waste	11789
Recycled material	24240
Composted organic waste	2088
Total	4389809

4.6 Tertiary Sector (TE)

All commercial, financial and service related activities such as finance agencies and banks, real estate, wholesale, retail, hotels and all public services including governmental agencies, hospitals, schools etc. but excluding transportation are encompassed in TE. In the model applied in this thesis, TE is considered as the storage- and- distribution hub for the system: sectoral products (products which are generated in sectors) are first transferred to TE and then delivered to consuming sectors. Sectoral products are reported in relevant sections of this chapter. Since all types of commercial activities are covered by TE, import and export activities are also included.

The allocation of societal products and imported & exported materials is conducted based on predictability of the consuming sector(s). To do this, the products are divided into two groups:

- Group 1: If the consuming sectors of the products are predictable explicitly, the products are directly transferred to the relevant sectors (such as: transferring fertilizers to AG Sector or minerals to IN sector).

- Group 2: However, there are products which can be consumed by any sectors. To map the distribution of these products from TE to other sectors, data about material transfer between the sectors would be necessary: such data are though unavailable for Turkey, and thus it is assumed that the exergy of these products are allocated to the sectors grounded on their shares of sectoral “fixed capital investment + purchases of goods and services” for which accurate data exist.

Allocation of energy carriers through the sectors is kept out of aforementioned procedure since exact data for sectoral energy use is available in published national energy budgets (Republic of Turkey-Ministry of Energy and Natural Resources, n.d.; IEA, 2008).

Water supply by mains is also a service by TE Sector and supplied water is another material transfer between TE and the other sectors.

In Table 4.30, exergy of material transfers from TE to the sectors are reported. In the table, “energy carriers” denotes all type of materials which are used for the purpose of energy generation to meet the energy need of sectoral activities (in the case of CO Sector, they are also used as raw materials of sectoral production). The sum of exergy content of the consumed commodities which are produced within the control volume (in this study: the society) is named “consumption of societal products” in Table 4.30. Additionally, exergy of commodities received by “import-export” is named “commodities from abroad” and seen in Table 4.30. Details of distribution of aforementioned exergy fluxes through the sectors are available in Appendix E.

Table 4.30 : Allocation of exergy fluxes from TE to the other sectors.

	Energy carriers for sectoral activities (TJ)	Consumption of societal products (TJ)	Commodities from abroad ("import-export") (TJ)	Water (TJ)	Total (TJ)
EX Sector	6166,8	5466,28	4705,59		16338,67
CO Sector	2581705,55	56261,26	32128,81	13	2670108,62
AG Sector	160794,18	303268,16	63949,33		528011,67
IN Sector	1348084,37	1795236,16	466870,77	2503,50	3612694,80
TR Sector	663682,24	69891,44	60165,29		793738,97
TE Sector	248407,86	438990,28	378013,89	62872,24	1128284,26
DO Sector	782513,78	765630,29	115358,00	192811,26	1856313,33

In Appendix E, total imported and exported energy carriers and other materials are shown. Hence, total exergy transfer via material interaction between Abroad (A) and TE is seen in Table 4.31.

Table 4.31 : Exergy of import and export.

	Import exergy (TJ)	Export exergy (TJ)	Import-Export (TJ)
Energy carriers	3337786	332220	3005566
Commodities	2207038	1085846	1121192
Total (TJ)	5544824	1418066	4126757

5. EXERGETIC EQUIVALENT OF THE EXTERNALITIES

5.1 Global Exergy Flux into the Control Volume (E_{in}) and Econometric Factors

5.1.1 Global exergy flux into the control volume (E_{in})

As stated in previous chapters of the present thesis, E_{in} (J/year) is global exergy input of the society. In other words, E_{in} is net exergy input received through the interaction of the system (the society) with the surroundings (environment and abroad, i.e., ENV and A). E_{in} consisting input and output fluxes are listed below:

Input fluxes:

- Extracted ores, minerals and raw (unrefined) fossil fuels
- Renewable energy sources (hydropower, geothermal heat, wind energy, solar energy)
- Import
- Water

Output fluxes:

- ➢ Export

This must be remarked that, EEA is a resource use evaluation method and resources are quantified in terms of exergy. E_{in} does not represent total exergy consumption of the society but the amount of resources received by the society. These resources are consumed directly and/or consumed in production of domestic products, labour, capital as well as a portion of E_{in} is wasted (not utilized within the society). EEA is a method to evaluate the efficiency of resource use within the society. This is because, not the total exergy consumption of the society but resource reception is accounted for in E_{in}. All kind of productions within the society (domestic product, labour, capital, etc.) is achieved via utilization of above listed resources (utilization is always limited to an extent). In this thesis, computation of E_{in} is necessary to use in determination of ee_C and ee_L (resource use equivalent of capital and labour for one monetary unit and one work hour, respectively) and also that of econometric factors:

α and β for which necessary formulations are presented in Section 2.4.1 and 2.4.2. Equation of E_{in} is:

$$E_{in} = \text{Input fluxes} - \text{Output fluxes} \qquad \textbf{(5.2)}$$

In the calculation of E_{in}, all exergy fluxes from surroundings to the system are accounted for, with the exception of the fluxes already taken into account within sectoral analysis (consumed by the receiver sectors). On the name fluxes and receiving sectors are presented in Table 5.1 (also revealed in the relevant chapters of the present thesis). The remaining fluxes transferred from the surroundings are accounted for in E_{in} to avoid double accounting.

Table 5.1: Allocation of direct fluxes from surroundings.

Flux from Environment	*Receiver*
Ores, minerals and raw (unrefined) fossil fuels	EX
Hydropower, geothermal heat, wind energy	CO
Solar energy for energy generation	AG, IN, TE, DO
Sectoral water use received from ENV	EX, CO, AG, IN, TE
Remaining solar energy	E_{in}
Remaining water received from ENV	E_{in}
Flux from/to Abroad	*Receiver*
Import	TE
Export	TE

As a result, equation (5.2) is the resulting equation for E_{in}:

$$\begin{aligned} E_{in} = {} & (\text{Total received solar exergy from ENV - Sectoral solar exergy consumption}) \\ & + \\ & (\text{Exergy of total received water from ENV - Exergy of sectoral water use received from ENV}) \end{aligned} \qquad \textbf{(5.2)}$$

Annually received solar exergy of the country is computed as:

$$E_{solar,total} = 365\ I_d\ A_{total}\ \zeta \qquad \textbf{(5.3)}$$

where I_d (kJ/ m^2-day) is the average solar radiation on horizontal surface, A_{total} (m^2) is the total area of the country, ζ is the exergy coefficient of solar energy (ratio of E_{solar}/En_{solar}). Numerical data is presented in Table 5.2.

Table 5.2 : I_d, A_{total}, ζ and $E_{solar,total}$.

		Reference
I_d	3,7 kWh/m^{2}day = 13320 kJ/ m^2-day	Ozturk et al, 2006
A_{total}	785347 km^2	Turkstat, 2009g
ζ	0,93	Szargut et al, 1988
$E_{solar,total}$	3,55 x 10^9 TJ	

Solar exergy consumption of the sectors is presented in Table 3.7. Sum of sectoral solar exergy consumption totals to 1,619 x 10^9 TJ.

As such, solar exergy contributes to E_{in} can be computed as seen in equation (5.4).

$$\begin{gathered}\text{(Total received solar exergy from ENV)}\\ -\\ \text{(Sectoral solar exergy consumption)} =\\ 3{,}55\,x\,10^9 - 1{,}619\,x\,10^9 = 1{,}932\,x\,10^9\ \text{TJ}\end{gathered} \tag{5.4}$$

The net amount of consumable water in the country ("gross water potential" which is computed considering: precipitation, evaporation, water coming from neighboring countries, groundwater reaching the surface and water feeds the groundwater) is 193x10^9 m^3 = 193x10^9 Ton (for details: Ozturk et al., 2009) which corresponds to 9,65x10^6 TJ exergy content (exergy of water is presented in Chapter 3).

Exergy of direct water transfer to the sectors from ENV are presented in Table 3.6 which amounts to 3,3 x 10^5 (330311,5) TJ.

Hence, net amount of exergy contribute to E_{in} via net water input is:

$$\begin{gathered}\text{(Exergy of total received water from ENV -}\\ \text{Exergy of sectoral water use received from ENV)} =\\ 9{,}65x10^6 - 3{,}3x10^5 = 9{,}32x10^6\ \text{TJ}\end{gathered} \tag{5.5}$$

Finally, E_{in} of the society is computed via equation (5.2) and presented in equation (5.6).

$$\begin{gathered}E_{in} = \text{(Total received solar exergy from ENV -}\\ \text{Sectoral solar exergy consumption)}\\ +\\ \text{(Exergy of total received water from ENV -}\\ \text{Exergy of sectoral water use received from ENV)} =\\ 1{,}932x10^9 + 9{,}32x10^6 = 1{,}941x10^9\ \text{TJ}\end{gathered} \tag{5.6}$$

5.1.2 Econometric factors: α, β, ee_C and ee_L

In this section, using the presented equations in Section 2.4.1 and 2.4.2, α, β, ee_C and ee_L are computed through equations (5.7) to (5.11). Employed country specific factors in the equations are presented in Table 5.3.

$$E_{used} = 365\, f\ e_{surv}\ N_h = 4351691{,}75\,\text{TJ} = 4{,}35\text{x}10^6\ \text{TJ} \tag{5.7}$$

$$\alpha = \frac{EE_L}{E_{in}} \cong \frac{E_{used}}{E_{in}} = \frac{4{,}35\text{x}10^6\ \text{TJ}}{1{,}941\text{x}10^9\ \text{TJ}} = 0{,}00224 \tag{5.8}$$

$$\beta = \frac{M_2 - S}{S} = \frac{208{,}2\text{x}10^9\$ - 170{,}78\text{x}10^9\$}{170{,}78\text{x}10^9\ \$} = 0{,}219 \tag{5.9}$$

$$ee_L = \frac{EE_L}{N_{wh}} \cong \frac{E_{used}}{N_{wh}} = \frac{4{,}35\text{x}10^{12}\ \text{MJ}}{2{,}83\text{x}10^{10}\ \text{workhours}} = 153{,}95\ \text{MJ/workhour} \tag{5.10}$$

$$ee_C = \frac{\alpha\beta E_{in}}{M_2 - S} = \frac{\frac{E_{used}}{E_{in}}\frac{M_2 - S}{S}E_{in}}{M_2 - S} = \frac{E_{used}}{S} = \frac{4{,}35\ \text{x}10^{12}\ \text{MJ}}{170{,}78\text{x}10^9\ \$} = 25{,}5\,\text{MJ}/\$ \tag{5.11}$$

Table 5.3 : Econometric factors and used country specific valuables.

		Reference
E_{in} (TJ)	$1{,}941\text{x}10^9$	
HDI	0,798	UNDP (2008)
HDI_0	0,055	Talens Peiró et al. (2010), Sciubba (2011)
f	14,51	
e_{surv} (J/person.day)	$1{,}05\text{x}10^7$	Talens Peiró et al. (2010), Sciubba (2011)
M_2 ($)	$208{,}2\ \text{x}10^9$	Turkstat (2008b)
S ($)	$170{,}78\ \text{x}10^9$	Turkstat (2007a)
N_{wh} (hours)	$2{,}83\ \text{x}10^{10}$	
N_h (persons)	78259264	Turkish Ministry of the Interior Affairs-General directorate of civil registration and nationality (n.d.)
α	0,00224	
β	0,219	
ee_L (MJ/hour)	153,95	
ee_C (MJ/$)	25,5	

Since the definitions of the variables in Table 5.3 are presented in Section 2.4.1 and 2.4.2, they are not repeated in this section.

5.2 Exergetic Equivalent of Sectoral Labour Input

The sectoral share of global amount of exergy embodied in labour is obtained by multiplying the sectoral working hours by specific exergetic equivalent of labour (ee_L) which is presented in Table 5.4. Since domestic labour (housekeeping, laundrying, cooking, etc.) is an internal flow within the DO sector, it is not taken into account within labour transfers: this neglection distorts somewhat the calculation of ee_L, and requires further study at system level, left for future studies. Annual labour generation by DO Sector and its allocation through the sectors are presented in Table 5.4. Numerical rounding errors may cumulate and cause minor differences in results. Details of the computation are presented in Appendix F.

Table 5.4 : Sectoral number of workers, annual work hours and exergetic equivalent of labour.

	Number of workers	Annual work hours (hours) (L_{sector})	Exergetic equivalent of labour (TJ) ($EE_{L,\ sector}$)
EX Sector	168066	203,28 $x10^6$	31295,52
CO Sector	128472	150,97 $x10^6$	23241,80
AG Sector	6088446	5970,32 $x10^6$	919144,66
IN Sector	5316236	6655, 48 $x10^6$	1,02 $x10^6$
TE Sector	10571008	12589,35 $x10^6$	1,94 $x10^6$
TR Sector	2227003	2697,09 $x10^6$	415223,70
Total	24499231	2826,65 $x10^7$	4351692

Exergetic equivalent of labour (Table 5.4) is computed as presented in equation (5.12).

$$EE_{L,\,sector} = ee_L \ x \ L_{sector} \tag{5.12}$$

where $EE_{L,sector}$ (J) is exergetic equivalent of sectorally consumed labour and L_{sector} is annual work hours consumed by the sectors.

5.3 Exergetic Equivalent of Sectoral Capital Input and Output

Sectoral capital input and output are retrieved from Central Bank of the Republic of Turkey (personal communication, November 20, 2009). The equivalent primary exergy of input and output monetary fluxes (EE_C) for the sectors are presented in Table 5.5. A specific distinction between the two possible ways of money transfer (virtual transfer or cash payment) was not necessary, because banks and both wholesale and retail activities are included in TE, and money is always transferred through TE from other sectors and abroad.

Table 5.5 : Sectoral capital input and output, exergetic equivalent of capital.

	Input C (10^8 \$)	Output C (10^8 \$)	Input C (10^3 TJ)	Output C (10^3 TJ)
EX Sector	141,17	131,99	359,99	336,58
CO Sector	754,57	728,88	1924,19	1858,67
AG Sector	533,50	275,65	1360,46	702,93
IN Sector	5357,04	4394,83	13660,71	11207,02
TR Sector	1509,28	1275,58	3848,73	3252,78
TE Sector	14173,98	13224,03	36144,34	33721,91
DO Sector	3610,82	3437,35	9207,76	8765,41

The amount of exergy embodied in capital is obtained by multiplying the monetary flux by the exergetic equivalent of capital (ee_C) which is presented in Table 5.3. The equation of EE_C is:

$$EE_C = ee_C \, x \, C \tag{5.13}$$

where EE_C (J) is exergetic equivalent of capital flow and C (\$) is capital flow.

Capital transfers between Turkey and abroad (A) are reported in Table 5.6 (Central Bank of the Republic of Turkey, n.d.).

Table 5.6 : Capital transfer between TE and A.

Input C from A (10^6 \$)	125487
Output C to A (10^6 \$)	157680
Input C (TJ)	$3{,}2x10^6$
Output C (TJ)	$4{,}02x10^6$

Exchange rate between \$, € and TL is: 1,8 TL = 1 €= 1,26 \$ for the year 2006 (Central Bank of the Republic of Turkey, n.d.). (TL is Turkish Lira, € is Euro and \$ is Dolar).

5.4 Environmental Remediation Cost (EE_{ENV}) Determination and Sectoral EE_{ENV} Inputs

The goal of the present section (Section 5.4) is determination of environmental remediation cost (EE_{ENV}) of solid, liquid and gas waste and EE_{ENV} input of Turkish sectors. In the present thesis, cooling of discharged heat to the environmental temperature is also accounted for in the content of EE_{ENV} since heat has also effects on temperature distribution of the surrounding atmosphere. In summary, the content of "waste" is classified into four groups: solid waste, gas emissions, liquid waste and discharge heat.

Alternative treatment technologies can be chosen and formulated to clean-up the pollutants and assess the environmental impact of aforementioned waste types. Solid & liquid waste and emission gases are in fact collective denominations for a very broad range of materials and it is almost impossible to deal with the environmental remediation cost of all types of pollutants. Considered fraction of sectoral solid and liquid waste and undertaken environmental remediation systems (treatment systems) are detailed in the relevant subsections below. As for gas emissions, due to lack of sufficiently disaggregated data and great variety of emission gases, only three types of greenhouse gases (CO_2, CH_4, N_2O) are analyzed in this thesis.

For Extraction Sector (EX Sector), environmental remediation cost of sectoral solid and liquid wastes are assumed to be zero as a result of the fact that solid waste of the sector is mostly soil with little amount of minerals etc. and they are buried into the land after the mining activity (i.e. discharged to the nature in the original form): since no data are available for the amount of exergy (mechanical, chemical and thermal) needed to complete this "landfilling" task, this item is neglected in the present calculation. For liquid waste, the discharge to the environment is 201 million m^3 (for the year of 2004, no data exist for 2006) (Turkstat, 2005c). As it is seen in Table 3.6, water use of the sector is 178 million m^3which is lower than sectoral discharge. During mining activities, extracted ground water is added to the used water (totally received from nature) by the sector and totally discharged directly to nature (Turkstat, 2005c). It is expected to exist particulate matter discharged by mining activities but their relative amount is negligible with respect to that of the water. In conclusion, solid and liquid discharge of the sector is coming from the environment and left to the environment (almost) without changing the physical and chemical structure, therefore, EE_{ENV} originated by solid and liquid discharges are assumed to be zero in this thesis.

5.4.1 The concept of environmental remediation cost (EE_{ENV})

As a result of EEA's being an exergy based "resource use assessment" methodology, "environmental impact" is also quantified by exergy. In theoretical structure of EEA methodology, the concept of "environmental remediation cost" relies on the "zero impact" approach which can be described as: converting effluent streams of the considered process into effluents which are at the state of complete equilibrium with the reference environment before being discharged into the environment (i.e., the discharged effluent has "zero impact" on the environment) (Sciubba, 2003b). The essence of this idea is representing the environmental impact of the effluent by the cumulative amount of resources (in terms of exergy) that must be consumed to attain an ideal, zero-impact disposal of the effluent. The cumulative amount of consumed resources is called "environmental remediation cost (EE_{ENV})". In brief, according to EEA, *exergetic cost which represents the environmental impact of the effluent (EE_{ENV}) is not proportional to the exergetic content of the effluent*, but it is equal to the extended exergy (sum of the material exergy and physical exergy, plus exergetic equivalent of externalities: i) labour and capital required by the installation and operation of the process and ii) environmental remediation cost of "*possible"* effluents from treatment (remediation) process which must be cleaned) ideally required to cool the effluent to T_0 and break it up into its constituents such that each one of them is in equilibrium conditions with the surroundings (Sciubba, 2005). In other words, environmental impact is quantified as the total exergy of resources "used up" in the environmental remediation processes. But in reality, since there is no totally "clean" technology (Sciubba, 2003b), because, in fact, the present treatment technologies do not always produce effluents in equilibrium with the surroundings, choosing the minimum environmentally hazardous technology and establishing a "consciously accepted" level of pollution for each of the substances is a reasonable approach, on the effluent side of the issue (Sciubba, 2001).

To attain this goal, a virtual or real environmental remediation (clean-up, treatment) system is inserted to the considered system which is called "environmental remediation system" and is represented as "S_t" in Figure 5.1. Since this effluent treatment process (S_t) has inputs of material, energy, labour and capital, exergetic equivalent of these production factors are accounted for in EE_{ENV}. Though a similar "environmental impact" computation route is proposed in Zero-ELCA (see Section

1.2.2), “environmental remediation cost (EE_{ENV}) results are more comprehensive and indicative since exergetic equivalent of externalities are included within the analysis in EEA methodology.

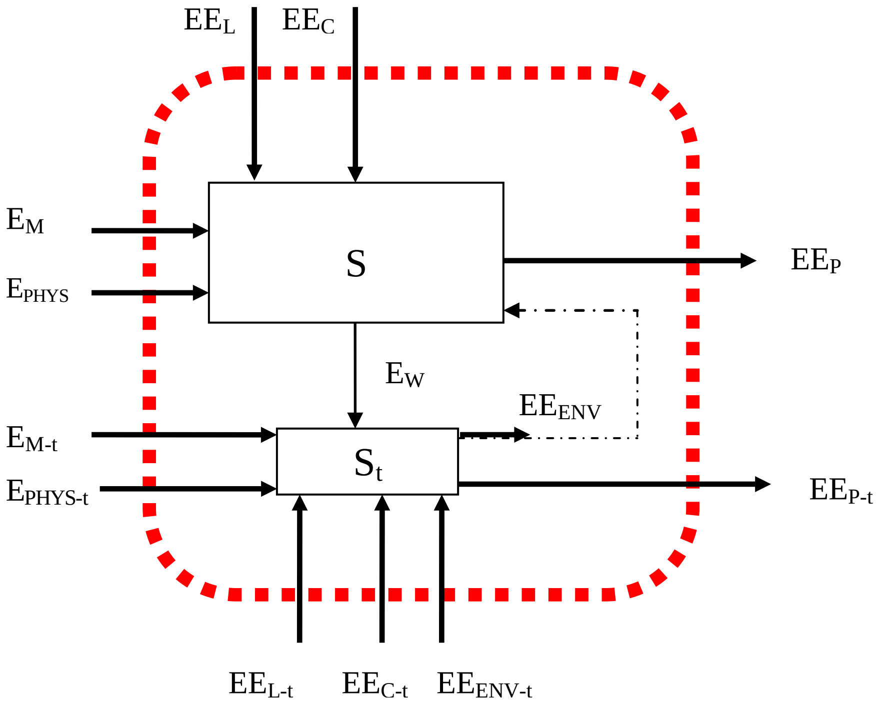

Figure 5.1: Representation of system (S) and treatment system (S_t).

Schematic representation of aforementioned “environmental remediation cost” concept is presented in Figure 5.1 where E_W is the exergy of effluent from S; S_t is the environmental remediation (treatment, clean up) system; E_{M-t}, E_{PHYS-t} are respectively the exergy of material and energy carriers received by the treatment system S_t; EE_{L-t} and EE_{C-t} are respectively the exergetic equivalent of labour and capital received by the treatment system S_t; EE_{P-t} is the extended exergy of the treatment system “*possible*” product P_t. (While some treatment systems clean up the effluent of S, the treatment system can produce additional products. In this case, additional products are denoted by P_t). The treatment system S_t may produce *possible “extra” effluents* (pollutants) which must be cleaned by “extra” treatment systems added to S_t. EE_{ENV-t} denotes the environmental remediation cost of these “extra” effluents from S_t (environmental remediation cost of S_t).

In Figure 5.1, extended exergetic balance of system S_t is:

$$E_{M\text{-}t} + E_{PHYS\text{-}t} + EE_{L\text{-}t} + EE_{C\text{-}t} + EE_{ENV\text{-}t} = EE_{ENV} + EE_{P\text{-}t} \qquad \textbf{(5.34)}$$

By the assumption of:

$$EE_{P\text{-}t} = E_{P\text{-}t} \qquad \textbf{(5.15)}$$

and inserting the equation (5.15) into equation (5.14), equation (5.16) is obtained:

$$EE_{ENV} = E_{M\text{-}t} + E_{PHYS\text{-}t} + EE_{L\text{-}t} + EE_{C\text{-}t} + EE_{ENV\text{-}t} - E_{P\text{-}t} \qquad \textbf{(5.16)}$$

EE_{ENV} can be obtained from equation (5.16) and it is a constituent of EE_P as presented in equation (2.24).

The physical meaning of the assumption which is done in equation (5.15) is de-allocating the fluxes of $E_{M\text{-}t}$, $E_{PHYS\text{-}t}$, $EE_{L\text{-}t}$, $EE_{C\text{-}t}$ and $EE_{ENV\text{-}t}$ between EE_{ENV} and $EE_{P\text{-}t}$ in equation (5.14). In other words, neglecting the above written fluxes required to produce P_t and assigning all the input fluxes of S_t to EE_{ENV}. Since it is impossible to do the exact allocation of these input fluxes between EE_{ENV} and $EE_{P\text{-}t}$, this assumption is necessary.

Exergy of the effluent of the system S (E_W) is not seen in above equations since systems S and S_t are considered to be combined, thereby E_W is an internal flow in the system "S+S_t". In other words, additional input fluxes to the EEA balance of S are $E_{M\text{-}t}$, $E_{PHYS\text{-}t}$, $EE_{L\text{-}t}$, $EE_{C\text{-}t}$ and EE_{ENV} which arise from insertion of S_t to S.

ee_{ENV} denotes "specific environmental remediation cost" which stands for environmental remediation cost per ton, kg or m^3 of considered effluent.

5.4.2 Environmental remediation cost of solid waste ($EE_{ENV\text{-}s}$)

It is generally recognized that no single solid waste solution is always appropriate everywhere. There is broad agreement among waste management authorities, regulatory agencies and industry that effective solid waste management requires an integrated approach which must be in accordance with relevant local needs and circumstances.

In below subsections, applied processes for sectoral solid waste treatment are presented. Set of processes and systems employed in environmental remediation (treatment) is totally named “environmental remediation system”. For the ease of explanation and not to repeat the same information for sectoral environmental remediation processes, the sectors which have a wider variety of constituting materials in waste composition are presented earlier. Thereby, the order of the sectors is different then commonly used order in earlier chapters of the thesis.

5.4.2.1 DO sector solid waste

Processing and utilizing from the energy potential of municipal wastes is technically reasonable due to the facts of: 1) a sizeable fraction of the waste, depending on the country, consists of combustible components, which can serve as a fuel in heat & energy generation processes (UNEP, 2005) and 2) a part of municipal waste can be recycled and reused in the country.

Most of the combustible components in municipal solid waste are also biodegradable, thus, after undergoing a biological conversion process, a combustible gas is obtained which is convenient to use in energy generation processes, or which can be stored or transported for later use. This possibility of recovering energy via biological conversion and producing a combustible gas, methane, serves a twofold function: namely waste treatment and energy production (UNEP, 2005).

Anaerobic digestion (biogasification, methane fermentation or biomethanization, denominated as AD in this thesis) is defined as the biological decomposition of organic matter under anaerobic conditions (without the presence of oxygen). The products are primarily methane (CH_4) with an accompanying production of other gases, chief of which is carbon dioxide (CO_2) (UNEP, 2005; EPA, 2002b). The residue of the AD process (digestate) can be composted further to produce “compost” (a kind of fertilizer) which is another product of AD process (MREC, 2003; EPA, 2002a, 2002b).

In a greenhouse gas assessment report prepared for European Union countries (Smith et.al., 2001), it has shown that source segregation of MSW (municipal solid waste) followed by recycling (for paper, metals, textiles and plastics) and AD/compositing (for putrescible waste) gives the lowest net flux of greenhouse gases, compared with other options for the treatment of bulk MSW. As a result in this thesis, AD and further composting is applied to organic fraction of considered waste compositions.

Environmental remediation system applied to DO, TE and IN sector (illustrated in Figure 5.2) can be described as: collected waste is transferred to MRF (Materials Reprocessing Facility) in which organic fraction of waste is separated from inorganic fraction as well as the inorganic part is sorted, pre-treated and recycled. The organic fraction is essentially made of kitchen garbage while mainly plastics, paper&cardboard, wood, textiles and rubber constitute the inorganic fraction. Non-recyclable part of considered inorganic materials are transferred to an incineration plant where electricity and heat are produced by a CHP (combined heat and power plant). Ash produced from recycling processes (in MRF) and from incineration of non-recyclables are landfilled (Figure 5.2). As it is seen in the figure, the only discharge to the environment is landfilled ash which has no green house gas emission capacity to the atmosphere after landfilling (Chen and Cheng, 2008). "TRP" stands for transportation line in Figure 5.2.

The organic fraction is then delivered to another plant where undergoes anaerobic digestion in order to produce biogas. Afterwards, biogas is upgraded by removing CO_2, H_2S etc. and volumetric fraction of CH_4 reaches 98% (in our system) which is convenient to be used as a substitute of natural gas. The digestate, i.e., the residue of the anaerobic digestion process, is composted and produced compost is taken out of the system as a system product. A similar treatment route for organic waste is elaborated and outlined also in Poschl et al. (2010) and EPA (2002a).

The composition of considered DO sector waste is seen in Table 5.7. In the available database for Turkey, solid waste of all sectors is collected at one center and then allocated to recycling, composting and incineration: the source of waste is not known. Therefore in this thesis, all the recycled waste of Turkey (metal recycling, composting, incineration, etc.) is assumed to be provided from the DO sector solid waste and transferred to TE from DO and then from TE to the relevant sector. Under these circumstances, calculation of the DO sector waste composition is presented in Appendix G.

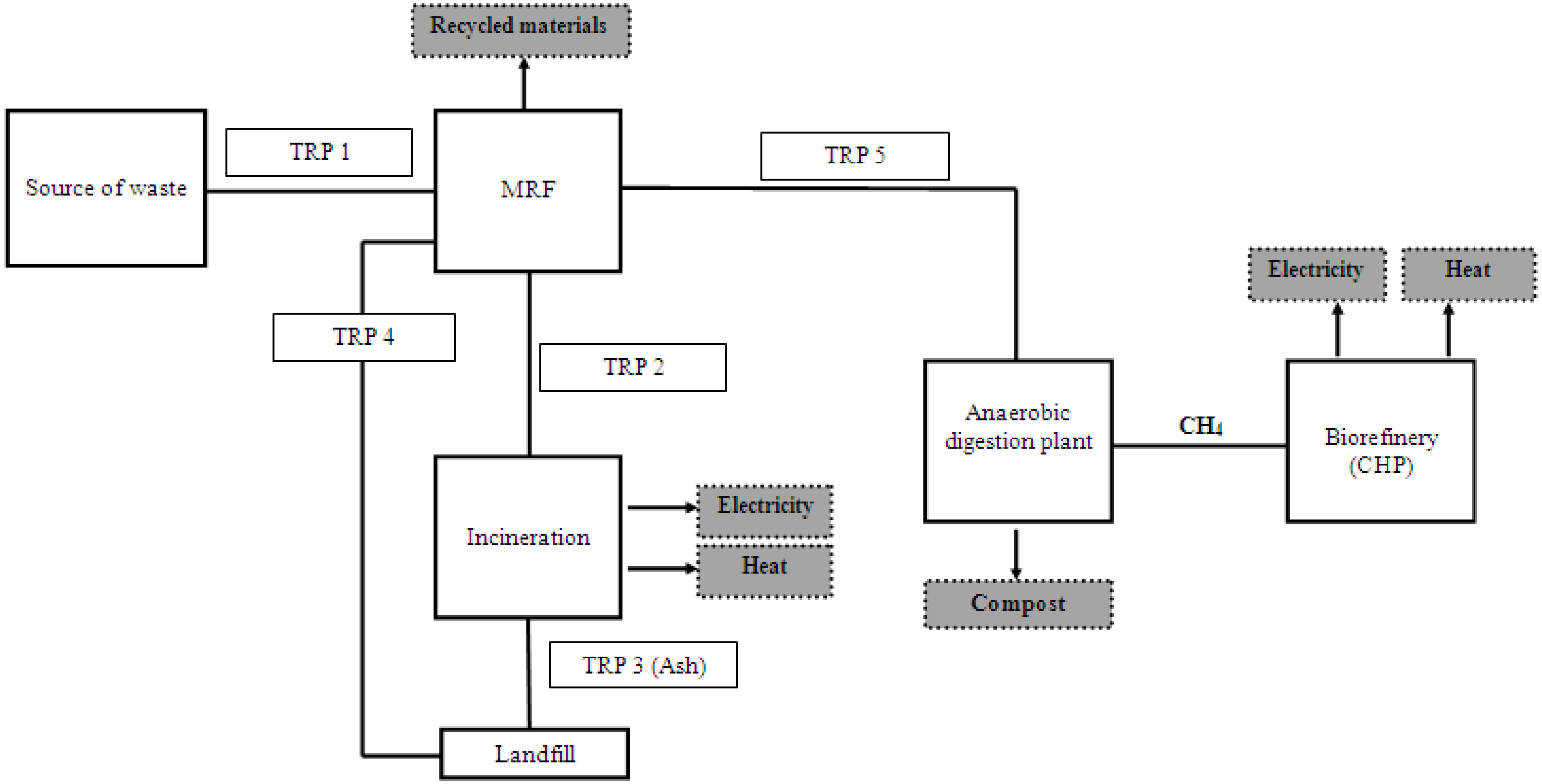

Figure 5.2 : Illustration of DO sector solid waste treatment.

Table 5.7: Composition of DO sector waste.

Composition	Percent (% wt.)	Amount (Ton)
Organic	53,92	9385332,68
Paper&cardboard	8,26	1437953,55
Textile	5,73	997768,57
Plastic	14,90	2593957,59
Diaper	4,23	736988,15
Tetra-pak	0,69	120941,64
Glass	5,80	1009043,08
Metal (Al)	0,47	82670,39
Metal (Fe)	0,69	120464,65
Other metals (Cu)	0,08	13227,99
Wood	0,55	96375,37
Other combustibles	2,26	393026,44
Ash	2,40	417626,62
Total	100	17405376,74

In Appendix G, details and data of individual systems and processes consisting the total environmental remediation system (which are illustrated in Figure 5.2), are presented. A biorefinery is described as a facility which is in charge of fuel, power, heat and some chemicals production from biomass. In this thesis, electricity and heat are produced in biorefinery.

As for calculation of material influxes (except for the trucks used in transportation), since no sufficiently reliable data were available on the exact material composition of the used items in the system, an analytical analysis was impossible. The corresponding portion of $EE_{ENV\text{-}t}$ is computed by converting the known monetary cost of the process into exergetic equivalent by means of ee_C.

The necessary truck numbers for each transportation line and exergetic content of the trucks are presented in Table 5.8. Exergy of one truck (0,045 TJ/truck) is computed in Appendix G. The number of trucks is computed in accordance with Appendix G.

Table 5.8 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	3200	145,51
TRP-2	25	1,13
TRP-3	13	0,59
TRP-4	46	2,09
TRP-5	432	19,64
Total	3716	168,96

The exergy of material flows originated from other system or processes except TRP lines are computed as explained above and presented in Table 5.9.

Table 5.9 : Material exergy ($E_{M\text{-}t}$) of systems and processes except transportation.

System/Process	Capital	Equivalent exergy (TJ)
MRF plant	100 €/Ton	20796,22
Incineration plant	64 €/Ton	4341,06
Anaerobic digestion plant	65 €/Ton	19601,17
Upgrading of biogas	0,26 €/m^3	10277,76
Biorefinery	7000 \$/KW_{el}	50609,66
Separation, drying, composting	35 €/Ton	4221,79
Total		109847,66

The cost of MRF plant includes preliminary sorting, pretreatment of recyclable materials and recycling; anaerobic digestion plant includes mixing, sterilization and anaerobic digestion part.

In conclusion, exergy of material transfers ($E_{M\text{-}t}$) into the system is the sum of Table 5.8 and 5.9 which is 110016,62 TJ.

The only exergy inflow of energy carriers ($E_{PHYS\text{-}t}$) are diesel fuel consumption of transportation lines. Calculation of diesel fuel consumption for each TRP line is shown in Appendix G, and the results are presented in Table 5.10.

Table 5.10 : Physical exergy ($E_{PHYS\text{-}t}$) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	418447,37	19402,03
TRP-2	2664,02	123,52
TRP-3	1332,01	61,76
TRP-4	4723,55	219,02
TRP-5	39479,33	1830,53
Total	466646,28	21636,86

As for capital flows, capital investment of the system (Investment cost, IC) is assumed to be supplied by bank credit with annual interest rate of 20% and payback time of 10 years. Annual cost (AC) is calculated using the methodology presented by Bejan et al. (2006) (annual payment is 23,85% of capital investment, calculation is seen in equation (5.17)). Annual “fixed and varying operation costs” (including insurance, wages, maintenance etc., cumulatively denominated as “OP”) are assumed to be 20% of capital investment. Capital flow of the system is sum of AC and OP for each process and system, results are seen in Table 5.11-5.13.

$$AC = IC\,x \left[\frac{r}{1-\left(\frac{1}{(1+r)^n}\right)} \right] = IC\,x \left[\frac{0,2}{1-\left(\frac{1}{(1+0,2)^{10}}\right)} \right] = IC\,x\,0,2385 \tag{5.17}$$

where r is the annual interest and n is the number of pay back years.

Table 5.11 : Exergetic equivalent of the capital of processes.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
MRF plant	100 €/Ton	20796,22	4960,37	4159,24	9119,62
Incineration plant	64 €/Ton	4341,06	1035,44	868,21	1903,65
Anaerobic digestion plant	65 €/Ton	19601,17	4675,33	3920,23	8595,56
Upgrading of biogas	0,26€/m^3	10277,76	2451,48	2055,55	4507,03
Biorefinery	7000 $/$KW_{el}$	50609,66	12071,557	10121,933	22193,49
Separation, drying, composting	35 €/Ton	4221,79	1006,99	844,36	1851,35
Landfilling	10 €/Ton	570,46	114,09	136,07	250,16
Total					48420,86

Use of trucks with an accompanying consumption of diesel fuel brings about capital inputs into the system. The number of trucks and diesel fuel consumption in each TRP line are presented in Table 5.12 and Table 5.13, respectively. It is assumed that investment cost of 1 truck is 100000 TL (69930,07 $) as well as annual operation and maintenance cost (OP) is 20% of the investment cost. Density of diesel fuel is taken as 0,835 kg/l and for the year 2006, the price of diesel fuel is 2,1 TL/l (1,47 $/l) (Turkish Energy News, 2011). Diesel fuel cost is accounted for in OP cost. As a result, its capital equivalent is not annualized in calculation.

Table 5.12 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	3200	5706,4	1361,11	1141,28	2502,39
TRP-2	25	44,58	10,63	8,91	19,54
TRP-3	13	23,18	5,52	4,64	10,16
TRP-4	46	82,03	19,57	16,4	35,97
TRP-5	432	770,36	183,75	154,07	337,82
Total	3716				2905,88

Table 5.13 : Exergetic equivalent of diesel fuel capital.

Transportation line	Diesel consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	501134572,39	18766,62
TRP-2	3190446,75	119,4767
TRP-3	1595223,37	59,74
TRP-4	5656941,76	211,84
TRP-5	47280631,18	1770,58
Total		20928,25

Due to the lack of data for landfilling, material flux of landfilling process (tractors, excavators, etc.), energy consumption and accompanying emissions are disregarded in this section.

In conclusion, sum of capital fluxes is the sum of Table 5.11, Table 5.12 and Table 5.13 which amounts to 72254,99 TJ.

In the matter of the labour consumption of the system, labour consumed by TRP lines are calculated based on driven distance and average speed of the trucks which are detailed in Appendix G. For the remaining part of the system, it is assumed that labour of a CHP system is 200 workers per 1000 MW_{h+el} generated energy, based on data (Bezdek and Wendling, 2008). Considering the whole system, number of workers is assumed to be 400 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker.

Generated electricity and heat power is presented later in Table 5.21 as 21455,57 TJ_{el} and 25746,68 TJ_h. Generated power is computed as:

$$\text{Generated power}\,(MW_{el+h}) = \frac{\text{Generated energy}\,(MJ_{el+h})}{\text{Annual working time}\,(s)} = \frac{(21455{,}57 + 25746{,}68)\text{x}\,10^6}{340\text{x}24\text{x}60\text{x}60} = 1606{,}83 \qquad \textbf{(5.18)}$$

Hence, labour consumed in the system (excluding transportation) is:

$$\text{Labour load (workhours/year)} = \left[\frac{\text{Worker number}}{1000\text{MW}}\right] \text{x} \left[\text{Annual work hours}\right] \left[\text{Generated power } (\text{MW}_{el+h})\right] \tag{5.19a}$$

$$\text{Labour load (workhours)} = \left[\frac{400(\text{workers})}{1000(\text{MW})}\right] \text{x} \left[1800(\text{hours / year worker})\right] \text{x} \left[1606{,}83(\text{MW})\right] \tag{5.19b}$$

$$\text{Labour load (workhours)} = 1156917{,}94 \tag{5.19c}$$

The exergetic equivalent of the labour is computed by means of ee_L:

$$EE_{L-t} = \text{Labour load (workhours) x } ee_L \text{ (MJ / hours)} = 1156917{,}94 \text{ x } 153{,}95 = 178110163{,}51 \text{ MJ} = 178{,}11 \text{ TJ} \tag{5.20}$$

Labour consumption through the system and its exergtic equivalent are presented in Table 5.14.

Table 5.14 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	10245333,33	1577,29
TRP-2	68000,00	10,47
TRP-3	35360,00	5,44
TRP-4	117300,00	18,06
TRP-5	979200,00	150,75
The remainder of the system	1201921,06	178,11
Total	12647114,39	1940,12

Environmental remediation cost of the system is originated mainly from transportation as well as processes like anaerobic digestion, incineration etc. The amount of emission gases is derived in accordance with Appendix G and presented in Table 5.15. Since liquid waste from anaerobic digestion and composting processes is not known, it can not be taken into account in this section.

Table 5.15 : Emissions from the TRP lines.

	Emission (Ton)		
	CO_2	N_2O	CH_4
TRP-1	1326818,40	69,83	69,83
TRP-2	8447,12	0,44	0,44
TRP-3	4223,56	0,22	0,22
TRP-4	14977,48	0,79	0,79
TRP-5	125181,57	6,59	6,59
Total	1479648,12	77,88	77,88

Emissions from other processes are seen in Table 5.16.

Table 5.16 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Incineration	3009323,85	131,27	984,51
Anaerobic digestion	33355,67	0,00	13247,55
Upgrading of biogas	1053555,55	0,00	8566,75
Biorefinery	1168106,84	2,08	20,82
Composting	495545,57	1126,24	15016,53
Total	5759887,48	1259,59	37836,17

Thereby, total CO_2, N_2O and CH_4 emissions of the system are the sum of Table 5.15 and Table 5.16, the result is presented in Table 5.17. The environmental remediation cost of considered emission gases are computed further in Section 5.4.3 and inserted into Table 5.17 to obtain the $EE_{ENV\text{-}t}$ for the whole environmental remediation system.

Table 5.17 : Environmental remediation cost of emission gases ($EE_{ENV\text{-}t}$).

CO_2 emissions (Ton)	7239535,61
N_2O emission (Ton)	1337,47
CH_4 emission (Ton)	37914,05
CO_2 $ee_{ENV\text{-}g}$ (TJ/Ton CO_2)	0,043
N_2O $ee_{ENV\text{-}g}$ (TJ/Ton N_2O)	0,010
CH_4 $ee_{ENV\text{-}g}$ (TJ/Ton CH_4)	0,267
CO_2 $EE_{ENV\text{-}g}$ (TJ)	312608,84
N_2O $EE_{ENV\text{-}g}$ (TJ)	12,90
CH_4 $EE_{ENV\text{-}g}$ (TJ)	10116,96
Total $EE_{ENV\text{-}t}$ (TJ)	322738,70

The products of the system are electricity and heat produced by incineration of non-recyclable part of the inorganic waste and biorefinery plant as well as recycled materials and produced compost (the ash generated in considered processes are assumed to have zero exergy, hence, its exergetic content is not included in exergy of products). The applied route of separating recyclable and non-recyclable parts and recycling processes are detailed in Appendix G. The amount of non-recyclables and their energy content are presented in Table 5.18.

Table 5.18 : Energy content (LHV) of the non- recyclables.

	Amount (Ton)	LHV (GJ/Ton)
Paper& cardboard	202354,27	11,50
Textile	74832,64	14,60
Plastic	357498,39	31,50
Diaper	736988,15	15,41
Glass	30271,29	0
Metal (Al)	100169,39	0
Metal (Fe)	110149,10	0
Other metals (Cu)	98764,03	0
Wood	6987,21	18,46
Other combustibles	393026,44	16,93
Total	2111040,92	

Hence, based on data in Table 5.18, energy content of total incinerated non-recyclables (LHV) is obtained as 32817,05 TJ. Efficiencies of heat and electricity production and produced energy via incineration are seen in Table 5.19.

Table 5.19 : Properties of incineration process.

		Electricity	Heat
Energy of non-recyclables (TJ)	32817,05		
Efficiencies		0,4	0,48
Produced energy (TJ)		13126,82	15752,19

The composition of biogas utilized in the biorefinery is 98% CH_4 and 2% CO_2 (% vol.). The biorefinery is a CHP plant and the efficiencies of heat and electricity generation are assumed to be the same as those in Table 5.19. The amount of the biogas utilized in biorefinery and produced energy can be seen in Table 5.20. LHVof CO_2 is almost zero (De Hullu et al., 2008).

Table 5.20 : Properties of biogas utilization.

CH_4 (m^3)	617310076,13
CO_2 (m^3)	12598164,82
LHV of CH_4 (MJ/m^3)	33,73
LHV of CO_2 (MJ/m^3)	0,00
LHV of biogas (TJ)	20821,87
Electricity generation efficiency	0,40
Heat generation efficiency	0,48
Generated electricity (TJ)	8328,75
Generated heat (TJ)	9994,50

As stated earlier, the energy need (both of heat and electricity) is met by the generated energy in the system, i.e., output of biorefinery and incineration process. The energy balance of the whole environmental treatment system is presented in Table 5.21. In the table, it is assumed that produced heat is at the temperature of 100°C. Energy consumption of different processes is detailed in Appendix G.

Table 5.21 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
MRF plant	preliminary sorting	259,86			
MRF plant	pretreatment of recyclable materials and recycling	3397,14	10562,56		
Incineration plant		590,71		13126,82	15752,19
Anaerobic digestion	mixing, sterilization	2027,23			
Anaerobic digestion	anaerobic digestion	333,15	2498,62		
Upgrading of biogas		1353,32	442,90		
Biorefinery		374,79		8328,75	9994,50
Composting	Separation, drying, composting	2209,68			
Total		10545,88	13504,09	21455,57	25746,68
Net production				10909,68	12242,59
Exergy of production				10909,68	2460,66

Recycling of the materials are analyzed in accordance with technical details of recycling processes given in the Appendix G. Amount of recycled materials and exergy contents are reported in Table 5.22.

Table 5.22 : Amount and exergy of recycled materials.

	Recycled material (Ton)	Specific exergy (MJ/Ton)	Exergy (TJ)
Paper& cardboard	1305643,53	17000,00	22195,94
Textile	593672,30	13904,76	8254,87
Plastic	1547691,80	32502,16	50303,33
Glass	948500,50	131,48	124,71
Metal (Al)	80912,59	32928,09	2664,30
Metal (Fe)	90589,42	6740,69	610,63
Other metals (Cu)	11905,19	2112,06	25,14
Wood	82400,94	20658,24	1702,26
Total	4661316,27		85881,19

As stated earlier in this chapter, residue of the AD process is composted to produce compost (Technical details are available in Appendix G). Amount of produced compost and its exergy content are presented in Table 5.23.

Table 5.23 : Amount and exergy of produced compost.

Amount of produced compost (Ton)	1501653,23
Exergy of compost (MJ/Ton)	18373,31
Exergy of total produced compost (TJ)	27590,33

Exergy of system products are presented in Table 5.21, Table 5.22 and Table 5.23 above and are summarized in Table 5.24 with their exergetic content.

Table 5.24 : Products of DO sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	10909,68
Heat	2460,66
Recycled materials	85881,19
Compost	27590,33
Total (E_{P-t})	126841,87

The formulation of EE_{ENV} is presented above in equation (5.16). E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, $EE_{ENV-\ t}$ fluxes and resulting EE_{ENV-s} for DO sector solid waste (computed via equation (5.16)) are presented in Table 5.25.

Table 5.25 : EE_{ENV-s} for DO sector solid waste.

	Exergetic equivalent (TJ)
E_{M-t}	110016,62
E_{PHYS-t}	21636,86
EE_{L-t}	1940,12
EE_{C-t}	72254,99
EE_{ENV-t}	322738,70
E_{P-t}	126841,87
EE_{ENV-s}	401745,43

5.4.2.2 TE sector solid waste

The sum of TE and DO sector solid waste consist MSW and there is no accurate data for the composition of DO and TE sector wastes, separately. Hence, due to lack of data and also to keep the right amount of the waste constituent materials of MSW presented by Kanat (2010), composition of the DO and TE sector solid waste is taken as average composition of MSW. Composition of TE sector solid waste is presented in Table 5.26. Since the constituent materials are the same as those in DO sector waste composition, the same remediation system (seen in Figure 5.2) are applied to TE sector solid waste. Technical details of the processes which consist the environmental remediation system are presented in Section 5.4.2.1 and Appendix G. Hence, they are not repeated in this present section.

Table 5.26 : Composition of TE sector waste.

Composition	Percent (% wt.)	Amount (Ton)
Organic	50,22	1727847,23
Paper& cardboard	13,30	457593,95
Textile	5,28	181661,36
Plastic	14,39	495096,01
Diaper	3,90	134181,68
Tetra-pak	0,64	22019,56
Glass	5,82	200240,36
Metal (Al)	0,68	23395,78
Metal (Fe)	0,88	30276,89
Other metals (Cu)	0,07	2408,39
Wood	0,51	17546,84
Other combustibles	2,10	72251,68
Ash	2,21	76036,29
Total	100	3440556,01

Material exergy fluxes ($E_{M\text{-}t}$) to TE sector solid waste environmental remediation system are seen in Table 5.27 and Table 5.28.

Table 5.27 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	633	28,78
TRP-2	5	0,23
TRP-3	3	0,14
TRP-4	9	0,41
TRP-5	80	3,64
Total	730	33,19

Table 5.28 : Material exergy ($E_{M\text{-}t}$) of systems and processes except transportation lines.

System/Process	Capital	Equivalent exergy (TJ)
MRF plant	100 €/Ton	4595,45
Incineration plant	64 €/Ton	865,89
Anaerobic digestion plant	65 €/Ton	3608,59
Upgrading of biogas	0,26 €/m^3	1892,14
Biorefinery	7000 $/$KW_{el}$	9317,28
Separation, drying, composting	35 €/Ton	777,23
Total		21056,58

In conclusion, exergy of material transfers ($E_{M\text{-}t}$) into the system is the sum of Table 5.27 and Table 5.28 which is 21089,77 TJ.

E_{PHYS-t} is calculated similar to Table 5.10 and presented in Table 5.29, below.

Table 5.29 : Physical exergy (E_{PHYS-t}) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	82715,34	3835,24
TRP-2	531,38	24,64
TRP-3	265,69	12,32
TRP-4	882,08	40,90
TRP-5	7268,18	337,00
Total	91662,66	4250,10

Sum of capital exergy (E_{C-t}) is the sum of Table 5.30, Table 5.31 and Table 5.32 which amounts to 13963,21 TJ.

Table 5.30 : Exergetic equivalent of the capital of processes.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
MRF plant	100 €/Ton	4595,45	1096,12	919,09	2015,21
Incineration plant	64 €/Ton	865,89	206,53	173,18	379,71
Anaerobic digestion plant	65 €/Ton	3608,59	860,73	721,72	1582,45
Upgrading of biogas	0,26 €/m^3	1892,14	451,32	378,43	829,75
Biorefinery	7000 €/KW_{el}	9317,28	2222,38	1863,46	4085,84
Separation, drying, composting	35 €/Ton	777,23	185,39	155,45	340,84
Landfilling	10 €/Ton	108,69	25,92	21,74	47,66
Total					9281,45

Table 5.31 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	633	1128,80	269,24	225,76	495,00
TRP-2	5	8,92	2,13	1,78	3,91
TRP-3	3	5,35	1,28	1,07	2,35
TRP-4	9	16,05	3,83	3,21	7,04
TRP-5	80	142,66	34,03	28,53	62,56
Total	730				570,86

Table 5.32 : Exergetic equivalent of diesel fuel capital.

Transportation line	Diesel consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	99060284,14	3709,64
TRP-2	636380,69	23,83
TRP-3	318190,35	11,92
TRP-4	1056378,07	39,56
TRP-5	8704401,89	325,96
Total		4110,91

Consumed labour and its exergetic equivalent are presented in Table 5.33.

Table 5.33 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	2026655,00	312,01
TRP-2	13600,00	2,09
TRP-3	8160,00	1,26
TRP-4	22950,00	3,53
TRP-5	181333,33	27,92
The remainder of the system	220216,92	33,90
Total	2472915,25	380,71

Emission gases and their environmental remediation cost (EE_{ENV-t}) are originated from transportation as well as other processes which are presented in Table 5.34 and Table 5.35, respectively.

Table 5.34 : Emissions from the TRP lines.

	Emission (Ton)		
	CO_2	N_2O	CH_4
TRP-1	262274,87	13,80	13,80
TRP-2	1684,90	0,09	0,09
TRP-3	842,45	0,04	0,04
TRP-4	2796,90	0,15	0,15
TRP-5	23046,03	1,21	1,21
Total	290645,15	15,30	15,30

Table 5.35 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Incineration	584746,54	25,5069	191,302
Anaerobic digestion	6140,805		2438,89
Upgrading of biogas	193960,42		1577,15
Biorefinery	215049,4	0,38333	3,83332
Composting	91230,334	207,342	2764,56
Total	1091127,50	233,23	6975,72

Thereby, total CO_2, N_2O and CH_4 emissions of the system are the sum of Table 5.34 and Table5.35 and the sum is presented in Table 5.36. The environmental remediation cost of considered emission gases is computed further in Section 5.4.3 and inserted into Table 5.36 to obtain the EE_{ENV-t} for the TE sector solid waste treatment system.

Table 5.36 : Environmental remediation cost of emission gases (EE_{ENV-t}).

CO_2 emissions (Ton)	1381772,65
N_2O emission (Ton)	248,53
CH_4 emission (Ton)	6991,02
CO_2 ee_{ENV-g} (TJ/Ton CO_2)	0,043
N_2O ee_{ENV-g} (TJ/Ton N_2O)	0,010
CH_4 ee_{ENV-g} (TJ/Ton CH_4)	0,267
CO_2 EE_{ENV-g} (TJ)	59666,03
N_2O EE_{ENV-g} (TJ)	2,3969133
CH_4 EE_{ENV-g} (TJ)	1865,4792
Total EE_{ENV-t} (TJ)	61533,91

Products of the system are the same as those of DO sector waste remediation system: electricity, heat, recycled materials and compost. In Table 5.37, energy balance of the system and net heat and electricity production are seen.

Table 5.37 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
MRF plant	preliminary sorting	51,37			
MRF plant	pretreatment of recyclable materials and recycling	654,67	2093,42		
Incineration plant		114,78		2550,69	3060,83
Anaerobic digestion	mixing, sterilization	373,22			
Anaerobic digestion	anaerobic digestion	61,33	460,00		
Upgrading of biogas		249,15	81,54		
Biorefinery		69,00		1533,33	1839,99
Composting	Separation, drying, composting	406,80			
Total		1980,31	2634,96	4084,02	4900,83
Net production				2103,71	2265,87
Exergy of production				2103,71	455,42

Amount of recycled materials and exergy contents are seen in Table 5.38.

Table 5.38 : Amount and exergy of recycled materials.

	Recycled material (Ton)	Specific exergy (MJ/Ton)	Exergy (TJ)
Paper& cardboard	405115,15	17000,00	6886,96
Textile	108088,51	13904,76	1502,94
Plastic	295166,40	32502,16	9593,55
Glass	188225,94	131,48	24,75
Metal (Al)	22103,65	32928,09	727,83
Metal (Fe)	22768,22	6740,69	153,47
Other metals (Cu)	2167,55	2112,06	4,58
Wood	15002,54	20658,24	309,93
Total	1058637,96		19204,00

Amount of produced compost and its exergy content are presented in Table 5.39.

Table 5.39 : Amount and exergy of produced compost.

Amount of produced compost (Ton)	276455,56
Exergy of compost (MJ/Ton)	18373,31
Exergy of total produced compost (TJ)	5079,40

Exergy of system products are presented in Table 5.37, Table 5.38 and Table 5.39 and summarized in Table 5.40 with their exergetic content.

Table 5.40 : Products of TE sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	2103,71
Heat	455,42
Recycled materials	19204,00
Compost	5079,40
Total (E_{P-t})	26842,54

By inserting the above presented E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, EE_{ENV-t} and E_{P-t} into equation (5.16), EE_{ENV-s} for TE sector solid waste is calculated as presented in Table 5.41.

Table 5.41 : EE_{ENV-s} for TE sector solid waste.

	Exergetic equivalent (TJ)
E_{M-t}	21089,77
E_{PHYS-t}	4250,10
EE_{L-t}	380,71
EE_{C-t}	13963,21
EE_{ENV-t}	61533,91
E_{P-t}	26842,54
EE_{ENV-s}	74375,17

5.4.2.3 IN sector solid waste

The considered composition of IN sector solid waste is presented in Table 5.42. The composition is estimated based on data (SWAP, 2005) due to the fact that there is neither official data nor study in the literature for average composition of Turkish IN sector waste. Since the type of the constituent materials are similar to those of TE and DO sector solid waste, the same treatment system (presented in Figure 5.2) are applied to the waste and results are seen below. In Table 5.42, the part of “hazardous waste” is seen as 4% of the industrial waste. Unfortunately in Turkey, hazardous waste is mostly landfilled and although very limited amount is recycled and reused. Uncontrolled production of hazardous waste and its illegally dumped or discharged to receiving water bodies are one of the primary problems arising along with industrial activities in Turkey (Salihoglu, 2010). As a result, treatment of hazardous waste is a very important issue for the country, but, since it takes special technologies and detailed analyses, it is taken out of the scope of this thesis. In other words, since the hazardous waste has a little share in the total composition of IN sector solid waste, environmental remediation cost of relevant part is neglected.

Table 5.42 : Composition of IN sector waste.

Composition	Percent (% wt.)	Amount (Ton)
Organic	18,21	3162955,78
Paper& cardboard	32,38	5625836,00
Textile	2,19	380048,51
Plastic	20,06	3484831,44
Glass	0,55	96144,71
Metal (Al)	0,23	40655,45
Metal (Fe)	10,31	1791825,71
Other metals (Cu)	0,12	20943,72
Wood	3,61	626703,61
Other combustibles	4,38	760097,01
Ash	3,97	689362,63
Hazardous waste	3,99	693859,43
Total	100	17373264,00

Material exergy fluxes (E_{M-t}) to IN sector solid waste environmental remediation system are seen in Table 5.43 and Table 5.44.

Table 5.43 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	3067	139,46
TRP-2	33	1,50
TRP-3	17	0,77
TRP-4	60	2,73
TRP-5	146	6,64
Total	3323	151,10

Table 5.44 : Material exergy ($E_{M\text{-}t}$) of systems and processes except transportation lines.

System/Process	Capital	Equivalent exergy (TJ)
MRF plant	100 €/Ton	38771,97
Incineration plant	64 €/Ton	5735,08
Anaerobic digestion plant	65 €/Ton	6605,80
Upgrading of biogas	0,26 €/m^3	3463,71
Biorefinery	7000 $/Kwel	17055,99
Separation, drying, composting	35 €/Ton	1422,79
Total		73055,34

In conclusion, exergy of material transfers ($E_{M\text{-}t}$) into the system is the sum of Table 5.43 and Table 5.44 which is 73206,44 TJ.

For IN sector solid waste environmental remediation system, flux of $E_{PHYS\text{-}t}$ is calculated similar to Table 5.10 and presented in Table 5.45.

Table 5.45 : Physical exergy ($E_{PHYS\text{-}t}$) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	400994,07	18592,78
TRP-2	3519,51	163,19
TRP-3	1759,75	81,59
TRP-4	6130,59	284,26
TRP-5	13304,95	616,91
Total		19738,72

Total capital exergy ($E_{C\text{-}t}$) is the sum of Table 5.46, Table 5.47 and Table5.48 which amounts to 54053,69 TJ.

Table 5.46 : Exergetic equivalent of the capital of processes.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
MRF plant	100 €/Ton	38771,97	9248,00	7754,39	17002,39
Incineration plant	64 €/Ton	5735,08	1367,95	1147,02	2514,96
Anaerobic digestion plant	65 €/Ton	6605,80	1575,63	1321,16	2896,79
Upgrading of biogas	0,26 €/m^3	3463,71	826,17	692,74	1518,92
Biorefinery	7000 €/KW_{el}	17055,99	4068,24	3411,20	7479,44
Separation, drying, composting	35 €/Ton	1422,79	339,3672	284,56	623,92
Landfilling	10 €/Ton	744,33	177,54	148,87	326,41
Total					32362,84

Table 5.47 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	3067	5469,23	1304,54	1093,85	2398,38
TRP-2	33	58,8473	14,0364	11,7695	25,81
TRP-3	17	30,32	7,23	6,06	13,29
TRP-4	60	106,995	25,52	21,40	46,92
TRP-5	146	260,355	62,1005	52,0709	114,17
Total	3323				2598,57

Table 5.48 : Exergetic equivalent of diesel fuel capital.

Transportation line	Diesel consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	480232424,77	17983,87
TRP-2	4214980,25	157,84
TRP-3	2107490,13	78,92
TRP-4	7342024,24	274,95
TRP-5	15934069,74	596,70
Total		19092,28

Consumed labour and its exergetic equivalent are presented in Table 5.49.

Table 5.49 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	9819511,67	1511,74
TRP-2	89760,00	13,82
TRP-3	46240,00	7,12
TRP-4	153000,00	23,55
TRP-5	330933,33	50,95
The remainder of the system	982070,50	151,19
Total		1758,37

Emission gases and their environmental remediation cost (EE_{ENV-t}) are originated from transportation as well as other processes which are presented in Table 5.50 and Table 5.51, respectively.

Table 5.50 : Emissions from the TRP lines.

	Emissions (Ton)		
	CO_2	N_2O	CH_4
TRP-1	1271477,27	66,92	66,92
TRP-2	11159,704	0,58735	0,58735
TRP-3	5579,8518	0,29368	0,29368
TRP-4	19438,956	1,0231	1,0231
TRP-5	42187,504	2,22039	2,22039
Total	1349843,28	71,04	71,04

Table 5.51 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Incineration	3531841,19	154,06	1155,46
Anaerobic digestion	11241,21		4464,57
Upgrading of biogas	355059,30		2887,09
Biorefinery	393664,29	0,70	7,02
Composting	167004,06	379,55	5060,73
Total	4458810,04	534,32	13574,85

Thereby, total CO_2, N_2O and CH_4 emissions of the system are the sum of Table 5.50 and Table5.51 and the sum is presented in Table 5.52. The environmental remediation cost of considered emission gases are computed further in Section 5.4.3 and inserted into Table 5.52 to obtain the EE_{ENV-t} for the IN sector solid waste treatment system.

Table 5.52 : Environmental remediation cost of emission gases (EE_{ENV-t}).

CO_2 emissions (Ton)	5808653,32
N_2O emission (Ton)	605,36
CH_4 emission (Ton)	13645,90
CO_2 ee_{ENV-g} (TJ/Ton CO_2)	0,043
N_2O ee_{ENV-g} (TJ/Ton N_2O)	0,010
CH_4 ee_{ENV-g} (TJ/Ton CH_4)	0,267
CO_2 EE_{ENV-g} (TJ)	250822,22
N_2O EE_{ENV-g} (TJ)	5,84
CH_4 EE_{ENV-g} (TJ)	3641,26
Total EE_{ENV-t} (TJ)	254469,32

Products of the system are the same as those of DO sector waste treatment system: electricity, heat, recycled materials and compost. In Table 5.53, energy balance of the system and net heat and electricity production are seen.

Table 5.53 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
MRF plant	preliminary sorting	249,02			
MRF plant	pretreatment of recyclable materials and recycling	5245,58	8544,63		
Incineration plant		693,27		15406,07	18487,28
Anaerobic digestion	mixing, sterilization	683,20			
Anaerobic digestion	anaerobic digestion	112,28	842,06		
Upgrading of biogas		456,08	149,26		
Biorefinery		126,31		2806,88	3368,25
Composting	Separation, drying, composting	744,69			
Total		8310,42	9535,95	18212,94	21855,53
Net production				9902,52	12319,58
Exergy of production				9902,52	2476,13

Exergy of recycled materials and compost are seen below in Table 5.53 and Table 5.54, respectively.

Table 5.54 : Amount and exergy of recycled materials.

	Recycled material (Ton)	Specific exergy (MJ/Ton)	Exergy (TJ)
Paper& cardboard	4810089,78	17000,00	81771,53
Textile	226128,86	13904,76	3144,27
Plastic	2043505,16	32502,16	66418,33
Glass	90376,03	131,48	11,88
Metal (Al)	35919,09	32928,09	1182,75
Metal (Fe)	1347452,94	6740,69	9082,76
Other metals (Cu)	18849,34	2112,06	39,81
Wood	535831,59	20658,24	11069,34
Total	9108152,79		172720,67

Table 5.55 : Amount and exergy of produced compost.

Amount of produced compost (Ton)	506072,92
Exergy of compost (MJ/Ton)	18373,31
Exergy of total produced compost (TJ)	9298,23

Exergy of total system products are presented in Table 5.43, Table 5.54 and Table 5.55 and summarized in Table 5.56 with their exergetic content.

Table 5.56 : Products of IN sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	9902,52
Heat	2476,13
Recycled materials	172720,67
Compost	9298,23
Total (E_{P-t})	194397,55

By inserting the above presented E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, $EE_{ENV-\,t}$ and E_{P-t} into equation (5.16), EE_{ENV-s} for IN sector solid waste is calculated as presented in Table 5.57.

Table 5.57 : EE_{ENV-s} for IN sector solid waste.

	Exergetic equivalent (TJ)
E_{M-t}	73206,44
E_{PHYS-t}	19738,72
EE_{L-t}	1758,37
EE_{C-t}	54053,69
EE_{ENV-t}	254469,32
E_{P-t}	194397,55
EE_{ENV-s}	208828,99

5.4.2.4 CO sector solid waste

As stated in CO sector definition in Section 2.5, energy generation plants, refineries and coke factories are included in CO sector. The amount and composition of CO sector solid waste are presented in Table 5.58 (the composition is determined based on data in (SWAP, 2005)). The amount of waste in Table 5.58 pertains to the year 2004 (due to the lack of available data for the year 2006) (Turkstat, 2005a). As stated in Section 5.4.2.3, transportation and processing of hazardous waste take special processes according to the composition of hazardous waste and disregarded in this thesis.

Table 5.58 : Composition of CO sector waste.

Composition	Percent (% wt.)	Amount (Ton)
Organic	9,48	11777,04
Paper& cardboard	35,68	44325,41
Plastic	19,12	23752,86
Glass	5,97	7416,56
Metal (Al)	0,23	286,97
Metal (Fe)	7,14	8870,05
Other metals (Cu)	0,12	147,83
Wood	0,03	37,27
Ash	2,40	2981,53
Hazardous waste	0,76	944,15
Others	19,06	23678,32
Total	100	124218,00

In Table 5.58, “Others” has 19,06% contribution to the composition which are originated from special processes of petroleum refining and coke processing. As a result of scarcity of sectoral waste composition data, the estimated composition of “Others” is presented in Table 5.59. Vacuum residue is the main by-product of the crude oil processing but -in particular for Turkey- not all the refineries have “residue upgrading technologies” like hydrocracking, fluid catalytic cracking (FCC) or vacuum destination, to convert vacuum residues into different fuels such as vacuum gas oil, gasoline, jet fuel, etc. (Republic of Turkey-State Planning Organization, 2000). Petrocoke is a by-product produced from “residue upgrading (converting)” processes. In this thesis, 50% of “Others” are assumed to be coke come from coke factories and the remaining is allocated evenly as vacuum residue and petrocoke similarly to Marin Sanchez and Rodriguez Toral (2007). In most of the studies of the literature, the composition of refinery waste is rather simplified and rudimentary and often one particular type of slop oil (which is the mixtures of oil, chemicals and water derived from a wide variety of sources in refineries) or sludge are considered as the waste composition (American Petroleum Institute, 2010). Since there are many physical property differences between waste oils and emulsions, there has been no systematic attempt to characterize the chemical composition of hydrocarbon waste from a refinery operation. However, the lack of information on all of the waste is not considered to be major concern, since the composition of the wastes are not static (change rapidly as they are collected and stored, type and amount of chemicals have a wide variety). As a result, the composition and necessary treatment processes are imprecise (American Petroleum Institute, 2010). Hence, the compositional information described in Table 5.59 should not be regarded as an absolute characterization, but rather as a possible composition that is subject to change depending on the type of crude oil being refined and processes applied in refineries to produce the waste being considered.

Table 5.59 : Composition of “Others” in Table 5.58.

	Percent (% wt.)	Amount (Ton)
Coke	50	11839,16
Vacuum residue	25	5919,58
Petrocoke	25	5919,58
Total		23678,32

The flow chart of environmental remediation system for CO sector solid waste is seen in Figure 5.3. Refinery and coke processing waste (described in Table 5.59) is subjected to IGCC (integrated gasification combined cycle) which is a gasification and combustion technology which has been widely used for syngas (or synthesis gas) production (Marin Sanchez and Rodriguez Toral, 2007). Syngas is a commodity which can be used to produce fuels, chemicals, intermediate products or power, through the chemical conversion of carbonaceous materials (Orr and Maxwell, 2000). Syngas is composed of mainly carbon monoxide and hydrogen (85%), with smaller quantities of carbon dioxide, nitrogen, methane and various other hydrocarbon gases. IGCC of coal has a wide application field, but its use has been also extended to refinery residuals as a result of easier handling of syngas pollutants than those from direct incineration of residuals. Another advantages are: syngas' being easy to transfer and possibility of its use as a fuel substitute for different processes (Marin Sanchez and Rodriguez Toral, 2007; U.S. Department of Energy National Energy Technology Laboratory, 2002a) In the treatment system applied to CO sector waste in this study, produced syngas is combusted in IGCC plants to generate electricity. Te constituent materials of the remaining sectoral waste (except "others in Table 5.58) are the same as those of DO, TE and IN sector waste, therefore, the remaining fraction of waste is subject to a set of processes (sorting, recycling, incineration, anaerobic degistion etc.) which are explained in detail in Section 5.4.2.1-5.4.2.3.

Material fluxes to CO sector solid waste environmental remediation system are seen in Table 5.60 and Table 5.61, depicting exergy of trucks and processes (converted from monetary equivalent into exergy), respectively. Cost data and other details of IGCC system are available in Appendix G. The details of the other processes employed in CO sector environmental treatment system are used in earlier sections of the present chapter and details are presented in Appendix G. It is noteworthy that, in the virtually designed proposal for sectoral solid waste, refinery and coke processing waste are collected separately and are delivered to IGCC plant for processing (dashed line in Figure 5.3).

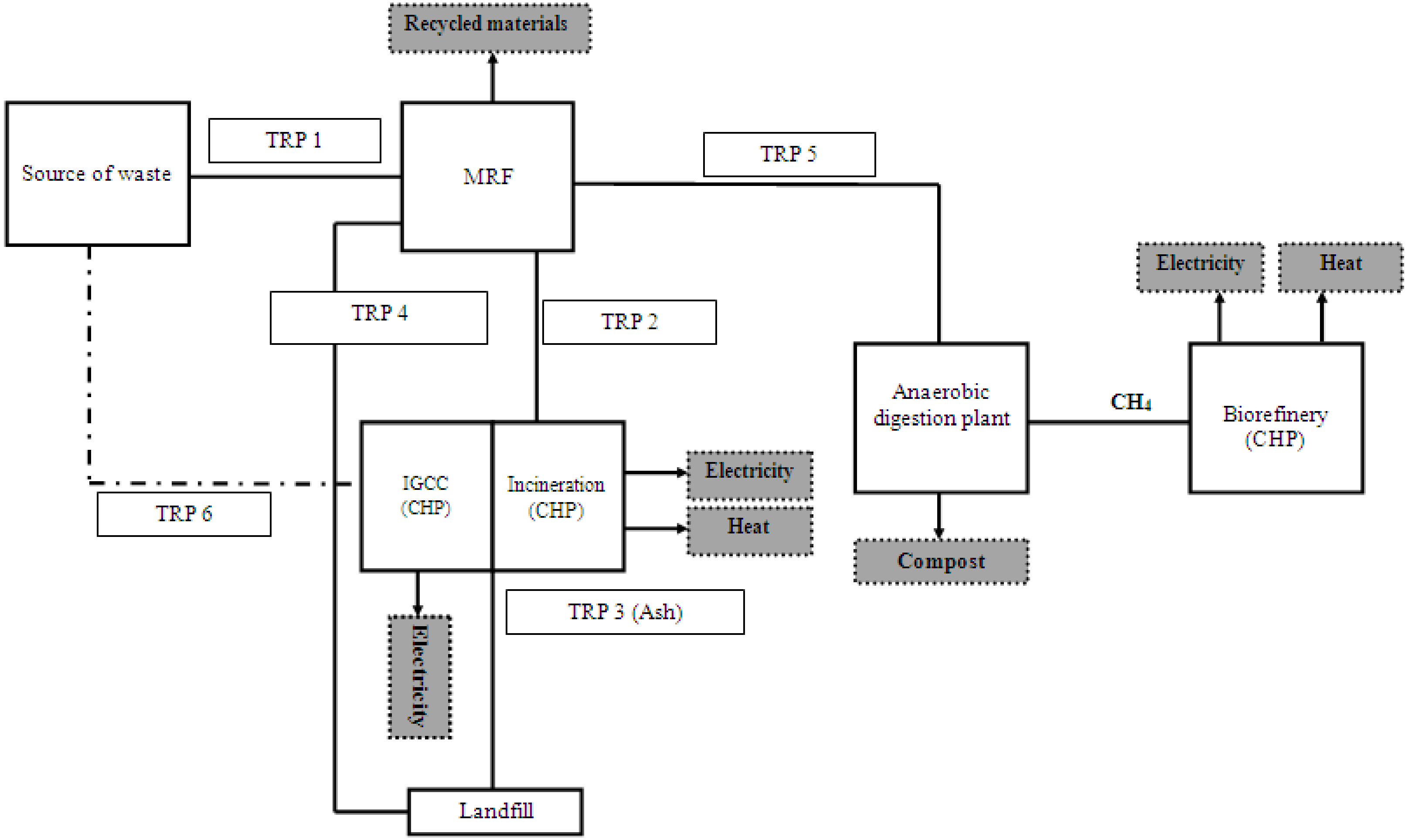

Figure 5.3 : Illustration of CO sector solid waste treatment.

Table 5.60 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	19	0,86
TRP-2	1	0,05
TRP-3	1	0,05
TRP-4	1	0,05
TRP-5	1	0,05
TRP-6	5	0,23
Total		1,27

Table 5.61 : Material exergy (E_{M-t}) of systems and processes except transportation lines.

System/Process	Capital	Equivalent exergy (TJ)
MRF plant	100 €/Ton	272,59
Incineration plant	64 €/Ton	27,62
IGCC Plant	2176 $/KW_{el}$	584,10
Anaerobic digestion plant	65 €/Ton	24,60
Upgrading of biogas	0,26 €/m^3	12,90
Biorefinery	7000 €/KW_{el}	63,51
Separation, drying, composting	35 €/Ton	5,30
Total		990,60

Exergy of material transfers (E_{M-t}) into the system is the sum of Table 5.60 and Table 5.61 which is 991,87 TJ.

E_{PHYS-t} is the exergy of diesel fuel consumed for transportation (TRP lines). Diesel consumption and its exergetic equivalent are presented in Table 5.62.

Table 5.62 : Physical exergy (E_{PHYS-t}) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	1578,04	73,17
TRP-2	16,95	0,79
TRP-3	10,57	0,49
TRP-4	32,18	1,49
TRP-5	49,54	2,30
TRP-6	405,05	18,78
Total		97,01

Exergetic equivalent of capital fluxes is the sum of following 3 tables (Table 5.63, Table 5.64 and Table 5.65) which amounts to 551,92 TJ.

Table 5.63 : Exergetic equivalent of the capital of processes.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
MRF plant	100 €/Ton	272,59	65,02	54,52	119,54
Incineration plant	64 €/Ton	27,62	6,59	5,52	12,11
IGCC Plant	2176 $/KW_{el}$	584,10	139,32	116,82	256,14
Anaerobic digestion plant	65 €/Ton	24,60	5,87	4,92	10,79
Upgrading of biogas	0,26 €/m^3	12,90	3,08	2,58	5,66
Biorefinery	7000 €/KW_{el}	63,51	15,15	12,70	27,85
Separation, drying, composting	35 €/Ton	5,30	1,26	1,06	2,32
Landfilling	10 €/Ton	4,08	0,97	0,82	1,79
Total					436,19

In Table 5.63, the cost of MRF plant includes preliminary sorting, pretreatment of recyclable materials and recycling; anaerobic digestion plant includes mixing, sterilization and anaerobic digestion part.

Table 5.64 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	19	33,88	8,08	6,78	14,86
TRP-2	1	1,78	0,43	0,36	0,78
TRP-3	1	1,78	0,43	0,36	0,78
TRP-4	1	1,78	0,43	0,36	0,78
TRP-5	1	1,78	0,43	0,36	0,78
TRP-6	5	8,92	2,13	1,78	3,91
Total					21,90

Table 5.65 : Exergetic equivalent of diesel fuel capital.

Transportation line	Diesel consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	1889864,34	70,77
TRP-2	20298,91	0,76
TRP-3	12654,43	0,47
TRP-4	38538,46	1,44
TRP-5	59329,39	2,22
TRP-6	485090,79	18,17
Total		93,84

As for labour consumption, the same calculation route presented in Section 5.4.2.1 is followed. Considering the whole system, number of workers is assumed to be 400 worker per 1000 MW_{h+el} with 1800 workhours/year workload for each worker. Consumed labour and its exergetic equivalent are presented in Table 5.66.

Table 5.66 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	40554,44	6,24
TRP-2	440	0,068
TRP-3	280	0,043
TRP-4	825	0,13
TRP-5	1333,33	0,21
TRP-6	11522,22	1,77
The remainder of the system	11964,35	1,84
Total		10,30

System emissions (originated from transportation activity as well as processes like anaerobic digestion, incineration, IGCC plant etc.) are presented in Table5.67 and Table 5.68. The emission gases are derived in accordance with Appendix G.

Table 5.67 : Emissions from the TRP lines.

	Emission (Ton)		
	CO_2	N_2O	CH_4
TRP-1	5003,66	0,26	0,26
TRP-2	53,74	0,003	0,003
TRP-3	33,50	0,002	0,002
TRP-4	102,04	0,005	0,005
TRP-5	157,08	0,008	0,008
TRP-6	1284,34	0,07	0,07
Total	6634,37	0,35	0,35

Table 5.68 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Incineration	15550,69	0,68	5,09
IGCC plant	61057,57	0,67	2,32
Anaerobic digestion	41,86		16,62
Upgrading of biogas	1322,04		10,75
Biorefinery	1465,78	0,003	0,03
Composting	621,83	1,41	18,84
Total	80059,77	2,77	53,65

Thereby, total CO_2, N_2O and CH_4 emissions of the system are the sum of Table5.67 and Table 5.68 and the results are presented in Table 5.69. The environmental remediation cost of considered emission gases is computed further in Section 5.4.3 and inserted into Table 5.69 to obtain the EE_{ENV-t} for the whole treatment system.

Table 5.69 : Environmental remediation cost of emission gases (EE_{ENV-t}).

CO_2 emissions (Ton)	86694,13
N_2O emission (Ton)	3,11
CH_4 emission (Ton)	54
CO_2 ee_{ENV-g} (TJ/Ton CO_2)	0,043
N_2O ee_{ENV-g} (TJ/Ton N_2O)	0,010
CH_4 ee_{ENV-g} (TJ/Ton CH_4)	0,267
CO_2 EE_{ENV-g} (TJ)	3743,52
N_2O EE_{ENV-g} (TJ)	0,03
CH_4 EE_{ENV-g} (TJ)	14,41
Total EE_{ENV-t} (TJ)	3757,96

Products of the remediation system are electricity and heat produced by incineration of non-recyclable part of the inorganic waste, biorefinery plant and IGCC plant. Recycled materials and produced compost (the ash generated in considered processes are assumed to have zero exergy and its exergetic content is not included in exergy of products). Principals of computing the produced and/or consumed energy by the processes are presented in Appendix G. Energy balance of the system and net heat and electricity production are presented in Table 5.70.

Table 5.70 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
MRF plant	preliminary sorting	1,49			
MRF plant	pretreatment of recyclable materials and recycling	31,56	88,92		
Incineration plant		3,05		67,83	81,40
IGCC plant		9,28		309,22	
Anaerobic digestion	mixing, sterilization	2,54			
Anaerobic digestion	anaerobic digestion	0,42	3,14		
Upgrading of biogas		1,70	0,56		
Biorefinery		0,47		10,45	12,54
Composting	Separation, drying, composting	2,77			
Total		53,28	92,61	387,51	93,94
Net production				334,23	1,33
Exergy of production				334,23	0,27

Amount of recycled materials and exergy contents are seen in Table 5.71.

Table 5.71 : Amount and exergy of recycled materials.

	Recycled material (Ton)	Specific exergy (MJ/Ton)	Exergy (TJ)
Paper& cardboard	37898,23	17000	644,27
Plastic	13928,68	32502,16	452,71
Glass	6971,56	131,48	0,92
Metal (Al)	253,54	32928,09	8,35
Metal (Fe)	6670,28	6740,69	44,96
Other metals (Cu)	133,05	2112,06	0,28
Wood	31,87	20658,24	0,66
Total	65887,20		1152,15

Amount of produced compost and its exergy content is presented in Table 5.72.

Table 5.72 : Amount and exergy of produced compost.

Amount of produced compost (Ton)	1884,33
Exergy of compost (MJ/Ton)	18373,31
Exergy of total produced compost (TJ)	34,62

The exergy of total system products is presented in Table 5.70, Table 5.71 and Table 5.72 and is summarized in Table 5.73 with their exergetic content.

Table 5.73 : Products of CO sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	334,23
Heat	0,27
Recycled materials	1152,15
Compost	34,62
Total ($E_{P\text{-}t}$)	1521,27

By inserting the above presented $E_{M\text{-}t}$, $E_{PHYS\text{-}t}$, $EE_{L\text{-}t}$, $EE_{C\text{-}t}$, $EE_{ENV\text{-}t}$ and $E_{P\text{-}t}$ into equation (5.16), $EE_{ENV\text{-}s}$ for CO sector solid waste is calculated as presented in Table 5.74.

Table 5.74 : $EE_{ENV\text{-}s}$ for CO sector solid waste.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	991,87
$E_{PHYS\text{-}t}$	97,01
$EE_{L\text{-}t}$	10,30
$EE_{C\text{-}t}$	551,92
$EE_{ENV\text{-}t}$	3757,96
$E_{P\text{-}t}$	1521,27
$EE_{ENV\text{-}s}$	3887,81

5.4.2.5 AG sector solid waste

Ag sector solid waste consists of manure, agricultural waste residues and wood. The amount of agricultural waste and its properties are presented in Table 5.75. Due to the lack of exact data, the estimated amount of agricultural waste residues is obtained from Balat (2005) and wood from Balat (2008) which pertain to the year 2001. The amount of manure is computed based on data for the year 2006 and details of the computation are presented in Appendix G. Balat (2005) reported that 50% of agricultural waste residues is wheat straw and the left is mainly other types of straws and shells. Hence in this thesis, the physical properties of agricultural waste residues are assumed to be the same as wheat straw. Since the manure from different animals have almost the same properties; composition of cattle manure is used as the general composition of animal manure. Properties of wood are presented in Appendix B.

Table 5.75 : Properties of agricultural waste.

	Agricultural residue	Wood	Manure
Amount (dry basis) (Ton)	54400000	18000000	16241970,67
DM (dry matter)	89,70% [4]	91,20% [5]	10,52% [6]
Amount (wet basis) (Ton)	60646599,78	19736842,11	154397353,92
Exergy (MJ/kg)	16,69	20,66	15,99
Total Exergy (TJ)	1012475,75	407728,34	2468160,63

The flowchart of AG sector solid waste environmental remediation system is seen in Figure 5.4.

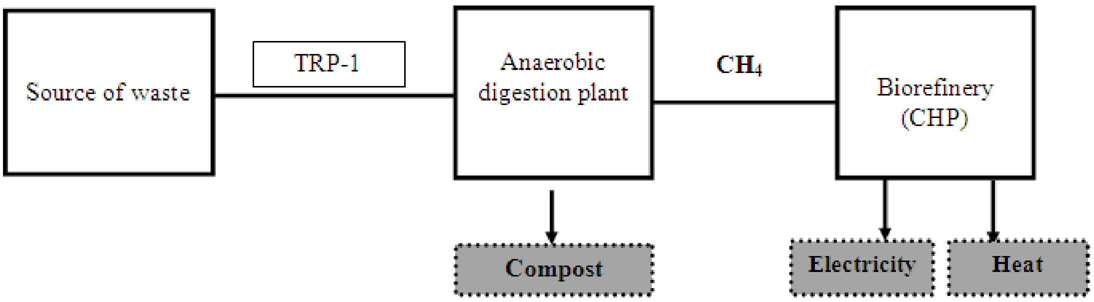

Figure 5.4 : Illustration of AG sector solid waste treatment.

As applied to organic fraction of other sectors' solid waste in previous sections, estimated agricultural waste (presented in Table 5.75) undergoes anaerobic digestion

[4] ECN, n.d.
[5] Bilgen et. al., 2004
[6] Gomez et. al., 2010

(AG) process in order to produce biogas (mainly CH_4+CO_2). Afterwards, biogas is upgraded by removing CO_2, H_2S etc. and by increasing the percentage of CH_4 up to 98% (in our system) in order to be used as a substitute of natural gas. The upgrated biogas (98% CH_4 + 2% CO_2) is delivered to biorefinery to generated heat and electrical power. The digestate, i.e., the residue of the anaerobic digestion, is composted and produced compost is taken out of the system as a system product. Technical details of AG sector solid waste environmental remediation system are presented in Appendix G. Summarizing tables which report the results of the material, energy carrier, capital and labour inflows into the treatment system are seen between Table 5.76 and Table 5.84, below.

Table 5.76 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	43159	1962,48

Table 5.77 : Material exergy (E_{M-t}) of systems and processes except transportation lines.

System/Process	Capital	Equivalent exergy (TJ)
Anaerobic digestion plant	65 €/Ton	490337,21
Upgrading of biogas	0,26 €/m^3	304353,02
Biorefinery	7000 €/KW_{el}	1519160,80
Separation, drying, composting	35 €/Ton	105611,09
Total		2419462,11

Material exergy flux (E_{M-t}) into the system is the sum of Table 5.76 and Table 5.77 which is 2421424,59 TJ.

The only exergy inflow of energy carriers (E_{PHYS-t}) is the diesel fuel consumption of TRP-1 line. Calculation of diesel fuel consumption is computed in correspondence to Appendix G, and the result is presented in Table 5.78.

Table 5.78 : Physical exergy (E_{PHYS-t}) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	4382490,73	203201,71

Exergy of capital (E_{C-t}) is the sum of Table 5.79, Table 5.80 and Table 5.81 which amounts to 39668263,3 TJ.

Table 5.79 : Exergetic equivalent of the capital of processes.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
Anaerobic digestion plant[7]	65 €/Ton	490337,21	116956,58	98067,44	215024,02
Upgrading of biogas	0,26 €/m^3	304353,02	72595,12	60870,60	133465,72
Biorefinery	7000 €/KW_{el}	1519160,80	38739331,48	303832,16	39043163,64
Separation, drying, composting	35 €/Ton	105611,09	25190,6485	21122,22	46312,87
Total					39437966,25

Table 5.80 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	43159	76963,31	18357,50	15392,66	33750,16

Table 5.81 : Exergetic equivalent of diesel fuel consumption.

Transportation line	Diesel consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	5248491887,17	196546,88

As for labour consumption, the same calculation route presented in Section 5.4.2.1 is followed. Considering the whole system, number of workers is assumed to be 300 worker per 1000 MW_{h+el} with 1800 workhours/year workload for each worker. Consumed labour and its exergetic equivalent are presented in Table 5.82.

Table 5.82 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	138180731,67	21273,24
The remainder of the system	10110526,42	1556,54
Total		22829,78

System emissions originated from transportation and processes included in the system and corresponding environmental remediation costs (EE_{ENV-t}) are presented in Table 5.83. The emission gases are derived in accordance with Appendix G.

[7] Anaerobic digestion plant includes mixing, sterilization and anaerobic digestion part

Table 5.83 : Emissions from transportation (TRP-1) and processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
TRP-1	13896059,00	731,37	731,37
Anaerobic digestion	1049035,98		397654,60
Upgrading of biogas	33170069,87		257149,98
Biorefinery	35063305,62	62,50	625,01
Composting	15600986,84	28173,70	375649,27
Total	98779457,31	28967,57	1031810,24

The environmental remediation cost of considered emission gases is computed further in Section 5.4.3 and inserted into Table 5.84 to obtain the $EE_{ENV\text{-}t}$ for the whole environmental remediation system.

Table 5.84 : Environmental remediation cost of emission gases ($EE_{ENV\text{-}t}$).

CO_2 emissions (Ton)	98779457,31
N_2O emission (Ton)	28967,57
CH_4 emission (Ton)	1031810,24
CO_2 $ee_{ENV\text{-}g}$ (TJ/Ton CO_2)	0,043
N_2O $ee_{ENV\text{-}g}$ (TJ/Ton N_2O)	0,010
CH_4 $ee_{ENV\text{-}g}$ (TJ/Ton CH_4)	0,267
CO_2 $EE_{ENV\text{-}g}$ (TJ)	4265374,65
N_2O $EE_{ENV\text{-}g}$ (TJ)	279,374782
CH_4 $EE_{ENV\text{-}g}$ (TJ)	275327,588
Total $EE_{ENV\text{-}t}$ (TJ)	4540981,61

The products of the environmental remediation system are produced energy (electricity and heat) in biorefinery plant and compost produced in composting process. The composition of biogas utilized in the biorefinery is the same as presented in previous sections (98% CH_4 and 2% CO_2). The biorefinery is a CHP plant and system biogas production, the efficiencies of heat and electricity generation and produced energy can be seen in Table 5.85.

Table 5.85 : Properties of biogas utilization.

CH_4 (m^3)	18529924709,13
CO_2 (m^3)	378161728,76
LHV of CH_4 (MJ/m^3)	33,73
LHV of CO_2 (MJ/m^3)	0
LHV of biogas (TJ)	625014,3604
Electricity generation efficiency	0,40
Heat generation efficiency	0,48
Generated electricity (TJ)	250005,74
Generated heat (TJ)	300006,89

As stated earlier, the energy need (both of heat and electricity) is met by the generated energy in the system, i.e., output of biorefinery. The energy balance of the whole environmental treatment system is presented in Table 5.86. In the Table, it is assumed that produced heat is at the temperature of 100°C. Energy consumption of different processes is detailed in Appendix G.

Table 5.86 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
Anaerobic digestion	mixing, sterilization	8348,44	23990,78		
Anaerobic digestion	anaerobic digestion	10000,23	75001,72		
Upgrading of biogas		40075,41	13115,59		
Biorefinery		11250,26		250005,74	300006,89
Composting	Separation, drying, composting	55276,79			
Total		124951,13	112108,09	250005,74	300006,89
Net production				125054,62	187898,80
Exergy of production				125054,62	37766,07

Residue of the AD process is composted to produce compost (Technical details are available in Appendix G). Amount of produced compost from AG sector solid waste and its exergy content is presented in Table 5.87.

Table 5.87 : Amount and exergy of produced compost.

Amount of produced compost (Ton)	37564927,33
Exergy of compost (MJ/Ton)	18373,31
Exergy of total produced compost (TJ)	690191,88

The exergy of system products are presented in Table 5.86 and Table 5.87 and listed in Table 5.88 with their exergetic content.

Table 5.88 : Products of AG sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	125054,62
Heat	37766,07
Compost	690191,88
Total (E_{P-t})	853012,57

By inserting the above presented E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, EE_{ENV-t} and E_{P-t} into equation (5.16), EE_{ENV-s} for AG sector solid waste is calculated as presented in Table 5.89.

Table 5.89 : $EE_{ENV\text{-}s}$ for AG sector solid waste.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	2421424,59
$E_{PHYS\text{-}t}$	203201,71
$EE_{L\text{-}t}$	22829,78
$EE_{C\text{-}t}$	39668263,30
$EE_{ENV\text{-}t}$	4540981,61
$E_{P\text{-}t}$	853012,57
$EE_{ENV\text{-}s}$	46003688,42

It is noteworthy that in original structure of EEA theory, vehicle use and energy consumption for internal movimentation of materials and goods of the sectors are allocated to the relevant sector. In this content, end of life tractors and waste of tractor tires are included in AG sector solid waste. The remaining end of life vehicles and vehicle waste tires are covered in TR sector solid waste. However, (as it is seen in next section) the whole TR sector $EE_{ENV\text{-}s}$ is much less (more than 1000 times) than AG sector $EE_{ENV\text{-}s}$. Hence, additional environmental remediation load of AG sector originated only from tractors and tractor tires is negligible and disregarded in AG sector solid waste remediation analysis, in this thesis.

5.4.2.6 TR sector solid waste

As mentioned in Section 4.4, all of the available transportation modes are included in TR sector. In analysis of environmental remediation cost of TR sector, solid waste pertaining to the road transportation subsector (which is expected to be by far the largest part of the total sectoral solid waste generation since Turkey's transportation infrastructure mainly relies on road transportation and is well documented in national statistics). Recycled batteries, motor oil and other fluids are neglected due to the unreliability of the available data.

A flowchart of TR sector solid waste remediation system is shown in Figure 5.5. Traditionally, End of Life Vehicle (ELV) parts are one of the most effectively recycled consumer goods. Components having an economic value are removed by scrappers or are used after shredding for refurbishing, reuse, recycling or energy recovery. The remainder of the ELVs is sent to landfill as waste (European Commission Environmental Department, 2006). Accordingly, in this study, it is assumed that ELVs undergo dismantling, shredding and recycling in MRF (materials reprocessing facility). Additionally, tires undergo shredding in MRF plant. Shredded tires are transferred to a nearby CHP (combined heat and power plant-incineration process in Figure 5.5) for tire incineration. Produced ash from recycling processes and from incineration of tires is landfilled.

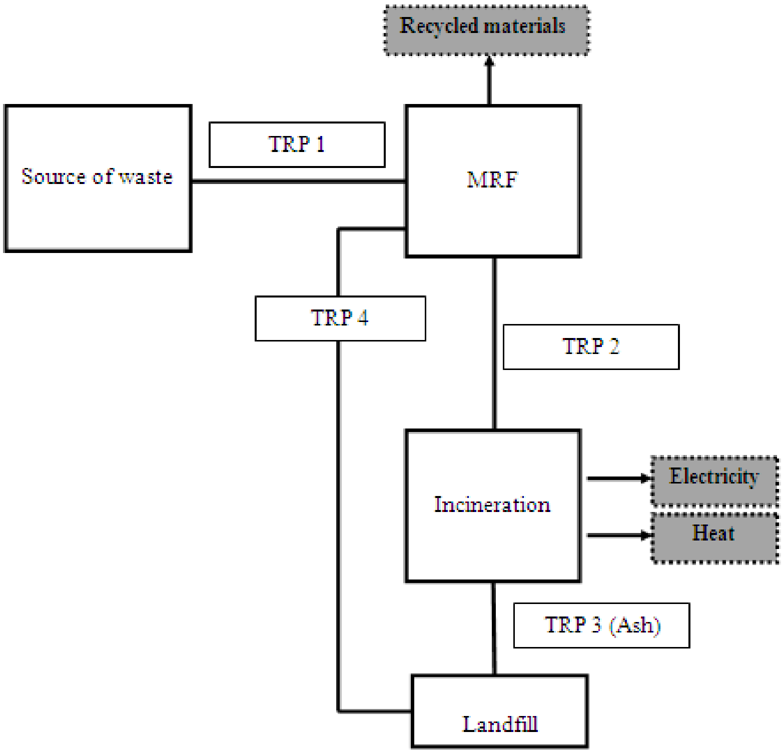

Figure 5.5 : Illustration of TR sector solid waste treatment.

ELVs are assumed to be transported to the MRF plant by self-driving. Waste tires from “in use vehicles” (IUV) are collected by trucks which have 8 tons carrying capacity. Details of transportation for collection are presented in Appendix G. For the year 2006, solid waste generation in TR sector is estimated 109326 Ton tires and 176832,68 Ton materials (excluding tires) extracted from ELVs (Details are presented in Appendix G). Constituting materials of solid waste which are extracted from ELV bodies are presented in Table 5.90.

Table 5.90 : Composition of ELVs, excluding tires.

Material	Amount (Ton)
Ferous metal	137280,44
Rubber	5533,28
Magnesium & Zinc	2685,19
Copper	2297,45
Aluminum	6124,58
Glass	5080,79
Fluids and lubricants, others (battery etc.)	9485,32
Plastic	8345,64
Total	176832,68

EEA flows received by the solid waste remediation system (exergy of material, energy carriers, capital, labour and environmental remediation cost) are as shown between Table 5.91 and Table 5.100. In the calculation of material fluxes (except for the trucks used in transportation), since no sufficiently reliable data were available on the exact material composition of the used items in the system, and thus an analytical analysis was impossible, the corresponding portion of EE_{ENV-s} is computed by converting the known monetary cost of the process into exergetic equivalent by means of ee_C as done in previous chapters. Calculation of annual cost is also repeated as done in previous chapters and presented in equation (5.17). Processes involved in MRF are dismantling, shredding and recycling of cars, and also tyre shredding. Sum of capital load of these processes consist the capital of MRF plant. Capital investment of MRF plant is obtained from literature for each process and reported in Table 5.92 and 5.94.

Exergy of material transfers (E_{M-t}) into the system is the sum of Table 5.91 and Table 5.92 which is 8839,47 TJ.

Table 5.91 : Number of trucks and their exergetic content.

Transportation line	Number of trucks	Exergy (TJ)
TRP-1	39	1,77
TRP-2	1	0,045
TRP-3	1	0,045
TRP-4	1	0,045
Total	42	1,91

The exergy of material flow originated by other system or processes except TRP lines is computed as explained above and is presented in Table 5.92.

Table 5.92 : Material exergy (E_{M-t}) of systems and processes except transportation lines.

System/Process		Capital	Equivalent exergy (TJ)
MRF plant			
	Dismantling of ELVs	6,6 $/ton	30,48
	Shredding of ELVs	124,15 $/ton	529,82
	Shredding of tires	12 $/ton	33,45
	Recycling	100 $/ton	537,70
Incineration plant		7000 $/$KW_{el}$	7706,11
Total			8837,56

E_{PHYS-t} of the system is the exergy of diesel fuel consumption in transportation lines. Calculation of diesel fuel consumption for each line is computed in correspondence to Appendix G and the results are presented in Table 5.93.

Table 5.93 : Physical exergy (E_{PHYS-t}) inflow of the environmental remediation system.

	Diesel consumption (Ton)	Exergy of diesel consumption (TJ)
TRP-1	5060,00	234,62
TRP-2	137,96	6,40
TRP-3	68,98	3,20
TRP-4	47,45	2,20
Total		246,41

Exergetic equivalent of capital flows (E_{C-t}) is the sum of Table 5.94, Table 5.95 and Table 5.96 which amounts to 4152,27 TJ.

Table 5.94 : Exergetic equivalent of the capital of processes.

System/Process		Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
MRF plant						
	Dismantling of ELVs	6,6 $/ Ton	30,48	7,27	6,10	13,37
	Shredding of ELVs	124,15 $/ Ton	529,82	126,37	105,96	232,34
	Shredding of tires	12 $/ Ton	33,45	7,98	6,69	14,67
	Recycling	100 $/ Ton	537,70	128,25	107,54	235,79
Incineration plant		7000 $/KW$_{el}$	7706,11	1838,08	1541,22	3379,30
Landfilling		10 €/Ton	12,81	3,06	2,56	5,62
Total						3881,09

Table 5.95 : Exergetic equivalent of the capital of trucks.

Transportation line	Number of trucks	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
TRP-1	39	69,55	16,59	13,91	30,50
TRP-2	1	1,78	0,43	0,36	0,78
TRP-3	1	1,78	0,43	0,36	0,78
TRP-4	1	1,78	0,43	0,36	0,78
Total	42				32,84

Table 5.96 : Exergetic equivalent of diesel fuel capital.

Transportation line	Diesel Consumption (l)	Exergetic equivalent of diesel cost (TJ)
TRP-1	6059879,17	226,93
TRP-2	165225,97	6,19
TRP-3	82612,99	3,09
TRP-4	56820,87	2,13
Total		238,34

As for labour consumption, the same calculation route presented in Section 5.4.2.1 is followed. Considering the whole system, number of workers is assumed to be 300 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker. Consumed labour and its exergetic equivalent are presented in Table 5.97.

Table 5.97 : Labour consumption and its exergetic equivalent (EE_{L-t}).

Transportation line	Labour (workhours)	Exergetic equivalent of labour (TJ)
TRP-1	124865	19,22
TRP-2	2720	0,42
TRP-3	1760	0,27
TRP-4	1200	0,18
The left of the system	50121,15	7,72
Total		27,81

System emissions originated from transportation as well as other processes which are included in the system presented in Table 5.98 and Table 5.99, respectively. The emission gases are derived in accordance with Appendix G.

Table 5.98 : Emissions from the TRP lines.

	Emission (Ton)		
	CO_2	N_2O	CH_4
TRP-1	16044,31	0,84	0,84
TRP-2	437,46	0,02	0,02
TRP-3	218,729	0,01	0,01
TRP-4	150,44	0,008	0,008
Total	16850,94	0,89	0,89

Table 5.99 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Incineration plant	270449,89	1,80	9,01

Thereby, total CO_2, N_2O and CH_4 emissions of the system are the sum of Table 5.98 and Table 5.99 and the sum is presented in Table 5.100. The environmental remediation cost of considered emission gases is computed further in Section 5.4.3 and inserted into Table 5.100 to obtain the EE_{ENV-t} for the TR sector solid waste remediation system.

Table 5.100 : Environmental remediation cost of emission gases (EE_{ENV-t}).

CO_2 emissions (Ton)	287300,83
N_2O emission (Ton)	2,69
CH_4 emission (Ton)	9,90
CO_2 ee_{ENV-g} (TJ/Ton CO_2)	0,043
N_2O ee_{ENV-g} (TJ/Ton N_2O)	0,010
CH_4 ee_{ENV-g} (TJ/Ton CH_4)	0,267
CO_2 EE_{ENV-g} (TJ)	12405,88
N_2O EE_{ENV-g} (TJ)	0,026
CH_4 EE_{ENV-g} (TJ)	2,64
Total EE_{ENV-t} (TJ)	12408,54

Products of the environmental remediation system are recycled materials in MRF plant and energy (electricity and heat) generated by incineration of tires in incineration plant. Recycling of the materials is analyzed in accordance with technical details of recycling processes given in the Appendix G. Amount of recycled materials and exergy contents are reported in Table 5.101. Specific exergy of the materials is retrieved from Szargut et al. (1988).

Table 5.101 : Amount and exergy of recycled materials.

	Recycled material (Ton)	Specific exergy (MJ/Ton)	Total Exergy (TJ)
Ferrous metal	129043,62	6800,00	877,50
Rubber	4055,89	32502,16	131,83
Magnesium, Zinc	2524,08	15628,64	39,45
Copper	2297,45	2112,06	4,85
Aluminum	5695,85	32928,09	187,55
Glass	5080,79	131,48	0,67
Plastic	6117,35	32502,16	198,83
Total			1440,67

The incineration plant is a CHP and the properties of heat and electricity generation are presented in Table 5.102.

Table 5.102 : Properties of incineration process.

Incinerated tires (Ton)	109326
Energy of tire (MJ/Ton, LHV)	29000
Total energy of tires (TJ, LHV)	3170,45
Efficiency of heat generation	0,46
Efficiency of electricity generation	0,4
Produced heat (TJ)	1458,41
Produced electricity (TJ)	1268,18

As stated earlier, the energy need (both of heat and electricity) is met by the generated energy in the system, i.e., output of incineration process. The energy balance of the environmental remediation system is presented in Table 5.103. In the Table, it is assumed that produced heat is at the temperature of 100 C. Energy consumption of different processes is detailed in Appendix G.

Table 5.103 : Energy balance of the system.

		Consumption		Production	
	Description	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
MRF plant:					
	Dismantling of ELVs	2,40			
	Shredding of ELVs	26,78			
	Shredding of tires	46,25			
	Recycling	55,97	254,64		
Incineration plant		57,07		1268,18	1458,41
Total		188,46	254,64	1268,18	1458,41
Net production				1079,72	1203,77
Exergy of production				1079,72	241,95

The exergy of total system products are presented in Table 5.101 and Table5.103 which are listed in Table 5.104 with their exergetic content.

Table 5.104 : Products of TR sector solid waste environmental remediation system.

Products	Exergy (TJ)
Electricity	1079,72
Heat	241,95
Recycled materials	1440,67
Total (E_{P-t})	2762,34

By inserting the above presented E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t}, $EE_{ENV-\ t}$ and E_{P-t} into equation (5.16), EE_{ENV-s} for TE sector solid waste is calculated as presented in Table 5.105.

Table 5.105 : EE_{ENV-s} for TR sector solid waste.

	Exergetic equivalent (TJ)
E_{M-t}	8839,47
E_{PHYS-t}	246,41
EE_{L-t}	27,81
EE_{C-t}	4152,27
EE_{ENV-t}	12408,54
E_{P-t}	2762,34
EE_{ENV-s}	22912,17

5.4.3 Environmental remediation cost of gas emissions ($EE_{ENV\text{-}g}$)

Detailed greenhouse gas emissions from the sectors are presented in Table 5.106. Data for sectoral allocation of emitted gases is available for CO_2, N_2O and CH_4 (Turkstat, 2010a; Ari, 2010). In Table 5.106, presented gas emissions have considerable amount of uncertainties especially about the CO_2 uptake by LULUCF (land-use, land use change and forestry) (Turkstat, 2010a). Greenhouse gas emissions caused by AG sector diesel consumption is presented in Section 5.4.5. Negative sign of AG sector CO_2 emission arises from the sector's CO_2 capture and sequestering ability. Data for AG sector CO_2 capture is obtained from Turkstat (2010b) and inserted into Table 5.106.

Table 5.106 : Sectoral emissions of CO_2, N_2O and CH_4 (Ari, 2010).

	CO_2 (Ton)	N_2O (Ton)	CH_4 (Ton)
EX Sector			
Coal Mining			76990
CO Sector	94783155	844,63	1624,05
AG Sector			
Sectoral activities	-76000000	480	772000
Diesel use	9963743,73	524,41	524,41
AG Sector total	-66036256,27	1004,41	772524,41
IN Sector			
Fossil fuel use	70599845	615,37	7125,95
Industrial processes	23000000	10000	2500
IN Sector total	93599845	10615,37	9625,95
TR Sector	43738000	1710	5930
TE Sector			
Fossil fuel use	9087782,02	255,74	4730,01
Waste			1431000
TE Sector total	9087782,02	255,74	1435730,01
DO Sector	32489217,98	914,26	16909,99
Total	207661743,73	14820,52	2319334,41

It is worthy to state that CH_4 emissions presented in Table 5.106 do not include the unrecorded (source of emission is not known) CH_4 emissions which are estimated to amount to 76990 Ton CH_4 (Ari, 2010) and correspond to only 3,3% of total CH_4 emissions.

Data for CH_4 emissions of EX sector (from coal mining activities) is retrieved from Turkstat (2010a). In Turkey, CH_4 is emitted from coal mining activities, especially the lignite and hard coal mining from underground and surface mines (Turkstat, 2010a). Since in national energy consumption data (IEA,2008; Republic of Turkey- Ministry of Energy and Natural Resources, n.d.), EX sector consumes only electricity (no fossil fuel combustion emissions), the only considerable emission from the sector is taken as aforementioned CH_4 emissions.

As for IN sector, total sectoral emissions are retrieved from Ari (2010). Emissions which are produced from industrial processes are derived from Turkstat (2010a). Thereby, the remaining part of total sectoral emissions is considered as emissions from fossil fuel use.

Data for TR, TE and DO sector emissions are derived from Ari (2010).

The principal objective of this section is computing $ee_{ENV\text{-}g}$ for CO_2, N_2O and CH_4 emissions and total $EE_{ENV\text{-}g}$ load of Turkish sectors. Due to the scarcity of publicated data for detailed sectoral allocation of other emission gases (such as SO_2 or HF), their treatment technologies and corresponding $ee_{ENV\text{-}g}$ values are not incorporated in the analysis.

5.4.3.1 Environmental remediation cost ($EE_{ENV\text{-}g}$) of CO_2

CO_2 capture and treatment receive noticeable attention as a "high potential greenhouse gas" mitigation option. In this section of CO_2 capturing, a lime ($CaCO_3$) based technology is adopted and a generalized modelling tool of the technology is analyzed to estimate "environmental remediation cost of CO_2" which is the amount of irrevocable resource consumption (in terms of exergy) of CO_2 environmental remediation (treatment) system. This is a new and promising technology that may help in mitigation of global warming and climate change caused by CO_2 emissions (Rubin et al., 2007; Manovic and Anthony; 2010). It is shown by some of the economic analysis for CO_2 treatment systems (Abanades et al., 2004; Abanades et al., 2007; Mac Kenzie et al., 2007) that i) Ca-based CO_2 capture systems are economically attractive, ii) system is advantageous since CaO is relatively inexpensive and abundant.

The schematic representation of the Ca-based CO_2 capture system via CaO-carbonation reaction (CO_2 environmental remediation system) is shown in Figure 5.6. The system is designed based on the system available in Romeo et al. (2010). During the carbonation step, particles of CaO are transformed to $CaCO_3$. CaO acts as a CO_2 absorbent, capturing CO_2 to form $CaCO_3$ (Alonsol et al., 2011). The composed $CaCO_3$ is landfilled in the present system. The mass balance presented in Figure 5.6 is for annual 1 kg CO_2 processing.

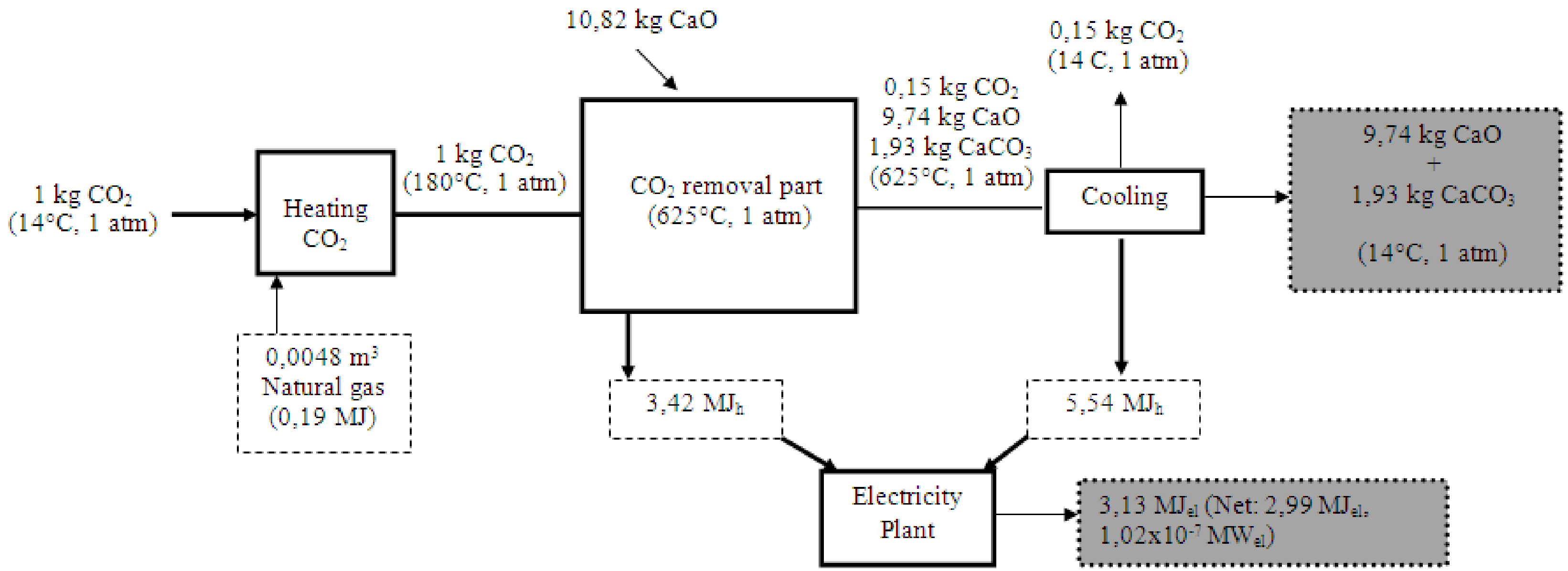

Figure 5.6 : Schematic overview of CO_2 environmental remediation system.

The amount of CaO which is fed to the system is computed based on mass balance data presented in Alonsol et al. (2011). The environmental remediation system is assumed to work 340 days a year/24 hours a day. The carbonation reaction can remove carbon dioxide at elevated temperatures (~600–750 °C) (Hughes et al., 2005) and atmospheric pressure (Shimizu et al., 1999; Abanades et al., 2003; Anthony and Wang, 2003) . The carbonization reaction is:

$$CaO\,(s) + CO_2\,(g) \longrightarrow CaCO_3\,(s) \qquad \Delta H = -177 \text{ KJ/mole} \qquad \textbf{(5.21)}$$

System CO_2 capture efficiency is 85%. 15% of input CO_2 is brought to input conditions (14°C, 1 atm) and will be an input again to CO_2 treatment system. 15% of "input CO_2"will be always released as "untreated CO_2 (non-converted into $CaCO_3$)" from the system but this CO_2 will be negligible after recursive processing. Because presented results are expressed in terms of exergetic cost for "unit treated CO_2", expanding the exergetic cost to total CO_2 emission gives the cost of CO_2 treatment including recursively processed "untreated CO_2".

Since heat content of the gas is recovered in Section 5.4.5, entering CO_2 to the system is at annual average temperature of Turkey (14°C, from Demir et al. (2008)) and atmospheric pressure. CO_2 is heated to 180°C and then underwent carbonization reaction in "CO_2 removal part" (Figure 5.6). Heating of CO_2 is done by a natural gas fuelled heater and natural gas consumption is seen in Figure 5.6 (details are seen in Appendix H). Carbonization reaction occurs at 625°C (which is assumed to be steady through the reactor (Romeo et al., 2010) and reaction product ($CaCO_3$), excessive CaO and untreated CO_2 leave the "CO_2 removal part" at this temperature. Heat release from carbonization reaction and cooling of $CaCO_3$, CaO and CO_2 are utilized in electricity generation (Figure 5.6). In other words, system has three types of products (P_t) as: electricity, CaO and $CaCO_3$. In Appendix H, details and data of individual systems and processes consisting the CO_2 environmental remediation system, which is illustrated in Figure 5.6, are presented.

As stated above, "environmental remediation system" concept in EEA proposes "zero exergy" discharge to the environment. The CO_2 treatment system considered in this thesis produces CaO and $CaCO_3$ which are taken out of the system as system products (Figure 5.6). It must be noticed that, CaO and $CaCO_3$ are also commercial commodities and can be reused in some of industrial processes such as in cement industry, glass industry, etc. That is why, they are considered under "system products". A more detailed analysis is always possible including the reuse of these products.

Summarizing tables for EEA analysis of CO_2 environmental remediation system which report the results of the material, energy carrier, capital and labour inflows to the system, are seen between Table 5.107 and Table 5.113., below.

As for calculation of material influxes, since no sufficiently reliable data were available on the exact material composition of the used items in the system, an analytical analysis was impossible. Hence, as done in previous chapters, the corresponding portion of $EE_{ENV\text{-}g}$ is computed by converting the known monetary cost of the process into exergetic equivalent by means of ee_C and seen in Table 5.108. Capital of electricity plant is derived from EIA (2010).

Exergy of material transfers ($E_{M\text{-}t}$) into the system is the sum of Table 5.107 and Table 5.108 which is 34,91 MJ. Exergy of CaO is derived from Szargut et al. (1988).

Table 5.107 : Exergy of CaO.

	Amount (kg)	Exergy (MJ/kg)	Total exergy (MJ)
CaO	10,82	1,9681	21,29

Table 5.108 : Material exergy ($E_{M\text{-}t}$) of natural gas fuelled heater and electricity plant.

System/Process	Capital	System Power (KW)	Equivalent exergy (MJ)
Natural gas heater	5 $/KW	$6,39 \times 10^{-6}$	$8,15 \times 10^{-4}$
Electricity plant	5000$/KW$_{el}$	$1,07 \times 10^{-4}$	13,62
Total			13,62

The exergy inflow via energy carriers ($E_{PHYS\text{-}t}$) is natural gas consumption for heating of CO_2. Detailed explanation for computing of consumed natural gas amount is presented in Appendix H. The results are reported in Table 5.109 with corresponding exergy of natural gas. (In this thesis, energy necessary to run the "CO_2 removal part" (calcination reaction reactor) is neglected.)

Table 5.109 : Physical exergy ($E_{PHYS\text{-}t}$) inflow of the environmental remediation system.

	Amount (m^3)	Exergy (MJ)
Natural gas	0,0048	0,17

As for capital flows, the same calculation route applied in Section 5.4.2 is applied and results are seen in Table 5.110 and 5.111. Since consumed CaO and natural gas cost are accounted in OP cost, they are not annualized in Table 5.110. Natural gas price is derived from BOTAS Petroleum Pipeline Corporation (n.d.).

Table 5.110 : Exergetic equivalent of CaO and natural gas capital.

	Amount	Capital	Exergetic equivalent of capital (MJ)
CaO	10,82 kg	0,063 \$/kg	17,37
Natural gas	0,0048 m^3	0,335 \$/m^3	0,042
Total			17,41

Table 5.111 : Exergetic equivalent of CO_2 heating process and electricity plant.

	Capital	System Power (KW)	Exergetic equivalent of IC (MJ)	Exergetic equivalent of AC (MJ)	Exergetic equivalent of OP (MJ)	AC+OP (MJ)
Heater	5 \$/KW	6,39 $x10^{-6}$	8,15 $x10^{-4}$	1,94 $x10^{-4}$	1,63 $x10^{-4}$	3,57 $x10^{-4}$
Electricity plant	5000\$/KW_{el}	1,07 $x10^{-4}$	13,62	3,25	2,72	5,97
Total						5,97

In conclusion, sum of capital fluxes is the sum of Table 5.110 and Table 5.110 which amounts to 23,38 MJ.

Labour consumption is computed based on the assumption that labour of a CHP system is 200 workers per 1000 MW_{h+el} generated energy, based on data (Bezdek and Wendling, 2008). Considering the whole system, number of workers is assumed to be 250 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker.

Generated electricity from the system is presented in Appendix H as 3,14 MJ. Corresponding power production is calculated via adopting equation (5.18) and obtained as 1,07x 10^{-7} MW_{el}. Labour consumption of the system is calculated via applying equation (5.19) and resulting labour consumption and its exergetic equivalent are computed as 4,81 x 10^{-5} workhours and 0,0074 MJ for 1 kg of CO_2 entering into the system. Labour consumption and exergetic equivalent of labour for the system are seen in Table 5.112 and details are available in Appendix H.

Table 5.112 : Labour consumption and its exergetic equivalent (EE_{L-t}).

	Labour (workhours)	Exergetic equivalent of labour (MJ)
Total system	4,81$x10^{-5}$	0,0074

Environmental impact of CO_2 environmental remediation system is originated from heating with natural gas and system CO_2 loss (untreated CO_2). Emissions are presented in Table 5.113. Details of emission computing are shown in Appendix H.

Table 5.113 : Emissions from the system.

	CO_2 (kg)	N_2O (kg)	CH_4 (kg)
Natural Gas	9,59 x10^{-3}	1,71 x10^{-8}	1,71 x10^{-7}
Untreated CO_2	0,15		
Total Emission	0,16	1,71 x10^{-8}	1,71 x10^{-7}

The products of the system are the produced electricity from the heat released by exothermic carbonization reaction in the "CO_2 removal part" and cooling of CO_2, CaO and $CaCO_3$ in "cooling part" of the system (see Figure 5.6). Other products are CaO and $CaCO_3$ left the system at 14°C and 1 atm.

Details of calculation for heat utilized in energy production are available in Appendix H. Released heat, efficiency and produced electricity are seen in Table 5.114. Electricity generation plant is assumed to consume 4,5% of generated electricity and the consumption is also presented in Table 5.114.

Table 5.114 : Net electricity production of the system.

Heat from carbonization reaction (MJ)	3,419
Heat from CaO cooling (MJ)	4,463
Heat from $CaCO_3$ cooling (MJ)	0,986
Heat from CO_2 cooling (MJ)	0,096
Total released heat (MJ)	8,964
Efficiency	0,35
Produced electricity (MJ)	3,137
Energy consumption (MJ)	0,141
Produced net electricity (MJ)	2,996

Environmental remediation system products and their exergetic content are seen in Table 5.115. In Table5.115, electricity is the net system production obtained in Table 5.114 and exergy data is from Szargut et al. (1988).

Table 5.115 : Products of the CO_2 environmental remediation system.

	Amount (kg)	Exergy (MJ)
Electricity		2,99
CaO	9,74	19,17
$CaCO_3$	1,93	0,019
Total (E_{p-t})		22,17

Constituent terms of equation (5.16) (exept EE_{ENV-t}) for CO_2 environmental remediation system are reported in Table 5.116.

Table 5.116 : Input fluxes (except EE_{ENV-t}) to the CO_2 environmental remediation system.

	Exergetic equivalent (MJ)
E_{M-t}	34,91
E_{PHYS-t}	0,17
EE_{L-t}	0,0074
EE_{C-t}	23,38
E_{P-t}	22,17

5.4.3.2 Environmental remediation cost (EE_{ENV-g}) of N_2O

In Figure 5.7, virtual environmental remediation system for N_2O treatment is presented (for 1 kg N_2O). Thermal decomposition of N_2O (decomposition without presence of catalyst) occurs at the temperature of T>850°C (Galle et al., 2001). As seen in Figure 5.7, "N_2O decomposition part" is assumed to be at the temperature of 900°C. Decomposition products (N_2 and O_2) have the same temperature and cooled down to 14°C (annual average environment temperature of Turkey). In this thesis, used fuel to run the "N_2O decomposition part" is neglected.

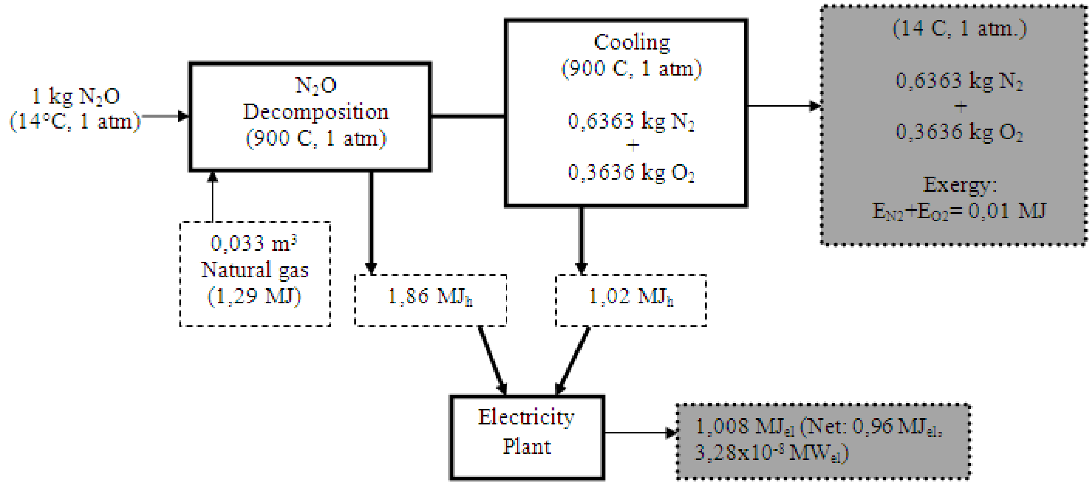

Figure 5.7 : Schematic overview of N_2O environmental remediation system.

The equation of the exothermic decomposition reaction is presented in equation (5.22) (Munke, 2007; Zakirov and Zhang, 2008).

$$N_2O \rightarrow N_2 + 1/2\,O_2 \qquad \Delta H = -82 \text{ KJ/mole} \tag{5.22}$$

N_2O is heated up to 900°C by a natural gas fuelled heater. Natural gas consumption is seen in Figure 5.7 and detailed calculation can be seen in Appendix H. Heat release from decomposition reaction and cooling of N_2 and O_2 are utilized in electricity generation (Figure 5.7). In other words, system has three types of products (P_t) as: electricity, N_2 and O_2. In Appendix H, details and data of individual systems and processes consisting the total environmental treatment system, which is illustrated in Figure 5.7, are presented. Properties of system products are summarized in Figure 5.7. The whole system is assumed to work 340 days a year/24 hours a day. Summarizing tables for EEA analysis of N_2O environmental remediation system which report the results of the material, energy carrier, capital and labour inflows to the system, are seen between Table 5.117 and Table 5.122, below.

As done in the previous chapters, material influxes are computed by converting the known monetary cost of the process into exergetic equivalent by means of ee_C and seen in Table 5.117.

Table 5.117 : Material exergy ($E_{M\text{-}t}$) inputs of the environmental remediation system.

System/Process	Capital	System Power (KW)	Equivalent exergy (MJ)
Natural gas heater	5 \$/KW	4,38 x10^{-5}	5,59 x10^{-3}
Electricity plant	5000\$/KW_{el}	3,43 x10^{-5}	4,38
Total			4,38

The exergy inflow of energy carriers ($E_{PHYS\text{-}t}$) is the natural gas consumption for heating of N_2O and presented in Table 5.118 with corresponding exergy. Detailed explanation for computing of consumed natural gas is presented in Appendix H.

Table 5.118 : Physical exergy ($E_{PHYS\text{-}t}$) inflow of the environmental remediation system.

	Amount (m^3)	Exergy (MJ)
Natural gas	0,033	1,18

As for capital flows, the same calculation route applied in Section 5.4.2.1 is applied and results are seen in Table 5.119 and Table 5.120. Since consumed natural gas cost is accounted in OP cost, they are not annualized in Table 5.119.

Table 5.119 : Exergetic equivalent of natural gas capital.

	Amount ($m^{3)}$	Capital (\$/m^3)	Exergetic equivalent of capital (MJ)
Natural gas	0,033	0,335	0,28

Table 5.120 : Exergetic equivalent of N_2O heating process and electricity plant.

System/Process	Capital	System Power (KW)	Exergetic equivalent of IC (MJ)	Exergetic equivalent of AC (MJ)	Exergetic equivalent of OP (MJ)	AC+OP (MJ)
Natural gas heater	5 \$/KW	4,38 x10^{-5}	5,59 x10^{-3}	1,33 x10^{-3}	1,12 x10^{-3}	2,45 x10^{-3}
Electricity plant	5000\$/KW_{el}	3,43 x10^{-5}	4,38	1,04	0,88	1,92
Total						1,92

In conclusion, sum of capital fluxes is the sum of Table 5.119 and Table 5.120 which amounts to 2,21 MJ.

In the matter of the labour consumption of the system, it is assumed that number of workers is 250 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker (Based on data presented by Bezdek and Wendling (2008)). Generated electricity from the system is presented in Appendix H as 1,01 MJ. Corresponding power production is calculated via adopting equation (5.18) and obtained as 3,43 x 10^{-8} MW_{el}. Labour consumption of the system is calculated via applying equation (5.19). Labour consumption and exergetic equivalent of labour for the system are seen in Table 5.121.

Table 5.121 : Labour consumption and its exergetic equivalent (EE_{L-t}).

	Labour (workhours)	Exergetic equivalent of labour (MJ)
Total system	1,55 x10^{-5}	2,38 x10^{-3}

The source of environmental impact of the remediation system is natural gas consumed in heating of N_2O. Emissions are presented in Table 5.122. Emission factors are presented in Appendix H.

Table 5.122 : Emissions from the system.

	CO_2 (kg)	N_2O (kg)	CH_4 (kg)
Natural Gas combustion	6,57 x10^{-2}	1,17 x10^{-7}	1,17 x10^{-6}

The products of the system are the produced electricity from the heat released by exothermic decomposition reaction and cooling of N_2 and O_2 (see Figure 5.7). Other products are N_2 and O_2 left the system at 14°C and 1 atm. Details of calculation for heat utilized in energy production are available in Appendix H. Released heat, efficiency and produced electricity are seen in Table 5.123. Electricity generation plant is assumed to consume 4,5% of generated electricity and the consumption is also presented in Table 5.123.

Table 5.123 : Net electricity production of the system.

Heat from decomposition reaction (MJ)	1,86
Heat from N_2 cooling (MJ)	0,69
Heat from O_2 cooling (MJ)	0,33
Total released heat (MJ)	2,88
Efficiency	0,35
Produced electricity (MJ)	1,01
Energy consumption (MJ)	0,05
Produced net electricity (MJ)	0,963

Environmental remediation system products and their exergetic content are seen in Table 5.124. In Table 5.124, electricity is the net system production obtained in Table 5.123. Exergy calculation for N_2 and O_2 are presented in Appendix H.

Table 5.124 : Products of the N_2O environmental remediation system.

	Exergy (MJ)
Electricity	0,963
Exergy of N_2+O_2	0,007
Total ($E_{P\text{-}t}$)	0,97

Constituent terms of equation (5.16) (except $EE_{ENV\text{-}t}$) for N_2O environmental remediation system are reported in Table 5.125.

Table 5.125 : Input fluxes (except $EE_{ENV\text{-}t}$) to the N_2O environmental remediation system.

	Exergetic equivalent (MJ)
$E_{M\text{-}t}$	4,38
$E_{PHYS\text{-}t}$	1,18
$EE_{L\text{-}t}$	0,0024
$EE_{C\text{-}t}$	2,21
$E_{P\text{-}t}$	0,97

5.4.3.3 Environmental remediation cost ($EE_{ENV\text{-}g}$) of CH_4

Virtual environmental remediation system of CH_4 emission is presented in Figure 5.8 (for 1 kg CH_4). Considering that CH_4 is the effluent transferred to environmental remediation system, it is the E_W (seen in Figure 5.1) flow into the system. Since CH_4 is also a fuel and can be used for energy generation, environmental remediation system includes a CHP (combined heat and power) which has 48% and 40% efficiency of heat and electricity generation, respectively (LHV of methane is 50,49

MJ/kg). Generated electricity and heat from the system is presented in Figure 5.8 as 20,2 MJ and 24,23 MJ, respectively (calculation is presented further). Corresponding power production (both for electricity and heat) is calculated via adopting equation (5.18) and obtained as 6,57 x 10^{-7} MW_{el} and 8,25 x 10^{-7} MW_h.

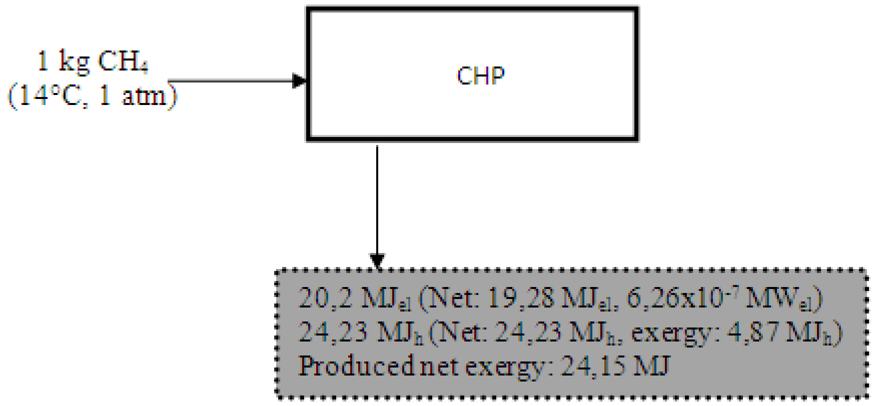

Figure 5.8: Schematic overview of CH_4 environmental remediation system.

As done in previous sections, material flow is computed via converting the known monetary cost of the process into exergetic equivalent by means of ee_C. Capital of the plant is taken as 7000 €/KW_{el} (based on EIA (2010)) and computed material exergy (exergetic equivalent of cogeneration plant capital) is presented in Table 5.126.

Table 5.126: Material exergy ($E_{M\text{-}t}$) input of the environmental remediation system.

System/Process	Capital	System Power (KW_{el})	Equivalent exergy (MJ)
Energy generation plant	7000\$/KW_{el}	6,57x10^{-4}	117,20

Since CH_4 is the only fuel utilized in the system, there are not any other type of physical exergy ($E_{PHYS\text{-}t}$) inputs into the system.

As for capital flows, details of CHP system are seen in Table 5.127.

Table 5.127 : Exergetic equivalent of CHP capital.

System/Process	Capital	System Power (KW_{el})	Exergetic equivalent of IC (MJ)	Exergetic equivalent of AC (MJ)	Exergetic equivalent of OP (MJ)	AC+OP (MJ)
Electricity plant	7000\$/KW_{el}	6,57 x10^{-4}	117,20	27,95	23,44	51,39

In the matter of the labour consumption of the system, it is assumed that number of workers is 200 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker (Based on data presented by Bezdek and Wendling (2008)). Labour consumption of the system is calculated via applying equation (5.19). Resulting labour consumption and exergetic equivalent of labour for the system are seen in Table 5.128.

Table 5.128 : Labour consumption and its exergetic equivalent (EE_{L-t}).

	Labour (workhours)	Exergetic equivalent of labour (MJ)
Total system	$5,33 \times 10^{-4}$	0,08

Environmental remediation cost (EE_{ENV-t}) of the system is originated from CH_4 combustion in CHP plant. Emission factors are presented in Appendix H. Emissions of 1 kg CH_4 processing system are presented in Table 5.129 (LHV of methane is taken as 50,49 MJ/kg).

Table 5.129 : Emissions from the system.

	CO_2 (kg)	N_2O (kg)	CH_4 (kg)
CH_4 combustion	2,83	$5,05 \times 10^{-6}$	$5,05 \times 10^{-5}$

The products of the system are the produced electricity and heat (Table 5.130). CHP is assumed to consume 4,5% of generated electricity and the consumption is presented in Table 5.130. Details are available in Appendix H.

Table 5.130 : Energy production of the system.

CH_4 energy content (MJ/kg) (LHV)	50,49
Electricity production efficiency	0,4
Heat production efficiency	0,48
Produced electricity (MJ_{el})	20,20
Produced heat (MJ_h)	24,23
Energy consumption (MJ_{el})	0,92
Produced net electricity (MJ_{el})	19,28
Produced net heat (MJ_h)	24,23

Environmental remediation system products and their exergetic contents are seen in Table 5.131. In Table 5.131, it is assumed that produced heat is at the average temperature of 100°C.

Table 5.131 : Products of the CH_4 treatment system.

	Energy (MJ)	Exergy (MJ)
Electricity	19,28	19,28
Heat	24,23	4,87
Total (E_{P-t})		24,16

Constituent terms of equation (5.16) (exept EE_{ENV-t}) for CH_4 environmental remediation system are reported in Table 5.132.

Table 5.132 : Input fluxes (except EE_{ENV-t}) to the CH_4 environmental remediation system.

	Exergetic equivalent (MJ)
E_{M-t}	117,20
E_{PHYS-t}	0
EE_{L-t}	0,08
EE_{C-t}	51,39
E_{P-t}	24,16

5.4.3.4 Environmental remediation cost of greenhouse gases

In sections 5.4.3.1, 5.4.3.2 and 5.4.3.3, E_{M-t}, E_{PHYS-t}, EE_{L-t}, EE_{C-t} of greenhouse gas treatment systems are presented which are constituents of equation (5.16). The only unknown is EE_{ENV-t} for each type of gas remediation system. As it is seen in Table 5.113, Table 5.122 and Table 5.129, each greenhouse gas treatment system emits also greenhouse gases. To obtain ee_{ENV-g} for each type of gases, equation (5.16) must be solved simultaneously for three types of unknown (ee_{ENV-g} of three types of gases).

$$EE_{ENV-g} = ee_{ENV-g} \text{ x} \left[\text{Treated amount of gas in the system}\right] \tag{5.23}$$

Combining equation (5.16) with equation (5.23), built mathematical formulations for each type of environmental remediation systems are seen in equations (5.24), (5.25) and (5.26), below.

For CO_2 environmental remediation system:

$$A + DX_3 + GX_2 = PX_1 \tag{5.24}$$

For N_2O environmental remediation system:

$$B + EX_3 + HX_1 = TX_2 \tag{5.25}$$

For CH_4 environmental remediation system:

$$C + FX_1 + MX_2 = KX_3 \tag{5.26}$$

where X_1, X_2 and X_3 (MJ/kg) are ee_{ENV-g} for CO_2, N_2O and CH_4, respectively.

A, B and C (MJ) are:

$$E_{M\text{-}t} + E_{PHYS\text{-}t} + EE_{L\text{-}t} + EE_{C\text{-}t} - E_{P\text{-}t} \quad \textbf{(5.27)}$$

for CO_2, N_2O and CH_4 environmental remediation systems, respectively.

D and E (kg) are CH_4 emission of CO_2 and N_2O environmental remediation systems, respectively. G and M (kg) are N_2O emission of CO_2 and CH_4 environmental remediation systems, respectively. H and F (kg) are CO_2 emission of N_2O and CH_4 environmental remediation systems, respectively.

P (kg) is CO_2 treated in CO_2 environmental remediation system. T (kg) is N_2O treated in N_2O environmental remediation system. K (kg) is CH_4 treated in CH_4 environmental remediation system. P, T and K are computed via equation (5.28), below.

$$[\text{Treated amount of gas in the system}] = [\text{Amount of gas entering into the system}] - [\text{System gas emission}] \quad \textbf{(5.28)}$$

Aforementioned physical quantities for environmental remediation systems and resulting $ee_{ENV\text{-}g}$ values are seen in Table 5.133.

Table 5.133 : $ee_{ENV\text{-}g}$ (X_1, X_2 and X_3) for CO_2, N_2O and CH_4.

A (MJ)	36,29
B (MJ)	6,81
C (MJ)	144,52
D (kg)	$1{,}71\text{x}10^{-7}$
E (kg)	$1{,}17\ \text{x}10^{-6}$
G (kg)	$1{,}71\ \text{x}10^{-8}$
M (kg)	$5{,}05\ \text{x}10^{-6}$
H (kg)	$6{,}57\ \text{x}10^{-2}$
F (kg)	2,83
P (kg)	0,84
T (kg)	$9{,}9999988\ \text{x}10^{-1}$
K (kg)	$9{,}9994951\ \text{x}10^{-1}$
$ee_{ENV\text{-}g}$ for CO_2 (TJ/Ton)	0,043
$ee_{ENV\text{-}g}$ for N_2O (TJ/Ton)	0,01
$ee_{ENV\text{-}g}$ for CH_4 (TJ/Ton)	0,267

5.4.3.5 Sectoral gas emissions and equivalent $EE_{ENV\text{-}g}$

In Table 5.106, considered gas emissions of the sectors are presented. In Table 5.134 below, sectoral gas emissions and corresponding $EE_{ENV\text{-}g}$ are reported.

Table 5.134 : EE_{ENV-g} of the sectors.

	EX Sector	CO Sector	AG Sector	IN Sector	TR Sector	TE Sector	DO Sector
CO_2 (Ton)		94783155	-66036256	93599845	43738000	9087782	32489218
N_2O (Ton)		845	1004	10615	1710	256	914
CH_4 (Ton)	76990	1624	772524	9626	5930	1435730	16910
EE_{ENV-g} CO_2 (TJ)		4075675,67	-2839559,02	4024793,34	1880734	390774,63	1397036,37
EE_{ENV-g} N_2O (TJ)		8,45	10,04	106,15	17,10	2,56	9,14
EE_{ENV-g} CH_4 (TJ)	20556,33	433,62	206264,02	2570,13	1583,31	383339,91	4514,97
Sectoral EE_{ENV-g} (TJ)	20556,33	4076117,73	-2633284,96	4027469,62	1882334,41	774117,10	1401560,48

5.4.4 Environmental remediation cost of liquid waste ($EE_{ENV\text{-}lq}$)

This section focuses on determining the environmental remediation cost of wastewater ($EE_{ENV\text{-}lq}$) emitted from the sectors. In spite of high energy consumption of wastewater treatment plants, they are essential in community service. It is also expected to see a rising line in energy consumption of waste water treatment processes due to population growth, increasingly restrictive environmental regulations, and demand for wastewater reuse (due to the degradation of clean water sources of the world) (European Commission, 2001a). Municipal wastewater treatment plants generate sludge as a by-product of the physical, chemical and biological processes. Many reasons such as: rapidly shrinking landfill space, increased environmental awareness and more stringent environmental standards on sludge disposal management make governing the disposal of sludge a worldwide problem (Xu and Lancaster, 2009). In wastewater treatment, the goal is twofold: to remove the pollutants from wastewater and to reduce the amount of sludge that needs to be disposed (Xu and Lancaster, 2009). In general, sludge must be subject to a treatment (remediation) process in order to change its characteristic. This treatment has many objectives such as: reduction of excess volume by eliminating the liquid portion of the sludge, decomposition of highly putrescible organic matter into relatively stable or inert organic and inorganic compounds, etc. A typical wastewater treatment plant consists of a set of processes including primary treatment, secondary treatment, tertiary treatment and sludge processing. In primary treatment, physical barriers remove larger solids from the wastewater. Secondary treatment covers biological processes that promote biodegradation by microorganisms. Some of secondary treatment methods: aerobic and anaerobic stabilization ponds, trickling filters and activated sludge process (European Commission, 2001b; Eggleston et al.,2006c). The activated sludge process is by far the most frequently used biological treatment (secondary treatment) process (Kim et al., 2002; M/J Industrial Solutions, 2003). Tertiary treatment is further treatment of wastewater and disinfection is one of the techniques of tertiary treatment (Eggleston et al., 2006c). Sludge is produced in all of the primary, secondary and tertiary treatment processes and this sludge must be processed before it is safely disposed of. Anaerobic digestion (AD) is a sludge stabilization method which furnishes a considerable power supply and as a result, the overall cost of sewage treatment is reduced (Qasim, 1999). Among widely used sludge stabilization techniques, anaerobic digestion is unique since it enables to produce energy gain by biogas utilization, providing cost effectiveness and minimizing the mass and volume of disposed final sludge (Tchobanoglous et al., 2002). As stated in Section 5.4.1, in AD process, after breaking down a large fraction of the organic matter (biodegradable part) into carbon dioxide (CO_2) and methane (CH_4), the remaining part (digestate) is dried and becomes a residual soil-like material. This material partially replaces the use of conventional fertilizer, since it contains compounds of agricultural value: it is rich in nitrates and performs well as a fertilizer. It contains also organic matter but it is under the level of having a significant positive impact on soil physical properties (European Commission, 2001b). This fertilizer like material (named “fertilizer” in this thesis) is another product of the wastewater remediation system. For these reasons, anaerobic sludge digestion is mostly preferred to reduce the cost of wastewater remediation and considered as a major and essential part of modern wastewater treatment plants (Appels et al., 2008).

In this section, anaerobic digestion of sludge which is produced through the wastewater treatment processes, and energy generation via biogas utilization are overviewed within the content of wastewater treatment. Due to the wide variety of wastewater composition emitted from refineries, different sub-industries, energy generation plants etc., wastewater treatment takes a particularly designed system for each type of sub-industry and also of type of processes encompassed in the sub-industries. Since the scope and volume of this thesis is limited and also analysis of wastewater composition for all sub-industries, refineries, coke factories and agricultural activities etc. are not available for Turkey, properly designing and detailed examination of wastewater remediation systems (which can bring the untreated wastewater of the sectors to the legal water discharge limits) were impossible. As an alternative, a virtual remediation system for municipal wastewater is analyzed under several assumptions. Specific wastewater environmental remediation cost ($ee_{ENV\text{-}lq}$, TJ/m^3) is calculated for municipal wastewater and the other sectors are assumed to have the same specific wastewater environmental remediation cost.

5.4.4.1 DO sector liquid waste and treatment system

The schematic representation of liquid waste treatment system undertaken in this section is presented in Figure 5.9. The system proposal and data of system flows are derived from a real application presented in Qasim (1999). The main steps of the processes can be listed as:

1. Wastewater collection
2. Wastewater treatment & sludge generation
    2.1. Preliminary and primary treatment
    2.2. Secondary treatment
    2.3. Tertiary treatment
3. Sludge processing
    3.1. Sludge blending
    3.2. Sludge thickening
    3.3. Sludge stabilization (AD) and biogas upgrading
    3.4. Biogas utilization (biorefinery)
    3.5. Digestate drying (fertilizer production)

In the system, tertiary treatment stage is disinfection process and does not produce sludge. Sludge production occurs only in primary and secondary treatment processes.

The characteristic of the raw wastewater (flow “1” in Figure 5.9) and the effluent of the system (treated wastewaster, flow “2” in Figure 5.9) and legal limits for “discharged wastewater to environment” in Turkish standards (Republic of Turkey-Ministry of Environment and Forestry, n.d.) are presented in Table 5.135. As it is seen in the table, the achieved characteristic of the system effluent is within the legal limits.

Table 5.135 : Properties of raw and treated wastewater and legal standards.

	Raw waste water (mg/L)	Legal maximum limit in treated wastewater (after 2 hours) (mg/L)	Treated water (mg/L)
Biochemical oxygen demand (BOI_5)	250	45	10
Chemical oxygen demand (COD)		100	
Total suspended solids (TSS)	260	60	10
Total phosphorus (TP)	6	3	1
Total nitrogen (TN)	36	20	10

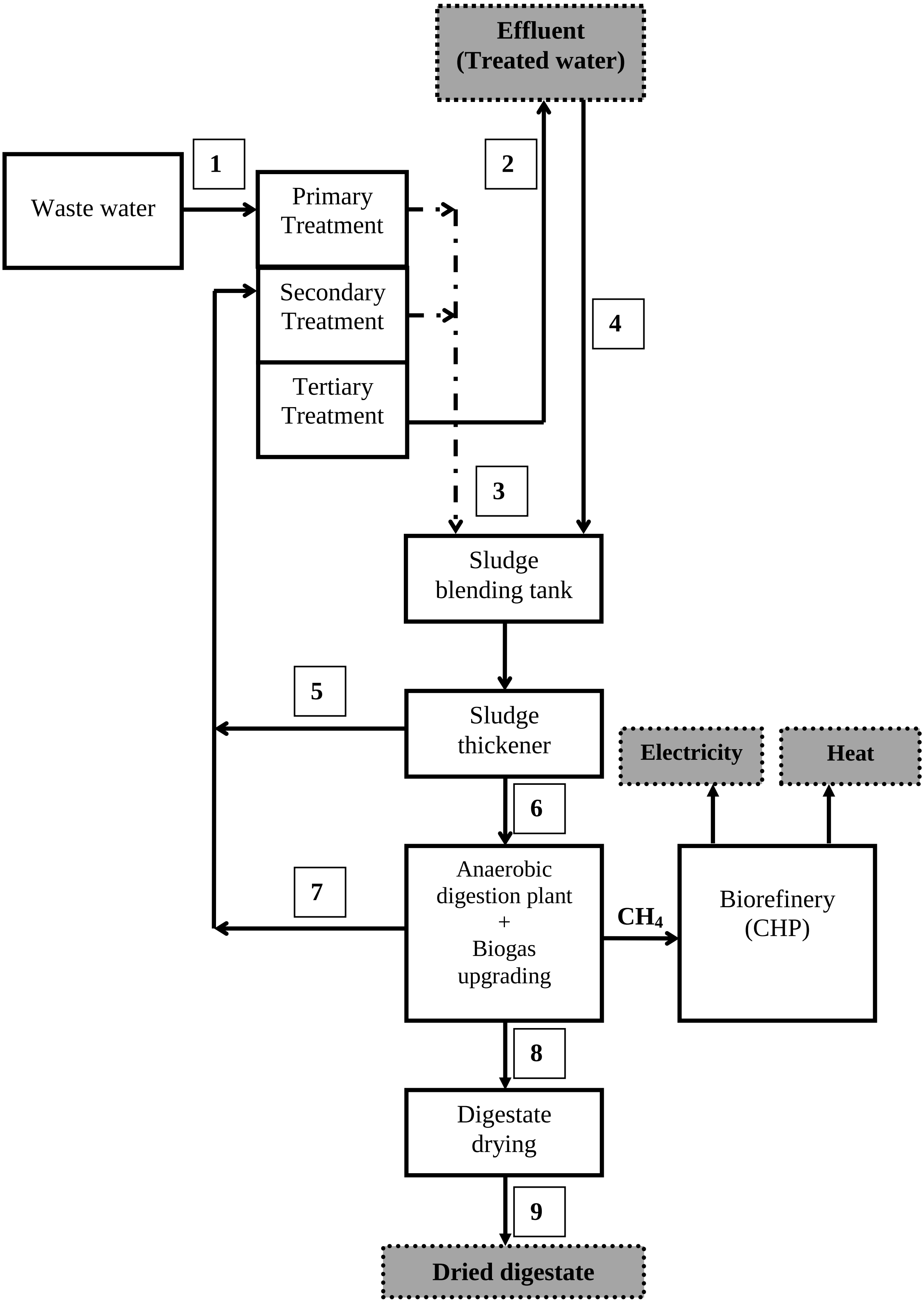

Figure 5.9 : Schematic representation of wastewater environmental remediation system.

In Table 5.136, Turkish DO sector wastewater generation, treated and untreated amounts are seen which are estimated based on national data of Turkey (Turkstat, n.d.).

Table 5.136 : DO sector wastewater generation.

Wastewater generated by population who are not served by sewerage system (m^3)	1810334337
Collected & untreated wastewater (m^3)	717086714
Collected & treated wastewater (m^3)	1326883145

The produced sludge through the process of wastewater treatment is mostly landfilled in Turkey (Salihoglu et al., 2007). For wastewater generated by the population who are not served by sewerage system or collected but untreated wastewater (both of them are discharged directly to the environment), treatment procedure (in Figure 5.9) is totally applied and corresponding environmental remediation cost is devoted as "$EE_{ENV\text{-}lq,w}$". For treated wastewater, the only treatment system effluent is the sludge. As a result, only the sludge processing process is applied (Step 3 on page 134) and corresponding environmental cost is devoted as "$EE_{ENV\text{-}lq,sl}$". $EE_{ENV\text{-}lq}$ for DO sector wastewater is the sum of $EE_{ENV\text{-}lq,w}$ and $EE_{ENV\text{-}lq,sl}$.

5.4.4.2 Untreated wastewater

As presented in Table 5.136, the amount of untreated wastewater is the sum of wastewater generated by population who are not served by sewerage system and collected but untreated wastewater in sewage system. The sum is 2527421051 m^3.

In Appendix I, details and data of processes which consist the wastewater environmental remediation system (illustrated in Figure 5.9) are presented.

As done in previous sections, for material influxes, since no sufficiently reliable data were available on the exact material composition of the used items in the system, an analytical analysis was impossible. The corresponding portion of $EE_{ENV\text{-}lq,w}$ is computed by converting the known monetary cost of the process into exergetic equivalent by means of ee_C. Details of calculations are available in Appendix I, results are seen in Table 5.137. In Table 5.137, material exergy (conversion of monetary value into exergy) of primary, secondary and tertiary treatment processes are not included due to huge monetary costs of treatment plants. For this kind of extreme monetary cases, the assumption brings the environmental remediation cost results to utopian exergetic values. To abstain from this, cost of wastewater treatment plants (primary, secondary and tertiary) are excluded from the computation of $EE_{ENV\text{-}lq}$. In Table 5.137, tDM refers to “ton dry matter of sludge”.

Table 5.137 : Material exergy ($E_{M\text{-}t}$) received by the system.

System/Process	Capital	Equivalent exergy (TJ)
Collection network	100 $/m	139754,47
Sludge thickener	31 $/tDM	356,96
Anaerobic digestion plant	65 $/tDM	748,46
Upgrading of biogas	0,26 €/m^3	1647,31
Biorefinery	7000 $/$KW_{el}$	11090,12
Post processing of digestate	215 $/tDM	1931,04
CaO		85,42
$FeCl_3$		20,83
Total		155634,61

Energy balance of the system is presented later in Table 5.143. As seen in the table, due to high energy consumption in wastewater collection, the produced electricity by the system can not provide sufficient energy surplus to compensate for all system energy requirement. Hence, electricity is extracted from regional electricity network and this energy is the $E_{PHYS\text{-}t}$ of the wastewater environmental remediation system as presented in Table 5.138.

Table 5.138 : Physical exergy ($E_{PHYS\text{-}t}$) received by the system.

Electricity input to the system (TJ)	1944,06
Exergy of the electricity ($E_{PHYS\text{-}t}$) (TJ)	1944,06

As for capital flows, capital investment of the system (Investment cost, IC) is assumed to be supplied by bank credit and the same calculation route which is presented in Sections 5.4.2.1 is applied. Results are seen in Table 5.139. .

Table 5.139 : Exergetic equivalent of the capital ($E_{C\text{-}t}$) received by the system.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
Collection network	100 $/m	139754,47	33334,62	27950,89	61285,52
Sludge thickener	31 $/tDM	356,96	85,14	71,39	156,53
Anaerobic digestion plant	65 $/tDM	748,46	178,53	149,69	328,22
Upgrading of biogas	0,26 €/m^3	1647,31	392,92	329,46	722,38
Biorefinery	7000 $/$KW_{el}$	11090,12	2645,25	2218,02	4863,27
Post processing of digestate	215 $/tDM	1931,04	460,60	386,21	846,80
Electicity input to the system	0,081 $/ KWh_{el}			1119,95	1119,95
CaO	0,063 $/kg			70,66	70,66
$FeCl_3$	0,4 $/kg			148,12	148,12
Total					69541,46

Since capital of annual electricity input from regional electricity network and consumed CaO and $FeCl_3$ for digestate stabilization are considered under OP cost, they are not annualized as seen in Table 5.139. Details are presented in Appendix I.

As for labour consumption of the system, it is assumed that labour of the system is 200 workers per 1000 MW_{h+el} generated energy, based on data (Bezdek and Wendling, 2008). Considering the whole system, number of workers is assumed to be 400 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker. Generated electricity and heat is presented later in Table 5.143 as 1825,08 TJ_{el} and 2190,10 TJ_h. To compute the exergetic equivalent of labour, equations (5.18), (5.19) and (5.20) are adapted and the results are seen in equations (5.29), (5.30) and (5.31). Exergetic equivalent of labour is calculated via equations presented below.

$$\begin{aligned}\text{Generated power } (MW_{el+h}) &= \frac{\text{Generated energy } (MJ_{el+h})}{\text{Annual working time (s)}} = \\ &= \frac{(1825{,}08 + 2190{,}10) \times 10^6}{340 \times 24 \times 60 \times 60} = 136{,}68\end{aligned} \tag{5.29}$$

Hence, labour consumed in the system is:

$$\begin{gathered}\text{Labour load (workhours)} = \\ \left[\frac{400(\text{workers})}{1000(\text{MW})}\right] x \left[1800(\text{hours / year worker})\right] x \left[136{,}68(\text{MW})\right] = 98411\end{gathered} \tag{5.30}$$

The exergetic equivalent of the labour is computed by means of ee_L:

$$\begin{gathered}EE_{L\text{-}t} = \text{Labour load (workhours) x } ee_L \text{ (MJ / hours)} = \\ 98411{,}34 \text{ x } 153{,}95 = 15150651{,}7 MJ = 15{,}15 TJ\end{gathered} \tag{5.31}$$

Environmental remediation cost of the system is originated from greenhouse gas emissions from AD, biogas upgrading and biogas incineration (in biorefinery). Details of emissions are presented in Appendix I. Total CO_2, N_2O and CH_4 emissions of the system are seen in Table 5.140. The environmental remediation cost of emission gases are computed in Section 5.4.3 and inserted into Table 5.141 to obtain the $EE_{ENV\text{-}t}$ for the whole wastewater treatment system.

Table 5.140 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Anaerobic digestion	3622,58		2902,94
Upgrading of biogas	111664,06		1877,24
Biorefinery	255967,91	0,46	4,56
Total	371254,55	0,46	4784,74

Table 5.141 : Environmental remediation cost of emissions ($EE_{ENV\text{-}t}$).

CO_2 emissions (Ton)	371254,55
N_2O emission (Ton)	0,46
CH_4 emission (Ton)	4784,74
CO_2 $ee_{ENV\text{-}g}$ (TJ/Ton CO_2)	0,043
N_2O $ee_{ENV\text{-}g}$ (TJ/Ton N_2O)	0,010
CH_4 $ee_{ENV\text{-}g}$ (TJ/Ton CH_4)	0,267
CO_2 $EE_{ENV\text{-}g}$ (TJ)	16031,06
N_2O $EE_{ENV\text{-}g}$ (TJ)	0,0044
CH_4 $EE_{ENV\text{-}g}$ (TJ)	1276,76
Total $EE_{ENV\text{-}t}$ (TJ)	17307,83

The biorefinery is a CHP plant and the composition of biogas utilized in the biorefinery involved in the system is 98% CH_4 and 2% CO_2 (vol. %). The amount of the biogas utilized in biorefinery, the efficiencies of heat and electricity generation and produced energy are presented in Table 5.142. LHVof CO_2 is almost zero (De Hullu, et al.).

Table 5.142 : Properties of biogas utilization.

CH_4 (m^3)	135271504,03
CO_2 (m^3)	2760642,94
LHV of CH_4 (MJ/m^3)	33,73
LHV of CO_2 (MJ/m^3)	0
LHV of biogas (TJ)	4562,71
Electricity generation efficiency	0,4
Heat generation efficiency	0,48
Generated electricity (TJ)	1825,08
Generated heat (TJ)	2190,10

The products of the treatment system are heat produced by biorefinery as well as produced fertilizer. As explained above, electricity produced in the system is not enough to meet the system electricity requirement. As such, electricity surplus does not occur in the system as a system product. The energy balance of the environmental remediation system is presented in Table 5.143. In the table, it is assumed that produced heat is at the temperature of 100°C. Energy consumption of different processes is summarized in Appendix I.

Table 5.143 : Energy balance of the system.

	Consumption		Production	
	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
Collection network	3258,60			
First, second, tertiary treatment	18,06			
Sludge blending	8,13			
Sludge thickening	81,28			
Anaerobic digestion	40,64	162,56		
Upgrading of biogas	216,91	70,99		
Biorefinery	82,13		1825,08	2190,10
Post processing of digestate	63,40			
Total	3769,15	233,55	1825,08	2190,10
Net production			-1944,06	1956,55
Supplied energy to the system			1944,06	
Exergy of production				393,25

As for the other product of the wastewater environmental remediation system, residue of the AD process (digestate) is conditioned and dried to produce fertilizer (Technical details are available in Appendix I). The amount of produced fertilizer and its exergy content are presented in Table 5.144.

Table 5.144 : Amount and exergy of fertilizer.

Amount of produced fertilizer (Ton)	352211,44
Exergy of fertilizer (MJ/Ton)	6415,74
Exergy of total produced fertilizer (TJ)	2259,70

In summary, exergy of produced heat (393,25 TJ, presented in Table 5.143) and exergy of fertilizer (2259,70 TJ, presented in Table 5.144) constituent the total exergy of the system products whose sum amounts to 2652,95 TJ exergy.

The formulation of EE_{ENV} is presented above in equation (5.16) for a general environmental remediation system. $E_{M\text{-}t}$, $E_{PHYS\text{-}t}$, $EE_{L\text{-}t}$, $EE_{C\text{-}t}$, $EE_{ENV\text{-}t}$ fluxes and resulting $EE_{ENV\text{-}lq,w}$ (EE_{ENV} for untreated wastewater environmental remediation system) are presented in Table 5.145.

Table 5.145 : $EE_{ENV\text{-}lq,w}$ for untreated wastewater.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	155634,61
$E_{PHYS\text{-}t}$	1944,06
$EE_{L\text{-}t}$	15,15
$EE_{C\text{-}t}$	69541,46
$EE_{ENV\text{-}t}$	17307,83
$E_{P\text{-}t}$	2652,95
$EE_{ENV\text{-}lq,w}$	241790,16

Specific environmental remediation cost ($ee_{ENV\text{-}lq,w}$) of wastewater is computed in equation (5.32).

$$ee_{ENV-lq,w} = \frac{EE_{ENV-lq,w}}{\text{Processed wastewater}} = \frac{241790{,}16 \times 10^{6}\ \text{MJ}}{2527421050{,}99\ \text{m}^3} = 95{,}66\ \text{MJ/m}^3 \qquad \textbf{(5.32)}$$

5.4.4.3 Treated wastewater (sludge processing)

As presented in Table 5.136, the amount of treated wastewater is 1326883145 m^3. In current application field of Turkey, sludge produced during wastewater treatment has a very limited use of fertilizer in agriculture. The general trend is dumping or sanitary landfilling of the produced sludge (Salihoglu et al., 2007). As a result, this sludge has an environmental remediation cost ($EE_{ENV\text{-}lq,sl}$) originated from required "sludge processing". The applied procedure of the remediation process is the same as process chain presented in Section 5.4.4.1 and 5.4.4.2 excluding the parts: i) wastewater collection and ii) wastewater treatment&sludge generation (since they are already applied to wastewater during treatment). The amount of produced sludge is calculated based on system used in Section 5.4.4.2 which is extracted from Qasim (1999). System details and estimation of sludge production in wastewater treatment are presented in Appendix I. Accordingly, exergetic equivalent of material, physical, capital, labour and environmental remediation cost for the sludge remediation system are seen in Table 5.146 - 5.149. It is noticeable that, electricity surplus posed by considering sludge processing system is a system product due to the fact that the "wastewater collection network" is not incorporated unlike the system presented in Section 5.4.4.2. Wastewater collection has by far the highest energy consumption among the processes as seen in Table 5.143.

Table 5.146 : Material exergy ($E_{M\text{-}t}$) received by the system.

System/Process	Capital	Equivalent exergy (TJ)
Sludge thickener	31 $/tDM	109,65
Anaerobic digestion plant	65 $/tDM	229,92
Upgrading of biogas	0,26 €/m^3	864,83
Biorefinery	7000 $/$KW_{el}$	5822,26
Post processing of digestate	215 $/tDM	593,18
CaO		26,24
$FeCl_3$		6,40
Total		7652,48

As it is seen later in Table 5.151, energy requirement of the system is met by the produced energy in the system. As such, there is no physical exergy transfer into the system.

As for capital flow, calculation (done in Section 5.4.4.2) is repeated for the system and results are seen in Table 5.147.

Table 5.147 : Exergetic equivalent of the capital ($E_{C\text{-}t}$) received by the system.

System/Process	Capital	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
Sludge thickener	31 $/tDM	109,65	26,15	21,93	48,09
Anaerobic digestion plant	65 $/tDM	229,92	54,84	45,98	100,82
Upgrading of biogas	0,26 €/m^3	864,83	206,28	172,97	379,25
Biorefinery	7000 $/$KW_{el}$	5822,26	1388,74	1164,45	2553,19
Post processing of digestate	215 $/tDM	593,18	141,49	118,64	260,12
CaO	0,063 $/kg			21,71	21,71
$FeCl_3$	0,4 $/kg			45,50	45,50
Total					3408,68

As for labour consumption of the system, number of workers is assumed to be 300 workers per 1000 MW_{h+el} with 1800 workhours/year workload for each worker. The same calculation route is applied as presented in Section 5.4.4.2 and the result is obtained as 5,97 TJ.

Environmental remediation cost of the system is originated from greenhouse gas emissions from AD, biogas upgrading and biogas incineration (in biorefinery). Details of emissions are presented in Appendix I. The results are presented in Table 5.148.

Table 5.148 : Emissions from the processes.

	Emission (Ton)		
	CO_2	N_2O	CH_4
Anaerobic digestion	1901,84		1524,03
Upgrading of biogas	58623,06		985,54
Biorefinery	134381,85	0,24	2,40
Total	194906,74	0,24	2511,97

Total CO_2, N_2O and CH_4 emissions of the system are seen in Table 5.148. The environmental remediation cost of considered emission gases is computed in Section 5.4.3 and inserted into Table 5.149 to obtain the $EE_{ENV\text{-}t}$ for the whole wastewater treatment system.

Table 5.149 : Environmental remediation cost of emissions ($EE_{ENV\text{-}t}$).

CO_2 emissions (Ton)	194906,74
N_2O emission (Ton)	0,24
CH_4 emission (Ton)	2511,97
CO_2 $ee_{ENV\text{-}g}$ (TJ/Ton CO_2)	0,043
N_2O $ee_{ENV\text{-}g}$ (TJ/Ton N_2O)	0,010
CH_4 $ee_{ENV\text{-}g}$ (TJ/Ton CH_4)	0,267
CO_2 $EE_{ENV\text{-}g}$ (TJ)	8416,23
N_2O $EE_{ENV\text{-}g}$ (TJ)	0,0023
CH_4 $EE_{ENV\text{-}g}$ (TJ)	670,29
Total $EE_{ENV\text{-}t}$ (TJ)	9086,52

The products of the environmental remediation system are electricity and heat produced by biorefinery as well as produced fertilizer. The amount of the biogas utilized in biorefinery, the efficiencies of heat and electricity generation and produced energy in biorefinery are presented in Table 5.150. LHVof CO_2 is almost zero (De Hullu, et al.).

Table 5.150 : Properties of biogas utilization.

CH_4 (m^3)	71016848
CO_2 (m^3)	1449323
LHV of CH_4 (MJ/m^3)	33,73
LHV of CO_2 (MJ/m^3)	0
LHV of biogas (TJ)	2395,40
Electricity generation efficiency	0,4
Heat generation efficiency	0,48
Generated electricity (TJ)	958,16
Generated heat (TJ)	1149,79

The energy balance of the system is presented in Table 5.151. In the table, it is assumed that produced heat is at the temperature of 100 C. Energy consumption of different processes is detailed in Appendix I.

Table 5.151 : Energy balance of the system.

	Consumption		Production	
	Electricity (TJ)	Heat (TJ)	Electricity (TJ)	Heat (TJ)
Sludge blending	2,50			
Sludge thickening	24,97			
Anaerobic digestion	12,48	49,94		
Upgrading of biogas	113,88	37,27		
Biorefinery	43,12		958,16	1149,79
Post processing of digestate	19,47			
Total	216,42	87,20	958,16	1149,79
Net production			741,74	1062,59
Exergy of production			741,74	213,57

As for the other product of the wastewater environmental remediation system, residue of the AD process is conditioned and dried to produce fertilizer (Technical details are available in Appendix I). The amount of produced fertilizer and its exergy content are presented in Table 5.152.

Table 5.152 : Amount and exergy of produced fertilizer.

Amount of produced fertilizer (Ton)	108193,78
Exergy of fertilizer (MJ/Ton)	6415,74
Exergy of total produced fertilizer (TJ)	694,14

In summary, exergy of produced heat & electricity presented in Table 5.151) and exergy of fertilizer (presented in Table 5.152) constituent the total exergy of the system products whose sum amounts to 1649,46 TJ exergy.

The formulation of EE_{ENV} is presented above in equation (5.16) for a general environmental remediation system. $E_{M\text{-}t}$, $EE_{L\text{-}t}$, $EE_{C\text{-}t}$, $EE_{ENV\text{-}t}$ fluxes and resulting $EE_{ENV\text{-}lq,sl}$ (EE_{ENV} for sludge environmental remediation system) is presented in Table 5.153.

Table 5.153 : $EE_{ENV\text{-}lq,sl}$ for treated wastewater.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	7652,48
$EE_{L\text{-}t}$	5,97
$EE_{C\text{-}t}$	3408,68
$EE_{ENV\text{-}t}$	9086,52
$E_{P\text{-}t}$	1649,46
$EE_{ENV\text{-}lq,sl}$	18504,18

Specific environmental remediation cost ($ee_{ENV\text{-}lq,sl}$) of treated wastewater is computed in equation (5.33).

$$ee_{ENV-lq,sl} = \frac{EE_{ENV-lq,sl}}{Processed \quad wastewater} = \frac{18504{,}18 \, x \, 10^6 \, MJ}{1326883145{,}23 \ m^3} = 13{,}95 \, MJ / m^3 \qquad \textbf{(5.33)}$$

As a result, $EE_{ENV\text{-}lq}$ for DO sector is the sum of $EE_{ENV\text{-}lq,w}$ and $EE_{ENV\text{-}lq,sl}$ which are presented in Table 5.145 and Table 5.153, respectively. Hence, $EE_{ENV\text{-}lq}$ of DO Sector (the sum of $EE_{ENV\text{-}lq,w}$ and $EE_{ENV\text{-}lq,sl}$) is computed as: 260294,34 TJ.

5.4.4.4 $EE_{ENV\text{-}lq}$ of the sectors

National statistical data on CO and IN sectors are seen in Table 5.154 based on data in Turkstat (2005b). As for CO sector, the amount of wastewater seen in Table 5.154 is generated by coal processing and petroleum refining facilities. As it is seen in the table, IN and CO sectors have direct discharge to regional sewage network and the left is discharged to the environment as untreated or treated wastewater.

Table 5.154 : Wastewater produced in IN and CO Sector.

		IN Sector (x1000 m^3)	CO Sector (x1000 m^3)
Wastewater from sectoral activities			
	Sewage discharge	46993	7
	Treated and discharged to ENV	160374	11152
	Untreated and discharged to ENV	354014	4
Domestic wastewater			
	Sewage discharge	23183	192
	Treated and discharged to ENV	30888	802
	Untreated and discharged to ENV	10141	6

In statistical data for wastewater management of Turkey, amount of wastewater discharged to regional sewage network from different sectors and the total amount of treated wastewater are reported. However, the sectoral allocation of wastewater which is treated in wastewater treatment plants is not known. In this thesis, it is assumed that treated wastewater is produced in DO and TE sectors. Hence, presented amount of "sewage discharge" wastewater generated in IN and CO sectors are assumed to be "untreated" in national sewage system and discharged directly to the environment.

Since treated wastewater is within the legal discharge limits and assumed to be harmless to the environment, it has no $EE_{ENV\text{-}lq}$. In conclusion, wastewater generated in IN and CO sectors which needs to subject to additional wastewater remediation is "Sewage discharge" and "Untreated and discharged to ENV" fractions of the sectoral wastewater.

It must also be noticed that, sectoral wastewater generation are classified into two parts: sectoral and domestic. Use of specific environmental remediation cost of DO sector wastewater ($ee_{ENV,lq-w}$ and $ee_{ENV,lq-sl}$) is completely right for domestic type wastewater emission of the sectors. As for wastewater from sectoral activities, “sewage discharged” wastewater have properties (defined by legal authorities) which are closed to municipal wastewater (DO sector wastewater). Hence, use of DO sector specific environmental remediation cost for this part is also right. Therefore, it is shown that the assumption partly affects the results via the remediation of “untreated and discharged to ENV” wastewater from sectoral activities. In Table 5.155, environmental remediation cost of IN and CO sector wastewater is computed.

Table 5.155 : $EE_{ENV\text{-}lq}$ for IN and CO sector.

	IN Sector	CO Sector
Untreated wastewater[12] (m^3)	$434331x10^3$	$209\ x10^3$
Treated and sludge generated wastewater[13] (m^3)	$191262\ x10^3$	$11954\ x10^3$
$ee_{ENV\text{-}lq,w}$ (MJ/m^3)	95,67	95,67
$ee_{ENV\text{-}lq,sl}$ (MJ/m^3)	13,95	13,95
$EE_{ENV\text{-}lq,w}$ (TJ)	41551,04	19,99
$EE_{ENV\text{-}lq,sl}$ (TJ)	2667,26	166,71
$EE_{ENV\text{-}lq}$[14] (TJ)	44218,30	186,70

As for TE sector, estimated amounts of treated and untreated wastewater (based on national data in Turkstat (n.d.)) and computed $EE_{ENV\text{-}lq}$ are seen in Table 5.156. Since sectoral wastewater is discharged to sewage network, the average composition of sectoral wastewater is the same as DO sector wastewater for which specific environmental remediation costs ($ee_{ENV\text{-}lq,w}$ and $ee_{ENV\text{-}lq,sl}$) are calculated in Section 5.4.4.2 and 5.4.4.3.

Table 5.156 : Produced wastewater and $EE_{ENV\text{-}lq}$ for TE Sector.

Untreated wastewater (m^3)	439432286
Treated and sludge generated wastewater (m^3)	813116855
$ee_{ENV\text{-}lq,w}$ (MJ/m^3)	95,67
$ee_{ENV\text{-}lq,sl}$ (MJ/m^3)	13,95
$EE_{ENV\text{-}lq,w}$ (TJ)	42039,06
$EE_{ENV\text{-}lq,sl}$ (TJ)	11339,40
$EE_{ENV\text{-}lq}$ (TJ)	53378,46

[12] Sum of “sewage discharge” and “untreated and discharged to ENV” wastewater, both from sectoral activities and domestic wastewater, presented in Table 5.154.
[13] Sum of “treated and discharged to ENV” wastewater from sectoral activities and domestic wastewater, presented in Table 5.154.
[14] $EE_{ENV\text{-}lq} = EE_{ENV\text{-}lq,w} + EE_{ENV\text{-}lq,sl}$

Wastewater created out of agricultural or farm activities is termed as agriculture wastewater. Due to diversified characteristic of wastewaters produced in the course of agricultural activities, the sector produces a range of wastewater requiring a variety of treatment technologies and management practices. This wastewater can harm the environment in a significant way as the water is usually discharged into streams, rivers and lakes. Unfortunately, there is not any available data for the amount and characteristics of AG sector wastewater.

Water use of Turkish AG sector for irrigation is 30 x 10^9 m^3 (Turkish Gold Miners Association, 2008). The area of AG sector is 358050 km^2 (Turkstat, 2009g) and the annual average precipitation in Turkey is 643 mm/m^2 (Ozturk et al., 2009). The forest area is not included in the calculation since the most of fertilizer use ise seen in agricultural side which causes the main part of the waste contamination in AG sector. As a result, annual precipitation on agricultural area is:

$$\begin{aligned}\text{Precipitation on Agricultural Area} &= (643\text{x}10^{-3})\ \text{x}\ (358050\,\text{x}\,10^{6}) \\ &= 230{,}23\,\text{x}\,10^{9}\ \text{m}^3\end{aligned} \tag{5.34}$$

Therefore, total water use is 260,23 x 10^9 m^3. Turkey has 536 x 10^9 m^3 water input and 274 x 10^9 m^3 is evaporated. In other words, 51% of the input is evaporated trough the country. Following the same route, it is assumed that 51% of the total water received by the sector is evaporated. Therefore, 127,2 x 10^9 m^3 is used by the sector. The water consumption of the sector is estimated to be 9,44 x 10^7 Ton= 9,44 x 10^7 m^3 in Chapter 3. The remaining part of the water is assumed to be contaminated by fertilizers etc. which amounts to:

$$127{,}2\,\text{x}10^{9} - 9{,}44\,\text{x}10^{7} = 127{,}11\,\text{x}10^{9}\ \text{m}^3 \tag{5.35}$$

For the treatment of this polluted water, $ee_{ENV\text{-}lq,w}$ is employed and $EE_{ENV\text{-}lq}$ is computed as seen in Table 5.157.

Table 5.157 : $EE_{ENV\text{-}lq}$ for AG sector.

Wastewater (10^9 m^3)	127,11
$ee_{ENV\text{-}lq,w}$ (MJ/m^3)	95,67
$EE_{ENV\text{-}lq}$ (TJ)	12159779,84

5.4.5 Environmental remediation cost of discharged heat (EE_{ENV-d})

Human induced anthropogenic heat discharge and its spatial pattern are key issues in global environmental change and critical to improve the understanding of human impacts on the environment. The costs of increasing atmospheric temperature are considerable in terms of environment, economics and thermal discomfort (Dhakal and Hanaki, 2002). One of the substantial and major factors of worsening the heat environment is heat discharge from buildings and transportation vehicles, especially in densely built urban cities (Dhakal and Hanaki, 2002; Ichinose et al., 1999; Urano et al., 1999). If it is impossible to mitigate the anthropogenic heat, managing the heat discharge may have the prospect of improving thermal environment. The objective of this section is the analysis of anthropogenic heat discharged from the sectors and determination of its environmental remediation cost (EE_{ENV-d}) within the frame of some specific assumptions.

Discharged heat is originated from different sources in each sector. In this study, EE_{ENV-d} is obtained by means of designing a waste heat utilization process for each case. Low temperature heat sources (such as heat loss from building walls, fertilizers, animal manure, etc.) don't have a high utilization capacity and disregarded in this section.

For EX sector, sectoral energy consumption is reported as electricity (IEA, 2008). The only considerable sectoral gas emission is the CH_4 originated from coal mining activities. The temperature of released gas is not high enough to be utilized in energy production. As a result, EX sector discharge heat is taken as 0 (zero) in this thesis.

5.4.5.1 DO sector discharge heat

Buildings act as heat sinks in urban environmental system. The incoming solar radiation from the sun is stored in the buildings and released to the atmosphere. Also, to meet the energy need of human activities (such as lighting, electrical appliances, heating and cooling) a considerable amount of energy is consumed every day in buildings (Dhakal et al., 2003). Discharged heat from buildings is assumed to be equal to building energy consumption in many of past studies (Dhakal et al., 2004). Such an approach ignores the temperature of discharged heat and its utilization capacity. As a result, heat transmitted from outside surface of walls, roofs, windows, doors and underground are disregarded in this thesis, since the temperature of released heat is not high enough to be utilized in energy generation (its exergy is very near to zero). Dhakal et al. (2003) simulated the aforementioned components of heat discharge for apartment buildings and it is shown that discharged heat from flue gas has by far the largest share in the total heat discharge of buildings. As such, flue gas from the buildings which is assumed to be at the average temperature of 150 °C (Bilgin, 2009) is analysed in this section.

The amounts of sectorally released CO_2, N_2O and CH_4 are available in national data (Ari, 2010) and seen in Table 5.158 with corresponding volumes. The flue gas composition employed in this study is presented in Table 5.159. The approximated fraction of CO_2, O_2, CO, SO_2, N_2 and H_2O are retrieved from Bulut (2011) and Bilgin (2009). The composition should not be viewed as an absolute characterization of building flue gas, but rather as a general picture that may subject to change (to a little extent) depending on the type of fuel combusted. Resulting volumetric composition of the chimney gas is seen in Table 5.159.

Table 5.158: Weight and volume of CO_2, N_2O and CH_4.

	Emissions (Ton)	Emissions (m^3)
CO_2	32489218	25652168485
N_2O	914,26	721866
CH_4	16910	36716467

Table 5.159 : Composition of flue gas released from DO sector.

	% vol.	Volume (m^3)
CO_2	13	25652168485
O_2	3	5919731189
CO	0,01	19732437
SO_2	0,01	19732437
N_2	70	138127061071
N_2O	$3,7 \times 10^{-4}$	721866
CH_4	$1,86 \times 10^{-2}$	36716467
H_2O	13,96	27548509006
Total	100	197324372959

Volume of the greenhouse gases presented in Table 5.158 are calculated via equation (5.36).

$$PV = nRT \tag{5.36}$$

where P is pressure (atm), V is volume (m^3), n is mole number, R is universal gas constant (8,314 J K^{-1} mol^{-1}; 0,08314 bar l K^{-1} mol^{-1}; 0,0821 atm l K^{-1} mol^{-1}) and T is temperature (K). For the case undertaken in this section, T =150°C, P=1 atm.

Since the volume of CO_2 and its volumetric fraction are known (seen in Table 5.158 and Table 5.159, respectively), volumes of other gases are computed proportional to their volumetric fraction in Table 5.159.

It is assumed that emitted gas is cooled down to annual average ambient temperature of Turkey (14 °C) (Demir et al., 2008) from 150°C (temperature of emission). Computed weight of H_2O, N_2, O_2, CO, SO_2 emissions are seen in Table 5.160. In Table 5.160, densities are presented for 150 °C, 1 atm conditions and retrieved from Incropera and De Witt (1996) and Cengel and Boles (1994).

Table 5.160 : Weight of H_2O, N_2, O_2, CO, SO_2.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	27548509006	0,5163	14224459
N_2	138127061071	0,8021	110785259
O_2	5919731189	0,9126	5402347
CO	19732437	0,7987	15760
SO_2	19732437	1,8207	35926

The discharged heat (Q_d) is calculated via:

$$Q_d = \int_{T_1}^{T_2} m\,c_p(T)\,dT \tag{5.37}$$

where Q_d (J) is discharged heat, m (kg) is mass, $c_p(T)$ (J/kgK) is specific heat capacity and T (K) is the temperature. T_1 (K) and T_2 (K) are initial and final temperature of considered gas. Variation of c_P with temperature is extracted from Cengel and Boles (1994) and results are presented in Table 5.161.

Table 5.161 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	32489218	0,126	4099
N_2O	914,26	0,131	0,12
CH_4	16910	0,342	5,79
H_2O	14224459	0,267	3800
N_2	110785259	0,149	16462
O_2	5402347	0,132	714,71
CO	15760	0,148	2,33
SO_2	35926	0,091	3,25
Total			25088

In this thesis, heat released from emissions is utilized in production of electricity. ORC (Organic Rankine Cycle) technology was proposed to recover the low-and medium temperature waste heat to produce power. ORC functions like a Clausius–Rankine steam power plant but uses an organic working fluid instead of water. For conversion of low-grade waste heat energy into power, ORC performs better than the conventional steam power cycle (Tamamoto et al., 2001; Dai et al., 2009; Wei et al., 2007; Desai and Bandyopadhyay, 2009; Saleh et al., 2007; He et al., 2012). Since the source of heat is at 150 °C, an ORC system is used for conversion of heat to electricity. First law efficiency of the cycle (η_I) is assumed to be 10% based on Saleh et al. (2007). Capital of ORC plant is taken as 3000 €/KW_{el} (3780 \$/KW_{el}) (Vanslambrouck, 2010). Produced power is calculated based on the assumption that plant runs 340 days (24 hours a day) annually. Accordingly, generated energy and power from the system are:

$$\text{Produced electricity} = Q_d \ x \ \eta_I = 25088x0{,}1 = 2508{,}8\,TJ \tag{5.38}$$

$$\text{Produced power}\ (KW_{el}) = \frac{\text{Produced electricty (KJ)}}{340x24x60x60\,(s)} = \frac{2508{,}78\,x\,10^9}{340x24x60x60} = 85402{,}4\,KW_{el} \tag{5.39}$$

Capital and exergetic equivalent of capital for the system is reported in Table 5.162.

Table 5.162 : Exergetic equivalent of ORC capital.

Capital of ORC (\$/KW_{el})	3780
Produced power (KW_{el})	85402
Total capital (\$)	322820975
ee_C (MJ/\$)	25,5
Exergetic equivalent of ORC capital (TJ)	8232

As for capital flows, capital investment of the system (Investment cost, IC) is assumed to be supplied by bank credit with annual interest rate of 20% and payback time of 10 years. Annual cost (AC) is calculated using the methodology presented by Bejan et al. (2006) (annual payment is 23,85% of capital investment, formulation is presented in equation (5.17)). Annual “fixed and varying operation costs” (including insurance, wages, maintenance etc., cumulatively denominated as “OP”) are assumed to be 20% of capital investment. Capital flows of the system are sum of AC and OP and results are seen in Table 5.163.

Table 5.163 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC + OP (TJ)
ORC process	8232	1963,54	1646,42	3610

As for calculation of material influx (E_{M-t}) to the system, since no sufficiently reliable data were available on the exact material composition of the used items in the system, an analytical analysis was impossible. The corresponding portion of EE_{ENV-d} is computed by converting the known monetary cost of the ORC process into exergetic equivalent by means of ee_C and already presented in Table 5.164 as 8232,09 TJ.

In the matter of the labour consumption of the system, it is assumed that labour of the system is 200 workers per 1000 MW_{el} (based on data in Bezdek and Wendling (2008)). System power is computed in equation (5.39). With the assumption of 1800 workhours/year workload for each worker, equation (5.19) and (5.20) are adopted: resulting labour consumption and its exergetic equivalant are derived as 30744,8 workhours and 4,73 TJ, respectively.

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of system energy production. Electricity production of the system is presented above in equation (5.38). Resulting net electricity production is seen in equation (5.40).

$$\begin{gathered}\text{Net electricty production} = \text{Produced electricity x} \,(1-0{,}045) = \\ 2508{,}8 \,\text{x}\, 0{,}955 = 2396\,\text{TJ}\end{gathered} \tag{5.40}$$

Based on equation (5.16), EE_{ENV-d} of the present heat recovery system can be formulized as:

$$EE_{ENV-d} = E_{M-t} + EE_{L-t} + EE_{C-t} - E_{P-t} \tag{5.41}$$

and resulting EE_{ENV-d} is seen in Table 5.164.

Table 5.164 : EE_{ENV-d} for DO sector heat discharge.

	Exergetic equivalent (TJ)
E_{M-t}	8232
EE_{L-t}	4,73
EE_{C-t}	3610
E_{P-t}	2396
EE_{ENV-d}	9451

5.4.5.2 TE sector discharge heat

The same calculation procedure presented in Section 5.4.5.2 is applied to the TE sector flue gas. The weight of sectorally emitted CO_2, N_2O and CH_4 gases are retrieved from Ari (2010) and corresponding volumes are presented in Table 5.165.

Table 5.165 : Weight and volume of CO_2, N_2O and CH_4.

	Emissions (Ton)	Emissions (m^3)
CO_2	9087782	7175344012
N_2O	255,74	201918
CH_4	4730	10270215

The volume and volumetric fraction of considered flue gases are seen in Table 5.166.

Table 5.166 : Composition of flue gas released from TE sector.

	% vol.	Volume (m^3)
CO_2	13	7175344012
O_2	3	1655848618
CO	0,01	5519495
SO_2	0,01	5519495
N_2	70	38636467757
N_2O	3,7 x 10^{-4}	201918
CH_4	1,86 x 10^{-2}	10270215
H_2O	13,96	7705782428
Total	100	55194953939

Since the volume of CO_2 and its volumetric fraction are known (seen in Table 5.165 and Table 5.166, respectively), volumes of other gases are computed proportional to their volumetric fraction in Table 5.166. Computed weight of H_2O, N_2, O_2, CO, SO_2 emissions are seen in Table 5.167. References of densities are presented in Section 5.4.5.1.

Table 5.167 : Weight of H_2O, N_2, O_2, CO, SO_2.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	7705782428	0,5163	3978821
N_2	38636467757	0,8021	30988505
O_2	1655848618	0,9126	1511127
CO	5519495	0,7987	4408,42
SO_2	5519495	1,8207	10049

The heat release from the gases are calculated via equation (5.37) and results are presented in Table 5.168. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)).

Table 5.168 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	9087782	0,126	1146,68
N_2O	255,74	0,131	0,03
CH_4	4730	0,342	1,62
H_2O	3978821	0,267	1062,92
N_2	30988505	0,149	4604,75
O_2	1511127	0,132	199,92
CO	4408,42	0,148	0,65
SO_2	10049	0,091	0,91
Total			7017,48

Adopting equations (5.38) and (5.39), produced electricity and power are computed as 701,7 TJ_{el} and 23888 KW_{el}, respectively. Based on the properties of ORC system (presented in Section 5.4.5.1), capital consumption is reported in Table 5.169.

Table 5.169 : Exergetic equivalent of ORC capital.

Capital of ORC ($/$KW_{el}$)	3780
Produced power (KW_{el})	23888
Total capital ($)	90298469
ee_C (MJ/$)	25,5
Exergetic equivalent of ORC capital (TJ)	2303

Exergetic equivalent of AC and OP are presented in Table 5.170.

Table 5.170 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC + OP (TJ)
ORC process	2303	549,24	460,53	1010

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of produced electricity as done in previous sections. Hence, produced net electricity is 670,2 TJ.

Consumed labour of the system is computed following the route presented in Section 5.4.5.1. The constituent terms of the $EE_{ENV\text{-}d}$ and resulting $EE_{ENV\text{-}d}$ which is computed via equation (5.41) are seen in Table 5.171.

Table 5.171 : $EE_{ENV\text{-}d}$ for TE sector heat discharge.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	2303
$EE_{L\text{-}t}$	1,32
$EE_{C\text{-}t}$	1010
$E_{P\text{-}t}$	670,2
$EE_{ENV\text{-}d}$	2644

5.4.5.3 IN sector discharge heat

The weight of CO_2, N_2O and CH_4 gases retrieved from Ari (2010) are presented in Table 5.172. Emissions originated from sectoral processes are not included. Computed CO_2, N_2O and CH_4 emission in sectoral flue gas emissions and corresponding volumes are presented in Table 5.172.

Table 5.172 : Weight and volume of CO_2, N_2O and CH_4.

	Emissions (Ton)	Emissions (m^3)
CO_2	70599845	55742773505
N_2O	615,37	485872
CH_4	7126	15472498

Adopting the computation route applied in previous sections, the volume and volumetric fraction of considered flue gases are seen in Table 5.173.

Table 5.173 : Composition of flue gas.

	% vol.	Volume (m^3)
CO_2	13	55742773505
O_2	3	12863716963
CO	0,01	42879057
SO_2	0,01	42879057
N_2	70	300153395794
N_2O	$1{,}1 \times 10^{-4}$	485872
CH_4	$3{,}61 \times 10^{-3}$	15472498
H_2O	13,98	59928962675
Total	100	428790565420

Since the volume of CO_2 and its volumetric fraction are known (seen in Table 5.172 and Table 5.173, respectively), volumes of other gases are computed proportional to their volumetric fraction in Table 5.173. Computed weight of H_2O, N_2, O_2, CO, SO_2 emissions are seen in Table 5.174. References of densities are presented in Section 5.4.5.1.

Table 5.174 : Weight of H_2O, N_2, O_2, CO, SO_2.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	59928962675	0,5163	30941323
N_2	300153395794	0,8021	240753039
O_2	12863716963	0,9126	11739428
CO	42879057	0,7987	34248
SO_2	42879057	1,8207	78070

The heat release from the gases is calculated via equation (5.37) and results are presented in Table 5.175. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)).

Table 5.175 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	70599845	0,126	8908,16
N_2O	615,37	0,131	0,08
CH_4	7126	0,342	2,44
H_2O	30941323	0,267	8266,48
N_2	240753039	0,149	35772,73
O_2	11739428	0,132	1553,09
CO	34248	0,148	5,06
SO_2	78070	0,091	7,07
Total			54515

Adopting equations (5.38) and (5.39), produced electricity and power are computed as 5451,5 TJ_{el} and 185577 KW_{el}, respectively. Based on the properties of ORC system (Section 5.4.5.1), capital consumption is reported in Table 5.176.

Table 5.176 : Exergetic equivalent of ORC capital.

Capital of ORC ($\$/KW_{el}$)	3780
Produced power (KW_{el})	185577
Total capital ($)	701480947
ee_C (MJ/$)	25,5
Exergetic equivalent of ORC capital (TJ)	17888

Exergetic equivalent of AC and OP are presented in Table 5.177.

Table 5.177 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
ORC process	17888	4266,72	3577,62	7844

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of produced electricity as applied in previous chapters. Hence, produced net electricity is 5206,2 TJ.

Consumed labour of the system is computed following the route presented in Section 5.4.5.1. The constituent terms of the $EE_{ENV\text{-}d}$ and resulting $EE_{ENV\text{-}d}$ which is computed via equation (5.41) are seen in Table 5.178.

Table 5.178 : $EE_{ENV\text{-}d}$ for IN sector heat discharge.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	17888
$EE_{L\text{-}t}$	10,29
$EE_{C\text{-}t}$	7844
$E_{P\text{-}t}$	5206,2
$EE_{ENV\text{-}d}$	20537

5.4.5.4 CO sector discharge heat

The weight of CO_2, N_2O and CH_4 gases retrieved from Ari (2010) and presented in Table 5.179 with corresponding volumes.

Table 5.179 : Weight and volume of CO_2, N_2O and CH_4.

	Emissions (Ton)	Emissions (m^3)
CO_2	94783155	74836934008
N_2O	844,63	666884
CH_4	1624	3526276

Adopting the computation route applied in previous sections, the volume and volumetric fraction of considered flue gases are seen in Table 5.180.

Table 5.180 : Composition of flue gas.

	% vol.	Volume (m^3)
CO_2	13	74836934008
O_2	3	17270061694
CO	0,01	57566872
SO_2	0,01	57566872
N_2	70	402968106195
N_2O	$1,16 \times 10^{-4}$	666884
CH_4	$6,13 \times 10^{-4}$	3526276
H_2O	13,98	80474294334
Total	100	575668723136

Since the volume of CO_2 and its volumetric fraction are known (seen in Table 5.179 and Table 5.180, respectively), volumes of other gases are computed proportional to their volumetric fraction in Table 5.180. Computed weight of H_2O, N_2, O_2, CO, SO_2 emissions are seen in Table 5.181. References of densities are presented in Section 5.4.5.1.

Table 5.181 : Weight of H_2O, N_2, O_2, CO, SO_2.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	80474294334	0,5163	41552277
N_2	402968106195	0,8021	323201882
O_2	17270061694	0,9126	15760658
CO	57566872	0,7987	45979
SO_2	57566872	1,8207	104810

The heat release from the gases are calculated via equation (5.37) and results are presented in Table 5.182. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)).

Table 5.182 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	94783155	0,126	11960
N_2O	844,63	0,131	0,11
CH_4	1624	0,342	0,56
H_2O	41552277	0,267	11100
N_2	323201882	0,149	48026
O_2	15760658	0,132	2085
CO	45979	0,148	6,79
SO_2	104810	0,091	9,49
Total			73188

Adopting equations (5.38) and (5.39), produced electricity and power are computed as 7318,8 TJ_{el} and 249143 KW_{el}, respectively. Based on the properties of ORC system (presented in Section 5.4.5.1), capital consumption is reported in Table 5.183.

Table 5.183 : Exergetic equivalent of ORC capital.

Capital of ORC ($\$/KW_{el}$)	3780
Produced power (KW_{el})	249143
Total capital ($)	941762279
ee_C (MJ/$)	25,5
Exergetic equivalent of ORC capital (TJ)	24015

Exergetic equivalent of AC and OP are presented in Table 5.184.

Table 5.184 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
ORC process	24015	5728,22	4803,08	10531

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of produced electricity as applied in previous chapters. Hence, produced net electricity is 6989,5 TJ_{el}.

Consumed labour of the system is computed following the route presented in Section 5.4.5.1. The constituent terms of the $EE_{ENV\text{-}d}$ and resulting $EE_{ENV\text{-}d}$ which is computed via equation (5.41) are seen in Table 5.185.

Table 5.185 : $EE_{ENV\text{-}d}$ for CO sector heat discharge.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	24015
$EE_{L\text{-}t}$	13,81
$EE_{C\text{-}t}$	10531
$E_{P\text{-}t}$	6989,5
$EE_{ENV\text{-}d}$	27571

5.4.5.5 AG sector discharge heat

Agriculture itself is the major contributor to increasing methane (CH_4) and nitrous oxide (N_2O) concentrations in Earth's atmosphere. Together with use of fossil fuels (for sectoral transportation), the sector is one of the major anthropogenic sources of CO_2, CH_4 and N_2O (Smith et al., 2007). The main sources of CH_4 and N_2O emissions are listed below (Gibbs et al., 2000).

- CH_4 emissions from enteric fermentation in domestic livestock

When this anaerobic decomposition occurs during animal digestion, it referred to as enteric fermentation. The amount of enteric emitted methane is driven primarily by the number of animals, amount and properties of animal feed, etc. The largest sources of enteric methane emissions are cattles, buffaloes and sheeps (Gibbs et al., 2000).

- CH_4 emissions from manure management

Livestock manure is principally composed of organic material. Methane (CH_4) is produced, in the case organic matter decomposes under anaerobic conditions. These conditions often occur when large number of animals is managed in a confined area and manure is typically stored in large piles or storage tanks (Gibbs et al., 2000).

- N_2O emissions from manure management

The nitrous oxide (N_2O) under this category is the produced N_2O during the storage and treatment of manure (before it is applied to land). Here, “manure” is used collectively to include both of solid and liquid manure (dung and urine) produced by animals(Gibbs et al., 2000).

- N_2O emissions from nitrogen used in agriculture

N_2O is produced in soils through the processes of nitrification and denitrification. A number of agricultural activities causes in nitrogen (N) increasement in soil. This nitrogen is available to be used in nitrification and denitrification. Hence, an ultimate N_2O emission results from these processes. Especially fertilizers (N containing) and manure cause in this kind of N_2O emissions (Gibbs et al., 2000).

All of the aforementioned emissions are not expected to be at a temperature high enough to be utilized in energy generation. As a consequence, in this study, only the exhaust emissions from sectorally used diesel fuel (consumed by tractors) are taken into consideration (As seen in Table E.7, only energy consumption of the sector is diesel fuel, electricity and geothermal heat). Emission factors are extracted from Eggleston et al. (2006 a). Results are reported in Table 5.186.

Table 5.186 : AG sector exhaust gas emissions (Emission factors are LHV based).

CO_2 emission factor (kg/TJ)	74100
N_2O emission factor (kg/TJ)	3,9
CH_4 emission factor (kg/TJ)	3,9
Consumed diesel fuel (10^3 Ton)	3103
Energy content (MJ/Ton, LHV)	42791
CO_2 emission (Ton)	9963744
N_2O emission (Ton)	524,41
CH_4 emission (Ton)	524,41

The volume of CO_2, N_2O and CH_4 gases are computed via equation (5.36) and presented in Table 5.187. Composition of exhaust gas is derived from (VW Motor Company, n.d.) and presented below in Table 5.188. The volume of other gases are computed based on CO_2 volumetric fraction in the composition. Temperature of gas emission is taken as 180°C (VW Motor Company, n.d.).

Table 5.187 : Weight and volume of CO_2, N_2O and CH_4.

	Emissions (Ton)	Emissions (m^3)
CO_2	9963744	8424711039
N_2O	524,41	443406
CH_4	524,41	1219366

Table 5.188 : Composition of exhaust gas.

	% vol.	Volume (m^3)
CO_2	12	8424711039
H_2O	11	7722651785
N_2	67	47037969965
CH_4	$1,74 \times 10^{-3}$	1219366
N_2O	$6,3 \times 10^{-4}$	443406
O_2	9,99	7013571940
Total		70200567501

VW Motor Company (n.d.) states that in volumetric composition of a diesel fuel propelled vehicle exhaust, total share of SO_2, HC, NO_x and CO etc. emissions is approximately 0,3% (vol.%). This part is neglected.

In Table 5.189, computed weight of H_2O, N_2 and O_2 are seen. References of densities are presented in Section 5.4.5.1. The heat release from the gases are calculated via equation (5.37) and results are presented in Table 5.190. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)).

Table 5.189 : Weight of H_2O, N_2 and O_2.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	7722651785	0,481	3716387
N_2	47037969965	0,749	35207921
O_2	7013571940	0,855	5999409

Table 5.190 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	9963744	0,150	1497,12
H_2O	3716387	0,315	1172,48
N_2	35207921	0,175	6175,02
CH_4	524,41	0,410	0,22
N_2O	524,41	0,156	0,08
O_2	5999409	0,156	938,43
Total			9783,34

The ORC (Organic Rankine Cycle) plant which is employed in previous sections is used for heat recovery. Produced electricity and power by ORC is computed via equations (5.38) and (5.39), respectively. Produced electricity and power are 978,3

TJ_{el} and 33304 KW_{el}, respectively. Following the same calculation route in previous sections, exergetic equivalent of ORC capital and anualized capital (AC) are presented in Table 5.191 and Table 5.192.

Table 5.191 : Exergetic equivalent of ORC capital.

Capital of ORC ($/$KW_{el}$)	3780
Produced power (KW_{el})	33304
Total capital ($)	125888586
ee_C (MJ/$)	25,5
Exergetic equivalent of ORC capital (TJ)	3210

Table 5.192 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
ORC process	3210	765,71	642,04	1408

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of produced electricity as applied in previous chapters. Hence, produced net electricity is 934,3 TJ_{el}.

Consumed labour of the system is computed following the route presented in Section 5.4.5.1. The constituent terms of the $EE_{ENV\text{-}d}$ and resulting $EE_{ENV\text{-}d}$ which is computed via equation (5.41) are seen in Table 5.193.

Table 5.193 : $EE_{ENV\text{-}d}$ for AG sector heat discharge.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	3210
$EE_{L\text{-}t}$	1,85
$EE_{C\text{-}t}$	1408
$E_{P\text{-}t}$	934,3
$EE_{ENV\text{-}d}$	3686

5.4.5.6 TR sector discharge heat

As presented in Section 4.6, transportation sector has four main modes: road, rail, air and marine. Turkish transportation sector relies mainly on road transportation mode. As a result, in the year 2004, 84%, 98% and 96,7% of produced CO_2, CO and CH_4 emissions from TR sector activities are emitted from road transportation vehicles (Pekin, 2006). Therefore, heat discharged in road vehicle exhaust emissions are by far the largest part of the sectorally discharged heat. Consequently in this thesis, sectoral heat discharge is calculated based on road vehicle emissions. in Table 5.194, share of road transportation in transportation sector emissions and road transportation emissions are presented (Ari, 2010; Pekin, 2006). The volume of gases is computed via equation (5.36). The temperature of exhaust gas emission is taken as 180°C.

Table 5.194 : Share of road transportation in total CO_2, N_2O and CH_4 emissions.

	CO_2	N_2O	CH_4
Road transportation share (%)	84	63	96,7
Transportation emission (Ton)	43738000	1710	5930
Road transportation emission (Ton)	36739920	1077,30	5734,31
Road transportation emission (m^3)	31064950882	910897	13333566

Approximate composition of exhaust gas is derived from (VW Motor Company, n.d.). The volume of the gases (except CO_2, N_2O and CH_4) are computed based on CO_2 volumetric fraction in the exhaust gas composition and reported in Table 5.195. VW Motor Company (n.d.) states that volumetric gas composition of a diesel fuel propelled vehicles has 1 % (vol.%) of HC, NO_x and SO_2 etc. This part of emission is assumed to be N_2 in Table 5.195.

Table 5.195 : Composition of exhaust gas.

	% vol.	Volume (m^3)
CO_2	14	31064950882
H_2O	13	28846025819
N_2	71,99	157543679473
CH_4	$0,6 \times 10^{-2}$	13333566
N_2O	$0,4 \times 10^{-3}$	910897
CO	1	2218925063
Total		219687825700

In Table 5.196, computed weight of H_2O, N_2 and CO are seen. References of densities are presented in Section 5.4.5.1. The heat release from the gases are calculated via equation (5.37) and results are presented in Table 5.197. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)).

Table 5.196 : Weight of H_2O, N_2 and CO.

	Emissions (m^3)	Density (kg/m^3)	Emissions (Ton)
H_2O	28846025819	0,481	13881629
N_2	157543679473	0,749	119582310
CO	2218925063	0,749	1660865

Table 5.197 : Heat release from the gases.

	Emission (Ton)	Heat release (MJ/kg)	Total heat release (TJ)
CO_2	36739920	0,150	5520,42
H_2O	13881629	0,315	4379,49
N_2	119582310	0,175	20973
CH_4	5734,31	0,410	2,35
N_2O	1077,30	0,156	0,17
CO	1660865,41	0,174	289,47
Total			31165

The ORC (Organic Rankine Cycle) plant which is employed in previous sections is used for heat recovery. Produced electricity and power by ORC is computed via equations (5.38) and (5.39), respectively. Produced electricity and power are 3116,5 TJ_{el} and 106090 KW_{el}, respectively. Exergetic equivalent of ORC capital and anualized capital are presented in Table 5.198 and Table 5.199.

Table 5.198 : Exergetic equivalent of ORC capital.

Capital of ORC ($/$KW_{el}$)	3780
Produced power (KW_{el})	106090
Total capital ($)	401021546
ee_C (MJ/$)	25,5
Exergetic equivalent of ORC capital (TJ)	10226

Table 5.199 : Exergetic equivalent of the annualized ORC capital.

System/Process	Exergetic equivalent of IC (TJ)	Exergetic equivalent of AC (TJ)	Exergetic equivalent of OP (TJ)	AC+OP (TJ)
ORC process	10226	2439,19	2045,25	4484

Product of the system is the net amount of produced electricity. ORC plant is assumed to consume 4,5% of produced electricity as applied in previous chapters. Hence, produced net electricity is 2976,3 TJ_{el}.

Consumed labour of the system is computed following the route presented in Section 5.4.5.1. The constituent terms of the $EE_{ENV\text{-}d}$ and resulting $EE_{ENV\text{-}d}$ which is computed via equation (5.41) are seen in Table 5.200.

Table 5.200 : $EE_{ENV\text{-}d}$ for TR sector heat discharge.

	Exergetic equivalent (TJ)
$E_{M\text{-}t}$	10226
$EE_{L\text{-}t}$	5,88
$EE_{C\text{-}t}$	4484
$E_{P\text{-}t}$	2976,3
$EE_{ENV\text{-}d}$	11740

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary, Results and Discussion

The goal of this study is to present the EEA analysis of Turkish Society for the year 2006. Its purpose was to investigate how effectively the society uses resources. This is the first study of global EEA analysis of Turkish society in the literature. The other initial contribution to the literature is determination of EE_{ENV} results. Sectoral solid, liquid and gas effluents display a broad diversity and it is impossible to deal with all of them in detail in a single global study. As a result, some restrictions are conducted such as: only road transportation waste is analyzed as TR Sector solid waste and only CO_2, N_2O and CH_4 are analyzed as gas emissions. Hazardous waste, extraction sector solid and liquid waste are not taken into account through EE_{ENV} computation.

As for the individual sectoral analysis, due to necessity of tremendous amount of data and unavailability of exact data about material transferred between the sectors and material consumption of the sectors, ad hoc assumptions are made on a case-to-case basis (each of them representing an educated engineering guess), which also limit the accuracy of the results. However, these assumptions may be regarded as solutions to fulfill the aimed analysis and the only way to see the global resource consumption picture of the society.

In Table 6.1, EE_{ENV} results which are composed of four components (solid and liquid waste, gas emissions and discharged heat) are reported.

Table 6.1 : EE_{ENV} components and EE_{ENV} of the sectors (TJ).

	Solid waste	Liquid waste	Gas emissions	Discharged heat	EE_{ENV}
EX Sector	0	0	20556	0	20556
CO Sector	3888	187	4076118	27571	4107764
AG Sector	46003688	12159779	-2633285	3686	55533868
IN Sector	208829	44218	4027470	20537	4301054
TR Sector	22912	0	1882334	11740	1916986
TE Sector	74375	53378	774117	2644	904514
DO Sector	401745	260294	1401560	9451	2073050

In this thesis, EEA efficiency (EEA_{eff}) is formulated as:

$$EEA_{eff} = \frac{\sum EE_{output}}{\sum EE_{input}} = \frac{\sum_{output} E_M + E_{PHYS} + EE_C + EE_L}{\sum_{input} E_M + E_{PHYS} + EE_C + EE_L + EE_{ENV}} \qquad \textbf{(6.4)}$$

The physical meaning of the formulation can be described as the answer of the question: how much of input resources are conveyed into sectoral products, or in other words, what is the efficiency of resource consumption to produce different types of resources (sectoral output)?. All the input and output resources are quantified in exergy terms as a unified metric.

Between Table 6.2 - Table 6.8, summarizing tables of input and output extended exergetic fluxes of the sectors and resulting sectoral EEA efficiencies (EEA_{eff}) are presented. The exergetic fluxes presented in the tables are available in the preceding chapters of the thesis. In the tables, the contractions (like "ENV,EX") indicate that the flux is from the first subsystem (in the example: ENV) to the second (in the example: EX).

Table 6.2 : Input and output fluxes and EEA_{eff} for EX Sector.

Fluxes	Exergy (TJ)
Input	
ENV,EX	988312
TE,EX	16339
TR,EX	28407
C_{input}	359990
L (DO,EX)	31295
EE_{ENV}	20556
EE_{input}	1444900
Output	
EX,TE	979412
C_{output}	336583
EE_{output}	1315995
EEA_{eff}	0,91

Table 6.3 : Input and output fluxes and EEA_{eff} for CO Sector.

Fluxes	Exergy (TJ)
Input	
ENV,CO	262800
TE,CO	2670109
TR,CO	2482
C_{input}	1924189
L (DO,CO)	23242
EE_{ENV}	4107764
EE_{input}	8990586
Output	
CO,TE	1978844
C_{output}	1858670
EE_{output}	3837514
EEA_{eff}	0,43

Table 6.4 : Input and output fluxes and EEA_{eff} for AG Sector.

Fluxes	Exergy (TJ)
Input	
ENV, AG	1618918488
TE,AG	528012
TR,AG	867
C_{input}	1360460
L (DO,AG)	919145
EE_{ENV}	55533868
EE_{input}	1677260840
Output	
AG,TE	1437856
AG,DO	42960
C_{output}	702928
EE_{output}	2183744
EEA_{eff}	0,0013

Table 6.5 : Input and output fluxes and EEA_{eff} for IN Sector.

Fluxes	Exergy (TJ)
Input	
ENV, IN	62088
TE,IN	3612695
TR,IN	28208
C_{input}	13660708
L (DO,IN)	1024627
EE_{ENV}	4301054
EE_{input}	22689380
Output	
IN,TE	1790801
C_{output}	11207020
EE_{output}	12997821
EEA_{eff}	0,57

Table 6.6 : Input and output fluxes and EEA_{eff} for TR Sector.

Fluxes	Exergy (TJ)
Input	
ENV,TR	0
TE,TR	793739
C_{input}	3848726
L (DO,TE)	415224
EE_{ENV}	1916986
EE_{input}	6974675
Output	
TR,EX	28407
TR,CO	2482
TR,AG	867
TR,IN	28208
TR,TE	2032
TR,DO	31213
C_{output}	3252783
EE_{output}	3345992
EEA_{eff}	0,48

Table 6.7 : Input and output fluxes and EEA_{eff} for TE Sector.

Fluxes	Exergy (TJ)
Input	
ENV, TE	263671
A,TE	5544824
EX,TE	979412
CO,TE	1978844
AG,TE	1437856
IN,TE	1790801
TR,TE	2032
DO,TE (processed waste)	38116
C_{input}	36144343
L (DO,TE)	1938159
EE_{ENV}	904514
EE_{input}	51022572
Output	
TE,A	1418066
TE,EX	16339
TE,CO	2670109
TE,AG	528012
TE,IN	3612695
TE,TR	793739
TE,DO	1856313
C_{output}	33721913
EE_{output}	44617186
EEA_{eff}	0,87

Table 6.8 : Input and output fluxes and EEA_{eff} for DO Sector.

Fluxes	Exergy (TJ)
Input	
ENV,DO	5471
TE,DO	1856313
AG,DO	42960
TR,DO	31213
C_{input}	9207757
EE_{ENV}	2073050
EE_{input}	13216764
Output	
DO,TE (processed waste)	38116
C_{output}	8765414
L_{TOTAL}	4351692
EE_{output}	13155222
EEA_{eff}	0,99

EX Sector analysis results in a high EEA_{eff} (0,91). The main reason of this high efficiency is high exergetic content of sectoral products ("EX,TE" flux in Table 6.2). This mainly results from the high lignite and boron extraction by the Sector since both of them have relatively high exergetic content.

EEA_{eff} of CO Sector is relatively low (0,43). The result is dominated by high EE_{ENV} of the Sector which lowers the EEA_{eff}. Considering the presented constituents of EE_{ENV} in Table 6.1, it is seen that environmental remediation cost of sectoral gas emissions is by far the largest constituent of sectoral EE_{ENV}. Gas emissions are mainly caused by combustion processes in the course of electricity and heat production which underlines the unfortunate non-renewable pattern in electricity and heat generation of the society (almost 50% of domestically consumed hard coal, 80% of that of lignite and 50% that of natural gas are consumed by heat and electricity generation plants within the Sector). As a result, it can be inferred that limited utilization of renewable energy sources in energy generation is the primary reason of high greenhouse gas emissions and resulting relatively low sectoral EEA_{eff}. Although high exergetic input of coal based and petroleum based combustible materials (which have high exergetic content) as raw material of refineries and fuel of energy generation plants is expected to be another reason of low EEA_{eff}. Sectoral products are mostly fuels and electricity (they have respectively high exergy intensities) which elevates the exergy content of sectoral output (Table 6.3). Hence, high exergetic input of sectoral energy carrier consumption can not be regarded as a determining factor of sectoral EEA_{eff} but this situation can underline the importance of system efficiency in the course of energy generation and also in refineries. Employing more efficient plants and changing or upgrading the current technologies in refineries arise as remedial approaches to heighten the amount of sectoral products with accompanying high exergy content and to raise the current EEA_{eff} of the Sector (for example, as stated in Section 5.4.2.4, all Turkish refineries do not have "residue upgrading technologies" which functions as converting vacuum residues into different types of fuels). This approach also causes in reduction of solid waste generation and lower EE_{ENV} in the Sector. As presented in Appendix G, use of waste in CO Sector for electricity production is quite limited but this issue should be concerned by policy makers to lower the EE_{ENV} load of CO Sector.

AG has a remarkably low EEA_{eff} (0,0013) which results from two concurring factors: 1) the very large input from the ENV (inputs from ENV to AG includes solar energy received by the agricultural area. Since agricultural area is almost %45,5 of the total land of the country, proportional amount of solar energy is transferred to AG Sector as a sectoral influx) and 2) the very low exergy content of the agricultural products. A rather high amount of labour input (21% of the total workforce) is another factor which contributes to the low EEA efficiency. As seen in Table 6.1, the sector has the advantage of negative environmental cost of gas emissions (as a result of sectors capture and sequestering ability) but sectoral EE_{ENV} is 80% of total EE_{ENV} of the society due to the tremendous amount of sectoral solid waste and corresponding $EE_{ENV\text{-}s}$ which plays not dominant but a non-negligible role as a reason of low EEA_{eff}.

The IN Sector has the relatively low efficiency of 0,57. The largest input fluxes to the sector are: EE_{ENV} (19%) and material influx from TE Sector (TE,IN) (16%). The Sector is capital intensive (60% of sectoral EE_{input}), but also generates a large output of capital. Hence, capital input (C_{input}) is somehow balanced with sectoral capital output (C_{output}). The material flux from TE to IN Sector ("TE,IN") is high but this can be viewed "normal" for a sector like IN Sector. In contrast, output flux ("IN,TE") is not high enough to compensate the EEA_{eff} lowering effect of "TE,IN" flux ("IN,TE" is 50% of "TE,IN"). As a result, it looks like energy generation and manufacturing processes within the sector do not operate very effectively. Indeed, since computation of "IN,TE" and also "TE,IN" relies on some fundamental assumptions, they should not be regarded as exact numbers and this makes is difficult to mention about these fluxes. A cleaner reality of the sector is predominant effect of environmental remediation cost (as an input flux) on EEA_{eff}. As it is seen in Table 6.1 that environmental cost of sectoral gas emissions predominantly contribute to the high EE_{ENV}. As a result, attempting to lower the use of fossil fuels (which cause high amount of gas emission) can be considered as an urgent approach to remedy the current resource dissipating situation of IN Sector.

EEA_{eff} of TR sector is 0,48. As a result of the unfortunate non-renewable pattern of Turkish transportation, the most active transportation mode is road transportation (82% of sectoral energy consumption) which completely dominate the use of energy carriers and lowering EEA_{eff} such as: 1) extensive use of fossil fuels (exergetically very ”expensive”) in road transportation causes in exergetically high influx to the sector 2) low efficiency of road transportation vehicles brings about exergetically low sectoral output 3) high greenhouse gas emissions resulting from combustion of fossil fuels. The only advantage of TR sector which raises the sectoral efficiency is its no liquid waste production and relatively low environmental remediation cost of solid waste (Table 6.1) which reduce its EE_{ENV} but these advantages are not sufficient to raise the efficiency because of the prevailing effects of the above listed efficiency lowering factors. The pursuit of more efficient and less polluting transportation may include the collective effort of vehicular improvements (for example: plug-in electric or hybrid cars), redesign of cities, more sucessful traffic management and development of efficient public transit infrastructure.

The TE Sector has a quite high EEA_{eff} (0,87). In spite of high labour input to the sector (44% of total produced labour within the society), the sectoral output has very high exergetic content (since in the model adopted in this study, the sector supplies the overwhelming majority of the material fluxes to the other sectors) which results in a high EEA efficiency. The sectoral efficiency strictly depends on imported and exported commodities (without taking into account the material interaction of the Sector with abroad, the sectoral EEA_{eff} is 94%). This shows that, being a net importer rather than exporter is the predominant reason of extended exergetic losses of TE Sector.

DO sector displays a high EEA_{eff} (0,99). Sector looks like quite “balanced” in terms of extended exergy. Indeed, the accuracy of the computed efficiency is limited by the assumptions made in this specific application and also by assumptions proposed by EEA methodology. The well balanced profile of the sector emerges from the fact that total produced labour within the society has a high exergetic equivalent and it is the product of the sector (sectoral output in Table 6.8) which raises the sectoral EE_{eff}.

As stated in Chapter 1, there are EEA analysis results for different societies and individual regions of countries in the literature. But, unlike the earlier studies, i) this present study is the most detailed analysis, ii) EE_{ENV} results are computed along the guidelines of original environmental remediation cost definition proposed by EEA theory and iii) distribution of domestically produced, imported and exported commodities follows a different route (TE Sector is a hub of material and capital distribution, as a result of covering all the commercial activities. This detail is not included in earlier studies). Another distinction from earlier EEA analyses is that exergetic content of imported and exported commodities are directly computed but not converted into exergy from monetary equivalent of the import and export. Thereby, the results of earlier performed EEA analyses are not found analogous with the results of this present thesis due to the systematic differences in application. One of the main contributions of this study to the literature is propounding the most pertinent application route of EEA method.

However, to date performed societal EEA analysis results are presented in Table 6.9 which enables to determine some notable and substantial properties of the analyzed societies. In Table 6.9, the last two columns are allocated for EEA results of Turkey, the first one presents the results of Turkish society EEA analysis where EE_{ENV} results are computed via converting the treatment monetary expenses into exergetic equivalent (Seçkin et al., 2012). The last column of Table 6.9 is the results of this present study.

Table 6.9: EEA analysis results of the present and earlier studies.

	Italy (1996)	Siena (2000)	Norway (2000)	UK (2004)	China (2005)	Turkey (2006)	Turkey (2006)
Reference	Milia and Sciubba (2006)	Sciubba et al. (2008)	Ertesvag (2005)	Gasparatos et al. (2009c)	Chen and Chen (2009)	Seçkin et al. (2012)	Present study
EX	0,86	0,33	0,95	0,91	0,88	0,82	0,91
CO	0,34	0,54	0,76	0,39	0,28	0,64	0,43
AG	0,7	0,61	0,61	0,49	0,56	0,0027	0,0013
IN	0,76	0,64	0,69	0,39	0,38	0,6	0,57
TR	0,39	0,26	0,63	0,31	0,24	0,53	0,48
TE	0,79	0,85	0,74	0,8	0,55	0,83	0,87
DO	0,87	0,83	-	-	-	0,85	0,99
ee_L (MJ/hours)	209	253	525,85	248,3	71,9	153,95	153,95
ee_C (MJ/$)	14	11,2	20,08	6,41	24,84	25,5	25,5

As it is seen in Table 6.9, the results of the present study are different from the study presented by Seçkin et al. (2012) which indicates the predominant role of accurate EE_{ENV} numbers in obtaining cleaner and deeper EEA_{eff} results. The most remarkable difference between Turkish results and other countries is seen in EEA_{eff} of AG Sector which emerges from accounting for the sectoral solar exergy reception as a sectoral input in Turkish society EEA analyses (the last two columns of Table 6.9).

These results can be inferred by evaluating the results of each societal EEA analysis (presented in Table 6.9): it is seen that ee_L is much lower for China and much higher for Norway than other countries. Although ee_L depends on several econometric factors, it is estimated that these results arise from the high population of Chinese society and low population of Norwegian society. High population results in generation of high workhours which lowers ee_L. ee_C of analyzed countries are closed, with an exception of UK. Sectoral EEA_{eff} of above mentioned societies have a great variation. As for EX sector, Siena province of Italy has a considerably low efficiency among the other societies, due to high capital input into the sector. For Italy, UK, China and Turkey, EEA_{eff} of CO sector is relatively low which results from the low efficiency of power & heat generation processes and high greenhouse gas emissions occurred in the course of energy generation. The EEA efficiency of Turkish AG sector is remarkably low due to high input of solar exergy to the sector (discussed above). China and UK have the lowest IN Sector EEA_{eff} through the sectors. As for Turkish IN sector, EEA efficiency is relatively lower than Italy, Siena and Norway. Considering that IN sector is an intensive energy and material consumer, the sector is significant from resource use point of view and a little higher efficiency may results in noticeably lower global extended exergy consumption (cumulative extended exergy consumption of a country). Within this frame, IN sector result of countries is worthy to notice, on the resource consumption side of the issue. As for TR sector, Italy, Siena, UK and China have relatively low EEA_{eff}. Results of Norway and Turkey are relatively higher but, in general, TR sector EEA_{eff} figures are lower than those of other sectors for all the societies presented in Table 6.9. The main reason is unavoidably high consumption of fossil fuels in the sector which is extensively discussed above for the case of Turkey. As for DO sector, efficiencies of different societies (including Turkey) are high and quite similar as a result of total labour production within the country is a DO Sector product which raises the sectoral

EEA_{eff} of DO Sector. As for TE sector, it is not scientifically meaningful to compare the results of Turkey with other countries due to the fact that TE sector is in charge of material and energy carrier distribution through the country which changes the intensity of the sectoral input and output flows in this study and Seçkin et al. (2012). One remarkable consequence from Table 6.9 is: TE Sector of China has a particularly low efficiency which shows that commercial and financial activities are not very strong in the society. The major part of above evaluation of Table 6.9 is published in Seçkin et al. (2012).

6.1.1 Sensitivity analysis of the results

Sensitivity analysis is one of the most effective methods in the analysis of the systems under investigation. In the method of sensitivity analysis, all parameters are assumed constant except one of them and that parameter is varied in a logical interval. Hence, a sensitivity analysis is carried out here by varying the quantity of some major input fluxes of the sectors to determine the effect of the uncertainties (emerges from assumptions done through the study) on the results. The sensitivity analysis was only performed for the fluxes which predominantly prevail the EEA_{eff} of the sectors.

As seen between Table 6.2 - Table 6.8, exergetic resource use equivalent of capital is the highest or one of the highest inputs to the sectors (25% for EX, 21% for CO, 60% for IN, 55% for TR, 71% for TE and 70% for DO) but capital inputs are published by the national data and has a definite characteristics. As a result, it is assumed that capital data is accurate and is not subjected to sensitivity analysis.

As for EX Sector (EEA_{eff} is 91%), the largest input into the sector is from ENV to EX (the flux of ENV,EX in Table 6.2 which corresponds to 68,4% of total input). Indeed, the exergy of fluxes from ENV is computed based on national data and assumptions on grade of ores are conducted basis on average grade of Turkish ores. As a result, a considerable amount of divergence (from the real exergetic content of inputs from the ENV) is not very expected. The most uncertain fluxes (due to the assumptions which are detailed in Appendix E and Appendix D) are TE,EX and TR,EX fluxes (Table 6.2) which constitute 1,1% and 2% of the total input flux. Hence, EEA_{eff} of EX sector is not expected to be strongly influenced by uncertainties (emerge from the assumptions) in the analysis. The only source of uncertainty which can affect the results may be the uncertainty of national data which is used in computation.

As for CO Sector (EEA_{eff} is 43%), the highest input fluxes are TE,CO and EE_{ENV} fluxes which constitute the share of 30% and 46% of total input, respectively. As explained in Section 4.6 and detailed in Appendix E, there are substantial assumption in computation of material distribution from TE. Hence, the quantity of TE,CO flux contains uncertainty. If the flux is reduced to -10% of its computed current exergy content (90% of the presented TE,CO flux), the EEA_{eff} of the sector is 44%. The sectoral efficiency is not affected strongly by the uncertainty of the assumptions performed in TE sector material distribution (detailed in Appendix E). EE_{ENV} results depends on the accuracy of the national waste and emission data, -10% reduction in EE_{ENV} results in the EEA_{eff} of 44,7%, It can be inferred that accuracy of data is moderately significant for CO Sector results.

As for IN Sector (EEA_{eff} is 57%), the sector is capital intensive and 60% of input flux is exergetic equivalent of capital input. Capital data of the country is definite and does not need a sensitivity analysis. Additionally, 19% of total input flux is constituted by EE_{ENV} of the sector. The accuracy of sectoral EE_{ENV} depends on the accuracy of the national waste and emission data which is computed based on some assumptions (Turkstat, 2010a, 2010b). But, reducing the EE_{ENV} to 90% and 80% of the present sectoral EE_{ENV} results in the EEA_{eff} of 57,5% and 58,5%, respectively. It can be inferred that accuracy of data is moderately significant for IN Sector results.

TR Sector (EEA_{eff} is 48%) is also a capital intensive sector which receives the 55% of the total influx as exergetic equivalent of capital input. Furthermore, 27% of the input flux is EE_{ENV} which is mainly constituted by sectoral gas emissions (Table 6.1). Reducing the quantity of EE_{ENV} to -10% of its presented exergetic resource use equivalent (90% of the presented EE_{ENV} in Table 6.5) causes in 49,3% EEA_{eff} (i.e., causes an considerable difference).

The highest input to the TE sector (EEA_{eff} is 87%) is capital input (71%of total input) but as it is stated above, capital fluxes are not subject to a sensitivity analysis. The second largest input is the exergy of imported materials (11%) and its effect on the sectoral EEA_{eff} is analyzed in Section 6.1.

As for DO sector (EEA_{eff} is 99%), the highest input fluxes are: capital (70%), EE_{ENV} (16%) and exergy of material consumption received from TE (TE,DO 14%). 10% increase in both of EE_{ENV} and TE,DO fluxes (separately) results in 98% EEA_{eff} which indicates that the effect of the fluxes except capital is not very dominant on the results.

6.2 Conclusion and Further Research Tasks

Since the system (Turkey) is a large and complex system and due to scarcity of necessary data, some assumptions which are made in computation of sectoral products and their transfers within the country were strictly necessary. It must be remarked that the accuracy of the results depends on some fundamental assumptions made in the specific applications and a sensitivity study for each of these assumptions ought to be carried out. This though exceeds the limits and the goals of the present thesis.

One of the main contributions of this thesis to the literature is the exact numbers of the environmental remediation cost (EE_{ENV}) for the solid and liquid waste and also gas emissions as well as discharged heat from the sectors obtained in line with the original calculation procedure of EE_{ENV} which is defined in EEA theory. To date in the literature, EE_{ENV} is computed by converting the monetary cost of effluent treatment process into exergetic equivalent (by means of ee_C). This is the first time in the scientific literature that numerical equivalents of environmental remediation costs are presented for a board range of effluent types. This must be also noticed that, in computation of environmental remediation costs, heat discharge and wastewater of the analyzed treatment systems are not taken into computation due to scarcity of data.

Effluent control & abatement techniques which are employed in this thesis are analyzed hypothetically but the analysis is conducted based on real data presented in the literature. Environmental remediation systems (treatment systems) are preferred primarily to be on “anaerobic digestion” and “recycling” based, to avoid from “incineration process” which is expected (on the basis of an educated guess) to have higher EE_{ENV} values originated by high incineration emissions and produced ash (25-30% wt. of the incinerated material) which must be discharged to the environment by trucks which is tantamount to consumption of fuel and having extra gas emissions due to transportation. But, it must be stated that, environmental remediation costs (EE_{ENV}) are computed on a defined disposal process chain for respective effluents. However, it is well known that different effluent remediation technologies carry different extended exergetic costs, and their EE_{ENV} values may differ. Hence, one of the welcome consequences of this thesis is the necessity of further examination of different effluent handling and treatment routes to determine the lowest extended exergetic cost of EE_{ENV}. But, present thesis presents the analysis of state-of-the-art, well-established and commercially mature industrial treatment technologies and the obtained EE_{ENV} results have the corresponding importance. The numerical results can in turn be used in the future EEA analyses.

It is worthy to state that computation route for the exergetic equivalent of labour and capital relies also on realistic assumptions which are proposed by EEA methodology. Hence, these values must be viewed as “approximate econometric indicators” rather than exact exergetic equivalents. However, they are very beneficial and instructive to compare the countries on the same basis.

On the basis of the study presented in this thesis, future work ought to be focused on the development and comparative assessment of alternative strategies to improve the societal resource consumption quality. It must be also highlighted that always there are possible remediation/improvement strategies which aim at raising the EEA_{eff} of the Sectors. But, not only the EEA_{eff} but also the total extended exergy (EE) consumption of each sector should be taken into account, since it is more reasonable to attack to the problem by striving for a little improvement in a high consumption sector: it is to be expected that such a strategy may require more immediate and less expensive (in an extended exergy sense) investments than making a global attack to other sectors with a lower extended exergy throughput. In other words, the answer of the question: *“at global scale (i.e., for the whole society) and in terms of resource use, is a net efficiency increase in a sector which covers a low percentage of the Country EE more beneficial or profitable than a smaller efficiency increase in a larger sector or not?”* must have been very well analyzed in planning and applying the improvements.

A cornerstone of sustainable development is the establishment of affordable, effective and truly sustainable resource management. The listed results of this thesis and presented remarks in Section 6.1 ought to be viewed as indicators of: quality of resource conversion in sectoral processes at the national level and resource consumption intensity in intrinsic societal resource utilization structure. However, a resource use analysis is necessary but not sufficient in order to conduct a strategy at national level and suggesting solutions for the diagnosed problems. Determination of resource use equivalent for different environmental remediation paths and choosing the less exergetically expensive solution of pollutant remediation, sustainability analysis of possible solutions are required further steps of this study. For instance, utilization of geothermal energy may be preferable from resource use consumption point of view in order to avoid from use of exergetically intensive fossil fuels and accompanying gas emissions but the use of geothermal energy is restricted by the renewability rate of geothermal resources. Hence, collective evaluation of the results from this and afformentioned further studies is necessary to gain a better understanding and deeper insight of the problems and thier solutions.

As it is seen in Section 5.4, EE_{ENV} of EX Sector solid and liquid waste is assumed to be zero. It is granted that this is a shortcoming of the presented study from the EEA application point of view but considering that no published data of solid and liquid waste composition of the sector and necessity of employing different techniques and technologies for the treatment, it was impossible to involve the treatment systems into this present thesis. This shortcoming of the study must be augmented by future reserches which include the technical details of the special systems of mining solid and liquid waste treatment.

In this study, buffering and capturing capacity of the environment (such as: photosynthesis, chemical buffering in the atmosphere and in the oceans, thermal evaporation and convection in the atmosphere and in the water reservoirs) is disregarded based on the fact that the analysis is performed for a very limited time scale (1 year). This poses another shortcoming of the present analysis and the effect of buffering by the environment must be internalized into the model.

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APPENDICES

APPENDIX A: Exergy of Minerals
APPENDIX B: Exergy of Fuels and Some Organic Materials
APPENDIX C: Exergy of Agricultural and Industrial Products
APPENDIX D: Energy and Exergy Consumption of Transportation Modes
APPENDIX E: Details of Material Transfer from TE to the Other Sectors
APPENDIX F: Sectoral Labour Consumption
APPENDIX G: Details of the Solid Waste Treatment Processes
APPENDIX H: Details of the Gas Emission Treatment Processes
APPENDIX I : Details of the Wastewater Treatment Process
APPENDIX J: Physical Exergy

APPENDIX A: Exergy of Minerals

Specific exergy of some minerals which are presented in Table 3.3 retrieved from Szargut et al.(1988). In Table A.1., details of specific exergy calculation is presented.

Table A.1: Chemical formula and exergy of some minerals.

	Chemical Formula	Molar weight (gr)	Chemical Exergy (KJ/mole)	Chemical Exergy (MJ/Ton)
Barite	$BaSO_4$	233,39	3,4	14,57
Boron	B	10,81	628,5	58135,23
Chert (Flint)	SiO_2	60,08	7,9	131,49
Dolomite	$CaMg(CO_3)_2$	184,41	15,1	81,88
Fluorite	CaF_2	78,08	11,4	146,01
Phosphate	$Ca_3(PO_4)_2$	310,18	19,4	62,54
Graphite	C	12	410,26	34188,33
Chalcedony	SiO_2	60,08	1,9	31,62
Kaolinite	$Al_2Si_2O_5(OH)_4$	258,16	197,8	766,19
Quartz	SiO_2	60,08	1,9	31,62
Quartz sand	SiO_2	60,08	7,9	131,49
Quartzite	SiO_2	60,08	7,9	131,49
Sulphur	S	32,06	609,6	19011,98
Magnesite	$MgCO_3$	84,31	37,9	449,53
Calcite	$CaCO_3$	100,09	1,00	9,99
Silex (Flintstone)	SiO_2	60,08	7,9	131,49
Sodium chloride	NaCl	58,44	14,30	244,70
Sodium sulfate	Na_2SO_4	142,04	21,4	150,66
Talc	$Mg_3Si_4O_{10}(OH)_2$	379,29	36,5	96,23
Salts	NaCl	58,44	14,30	244,70
Carbonmonoxide	CO_2	44,01	19,87	451,49
Limestone	%90 $CaCO_3$	100,09	1,00	9,99
Greywacke	70% SiO_2	60,08	7,9	131,49
Serpentine (Crysolite)	$Mg_3Si_2O_5(OH)_4$	277,11	61,3	221,21
Gypsum	$CaSO_4$.$2H_2O$	172,17	8,6	49,95
Marble	%95 $CaCO_3$	100,09	1,00	9,99
Onyx	$CaCO_3$	100,09	1,00	9,99
Travertine	$CaCO_3$	100,09	1,00	9,99
Dressing stone+ Mosaic+Slate	$CaCO_3$	100,09	1,00	9,99
Unroasted iron pyrites	FeS_2	119,97	1428,7	11908,31
Graphite	C	12	410,26	34188,33
Sand	SiO_2	60,08	7,9	131,49
Phosphate	$Ca_3(PO_4)_2$	310,18	19,4	62,54
Zircon	$ZrSiO_4$	183,31	20	109,10
Celestine	$SrSO_4$	183,68	7,1	38,65

Exergy of feldspar is obtained from Valero (2008). Although the reference environment is composed differently in Valero (2008), results are closed to Szargut et al. (1988). Hence, exergy of feldspar (Feldspar Orthoclase/ K-feldspar, $KAlSi_3O_8$) is taken as 99,9 KJ/mole (358,917 MJ/Ton).

The exergy of the remaining minerals are calculated and presented in Table A.2. A mineral deposit is an aggregate of rocks. Rocks are aggregates of mineral grains. Mineral grains are aggregates of molecules which in turn are organized aggregates of atoms (Rosa and Rosa, 2008; Valero et al., 2002). Equation (A.1) summarizes this explained structure of minerals.

$$\mathrm{Mine} = \sum \mathrm{rocks} = \sum\sum \mathrm{minerals} = \sum\sum\sum \mathrm{molecules} = \sum\sum\sum\sum \mathrm{atoms} \qquad \textbf{(A.1)}$$

In equation (A.1), the aggregation of molecules, atoms etc. is fulfilled by cohesion or bond energy (Rosa and Rosa, 2008). In this thesis, these energies between molecules of considered minerals are neglected. In Table A.2., molar weight and chemical exergy of compounds composing the minerals are presented (Szargut et al., 1988). In Table A.3., composition and chemical exergy of considered minerals are seen.

Table A.2 : Molar weight and chemical exergy of compounds.

	Molar weight (gr)	Chemical exergy (KJ/mole)	Chemical exergy (MJ/Ton)
K_2O	94,20	413,10	4385,21
Al_2O_3	101,96	200,40	1965,48
H_2O	18,00	0,90	50,00
SO_3	80,06	249,10	3111,42
Fe_2O_3	159,69	16,50	103,33
CaO	56,08	110,20	1965,05
MgO	40,31	66,80	1657,16
Na_2O	61,98	296,20	4778,96
TiO_2	79,90	21,40	267,83
BaO	153,34	224,60	1464,72
SiO_2	60,09	7,90	131,48
FeO	71,85	127,00	1767,67
CO_2	44,01	19,87	451,49
P_2O_5	142,39	412,80	2899,08
MnO	70,93	119,40	1683,35

Table A.3 : Chemical exergy of minerals.

	Alunite	Bentonite	Diatomite	Illite	Montmorillonite	Olivine	Perlite	Rottenstone (pumice)
Composition (wt.%)								
K_2O	11,37			7,26			5,00	4,00
Al_2O_3	36,92	32,74	4,60	17,00	18,00		12,50	15,00
H_2O	13,05	9,26	5,30	12,03	36,09		2,00	
SO_3	38,66							
Fe_2O_3			2,00				1,50	3,00
CaO			2,50		1,02		2,00	3,00
MgO			0,64	3,11		42,06	0,50	3,00
Na_2O		3,98	1,60		1,13		3,00	4,00
TiO_2			0,23				0,20	
BaO								
SiO_2		54,02	83,13	56,00	43,77	39,19	73,30	68,00
FeO				4,60		18,75		
CO_2								
P_2O_5								
MnO								
Exergy (MJ/Ton)	2433,65	909,36	340,62	814,16	514,63	1079,97	754,83	862,56

Table A.3 (continued) : Chemical exergy of minerals.

	Sepiolite	Trona	Grindstone	Clay	Pyrophyllite	Trass	Diabase	Ignimbrite	Andesite
Composition (wt.%)									
K_2O				0,08		2,44		4,81	
Al_2O_3			65,00	2,50	28,30	12,35	15,20	15,33	18,10
H_2O	17,00	19,93	2,00		5,00				
SO_3									
Fe_2O_3			32,00	31,60		1,40		4,90	7,10
CaO						2,42	11,50	2,00	11,60
MgO	26,27			27,20		0,45		0,53	4,00
Na_2O		41,13		2,14		4,13	1,70	5,46	
TiO_2				1,00				0,42	0,70
BaO									
SiO_2	56,73		1,00	35,50	66,70	76,82	71,60	66,55	58,50
FeO									
CO_2		38,94							
P_2O_5									
MnO									
Exergy (MJ/Ton)	521,19	439,90	1312,94	697,99	646,43	687,03	674,21	914,73	601,79

Table A.3 (continued) : Chemical exergy of minerals.

	Basalt	Granite	Andalusite	China Clay	Leucite	Vermi-culite	Mica	Ceramic clay	Asbestos (Tremolite)
Composition (wt.%)									
K_2O	0,82	4,12			21,58	5,93	11,80		
Al_2O_3	15,82	14,42	62,70	39,50	23,36	12,01	38,50	34,66	
H_2O				13,96		5,29	4,50	24,48	2,22
SO_3									
Fe_2O_3	8,29	1,22				13,00			
CaO	9,51	1,82				1,54			13,80
MgO	7,39	0,71				20,63			24,81
Na_2O	4,67	3,69							
TiO_2	2,35	0,30				1,44			
BaO									
SiO_2	49,88	72,04	37,30	46,54	55,06	40,16	45,20	40,86	59,17
FeO		1,68							
CO_2									
P_2O_5	1,27	0,12							
MnO		0,05							
Exergy (MJ/Ton)	977,06	820,96	1281,40	844,53	1477,86	951,51	1335,84	747,29	761,22

In Table A.4, references for the composition of minerals which are listed in Table A.3 are presented.

Table A.4: References of mineral compositions.

Mineral	Reference
Alunite, bentonite, illite, montmorillonite, olivine, sepiolite, trona, grindstone, pyrophyllite, diabase, granite, leucite and asbestos (tremolite)	Url-5
Diatomite and perlite	Republic of Turkey-State Planning Organization (2001a)
Rottenstone (pumice)	Ozkan and Tuncer (2001)
Clay	Sturz et al. (1998)
Trass	Celik and Yurter (2004)
Ignimbrite	Simsek and Erdal (2004)
Andesite	Khizanishvili and Gaprindashvili (2006)
Basalt	Uz (1999)
Andalusite	Republic of Turkey-State Planning Organization (2001b)
China clay	Url-3
Vermiculite	Republic of Turkey-State Planning Organization (2001d)
Mica	Url-4
Ceramic clay	Republic of Turkey-State Planning Organization (2001c)

Domestic ore production of Turkish mines is presented in Table 3.1. Data necessary for ore exergy calculation is presented in Table A.5 and A.6. In the tables, standard chemical exergy of minerals and metals is obtained from Szargut et al.(1988).

Table A.5 : Ore (domestic production) exergy calculation.

Ore	Mineral	Standard Chemical Exergy of Mineral (KJ/mole)	Ore Grade (%wt. metal)	Metal Molar Weight (g)	Mole of Metal (mole/ore ton)	Mole of Mineral (mole/ore ton)	Exergy of ore (MJ/Ton)
Iron	Fe_2O_3 (Hematite)	16,5	54	55,85	9669,62	4834,81	79,77
Antimony	Sb_2S_3 (Stibnite)	2526,7	8,01	121,76	657,85	328,93	831,1
Copper	$CuFeS_2$ (chalcopyrite)	1538,9	2,16	63,55	339,91	339,91	523,09
Zinc	ZnS (Sphalerite)	747,6	10,83	65,41	1655,74	1655,74	1237,83
Cadmium	CdS (Greenockite)	746,9	0,055	121,41	4,53	4,53	3,38
Chromium	$FeCr_2O_4$ (Chromite)	129,1	40	52	7692,9	3846,45	496,58
Lead	PbS (Galena)	743,7	7,73	106,42	726,37	726,37	540,2
Manganese	MnO_2 (Pyrolusite)	21,2	34,54	54,94	6287,09	6287,09	133,29
Nickel	NiAs (Nickeline)	726,5	1,73	58,69	294,75	294,75	214,14
Pyrite	FeS_2 (Pyrite)	1428,7	30	55,85	5372,01	5372,01	7674,99
Bauxite	Al_2O_3 (Corundum)	200,4	30	26,98	11119,35	5559,67	1114,16

In Table A.6, computed exergy of gold and silver ores are presented.

Table A.6 : Gold and silver ore exergy calculation.

Ore	Metal	Standard chemical exergy of metal (KJ/mole)	Ore Grade (g metal/Ton)	Metal Molar Weight (g)	Mole of Element (mole/ore ton)	Exergy of ore (MJ/Ton)
Gold	Au (Gold)	15,4	7,25	196,97	0,037	0,0046
Silver	Ag (Silver)	70,2	83,49	107,87	0,77	0,05

Presented ore grades in Table A.5 and A.6 are computed as the average of Turkish reserves which are retrieved from references seen in Table A.7.

Table A.7 : References of ore grades.

Ore	Reference
Iron	Republic of Turkey-State Planning Organization (2001h)
Antimony	Republic of Turkey-State Planning Organization (2001i)
Copper	Republic of Turkey-State Planning Organization (2001e)
Zinc	Republic of Turkey-State Planning Organization (2001k)
Cadmium	Republic of Turkey-State Planning Organization (2001k)
Chromium	Republic of Turkey-State Planning Organization (2001j)
Lead	Republic of Turkey-State Planning Organization (2001k)
Manganese	Republic of Turkey-State Planning Organization (2001i)
Nickel	Republic of Turkey-State Planning Organization (2001i)
Pyrite	Republic of Turkey-State Planning Organization (2001e)
Bauxite	Republic of Turkey-State Planning Organization (2001f)
Gold	Republic of Turkey-State Planning Organization (2001g)
Silver	Republic of Turkey-State Planning Organization (2001g)

APPENDIX B: Exergy of Fuels and Some Organic Materials

B.1. Exergy of Fuels

Specific standard chemical exergy, e^0_{ch} (MJ/Ton), for solid and liquid fuels, CHP (combined heat and power) and geothermal heat are computed as detailed below.

As for fuels which are listed in Table B.1, specific high energy content, HHV (MJ/Ton), is retrieved from Republic of Turkey-Ministry of Energy and Natural Resources (n.d.). For fuels in Table B.1, following the standard chemical exergy calculation methodology presented in Section 2.3.1, equation (B.1) is employed. In Table B.1, β_{HHV} values of fuels are presented. (For the sake of simplicity, specific standard chemical exergy, e^0_{ch}, is abbreviated as "specific exergy" in this thesis and in Table B.1)

$$e^0_{ch} = \beta_{HHV} \text{ x HHV} \tag{B.1}$$

Table B.1: Specific exergy and β_{HHV} for fuels.

	Specific Energy (HHV) (MJ/Ton)	β_{HHV}	Specific Exergy (MJ/Ton)	Reference
Hard Coal	27048,9	1,03	27860,36	Szargut et al. (1988)
Asphaltite	18062,52	1,03	18604,4	Szargut et al. (1988)
Lignite	7941,61	1,04	8259,27	Szargut et al. (1988); Camdali and Ediger (2007)
Crude Oil	43945,91	0,99	43506,45	Camdali and Ediger (2007)
Coke	29260	1,04	30430,4	Szargut et al. (1988); Oladiran and Meyer (2007)
Briquette	15500,98	1,04	16121,02	Assumed as the same as lignite and coke.
Rafinery Gas	36760,1	0,92	33819,29	Szargut et al. (1988); Oladiran and Meyer (2007)
LPG	47310,86	0,99	46837,75	Utlu and Hepbasli (2007b)
Motor gasoline	44798,76	0,99	44350,77	Szargut et al. (1988); Oladiran and Meyer (2007)
Aviation fuel	44589,42	1,00	44589,42	Assumed to be "1"
Karosene	43752,06	0,99	43314,54	Oladiran and Meyer (2007); Dincer et al. (2005)
Diesel	43333,38	1,07	46366,72	Utlu and Hepbasli (2006b)
Heavy fuel oil	40193,28	0,99	39791,35	Szargut et al. (1988)
Naphtha	45008,1	1,00	45008,1	Assumed to be "1"
Petroleum Coke	31819,69	1,04	33092,47	Utlu and Hepbasli (2006c)
Other petroleum products	40193,28	1,00	40193,28	Assumed to be "1"
Liquid bio-mass	41868	1,05	43961,4	Assumed to be the same as solid biomass
Biogas		1,05		Assumed to be the same as solid biomass
Coke oven gas		0,89		Szargut et al. (1988)
Blast Furnace Gas		0,97		Szargut et al. (1988)
Solid Biomass		1,05		Computed later in this section
Natural Gas		0,92		Szargut et al. (1988); Camdali and Ediger (2007)

In the published country energy balance for Turkey (IEA, 2008), for biogas, coke oven gas, blast furnace gas, solid biomass and natural gas, only the energetic equivalent

(HHV) of production and consumption is available. Hence, β_{HHV} is used to obtain the exergetic equivalent. This is because, only β_{HHV} is presented in Table B.1.

B.2. Exergy of Agricultural Waste

Exergy of agricultural waste and wood (together consisting of solid biomass) is calculated on the basis of equation (2.10) and (2.11), respectively.

For agricultural waste, an approximate composition (as received) is obtained form Bilgen et al. (2004) and presented in Table B.2.

Table B.2 : Ultimate analysis of agricultural waste and wood (ar).

	Agricultural waste (wt.% ar)	Wood (wt.% ar)
C	48,3	52,1
H	5,7	6,1
O	45,3	41
N	0,7	0,2

HHV of the waste is calculated by the empiric equation proposed by Bilgen et al. (2004) for biomass samples (equation (B.2)).

$$HHV_{ar}\,(MJ/kg) = \left[33{,}5(C) + 142{,}3(H) - 15{,}4(O) - 14{,}5(N)\right] x 10^{-2} \qquad \textbf{(B.2)}$$

where HHV_{ar} is HHV of as received (wet basis) sample, C is weight percent of carbon, H is weight percent of hydrogen, O is weight percent of oxygen, N is weight percent of nitrogen in the considered sample.

$$LHV_{ar} = HHV_{ar} - \frac{m_{H2O}}{m_{fu}} h_{fg} = HHV - 8{,}94 X_H\, h_{fg} \qquad \textbf{(B.3)}$$

where LHV_{ar} is LHV of as received (wet basis) sample, m_{H2O}(kg) is the mass of H_2O produced by combustion of the sample, m_{fu}(kg) is the mass of the sample, X_H is the mass friction of hydrogen in the sample, h_{fg} (MJ/kg).is the enthalpy of the evaporation of water (at standard environmental conditions); the numerical value (8,94 X_H) is equal to the ratio of $\frac{m_{H2O}}{m_{fu}}$. At the standard environmental conditions (25°C and 1 atm) h_{fg} is the 2,4423 MJ/kg (Ertesvag, 2000).

To calculate β_{LHV}, equation (2.19) is used as presented in equation (B.4).

$$\beta_{LHV} = \frac{1{,}0412 + 0{,}216\left(\frac{z_{H_2}}{z_C}\right) - 0{,}2499\left(\frac{z_{O_2}}{z_C}\right)\left[1 + 0{,}7884\left(\frac{z_{H_2}}{z_C}\right)\right] + 0{,}045\left(\frac{z_{N_2}}{z_C}\right)}{1 - 0{,}3035\left(\frac{z_{O_2}}{z_C}\right)} \tag{B.4}$$

where z_{H2}, z_C, z_{O2},z_{N2} are hydrogen, carbon, oxygen and nitrogen mass fractions in the sample.

For the calculation of exergy (E) and β_{HHV}:

$$E = \beta_{LHV} \text{ x } LHV \tag{B.5}$$

$$E = \beta_{HHV} \text{ x } HHV \Rightarrow \beta_{HHV} = E / HHV \tag{B.6}$$

equations are used.

Applying the set of equations between (B.2) and (B.6) to the considered sample, HHV, LHV, β_{LHV}, E and β_{HHV} results of the agricultural waste and wood are presented in Table B.3. As it is seen in the table, β_{HHV} is 1,05 for both of the samples.

Table B.3 : HHV, LHV, β_{LHV}, β_{HHV} and E of agricultural waste and wood.

	Agricultural waste	Wood
HHV_{ar} (MJ/kg)	17,21	19,79
LHV_{ar} (MJ/kg)	15,96	18,46
β_{LHV}	1,13	1,12
β_{HHV}	1,05	1,05
E (MJ/kg)	18,1	20,66

Density of different types of wood varies in a board range (Přemyslovská et al., 2007; FAO, n.d.). In this thesis, wood products are assumed to have the average density of 420 kg/m^3 (Torgovnikov and Vinden, 2009). Hence, exergy of wood is equal to 8676,44 MJ/m^3.

B.3. Geothermal Heat for Direct Use and CHP Heat

Geothermal energy is used for both of electricity generation and direct use (heat utilization). For direct use, it is assumed that hot water reaches the ground at the temperature of 60°C (333,15 K) on average (based on the data in Gunerhan et al. (2001)). As stated in Section 2.3.2., exergy of utilized geothermal energy (E_{geo}) is calculated as:

$$E_{geo} = \left(\frac{T - T_0}{T}\right) Q_{geo} \qquad \textbf{(B.7)}$$

where T is the temperature of geothermal hot water, T_0 is the temperature of the environment. Average environmental temperature of Turkey is 14°C (278,15 K) in 2006 and Q_{geo} is the geothermal heat transferred to earth surface.

Correlating the equation (B.7) with equation (B.6) and defining $\left(\frac{T - T_0}{T}\right)$ as exergy coefficient (β_{HHV}) for geothermal heat, β_{HHV} is obtained as 0,13.

B.4. Exergy of Asphalt

In Url-1, composition of asphalt (wt%) is presented as: 79–88% carbon, 7–13% hydrogen, 7-8% sulfur, 2–8% oxygen, and 2-3% nitrogen. In Table B.4, assumed composition of asphalt is presented.

Table B.4 : Ultimate analysis of asphalt.

Element	wt% ar
C	81%
H	7%
S	7%
O	3%
N	2%

Another empiric equation, Boie correlation (for solid fuels), is employed for calculation of HHV_{ar} which is presented in equation (B.8) (Ringen et al., 1979).

$$HHV_{ar}(\text{cal/mole C}) = 100890 + 27990\left(\frac{H}{C}\right)_a - 42400\left(\frac{O}{C}\right)_a + 21010\left(\frac{N}{C}\right)_a + 80160\left(\frac{S}{C}\right)_a \qquad \textbf{(B.8)}$$

where coefficients $\left(\frac{H}{C}\right)_a$, $\left(\frac{O}{C}\right)_a$, $\left(\frac{N}{C}\right)_a$ and $\left(\frac{S}{C}\right)_a$ are the ratios of atom numbers of hydrogen, oxygen, nitrogen and sulfur elements to the number of carbon atoms, respectively.

For the presented composition of asphalt in Table B.4, $\left(\frac{H}{C}\right)_a$, $\left(\frac{O}{C}\right)_a$, $\left(\frac{N}{C}\right)_a$ and $\left(\frac{S}{C}\right)_a$ are presented in Table B.5.

Table B.5 : Coefficients of Boie correlation for asphalt.

Coefficients	
$\left(\frac{H}{C}\right)_a$	1,037
$\left(\frac{S}{C}\right)_a$	0,032
$\left(\frac{O}{C}\right)_a$	0,028
$\left(\frac{N}{C}\right)_a$	0,042

β_{LHV} is calculated via equation (2.16):

$$\beta_{LHV} = 1,0437 + 0,014\left(\frac{H}{C}\right)_a + 0,0968\left(\frac{O}{C}\right)_a + 0,0467\left(\frac{N}{C}\right)_a \qquad \textbf{(B.9)}$$

Applying the equation (B.8), (B.3), (B.9), (B.5) and (B.6), obtained results of HHV, LHV, β_{LHV}, β_{HHV} and E of asphalt are presented in Table B.6.

Table B.6 : HHV, LHV, β_{LHV}, β_{HHV} and E of asphalt.

HHV (MJ/kg)	37,31
LHV (MJ/kg)	35,78
β_{LHV}	1,06
β_{HHV}	1,02
E (MJ/kg)	38,03

B.5. Exergy of Paraffine Wax

Chemical formula of the paraffine wax is $C_{25}H_{52}$ (n-Pentacosane). Lloyd correlation (for liquid fuels) is employed for calculation of HHV_{ar} (as received) and is presented in equation (B.10) (Lloyd and Davenport, 1980).

$$HHV_{ar}\,(cal/moleC) = 102720 + 27360\left(\frac{H}{C}\right)_a - 32320\left(\frac{O}{C}\right)_a + 19890\left(\frac{N}{C}\right)_a + 85740\left(\frac{S}{C}\right)_a \quad \textbf{(B.10)}$$

To compute β_{LHV}, equation 2.13 is used as:

$$1{,}0406 + 0{,}0144\left(\frac{H}{C}\right)_a \quad \textbf{(B.11)}$$

For the presented composition of paraffine wax, $\left(\frac{H}{C}\right)_a$ is 2,08.

Following the same calculation route in Section B.4, obtained results are seen in Table B.7.

Table B.7 : HHV, LHV, β_{LHV}, β_{HHV} and E of paraffine wax.

HHV (MJ/kg)	47,39
LHV (MJ/kg)	42,27
β_{LHV}	1,07
β_{HHV}	0,96
E (MJ/kg)	45,30

APPENDIX C: Exergy of Agricultural and Industrial Products

C.1. Exergy of Agricultural Products

Exergetic content of the agricultural products are inserted into Table 4.4, Table 4.10 and Table 4.12 by means of exergy data available in the literature. Exergy of the products and the respective source of data are presented in Table C.1.

Table C.1: Exergy of AG sector products.

	Specific Exergy (MJ/Ton)	Reference
Fruit	1900	Chen and Chen,2009; Chen and Chen,2006; Ertesvag and Mielnik,2000
Cereals		
Barley	14800	Ertesvag and Mielnik,2000
Wheat	17400	Wall et al.,1994
Maize	16400	Wall et al.,1994
Rice	15200	Chen and Chen,2009; Chen and Chen,2006; Wall et al.,1994
Leguminous seeds	16900	Wall et al.,1994
Vegetables	1900	Chen and Chen,2009; Chen and Chen,2006; Ertesvag and Mielnik,2000; Wall et al., 1994
Meat	10000	Chen and Chen,2009; Chen and Chen,2006; Wall et al.,1994
Poultry	4500	Chen and Chen,2009; Chen and Chen,2006
Fish products	5750	Chen and Chen,2009; Chen and Chen,2006; Ertesvag and Mielnik,2000
Milk	4900	Chen and Chen,2009; Chen and Chen,2006; Ertesvag and Mielnik,2000
Egg	7000	Ertesvag and Mielnik,2000; Wall et al.,1994
Honey	15200	Ertesvag and Mielnik,2000
Bee wax	15200	Ertesvag and Mielnik,2000
Others		
Olive	19000	Wall et al.,1994
Tobacco	10700	Chen and Chen,2009; Chen and Chen,2006
Sunflower	19000	Wall et al.,1994
Rape	37000	Chen and Chen,2009; Chen and Chen,2006
Cotton	16700	Chen and Chen,2009; Chen and Chen,2006
Soybean	16600	Wall et al.,1994
Sugar beet	4200	Chen and Chen,2009; Chen and Chen,2006; Wall et al.,1994
Tea	10700	Ertesvag and Mielnik,2000
Potato	4200	Chen and Chen,2009; Chen and Chen,2006; Wall et al.,1994

As for AG sector products seen in Table 4.6, exergy of puppy, lupin and hop is assumed to be equal to the exergy of hay (15300 MJ/Ton) which is available in the studies of Ertesvag and Mielnik (2000) and Wall et al. (1994). Products which are used for fodder industry (cow vetches, sainfoin, wild vetches, fodder beet, clover, and alfalfa) are assumed to have the same exergetic content of the “green fodder” whose exergy content (16700 MJ/Ton) is obtainable in the study of Ertesvag and Mielnik (2000) and a closed value is also assigned to that of “fodder” in the study of Wall et al. (1994). As for the products used in textile industry (silk cocoons, wool, hair, mohair, hemp), presented exergetic contents are totally derived from Chen and Chen (2009) and Chen and Chen (2006). Exergy of cotton is already presented in Table C.1. Exergy of flax is assumed to be equal to the exergy of hemp. Exergy of hide is calculated in Section C.4. Exergetic content for most of the AG products used in “seed industry” and “other industrial purposes” have already presented above in this chapter. As it is seen in Table 4.4., chickpea, dry bean, red lentil, green lentil are included in the group of leguminous seeds and their exergy is presented in Table C.1. The exergy of paddy, sorghum, sudan grass is assumed to be the same as exergy of “green fodder” (16700 MJ/Ton). The source of exergy data for groundnut and sesame is Chen and Chen (2009) and Chen and Chen (2006).

C.2. Exergy of Industrial Sector Products

Exergy of materials presented in Section 4.3 (as industrial sector outputs) is presented in Table C.2.

Table C.2 : Exergy of IN sector products.

	Specific Exergy (MJ/Ton)	Reference
Silk	4560	Chen and Chen,2009; Chen and Chen,2006
Wool, animal hair, yarns	5850	Assumed as the average of mohair and wool
Cotton yarn	16700	Zhang and Chen, 2010
Natural fiber	4,93	Chen and Chen,2006
Synthetic fibre	18484,54	Chen and Chen,2009; Chen and Chen,2006
Other fabric	4,16	Chen and Chen,2006
Paper and cupboard	17000	Chen and Chen,2009; Chen and Chen,2006; Ertesvag and Mielnik,2000; Gasparatos et al., 2009a
Plastic	32502,16	Chen and Qi, 2007; Chen and Chen,2009
Synthetic rubber	32502,16	Assumed as the same as plastic
Cement	1500	Chen and Chen,2009; Chen and Chen,2006; Zhang and Chen, 2010
Glass (SiO_2)	131,48	Szargut, 1988
Concrete	1500	Assumed as the same as cement
Brick	1079,97	Assumed as the same as olivine – Appendix A
Tile	1079,97	Assumed as the same as olivine - Appendix A
Lime	9,99	Assumed as the same as limesone – Appendix A
Plaster ($CaSO_4 .2H_2O$)	49,95	Szargut, 1988

C.3. Exergy of Metals

As for exergy of metals in Table 4.19, exergy of steel is obtained from Chen and Chen (2009), Chen and Chen (2006), Zhang and Chen (2010), Ertesvag and Mielnik (2000) and Gasparatos et al. (2009) as 6800 MJ/Ton. Exergy of the remaining metals is derived from Szargut et al. (1988).

In Table 4.20, “metal” is assumed to be half iron and half aluminium since they are the most recycling matels in Turkey. Exergy of iron and aluminium are extracted from Szargut et al. (1988) and the average (exergy of metal) is presented in Table C.3.

Table C.3 : Exergy of metal.

	Exergy (MJ/Ton)
Iron	6740,69
Aluminium	32903,70
Average	19834

C.4. Exergy of Hide

Composition of hide is retrieved from ECN (n.d.) and presented in Table C.4.

Table C.4 : Ultimate analysis of hide.

	wt.% dry	wt.% ar
C	50,40	44,90
H	7,76	6,90
O	22,80	20,30
N	11,60	10,33
S	1,85	1,65
w		10,9
ash	5,3	4,7

In Table C.4., C, H, O, N, S, w and ash signify weight percent of carbon, hydrogen, oxygen, nitrogen, sulphur, water and ash in the composition of the sample, respectively. “wt% dry” and “wt% ar” denote the composition in “dry material” and in “as received material”, respectively.

In equation (C.1), Milne formula is presented where C_{dry}, H_{dry}, O_{dry}, N_{dry}, S_{dry} and ash_{dry} are the weight percent of carbon, hydrogen, oxygen, nitrogen, sulphur and ash in dry material. HHV_{dry} (MJ/kg) is the high heating value of dry material. Equation (C.1) is an empirical formula to calculate the HHV_{dry} of organic substances (Milne et al.,1990; ECN, n.d.).

$$HHV_{dry} = 0{,}341C_{dry} + 1{,}322\,H_{dry} - 0{,}12\,O_{dry} - 0{,}12\,N_{dry} + 0{,}0686S_{dry} - 0{,}0153ash_{dry} \quad \textbf{(C.5)}$$

Substituting the necessary data from Table C.4, HHV_{dry} of hide is obtained as 23,36 MJ/kg. HHV_{ar} is calculated via equation (C.2) (Ertesvag, 2000; ECN, n.d.):

$$HHV_{ar} = HHV_{dry}\,(1 - \frac{w}{100}) \quad \textbf{(C.2)}$$

LHV_{ar} is calculated via equation (C.3) (Ertesvag, 2000):

$$LHV_{ar} = HHV_{ar} - \frac{m_{H2O}}{m_{fu}} h_{fg} = HHV - 8{,}94 X_H\, h_{fg} \quad \textbf{(C.3)}$$

where m_{H2O}(kg) is the mass of H_2O produced by combustion of the sample, m_{fu}(kg) is the mass of the sample, X_H is the mass friction of hydrogen in the sample (in as received composition, 0,069 for hide, see Table C.4), h_{fg} (MJ/kg) is the enthalpy of evaporation of water (at standard environmental conditions); the numerical value (8,94 X_H) is equal to the ratio of $\frac{m_{H2O}}{m_{fu}}$. At the standard environmental conditions (25°C and 1 atm) h_{fg} is the 2,4423 MJ/kg (Ertesvag, 2000). In earlier chapters of the thesis, HHV and LHV are used to denote HHV_{ar} and LHV_{ar}.

$\left(\frac{H}{C}\right)_a$, $\left(\frac{O}{C}\right)_a$, $\left(\frac{N}{C}\right)_a$ are atomic ratio of the corresponding elements and they are 1,84, 0,34 and 0,2 for hide, respectively. For organic materials which complies $\left(\frac{O}{C}\right)_a \leq 0{,}5$, equation (2.16) is appropriate to calculate β_{LHV} as presented in equation (C.4).

$$\beta_{LHV} = 1{,}0437 + 0{,}014\left(\frac{H}{C}\right)_a + 0{,}0968\left(\frac{O}{C}\right)_a + 0{,}0467\left(\frac{N}{C}\right)_a \quad \textbf{(C.4)}$$

Exergy (E) and β_{HHV} of the considered sample is calculated via equations (C.5) and (C.6).

$$E = \beta_{LHV} \text{ x } LHV_{ar} \quad \textbf{(C.5)}$$

$$\beta_{HHV} = E / HHV_{ar} \quad \textbf{(C.6)}$$

Results of the above equations for hide are presented in Table C.5.

Table C.5 : HHV_{ar}, LHV_{ar}, β_{LHV}, β_{HHV} and E of hide.

HHV_{dry} (MJ/kg)	23,36
HHV_{ar} (MJ/kg)	20,81
LHV_{ar} (MJ/kg)	18,78
β_{LHV}	1,11
β_{HHV}	1,01
E (MJ/kg)	20,848

C.5. Exergy of Organic Waste

An approximate composition (as received) of organic municipal solid waste is obtained form Cherubini et al. (2009) and presented in Table C.6.

Table C.6 : Ultimate analysis of organic solid waste.

	wt.% ar
C	48
H	6,4
O	37,6
N	2,6
S	0,4
ash	5

HHV_{ar} of organic waste is calculated by the empiric equation proposed by Bilgen et al. (2004) for biomass samples and presented in equation (C.7).

$$HHV_{ar}\ (MJ / kg) = [33{,}5(C) + 142{,}3(H) - 15{,}4(O) - 14{,}5(N)]x10^{-2} \quad \textbf{(C.7)}$$

where HHV_{ar} is HHV of as received (wet basis) sample (MJ/kg), C, H, O, N, S and ash signify weight percent of carbon, hydrogen, oxygen, nitrogen, sulphur and ash in the composition of the sample which is provided in Table C.6.

Applying the calculation route n Section C.4, obtained results are presented in Table C.7. As for calculation of β_{LHV}, equation (2.17) is used.

Table C.7 : HHV_{ar}, LHV_{ar}, β_{LHV}, β_{HHV} and E of organic waste.

HHV_{ar} (MJ/kg)	19,02
LHV_{ar} (MJ/kg)	17,78
β_{LHV}	1,12
β_{HHV}	1,05
E (MJ/kg)	19,92

C.6. Exergy of Compost

Composition of composted organic waste is presented in Table C.8 which is extracted from Kratzeisen et. al. (2010).

Table C.8 : Ultimate analysis of compost.

	wt% ar
C	45,3
H	5,2
O	28,4
N	2,9
S	0,9

Following the same calculation route in Section C.5 and occupying equation (2.16) for calculation of β_{LHV}, results presented in Table C.9 are derived.

Table C.9 : HHV_{ar}, LHV_{ar}, β_{LHV}, β_{HHV} and E of compost.

HHV_{ar} (MJ/kg)	17,78
LHV_{ar} (MJ/kg)	16,54
β_{LHV}	1,11
β_{HHV}	1,03
E (MJ/kg)	18,37

APPENDIX D: Energy and Exergy Consumption of Transportation Modes

D.1. Energy and Exergy Consumption of Transportation Modes

Energy and exergy consumption of transportation modes are seen in Table D.1 based on data presented in IEA (2008).

Table D.1: Energy carrier and exergy consumption in transportation modes.

	LPG (1000 Ton)	Motor Gasoline (1000 Ton)	Aviation Fuel (1000 Ton)	Diesel (1000 Ton)	Heavy Fuel Oil (1000 Ton)	Liquid Biomass (1000 Ton)
Rail	0	0	0	214	0	0
Air	0	0	1723	0	0	0
Marine	0	0	0	345	112	0
Road	1570	2702	0	7661	0	2
Pipeline transport	0	0	0	0	0	0
Non specified	0	0	0	0	0	0
Total Consumption	1570	2702	1723	8220	112	2
Energy (HHV) (MJ/Ton)	47310,9	44798,77	44589,4	43333,38	40193,3	41868
Total Energy (HHV) (TJ)	74278,06	121046,26	76827,56	356200,38	4501,65	83,74
Exergy (MJ/Ton)	46837,8	44350,77	44589,4	46366,72	39791,4	43961,4
Exergy coefficient (β_{HHV})						
Total Exergy (TJ)	73535,28	119835,79	76827,57	381134,41	4456,63	87,92

Table D.1 (continued): Energy carrier and exergy consumption in transportation modes.

	Natural Gas (TJ)	Electricity (TJ)	Total Energy (HHV) (TJ)	Total Exergy (TJ)
Rail	0	810	10083,34	10732,48
Air	0	0	76827,56	76827,57
Marine	0	0	19451,66	20453,15
Road	165	0	527550,07	548826,21
Pipeline transport	5227	522	5749,00	5330,84
Non specified	0	1512	1512	1512
Total Consumption	5392	2844		
Energy (HHV) (MJ/Ton)				
Total Energy (HHV) (TJ)	5392	2844	641173,65	
Exergy (MJ/Ton)				
Exergy coefficient (β_{HHV})	0,92	1		
Total Exergy (TJ)	4960,64	2844,00		663682,24

D.2. Allocation of Fuel Consumption in TR Sector Service

Below listed assumptions are applied in order to determine the transportation sector output.

1) In each transportation mode, allocation of energy use between freight and passenger transportation is conducted based on total freight-km (ton-km) and passenger-km (retrieved from Republic of Turkey Prime Ministry-Investment Support and Promotion Agency of Turkey (2010a)). Energy use for *unit ton-km* and *passenger-km* has been retrieved from Union of Chambers of Turkish Engineers and Architects-Chamber of Mechanical Engineers (2010) for the year 2006.

2) *Passenger transportation activity* by rail and sea is devoted solely to private passengers (DO sector). In other worlds, it is assumed that no business travel in rail and see ways.

3) As for airways, 50% of *passenger transportation service* is assigned to households (Domestic sector, DO) and the remaining is allocated to other sectors proportional to respective share of sectoral "employed personnel".

4) As for *road passenger transportation*, energy use of *private passenger vehicles* is assumed to be proportional to the ratio *"private passenger vehicles/total passenger vehicles"* (92,4%) and this service of TR sector is assigned to (i.e., performed in favour of) DO. The same for "governmental vehicles" for which the ratio of 1,1% is assigned to TE (Tertiary sector). (The ratios are retrieved from Turkstat, 2009g) The remaining is allocated to the sectors the same as done for airway transportation.

5) As for *freight transportation*, data for "freight traffic (ton-km) by type of commodity" are available for railway freight transport activities (Turkish State Railways, 2010). Due to scarcity of data, it is assumed that the same ratio is applicable to the other modes of transportation. Hence, energy use of TR sector services to other sectors is determined accordingly. Only for road transportation, it is seen in national data (Turkstat, 2009g) that 2,83% of freight vehicles are governmental vehicles and the same share of the freight transportation fuel consumption is assigned to TE Sector. The remaining of consumed fuel for road freight transportation is allocated the same as other transportation modes.

6) Output of pipeline transport service is dissipated evenly over 7 sectors.

7) Again for the lack of data, non specified transportation service is assigned to the DO sector.

In Table D.2, along the guideline of assumption 1, consumed energy for passenger and freight transportation in different transportation modes are reported.

Table D.2: Allocation of consumed energy between freight and passenger transportation.

	Total (TJ)	Freight transportation (TJ)	Passenger transportation (TJ)	Fright transportation/Total (%)	Passenger transportation/Total (%)
Rail	10083,34	2433,53	7649,81	24,13	75,87
Air	76827,56	75158,91	1668,66	97,83	2,17
Marine	19451,66	19388,80	62,87	99,68	0,32
Road	527550,07	309089,02	218461,05	58,59	41,41

Total sectoral fuel consumption is presented in Table D.1. Allocation of consumed fuels (between freight and passenger transportation) is conducted proportional to corresponding energy consumption (Table D.2). In order to apply above mentioned assumptions, required knowledge of "freight traffic (ton-km) by sectors" for rail transportation and respective sectoral share of "employed personnel" are presented in Table D.3 and TableD.4 (based on data in Turkish State Railways (2010)), respectively. In line with above listed assumptions, fuel allocation (consumed in order to serve the sectors) is seen in Table D.5, Table D.6, Table D.7 and Table D.8 for rail, air, marine and road transportation, respectively.

Table D.3: Freight traffic (ton-km) by sectors in railway transportation.

Sector	Share (%)
AG Sector	0,57
EX Sector	45,97
CO Sector	3,61
IN Sector	45,28
DO Sector	4,57

Table D.4: Share of sectoral employers.

Sector	Share (%)
EX Sector	0,69
CO Sector	0,52
AG Sector	24,85
IN Sector	21,70
TE Sector	43,15
TR Sector	9,09

Table D.5: Allocation of consumed energy carriers through service receiving sectors (rail transportation).

		Diesel (1000 Ton)	Electricity (TJ)
Total energy carrier consumption		214	810
Passenger transportation total		162,35	614,51
	Sectors		
	DO	162,35	614,51
Freight transportation total		51,65	195,49
	Sectors		
	AG	0,29	1,11
	EX	23,74	89,86
	CO	1,87	7,07
	IN	23,39	88,53
	DO	2,36	8,93

Table D.6: Allocation of consumed energy carriers through service receiving sectors (air transportation).

		Aviation Fuel (1000 Ton)
Total energy carrier consumption		1723
Passenger transportation total		37,42
	Sectors	
	DO	18,71
	EX	0,13
	CO	0,10
	AG	4,65
	IN	4,06
	TE	8,07
	TR	1,70
Freight transportation total		1685,58
	Sectors	
	AG	9,54
	EX	774,79
	CO	60,93
	IN	763,31
	DO	77,00

Table D.7: Allocation of consumed energy carriers through service receiving sectors (marine transportation).

		Diesel (1000 Ton)	Heavy Fuel Oil (1000 Ton)
Total energy carrier consumption		345	112
Passenger transportation total		1,12	0,36
	Sectors		
	DO	1,12	0,36
Freight transportation total		343,88	111,64
	Sectors		
	AG	1,95	0,63
	EX	158,07	51,32
	CO	12,43	4,04
	IN	155,73	50,56
	DO	15,71	5,10

Table D.8: Allocation of consumed energy carriers through service receiving sectors (road transportation).

		LPG (1000 Ton)	Motor Gasoline (1000 Ton)	Diesel (1000 Ton)	Liquid Biomass (1000 Ton)	Natural Gas (TJ)
Total energy carrier consumption		1570	2702	7661	2	165
Passenger transportation total		650,14	1118,91	3172,46	0,83	68,33
	Sectors					
	DO	622,05	1070,56	3035,38	0,79	65,37
	EX	0,14	0,24	0,69	0,0002	0,015
	CO	0,11	0,19	0,53	0,0001	0,011
	AG	5,15	8,87	25,15	0,007	0,54
	IN	4,50	7,75	21,96	0,006	0,47
	TE	16,30	28,05	79,53	0,021	1,71
	TR	1,89	3,25	9,20	0,002	0,2
Freight transportation total		919,86	1583,09	4488,54	1,17	96,67
	Sectors					
	AG	5,06	8,70	24,68	0,0064	0,53
	EX	410,82	707,03	2004,66	0,52	43,18
	CO	32,31	55,60	157,65	0,041	3,40
	IN	404,74	696,56	1974,96	0,52	42,54
	DO	40,83	70,27	199,23	0,052	4,29
	TE	26,10	44,92	127,37	0,033	2,74

In Table D.9 and Table D.10, energy carrier distribution (consumed to serve the sectors) of pipeline transport and "non specified transportation" is presented, respectively. Distributions are conducted in line with the assumptions listed above.

Table D.9: Allocation of consumed energy carriers through service receiving sectors (pipeline transport).

	Natural Gas (TJ)	Electricity (TJ)
Total energy carrier consumption	5227	522
Sectors		
EX	746,71	74,57
CO	746,71	74,57
AG	746,71	74,57
IN	746,71	74,57
TR	746,71	74,57
TE	746,71	74,57
DO	746,71	74,57

Table D.10: Allocation of consumed energy carriers through service receiving sectors (non specified transportation).

	Electricity (TJ)
Total energy carrier consumption	1512
Sectors	
DO	1512

APPENDIX E: Details of Material Transfer from TE to the Other Sectors

E.1. Methodology for Material Distribution from TE to the Sectors

Any type of material (commodity) consumption within the society is computed as:

$$\text{Societal consumption} = \text{Production} + \text{Import} - \text{Export} \qquad \textbf{(E.6)}$$

The rationale behind computing the exergy of commodities which are transferred from TE to the other sectors is based on the same idea in equation (E.1), namely, exergy of commodities (transferred from TE and sectorally consumed) is computed according to equation (E.2) and is assigned to sectoral consumption of the commodity consuming sector(s).

$$\text{Sectoral exergy consumption} = \text{Exergy of } (\text{Production} + \text{Import} - \text{Export}) \qquad \textbf{(E.2)}$$

If the consuming sectors of the commodities are predictable explicitly, exergy of consumption (via equation (E.2)) is directly assigned to the exergy consumption of commodity consuming sector (such as: transferring fertilizers to AG Sector or minerals to IN sector). However, there are commodities which can be consumed by any sectors. To map the distribution of these commodities from TE to other sectors, data about material transfer between the sectors would be necessary: such data are though unavailable for Turkey, and thus it is assumed that the exergy of these commodities are allocated to the sectors proportionally to the sectoral "fixed capital investment + purchases of goods and services" for which accurate data exist and presented in Table E.1. In Table E.1, data of sectoral "fixed capital investment" is retrieved from Republic of Turkey-State Planning Organization (2007), that of "purchases of goods and services" is retrieved from Turkstat (2007a).

Allocation of fuels through the sectors is kept out of aforementioned procedure since exact data for sectoral fuel consumption is available in published national energy budgets (IEA, 2008; Republic of Turkey-Ministry of Energy and Natural Resources, n.d.). In following sections below, allocation of sectoral products and that of imported & exported commodities through the sectors are detailed.

Table E.1 : Fixed capital investment and purchases of goods and services of the sectors.

	Million TL	Million Dolar	% share
	Fixed capital investment		
EX Sector	2130	1489,51	
CO Sector	5485	3835,66	
AG Sector	5223	3652,45	
IN Sector	40421	28266,43	
TR Sector	25576	17885,31	
TE Sector	44734	31282,52	
DO Sector	23377	16347,55	
	Purchases of goods and services		
EX Sector	7348,35	5138,70	
CO Sector	59231,24	41420,45	
AG Sector	10806,10	7556,72	
IN Sector	374562,32	261931,69	
TR Sector	95613,42	66862,53	
TE Sector	716460,47	501021,31	
DO Sector	259952	181784,62	
	Fixed capital investment+Purchases of goods and services		
EX Sector	9478,35	6628,21	0,57
CO Sector	64716,24	45256,11	3,87
AG Sector	16029,10	11209,16	0,96
IN Sector	414983,32	290198,13	24,84
TR Sector	121189,42	84747,85	7,25
TE Sector	761194,47	532303,83	45,56
DO Sector	283329	198132,17	16,96

E.2. Transferred AG Sector Products from TE to DO and IN

AG sector products transferred from AG sector to TE (part 1) and DO (part 2) Sectors are listed in Table 4.4. The allocation of part 1 which is transferred from TE to IN and DO (for food processing and direct consumption by DO sector, respectively) is seen in Table E.2.

Table E.2 : AG sector products transferred from TE to IN and DO.

	AG products in TE (Ton)	AG products transferred to IN (Ton)	AG products transferred to DO (Ton)	Specific Exergy (MJ/Ton)	Exergy transfered to IN (TJ)	Exergy transfered to DO (TJ)
Fruit						
Total fruit consumption	6663840,8	646387,92	6017452,88	1900	1228,14	11433,16
Cereals						
Total cereal consumption	18165220	18165220	0			
Barley	89800	89800	0	14800	1329,04	0
Wheat (Total)	16490600	16490600	0	17400	286936,44	0
Maize	1029500	1029500	0	16400	16883,80	0
Rice	555320	555320	0	15200	8440,86	0
Leguminous seeds						
Total Leguminous seeds consumption	712883,2	35644,16	677239,04	16900	602,39	11445,34
Dry bean	166745,6	8337,28	158408,32			
Red lentil	214927,2	10746,36	204180,84			
Chickpea	292384,8	14619,24	277765,56			
Green lentil	38825,6	1941,28	36884,32			
Vegetables						
Total vegetables consumption	16268929,56	3877223,97	12391705,59	1900	7366,73	23544,24
Meat	438530	438530	0	10000	4385,30	0
Poultry	934731,97	934731,97	0	4500	4206,29	0
Fish products	661991	57000	604991,00	5750	327,75	3478,70
Milk	9561680	9561680,00	0	4900	46852,23	0
Egg	586678,4	29333,92	557344,48	7000	205,34	3901,41
Honey	67073,6	33536,80	33536,80	15200	509,76	509,76
Beewax	3483,65	3483,65	0	15200	52,95	0
Others						
Olive	1413399,2	1182699,60	230699,60	19000	22471,29	4383,29
Tobacco	98137	98137	0	10700	1050,07	0
Sunflower	1902805	1360505,58	542299,43	19000	25849,61	10303,69
Rape	229958	229958,00	0	37000	8508,45	0
Cotton	1361165	1361165,00	0	16700	22731,46	0
Soybean	1026872,8	1026872,80	0	16600	17046,09	0
Sugar beet	13743812	13743812,00	0	4200	57724,01	0
Tea	741845,6	741845,60	0	10700	7937,75	0
Potato	2952707,2	147635,36	2805071,84	4200	620,07	11781,30
Total		53675403,33	23860340,65		543265,80	80780,89

E.3. Distribution of Commodities from TE to the Sectors

E.3.1. Distribution of Energy Carriers Through the Sectors

Total imported and exported energy carriers and corresponding exergy content are reported in Table E.3 and TableE.4.

Table E.3 : Imported energy carriers and exergy content.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Hard Coal	20286000	27860,36	565175,30
Lignite	29000	8259,27	239,52
Crude Oil	24063000	43506,45	1046895,70
Coke	454000	30430,40	13815,40
LPG	2800000	46837,75	131145,71
Motor gasoline	850000	44350,77	37698,16
Aviation fuel	274000	44589,42	12217,50
Diesel	6436000	46366,72	298416,19
Heavy fuel oil	468000	39791,35	18622,35
Other petroleum products	1776000	40193,28	71383,27
Petroleum coke	1889000	33092,47	62511,68
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Natural Gas	1171307	0,92	1077602,44
Electricity	2062,8	1	2062,8
Total			3337786,01

Table E.4 : Exported energy carriers and exergy content.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
LPG	66000	46837,75	3091,29
Motor gasoline	1673000	44350,77	74198,84
Aviation fuel	88000	44589,42	3923,87
Diesel	2182000	46366,72	101172,18
Heavy fuel oil	2686000	39791,35	106879,56
Naphtha	446000	45008,1	20073,61
Other petroleum products	369000	40193,28	14831,32
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Electricity	8049,6	1	8049,6
Total			332220,27

For each sector, exergy of received energy carriers is seen between Table E.5 - Table E.11.

Table E.5 : Exergy of energy carriers transferred to EX sector.

	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Electricity	6166,8	1	6166,8

Table E.6 : Exergy of energy carriers transferred to CO sector.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Hard Coal	10221000	27860,36	284760,76
Lignite	49899000	8259,27	412129,45
Crude Oil	26479000	43506,45	1152007,28
Refinery Gas	600000	33819,29	20291,58
Diesel	16000	46366,72	741,87
Heavy fuel oil	1964000	39791,35	78150,21
Naphtha	70000	45008,10	3150,57
Other petroleum products	15000	40193,28	602,90
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Solid biomass	319	1,05	334,95
Biogas	331	1,05	347,55
Blast furnace gas	18239	0,97	17691,83
Coke oven gas	11113	0,89	9890,57
Electricity	28209,6	1	28209,6
Natural gas	623257	0,92	573396,44
Total			2581705,55

Table E.7 : Exergy of energy carriers transferred to AG sector.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Diesel	3103000	46366,72	143875,92
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Electricity	15984	1	15984
Geothermal Heat	7070,62	0,132	934,26
Total			160794,18

Table E.8 : Exergy of energy carriers transferred to TE sector.

	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Electricity	127249,20	1	127249,2
Geothermal Heat	14804,10	0,132	1956,10
Natural gas	129568	0,92	119202,56
Total			248407,86

Table E.9 : Exergy of energy carriers transferred to IN sector.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Hard Coal	11672000	27860,36	325186,14
Asphaltit	120000	18604,40	2232,53
Lignite	4897000	8259,27	40445,66
Coke	3612000	30430,40	109914,60
LPG	392000	46837,75	18360,40
Motor gasoline	21000	44350,77	931,37
Diesel	298000	46366,72	13817,28
Heavy fuel oil	2754000	39791,35	109585,37
Naphtha	941000	45008,10	42352,62
Other petroleum products	4523000	40193,28	181794,21
Petroleum coke	1981000	33092,47	65556,18
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Natural Gas	161447	0,92	148531,24
Electricity	234842,4	1	234842,40
Coke oven gas	11016	0,89	9804,24
CHP heat	40109,54	0,67	26873,39
Blast furnace gas	18409	0,97	17856,73
Total			1348084,37

Table E.10 : Exergy of energy carriers transferred to TR sector.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
LPG	1570000	46837,75	73535,28
Motor gasoline	2702000	44350,77	119835,79
Aviation fuel	1723000	44589,42	76827,57
Diesel	8220000	46366,72	381134,41
Heavy fuel oil	112000	39791,35	4456,63
Liquid biomass	2000	43961,4	87,92
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Natural Gas	5392	0,92	4960,64
Electricity	2844	1	2844
Total			663682,24

Table E.11 : Exergy of energy carriers transferred to DO sector.

	Amount (Ton)	Specific Exergy (MJ/Ton)	Exergy (TJ)
Hard Coal	905000	27860,362	25213,63
Asphaltit	482000	18604,40	8967,32
Lignite	5388000	8259,2728	44500,96
Coke	36000	30430,40	1095,49
Briquette	155000	16121,02	2498,76
LPG	1528000	46837,75	71568,09
Kerosene	24000	43314,54	1039,55
Heavy fuel oil	264000	39791,35	10504,92
	Amount (TJ)	Exergy Coefficient (β_{HHV})	Exergy (TJ)
Solid biomass	214605	1,05	225335,25
Geothermal Heat	23384,59	0,132	3089,86
Electricity	124077,6	1,00	124077,6
Natural gas	287633	0,92	264622,36
Total			782513,78

E.3.2. Distribution of Societal Products through the Sectors

Sectoral products (which are directly transferred to TE sector with only one exception of some food products in AG Sector, detailed in Section 4.2) and exergy of produced commodities are presented in the sections of Chapter 4.

Products of EX Sector (ores, minerals, etc.) are totally transferred to IN sector to be used in manufacturing of industrial products.

Products of CO Sector are composed of two groups: energy carriers (fuels, electricity and heat) and process by-products (wax, asphalt, etc.). Energy carrier consumptions are distributed through the sectors in Section E.3.1. Refinery by-products are transferred to IN sector to be used in manufacturing of industrial products.

As detailed in Section 4.2, some of AG sector products are directly transferred to DO Sector. The remaining part is delivered to TE and afterwards from TE to IN and DO Sectors to be used in industrial processes and household consumption, respectively. Details are available in Section 4.2 and Section E.2. Manure for biogas production is provided by AG and supplied to CO Sector for energy generation. Distribution of solid biomass (produced by AG) is seen in Section E.3.1.

Except labour, products of the DO sector are some solid waste materials which are recycled in different ways. Materials are transferred to the relevant sectors for recycling processes (to CO Sector for incineration; to IN Sector for material recycling and compositing).

As for the sectoral products of IN Sector, products of food processing industry are transferred to DO. Processed seed, fodder, fertilizer and compost are transferred from TE to AG Sector. Produced scrap is collected by enterprises in the TE Sector and used in IN Sector processes. IN Sector products are realigned in Table E.12 (details are available in Section 4.3). The consuming sector of the remaining commodities ("other products" in Table E.12) is unpredictable and commodities are distributed through the sector in line with pattern of allocation described in Section E.1. Distribution of "Other products" is seen in Table E.13. Blast furnace gas is inserted into Table E.12 to show all IN sector products in a sole table, but distribution of blast furnace gas is already presented in Section E.3.1.

Table E.12 : Products of IN Sector.

Product	Transferred to	Exergy (TJ)
Food	DO	478490,48
Fodder	AG	286363,77
Seed	AG	5784,42
Fertilizer	AG	1422,92
Compost	AG	452,87
Scrap	IN	19096,62
Blast furnace gas	CO&IN	35548,56
Other products		963640,20
Total		1790799,84

Table E.13 : Distribution of "Other products".

	Sectoral share (%)	Sectoral share in IN Sector products (TJ)
EX Sector	0,57	5466,28
CO Sector	3,87	37322,66
AG Sector	0,96	9244,18
IN Sector	24,84	239326,02
TR Sector	7,25	69891,44
TE Sector	45,56	438990,28
DO Sector	16,96	163399,34
Total	100	963640,20

Consequently, resulting exergy transfers from TE sector to the sectors are reported from Table E.14 to Table E.20. Total amount of agricultural products which are delivered to TE Sector is presented in Section 4.2. "Raw food transfer from TE to DO” and “food processing industry raw materials” are computed in Section E.2.

Table E.14 : EX Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	5466,28
Total	5466,28

Table E.15 : CO Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	37322,66
Manure for biogas production	7149,73
Waste for incineration process	11788,87
Total	56261,26

Table E.16 : AG Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	9244,18
Fodder	286363,77
Seed	5784,42
Fertilizer	1422,92
Compost	452,87
Total	303268,16

Table E.17 : IN Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	239326,02
Scrap metal	19096,62
Extracted ores	5801,74
Extracted minerals	267795,70
Asphalt, paraffine wax, etc.	150430,60
Food processing ind. raw materials	543265,80
Agricultural products for industrial use	419804,41
Industrial wood	123387,71
Organic waste for composting	2088
Waste for material recycling	24239,56
Total	1795236,16

Table E.18 : TR Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	69891,44
Total	69891,44

Table E.19 : TE Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	438990,28
Total	438990,28

Table E.20 : DO Sector exergy consumption from societal products.

	Exergy (TJ)
IN Sector products	163399,34
Direct raw food transfer from AG to DO	42959,57
Products of food processing ind.	478490,48
Raw food transfer from TE to DO	80780,89
Total	765630,29

E.3.3. Water Transfer by Mains (National Water Network)

The amount of sectorally consumed water from mains and exergy content are reported in Table E.21 for each sector (Turkstat, 2009c; Tusiad, 2008). Exergy of water is presented in Section 3.2.

Table E.21 : Water supplied by mains.

Sector	Water (m^3)	Exergy (TJ)
CO	260000	13
IN	50070000	2503,50
TE	1257444766	62872,24
DO	3856225234	192811,26

E.3.4. Distribution of Imported and Exported materials through the Sectors

As seen in equation (E.2), exergy of "import-export" is a constituent of sectoral exergy consumption. Table E.22 reports the imported and exported materials and exergy of "import-export". Data of imported and exported commodities is extracted from Turkstat (personal communication, December 20, 2009e), TUGEM (n.d.b), Turkish Republic-General Directorate of Mineral Research and Exploration (n.d.).

As applied in Section E.3.2, if the consuming sectors of the imported & exported products are predictable, exergy of "import-export" is attributed to the consuming sector (seen in Table E.22). As for commodities whose consuming sectors are unpredictable (the part of "Products distributed through the sectors" in Table E.22), the methodology which is presented in Section E.1 is applied and results are seen in Table E.23.

Due to the wide variety in products and impossibility of obtaining the exact composition, it was not possible to use the standard exergy computation procedures described by Szargut et al. (1988). As such, when computing the exergy of imported and exported chemical products, art works and "other industrial products" (industrial products which are not specifically stated in Table E.22), their monetary costs is converted into exergy equivalents by means of ee_C (discussed in Section 5.3) and details are available in Table E.24.

Table E.22 : Exergy of imported and exported commodities.

	Import (Ton)	Export (Ton)	Specific exergy (MJ/Ton)	Import Exergy (TJ)	Export Exergy (TJ)	Exergy (Import - Export) (TJ)
Products transferred to AG sector:						
Livestock	465,15	2108,31	10000	4,65	21,08	
Seed						
Wheat	638	5070	17400	11,10	88,22	
Barley	35	49	14800	0,52	0,73	
Maize	1123	7008	16400	18,42	114,93	
Paddy	32	0	16700	0,53	0	
Sunflower	155	4325	19000	2,95	82,18	
Soybean	413	0	16600	6,86	0	
Sugar beet	50	0	4200	0,21	0	
Potato	17893	30	4200	75,15	0,13	
Cotton	109	4298	16700	1,82	71,78	
Rape	149	0	37000	5,51	0,00	
Vegetable	3452	1162	1900	6,56	2,21	
Alfalfa	1472	6	16700	24,58	0,10	
Sainfoin	983	0	16700	16,42	0	
Cow vetches	200	0	16700	3,34	0	
Sorghum	560	0	16700	9,35	0	
Sudan grass	23	0	16700	0,38	0	
Fodder beet	37	0	16700	0,62	0	
Knotgrass	4105	71	15300	62,81	1,09	
Fodder						
Rey&oat	20167	0	15500	312,59	0,00	
Corn	1672120	6509,57	16400	27422,76	106,76	
Oil seeds	1430406	236	19000	27177,72	4,48	
Mixed fodder	31000	728,629	16400	508,40	11,95	
Fertilizer						
Nitrogen-N	831897	43417	25,71	21,39	1,12	
Phosphate- P_2O_5	247738	21993	2899,08	718,21	63,76	
Potash - K_2O	35393	1364	4385,21	155,21	5,98	
Exergy transferred to AG sector				***56568,06***	***576,48***	***55991,58***
Products transferred to IN sector:						
Hide& leather (raw)	186997,39	37844,66	20847,63	3898,45	788,97	
Industrial wood	1130640 (2622000 m3)	1260 (3000 m3)	20658,20	23356,99	26,03	
Wood Pulp	557367,12	461,27	17000	9475,24	7,84	
Plastic raw material	3454000	280000	32502,16	112262,48	9100,61	
Rubber raw material	402232	292232,09	32502,16	13073,41	9498,18	
Non-metallic mineral products						
Cement	2296654,14	7058264,43	1500	3444,98	10587,40	
Clinker	1623000	1500000	6,5	10,55	9,75	
Glass	614208,59	561203,80	31,62	19,42	17,75	
Concrete products	2061,52	227209,18	1500	3,09	340,81	
Brick	279,84	30620,84	1079,97	0,30	33,07	

Table E.22 (continued): Exergy of imported and exported commodities.

	Import (Ton)	Export (Ton)	Specific exergy (MJ/Ton)	Import Exergy (TJ)	Export Exergy (TJ)	Exergy (Import - Export) (TJ)
Tile	46,64	32694,12	1079,97	0,05	35,31	
Lime	672,96	57354,03	9,99	0,01	0,57	
Plaster	2369,57	111756,53	49,95	0,12	5,58	
Basic metals						
Steel blum	1521000	1582000	6800	10342,80	10757,60	
Steel slab	1317000	0	6800	8955,60	0	
Long Steel Product	743000	9567000	6800	5052,40	65055,60	
Flat plate steel product	7296000	1368000	6800	49612,80	9302,40	
High Quality Steel	841000	148000	6800	5718,80	1006,40	
Iron	486789,901	37859,02	6721,43	3271,92	254,47	
Steel scrap	15073139,67	95801,04	6800	102497,35	651,45	
Ferro manganese	60212,95	1196,90	10667,09	642,30	12,77	
Ferro silisium	72598,62	382,10	25165,32	1826,97	9,62	
Ferro-silico-manganese	243380,80	12,50	11914,97	2899,87	0,15	
Ferro-chrome	4609,77	60952,11	9596,93	44,24	584,95	
Ferro-silico-chrome	416,00	5	19778,95	8,23	0,10	
Ferro-nickel	0,21	0	6963,87	0,0014	0	
Ferro-molybdenium	1020,31	12,40	7552,17	7,71	0,09	
Ferro- volfram	13,05	0,00	5395,03	0,07	0,00	
Ferro-titanium	649,85	1,00	13890,07	9,03	0,01	
Ferro-vanadium	482,51	60,45	11680,42	5,64	0,71	
Ferro-niobium	435,12	0	9429,51	4,10	0,00	
Ferro-phosphor	1452,00	15,75	12778,21	18,55	0,20	
Ferro-silico-magnesium	3128,60	30,58	19365,56	60,59	0,59	
Other ferro	3237,31	29,92	12629,08	40,88	0,38	
Refinery products						
Asphalt (Bitumen)	372,38	10258,21	38029,11	14,16	390,11	
Engine Oil	325995,87	65957,27	44350,77	14458,17	2925,26	
Others (Paraffine Wax)	186778,79	273528,19	45303,60	8461,75	12391,81	
Metalic mines						
Iron ore	7208900,80	791,25	103,41	745,48	0,08	
Manganese ore	383,47	3712,40	270,12	0,10	1,00	
Copper ore	18111,49	169422,61	5327,76	96,49	902,64	
Nickel ore	0,35	91828,07	433,23	0,00	39,78	
Aluminum ore	65053,16	89763,93	2404,63	156,43	215,85	
Lead ore	0,00	18415,40	4891,84	0,00	90,09	
Zinc ore	40,31	244524,38	8000,73	0,32	1956,37	
Chromium ore	84466,97	1079870,44	869,01	73,40	938,42	
Molybdenum ore	2,03	0	12572,13	0,03	0	

Table E.22 (continued): Exergy of imported and exported commodities.

	Import (Ton)	Export (Ton)	Specific exergy (MJ/Ton)	Import Exergy (TJ)	Export Exergy (TJ)	Exergy (Import - Export) (TJ)
Titanium ore	6831,00	129,04	8,94	0,06	0	
Gold ore	0	0		0	0	
Antimony ore	0	678,90	8300,59	0	5,64	
Minerals						
Salts	417898,08	28186,87	244,70	102,26	6,90	
Iron pyrites	230,73	5,00	11908,31	2,75	0,06	
Sulphur	162186,76	151,73	19011,98	3083,49	2,88	
Graphite	9687,78	292,25	34188,33	331,21	9,99	
Sand	314518,10	165554,32	131,49	41,36	21,77	
Quartz	3048,71	103242,79	31,62	0,10	3,27	
Quartzite	344,53	14601,76	131,49	0,05	1,92	
China clay	292585,15	192298,09	844,53	247,10	162,40	
Bentonite	5462,58	293294,77	909,34	4,97	266,70	
Clay	296276,22	42409,79	697,99	206,80	29,60	
Andalusite	3901,13	0	1281,40	5,00	0	
Phosphate	744503,84	0,12	62,54	46,56	0,00001	
Barite	278,83	159128,48	14,57	0,004	2,32	
Diatomite	1619,49	29027,36	340,62	0,55	9,89	
Rottenstone (or pumice)	17,82	206011,94	862,56	0,02	177,70	
Grindstone	33,26	19820,41	1312,94	0,04	26,02	
Silex (flintstone)	2272,74	735035,54	131,49	0,30	96,65	
Magnesite	52937,23	234926,24	449,52	23,80	105,60	
Gypsum	278129,14	693516,59	49,95	13,89	34,64	
Limestone	723,32	57435,51	9,99	0,01	0,57	
Asbestos (Tremolite)	6123,50	3,05	761,22	4,66	0,002	
Mica	413,06	860,77	1335,84	0,55	1,15	
Talc	17143,39	1194,89	96,23	1,65	0,11	
Feldspar	44158,67	4598618,66	358,92	15,85	1650,52	
Fluorite	26455,96	965,03	146,02	3,86	0,14	
Leucite	670,50	0	1477,86	0,99	0	
Perlite	258,84	257901,50	754,83	0,20	194,67	
Vermiculite	1996,52	5,75	951,51	1,90	0,01	
Sepiolite	215,14	23611,86	521,18	0,11	12,31	
Zircon	28047,61	30,43	109,10	3,06	0,003	
Sodium sulfate	0	23,08	150,66	0	0,003	
Celestine	24	6216,60	38,65	0,001	0,24	
Dolomite	7038,10	20657,81	81,88	0,58	1,69	
Marble	2216,31	2160377,24	9,99	0,02	21,58	
Onyx	8,84	4437,93	9,99	0,00	0,04	
Travertine	2725,94	137741,47	9,99	0,03	1,38	
Granite	143513,57	159936,02	820,96	117,82	131,30	
Slate	1167,10	975,17	9,99	0,01	0,01	
Textile raw materials						
Silk	540,71	111,71	4560	2,47	0,51	
Wool, animal hair, yarns made from these	57782,44	26778,68	5850	338,03	156,66	
Cotton, cotton yarn and cotton fabric	991140,04	363955,40	16500	16353,81	6005,26	
Natural fiber	139189,53	9700,95	4,93	0,69	0,05	
Synthetic fiber	852042,04	505847,02	18500	15762,78	9358,17	

Table E.22 (continued): Exergy of imported and exported commodities.

	Import (Ton)	Export (Ton)	Specific exergy (MJ/Ton)	Import Exergy (TJ)	Export Exergy (TJ)	Exergy (Import - Export) (TJ)
Other fabric	63384,10	59148,78	4,16	0,26	0,25	
Exergy transferred to IN sector				***417290,90***	***156441,35***	***260849,55***
Products transferred to DO sector:						
Food and food products						
Meat and meat products	27,70	38314,01	10000	0,28	383,14	
Fish and fish products	54173,70	50084,81	5750	311,50	287,99	
Milk and Diary Products	28478,55	47616,59	4900	139,54	233,32	
Eggs	631,06	2694,92	7000	4,42	18,86	
Honey	19,80	9300,11	15200	0,30	141,36	
Other animal products	3951,37	3280,24	10000	39,51	32,80	
Edible vegetable	144885,61	1192849,80	1900	275,28	2266,41	
Edible fruit	338624,11	2617172,54	1900	643,39	4972,63	
Tea and Coffee	25339,20	34701,34	10700	271,13	371,30	
Cereal	636029,90	1740543,67	15930	10131,96	27726,86	
Wheat & wheat products	29486,38	1316231,44	17400	513,06	22902,43	
Oils	1611146,71	422647,98	23000	37056,37	9720,90	
Sugar and sugar products	158111,83	260988,78	17000	2687,90	4436,81	
Cacao and cacao products	83939,82	116973,35	10700	898,16	1251,61	
Other foods	77576,19	141667,54	10000	775,76	1416,68	
Beverages (with or without alcohol, vinegar)	69396,16	328133,30	7570	525,33	2483,97	
Tobacco	67564,45	154420,36	10700	722,94	1652,30	
Exergy transferred to DO sector				***54996,83***	***80299,38***	***-25302,55***
Products transferred to TE sector:						
Art work				7492,06	7378,20	
Exergy transferred to TE sector				***7492,06***	***7378,20***	***113,86***
Products distributed through the sectors:						
Plants (alive)	39880,21	19746,67	15300	610,17	302,12	
Leather & hide products	23464,79	7479,27	20847,63	489,19	155,93	
Wooden products	3311083,44	513065,28	20658,20	68401,02	10599,01	
Paper and paper products	2371122,71	423325,07	17000,00	40309,09	7196,53	
Plastic products	775000	1038000	32502,16	25189,18	33737,25	
Rubber products	106225	58446,42	32502,16	3452,53	1899,64	
Other chemical products				297802,37	63342,47	

Table E.22 (continued): Exergy of imported and exported commodities.

	Import (Ton)	Export (Ton)	Specific exergy (MJ/Ton)	Import Exergy (TJ)	Export Exergy (TJ)	Exergy (Import - Export) (TJ)
Steel Products	583994,28	2686869,75	6800	3971,16	18270,71	
Gold and gold products	192,00	111	78,17	0,02	0,01	
Silver and silver products	107,40	90	650,78	0,07	0,06	
Aluminium and Aluminium products	619031,58	323920,81	32903,70	20368,43	10658,19	
Lead and lead products	81739,88	4688,84	1124,64	91,93	5,27	
Zinc and Zinc products	145966,74	3575,76	5178,63	755,91	18,52	
Tin and Tin products	2573,44	54,46	4589,72	11,81	0,25	
Copper and Copper products	365926,97	123891,39	2111,72	772,74	261,62	
Nickel and nickel products	4870,14	440,46	3944,07	19,21	1,74	
Volfram and volfram products	33,58	63,62	4497,28	0,15	0,29	
Molybdenum and molybdenum products	6,08	19,33	7607,29	0,05	0,15	
Magnesium and magnesium products	6455,53	1408,35	26082,30	168,38	36,73	
Cobalt and cobalt products	186,40	2,18	4491,53	0,84	0,01	
Cadmium and cadmium products	8,78	27,31	2600,00	0,02	0,07	
Titanium and titanium products	162,92	45,71	18972,80	3,09	0,87	
Chrome and chrome products	32,65	179,23	10467,31	0,34	1,88	
Manganese and manganese products	509,34	4,05	8769,09	4,47	0,04	
Other industrial products				1208267,81	694661,39	
Exergy distributed through the sectors				***1670689,96***	***841150,73***	***829539,23***
Total import and export				***2207037,81***	***1085846,13***	***1121191,68***

Table E.23 : Allocation of exergy of “products distributed through the sectors”.

	% share	Exergy (TJ)
EX Sector	0,57	4705,59
CO Sector	3,87	32128,81
AG Sector	0,96	7957,75
IN Sector	24,84	206021,21
TR Sector	7,25	60165,29
TE Sector	45,56	377900,03
DO Sector	16,96	140660,55
Total	100	829539,23

Table E.24 : Exergetic equivalent of “other chemical products”, “other industrial products” and “art works”.

	Other chemical products	Other industrial products	Art works
Import ($)	11678304009	47382157189	293800885
Export ($)	2483971619	27241108890	289335722
Import Exergy (TJ)	297802,37	1208267,81	7492,06
Export Exergy (TJ)	63342,47	694661,39	7378,20
Exergy (Import - Export) (TJ)	234459,90	513606,43	113,86

Finally, distribution of “import-export” exergy through the sectors are reported in Table E.25.

Table E.25 : Distribution of “import-export” exergy through the sectors.

	"import-export" (TJ)
EX Sector	4705,59
CO Sector	32128,81
AG Sector	63949,33
IN Sector	466870,77
TR Sector	60165,29
TE Sector	378013,89
DO Sector	115358,00
Total	1121191,68

APPENDIX F: Sectoral Labour Consumption

F.1. Allocation of working hours

Number of workers and working hours for regular and part-time, seasonal and occasional employee data are extracted from Turkstat (2007b, 2009b, 2009a) and Republic of Turkey Prime Ministry-State Personnel Presidency (2008). Since accurate data were not available for all employers and unpaid family workers, it is assumed here that their average work load is 35 hours/week. NACE (Statistical classification of economic activities in the European Community) classification (Eurostat, 2008) and the sectors which cover tabulated NACE classes are presented in Table F.1. Number of workers and weekly working hours are seen in Table F.2 and Table F.3, respectively.

Table F.1 : NACE classification.

Sector	NACE Classification	Activity of the sector
AG	**A**	Agriculture, hunting and forestry
AG	**B**	Fishing
EX	**C**	Mining and quarrying
	D	Manufacturing
IN	**(DA)**	Manufacture of food products, beverages and tobacco
IN	**(DB)**	Manufacture of textiles and textile products
IN	**(DC)**	Manufacture of leather and leather products
IN	**(DD)**	Manufacture of wood and wood products
IN	**(DE)**	Manufacture of pulp, paper and paper products; publishing and printing
CO	**(DF)**	Manufacture of coke, refined petroleum products and nuclear fuel
IN	**(DG)**	Manufacture of chemicals, chemical products and man-made fibres
IN	**(DH)**	Manufacture of rubber and plastic products
IN	**(DI)**	Manufacture of other non-metallic mineral products
IN	**(DJ)**	Manufacture of basic metals and fabricated metal products
IN	**(DK)**	Manufacture of machinery and equipment n.e.c.
IN	**(DL)**	Manufacture of electrical and optical equipment
IN	**(DM)**	Manufacture of transport equipment
IN	**(DN)**	Manufacturing of others and recycling
CO, TE	**E**	Electricity, gas and water supply
IN	**F**	Construction
TE	**G**	Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
TE	**H**	Hotels and Restaurants
TR	**I**	Transport, Storage and Communication
TE	**J**	Financial Intermediation
TE	**K**	Real Estate, Renting and Business Activities
TE	**L**	Public administration and defence; compulsory social security
TE	**M**	Education
TE	**N**	Health and Social Work
TE	**O**	Other Community; Social and Personal Service Activities
TE	**P**	Private households with employed persons
TE	**Q**	Extra-territorial organizations and bodies

Table F.2 : Number of workers.

NACE Classification	Regular&casual employee	Self employed	Employer	Unpaid family worker	Total workers
A+B	530000	2279913	524533	2754000	
C	138885	21122	4859	3200	
D	3573135	543403	125019	82334	
(DA)	442025	67223	15466	10185	
(DB)	1083425	164768	37908	24965	
(DC)	67614	10283	2366	1558	
(DD)	61893	9413	2166	1426	
(DE)	134227	20413	4696	3093	
(DF)	10281	1564	360	237	
(DG)	125388	19069	4387	2889	
(DH)	171697	26112	6007	3956	
(DI)	236719	36000	8282	5455	
(DJ)	370255	56309	12955	8532	
(DK)	256626	39028	8979	5913	
(DL)	154900	23557	5420	3569	
(DM)	250777	38138	8774	5779	
(DN)	207307	31527	7253	4777	
(E)	146687	22308	5132	920	
(E) CO Sector part	97231	14787	3402	610	
(E) TE Sector part	49456	7521	1730	310	
(F)	828293	125967	28981	21546	
(G)	2073776	1248470	287231	290131	
(H)	442224	266231	61251	61869	
(I)	1862899	279879	64391	19834	
(J)	119439	94000	114704	0	
(K)	1930013	289962	66711	20549	
(L)	1841088	0	0	0	
(M)	419363	63004	14495	4465	
(N)	371243	55775	12832	3953	
(O+P+Q)	300483	45144	10386	3199	
Total	14577527	5335179	1320525	3266000	24499231

Table F.3 : Average weekly work hours.

NACE Classification	Regular&casual employee and self employed	Employer and unpaid family worker
C	41,4	35
D	42,7	35
(DA)	43,1	35
(DB)	42,4	35
(DC)	42,2	35
(DD)	42,9	35
(DE)	42,6	35
(DF)	41,0	35
(DG)	41,7	35
(DH)	43,6	35
(DI)	43,6	35
(DJ)	43,4	35
(DK)	42,3	35
(DL)	42,0	35
(DM)	42,6	35
(DN)	42,4	35
(E)	40,0	35
(E) CO Sector part	40,0	35
(E) TE Sector part	40,0	35
(F)	43,9	35

Table F.3 (continued): Average weekly work hours.

(G)	43,0	35
(H)	44,6	35
(I)	41,4	35
(J)	38,0	35
(K)	42,6	35
(L)	35,0	35
(M)	39,0	35
(N)	41,2	35
(O+P+Q)	41,3	35

As for agricultural sector (class A+B in Table F.2), annual working hours of "regular&casual employee" and "self employed" workers are taken as 882 hours/year and that for "employers" and "unpaid family workers" is taken as 990 hours/year, based on data presented in Turkstat (2009a). Number of working weeks is 29,43 weeks for 2006. Finally, labour received by the sectors are computed via equation (F.1) and presented in Table 5.4.

$$\begin{aligned} \text{Labour} = & (\text{Number of working weeks}) \text{ x } (\text{Average weekly workhours}) \\ & \text{x } (\text{Number of workers}) \end{aligned} \tag{F.1}$$

APPENDIX G: Details of the Solid Waste Treatment Processes

G.1 Composition of DO sector solid waste

All the recycled waste of Turkey is assumed to be provided by the DO sector. The recycled materials are listed as:

- Waste for energy generation
- Waste for material recycling
- Waste for compost production

In statistics pertaining to Turkey, energy produced from waste is declared as 1152 TJ electrical energy (IEA, 2008). It is assumed that MSW (municipal waste) is directly incinerated to produce this energy. Ultimate composition of MSW (Ozturk, 2009) and its energy content (HHV_{dry} and HHV_{ar} for dry matter and as received composition, respectively) are presented in Table G.1. The results in Table G.1 are derived by applying the same computation procedure in Section C.4. Amount of waste used to produce energy with the efficiency of 30% is presented in Table G.2. Incinerated waste is directly extracted from the total amount of DO sector waste.

Table G.1 : Ultimate composition of MSW (dry matter).

	wt. %
C	51,9
H	7
O	39,6
S	0,37
N	1,1
ash	0,03
HHV_{dry} (MJ/kg)	22,09
HHV_{ar} (MJ/kg)	6,4

Table G.2 : Amount of waste used in energy generation.

Energy content of MSW (MJ/Ton)	6406,9
Electricity generation efficiency	30%
Produced electricity (TJ)	1152
Amount of waste incinerated (Ton)	599352,08

The amount of recycled material and necessary amount of relevant raw material are presented in Table G.3 (Republic of Turkey-Ministry of Environment and Forests, 2009; LASDER, personal communication, September 20, 2009). Process efficiencies are taken from Rigamonti et al. (2009).

Table G.3 : Recycled waste materials.

Material	Recycled material (Ton)	Recycling efficiency	Consumed waste material (Ton)
Plastic & rubber	91874	0,733	125339,70
Metal	85244	0,93	91660,22
Paper & cardboard	1075365	1	1075365
Glass	90770	1	90770
Composite material	3432	0,9	3813,33
Total	1346685		1386948,25

Added to this, 104807 Ton organic material are consumed to produce compost (Turkstat, 2008a) and extracted from organic part of the DO sector waste.

Due to the lack of data for average composition of MSW through the country, the MSW composition of Istanbul (Kanat, 2010) is taken as DO sector solid waste composition. In Table G.4, amount and composition of DO sector waste and resulting amount of waste after extracting the above mentioned recycled parts are presented. Other metals are assumed to be Copper (Cu) which is the most common metal in MSW after ferrous metals and aluminium (Kanat, 2010).

Table G.4 : DO sector solid waste composition.

	Original MSW from DO		DO sector waste	
	% wt.	Amount (Ton)	% wt.	Amount (Ton)
Organic	50,22%	9791134,30	53,92%	9385332,68
Paper & cardboard	13,30%	2593032,38	8,26%	1437953,55
Textile	5,28%	1029414,36	5,73%	997768,57
Plastic	14,39%	2805544,06	14,90%	2593957,59
Diaper	3,90%	760362,88	4,23%	736988,15
Tetra-pak	0,64%	124777,50	0,69%	120941,64
Glass	5,82%	1134695,37	5,80%	1009043,08
Metal (Al)	0,68%	132576,09	0,47%	82670,39
Metal (Fe)	0,88%	171569,06	0,69%	120464,65
Other metals (Cu)	0,07%	13647,54	0,08%	13227,99
Wood	0,51%	99432,07	0,55%	96375,37
Other combustibles	2,10%	409426,17	2,26%	393026,44
Ash	2,21%	430872,30	2,40%	417626,62
Total	100%	19496484,06	100%	17405376,74

G.2 Solid waste processing

G.2.1 DO sector solid waste environmental remediation system

G.2.1.1 TRP-1

Properties of transportation lines are derived based on Berglund and Borjesson (2006) and summarized in Table G.5.

Table G.5 : Transportation distance and energy consumption.

	Energy Input (Excluding empty return) (MJ/Ton-km)	Energy Input (Including empty return) (MJ/Ton-km)	Distance driven (km)
City			
Collection route	12	18	3,5
Direct transportation	2,4	3,6	
Suburb			
Collection route	9	13,5	11,5
Direct transportation	2,4	3,6	
Rural			
Collection route	4,5	6,75	23,5
Direct transportation	2,4	3,6	

It is assumed that 1/3 of sectoral solid waste is collected in cities, 1/3 of that in suburb and the left is collected in rural area. Additionally, it is assumed that after collection, 150 km distance is driven in rural area to deliver the waste to MRF plant.

$$\text{transportation distance} = 3,5 + 11,5 + 23,5 + 150 = 188,5 \ \text{km} \qquad \textbf{(G.7)}$$

Hence, resulting energy consumption of waste collection is computed as seen in equation (G.2).

$$\text{Energy consumption} = \frac{\left[\left(\frac{18 \text{ x } 3,5}{3}\right) + \left(\frac{13,5 \text{ x } 11,5}{3}\right) + \left(\frac{6,75 \text{ x } 23,5}{3}\right)\right] + 3,6\text{x}150}{188,5} = 5,46 \, \text{MJ / Ton km} \qquad \textbf{(G.2)}$$

Properties of TRP-1 line are presented in Table G.6.

Table G.6 : Exergy of fuel and fuel capital for TRP-1.

Average transportation distance (km)	188,5
Total distance travelled (including return) (km)	377
Average energy consumption (MJ/Ton-km)	5,46
Transported waste (Ton)	17405376,74
Total energy consumption (TJ)	17905,78
Diesel fuel energy content (MJ/Ton)	42791,00
Diesel fuel consumption (Ton)	418447,37
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	19402,03
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	501134572,39
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	18766,61

Employed number of trucks and consumed labour through TRP-1 line are summarized in Table G.7.

Table G.7 : Exergy of trucks and labour for TRP-1.

Load capacity (Ton/truck)	16
Waste (Ton)	17405376,74
Average speed of truck (km/h)	40
Average distance of transportation (km)	188,5
Total distance travelled (including return) (km)	377
Travel time (including return) (hours)	9,42
Daily ring number	1
Annual working days (days)	340
1 truck annual load capacity (Ton/truck)	5440
Truck number (trucks)	3200
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	145,51
Annual working hours (Labour) (hours)	10245333,33
Exergetic equivalent of labour (TJ)	1577,29

Since collection activity decreases the average speed through the transportation, average speed of trucks is assumed to be 40 km/h. (The speed is assumed to be 60 km/h for other TRP lines. Mathematical formulations for some of the items seen in Table G.7 are presented in equation (G.3), (G.4) and (G.5).

$$\begin{gathered}\text{1 truck annual load capacity (Ton/truck year)} = \\ \text{Annual working days x Load capacity x Daily ring number}\end{gathered} \qquad \textbf{(G.3)}$$

$$\text{Necessary truck number (trucks)} = \frac{\text{Transported waste (Ton)}}{\text{1 truck annual load capacity (Ton / Truck)}} \qquad \textbf{(G.4)}$$

$$\text{Annual working hours (hours)} = \text{Necessary truck number} \times \text{Daily ring number} \times \text{Travel time} \times \text{Annual working days} \qquad \textbf{(G.5)}$$

G.2.1.2 MRF Plant

First sorting (preliminary sorting of waste before recycling), pretreatment of recyclables and recycling are achieved in MRF plant. Energy consumption of first sorting stage for DO sector solid waste is reported in Table G.8 (based on Craighilla and Powell (1996)).

Table G.8 : Energy consumption of preliminary sorting stage.

Energy consumption (MJ_{el}/Ton)	14,93
Sorted waste (Ton)	17405376,74
Total energy consumption (TJ_{el})	259,86

For the processes, pretreatment of recyclable materials and recycling, process efficiencies and computed recycled materials are presented in Table G.9. Produced ash from the recycling process is assumed to be the loss of mass in the recycling process and called as “resulting ash” in Table G.9. Energy consumption in pretreatment and recycling processes is presented in Table G.10 for each type of material in waste. Both of Table G.9 and Table G.10 are built on the data presented by Rigamonti et al. (2009). (Energy consumption data is given per recycled material except for plastic which is given for per plastic material accessing the process).

Exergy of recycled materials are presented in Table G.11. Exergy of materials are derived from Szargut et al. (1988).

Table G.9 : Properties of recycling process.

	Material in waste composition (Ton)	Selection efficiency	Material accessing the recycling process (Ton)	Tetra-pak constituents[11] (Ton)
Paper&Cardboard	1437953,55	0,855	1229450,29	76193,24
Textile	997768,57	0,85	848103,28	
Plastic	2593957,59	0,8	2075166,07	36282,49
Tetra-pak	120941,64	1		
Glass	1009043,08	0,94	948500,50	
Metal (Al)	82670,39	0,95	78536,87	8465,92
Metal (Fe)	120464,65	0,8	96371,72	
Other metals (Cu)	13227,99	0,9	11905,19	
Wood	96375,37	0,855	82400,94	
Total	6472402,85		5370434,88	120941,64

[11] Composition of tetra-pak is 63% cardboard, 30% plastic and 3% aluminium (% wt.) (Korkmaz et al., 2009)

Table G.9 (continued): Properties of recycling process.

Total material accessing the recycling process[12] (Ton)	Recycling efficiency	Recycled material (Ton)	Produced ash (Ton)[13]	Non-recycled mixed material (Ton)[14]
1305643,53	1	1305643,53		208503,27
848103,28	0,7	593672,30		149665,29
2111448,57	0,733	1547691,80		518791,52
948500,50	1	948500,50		60542,58
87002,79	0,93	80912,59		4133,52
96371,72	0,94	90589,42		24092,93
11905,19	1	11905,19		1322,80
82400,94	1	82400,94		13974,43
5491376,52		4661316,27	830060,25	981026,33

Table G.10 : Energy consumption in pretreatment and recycling.

	Electricity (MJ/Ton)	Heat (MJ/Ton)	Total Electricity (TJ)	Total Heat (TJ)
Paper&Cardboard	25,2	15	32,90	19,58
Textile	25,2	15	14,96	8,91
Plastic	1490,4	2291	3146,90	4837,33
Glass	66,24	5460	62,83	5178,81
Metal (Al)	284,4	4885	23,01	395,26
Metal (Fe)	255,6	820,8	23,15	74,36
Other metals (Cu)	72	120	0,86	1,43
Wood	1122,86	569,05	92,52	46,89
Total			3397,14	10562,56

Table G.11 : Exergy of recycled materials.

	Exergy (MJ/Ton)	Recycled material (Ton)	Total produced exergy (TJ)
Paper & Cardboard	17000	1305643,53	22195,94
Textile	13904,76	593672,30	8254,87
Plastic	32502,16	1547691,80	50303,33
Glass	131,48	948500,50	124,71
Metal (Al)	32928,09	80912,59	2664,30
Metal (Fe)	6740,69	90589,42	610,63
Other metals (Cu)	2112,06	11905,19	25,14
Wood	20658,24	82400,94	1702,26
Total		4661316,27	85881,19

In Table G.9, "selection efficiency" stands for the efficiency of reaching the recyclable materials without impurities (Rigamonti et al., 2009). Impure part is assumed to be half

[12] Material accessing the recycling process + Relevant constituent of tetra-pak
[13] Total material accessing the recycling process – Total recycled material
[14] Material in waste composition - Material accessing the recycling process

of the material itself, the other part is assumed to be an even mixture (by wt.) of plastic, iron, aluminium, copper, paper&cardboard. The constituents of non-recycled part are presented in Table G.12. Non-recycled materials are transferred to incineration plant.

Table G.12 : Constituents of non-recycled mixed material.

	Non-recycled mixed material (Ton)	Constituents (Ton)		Total non-recycled mixed material (Ton)
Paper & Cardboard	208503,27	104251,63	98102,63	202354,27
Textile	149665,29	74832,64		74832,64
Plastic	518791,52	259395,76	98102,63	357498,39
Glass	60542,58	30271,29		30271,29
Metal (Al)	4133,52	2066,76	98102,63	100169,39
Metal (Fe)	24092,93	12046,47	98102,63	110149,10
Other metals (Cu)	1322,80	661,40	98102,63	98764,03
Wood	13974,43	6987,21		6987,21
Total	981026,33	490513,17	490513,17	981026,33

Capital of MRF plant is assumed to be 100 €/Ton (per material accessing into the MRF plant) (Smith et al, 2001). As it is seen in Table G.13, 6472402,85 Ton waste accessed to the MRF plant. Capital and exergetic equivalent of capital for MRF plant is presented in Table G.13.

Table G.13 : Capital of MRF plant.

Capital of MRF (€/Ton)	100
Processed waste (Ton)	6472402,85
Total capital (€)	647240285,28
Total capital ($)	815522759,45
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	20796,22

G.2.1.3 TRP-2

Non recycled materials, diaper and other combustibles are dispatched from MRF to incineration plant through TRP-2 transportation line. Properties of TRP-2 line are computed similar to TRP-1 line. Distance between MRF and incineration plant is assumed to be 15 km. Properties of TRP-2 transportation line is presented in Table G.14 and Table G.15.

Table G.14 : Exergy of fuel and fuel capital for TRP-2.

Average transportation distance (km)	15
Total distance travelled (including return) (km)	30
Average energy consumption (MJ/Ton-km)	3,6
Transported waste (Ton)	2111040,92
Total energy consumption (TJ)	114,00
Diesel fuel energy content (MJ/Ton)	42791
Diesel fuel consumption (Ton)	2664,02
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	123,52
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	3190446,75
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	119,47

Table G.15 : Exergy of trucks and labour for TRP-2.

Load capacity (Ton/truck)	16
Transported waste (Ton)	2111040,92
Average speed of truck (km/h)	60
Average distance of transportation (km)	15
Total distance travelled (including return) (km)	30
Travel time (including return) (hours)	0,5
Daily ring number	16
Annual working days (days)	340
1 truck annual load capacity (Ton)	87040
Truck number (trucks)	25
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	1,13
Annual working hours (Labour) (hours)	68000
Exergetic equivalent of labour (TJ)	10,47

G.2.1.4 Incineration plant

The materials incinerated in the incineration plant are reported in Table G.16 with relevant energy content (Smith et al., 2001; Weinstein, 2006). Landfilling, incineration, composting, biogasification are treatment methods commonly used for processing of diapers. There has also been limited exploration of diapers recycling. The use of each option varies widely depending on the waste management practices and policies of each country (EDANA, 2001). In this thesis, diapers are directly incinerated in incineration plant. Properties of incineration process are presented in Table G.17. The efficiency of the process is obtained from Poschl et al. (2010) and is defined based on LHV of the materials. Incineration plant is assumed to consume 4,5% of generated electricity (Poschl et al., 2010) and the consumption is also presented in Table G.17.

Table G.16 : Energy content of incinerated materials.

	Material (Ton)	LHV (MJ/kg)	Total energy content (TJ)
Paper & Cardboard	202354,27	11,5	2327,07
Textile	74832,64	14,6	1092,56
Plastic	357498,39	31,5	11261,20
Diaper	736988,15	15,41	11353,30
Glass	30271,29	0	0
Metal (Al)	100169,39	0	0
Metal (Fe)	110149,10	0	0
Other metals (Cu)	98764,03	0	0
Wood	6987,21	18,46	128,98
Other combustibles	393026,44	16,93	6653,94
Total	2111040,92		32817,05

Table G.17 : Energy generation and consumption of incineration process.

	Electricity	Heat
Efficiency (%)	40%	48%
Produced energy (TJ)	13126,82	15752,19
Energy consumption (TJ)	590,71	

Ash produced from a MSW incineration process is 25% (by wt.) of the incinerated waste (Ozturk, 2009). Accordingly, produced ash is 527760,23 Ton.

G.2.1.5 TRP-3 and TRP-4

Ash generated in MRF plant and incineration process is dispatched to landfill area by trucks. As seen in Figure 5.2, TRP-3 is the transportation line between incineration plant and landfill area, and TRP-4 is that of between MRF and landfill area. As calculation route is presented in Section G.2.1.1, exergy of diesel fuel, fuel capital, trucks and labour consumed through TRP-3 line are presented in Table G.18 and Table G.19.

Table G.18 : Exergy of fuel and fuel capital for TRP-3.

Average transportation distance (km)	30
Total distance travelled (including return) (km)	60
Average energy consumption (MJ/Ton-km)	3,6
Transported waste (Ton)	527760,23
Total energy consumption (TJ)	57
Diesel fuel energy content (MJ/Ton)	42791
Diesel fuel consumption (Ton)	1332,01
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	61,76
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	1595223,37
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	59,74

Table G.19 : Exergy of trucks and labour for TRP-3.

Load capacity (Ton/truck)	16
Transported waste (Ton)	527760,23
Average speed of truck (km/h)	60
Average distance of transportation (km)	30
Total distance travelled (including return) (km)	60
Travel time (including return) (hours)	1
Daily ring number	8
Annual working days (days)	340
1 truck annual load capacity (Ton)	43520
Truck number (trucks)	13
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	0,59
Annual working hours (Labour) (hours)	35360
Exergetic equivalent of labour (TJ)	5,44

Exergy of diesel fuel, fuel capital, trucks and labour consumed through TRP-4 are presented in Table G.20 and Table G.21.

Table G.20 : Exergy of fuel and fuel capital for TRP-4.

Average transportation distance (km)	45
Total distance travelled (including return) (km)	90
Average energy consumption (MJ/Ton-km)	3,6
Transported waste (Ton)	1247686,87
Total energy consumption (TJ)	202,13
Diesel fuel energy content (MJ/Ton)	42791
Diesel fuel consumption (Ton)	4723,55
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	219,02
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	5656941,76
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	211,84

Table G.21 : Exergy of trucks and labour for TRP-4.

Load capacity (Ton/truck)	16
Transported waste (Ton)	1247686,87
Average speed of truck (km/h)	60
Average distance of transportation (km)	45
Total distance travelled (including return) (km)	90
Travel time (including return) (hours)	1,5
Daily ring number	5
Annual working days (days)	340
1 truck annual load capacity (Ton)	27200
Truck number (trucks)	46
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	2,09
Annual working hours (Labour) (hours)	117300
Exergetic equivalent of labour (TJ)	18,06

G.2.1.6 Landfilling

Total ash which come from MRF and incineration plant is landfilled with capital cost of 10€/Ton (EVD, 2008).

G.2.1.7 TRP-5

Organic waste which is sorted in MRF plant is delivered to anaerobic digestion (AD) plant. Following the same calculation route in Section G.2.1.1, details are presented in Table G.22 and Table G.23.

Table G.22 : Exergy of fuel and fuel capital for TRP-5.

Average transportation distance (km)	50
Total distance travelled (including return) (km)	100
Average energy consumption (MJ/Ton-km)	3,6
Transported waste (Ton)	9385332,68
Total energy consumption (TJ)	1689,36
Diesel fuel energy content (MJ/Ton)	42791
Diesel fuel consumption (Ton)	39479,33
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	1830,53
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	47280631,18
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	1770,54

Table G.23 : Exergy of trucks and labour for TRP-5.

Load capacity (Ton/truck)	16
Transported waste (Ton)	9385332,68
Average speed of truck (km/h)	60
Average distance of transportation (km)	50
Total distance travelled (including return) (km)	100
Travel time (including return) (hours)	1,67
Daily ring number	4
Annual working days (days)	340
1 truck annual load capacity (Ton)	21760
Truck number (trucks)	432
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	19,64
Annual working hours (Labour) (hours)	979200
Exergetic equivalent of labour (TJ)	150,75

G.2.1.8 Anaerobic digeston (AD) plant and upgrading

Sectoral organic waste is subject to AD process to produce a combustible gas (mainly CH_4). Stages of AD process are seen below.

Before anaerobic digestion process, pre-treatment (mixing, drying and sterilization) is applied to the organic waste and energy consumption is presented in Table G.24 (Data is extracted from Poschl et al. (2010)).

Table G.24 : Energy consumption in mixing and sterilization of organic waste.

Organic waste (Ton)	9385332,68
Energy consumption (KWh_{el}/Ton)	60
Energy consumption (MJ_{el}/Ton)	216
Total energy consumption (TJ_{el})	2027,23

Anaerobic digestion reaction is presented in **(G.6)** (Gerardi, 2003) and applied to the organic waste composition presented in Table G.25 (Bilgen et al., 2004). Since drying occurs in pretreatment, dry composition of waste is used in calculations.

$$\begin{gathered} C_cH_hO_oN_nS_s + 1/4\ (4c - h - 2o + 3n + 2s)\ H_2O \rightarrow \\ 1/8\,(4c - h + 2o + 3n + 2s)\,CO_2 + 1/8\,(4c + h - 2o - 3n - 2s)\,CH_4 + nNH_3 + sH_2S \end{gathered} \quad \textbf{(G.6)}$$

In **(G.6)**, c, h, o, n, s are atom numbers of carbon, hydrogen, oxygen, nitrogen and sulfur in the the organic compound, respectively.

Table G.25 : Composition of organic waste (dry composition).

Element	Composition (%wt.)
C	48
H	6,4
O	37,6
N	2,6
S	0,4

Organic carbon mass in the organic waste is calculated via equation (G.7).

$$\begin{gathered} \text{Organic carbon mass} = \text{Organic waste (Ton) x OM x DM x (C\%)} = \\ 9385332{,}68 \text{ x } 0{,}8 \text{ x } 0{,}3 \text{ x } 0{,}48 = 1081190{,}33 \text{ Ton} \end{gathered} \quad \textbf{(G.7)}$$

where OM (organic matter) is 80% (Angelis-Dimakis et al., 2011) and DM (dry matter) is 30% (Angelis-Dimakis et al., 2011; Kanat, 2010; Cherubini et al., 2009) for organic waste. C% (by wt.) is already presented in Table G.25.

Digested carbon mass is assumed 60% of organic carbon mass, based on Stegmann (2007) and Banks (2009). Hence the amount of digested carbon is:

$$\begin{aligned}&\text{Digested carbon mass} = \text{Organic carbon mass x } 0{,}6 = \\ &1081190{,}33 \text{ x } 0{,}6 = 648714{,}2 \text{Ton}\end{aligned} \tag{G.8}$$

Mole number of digested carbon (54059516264,11 moles) is the sum of CO_2 and CH_4 mole numbers as seen in equation (G.6). In accordance with presented composition of organic waste in Table G.25, produced gas composition is presented in Table G.26.

Table G.26 : Produced gas from anaerobic digestion.

	Gas volume (m^3)
CO_2	561543225,19
CH_4	649389939,12
H_2S	3784166,138
NH_3	51897135,61
Total	1266614466,07

Electricity and heat consumption of the anaerobic digestion stage is taken as 4% of electricity and %25 of heat produced in biorefinery (Poschl et al., 2010). Produced energy in biorefinery is presented in Table 5.21 and AD energy consumption is presented in Table G.27.

Table G.27 : Energy consumption in AD.

	Description	Consumption (TJ)
Heat	25% of biorefinery production	2498,62
Electricity	4% of biorefinery production	333,15

Capital for the pretreatment and anaerobic digestion stages is taken as 65 € per ton of accessed organic waste (Smith et al., 2001) into the anaerobic digestion plant and the results are presented in Table G.28.

Table G.28 : Capital of pretreatment and AD stages.

Capital (€/Ton)	65
Total organic waste (Ton)	9385332,68
Total capital (€)	610046625
Total capital ($)	768658746,9
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	19601,17

To produce biomethane (methane produced from AD) as pure as possible, produced gas undergoes upgrading process. Energy consumption and produced gas from upgrading process are presented in Table G.29 and Table G.30, respectively (De Hullu et al., 2008).

Table G.29 : Energy consumption in upgrading.

	Energy demand (MJ/m^3 biogas)	Energy consumption (TJ)
Electricity	1,1	1353,32
Heat	0,36	442,9

Table G.30 : Gas composition after upgrading.

	Volume (m^3)	Volume ratio (%)
CH_4	617310076,13	98%
CO_2	12598164,82	2%

Volume of CH_4 is less than presented CH_4 volume in Table G.26 due to gas leakage during the process (undertaken under system emissions in Section G.2.1.11). Capital of upgrading is taken as 0,26 €/m^3 (per m^3 gas accessed to the process) and presented in Table 5.11 (De Hullu et al., 2008)

G. 2.1.9 Biorefinery

The biogas was combusted at a nearby CHP plant fuelled by biogas. Energy consumption and system installation for transfer of biogas is neglected. Properties of energy production in the biorefinery are presented in Table G.31. Energy production efficiency is derived from Poschl et al. (2010). Biorefinery is assumed to consume 4,5% of generated electricity in the plant (Poschl et al., 2010) and the consumption is 374,79 TJ.

Table G.31 : Energy production in biorefinery.

Composition of biogas		
	CH_4 (m^3)	617310076,13
	CO_2 (m^3)	12598164,82
Energy content of gases		
	CH_4 LHV (MJ/m^3)	33,73
	CO_2 LHV (MJ/m^3)	0
Biogas energy content (TJ) (LHV)		20821,87
Energy production efficiency		
	Electricity	40%
	Heat	48%
Produced energy (TJ)		
	Electricity	8328,75
	Heat	9994,50

Produced power is calculated based on the assumption that plant runs 340 days annually. Capital consumption is the system is reported in Table G.32 based on EIA (2010).

$$\text{Produced power}\,(KW_{el}) = \frac{\text{Produced electricty}\ (KJ_{el})}{340x24x60x60\,(s)} = \frac{8328{,}75\,x\,10^9}{340x24x60x60} = 283522{,}18\,KW_{el} \quad \textbf{(G.9)}$$

Table G.32 : Capital of biorefinery.

Capital of biorefinery ($/KW$_{el}$)	7000
Produced power (KW$_{el}$)	283522,18
Total capital ($)	1984655257,01
ee$_C$ (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	50609,71

G. 2.1.10 Composting (Digestate Processing)

In compost production, digestate processing (separation and composting of the produced digestate) is considered. 1 ton of organic matter processed in AD plant was assumed to correspond to 0,4 ton of digestate and 0,16 ton compost, based on Poschl et al. (2010) and Hansen (1996) and presented in Table G.33. Energy consumption of the composting process is reported in Table G.34 (Poschl et al.,2010). Smith et al. (2001) states that composting capital is 35-50 €/Ton digestate. Capital consumption in composting process is also presented in Table G.34. Exergy of compost is calculated in Appendix C.

Table G.33 : Produced compost and exergy content.

Total organic matter	9385332,68
Produced compost (Ton)	1501653,23
Compost exergy (MJ/Ton)	18373,31
Total exergy (TJ)	27590,33

Table G.34 : Energy consumption and capital of composting.

Separation (MJ$_{el}$/Ton digestate)	78,60
Composting (MJ$_{el}$/Ton digestate)	510,00
Total energy consumption (MJ$_{el}$/Ton digestate)	588,60
Produced digestate	3754133,07
Energy consumption (TJ$_{el}$)	2209,68
Capital (€/Ton digestate)	35
Total invested capital (€)	131394657,59
Total invested capital ($)	165557268,56
Exergy of capital (TJ)	4221,79

G.2.1.11 Emissions

Emissions from composting, anaerobic digestion in biogas facilities and incineration depend on factors such as type of waste composted, temperature, moisture content etc. Table G.35 discloses default emission factors for the processes (Eggleston et al., 2006a).

Table G.35 : Emission factors.

	CO_2	N_2O	CH_4
Transportation (kg/TJ LHV diesel)	74100	3,9	3,9
Inorganic MSW incineration (kg/TJ LHV fuel)	91700	4	30
Biorefinery (kg/ TJ LHV fuel)	56100	0,1	1
Composting (kg/kg digestate)	0,132	0,3	4

In anaerobic digestion process, it is assumed that, 3% of produced CO_2 and CH_4 in anaerobic digestion plant are emitted to the atmosphere. The loss of gasses is difficult to measure and varies according to the facility. Eggleston et al. (2006b) reported losses between 0% and 10%. A loss of 3% is therefore in the low end of the scale, nevertheless, this was considered as a reasonable level for current plants (Fruergaard and Astrup, 2011). Similarly, 2% of loss from the CH_4 transferred to upgrading is assumed to be lost in upgrading process, according to Jury (2010). For DO sector solid waste, results are presented in Table G.36. Resulting gas from upgrading process has the composition of 98% CH_4 and 2%CO_2 (% vol.).

Table G.36 : Emission of gasses from AD and upgrading.

	CO_2	CH_4
Gas production in AD (m^3)	561543225,19	649389939,12
Emitted gas from AD (m^3)	16846296,76	19481698,17
Transferred gas to upgrading (m^3)	544696928,44	629908240,95
Emitted gas from upgrading (m^3)	532098763,62	12598164,82
Produced gas from upgrading (m^3)	12598164,82	617310076,13
Density (kg/m^3)	1,98	0,68
Emitted gas from AD (Ton)	33355,67	13247,55
Emitted gas from upgrading (Ton)	1053555,55	8566,75

Total emissions of the processes are reported in Table G.37.

Table G.37 : Emissions from TRP lines and processes.

	CO_2 (Ton)	N_2O (Ton)	CH_4 (Ton)
TRP-1	1326818,40	69,83	69,83
TRP-2	8447,12	0,44	0,44
TRP-3	4223,56	0,22	0,22
TRP-4	14977,48	0,79	0,79
TRP-5	125181,57	6,59	6,59
Incineration	3009323,85	131,27	984,51
AD	33355,67	0,00	13247,55
Upgrading of biogas	1053555,55	0,00	8566,75
Biorefinery	1168106,84	2,08	20,82
Composting	495545,57	1126,24	15016,53
Total	7239535,61	1337,47	37914,05

The same calculation route (presented above) is applied to TE and IN sector solid waste and corresponding results are presented in Section 5.4.2.2 and 5.4.2.3.

G.2.2 CO sector solid waste environmental remediation system

The fraction of CO sector solid waste matching with DO sector solid waste composition (Table 5.58) undergoes the same treatment procedure explained in Section G.2.1. As for the part of “others” which consists of refinery and coke factories waste, below detailed procedure is applied.

G.2.2.1 TRP-6

Transportation distance of TRP-6 (Figure 5.3) is assumed to be equal to sum of that of TRP-1 and TRP2. Distances of TRP-1 and TRP-2 are presented in Table G.6 and Table G.14 as 188,33 and 15 km, respectively. As a result, TRP-6 transportation distance is 203,33 km. Properties of TRP-6 transportation line is presented in Table G.38 and Table G.39.

Table G.38 : Exergy of fuel and fuel capital for TRP-6.

Average transportation distance (km)	203,33
Total distance travelled (including return) (km)	406,67
Average energy consumption (MJ/Ton-km)	3,6
Transported waste (Ton)	23678,32
Total energy consumption (TJ)	17,33
Diesel fuel energy content (MJ/Ton)	42791
Diesel fuel consumption (Ton)	405,05
Diesel fuel exergy content (MJ/Ton)	46366,72
Total diesel exergy consumption (TJ)	18,78
Density of diesel fuel (kg/l)	0,835
Volume of consumed diesel fuel (l)	485090,79
Price of diesel fuel ($/l)	1,47
Exergetic equivalent of capital (TJ)	18,17

Table G.39 : Exergy of trucks and labour for TRP-6.

Load capacity (Ton/truck)	16
Transported waste (Ton)	23678,32
Average speed of truck (km/h)	60
Average distance of transportation (km)	203,33
Total distance travelled (including return) (km)	406,67
Travel time (including return) (hours)	6,78
Daily ring number	1
Annual working days (days)	340
1 truck annual load capacity (Ton)	5440
Truck number (trucks)	5
1 truck exergy (TJ/truck)	0,045
Total exergy of trucks (TJ)	0,23
Annual working hours (Labour) (hours)	11522
Exergetic equivalent of labour (TJ)	1,77

G.2.2.2 IGCC plant

The composition of petroleum refining and coke processing waste which is considered in this thesis, is presented in Table G.40. Produced syngas from raw materials (coke, vacuum residue and petrocoke) are assumed to be 2,85 m^3/kg-raw-material (Tian et al., 2009). Energy need of the system is assumed to be 3% of the system energy production (Marin Sanchez and Rodriguez Toral, 2007). Properties of produced syngas and generated electricity with efficiecy of 40% (based on LHV) are presented in Table G.40. In Table G.40, LHV and HHV of produced syngas is retrieved from Marin Sanchez and Rodriguez Toral (2007) and U.S. Department of Energy National Energy Technology Laboratory (2002b).

Table G.40 : Properties of syngas and electricity production in IGCC.

	Coke	Vacuum residue	Petrocoke	Total
Raw material (Ton)	11839,16	5919,58	5919,58	23678,32
Produced syngas (m^3)	33741606	16870803	16870803	67483212
Syngas LHV (MJ/m^3)	10,69	14,09	10,35	
Syngas HHV (MJ/m^3)	10,92	14,4	10,57	
Energy (LHV) of syngas (TJ)	360,75	237,76	174,55	773,06
Energy (HHV) of syngas (TJ)	368,58	242,92	178,3	789,80
Produced energy (TJ_{el})				309,22
IGCC energy consumption (TJ_{el})				9,28
Net energy production (TJ_{el})				299,94

Cost of IGCC plant is computed based on data retrieved from Garcia et al. (2006) and exergetic equivalent of capital is computed in Table G.41. Power is computed by the equation (5.18).

Table G.41 : Capital of IGCC plant.

Capital of IGCC ($\$/KW_{el}$)	2176
Produced power (KW_{el})	10526,35
Total capital ($)	22905348,23
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	584,09

Emissions from the IGCC plant is estimated by using default emission factors for greenhouse gases (CO_2, CH_4 and N_2O) presented in Marin Sanchez and Rodriguez Toral (2007) and reported in Table G.42 (emission factors are HHV based). Total emissions from the combustion of syngas for the present case are also seen in Table G.42.

Table G.42 : Emission factors and emissions from IGCC plant.

	Coke	Vacuum residue	Petrocoke	Total
Emission factors (Ton/TJ HHV)				
CO_2	77,1	77,4	77,1	
N_2O	0,001	0,0006	0,001	
CH_4	0,003	0,003	0,003	
Emission (Ton)				
CO_2	28523,63	18799,13	13798,43	61057,57
N_2O	0,37	0,14	0,18	0,69
CH_4	1,11	0,73	0,53	2,37

Ash generated in IGCC plant is assumed to be 0,035 Ton ash/Ton input waste (Deb Mondol, 2009).

G.2.3 AG sector solid waste environmental remediation system

G.2.3.1 Manure generation estimation

Estimated amount of manure produced within the country is presented in Table G.43. Data for number of animals are retrieved from Turkstat (2009f, 2009g). Data for manure generation rate and DM of manure are taken from Gomez et al. (2010) and Batzias et al. (2005).

Table G.43 : Manure generation.

	Number of animals	Manure generation rate (kg/year head)	DM (kg dry solids /kg manure)	Manure production (wet TON)	Manure production (dry TON)
Poultry	344820000	40	0,16	13792800	2206848
Turkey	3227000	134	0,16	432418	69186,88
Duck	525000	40	0,16	21000	3360
Geese	830000	40	0,16	33200	5312
Rubbit	415000	56	0,52	23240	12084,80
Sheep	25616912	394	0,23	10093063,33	2321404,57
Goat	6643294	958	0,25	6364275,65	1591068,91

Camel	1004	10000	0,32	10040	3212,80
Pig	1362	1870	0,08	2546,94	203,76
Cattle	10871364	10950	0,08	119041435,80	9523314,86
Buffaloes	100516	10950	0,08	1100650,20	88052,02
Horse	204352	9125	0,12	1864712	223765,44
Asses	329475	4000	0,12	1317900	158148
Mules	75018	4000	0,12	300072	36008,64
Total	393660297			154397353,92	16241970,67

G.2.3.2 TRP-1 line

Transportation distance of TRP-1 line is computed as done in previous sections (188,33 km). Since agricultural waste is collected from rural area, corresponding energy consumption is used in equation (G.10) which is presented in Table G.5. The other properties of TRP-1 line are calculated similar to Section G.2.2.1.

$$\text{Energy consumptio n} = \frac{6{,}75\,\text{x}\,23{,}5 + 3{,}6\text{x}150}{188{,}5} = 4{,}24\,\text{MJ / Tonkm} \qquad \textbf{(G.10)}$$

G.2.3.3 Anerobic digestion of AG sector solid waste

Amount of waste is already presented in Table 5.75. Compositions of wheat straw and cattle manure are presented in Table G.44. Equation (G.6) is applied to the agricultural waste and resulting gas composition of AD process is presented in Table G.45. In Table G.44, ODM is "organic dry matter" which indicates the organic matter in dry matter of the substance and its formulation presented in equation (G.11), below. ODM data is retrieved from Angelis-Dimakis et al. (2011).

Table G.44 : Composition of agricultural sector waste (%wt.) and ODM.

Element	Wheat straw	Cattle manure	Wood
C	42,50	39,10	51,2
H	5,30	4,60	6,1
O	37,10	26,70	41
N	0,52	0,83	0,2
S	0,06	0,25	0,03
ODM	85%	80%	90%

Table G.45 : Gas composition from AD process (m^3).

	Wheat straw	Cattle manure	Wood	Total
CO_2	10579943200	2611715381,11	4468879840,43	17660538421,54
CH_4	11430296800	3078431656,81	4984144159,57	19492872616,38
H_2S	11652480	13643255,37	2077080,47	27372815,83
NH_3	230830080	103532817,86	31650750,00	366013647,86

$$ODM = DM \times OM \tag{G.11}$$

Energy consumption of waste mixing and sterilization before AD process (pretreatment) is taken as presented in Table G.46.

Table G.46 : Energy consumption in pre-treatment (mixing and sterilization) of AD process.

	Heat (KWh/Ton)	Electricity (KWh/Ton)
Manure	31,5	24
Agricultural residue	22,4	24
Wood	22,4	24

As for the left of AG sector solid waste environmental remediation system, the same systematic applied in other sectors is applied.

G.2.4 TR sector solid waste environmental remediation system

Composition and constituent materials of TR sector solid waste are presented in Table G.47 and Table G.48. Since end of life tractors and waste tractor tires are originated from AG sector, not included in TR sector waste. ELV composition is extracted from Giannouli et al. (2007). In Table G.48, average vehicle weight and number of ELVs are derived from Recycling Council of Ontario (2010) and Turkstat (2009g), respectively.

Table G.47 : ELV composition (% wt.) including tires.

	Car	Minibus	Bus	Light Truck	Truck	Motorcycle
Ferrous metal	66	72	72	85	85	67
Rubber	4,3	4	4	4	4	4,5
Magnesium&Zinc	1,7	2	2	1	1	2
Copper	1,4	1,5	1,5	1	1	3
Aluminium	7,2	2,5	2,5	2	2	3
Glass	2,9	4	4	2	2	0
Others (Fluids, lubricants, etc.)	9	8	8	3	3	10,5
Plastic	7,5	6	6	2	2	10

Table G.48 : Weight and components of ELV (including tires).

	Car	Minibus	Bus	Light truck	Truck	Motorcycle
Average vehicle weight (Ton)	1,5	3,5	12	2	5	0,25
Number of ELVs	28295	3712	3580	9257	12416	7738
Total ELV weight (Ton)	42442,5	12992	42960	18514	62080	1934,5
Constituents:						
Ferrous metal (Ton)	28012,05	9354,24	30931,20	15736,90	52768,00	1296,12
Rubber (Ton)	1825,03	519,68	1718,40	740,56	2483,20	87,05
Magnesium&Zinc (Ton)	721,52	259,84	859,20	185,14	620,80	38,69
Copper (Ton)	594,20	194,88	644,40	185,14	620,80	58,04
Aluminium (Ton)	3055,86	324,80	1074,00	370,28	1241,60	58,04
Glass (Ton)	1230,83	519,68	1718,40	370,28	1241,60	0,00
Others (Fluids, lubricants, etc.) (Ton)	3819,83	1039,36	3436,80	555,42	1862,40	203,12
Plastic (Ton)	3183,19	779,52	2577,60	370,28	1241,60	193,45

Composition of tire is presented in Table G.49 (Shulman, 2009). In this thesis, it is accepted that 4 tires are extracted from each ELV (2 tires from each motorcycle) and one from each IUV, annually. Table G.50 presents the corresponding results. In Table G.50, average tire weight is retrieved from Ferrao et al. (2008).

Table G.49 : Composition (% wt.) of tires.

	Composition (% wt.)
Rubber	45
Carbon black	23
Steel	20
Textile	6
Others	6
Total	100

Table G.50 : Weight of tires (from IUV+ELV).

	Car	Minibus	Bus	Light truck	Truck	Motorcycle
Average tire weight (kg)	5,91	10,58	13,5	10,58	52,67	4,1
Number of ELVs	28295	3712	3580	9257	12416	7738
Number of IUVs	6140992	357523	175949	1695624	709535	1822831
Total tire number	6254172	372371	190269	1732652	759199	1838307
Total tire weight (Ton)	36962,16	3939,69	2568,63	18331,46	39987,01	7537,06

Total tire weight which is incinerated in incineration plant is the sum of the last line in Table G.50. The sum amounts to 109326 Ton tires. In Table G.51, materials consisting ELV tires are presented. ELV composition (excluding tire) is presented in Table G.52. Rubber and steel are extracted from the matching materials of ELV composition presented in Table G.48. The other components of tires are extracted from the part "others" in Table G.48.

Table G.51 : Weight of constituting materials in ELV tires.

	Car	Minibus	Bus	Light truck	Truck	Motorcycle
Average tire weight (kg)	5,91	10,58	13,5	10,58	52,67	4,1
Number of ELVs	28295	3712	3580	9257	12416	7738
Total tire weight from ELV (Ton)	668,89	157,09	193,32	391,76	2615,80	63,45
Constituents:						
Rubber (Ton)	301,00	70,69	86,99	176,29	1177,11	28,55
Carbon black (Ton)	153,85	36,13	44,46	90,10	601,63	14,59
Steel (Ton)	133,78	31,42	38,66	78,35	523,16	12,69
Textile (Ton)	40,13	9,43	11,60	23,51	156,95	3,81
Others (Ton)	40,13	9,43	11,60	23,51	156,95	3,81

Table G.52 : Constituting materials in ELV (excluding tires).

	Car	Minibus	Bus	Light truck	Truck	Motorcycle	Total
Ferrous metal (Ton)	27878,27	9322,82	30892,54	15658,55	52244,84	1283,42	137280,44
Rubber (Ton)	1524,03	448,99	1631,41	564,27	1306,09	58,50	5533,28
Magnesium&Zinc (Ton)	721,52	259,84	859,20	185,14	620,80	38,69	2685,19
Copper (Ton)	594,20	194,88	644,40	185,14	620,80	58,04	2297,45
Aluminium (Ton)	3055,86	324,80	1074,00	370,28	1241,60	58,04	6124,58
Glass (Ton)	1230,83	519,68	1718,40	370,28	1241,60	0,00	5080,79
Others (Fluids and lubricants) (Ton)	3585,71	984,38	3369,14	418,31	946,87	180,91	9485,32
Plastic (Ton)	3183,19	779,52	2577,60	370,28	1241,60	193,45	8345,64
Total (Ton)	41773,61	12834,91	42766,68	18122,24	59464,20	1871,05	176832,68

In Table G.53, exergy of one truck is computed based on the composition of the truck presented in Table G.47.

Table G.53 : Exergy of trucks.

	Truck Constituent Materials	Specific Exergy (MJ/Ton)
Average vehicle weight (Ton)	5	
Constituents:		
Ferrous metal (Ton)	4,25	6800
Rubber (Ton)	0,20	32502,16
Magnesium&Zinc (Ton)	0,05	15628,64
Copper (Ton)	0,05	2112,06
Aluminium (Ton)	0,10	32928,09
Glass (Ton)	0,10	131,48
Others (Fluids and lubricants) (Ton)	0,15	17514,94
Plastic (Ton)	0,10	32502,16
Exergy of truck (TJ/truck)		0,045

G.2.4.1 TRP-1

The same calculation route applied in Section G.2.1. However, the energy consumption of trucks (per ton of tire) is taken as 2 times more than that in G.2.1.1

since tires have holes in their centers and it is assumed that 1 truck tire carrying capacity is 8 Ton in collection phase. Hence average energy consumption of waste collection is:

$$\text{Energy consumption} = 5{,}46 \text{ x } 2 = 10{,}92 \quad \text{MJ / Tonkm} \tag{G.12}$$

The properties of the TRP line are computed in line with the Section G.2.1.1. The computation route applied in other TRP lines of TR sector is identical to that of presented TRP lines in Section G.2.1.1.

G.2.4.2 MRF Plant

Processes involved in MRF are dismantling, shredding and recycling and also tyre shredding. Capital and energy consumption of MRF plant are sum of capital and sum of energy consumption of these processes. Results are presented below.

Dismantling of ELVs

Energy consumption and capital of the dismantler are presented in Table G.54 and Table G.55, respectively. Data is obtained based on Ferrao and Amaral (2006).

Table G.54 : Energy consumption of dismantling process.

Energy consumption	3,68 KWh/ton (13,25 MJ/ton)
Total weight of vehicles (Ton)	180923
Total energy consumption (TJ)	2,40

Table G.55 : Capital of dismantling.

Capital of dismantler (€/Ton)	5,24
Capital of dismantler ($/Ton)	6,6
Total weight of vehicles (Ton)	180923
Total capital (€)	948657,87
Total capital ($)	1195308,92
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	30,48

Shredding of ELVs

The part of vehicles which are subject to shredding is total weight of vehicles excluding tires except the part “others” in Table G.52. Energy consumption and capital of the process are presented in Table G.56 and Table G.57, respectively. Data is obtained based on Ferrao and Amaral (2006).

Table G.56 : Capital of ELV shredding.

Capital of shredding (€/Ton)	98,54
Capital of shredding ($/Ton)	124,15
Total weight of vehicles (Ton)	167347,37
Total capital (€)	16489462,92
Total capital ($)	20776723,28
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	529,81

Table G.57 : Energy consumption of ELV shredding process.

Energy consumption	44,44 KWh/ton (160 MJ/ton)
Total weight of vehicles (Ton)	167347,37
Total energy consumption (TJ)	26,78

Shredding of tires

Properties of the tire shredding process are presented in Table G.58 and Table G.59 (Data is retrieved from Pehlken and Essadiqi (2005)).

Table G.58 : Energy consumption of tire shredding process.

Energy consumption (MJ/Ton)	423,01
Total weight of tires (Ton)	109326
Total energy consumption (TJ)	46,25

Table G.59 : Capital of tire shredding.

Capital of dismantler ($/Ton)	12
Total weight of tires (Ton)	109326
Total capital ($)	1311912,02
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	33,45

G.2.4.3 Material recycling

Produced recycled materials from shredded materials of ELV body (amount of materials are presented in Table G.52) are seen in Table G.60. Energy consumption of recycling process is reported in Table G.61. Energy consumption data is given per recycled material except for plastic which is given for per plastic material accessing the process. Capital of recycling processes is computed similar to Table G.13.

Table G.60 : Properties of recycling of ELVs.

	Material in waste composition (Ton)	Recycling efficiency	Recycled material (Ton)	Produced ash (Ton)
Ferrous metal (Ton)	137280,44	0,94	129043,61	
Rubber (Ton)	5533,28	0,733	4055,89	
Magnesium&Zinc (Ton)	2685,19	0,94	2524,08	
Copper (Ton)	2297,45	1	2297,45	
Aluminium (Ton)	6124,58	0,93	5695,86	
Glass (Ton)	5080,79	1	5080,79	
Plastic (Ton)	8345,64	0,733	6117,35	
Total (Ton)	167347,37		154815,04	12532,33

Table G.61 : Energy consumption in recycling.

	Electricity (MJ/Ton)	Heat (MJ/Ton)	Total Electricity (TJ)	Total Heat (TJ)
Ferrous metal	255,6	820,8	32,98	105,92
Rubber	1490,4	2291	8,25	12,68
Magnesium	72	11400	0,09	14,39
Zinc	72	37000	0,09	46,70
Copper	72	120	0,17	0,28
Aluminium	284,4	4885	1,62	27,82
Glass	66,24	5460	0,34	27,74
Plastic	1490,4	2291	12,44	19,12
Total			55,97	254,64

G.2.4.4 Incineration of tires

Energy generation and energy need of tire incineration process is presented in Table G.62. Incineration plant is assumed to consume 4,5% of generated electricity by the CHP plant (Poschl et al., 2010) and the consumption is also presented in Table G.62. In Table G.62, tire energy content is obtained from Vest (2000).

Table G.62 : Energy generation and consumption of incineration process.

		Electricity	Heat
Tire weight (Ton)	109326		
Tire energy content (MJ/Ton)	29000		
Efficiency (%)		40%	46%
Produced energy (TJ)		1268,18	1458,41
Energy consumption (TJ)		57,07	

Ash produced from tire incineration process is taken as 25% (by wt.) of the incinerated tires based on Ozturk (2009). Accordingly, produced as from the process is 27331,50 Ton which is landfilled.

Capital of tire incineration plant is presented in Table G.63. Produced power is calculated as presented in equation (G.9).

Table G.63 : Capital of incineration.

Capital of biorefinery ($/$KW_{el}$)	7000
Produced power (KW_{el})	43170,67
Total capital ($)	302194693,38
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	7706,11

G.2.4.5 Emissions

Emissions originated from transportation are calculated based on emission factors presented in Table G.35. The other source of system emissions is tire incineration and emission factors are presented in Table G.64. Emission factors are extracted from California Environmental Protection Agency- Air Resources Board (2008). In Table G.64, emission factors are presented based on HHV of tire.

Table G.64 : Emissions of tire incineration.

		CO_2	N_2O	CH_4
Tire incineration emission factors (kg/TJ tire)		85303,2	0,57	2,84
Weight of tire (Ton)	109326			
Tire energy content (MJ/Ton)	29000			
Emissions (Ton)		270450	1,8	9,01

APPENDIX H: Details of the Gas Emission Treatment Processes

H.1. CO_2 environmental remediation system

H.1.1 Natural gas fuelled heating of CO_2

Heat needed to heat up CO_2 from 14°C (287,15 K) to 180°C (453,15 K) is calculated via:

$$Q = \int_{T_1}^{T_2} m\, c_p(T)\, dT \qquad \textbf{(H.1)}$$

where Q (J) is heat, m (kg) is mass, $c_p(T)$ (J/kgK) is temperature dependent specific heat capacity, T (K) is temperature, T_1 (K) is initial temperature of gas and T_2 (K) is final temperature of gas. (In this case T_1=287,15 K, T_2=453,15 K). Variation of c_P with temperature is extracted from Cengel and Boles (1994). For 1 kg of CO_2, Q is computed as 0,15 MJ.

The properties of natural gas fuelled heater and energy consumption is presented in Table H.1.

Table H.1 : Properties of natural gas fuelled heater.

Required heat (MJ)	0,15
Natural gas fuelled heater efficiency	0,8
Energy content of consumed natural gas (MJ, HHV)	0,188
Energy content of natural gas (MJ/m^3, HHV)	38,73
Consumed natural gas (m^3)	0,00485
Exergy coefficient for natural gas (β_{HHV})	0,92
Exergy content of consumed natural gas (MJ)	0,17

System is assumed to work 340 days a year and 24 hours a day. Hence, power of the system is computed via the equation:

$$\text{System power (KW)} = \frac{\text{Consumed fuel energy (KJ)}}{340x24x60x60(s)} = \frac{0{,}188x10^3}{340x24x60x60} = 6{,}39x10^{-6} \qquad \textbf{(H.2)}$$

H.1.2 Heat release from CO_2, CaO and $CaCO_3$ and carbonization reaction

Heat released from cooling of CO_2, CaO and $CaCO_3$ (625 – 14 °C) is calculated via equation (H.1) and presented in Table H.2. Variation of c_P with temperature for CO_2 and c of CaO and $CaCO_3$ are extracted from Cengel and Boles (1994).

Table H.2 : Heat release from CaO, $CaCO_3$ and CO_2.

c of $CaCO_3$ (KJ/kg K)	0,75
c of $CaCO_3$ (KJ/kg K)	0,835
Amount of CaO (kg)	9,74
Amount of $CaCO_3$ (kg)	1,93
Amount of CO_2 (kg)	0,15
Heat release from CaO (MJ)	4,463
Heat release from $CaCO_3$ (MJ)	0,986
Heat release from CO_2 (MJ)	0,096
Total heat release from CaO + $CaCO_3$ + CO_2 (MJ)	5,54

As explained in Section 5.4.3.1, calcination reaction is an exothermic reaction and released heat from the reaction is 177 KJ/mole (4,02 MJ/kg CO_2). The efficiency of calcination reaction is 0,85 (which means 0,85 kg of 1 kg CO_2 undergoes calcination reaction). Heat release from calcination reaction is:

$$Q_r = 0{,}85(\mathrm{kg})\,\mathrm{x}\,4{,}02(\mathrm{MJ/kg}) = 3{,}42\,\mathrm{MJ} \quad \textbf{(H.3)}$$

As a result, total heat released from the system is the sum of total heat release from CaO + $CaCO_3$ + CO_2 (Table H.2) and heat release from the calcination reaction (equation (H.3)). The sum is:

$$Q_r = 5{,}54 + 3{,}42 = 8{,}96\,\mathrm{MJ} \quad \textbf{(H.4)}$$

Efficiency of electricity generation is assumed as 0,35. Hence produced electricity is:

$$\mathrm{Produced\ electricity} = 8{,}96\,\mathrm{x}\,0{,}35 = 3{,}14\,\mathrm{MJ} \quad \textbf{(H.5)}$$

$$\mathrm{Produced\ power}\,(\mathrm{KW_{el}}) = \frac{\mathrm{Produced\ electricity\ (KJ)}}{340\mathrm{x}24\mathrm{x}60\mathrm{x}60\,(\mathrm{s})} = \quad \textbf{(H.6)}$$

$$\frac{3{,}14\,\mathrm{x}\,10^3}{340\mathrm{x}24\mathrm{x}60\mathrm{x}60} = 1{,}07\,\mathrm{x}\,10^{-4}\,\mathrm{KW_{el}}$$

H.1.3 Emissions

System energy carrier consumption is natural gas consumption for CO_2 heating. Emission factors are extracted from (Eggleston et al., 2006a) and presented in Table H.3. In Table H.3, emission factors are given based on LHV of fuels. (LHV/HHV=0,91 for natural gas) HHV of consumed natural gas by the system is presented in Table H.1. LHV content of consumed natural gas (per kg CO_2) is 0,17 MJ.

Table H.3 : Emissions of natural gas combustion.

		CO_2	N_2O	CH_4
Natural Gas				
Consumption (MJ) (LHV)	0,17			
Emission factors (TJ/kg)		56100	0,1	1
Emission (kg)		$9{,}59 \times 10^{-3}$	$1{,}71 \times 10^{-8}$	$1{,}71 \times 10^{-7}$

H.1.4 Exergy of products (CaO and $CaCO_3$)

As stated in Section 5.4.3.1 and seen in Figure 5.6, produced CaO and $CaCO_3$ from the system are at 14°C and 1 atm. As stated in Chapter 2, chemical exergy of substances are tabulated for standard reference state (298,15 K, 1 atm) in Szargut et al. (1988). Since the produced CaO and $CaCO_3$ are at different temperature from that of standard state, physical exergy of CaO and $CaCO_3$ also contribute to exergy of the products. Physical exergy of the substances are computed via equation (H.7) (Szargut et al., 1988).

$$e_{ph} = (u - u_0) + P_0 (v - v_0) - T_0 (s - s_0) = h - h_0 - T_0 (s - s_0) \qquad \textbf{(H.7)}$$

where u and u_0 (J/kg) are specific internal energy of the substance at initial state and at the state of reference environment; h and h_0 (J/kg) are specific enthalpy of the substance at initial state and at the state of reference environment; T_0 (K) is the temperature of the reference environment; s and s_0 (J/kg K) are specific entropy of the substance at initial state and at the state of reference environment.

For incompressible substances (Cengel and Boles, 1994):

$$c_p = c_v = c \qquad \textbf{(H.8)}$$

$$s - s_0 = c \ln\left(\frac{T}{T_0}\right) \quad \textbf{(H.9)}$$

where c_p and c_v (J/kgK) are specific heat capacity at constant pressure and temperature, respectively.

As a result, equation (H.7) can be rewritten as equation (H.10) (Cengel and Boles, 1994).

$$e_{ph} = c\,(T - T_0) - T_0\, c \ln\left(\frac{T}{T_0}\right) \quad \textbf{(H.10)}$$

Chemical, physical and total exergy of the produced CaO and $CaCO_3$ are reported in Table H.4.

Table H.4 : Exergy of produced CaO and $CaCO_3$.

c of CaO (KJ/kg K)	0,75
c of $CaCO_3$ (KJ/kg K)	0,835
T_0 (K)	298,15
T (K)	287,15
Produced CaO (kg)	9,74
Produced $CaCO_3$ (kg)	1,93
e_{ph} of CaO (KJ/kg)	0,156
e_{ph} of $CaCO_3$ (KJ/kg)	0,174
E_{ph} of CaO (MJ)	0,00152
E_{ph} of $CaCO_3$ (MJ)	0,00034
e_{ch} of CaO (MJ/kg)	1,97
e_{ch} of $CaCO_3$ (MJ/kg)	0,01
E_{ch} of CaO (MJ)	19,17
E_{ch} of $CaCO_3$ (MJ)	0,019
(E_{ph} + E_{ch}) for CaO (MJ)	19,17
(E_{ph} + E_{ch}) for $CaCO_3$ (MJ)	0,019

H.2 N_2O environmental remediation system

H.2.1 Natural gas fuelled heating of N_2O

Heat consumed in rising the temperature of N_2O from 14°C to 900°C is calculated via equation (H.1) and computed as 1,03 MJ. (Variation of c_P with temperature is extracted from Cengel and Boles (1994)). The properties of natural gas fuelled heater and energy consumption is presented in Table H.5.

Table H.5 : Properties of natural gas fuelled heater.

Required heat (MJ)	1,03
Natural gas fuelled heater efficiency	0,8
Energy content of consumed natural gas (MJ, HHV)	1,29
Energy content of natural gas (MJ/m^3, HHV)	38,73
Consumed natural gas (m^3)	0,033
Exergy coefficient for natural gas (β_{HHV})	0,92
Exergy content of consumed natural gas (MJ)	1,18

Power of the system is computed via the equation (H.2) and obtained as 4,38 x 10^{-5} KW.

H.2.2 Heat release from decomposition reaction, N_2 and O_2

The released from cooling of N_2 and O_2 (900 – 14 °C) is calculated via equation (H.1) and presented in Table H.6. Variation of c_P with temperature for N_2 and O_2 are extracted from Cengel and Boles (1994).

Table H.6 : Heat release from N_2 and O_2.

Amount of N_2 (kg)	0,64
Amount of O_2 (kg)	0,36
Temperature gradient (K)	886
Heat release from N_2 (MJ)	0,69
Heat release from O_2 (MJ)	0,33
Total heat release from N_2+O_2 (MJ)	1,02

As explained in Section 5.4.3.2 decomposition reaction is an exothermic reaction and released heat from the reaction is 82 KJ/mole (1,86 MJ/kg N_2O). Hence, heat release from decomposition of 1 kg N_2O is 1,86 MJ. As a result, total heat released from the system is:

$$Q = 1{,}02 + 1{,}86 = 2{,}88 \, MJ \tag{H.11}$$

Efficiency of electricity generation is 0,35. Thereby, produced electricity is:

$$\text{Produced electricity} = 2{,}88 \, x \, 0{,}35 = 1{,}01 \, MJ \tag{H.12}$$

Power of electricity plant is:

$$\text{Produced power (KW}_{el}) = \frac{\text{Produced electricty (KJ)}}{340x24x60x60(s)} = \frac{1{,}01x10^3}{340x24x60x60} = 3{,}43x10^{-5}\,KW_{el} \quad \textbf{(H.13)}$$

H.2.3 Emissions

System energy carrier consumption is natural gas consumption for N_2O heating. Emission factors are extracted from (Eggleston et al., 2006a) and presented in Table H.7. In Table H.7, emission factors are given based on LHV of fuels (LHV/HHV=0,91 for natural gas). HHV of consumed natural gas by the system is presented in Table H.5. Resulting LHV content of natural gas consumption (per kg N_2O) is 1,17 MJ.

Table H.7 : Emissions of natural gas combustion.

Natural Gas		CO_2	N_2O	CH_4
Consumption (MJ) (LHV)	1,17			
Emission factors (TJ/kg)		56100	0,1	1
Emission (kg)		0,066	$1{,}2x10^{-7}$	$1{,}2\ x10^{-6}$

H.2.4 Exergy of products (N_2 and O_2)

Since the temperature of N_2 and O_2 (14°C) is lower than reference environmental temperature (25°C), physical exergy is a constituent of products' exergy (N_2 and O_2).

General form of formula for physical exergy (e_{ph}) is presented in equation (H.7).

With the ideal gas assumption (Cengel and Boles, 1994):

$$h - h_0 = \int_{T_0}^{T} c_P(T)\ dT \quad \textbf{(H.14)}$$

$$s - s_0 = s^0 - s_0^0 - R \ln \frac{P}{P_0} \quad \textbf{(H.15)}$$

where s^o is a function which is presented in equation (H.16) (extracted from Cengel and Boles (1994))

$$s^0 = \int_0^T c_P(T)\frac{dT}{T} \qquad \textbf{(H.16)}$$

In equation (H.15), s^0 is computed via equation (H.16) at initial state (T=14°C= 287,15 K) and s_0^0 is at the state of reference environment (T= 25 C= 298,15 K). Variation of s^o with temperature for different gases are calculated and tabulated in thernodynamic tables (available in Cengel and Boles (1994)). Since in our case P_1 = P_0 = 1 atm., equation (H.15) becomes:

$$s - s_0 = s^0 - s_0^0 \qquad \textbf{(H.17)}$$

In Table H.8 and Table H.9, aforementioned terms and resulting e_{ph} are seen for N_2 and O_2, respectively. Function of $c_P(T)$ is derived from Cengel and Boles (1994). Chemical exergy, s_0 and s_0^0 of N_2 and O_2 are derived from Szargut et al., 1988.

Table H.8 : E_{ph} of produced N_2.

T_0 (K)	298,15
T (K)	287,15
Produced N_2 (kg)	0,64
h-h_0 (KJ/kg)	-13,42
s^0 (KJ/kgK)	6,79
s_0^0 (KJ/kgK)	6,84
e_{ph} of N_2 (KJ/kg)	3,61
E_{ph} of N_2 (MJ)	0,0023

Table H.9 : E_{ph} of produced O_2.

T_0 (K)	298,15
T (K)	287,15
Produced O_2 (kg)	0,36
h-h_0 (KJ/kg)	-11,34
s^0 (KJ/kgK)	7,29
s_0^0 (KJ/kgK)	7,33
e_{ph} of O_2 (KJ/kg)	1,43
E_{ph} of O_2 (MJ)	0,00052

Chemical exergy of gas mixture exits the system is a mixture of N_2 and O_2. The exergy equation of a gas mixture is presented in equation (H.18) (Szargut et al.,1988).

$$e_{ch} = RT_0 \sum_i y_i \ln(\frac{y_i}{y_{0i}}) \quad \textbf{(H.18)}$$

where y_i and y_{0i} are molar fractions of gases in considered gas mixture and reference environment, respectively. R is universal gas constant (8,314 $Jmole^{-1}K^{-1}$), T_0 is 25°C. Constituent terms of equation (H.18) are presented in Table H.10.

Table H.10 : Chemical exergy of N_2+O_2 mixture.

T_0 (K)	298,15
Produced N_2 (kg)	0,64
Produced O_2 (kg)	0,36
Mole number of N_2	22,73
Mole number of O_2	11,36
$y_{i\text{-}O2}$	0,33
$y_{i\text{-}N2}$	0,67
$y_{0i\text{-}O2}$	0,21
$y_{0i\text{-}N2}$	0,78
E_{ch} of gas mixture (J/mole)	126,26
Total mole number of the gas mixture	34,09
Total E_{ch} of the gas mixture (MJ)	0,0043

The sum of exergies presented in Table H.8, Table H.9 and Table H.10 is the exergy of produced N_2 and O_2 which amounts to 0,007 MJ.

APPENDIX I: Details of the Wastewater Treatment Process

I.1 $EE_{ENV\text{-}lq,w}$ for untreated wastewater

I.1.1 Wastewater collection

Building a wastewater collection infrastructure is needed by the population who are not served by sewerage system. In the year 2006, total population is 78259264 persons and population who are served by sewerage system is 50856943 persons (Turkstat, 2009d). The left of the population is 27402321 persons who are not served by sewerage system.

Esen (2002) reported Table I.1 which includes template values of required per capita length of sewage system. As an average, it is taken as 2 m/person in this thesis. In Esen (2002), the cost of sewage system which transfers the wastewater to treatment plants is stated as between 90-130 $/m. In this thesis, it is taken as 100 $/m.

Table I.1 : Per capita length of sewage system.

Population	Lenght of sawege (m/person)
<5000	2,26
5000 - 20000	2,25
20000 - 50000	3,85
50000 - 100000	2,19
100000 - 200000	2
200000 - 400000	1,12
400000 - 1000000	1,05
> 1000000	1,03

In conclusion, the cost of the wastewater collection system is seen in equation (I.1).

$$\begin{aligned} C(\$) &= \text{Population (persons) x average system length (m/person) x} \\ &\quad \text{system cost (\$/m)} = 27402321 \text{x} 2 \text{x} 100 = 5480464200 \end{aligned} \tag{I.1}$$

Energy consumption of water collection is assumed to be 0,5 KWh_{el}/m^3 based on Dancee (2004). As presented in Table 5.136, generated wastewater by the population who is served sewage is 1810334336,87 m^3 (Amount of wastewater generated per capita is taken as 181 liter/person-day from Turkstat (n.d.)). Hence, energy consumption of the wastewater collection is:

$$\text{Collection energy generation} = \text{Wastewater } (m^3) \times \text{energy } (KWh/m^3) = 1810334337\ m^3 \times 0{,}5\, KWh_{el}/m^3 = 905167168{,}4\, KWh_{el} = 3258{,}60\ TJ \qquad \textbf{(I.2)}$$

I.1.2 Wastewater treatment and sludge generation

Amount of untreated wastewater of DO sector and total DM are seen in Table I.2. The range of possible dry matter (DM) content of raw domestic wastewater is reported by Tchobanoglous (2002) as 390-1230 mg/l. Considered wastewater is assumed to be medium strength wastewater with DM content of 700 mg/l.

Table I.2 : DM content of DO sector untreated wastewater.

DO sector untreated wastewater (m^3)	2527421050,99
DM content (mg/l; kg/m^3)	700; 0,7
DM of untreated wastewater (Ton)	1769194,74

The considered wastewater environmental remediation system is derived from Qasim (1999) and illustrated in Figure 5.9. The system includes primary, secondary and tertiary treatment stages. Primary and secondary treatment produce sludge and total amount of the sludge is referred as flow “3” in Figure 5.9. In Table I.3, sludge generation coefficients of primary and secondary treatment processes (based on Qasim (1999)), the amount of generated sludge through the processing of DO sector untreated wastewater and DM content of the sludge are seen. Secondary treatment stage produces “activated sludge”. Mathematical formulation of “coefficient of sludge generation” in Table I.3 is seen in equation (I.3).

$$\text{Coefficient of sludge generation} = \frac{\text{Sludge generation } (m^3)}{\text{Raw wastewater processed in the system } (m^3)} = \frac{\text{Sludge generation } (m^3)}{2527421050{,}99\ m^3} \qquad \textbf{(I.3)}$$

Table I.3 : Sludge generation.

DO sector untreated wastewater (m^3)	2527421050,99
Coefficient of primary sludge generation (m^3/m^3)	0,0035
Coefficient of secondary sludge generation (m^3/m^3)	0,017
Generated primary sludge (m^3)	8908733,713
Generated secondary sludge (m^3)	43081040,64
Total generated sludge (m^3)	51989774,35
DM of primary sludge (g/l = kg/m^3)	12
DM of secondary sludge (g/l = kg/m^3)	8
Total DM in primary sludge (Ton)	106904,80
Total DM in secondary sludge (Ton)	344648,33
Total DM in sludge (Ton)	451553,13

I.1.3 Sludge blending

Energy consumption of sludge blending is reported as 5 KWh/tDM (18000 KJ/tDM) of electricity (1 tDM = 1 ton of the mixed sludge in dry basis) which incorporates the energy consumption of pumping and blending of the sludge (Suh and Rousseaux, 2002).

$$\begin{gathered}\text{Sludge blending energy consumption} = \\ 18000\text{x}10^{-9}\,(\text{TJ / tDM})\ \text{x}\ 451553{,}13\,(\text{tDM}) \ = \ 8{,}13\,\text{TJ}\end{gathered} \tag{I.4}$$

Due to the absence of data, capital cost of the blending tank is not included in the calculation.

I.1.4 Sludge thickening

Gravity belt thickening is applied in the considered system obtained from Qasim (1999). The energy consumption of the thickening process is retrieved from (Suh and Rousseaux, 2002) as 50 KWh/tDM (180000 KJ/tDM) of electricity. Energy consumption in gravity belt thicking stage is:

$$\begin{gathered}\text{Thickening energy consumption} = \\ 180000\text{x}10^{-9}\,(\text{TJ / tDM})\ \text{x}\ 451553{,}13\,(\text{tDM}) = 81{,}28\,\text{TJ}\end{gathered} \tag{I.5}$$

Cost of gravity belt thickening process is computed based on data retrieved from Sloan et al. (2009) and exergetic equivalent of capital is computed in Table I.4.

Table I.4 : Capital of gravity belt thickening process.

Capital of thickening ($/tDM)	31
DM of thickened sludge (Ton)	451553,13
Total capital ($)	13998147,03
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	356,96

In the course of gravity belt thickening process, 4 kg of polymer consumption per tDM sludge is reported in Suh and Rousseaux (2002). Due to the lack of exact chemical composition of polymers, it is not counted in material flows of the system. The excessive liquid from the thickening process, in the form of supernatant, is sent back to secondary treatment stage for further treatment as seen in Figure 5.9 (flow “5”).

I.1.5 Anaerobic digestion (AD) process

Energy consumption of AD process is 25 KWh electricity and 100 KWh heat per tDM of sludge. DM content of the sludge is presented in Table I.5 and energy consumption is calculated in accordance with equation (I.4) an (I.5). Results are seen in Table 5.143.

Cost and exergetic equivalent of the AD system are presented in Table I.5 by using data reported in Sloan et al. (2009).

Table I.5 : Capital of AD process.

Capital of AD (\$/tDM)	65
DM of thickened sludge (Ton)	451553,13
Total capital (\$)	29350953,45
ee_C (MJ/\$)	25,5
Exergetic equivalent of capital (TJ)	748,46

In Table I.6, properties of biogas production and produced biogas in AD process are listed. Volume of the input sludge to AD is computed adopting the system properties presented in Qasim (1999).

Table I.6 : Properties of CH_4 generation in AD process.

Coefficient of input sludge to AD process (m^3/m^3) [15]	0,00331
Volume of input sludge to AD process (m^3)	8376869,01
BOD_5 ratio in the input sludge (kg BOD_5/m^3 sludge)	32,09
Total BOD_5 in input sludge (Ton)	268791,12
BOD_5 reduction in AD	60%
Total BOD_5 reduction in AD (Ton)	161274,67
Produced CH_4 (kg CH_4/kg BOD_5 reduction) [16]	0,6
Produced CH_4 (Ton)	96764,80
Density of CH_4 (kg/m^3)	0,68
Produced CH_4 (m^3)	142301182,45

Composition of a standard gas mixture obtained from AD process of wastewater treatment sludge is assumed to have the volumetric composition of 30%:70% (CO_2:CH_4) (Appels et al., 2008; Schievano et al., 2010). Consequently, the volume of CO_2 is computed as 60986221,05 m^3. The liquid, in the form of supernatant, from AD process is sent back to secondary treatment stage for further treatment as seen in

[15] The formula of coefficient is presented in equation (I.3).
[16] Eggleston et al. (2006c)

Figure 5.9 (flow "7"). System gas leakage is presented in Appendix G. Resulting gas which is transferred to upgrading process is presented in Table I.7.

Table I.7 : Biogas composition from AD process.

	Gas volume (m^3)
CH_4	138032146,97
CO_2	59156634,42

I.1.6 Upgrading of biogas

Produced biogas in AD is subject to upgrading process to increase the gas purity and methane content. Energy consumption (Hullu et al., 2008) and produced gas (Poschl et al., 2010) from upgrading process are presented in Table I.8 and Table I.9, respectively.

Table I.8 : Energy consumption in upgrading.

	Energy demand (MJ/m^3 biogas)	Energy consumption (TJ)
Electricity	1,1	216,91
Heat	0,36	70,99

Table I.9 : Produced gas after upgrading.

	Volume (m^3)	Volume ratio (%)
CH_4	135271504,03	98%
CO_2	2760642,94	2%

Volume of CH_4 is less than presented CH_4 volume in Table I.7 due to gas leakage during upgrading presented under system emissions in Section I.9.

Capital of upgrading is computed as 0,26 €/m^3 (per m^3 gas accessed to the process which is presented in Table I.7) and seen in Table 5.139.

I.1.7 Transfer of biogas and biorefinery

The biogas was combusted at a nearby CHP plant fuelled by natural gas. Energy consumption and system installation for transfer of biogas are neglected.

Properties of energy production in the biorefinery are presented in Table I.10 (Energy production efficiency is derived from Poschl et al. (2010)). As applied in the course of solid waste remediation and detailed in Appendix G, biorefinery is assumed to consume 4,5% of the generated electricity by the plant. As for obtaining the exergetic equivalent of capital, the same calculation route (which is presented in Appendix G) is followed.

Table I.10 : Energy production in biorefinery.

Composition of biogas		
	CH_4 (m^3)	135271504,03
	CO_2 (m^3)	2760642,94
Energy content of gases		
	CH_4 LHV (MJ/m^3)	33,73
	CO_2 LHV (MJ/m^3)	0
Biogas energy content (TJ) (LHV)		4562,71
Energy production efficiency		
	Electricity	40%
	Heat	48%
Produced energy (TJ)		
	Electricity	1825,08
	Heat	2190,10

I.1.8 Post processing of digestate

After AD process, the remaining sludge (digestate) is recycled by post-processing and a fertilizer-like material is produced (which is named "fertilizer" in this thesis).

In AD of municipal wastewater, 30-35% of total solid (DM) of the input sludge to AD process is destructed (European Commission, 2001b). In this thesis, DM destruction is assumed to be 35%. In Table I.11, DM content of input and output sludge and DM destruction in AD are presented. The output sludge of the AD process is referred as digestate.

Table I.11 : DM of input & output sludges and DM destruction in AD.

DM of AD input sludge (Ton)	451553,13
% DM destruction	35%
Destructed DM in AD (Ton)	158043,60
DM of AD output sludge (digestate) (Ton)	293509,53

Initial conditioning and following drying processes are incorporated in post-processing of digestate (Ozturk, 1999; European Commission, 2001b). In the course of conditioning, 0,05 Ton $FeCl_3$/tDM digestate and 0,15 Ton CaO/tDM digestate are added to the digestate (Ozturk, 1999). Amount, exergetic content and capital of $FeCl_3$ and CaO are presented in Table I.12.

The estimated energy consumption for drying is reported in Table I.13 based on data in European Commission (2001b). Due to lack of data, energy consumption of conditioning process is not included in Table I.13.

Table I.12 : Exergy and capital of $FeCl_3$ and CaO.

DM of digestate (Ton)	293509,53
$FeCl_3$ addition (Ton)	14675,48
CaO addition (Ton)	44026,43
$FeCl_3$ exergy (KJ/gr)	1,42
CaO exergy (KJ/gr)	1,94
Exergy of added $FeCl_3$ (TJ)	20,83
Exergy of added CaO (TJ)	85,42
Capital of $FeCl_3$ (TL/kg; $/kg)	0,566; 0,4
Capital of CaO (TL/kg; $/kg)	0,09; 0,063
Total capital of $FeCl_3$ ($)	5808615,26
Total capital of CaO ($)	2770894,20
Exergetic equivalent of $FeCl_3$ capital (TJ)	148,12
Exergetic equivalent of CaO capital (TJ)	70,66
DM content of digestate after conditioning[17]	352211,44

Table I.13 : Energy consumption of drying.

Energy consumption (KWh/tDM; TJ/tDM)	50; 0,00018
DM of the processed sludge	352211,44
Total energy consumption (TJ)	63,40

Capital of drying process is presented in Table I.14 in which data is obtained from Sloan et al. (2009).

Table I.14 : Capital of drying.

Capital of drying ($/tDM)	215
DM of sludge (Ton)	352211,44
Total capital ($)	75725459,85
ee_C (MJ/$)	25,5
Exergetic equivalent of capital (TJ)	1931,04

I.1.9 Emissions

It is assumed that, 3% and 2% of produced CO_2 and CH_4 are lost in AD and upgrading, respectively. Emission of CO_2 from upgrading process is calculated in such a way as to reach the composition of 98% CH_4 and 2% CO_2 (% vol.) in resulting gas. The left of CO_2 contributes to CO_2 emission of upgrading. For DO sector untreated wastewater, results are presented in Table I.15. Emission factors which are used to obtain emissions from combustion of biogas in biorefinery are presented in Appendix G. Necessary data of LHV of produced biogas is presented in Table I.10 above.

[17] DM of digestate+$FeCl_3$ addition+CaO addition

Table I.15 : Emission of gases from AD and upgrading.

	CO_2	CH_4
Gas production in AD (m^3)	60986221,05	142301182,45
Emitted gas from AD (m^3)	1829586,63	4269035,47
Transferred gas to upgrading (m^3)	59156634,42	138032146,97
Emitted gas from upgrading (m^3)	56395991,48	2760642,94
Produced gas from upgrading (m^3)	2760642,94	135271504,03
Density (kg/m^3)	1,98	0,68
Emitted gas from AD (Ton)	3622,58	2902,94
Emitted gas from upgrading (Ton)	111664,06	1877,24

I.1.10 Imported electricity from regional electricity network

Electricity is supplied to the system from regional electricity network (Table 5.143). Capital and exergetic equivalent of capital are presented in Table I.16. Average annual cost of electricity in 2006 is derived from Republic of Turkey - Energy Market Regulatory Authority (2010).

Table I.16 : Capital of supplied electricity from regional electricity network.

Price of electricity ($cent/KWh)	8,13
Electricity (TJ; KWh)	1944,06; 540017377,88
Cost of electricity ($)	43918895,84
ee_C (MJ/$)	25,50
Exergy of capital (TJ)	1119,95

I.2 $EE_{ENV\text{-}lq,sl}$ of Treated Wastewater (Sludge Environmental Remediation System)

Type and amount of sectorally produced sludge are extracted from national data of Turkey (Turkstat, n.d.) and seen in Table I.17. The amount of produced sludge is derived by sludge production factors (retrieved from Qasim (1999)) and presented in Table I.17.

Table I.17 : Sludge generation and properties of sludge.

Treated wastewater by primary treatment (m^3)	442500964,8
Treated wastewater by secondary treatment (m^3)	574507555,2
Treated wastewater by tertiary treatment (m^3)	309874625,2
Coefficient of primary sludge generation (m^3/m^3)	0,0035
Coefficient of secondary sludge generation (m^3/m^3)	0,017
Coefficient of tertiary sludge generation (m^3/m^3)	0,017
Generated primary sludge (m^3)	1559741,41
Generated secondary sludge (m^3)	9717181,13
Generated tertiary sludge (m^3)	5281953,84
Total generated sludge (m^3)	16558876,38
DM of primary sludge ($g/l = kg/m^3$)	12
DM of secondary sludge ($g/l = kg/m^3$)	8
DM of tertiary sludge ($g/l = kg/m^3$)	8
Total DM in primary sludge (Ton)	18716,90
Total DM in secondary sludge (Ton)	77737,45
Total DM in tertiary sludge (Ton)	42255,63
Total DM in sludge (Ton)	138709,98

Afterwards, the same sludge treatment route (blending, thickening, AD, biorefinery digestate post-processing) presented in Section I.1 is applied.

I.3 Exergy of dried digestate

Composition of hide is retrieved from ECN (n.d.) and presented in Table I.18.

Table I.18 : Ultimate analysis of dried digestate.

	wt. %
C	19,7
H	2,44
O	19,6
N	1,25
S	1,06

HHV_{ar} of organic waste is calculated by the empiric equation proposed by Bilgen et al. (2004) for biomass samples and seen in equation (I.6).

$$HHV_{ar}\ (MJ/kg) = \left[33{,}5(C) + 142{,}3(H) - 15{,}4(O) - 14{,}5(N)\right] x 10^{-2} \qquad \textbf{(I.6)}$$

where HHV_{ar} is HHV of as received (wet basis) sample, C, H, O, N and S signify weight percent of carbon, hydrogen, oxygen, nitrogen and sulphur in the composition of the sample which is provided in Table I.18.

After computation of HHV_{ar} for dried digestate, the calculation route presented in Section C.4 applied and the results presented in Table I.19 are obtained. As for calculation of β_{LHV}, equation (2.17) is occupied.

Table I.19 : HHV_{ar}, LHV_{ar}, β_{LHV}, β_{HHV} and E of dried digestate.

HHV_{ar} (MJ/kg)	6,87
LHV_{ar} (MJ/kg)	5,63
β_{LHV}	1,14
β_{HHV}	0,93
E (MJ/kg)	6,42

APPENDIX J: Physical Exergy

J.1 Derivation of physical exergy equation

Definition and physical meaning of chemical and physical exergy are presented in Section 2.1. Below, derivation of the physical exergy which is based on combination of first and second law of the thermodynamics is seen. The derivation is available in Szargut et al. (1988), Kotas (1995) and Bejan et al. (1996).

The 1st law of thermodynamics equation (energy balance equation) is seen in equation (J.1) for an open system (control volume). A sketch of a generic apparatus for control volume analysis is given in Figure J.1.

$$\frac{d(En_{CV})}{dt} = \frac{d(En_k)}{dt} + \frac{d(En_p)}{dt} + \frac{d(U)}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) \quad \textbf{(J.1)}$$

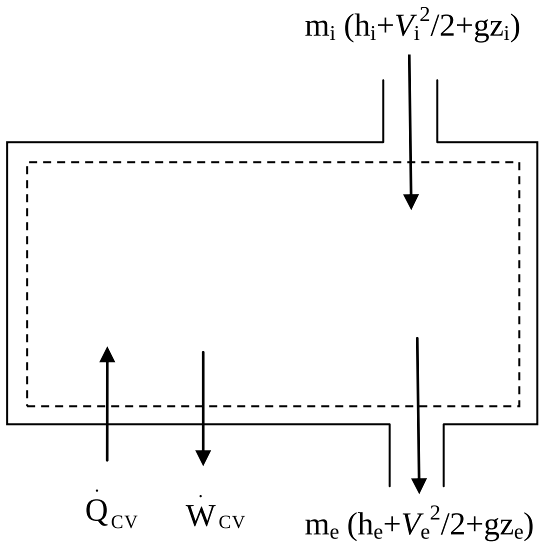

Figure J.1: Sketch of the control volume configuration.

where t(s) is time; En_{CV}(J) is energy of control volume; En_k(J) is kinetic energy of control volume; En_p(J) is potential energy of control volume; U(J) is internal energy of control volume; $\dot{Q}_{CV}$(J) and $\dot{W}_{CV}$ (J) are heat transfer rate into the control volume and the rate of work leaving the control volume, respectively; m_i and m_e (kg) are the mass input and output of the control volume, respectively; h_i and h_e(J/kg) are specific entalpy of the input and output fluxes, respectively; V_i and V_e(m/sn) are velocity of input and output fluxes, respectively; z_i and z_e (m) are the height of input and output fluxes.

Entropy balance of the control volume is seen equation (J.2):

$$\frac{d(S_{CV})}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_{generated,CV} \qquad \textbf{(J.2)}$$

where S_{CV} (J/K) is entropy of the control volume; j is the system boundary where heat transfer occurs; $\dot{Q}_j$ is the time rate of heat transfer through j; T_j is the temperature of j; s_i and s_e(J/kgK) are specific entropy of the input and output fluxes, respectively; $\dot{S}_{generated,CV}$ is the time rate of entropy generation within the control volume.

In Figure J.2, simplified illustration of an idealized device (control volume) which is used to compute exergy is seen. Since exergy is the amount of work obtainable when the considered substance is brought to a state of thermodynamic equilibrium with the components of its surrounding nature by means of *reversible* processes (Szargut et al., 1988), all the considered processes are reversible in Figure J.2.

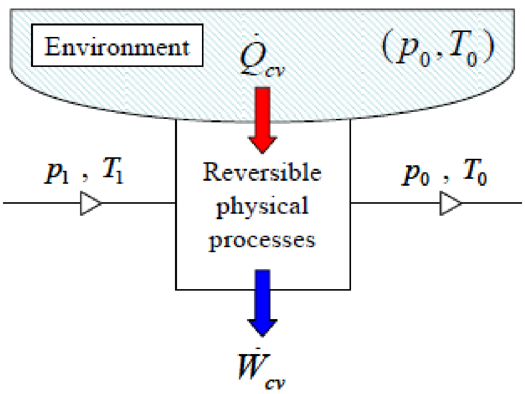

Figure J.2: A reversible device used to determine exergy.

The temperature and pressure conditions of the environment are P_0 and T_0, respectively and those of the initial state of the process fluid are P_1,T_1 (Figure J.2). The heat transfers to/from the ideal reversible module in Figure J.2 take place between the environment and the system at the temperature of T_0, the produced work ($\dot{W}_{CV}$) is the maximum possible amount of work (since the processes are reversible) when the process fluid is brought to equilibrium with its natural surroundings (here referred as the environment).

The energy balance equation of the reversible device is seen in equation (J.3) (based on equation (J.1)), assuming steady state conditions and neglecting the changes in kinetic and potential energy of the process fluid. Equation (J.3) includes the change of state for the fluid passing through the ideal device in Figure J.2, as well as the exchange of heat and work.

$$\frac{d(En_{CV})}{dt} = 0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}(h_1 - h_0) \quad \textbf{(J.3)}$$

Similarly, the entropy balance of the control volume (assuming no irreversibilities) is obtained from equation (J.2) and seen in equation (J.4).

$$\frac{d(S_{CV})}{dt} = 0 = \frac{\dot{Q}_{CV}}{T_0} + \dot{m}(s_1 - s_0) \quad \textbf{(J.4)}$$

Equation (J.4) can be rewriten as equation (J.5).

$$\dot{Q}_{CV} = \dot{m}T_0(s_0 - s_1) \quad \textbf{(J.5)}$$

Substituting equation (J.5) into equation (J.3), the formulation of reversible work which can be obtained from the process in Figure J.2 can be written as equation (J.6).

$$\dot{W}_{CV} = \dot{m}[T_0(s_0 - s_1) - (h_0 - h_1)] \quad \textbf{(J.6)}$$

By definition, physical exergy is equal to $\dot{W}_{CV}$ and physical exery (E_{ph}) of the fluid working in the system in Figure J.2 is seen in equation (J.7).

$$E_{ph} = \dot{W}_{CV} = \dot{m}\left[T_0\left(s_0 - s_1\right) - \left(h_0 - h_1\right)\right] = \dot{m}\left[\left(h_1 - h_0\right) - T_0\left(s_1 - s_0\right)\right] \qquad \textbf{(J.7)}$$

A extensive explanation of chemical exergy computation is presented in detail in Szargut et al. (1988).

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PUBLICATIONS/PRESENTATIONS ON THE THESIS

▪ **Seckin, C.,** Sciubba, E. and Bayulken, A. R. (2012). Extended exergy analysis of Turkish transportation sector. *Journal of Cleaner Production* (accepted manuscript, available on sciencedirect.com).

▪ **Seckin, C.,** Sciubba, E. and Bayulken, A. R. (2012). An application of the extended exergy accounting method to the Turkish society, year 2006. *Energy*, **40**, 151-163.

▪ **Seckin, C.** and Bayulken, A. R. (2012). Environmental Remediation Cost of Solid Waste in EEA Methodology – An Application to Turkish Tertiary Sector Solid Waste. *GCGW 2012 - Global Conference on Global Warming 2012*, Istanbul, Turkey, July 8–12.

▪ **Seckin, C.,** Sciubba, E. and Bayulken, A. R. (2012). Resource Use Evaluation of Turkish transportation Sector via Extended Exergy Accounting Method. *The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2012)*, Perugia, Italy, June 26–29.

▪ **Seckin, C.,** Sciubba, E. and Bayulken, A. R. (2012). Determination of environmental remediation cost of municipal waste in terms of extended exergy. *The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2012)*, Perugia, Italy, June 26–29.

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