Interim Report   **IR-12-002**

Constructing a network of the Social-economic Consumption System of China using Extended Exergy Analysis

Jing Dai   (daijing0532@mail.bnu.edu.cn)
Brian Fath (bfath@towson.edu)

Approved by

Arkady Kryazhimskiy
Head, Advanced Systems Analysis Program

February, 2012

Contents

Abstract

The prominent conflict between consumption and environmental resources is acknowledged as a significant force in affecting the social-ecological community balance. The whole process of resource allocation, utilization, efficiency and outcome are crucial clues in uncovering the structural and functional characteristics in complex consuming systems. Herein, networks provide a systems-oriented modelling technique for examining the structure as well as the flow of materials or energy from an input-output perspective. Meanwhile, extended exergy, the only currently available thermodynamic based metric for social-economic environmental impacts associated with energy consumption, manpower, and monetary operation as well as environmental emission, is an extension of the labor theory of value and a possible sustainability metric. The core purpose of this research is to construct a network of the consumption system of China using extended exergy analysis to explain the interrelationship among different sectors within a thermodynamic metric. Therefore, we first make a database of Chinese consumption using extended exergy accounting. Data are available for 2007, which can be divided into seven sectors based on the reclassification of the regularly published 42-sector Input-Output Table, namely, 1) Agriculture, 2) Extraction, 3) Conversion, 4) Industry, 5) Transportation, 6) Tertiary, and 7) Domestic sectors. Then we construct an extended exergy network to gain insight into the thermodynamic distribution within sectoral criterion. Lastly, the network results explain how China's social metabolism is maintained by a large quantity of energy, resources, and labor.

Key words: Ecological accounting, extended exergy, input-output tables, socio-ecological system, network construction, China

Acknowledgments

About the Authors

Jing Dai is a Ph.D student in the School of Environment, Beijing Normal University, Beijing, China. She was also a research assistant in the Advanced Systems Analysis Program at IIASA in the summer of 2011.

Brian D. Fath is a Professor in the Department of Biological Sciences at Towson University, Maryland, USA. He is also a research scholar in the Advanced Systems Analysis Program at IIASA.

Constructing a network of the Social-economic Consumption System of China using Extended Exergy Analysis

Jing Dai and Brian Fath

1. Introduction

Humans extensively consume ecological resources for the sake of supporting social and economic development. However, the over-exploitation and low-efficiency of energy and resource use has led the world to face shortages of vital natural capital. In addition, the wastes generated from this social and economic production and emitted into the surrounding environments cause ecological pressure on both the regional and global systems. Therefore, it is necessary that we have adequate tools to evaluate the extent of the natural resource shortages, as well as to estimate the ecological impacts for both the scientific and broader communities.

In traditional environmental resource analysis, it is common to value the combination of socioeconomic, material, and ecological influence in terms of economic currency However, these monetary valuations lack a scientific definition based on energetic or physical explanations. To identify the status, stage, and trend of the system growth and development, a new method, which can value the physical quantity and quality of all socio-ecological processes, is urgently needed in the current evaluation framework.

In contrast to these monetary based approaches, some researchers, particular those working in the field of ecological economics, have proposed methods to consider all processes and activities in terms of their energetics. In this manner, one can apply first principles such as the laws of thermodynamics, mass balance, and stoichiometry, to socio-ecological problems. Specifically, the concept of exergy, or useful work, provides a unified indicator of different forms of material and energy flows on the basis of evaluating the distance from the studied system to thermodynamic equilibrium [1-2].

Historically, the exergy analysis method was first applied in thermodynamic engineering process evaluation and thermo-chemical system analysis. It can evaluate work based on the Second Law of Thermodynamics instead of general energy flow metrics; therefore, it became a widely accepted method in thermal processing analysis [3-4]. Subsequently, exergy analysis was developed in combination with systems ecology, as a measure of ecological complexity regarding how far the observed ecosystem is from a reference environment [5] and applied to reveal the ecosystem resource availability, buffering capacity, and environmental impacts [6-8]. Therefore, exergy analysis provides a quantifiable method with physical meaning for assessing environmental and ecological degradation.

For the reason that exergy can be used as a consistent measure of material, energy, and information, Wall [1-2] creatively introduced exergy into the accounting work of social

resource consumption. In recent years, there has been an increasing interest in applying exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving strategies [4]. Within different national and sectoral levels, there are many established cases applying exergy evaluation: 1) For national levels, Japan [9], Sweden [2], Norway [10], America [11], Saudi Arabia [12-13], China [14], UK [15-16], Italy [17], etc. These studies have quantified the exergy associated with the available energy flow structure and efficiency for natural resources to assist the country's energy policy and resource managers. 2) In the social sectoral level, Dincer and his group have published a series of papers in transportation, industry, domestic, public and private sectors [12-13, 18-19] to illustrate the efficiency and performance of an exergy analysis of available energy, to evaluate the "resource content" of social-economical input as well as environmental discharges [18, 20], and to show several key perspectives of quality, energy conservation, ecological input, economy, environment and sustainable development of subsystem perspectives. Their exergy analysis research results can exhibit the potential usefulness of exergy in addressing and diagnosing environmental problems and moving toward sustainable development, since exergy can characterize the largest amount of energy that can be extracted from material energy. Therefore, unlike energy flow which is only about the quantity, exergy is a measure of quantity and quality of the energy resources.

On the basis of cumulative research on exergy connotations and applications, it is widely acceptable that the exergy-based assessment can be correctly regarded as a physical and thermodynamical based metric in evaluating the scarcity and utility of ecological resources [20-24]. What we want to accomplish in this study is to construct an accounting diagram among social-economic sectors with a network view, to further apply exergy theory in revealing its available energy capacity and metabolic interrelationship within a sub social-economic system level. However, in view of the varied social and economic impacts from energy and resource use within the whole social system, we need a more extensive and inclusive metric to account for the intrinsic (money and primary resources) expenses and social (money and services) "payback" in different social levels. Meanwhile, for the human dominated society, systematic accounting of social exergy flux, is a comprehensive, synthetical, and unified metric for ecological and social factors, which can reveal the natural wealth in the process of socio-economic diagnoses and decision making.

Therefore, in recent years, nonmaterial energy resource elements, labor production factors, and economic parameters have been incorporated into the horizon of exergy research. This approach is called Extended Exergy Accounting (EEA) [21]. EEA is an "embodied" measure for the total primary exergy resource equivalent consumption [22, 25]. It is an extension of traditional exergy analysis by including socio-economic factors such as labor and capital costs in physical terms of the equivalent primary resource consumption. EEA had been revised and published in a series of theoretical research and applications issues [21-22, 24, 26]. The intrinsic measurement of extended exergy

(EE) is the amount of primary exergy homogeneously expressed in Joules that being cumulatively used over the production, operation, and disposal process. EEA includes four basic parts: 1) the standard material and energy primary resource exergy (quantified by their respective cumulative exergy content), 2)-3) labor and capital (two social, economic factors), and 4) environmental remediation costs. The latter three parts represent the primary resource cost equivalent of the so-called "externalities". The advantage of EEA is that it is much easier and more meaningful to compare within one unified and rational criterion different commodities and different production processes [27]. As an extension of traditional exergy analysis, EEA is widely accepted as a comprehensive method based on the concept of a physical cost based not on a monetary proxy, but on the equivalent primary resource consumption. Furthermore, such an effective measure of natural-social-environmental impacts can be considered in some sense as the real "ecological cost" of all material and energy resources, human labor, capital, and environmental remediation costs related to a certain system. Thus, EEA considerations provide a vivid and global understanding of the physical, thermodynamic, economical and ecological costs that bridges the gap about the 'production of value' which separates most economics and biophysical-based approaches [28-29].

In a nutshell, EEA is a socio-economic construct with biophysical references, intended to integrate the labor theory of value and the current thermodynamic theory, so that the "extended exergy cost" (i.e., the equivalent amount of primary resources required for the production of a commodity) can be used as a goal function to optimize the allocation and distribution of the involved "values" (meaning "use values" in this study). Since the quantifier is the primary resource base, it is possible to use EEA to propose and explore scenarios aiming at development of a society towards reduction and improved efficiency of long-term exergetic resource consumption. Given the current unsustainable state of affairs, EEA can be considered as a proper tool to measure the cost to decrease our degree of unsustainability: it does so not only by displaying the loss of available energy at each step of a productive chain, but also supplying input conditions and allocations, for "more sustainable" solutions may in some cases require greater resource consumption than "less sustainable" ones [30]. Furthermore, new light is shed by EEA on the so-called "environmental externalities quantification" problem, in that this theory associates the internal irreversibility of a system not only with material- and energy use but also with its waste emissions.

The whole process of resource allocation, utilization, efficiency, outcome and environmental impacts are crucial clues in uncovering the structural and interrelationship characteristics in complex consuming systems, both exergy generation and consumption processes contain large exergy flow distribution as well.

For an integrated system, different subsystems have variable exergy supply-demand relations and play diverse roles in maintaining social life and human requirements. To analyze the exergy and extended exergy flow characteristics in a systematic and

structural perspective, we need to decompose different flows within a whole social and economic system boundary. However, judging from the present existing studies, analyses of the inherent structure and functions of the social resource metabolism are lacking a systematic basis and network perspective. Furthermore, to optimize the structure by measuring and adjusting the relationships among compartments, it is necessary to use ecological network analysis (ENA) for national social-economic ecosystem research. ENA, a general version of network analysis, has been recently proposed as a generic tool for systematic and functional assessment in the context of ecosystem-based management [31-37]. Meanwhile, the truth that it can encounter flow incompatibility in a material- or energy-oriented ecosystem remains impeditive when evaluating different flow configurations. Energy and material, the conventionally used units for network analysis, are widely acceptable and adaptable for exergy and extended exergy based analysis.

In this study, to be congruent with the theoretical requirements and internally consistent, we first provide a concise overview of the exergy origin, and its development and application, followed by the current status of extended exergy to include social economic factors. The rest of the paper is organized as follows: 1) An illustrative example is given to demonstrate how extended exergy accounting can be applied in a more realistic and meaningful assessment than the conventional energy analysis of the efficiency and performance for a flowing and consuming system. 2) To analyze the resource flow metabolism and it corresponding input-output relationship within system and subsystem levels in China 2007, by means of the extended exergy analysis. 3) Finally, using the results to construct a network of the social-economic consumption system of China.

2. Methodology and Data

2.1 EEA

As stated above, the unique feature of EEA is that it is a composite measure of the material thermo-mechanical and chemical exergy values plus the labor and capital inputs and environmental remediation costs all expressed in energetic units (joules). The procedure for converting all pieces to a common dimensional quantity is given below. The calculation of the EE of a generic (material or immaterial) commodity is formulated as follows:

$$EE = CEC + E_K + E_L + E_R \qquad (1)$$

where CEC represents the cumulative exergy consumption of material flows as defined by Szargut [38], E_K is the exergy equivalent of capital flows (or active monetary circulation), E_L is the exergy equivalent of human labor, and E_R stands for the environmental impact or remediation cost.

In eqn. (1), **CEC** expresses the cumulative exergy consumption (including both primary resources consumption and secondary semi- or completed- manufactured material input). From a consumption viewpoint, **CEC** consists of three distinct portions:

1) The direct "energetic" natural resources inputs (coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, etc.), which are quantified by their respective **CEC** transformation factors (listed in Results, Fig. 4), which are of the same order of magnitude as their lower heating values [38];

2) The "secondary energy resources", like electricity, heating energy, etc. They are quantified by their respective **CEC** transformation factors (also listed in Results, Fig. 4);

3) The natural exergy consumed, and therefore "embodied" as a cost, in all manufactured (material) goods' transport equipment (vehicles, batteries, engines, airplanes, etc. and their components). An average value for each one of these flows was calculated for 2007 and the total was included in the balance as an exergy flow from one sector to another sector.

Exergy factors of fossil fuel can be acquired from [38-39] which are summarized in Fig. 4, and all physical data have been extracted from [40-41] shown in Fig.4 and 5. In order to show the **CEC** input clearly, we combine the second portion and the third portion together, namely the "secondary energy resources" and "embodied cost exergy", as the non-direct natural resource exergy input and label this as **CEC-2** (see Fig. 1).

For each sector in this research, we establish a commonly used EEA model to show the EEA structure and accounting boundary in Fig. 1.
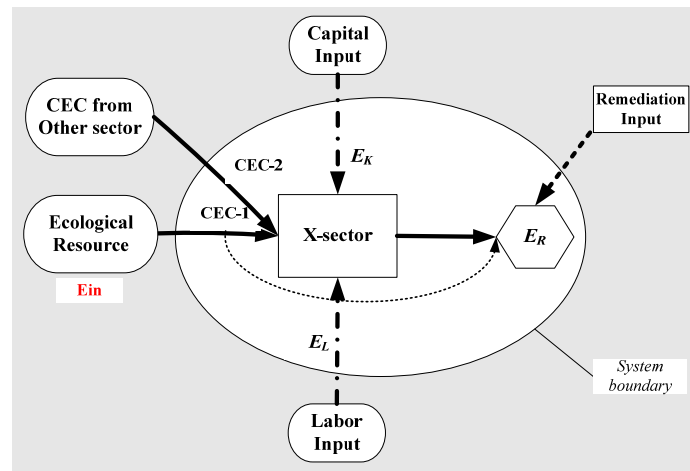
Fig. 1 - EEA accounting boundary for each sector in this study

In Fig. 1, **CEC-1** refers to the ecological resource directly from environment; and **CEC-2** is the exergy input from the other sectors, for example, the processed goods, instruments, secondary materials, etc; and E_{in} will be explained clearly in the following part.

2.2 Converting Labor and Capital into Exergy

EEA is based on two major postulates: first, that E_{in} (the global influx of exergy resources into a society or community) is primarily used to sustain the total population of the society in order to generate labor (E_L); second, that the equivalent exergy flux required to generate the capital (E_K) circulation M2 is proportional to the **EE** of Labor:

$$E_L = \alpha \times E_{in} \tag{2}$$

$$E_K = \beta \times E_L \tag{3}$$

In [19-20, 27, 43-46] the expressions for α and β are:

$$\alpha = \frac{f \times e_{surv} \times N_h}{E_{in}} \tag{4}$$

$$\beta = \frac{M2}{sN_W W} \tag{5}$$

where f is correction factor related with the life standard level in a certain social system (f=HDI/HDI$_0$, HDI is Human Development Index of life expectancy, wealth and education used in socioeconomics published by the United Nations every year); e_{surv} refers to the exergy consumption for human survival; N_h is the total population in the study system; $M2$ is the amount of money stock in a certain year ($M2$ stands for purchasing power, in China a large portion of the M2 is in time and saving deposits, which is not the monetary circulation in accordance with those of the western banking system, and also checks cannot be freely cashed as in the western countries. Therefore, and only for this reason, we were forced to take the GDP as the monetary circulation indicator); s is average wage; N_w is the number of workers; W is the average workload. In eqn. (4) and (5), α and β introduced here represent the fraction of the primary exergy embodied into Labor and the fraction of the Labor exergy embodied into Capital, respectively. Here are all the parameters used in the whole accounting process:

Table 1 - List of the parameters used in the evaluation of α and β

Parameter	Unit	Value (for China, 2007)
f	/	13.75
e_{surv}	J/(person×day)	10^7J/(person×day)
N_h	Population	1.33×10^9
E_{in}	J/yr	Total ecological resource exergy input into the system
$M2$	RMB/yr	**GDP** (3.03×10^{13}RMB)
s	RMB/yr	Depends on different sectors or system
N_w	Population	Depends on different sectors or system
W	Workhours/ (person×yr)	2000h/(person×yr)=8h/day×250day/year

Note:
1. **HDI$_0$**=0.055, e_{surv}=10^7J/(person×day) (Sciubba, 2011);
2. **HDI$_{(2007,China)}$**=0.756 [41, 42];
3. **N$_h$**=1.33×10^9, **GDP**=3.03×10^{13}RMB (CSY, 2008); **W**=2000h/(person×yr) (Chen and Chen, 2009);

4. E_{in} will be calculated in the results, s and N_w can be collected in CLSY (2008);

5. **GDP** is used as a quantifier of the monetary circulation[1].

2.3 E_R evaluation method

The possibility of using exergy as a measure of potential to cause environmental change, has been debated for a long time, because exergy cannot characterize the extent of environmental toxicity or impacts, such as greenhouse effects, eco-degradation, etc. However, EEA takes a completely innovative strategy to explain the treatment of pollutants: it calculates the added equivalent exergy caused by primary resource consumption by an implemented or proposed treatment process to remove the emitted pollutant. This environmental emission equivalent exergy can be regarded as the "environmental externalities" or "environmental disturbance".

To apply this method, the exact amount of each (material or immaterial) "emission" must be known together with its exact chemical composition. These data are partly absent in the available database for the Chinese society, and therefore, for the existing emission lists we can calculate their chemical exergy as the environmental influence exergy, and for the absent emission parts, the annual monetary expenditure for environmental remediation and management $E_{RC'}$ (which is available in the database) was converted into an equivalent extended exergy environmental cost E_R, as follows:

$$E_{R'} = E_{RC'} = ee_K \times I_{env} \qquad (6)$$

$$ee_K = \frac{\alpha\beta E_{in}}{M2} \qquad (7)$$

where ee_K is the specific exergy equivalent of the monetary unit, and I_{env} is the monetary rate of investment in remediation measures. This is not exactly in line with the original EEA formulation, in which the environmental remediation cost is calculated on the basis of a real or ideal process in which the effluents are treated [47]. Such a calculation is impossible for the present case study. Our assumption must be viewed as an approximation due to data shortage, which provides another approach that others with data scarcity may apply.

2.4 System boundary

The societal accounting initially proposed by Wall [1] focused on the cross-section from the resource base to end-use sectors: it followed indirectly the approach originally suggested by Szargut [48], and was improved by Ertesvåg [10] and Milia and Sciubba

---

[1] 1) its numerical value is different from the real monetary circulation;

2) even conceptually the **GDP** is not a correct indicator of monetary circulation, because it merely represents the monetary measure of the goods & services generated, imported and exported.

[49], who divided the society into seven subsystems interacting with their environment and labeling all fluxes of matter and energy in a metabolic-like process. Later, Chen et al. [19] established a pyramidal scheme consisting of seven sectors, aiming at revealing the exergetic consumption structure of the society. In this study, we further modified the framework to show the extended exergetic structure of the society corresponding to the special socio-economic characteristics of the society, and the societal system was subdivided based on the 2007 Input-Output (IO) Table for China. The IO Table is known as a balanced sheet, reflecting the interactions between various sectors within a certain period based on material and its corresponding currency flows. The IO Table is divided into physical form and economic value form, respectively, based on different measurement units. We choose economic value date in this research with the purpose to unify the embodied physical exergy flows from different types of primary and secondary products and services between different sectors under a certain productive technology level. Meanwhile, in order to simplify the complexity of the whole system and clarify the interactions between economic sectors based on an ecological trophic and network structure, we aggregate the 42 subsectors into 7 main sectors of the social and ecological exergy flow system partly in the consideration of the previous research and functional similarity of different subsectors. New classification contents are showing in the following table:

Table 2 - Classification of total sectors used in this study number each subsector from the original

| Sector (7)	Content	Sub-sector (42)
Extraction (X1)	Extraction, including mining and quarrying, oil and natural gas, refining and pre-processing	Mining and Washing of Coal (02) Extraction of Petroleum and Natural Gas (03) Mining and Processing of Metal Ores (04) Mining and Processing of Non-metal Ores and Other Ores (05)
Conversion (X2)	Conversion of primary energy & materials into heat, power and electricity	Production and Supply of Electric Power and Heat Power (23) Production and Supply of Gas (24) Production and Supply of Water (25)
Agriculture (X3)	Harvesting, forestry, animal husbandry, fishery, water cultures, and food processing	Agriculture, Forestry, Animal Husbandry, Fishery (01)
Industry (X4)	Industry, manufacturing industry except oil refineries	Manufacture of Foods and Tobacco (06) Manufacture of Textile (07) Manufacture of TextileWearing Apparel, etc (08) Processing of Timber and Manufacture of Furniture (09) Manufacture of Paper, Printing, Articles, etc(10) Processing of Petroleum, Coking, Processing of Nuclear Fuel (11) Chemical Industry (12) Manufacture of Non-metallic Mineral Products (13) Smelting and Pressing of Metals (14) Manufacture of Metal Products (15) Manufacture of General, Special Purpose Machinery (16) Manufacture of Transport Equipment (17) Manufacture of Electrical Machinery and Equipment (18) Manufacture of Communication Equipments (19) Manufacture of Measuring Instruments and etc (20) Manufacture of Artwork and Other Manufacturing (21) Recycling and Disposal of Waste (22) Architecture Industry (26)
Transportation (X5)	Transportation services	Transport, Storage (27) Post (28) Information transfer, Computer Services and Software (29) Wholesale and Retail Trades (30) Hotels and Catering Services (31) Financial industry (32) Real estate (33) Rent and Commercial Service Industry (34) Research and experimental developing Industry (35)
Tertiary (X6)	Tertiary, including construction and real estate	Integrated technical service (36) Management of Water Conservancy, Environmental and Public Establishment (37) Neighborhood Services & other services (38) Education (39) Sanitary, Social Security and Public Welfare (40) Culture, sports and entertainment industry (41) Public management and social organization (42)
Domestic (X7)	Domestic sector, households	Rural consumer expenditure (final consuming) Urban consumer expenditure (final consuming)

According to the resource input and flow distribution processes, an exergy based sectoral hierarchy system chart is described here to show the extended exergy input-output procedure and its allocation within the seven sectors (see Fig. 2).
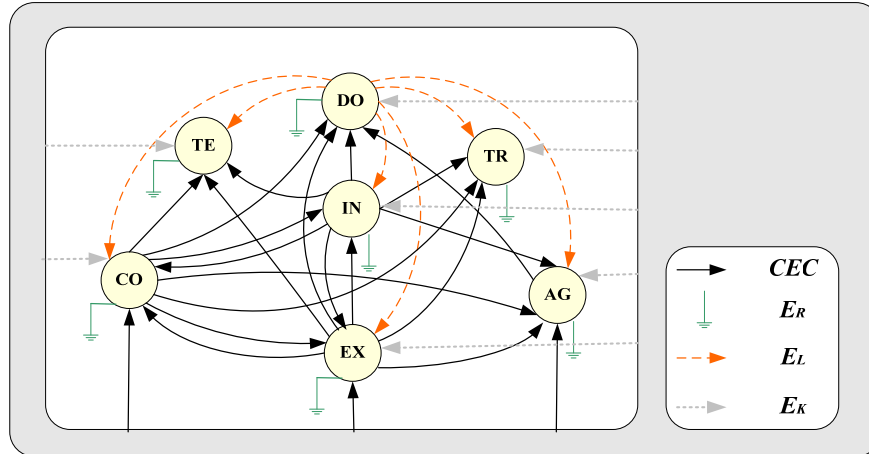
Fig. 2 - System diagram for sectoral metabolism hierarchyextended-exergy flows where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

In Figure 2, full lines refer to exergy flow based on material resource delivered among different sectors, dotted lines are labor and capital exergy which are the productions of Domestic sector after substantial resource consumption.

The interactions between economic sectors could be depicted in a network analogous to an ecological trophic structure. In order to decompose every exergy input and output flow into the seven sectors, we make a pyramid structure with three different trophic levels to unequivocally illustrate each extended exergy accounting step in the whole system (see Fig. 3). First of all, Extraction, Conversion, and Agriculture are the first three sectors gaining ecological resource (E_{in}) directly from natural surroundings. Second, the primary process, exergy embodied in energy resource (**CEC-1**) is invested into second level sectors for further manufacturing and sub-treating, after which the different types of products and services are generated. Third, the exergy embodied in products and services' costs (**CEC-2**) are input to the other sectors for subsequent handling and value creating. The last step, Domestic sector is regarded as a final consumption sector, which occupies all the ultimate system embodied resource exergy for the sake of delivering labor and capital (E_L and E_K) to the whole system. In addition, environment emissions (E_R), the disturbance to previous environmental and ecological equilibrium, always exists during the whole process of material resource depletion.
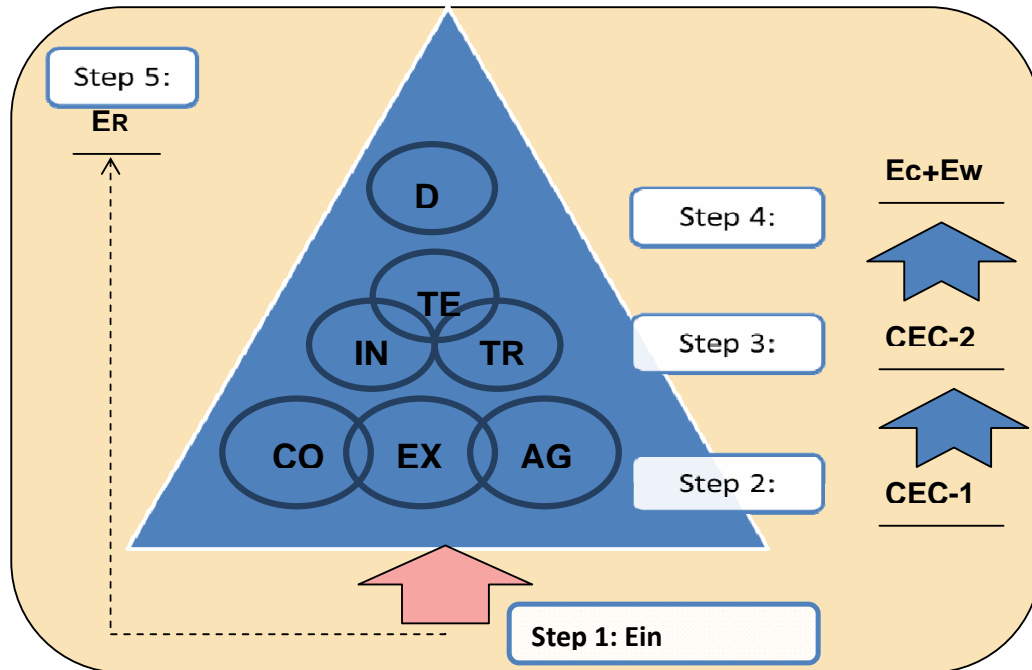
Fig. 3 - An ecological trophic structure of interactions between seven economic sectors based on extended exergy accounting where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

3. Results

3.1 EEA in seven sectors in China (2007)

3.1.1 CEC accounting

Table 3 shows the **CEC** ingredients' list for seven sectors: for the natural resource part, **CEC** can be evaluated on the basis of cumulative exergy consumption as defined by Szargut and the transformation factor for different resource types [38].

Table 3 - **CEC** accounting ingredients in seven sectors in China (2007)

Sector	CEC ingredients
EX-sector	Fossil energy, electricity, metals, inorganic minerals, input from other sectors
CO-sector	Fossil energy, electricity, hydropower, thermal power, nuclear power, input from other sectors
AG-sector	Fossil energy, electricity, farm products, forest products, livestock products, aquatic products, input from other sectors
IN-sector	Fossil energy, electricity, input from other sectors
TR-sector	Fossil energy, electricity, input from other sectors
TE-sector	Fossil energy, electricity, input from other sectors
DO-sector	Fossil energy, electricity, input from other sectors, farm products, forest products, livestock products, aquatic products

Table 4 - E_{in} input in EX, CO and AG sectors

E_{in} items	exergy conversion coefficient	coefficient unit	Yield/PJ	Export/PJ	Import/PJ	E_{in} input/PJ
EX-sector						
Raw Coal	22.16	PJ/Mton	5.60E+04	1.25E+03	1.16E+03	5.59E+04
Crude Oil	44.32	PJ/Mton	8.26E+03	3.83E+01	6.32E+01	8.28E+03
Natural Gas	4.13	PJ/10^{8}cu.m	2.86E+03	1.07E+02	1.66E+02	2.92E+03
				Net import-export/PJ		
Copper	1.1	PJ/Mton	4.29E+00	1.001		5.29E+00
Aluminum	2	PJ/Mton	3.02E+01	0.4		3.06E+01
Lead	0.02	PJ/Mton	5.80E-02	0.003		6.10E-02
Zinc	0.05	PJ/Mton	2.02E-01	-		2.02E-01
Nickel	4	PJ/Mton	1.00E+00	0.488		1.49E+00
Tin	3	PJ/Mton	4.62E-01	0.024		4.86E-01
Iron	0.42	PJ/Mton	3.46E+02	159.6252		5.06E+02
Steel	6.8	PJ/Mton	7.38E+03	-287.98		7.10E+03
Phosphorus minerals	0.1	PJ/Mton	5.07E+00	-		5.07E+00
Crude salt	0.2	PJ/Mton	1.19E+01	-		1.19E+01
CO-sector	exergy conversion coefficient (calorific value calculation)	coefficient unit	Yield unit	Yield amount		E_{in} input/PJ
Hydro Power	0.36	PJ/10^{8}kwh	10^8 kW.h	5963.89		2.15E+03
Nuclear Power	0.36	PJ/10^{8}kwh	10^8 kW.h	621		2.24E+02
AG-sector	exergy conversion coefficient	coefficient unit	Yield/PJ	Export/PJ	Import/PJ	E_{in} input/PJ
Rice	15.8	PJ/Mton	3.03E+05	1.53E+03	5.21E+02	3.02E+05
Wheat	13.9	PJ/Mton	1.56E+05		1.56E+03	1.58E+05
Corn	8.6	PJ/Mton	1.43E+05	2.32E+02	4.30E+01	1.42E+05
Beans	3.9	PJ/Mton	7.97E+03	1.83E+02	1.46E+04	2.24E+04
Tubers	3.3	PJ/Mton	9.83E+03			9.83E+03
Peanuts	24.6	PJ/Mton	3.51E+04	5.66E+02		3.46E+04
Rapeseeds	37	PJ/Mton	4.48E+04	3.26E+03	3.26E+04	7.41E+04
Sesame	29	PJ/Mton	1.70E+03			1.70E+03
Cotton and Fiber Crops	16.4	PJ/Mton	1.33E+04	2.62E+01	3.46E+03	1.67E+04
Sugarcane and Beetroots	5	PJ/Mton	6.71E+04	2.90E+01	3.90E+02	6.75E+04
Tea and Tobacco	10.7	PJ/Mton	4.38E+03	4.42E+02	2.40E+01	3.96E+03
Silkworm Cocoons	4.5	PJ/Mton	4.09E+02			4.09E+02
Fruits	1.9	PJ/Mton	3.65E+04	5.42E+02	3.25E+02	3.63E+04
Timber	8	PJ/Mton	9.99E+01		5.69E+01	1.57E+02
Meat	4.6	PJ/Mton	3.35E+04	3.34E+02		3.31E+04
Milk	4.9	PJ/Mton	1.85E+04			1.85E+04
Poultry Eggs	6.1	PJ/Mton	1.65E+04	3.71E+00		1.65E+04
Wool and Cashmere	3.7	PJ/Mton	1.59E+03	1.19E+01	1.07E+02	1.68E+03
Aquatic Products	5.8	PJ/Mton	2.84E+04	1.02E+03	1.04E+03	2.84E+04

Table 5 - *CEC-1* accounting based on E_{in} consumption in seven sectors

Sectors	E_{in} items	E_{in} Consumption	Consumption unit	Exergy of E_{in} consumption/PJ
EX-sector	Coal	1.77E+04	10^4 tn	3.91E+03
	Coke	2.17E+02	10^4 tn	6.48E+01
	Crude oil and oil products	1.65E+03	10^4 tn	7.30E+02
	Natural Gas	9.63E+01	10^8 cu.m	3.98E+02
	Electricity	1.61E+03	10^8 kW.h	5.81E+02
CO-sector	Coal	1.32E+05	10^4 tn	2.92E+04
	Coke	7.35E+00	10^4 tn	2.19E+00
	Crude oil and oil products	9.01E+02	10^4 tn	3.99E+02
	Natural Gas	7.08E+01	10^8 cu.m	2.92E+02
	Electricity	4.64E+03	10^8 kW.h	1.67E+03
AG-sector	Coal	2.94E+03	10^4 tn	6.51E+02
	Coke	1.61E+01	10^4 tn	4.80E+00
	Crude oil and oil products	1.69E+02	10^4 tn	7.48E+01
	Natural Gas	2.91E+00	10^8 cu.m	1.20E+01
	Electricity	6.34E+02	10^8 kW.h	2.28E+02
IN-sector	Coal	2.91E+04	10^4 tn	6.44E+03
	Coke	3.27E+04	10^4 tn	9.75E+03
	Crude oil and oil products	6.29E+04	10^4 tn	2.79E+04
	Natural Gas	3.24E+02	10^8 cu.m	1.34E+03
	Electricity	1.63E+04	10^8 kW.h	5.86E+03
TR-sector	Coal	6.85E+02	10^4 tn	1.52E+02
	Coke	5.50E-01	10^4 tn	1.64E-01
	Crude oil and oil products	1.22E+04	10^4 tn	5.43E+03
	Natural Gas	1.69E+01	10^8 cu.m	6.98E+01
	Electricity	5.32E+02	10^8 kW.h	1.91E+02
TE-sector	Coal	8.10E+03	10^4 tn	1.80E+03
	Coke	7.64E+01	10^4 tn	2.28E+01
	Crude oil and oil products	6.59E+02	10^4 tn	2.92E+02
	Natural Gas	1.33E+02	10^8 cu.m	5.51E+02
	Electricity	3.62E+03	10^8 kW.h	1.30E+03
DO-sector	Coal	1.97E+04	10^4 tn	4.37E+03
	Coke	2.25E+03	10^4 tn	6.70E+02
	Crude oil and oil products	3.50E+03	10^4 tn	1.55E+03
	Natural Gas	3.53E+01	10^8 cu.m	1.46E+02
	Electricity	2.95E+03	10^8 kW.h	1.06E+03
	Rice	1.91E+04	10^6 ton	3.02E+05
	Wheat	1.14E+04	10^6 ton	1.58E+05
	Corn	1.66E+04	10^6 ton	1.42E+05
	Beans	5.74E+03	10^6 ton	2.24E+04
	Tubers	2.98E+03	10^6 ton	9.83E+03
	Peanuts	1.41E+03	10^6 ton	3.46E+04
	Rapeseeds	2.00E+03	10^6 ton	7.41E+04
	Sesame	5.86E+01	10^6 ton	1.70E+03
	Cotton and Fiber	1.02E+03	10^6 ton	1.67E+04

Crops			
Sugarcane and Beetroots		10^6 ton	6.75E+04
Tea and Tobacco	3.71E+02	10^6 ton	3.96E+03
Silkworm Cocoons	9.09E+01	10^6 ton	4.09E+02
Fruits	1.91E+04	10^6 ton	3.63E+04
Timber	1.96E+01	10^6 ton	1.57E+02
Meat	7.21E+03	10^6 ton	3.31E+04
Milk	3.78E+03	10^6 ton	1.85E+04
Poultry Eggs	2.70E+03	10^6 ton	1.65E+04
Wool and Cashmere	4.55E+02	10^6 ton	1.68E+03
Aquatic Products	4.90E+03	10^6 ton	2.84E+04

For the input-output (equivalent to production-consumption relationship) exergy in E_{in} and *CEC-1* accounting, primary substantial resource exergy has been accounted in Table 4 and 5. However, the secondary resource exergy flow from one sector to another, embodied as the cost of products and services, is calculated by means of IO Table. Here are the original economic data (Table 6-a) and accounting results (Table 6-b). The empty value is in *CEC-1* accounting showed in the previous part.

Table 6-a - *CEC-2* accounting based on IO Table for currency flows among seven sectors (Unit: 10^4 RMB)

e	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector
EX-sector	-	-	7.81E+05	7.47E+07	1.22E+07	1.97E+07
CO-sector	-	-	2.48E+08	2.86E+09	1.48E+08	3.23E+08
AG-sector	-	-	6.88E+07	9.76E+07	7.97E+06	2.30E+07
IN-sector	-	-	5.71E+03	5.11E+07	4.00E+06	2.65E+07
TR-sector	-	-	3.80E+06	1.05E+08	2.26E+07	3.77E+07
TE-sector	-	-	2.17E+07	3.42E+08	5.62E+07	2.71E+08
DO-sector	-	-	-	3.00E+07	2.41E+07	4.34E+08

Table 6-b - *CEC-2* accounting based on IO Table for exergy flows among seven sectors (Unit: PJ)

	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector
EX-sector	-	-	6.53E+01	6.25E+03	1.02E+03	1.64E+03
CO-sector	-	-	2.08E+04	2.39E+05	1.24E+04	2.70E+04
AG-sector	-	-	5.75E+03	8.16E+03	6.67E+02	1.92E+03
IN-sector	-	-	4.78E-01	4.27E+03	3.35E+02	2.22E+03
TR-sector	-	-	3.17E+02	8.75E+03	1.89E+03	3.15E+03
TE-sector	-	-	1.81E+03	2.86E+04	4.70E+03	2.26E+04
DO-sector	-	-	-	2.51E+03	2.02E+03	3.63E+04

3.1.2 E_L and E_K accounting

According to the Chinese Labor Statistical Yearbook [50], the economically active population was 786.45 million, and the actual employee number was 769.90 million.

Based on these social and economic data, we calculate the values of the important two EE factors α and β as 6.12×10^{-2} and 4.87×10^{-1}, respectively, for China in 2007. Meanwhile, labor productivity is assumed to be non-discriminatory between different individuals within a certain period. The employee's sectoral distribution and salary difference as well as the final human embodied exergy input in six sectors were collected in Table 7.

Table 7 - Original sectoral data andfinal human embodied exergy input in six sectors

Sectors	Employed population (million)	Average salary (RMB/(person×yr)	E_L (PJ)	E_K(PJ)
EX-sector	1.89E+01	28046.73	1.58E+03	7.72E+02
CO-sector	1.07E+01	33378.38	8.99E+02	4.38E+02
AG-sector	3.21E+02	10898.43	2.70E+04	1.31E+04
IN-sector	1.59E+02	20343.21	1.34E+04	6.51E+03
TR-sector	2.20E+01	27730.70	1.85E+03	8.99E+02
TE-sector	2.55E+02	27717.60	2.14E+04	1.04E+04

3.1.3 E_R accounting

To evaluate comprehensively the environmental emission influences, we construct an inclusive framework for different types of embodied exergy interference originally from resource consumption, in which we choose the most meaningful emissions, as well as in consideration of data availability. The E_R accounting frame is shown in Fig. 4 as follows:
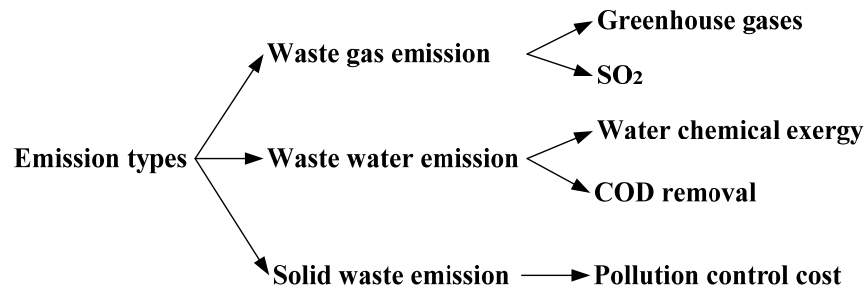
Fig. 4 - The E_R accounting frame for environmental emissions in China

In this study, greenhouse gas emission factors from the IPCC [51] are partly revised on account of China's energy structure and quality. In addition, with the limitation of precise and sectoral environmental data, we collect and sort all existing databases together exhibited in the following tables. For waste gas and water emissions, the pollutants' exergy can be evaluated according to their chemical ingredients. However, the complexity of solid waste lists made it impossible to calculate emission exergy

based on detailed account. Therefore, we use the embodied emission exergy (Method 2.3) to estimate this part. The accounting parameters used in this part are listed in Table 8 and the following Table 9 is the integrated value of E_R.

Table 8-a - Accounting parameters used in E_R evaluation

Items	Unit	Revised green gas emission factors
Coal	Kg CO_2/kg	2.21
Crude oil	Kg CO_2/kg	3.4
Natural gas	Kg CO_2/m^3	2.88
Electricity	Kg CO_2/MJ	0.19
Items	Unit	Standard chemical exergy (ScEx)
CO_2	kJ/kg	451.6
NOx	kJ/kg	2963.3
SO_2	kJ/kg	4892.3
COD	PJ/Mt	13.6
Water	kJ/kg	50kJ/kg

Table 8-b - Sectoral emissions of SO_2 and NO_X in China (2007)

Sector	SO_2 Emission (10000 ton)	NO_X Emission (10000 ton)
EX-sector	51.04	1.89E+02
CO-sector	1149.74	1.34E+03
AG-sector	2.94E+03	-
IN-sector	771.46	9.83E+02
TR-sector	6.88E+02	9.31E+04
TE-sector	1.97E+04	3.76E+01
DO-sector	8.12E+03	2.53E+01

**Table 9** - The integrated value of E_R

Sector	CO_2(PJ)	SO_2(PJ)	NO_x(PJ)	waste water (PJ)	Solid waste emission exergy (PJ)	Environmental emission (PJ)
EX-sector	2.66E+02	2.50E+00	5.59E+00	2.48E+00	2.45E+00	2.71E+02
CO-sector	1.35E+03	5.62E+01	3.97E+01	1.24E+00	9.76E-01	1.44E+03
AG-sector	3.41E+01	1.44E+02	-	6.95E+01	-	2.47E+02
IN-sector	1.64E+03	3.77E+01	2.91E+01	5.80E+01	7.18E-01	1.77E+03
TR-sector	1.96E+02	3.37E+01	1.13E+01	-	-	2.41E+02
TE-sector	2.82E+02	9.65E+02	1.12E+00	-	-	1.25E+03
DO-sector	3.50E+03	3.97E+02	7.50E-01	1.18E+02	-	4.01E+03

Note: In China, wastewater generated in Transportation and Tertiary sectors is statistically recorded in the Domestic sector, and pollution control costs for solid waste pollution are only available in broad production sectors (Extraction, Conversion, and Industry, for instance). For the other vacant sectors, data are blended with social capital

input, making it hard to be certain all emissions are accounted. Likely, the overall method underestimates the emissions and required exergy to remediate them.

3.2 Extended exergy input-output relationships among seven sectors

The following figure demonstrates the complete extended exergy flows for the seven sectors. From the exergy values labeled in the figure, it is explicitly shown that the basic sectors, Extraction, Conversion, and Agriculture, have direct input from ecological resources, *CEC-2* input from the other five sectors into one certain sector, E_L and E_K inputs from the Domestic sector, and environmental influences based on material resource depletions as well. The Domestic sector plays the part of labor provider and capital creator, so all the embodied exergy through this sector is related to substantial base flows. Moreover, for the other sectors, they consumed the primary resources after the elementary manufacture in basic sectors, secondary products and services from other parts, as well as the social-economic input from Domestic sector. All the embodied exergy input-output flows, with various sources, different directions among seven sectors are summarized in Fig. 5 as follows:

(1) EX-sector

(2) CO-sector

(3) AG-sector

(4) IN-sector
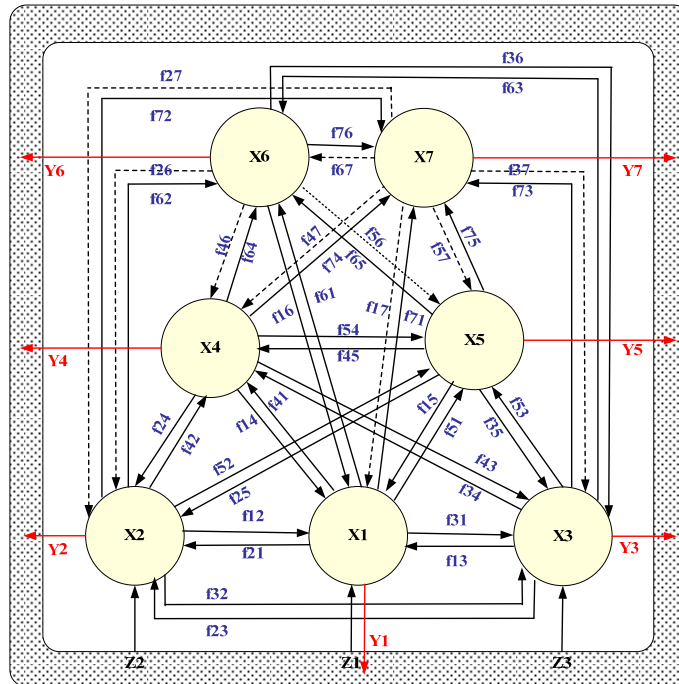
5) TR-sector

(6) TE-sector

(7) DO-sector
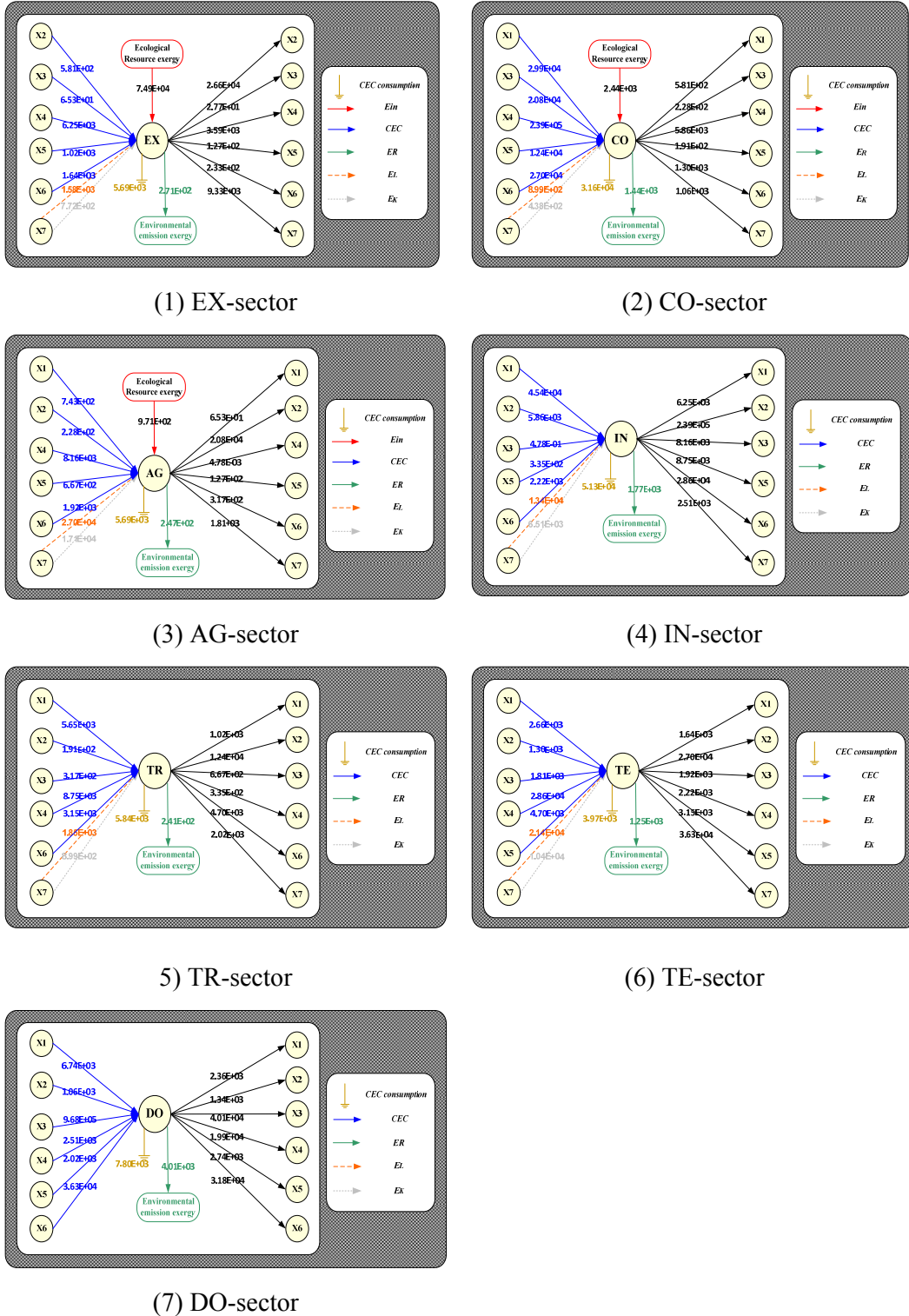
Fig. 5 - Extended exergy input-output relationships in seven sectors where X1: Extraction; X2: Conversion; X3: Agriculture; X4: Industry; X5: Transportation; X6: Tertiary; X7: Domestic, Unit: PJ

3.3 Total extended exergy flow in seven sectors, network relationship and analysis

Based on the decomposed extended exergy allocations within the seven sectors in Section 3.2, a general extended exergy distribution flow matrix is constructed in Table 10. Meanwhile, in order to vividly reveal the flow disparity, we construct a sectoral metabolism hierarchical network of the social-economic consumption system on account of extended exergy distribution flows (see Fig. 6).

Table 10 - Extended exergy based distribution flow matrix in seven sectors

i sector / *j* sector	Resource input	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector	DO-sector
EX-sector	7.70E+04	5.11E+03	5.81E+02	6.53E+01	6.25E+03	1.02E+03	1.64E+03	2.36E+03
CO-sector	2.44E+03	2.99E+04	1.67E+03	2.08E+04	2.39E+05	1.24E+04	2.70E+04	1.34E+03
AG-sector	9.96E+05	7.43E+02	2.28E+02	5.75E+03	8.16E+03	6.67E+02	1.92E+03	4.01E+04
IN-sector	-	4.54E+04	5.86E+03	4.78E-01	4.27E+03	3.35E+02	2.22E+03	1.99E+04
TR-sector	-	5.65E+03	1.91E+02	3.17E+02	8.75E+03	1.89E+03	3.15E+03	2.74E+03
TE-sector	-	2.66E+03	1.30E+03	1.81E+03	2.86E+04	4.70E+03	2.26E+04	3.18E+04
DO-sector	-	6.74E+03	1.06E+03	9.68E+05	2.51E+03	2.02E+03	3.63E+04	-
Environmental emission	-	2.74E+02	1.44E+03	2.47E+02	1.77E+03	2.41E+02	1.25E+03	4.01E+03

Fig. 6 - Network relationships for sectoral metabolism hierarchical extended-exergy flows, where X1: Extraction; X2: Conversion; X3: Agriculture; X4: Industry; X5: Transportation; X6: Tertiary; X7: Domestic

In this figure, Z represents the E_{in} input directly from natural resources; Y is the output of the sector that contains environmental emission exergy and unemployed exergy emission; f_{ij} means exergy flow from j sector into i sector. Full lines refer to exergy flow based on material resource delivered among different sectors, dotted lines are labor and capital exergy which are the production of Domestic sector after substantial resource consumption.

3.4 Indicator analysis

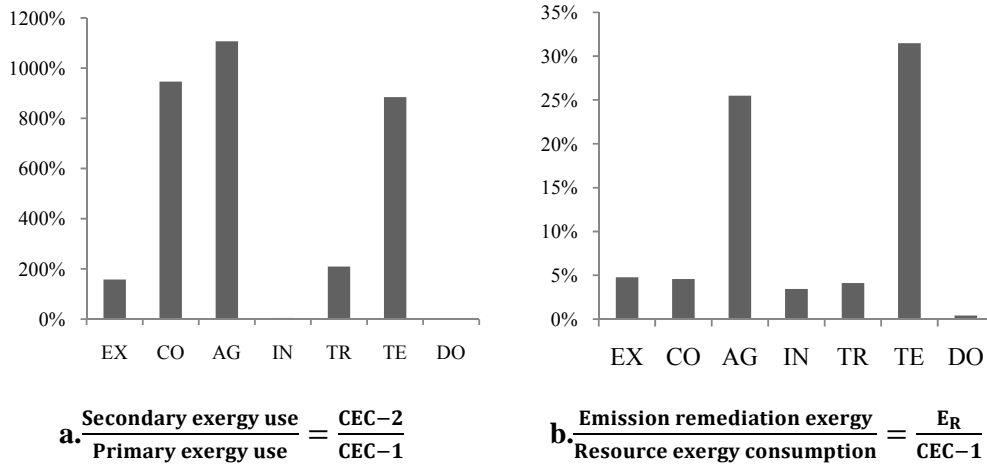### 3.4.1 Extended exergy in sectoral allocation

Fig. 7 clearly indicates: 1) Conversion and Domestic are the two largest sectors for *CEC* consumption, in which Domestic is the final material based expenditure sector for the sake of supporting basic human survival and development; however, in Conversion more than 65% of the electricity in 2007 [41] was generated from fossil fuels, which is determined by energy structure in China. 2) Labor is concentrated in the Agriculture, Industrial and Tertiary sectors, employing more than 93% of the population in 2007. 3) The Agriculture and Tertiary sectors need more than 73% of the supporting embodied exergy capital. Therefore, from Figures 7b and 7c, Agriculture and Tertiary are labor and fund intensive sectors. To optimize the existing manpower structure in China, Agriculture and Tertiary are the key sectors for regulation. 4) The Transportation sector generates the largest amount of environmental emission exergy. Compared with its *CEC* consumption, it is obvious that Transportation has a low efficiency of environmentally friendly input-output ratio for energy use.

a. *CEC* consumption (PJ)

b. E_L emission (PJ)

c. E_K input (PJ)

d. E_R input (PJ)
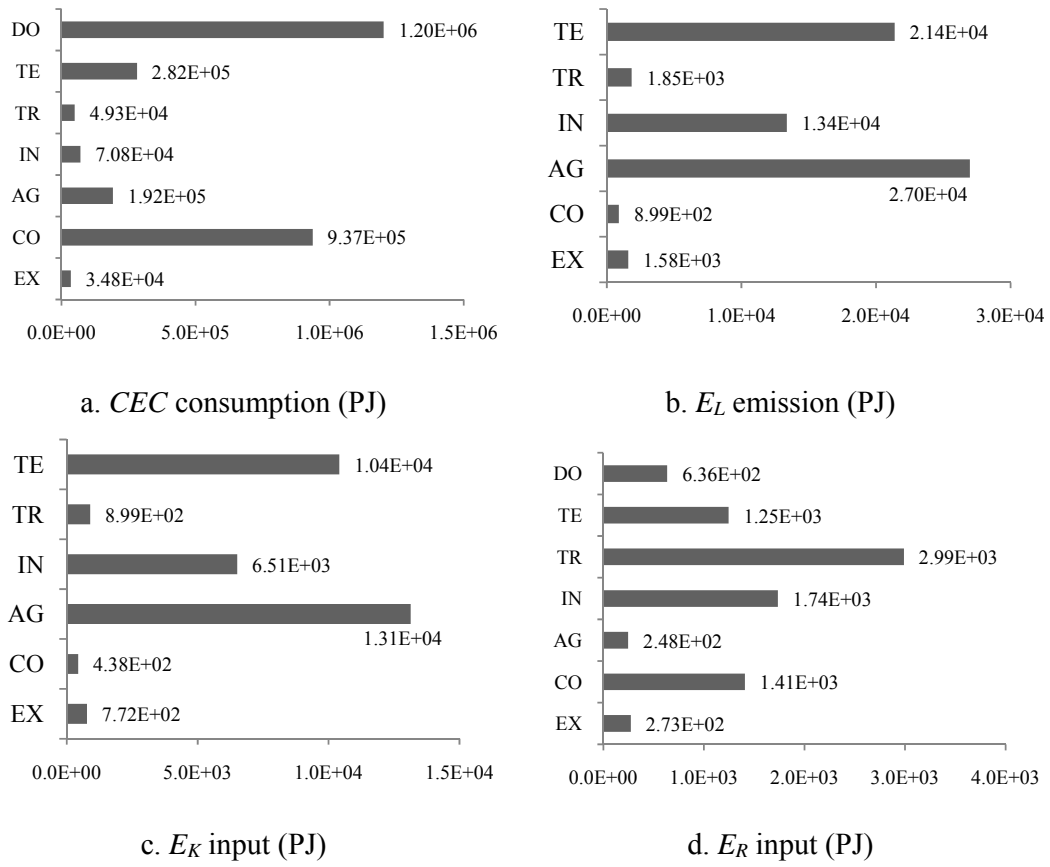
Fig. 7 - Four parts of extended exergy allocation in seven sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

21

### 3.4.2 Extended exergy efficiency metrics

(1) Resource exergy efficiency metrics

$$a. \frac{\textbf{Secondary exergy use}}{\textbf{Primary exergy use}} = \frac{CEC-2}{CEC-1} \qquad b. \frac{\textbf{Emission remediation exergy}}{\textbf{Resource exergy consumption}} = \frac{E_R}{CEC-1}$$

Fig. 8 - Resource exergy efficiency metrics in seven sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

Figure 8 shows that both the Agriculture and Tertiary sectors have high levels of *CEC-2* rate and E_R compared with *CEC-1*. Therefore, a large amount of secondary exergy investment plays an extremely important role in supporting the regular production and operation activities. Meanwhile, in these two sectors, a high percentage of environmental emissions based on *CEC-1* consumption are emitted into the surroundings, implying the low environmental efficiency and high pollution based. Meanwhile, for the Conversion sector, plenty of *CEC-2* is fossil fuels for thermoelectric generation, therefore, the *CEC-2*/*CEC-1* ratio has a high value, but the environmental emission of secondary energy is accounted as the indirect emission of the final consumption sector as shown in the EEA accounting boundary in Fig.1. For example, since the Tertiary sector exhausts the electricity, it is Tertiary not Conversion sector that should take responsibility for the emission of this electricity generation. Thus, emission exergy in Conversion is lower than that in Agriculture and Tertiary, due to the fact that its emission burdens are distributed into the other final consumer sectors. Furthermore, in the Industrial and Domestic sectors, they exceedingly depend on *CEC-1* depletion. The Domestic sector is mainly consuming agriculture products for human survival, while Industry is principally depleting primary or non sustainable resources. Though the environmental emission rate is low, the total amount of environmental disturbance is considerable.

(2) Exergy output/input efficiency metrics: $\dfrac{\textbf{Exergy output}}{\textbf{Exergy input}}$
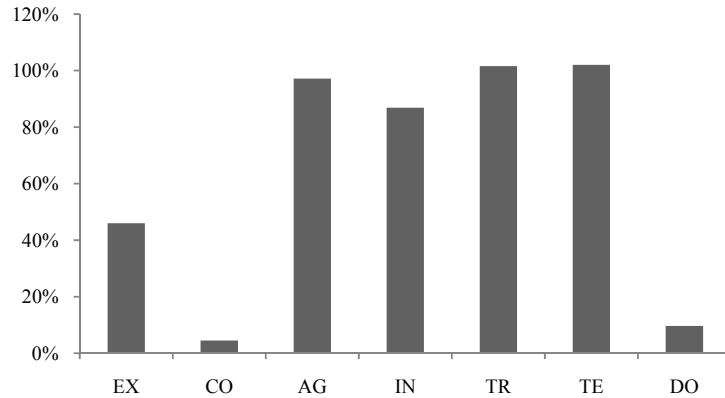
Fig. 9 - Exergy output/input effiency metrics in seven sectors where EX: Extraction; CO:Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

In Fig. 9, Agriculture, Industry, Transportation and Tertiary have nearly full value of output-input ratio, demonstrating them as almost pure exergy carriers or transmitters of the whole system. They use up a small amount of the input exergy within their own sectors, and then act as full exergy providers to next exergy acceptor after the their internal processing.

(3) Social economic exergy proportion metrics: $\frac{E_L+E_K}{EE}$
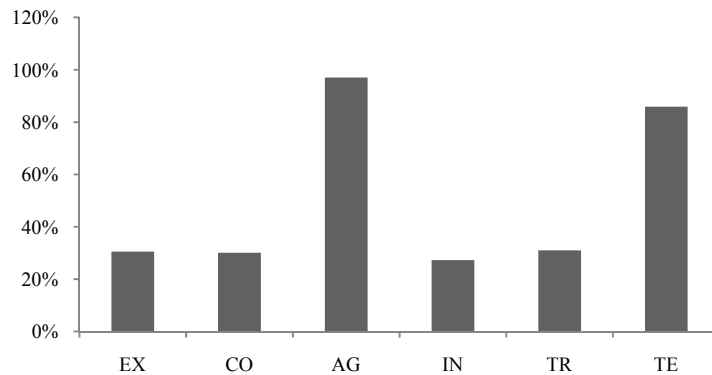
Fig. 10 - Social economic exergy proportion metrics in six sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic

Figure 10 shows the labor and capital input from the domestic sector to the other sectors. It highlights the result that the Agriculture and Tertiary utilize the largest amount of labor and capital investments in the entire system. The extensive use of labor in these sectors implies that they offer the most potential in optimizing labor allocation.

4. Conclusion

The thermodynamic concept of extended exergy (EEA) is introduced to unify the assessment of the different production sectors that contribute to the cost formation processes in the Chinese social-economic system in 2007. Once we accept to calculate "cost" on a physical basis, and to express it using exergy of consumed resources (expressed equivalently in the unit of Joules), EEA provides a scientific and objective measure for material resource input, labor and capital expenditures, and physical remediation costs of environmental impacts. The four components of the extended exergy cost were calculated for seven aggregated sectors based on the 42 sector Input-Output Table. Our results show that: the interactions between economic sectors could be explained in the form of a network, which is analogous to an ecological trophic structure; and primary resource sectors act as base for consumption of the socio-ecological trophic structure; furthermore, Agriculture, Industry, Transportation, and Tertiary sectors play as exergy carriers or transmitters of the entire social-economic system.

Another conclusion is that, different sectors need different strategies to become a more sustainable. Specifically, we find:

(1) For the Conversion sector: it is urgent to lower the primary exergy input by decreasing the fossil based electricity, so as to reduce both natural resource consumption and environmental emissions; as well as, it is necessary to advocate for cleaner energy, hydroelectric, wind power, tidal power etc., to replace nonrenewable energy and (or) exergy saving during the long-term sustainable developing process.

(2) For the Transportation sector: it has the highest level of E_R emission. The Transportation sector, basically depending on fossil sources, is one of the major contributors both to the energy final use and to the GHG emissions. The Transportation sector continues to be the most important sector for policy makers to control environmental emissions by developing cleaner transport fuel substitution, optimizing traffic flows, and advocating energy saving travel modes, etc.

(3) For the Agriculture and Tertiary sectors: Human behavior dominates their regular operations. These sectors will play a vital role in the transition from a labor oriented to technical oriented mode as the labor force demographics ages and changes.

Lastly, an obvious conclusion is that previous results using only monetary methods greatly underestimate the environmental effects on both ends (extraction of resources and final disposal): i.e., the real impact of the Transportation sector is definitely worse than what the standard analyses demonstrate. For example, long term ecological impacts on biodiversity, climate change, ecological degradation cannot be interpreted only by extended exergy accounting in social-economic system. That would be the next largest problem for further exploration. However, what is important is to realize that any "ecological viewpoint" in evaluation the human influence on ecological resource consumption must be founded on a cost measure quantified by the physical or eco-

thermodynamic metric of resources consumption rather than solely monetary proxies thereof.

References

[1] Wall, G. (1977) Exergy - a useful concept within resource accounting. Report no. 77-42, Institute of Theoretical Physics, Chalmers University of Technology and University of Göteborg, Sweden..

[2] Wall, G. (1987) Exergy conversion in the Swedish society. Resources and Energy 1987 – 9 (1): 55-73.

[3] Szargut, J., Petela, R. (1965) Exergy. Warsaw: WNT.

[4] Utlu, Z., Hepbasli, A. A. (2007) Review on analyzing and evaluating the energy utilization efficiency of countries. Renewable & Sustainable Energy Reviews 2007;11(1):1-29.

[5] Jørgensen, S.E., Mejer, H. (1977) Ecological buffer capacity. Ecological Modelling 3(1):39-61.

[6] Jørgensen, S.E., Nielsen, SN., Mejer, H. (1995) Energy, environ, exergy and ecological modelling. Ecological Modelling 77(2-3):99-109.

[7] Szargut, J. (2002) Application of exergy for the determination of the pro-ecological tax replacing the actual personal taxes. Energy 27(4):379-389.

[8] Chen, G.Q., Qi, Z.H. (2007) Systems account of societal exergy utilization: China 2003. Ecological Modelling 208(2-4):102-118.

[9] Wall, G. (1990) Exergy conversion in the Japanese society. Energy 15(5):435-444.

[10] Ertesvåg, I.S., Mielnik, M. (2000) Exergy analysis of the Norwegian society. Energy 25(10):957-973.

[11] Ayres, R.U., Ayres, L.W., Warr, B. (2003) Exergy, power and work in the US economy, 1900-1998. Energy 28(3):219-273.

[12] Dincer, I., Hussain, M.M., AL-Zaharnah, I. (2004) Energy and exergy use in public and private sector of Saudi Arabia. Energy Policy 32(14):1615-1624.

[13] Dincer, I., Hussain, M.M., AL-Zaharnah, I. (2004) Energy and exergy utilization in transportation sector of Saudi Arabia. Applied Thermal Engineering 24(4):525-538.

[14] Chen, B., Chen, G.Q. (2006) Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system. Energy 31(8-9):1115-1150.

[15] Gasparatos, A., El-Haram, M., Horner, M. (2009) Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. Renewable & Sustainable Energy Reviews 13(5):1074-1081.

[16] Gasparatos, A., El-Haram, M., Horner, M. (2009) Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renewable & Sustainable Energy Reviews 13(5):956-970.

[17] Wall, G., Sciubba, E., Naso, V. (1994) Exergy use in the Italian society. Energy 19(12):1267-1274.

[18] Dincer, I. (2002) The role of exergy in energy policy making. Energy Policy 30(2):137-149.

[19] Chen, B., Chen, G.Q., Yang, Z.F. (2006) Exergy-based resource accounting for China. Ecological Modelling 196(3-4):313-328.

[20] Chen, G.Q. (2006) Scarcity of exergy and ecological evaluation based on embodied exergy. Communications in Nonlinear Science and Numerical Simulation 11(4):531-552.

[21] Sciubba, E. (2001) Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. Exergy, An International Journal 1(2):68-84.

[22] Sciubba, E. (2003) Cost analysis of energy conversion system via a noval resource-based quantifier. Energy 28:457-477.

[23] Sciubba, E. (2003) Extended-exergy accounting applied to energy recovery from waste: the concept of total recycling. Energy 28:1316-1334.

[24] Sciubba, E. (2004) Exergoeconomics. In: Cleveland, C.J. ed. Encyclopedia of Energy.New York, USA: Elsevier science publishers; pp.577-591.

[25] Sciubba, E., Bastianoni, S., Tiezzi, E. (2008) Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. Journal of Environmental Management 86(2):372-382.

[26] Ptasinski, K.J., Koymans, M.N., Verspagen, H.H.G. (2006) Performance of the Dutch Energy Sector based on energy, exergy and Extended Exergy Accounting. Energy 31(15):3135-3144.

[27] Sciubba, E. (2011) A revised calculation of the econometric factors α and β for the extended exergy accounting method. Ecological Modelling 222(4):1060-1066.

[28] Chen, G.Q., Chen, B. (2009) Extended-exergy analysis of the Chinese society. Energy 34(9):1127-1144.

[29] Ertesvåg, I.S. (2005) Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 30(5):649-675.

[30] Tainter, J.A. (2000) Problem solving: complexity, history, sustainability. Population and Environment 22:3-41.

[31] Patten, B.C. (1978) Systems approach to the concept of environment. Ohio Journal of Science 78:206-22.

[32] Patten, B.C. (1981) Environs: the superniches of ecosystems. American Zoologist 21:845-852.

[33] Patten, B.C. (1982) Environs: relativistic elementary particles or ecology. American Naturalist 119:179-219.

[34] Fath, B.D., Patten, B.C. (1999) Review of the Foundations of Network Environ Analysis. Ecosystems 2(2):167-179.

[35] Fath, B.D., Jørgensen, S.E., Patten, B.C., Straskraba, M. (2004) Ecosystem growth and development. Biosystems 77(1-3):213-228.

[36] Dame, J.K., Christian, R.R. (2006) Uncertainty and the use of network analysis for ecosystem-based fishery management. Fish 31:331-341.

[37] Christian, R.R., Brinson, M.M., Dame, J.K., Johnson, G., Peterson, C.H., Baird, D. (2009) Ecological network analyses and their use for establishing reference domain in functional assessment of an estuary. Ecological Modelling 220:3113-3122.

[38] Szargut, J., Morris, D.R., Steward, F.R. (1988) Energy analysis of thermal, chemical and metallurgical processes. New York, USA: Hemisphere Publishing, pp.332.

[39] Kotas, T.J. (1985) The Exergy Method of Thermal Plant Analysis. London, UK: Butterworths.

[40] CSY (2008) China Statistical Yearbook.Beijing: China Statistics Press.

[41] CESY (2008) China Energy Statistic Yearbook. Beijing: China Environment Yearbook Press.

[42] UNDP (2008) China's human development report. United Nations Development Program.

[43] Chen, G.Q., Qi, Z.H. (2007) Systems account of societal exergy utilization: China 2003. Ecological Modelling 208(2-4):102-118.

[44] Chen, G.Q. (2005) Exergy consumption of the earth. Ecological Modelling 184(2-4):363-380.

[45] Cornelissen, RL., Hirs, G.G. (2002) The value of the exergetic life cycle assessment besides the LCA. Energy conversion and management 43(9-12):1417-1424.

[46] Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B.R., Grubb, G.F., Paulus, D.M., Sciubba, E. (2008) Exergy: its potential and limitations in environmental science and technology. Environmental Science & Technology 42(7):2221-2232.

[47] Creyts, J.C. (2000) Use of extended exergy analysis as a tool to optimize the environmental performance of industrial processes. Ph.D. Dissertation, University of California, Berkeley, CA, USA.

[48] Szargut, J. (2001) Sequence method of determination of partial exergy losses in thermal systems. Exergy, An International Journal 1(2):85-90.

[49] Milia, D., Sciubba, E. (2006) Exergy-based lumped simulation of complex systems: an interactive analysis tool. Energy 31(1):100-111.

[50] CLSY (2008) China Labor Statistical Yearbook. Beijing: China Statistics Press.

[51] IPCC (2007) IPCC Guidelines for National GHG Inventories. Japan: IGES.