Available online at www.sciencedirect.com
ScienceDirect
Procedia Environmental Sciences 5 (2011) 51–59
Procedia Environmental Sciences

2010 International workshop from the International Congress on Environmental Modeling and Software (iEMSs2010)

# How to guide a sustainable industrial economy: Emergy account for resources input of Chinese industry

B. Zhang[a], G.Q. Chen[a], Q. Yang[a], Z.M. Chen[a], B. Chen[b,*], Z. Li[a]

[a] *State Key Laboratory of Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, China*
[b] *State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China*

**Abstract**

Emergy analysis provides a feasible approach to evaluate the status and position of different energy carriers in the universal energy hierarchy. In this paper, an emergy-based method is conducted to measure the resources input of Chinese industry from 1997 to 2006. Resources inflows including fossil fuels, mineral resources, agricultural products, and other imported materials are accounted, based on which related indicators including resources intensity, industrial output, and environmental emissions are investigated. Results show a steady upward trend for the total resources input of Chinese industry during the past decade. The total resources input amounted to $1.53\times10^{25}$ sej in 2006, of which non-renewable one accounted for 70.65% owing to the dominating input of fossil fuels and nonmetal minerals. Resources intensity measured by the ratio of resources input to industrial value added declined gradually during 1997–2002, but the rapid expansion of resource–intensive sub–sectors resulted in a reverse trend since 2003. The current resources use pattern of Chinese industry is characterized by increasing input of non-renewable resources, excessive expansion of resource–intensive production, and tremendous challenge from environmental pressure.



*Keywords:* Emergy; Resources input; Chinese industry

## 1. Introduction

The sustainability of human societies relies on the physical factors input to provide the energy and materials consumption [1, 2]. An understanding of the detailed resources situation will be contributed to drive correct conclusion about resources management. The focus in environmental research is now also shifting from only emissions abatement to critical process analysis, including the assessment of resources input [3]. Industrial sector plays an important role for economic development, which provides most energy and matter used in modern society. During the past 10 years, China' industry has experienced a rapid economic growth with an average growth rate of industrial value added 10.49%. Around 40% of gross domestic product (GDP) came from industrial economy and the contribution of industrial economy in 2006 to the increase of the GDP reached 48.8% [4]. The challenge for

* Corresponding author. Tel.:+86-10-5989-3227.
*E-mail address*: chenb@pku.edu.cn

1878-0296 © 2011 Published by Elsevier Open access under CC BY-NC-ND license.
doi:10.1016/j.proenv.2011.03.047

Chinese industry is the situation of rapid economic development relying on the ever–increasing consumption of natural resources. The efficient understand of industrial resource situation against drastic socioeconomic transitions demands systematic research based on overall and unified accounting at different scales.

As a thermodynamic–based environmental accounting approach, emergy analysis using the thermodynamic basis of all forms of energy and materials and converting them into equivalents of sunlight is a type of embodied energy analysis that can provide common units (emergy) for comparison of environmental and economic goods by summing the energy into one type required directly for production of goods [5], which provides a more feasible approach to evaluate the status and position of different energy carriers in the universal energy hierarchy [6]. Emergy analysis makes bridges between material production, economic production and environmental production, which has been widely used in analyzing and evaluating industrial systems, with extensive literature at industrial process or production [7–9], transformities for industrial products [10,11], typical industrial systems such as power plant [12,13], waste treatment in industrial system [14], and other fields [15]. Although the resources consumption increases, resources intensity and energy intensity change drastically indicated by other indices, e.g., energy intensity (e.g., [16–18]), efficiency analysis (e.g., [19–21]), the scholars studied on the overall raw material input in Chinese industry have been rare and led to the conclusions and suggestions difficult to carry on adequately.

The aim of this paper is to present an emergy–based unified account of resources input in Chinese industry, and to compare the performance in both non-renewable and renewable resources. By accounting and assessing the fundamental utility of resources based on a unified measure, the resources situation of Chinese industry is elucidated, which can be added to the poor knowledge between economic profitability and ecological sustainability and contribute to resources management and environmental regulation for the policymakers.

## 2. Methodology and data sources

### 2.1. Emergy methodology

Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a service or product, usually quantified in solar energy equivalents and expressed as solar emJoules (sej) [5]. In emergy calculation, we generally translate each form of resource in the industrial system into its solar energy equivalent, or solar emergy, by way of a conversion factor (transformity) that reflects the energy's qualitative value. Transformity defined as the quantity of one type of emergy required to generate a unit of resource, usually expressed in solar emergy joules per joule or gram of output flow, i.e., sej/J or sej/g [5,22], can be obtained from some references. Theoretically, the larger the transformity, the more solar energy is required for the produce of the resource, and the higher their position in the energy hierarchy of the universe.

Compared to an ecosystem, the important factors for emergy analysis of industrial system are different. The factors such as climate and sunlight are usually not accounted for industrial systems. Furthermore, only a very small part of resources inflow from renewable resources, e.g., within agriculture and forestry, is used in the industrial sector. The greater parts of the resources inflow are seen to come from non-renewable resources including fossil fuels, minerals, etc. As a result, emergy with regard to the varied qualities of energy inherent in the hierarchy of system components can be used to compare the different resources input in a common unit. The different input to the industrial system can be summed to evaluate the total emergy requirement of Chinese industry.

### 2.2. Data sources

In this paper, industry refers to the material production sector which is engaged in the extraction of natural resources and processing and reprocessing of minerals and agricultural products, including (1) extraction of natural resources, such as mining and salt production; (2) processing and reprocessing of agricultural products, such as rice husking, flour milling, wine making, oil pressing, silk reeling, spinning and weaving, and leather making; (3) manufacture of industrial products, like steel making, iron smelting, chemicals manufacturing, petroleum processing, machine building, timber processing; water and gas production and electricity generation and supply; (4) repairing of industrial products such as the repairing of machinery and means of transport (including cars). For the national–scale system, the emergy input in Chinese industry contains the imported, gathered, constrained and extracted commodities as emergy carriers. Most of data are adopted or derived from the official databases and public issued official statistical yearbooks.

## 3. Results and discussions

### *3.1. Emergy account of resources input*

3.1.1. Total emergy

As the sum of all input fluxes outside the system boundary, the detailed emergy account for resources input in Chinese industry is performed. Compared with $7.95\times10^{24}$ sej in 1997, resources input in 2006 increased by 92.5% and reached $1.53\times10^{25}$ sej. The annual growth rates of the total amount of resources input kept less than 4.53% during 1997–2001; while afterwards, it increased from $9.22\times10^{24}$ sej in 2001 to $1.53\times10^{25}$ sej in 2006, with an average growth rate of 10.6%.

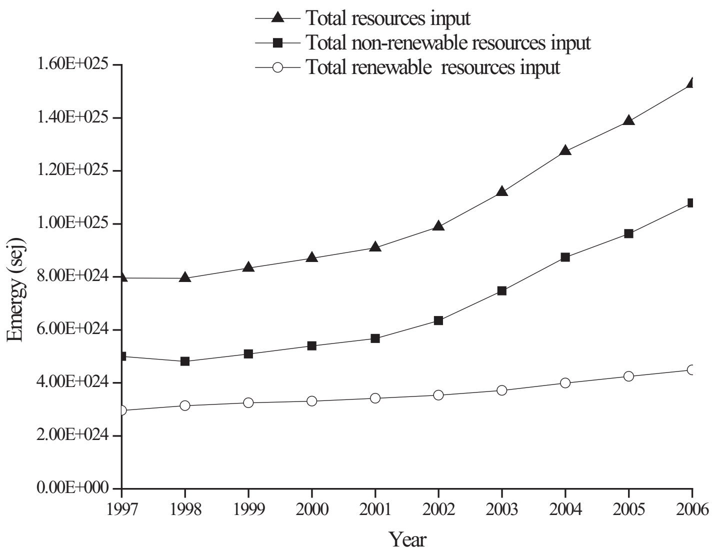


Fig. 1. Resources input in Chinese industry.

Two categories of resources input are divided, i.e., non-renewable and renewable resources, with corresponding results of emergy account shown in Fig. 1. Non-renewable resources input accounted for 61.10%–70.65% of the total, which determined the trend of total resources input to some extent. A rapid increment of the non-renewable resources input in recent 5 years can be found, from $6.35\times10^{24}$ sej in 2002 to $1.08\times10^{25}$ sej in 2006, owing to the large input of fossil fuels, metal and non-metal minerals in industrial sub–sectors. Correspondingly, renewable resources increased slightly from $2.95\times10^{24}$ sej in 1997 to $4.48\times10^{24}$ sej in 2006, due to the development of the processing of food from agricultural products and livestock products.

3.1.2. Non-renewable resources

The greater parts of the resources inflow into industrial system were seen to come from non-renewable resources including fossil fuels, metal minerals, etc. Figure 2 shows the detailed non-renewable resources input in Chinese industry during 1997–2006. Of all the non-renewable resources, energy minerals was the largest, with the amount of $2.29\times10^{24}$ sej in 1997 and $4.29\times10^{24}$ sej in 2006, accounting for 45.81% and 39.74% of the total respectively. Coal was the dominated fossil fuel with the proportion among 68.73%–74.51% of the total energy minerals. The coal consumption in 1997 ($1.71\times10^{24}$ sej) and 2001 ($1.59\times10^{24}$ sej) changed drastically, which can be contributed to rectification and readjustment of coal production performed to balance the wide gap between the supply and demand [23]. After 2001, the coal production rebounded, restored and continued to increase due to the rapid rise of coal consumption and electricity demand.

Limestone, as a primary raw material for the cement industry, was the second emergy input of the non-renewable resources, which expanded 2.4 times during the past 10 years and amounted to $2.32\times10^{24}$ sej in 2006. The iron ore and scrap steel resources input increased by 176.16%, from $5.83\times10^{23}$ sej in 1997 to $1.61\times10^{24}$ sej in 2006. The imported iron ore sand rose rapidly and amounted to $4.70\times10^{23}$ sej in 2006, compared with $7.94\times10^{22}$ sej in 1997. Nonferrous ores and scrap resources input had also increased by more than 3.90 times from $2.95\times10^{23}$ sej in 1997 to $1.15\times10^{24}$ sej in 2006.

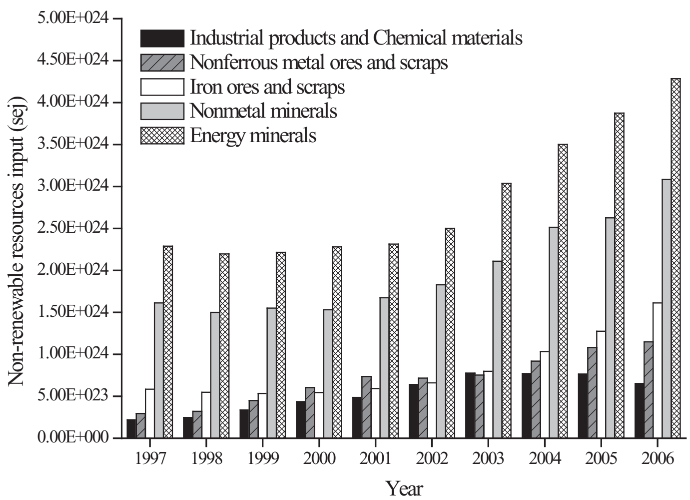


Fig. 2. Non-renewable resources input in Chinese industry.

### 3.1.3. Renewable resources

A smaller part of resources inflow from renewable resources, e.g., within agriculture and forestry, is used in the industrial sector. The emergy input of renewable resources is presented in Fig. 3. Of all the renewable resources input, livestock products made up the largest fraction in terms of emergy. Take the year 2006 for instance, with the amount of $1.58\times10^{24}$ sej, all forms of livestock products accounted for 55.24% of the total renewable resources ($2.48\times10^{24}$ sej). High emergy input of livestock products is attributed to the large input of pork (69.27% of total livestock products in 2006) and high transformities of livestock products. Compared with crops and vegetables, animals take up higher energy hierarchy in nature with more solar energy consumed [24]. So when be expressed in emergy unit, stockbreeding production takes more share in total yield. It should be noted that the most inputs of agricultural and livestock products into industrial system are processed roughly, such as rice husking, flour milling and livestock slaughtering.

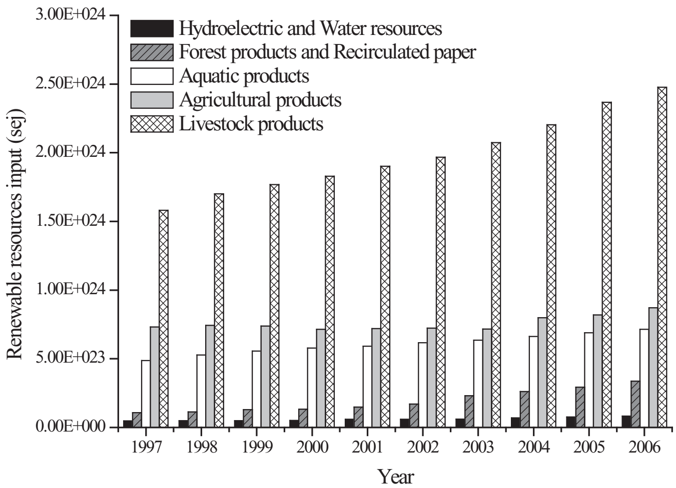


Fig. 3. Renewable resources input in Chinese industry.

Light industry refers to the industry that produces consumer goods and hand tools [25]. The main materials supply from renewable resources to the light industry also increased remarkable. For instance, wood products and paper related raw materials supplied to the paper industry and wood processing industry increased from $6.90\times10^{22}$ sej in 1997 to $2.30\times10^{23}$ sej in 2006, with an average annual growth rate 14.44%. Hydroelectric resource input in 2006 was 2.22 times of that in 1997. Due to the improvement of the use efficiency, the emergy input of water resource increases not much.

*3.2. Resources intensity analysis*

Resources intensity (RI), as the ratio of the total emergy input of resources to the industrial value added (IVA), is a critical parameter for resource policies that aims to reduce resource consumption while maintaining or even boosting economic growth. The lower the ratio, the fewer the resources input to yield per unit IVA. The total RI of Chinese industrial economy decreased from $2.50\times10^{12}$ sej/RMB in 1997 to $2.00\times10^{12}$ sej/RMB in 2002. However, it started to increase by 2.63% over 2003–2004, and declined by 2.22% in 2005 and 4.35% in 2006, as shown in Fig. 4.

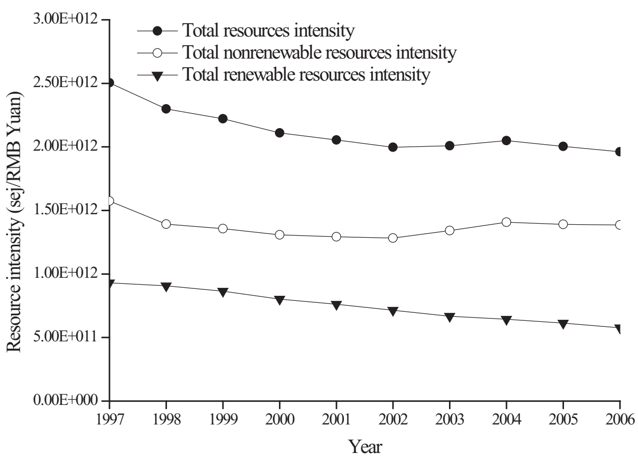

Fig.4. Resources intensity of Chinese industry.

Non-renewable resources intensity had the same trend with the RI while renewable resources intensity gradually decreased during 1997–2006. Due to the largest portion of non-renewable resources, the energy intensity reflected by the energy minerals input per unit IVA, including coal, oil and natural gas. Energy intensity decreased by 29.85% in 1997–2002 and rose by 7.83% in 2003 or 11.43% in 2004, then slightly declined by 2.33% over 2005–2006. Some researches in energy intensity (measured by energy consumption with mass units per unit of GDP) have similar results [18–21]. The primary driving force for the decline in China's energy intensities during 1997–2002 was efficiency effect (i.e. sectoral energy intensities at lower level) rather than sectoral structural shifting [18–21]. Liao et al. [18] found that the excessive expansion of high–energy consuming sector and the high investment ratio were foremost sources of the increasing energy intensity during 2003–2005. It implies, therefore, that technical progress made a notable contribution in Chinese industrial economy during 1997–2002. Due to the special stage from 2003 to 2005 in China, most energy–intensive sectors and products have expanded rapidly.

### 3.3. Resources input and industrial output

The resources input also can be associated with the output of industrial products. As shown in Fig. 5, the main industrial products (produced by non-renewable resources) had a rapid increase indicated by the industrial product output index. Along with the rapid growth of Chinese industrial economy, main industrial product, especially most energy–intensive products increased rapidly during 1997–2006. The outputs of crude steel, motor vehicles, ethylene, cement, plate glass, electricity, chemical fiber and primary plastic in 2006 were 3.85, 4.60, 2.62, 2.42, 2.80, 2.52, 4.40 and 3.80 times of those in 1997, respectively. The statistics data of 419.15 million ton crude steel, 19.17 million ton ten major nonferrous metals, 1236.76 million ton cement and 20.73 million ton chemical fiber in 2006 were the largest output in the world [25]. Correlation analysis also shows that the correlation coefficients between mineral resource inflow in iron and steel industry and energy sources inflow (coal, petroleum, natural gas) were higher than 0.90. Similar results can be found in nonferrous industry. Chinese industry is characterized by the large proportion and sustained growth of heavy industry. In 2006, the industrial value added of heavy industry to that of light industry reached 70:30. China is adopting energy–intensive technology and investing the excessive expansion of high–energy consuming sectors, such as iron and steel, cement, and electrolysis aluminum [18].

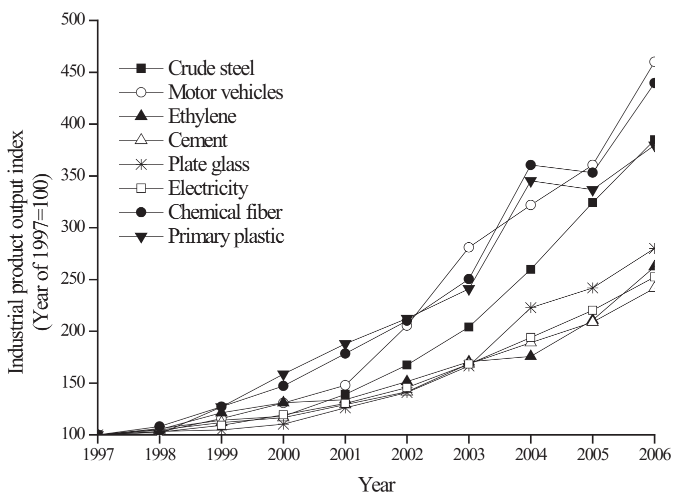

Fig. 5. Major industrial products output index for heavy industry.

Meanwhile, the main industrial products from light industry produced by renewable resources are investigated, as shown in Fig. 6. Rapid increased industrial products in the light industry can be found, but the growth rates were less than those of some energy-intensive products.

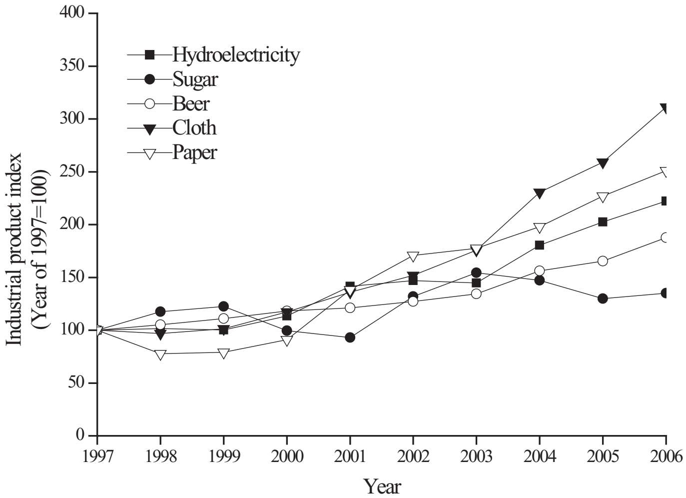


Fig.6. Major industrial products output index for light industry.

### 3.4. Resources input and environmental emissions

Industrial activities characterized by huge resources consumption have engendered striking environmental emissions. Average 81.4% of the $SO_2$ emission, 80.9% of the soot emission and 47.8% of the waste water discharge resulted from Chinese industry during 1997-2006 [26]. For the year 2006, 24.02 billion ton industrial waste water, 22.34 million ton $SO_2$ and 13.02 million ton solid waste were discharged into the environment. The share of $CO_2$ emissions from secondary industry accounted for more than two thirds of the total energy–related $CO_2$ emissions in China [27]. Environment crises have become the restricting factor for Chinese industry.

The energy or raw materials utility sectors are the major source of industrial environmental emissions. According to the Annual Statistic Report on Environment in China 2004 issued by SEPA [28], the sources of air pollution centralized on the sectors of electric power, extraction, nonmetal ore goods, iron and steel production, nonferrous smelting, which accounted for about 90% of industrial $SO_2$, soot and solid waste emissions. Four industrial subsectors (i.e., pulp & paper, food of processing and products, beverages, chemical materials and products, and textile) accounted for 72.4% of the total COD load in 2006 [26]. It is remarkable that the environmental emissions are closely related with resources consumption, especially energy consumption. Coal is the dominant energy resource for Chinese industry, and coal combustion is the main source of emissions of $CO_2$, $SO_2$ and other air pollutants. The rapid growth of materials production and the energy demand for electricity and coal in some major industries (e.g., steel, electrolytic aluminum, cements and paper industry) with high–energy intensity and heavy environmental emissions contribute the emissions profile of Chinese industry [29].

## 4. Concluding remarks

Based on the thermodynamic concept of emergy as a unified measure, detailed resources input for Chinese industry has been accounted. Compared with $7.95\times10^{24}$ sej in1997, resources input in 2006 increased by 92.5% and reached $1.53\times10^{25}$ sej. The non-renewable resources input accounting for 61.10%–70.65% of the total resources input determined the trend of total resources input to some extent. Of all the non-renewable resources, energy minerals was the largest, followed by limestone, iron ore and scrap steel resources, and nonferrous ores and scrap resources. The main input of renewable resources was agricultural products and livestock products.

Resources intensity analysis indicates that the development of resources input can be split into two main periods with different characteristics: the first period from 1997 to 2002 corresponding to the decreased non-renewable resources intensity; the second period from 2002 onwards with the rapid increased non-renewable resources input for energy or resource–intensive industrial sectors. The resources input also can be associated with the output of industrial products.

The situation of resources utilization and resources reserves in China has restricted the provision of industrial raw materials. The resource utilization level of Chinese industry still has large gaps in production process, technology, and management, compared with other OECD countries or the international advanced level. The average resource extraction efficiency in China is lower than 20%–30% of the global advanced average [30]. As the energy consumption of production process, synthetic energy consumption of equipment and technology in China is more than 10% of that in OECD countries [31]. For instance, synthetic energy consumption per ton of steel, cement, oil refining, ethylene and calcium carbide in 2004 were higher than 15.6%, 23.3%, 53.4%, 59.6% and 19.4% of those in OCED countries, respectively [32]. Therefore, the potential for promoting resource utilization level is substantial and urgent, especially in some resource–intensive or energy–intensive sectors, e.g., iron and steel industry, nonferrous industry and nonmetal industry. At the same time, Chinese industry faces the tremendous challenges of limit resources supply in domestic reserves. Domestic resources reserves such as oil and iron ores cannot meet the gap between the huge and increasing demand and limit domestic supply, and then a large amount of resources need to be imported. One can only attempt to reduce the overall consumption of materials, and recycle as much of it as possible.

Industrial activities characterized by huge resources input have engendered striking environmental pollution. Ongoing industrialization and urbanization of the Chinese economy and growing population with infrastructure and housing requirements (reflected by the large amounts of construction minerals input) and energy demand (increasing extraction and import of fossil fuels) influence the resources situation and status of Chinese industry. Pressure of environmental protection becomes serious limit for Chinese industrial development with elevated environmental standard and statutes. The increasing supply costs of water, air and land have pushed the production cost rising.

For Chinese industry, a large effort has to be made to decrease resources consumption, promote restructuring and transformation of the pattern of growth, enhance the knowledge of resources savings, improve related legal systems, strengthen resources management and resource efficiency improvement, rationalize resources prices and market mechanism, improve policies on energy saving and alternative energy technology, establish a general responsibility system for meeting energy saving and pollution discharge reduction targets, and promote circular economy and environmental management.

## Acknowledgements

This study has been supported by the National Natural Science Foundation of China (Grant Nos. 70903005 and 40971052).

## References

[1] Arrow K, Bolin B, Costanza R, Dasgupta P, Folke C, Holling CS, Jansson BO, Levin S, Mäler KG, Perrings C, Pimentel D. Economic growth, carrying capacity, and the environment. *Science* 1995;**268**(5210):520–521.

[2] Cleveland CJ. Biophysical economics: from physiocracy to ecological economics and industrial ecology, In: K. Mayumi and J.M. Gowdy (Eds.), *Bio-economics and sustainability: essays in honor of Nicholas Georgescu–Roegen*. Cheltenham: Edward Elgar 1999.

[3] Meester BD, Dewulf J, Janssens A, Langenhove HV. An improved calculation of the exergy of natural resources for exergetic life cycle assessment (ELCA). *Environment Science & Technology* 2006;**40**(21):6844–6851.

[4] SYC. Statistical Yearbook of China. Beijing: China Statistical Publishing House 1998–2007 [in Chinese].

[5] Odum HT. Environmental accounting: emergy and environmental decision making. *New York: Wiley* 1996.

[6] Jiang MM, Chen B, Zhou JB, Tao FR, Li Z, Yang ZF, Chen GQ. Emergy account for biomass resource exploitation by agriculture in China. *Energy Policy* 2007;**35**(9):4704–4719.

[7] Feng X, Wang L, Min S. Industrial emergy evaluation for hydrogen production systems from biomass and natural gas. *Apply Energy* 2009;**86**(9):1767–1773.

[8] Cavalett O, Ortega E. Emergy, nutrients balance, and economic assessment of soybean production and industrialization in Brazil. *Journal of Cleaner Production* 2009;**17**(8):762–771.

[9] Dong X, Ulgiati S, Yan M, Zhang X, Gao W. Energy and eMergy evaluation of bioethanol production from wheat in Henan Province, China. *Energy Policy* 2008;**36**(10):3882–3892.

[10] Bastianoni S, Campbell DE, Ridolfi R, Pulselli FM. The solar transformity of petroleum fuels. *Ecological Modelling* 2009;**220**(1):40–50.

[11] Pulselli RM, Simoncini E, Ridolfi R, Bastianoni S. Specific emergy of cement and concrete: an energy–based appraisal of building materials and their transport. *Ecological Indicators* 2008;**8**(5):647–656.

[12] Peng T, Lu HF, Wu WL, Campbell DE, Zhao GS, Zou JH, Chen J. Should a small combined heat and power plant (CHP) open to its regional power and heat networks Integrated economic, energy, and emergy evaluation of optimization plans for Jiufa CHP. *Energy* 2008;**3(3)**:437–445.

[13] Wang L, Ni W, Li Z. Emergy evaluation of combined heat and power plant eco–industrial park (CHP plant EIP). *Resources, Conservation and Recycling* 2006;**48**(1):56–70.

[14] Yang H, Li Y, Shen J, Hu S. Evaluating waste treatment, recycle and reuse in industrial system: an application of the eMergy approach. *Ecological Modelling* 2003;**160**(1–2):13–21.

[15] Pulselli RM, Simoncini E, Pulselli FM, Bastianoni S. Emergy analysis of building manufacturing, maintenance and use: Em–building indices to evaluate housing sustainability. *Energy Buildings* 2007;**39**(5):620–628.

[16] Zhang B, Bi J, Fan Z, Yuan Z, Ge J. Eco–efficiency analysis of industrial system in China: a data envelopment analysis approach. *Ecoogical Economics* 2008;**68**:306–316.

[17] Watanabe M, Tanaka K. Efficiency analysis of Chinese industry: a directional distance function approach. *Energy Policy* 2007;**35**:6323–6331.

[18] Liao H, Fan Y, Wei YM. What induced China's energy intensity to fluctuate: 1997–2006? *Energy Policy* 2007;**35**:4640–4649.

[19] Ma CB, Stern DI. China's changing energy intensity trend: a decomposition analysis. *Energy Economics* 2008;**30**:1037–1053.

[20] Zha DL, Zhou DQ, Ding N. The contribution degree of sub–sectors to structure effect and intensity effects on industry energy intensity in China from 1993 to 2003. *Renewable & Sustainable Energy Reviews* 2009;**13**(4):895–902.

[21] Zhang Z. Why did the energy intensity fall in China's industrial sector in the 1990s? The relative importance of structural change and intensity change. *Energy Economics* 2003;**25**(6):625–638.

[22] Ulgiati S, Brown MT. Emergy and ecosystem complexity. *Communications in Nonlinear Science and Numerical Simulation* 2009;**14**:310–321.

[23] Chen GQ, Chen B. Resource analysis of the Chinese Society 1980–2002 based on exergy–part 1: fossil fuels and energy minerals. *Energy Policy* 2007;**35**(4):2038–2050.

[24] Chen GQ, Jiang MM, Chen B, Yang ZF., Lin C. Emergy analysis of Chinese agriculture. *Agriculture, Ecosystems & Environment* 2006;**115**(1–4):161–173.

[25] SYC. Statistical Yearbook of China. *Beijing: China Statistical Publishing House* 1998–2007 [in Chinese].

[26] CEY. China Environment Yearbook. *Beijing: China Environment Yearbook Press* 1998–2007 [in Chinese].

[27] Zhang M, Mu H, Ning Y. Accounting for energy–related $CO_2$ emission in China, 1991–2006. *Energy Policy* 2009;**37**:767–773.

[28] SEPA, State Environmental Protection Administration of China. *Annual statistic report on environment in China* 2004. Beijing: China Environmental Science Press 2005 [in Chinese].

[29] Zhang KM, Wen ZG. Review and challenges of policies of environmental protection and sustainable development in China. *Journal of Environmental Management* 2008;**88**(4):1249–1261.

[30] Tong C, Song GB, Chen BR, Ye WH. Macroeconomic efficiency of use of non–renewable resources in the industrial economy during a period of rapid economic growth in China. *Resources, Conservation and Recycling* 2008;**52**(5):737–746.

[31] Lang YH, Zhou P, Shen L. Analysis on the saving potentials of mineral resources in China. *Resource Science* 2005;**27**(6):23–27 [in Chinese].

[32] Wang MQ. China forwards new models of economic growth. *Beijing: Social Science Academic Press* 2007 [In Chinese].