Exergy efficiency and environmental impact of nonferrous metals smelting sector in China: A data envelopment analysis approach

Hai Qi, Haizhong An*, Wei Fang, Shupei Huang, Nairong Liu

* *School of Humanities and Economic Management, China University of Geosciences, Beijing 100083, China, ahz369@163.com*

Abstract

The increasing production of nonferrous metals presents an obstacle to the sustainability of Chinese society for the sector consuming a great deal of energy and discharging plenty of emissions. The effective utilization of the nonferrous metal industry is a serious problem to be faced. The exergy concept was introduced into this study. We present an application of data envelopment analysis (DEA) approach with considering undesirable outputs, examines the exergy efficiency performance of the main smelting of nonferrous metals sector in China in 2010. Environmental DEA technology is adopted, which treats undesirable measures by distinguishing between weak and strong disposability. The output directional distance function is used, which explicitly expands desirable outputs and simultaneously reduces undesirable outputs. From the empirical results, we find that aluminum is more efficient in the copper, aluminum, lead and zinc, and tin smelting from the constant returns of scale (CRS), non-increasing returns of scale (NIRS), and variant returns of scale (VRS). In order to get one unit desirable output we have to consume more exergy and have more emissions in lead and zinc series than other series.

Keywords:

Exergy efficiency; Data envelopment analysis (DEA); Smelting sector; Nonferrous metals; China

1. Introduction

Smelting and pressing of non-ferrous metals sector is one of the energy-intensive sectors in China. In 2010, the smelting and pressing of non-ferrous Metals sector was responsible for consuming 128.41 million tons of SCE [1] and the production of ten kinds of nonferrous metals was 31.2 million tons [2]. While the smelting and pressing of ferrous metals sector consumed 575.34 million tons of SCE [1] and the production of kinds of ferrous metals was 2037.33 million tons [2]. The energy consumption per unit output of the smelting and pressing of non-ferrous metals sector is 14.6 times that of the smelting and pressing of ferrous metals sector. Emissions from the smelting and pressing of non-ferrous metals comprise greenhouse gas emissions, such as carbon dioxide (CO_2) and noxious emissions, namely, carbon monoxide (CO), Hydrocarbon (HC), Nitrogen oxides (NOx), and particulate matter (PM). China faces problems in resources and environment challenge.

With the concern on environmental issues and sustainable development, energy efficiency and environment evaluation become more important. Being a developing country China has huge population and scarce resources. Therefore, balancing the development, resource conservation, and environmental protection is the key to the Chinese Government. By improving energy efficiency and increasing energy conservation efforts are able to achieve the aim.

Not based on the first law of thermodynamics, some scholars prefer to consider all processes and activities in terms of energetics. In this way people are able to apply the second laws of thermodynamics to society and ecological problems. Particularly the concept of exergy 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 [3-9]. That is to say, exergy is defined as the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state. It is able to be thought of as a measure of its quality or potential to cause change. In contrast to energy, exergy is not subject to the conservation law except for ideal or reversible processes, and instead is consumed or destroyed due to the unavoidable irreversibility within any real process. Unlike energy flow which is only about the quantity, exergy is a measure of quantity and quality of the energy resources [3, 4].

For exergy to be able to unify the material, energy, and information, Wall creatively introduced exergy into accounting work of social resource consumption [3, 4]. Some scholars have studied different national and sectorial levels applying exergy evaluation, and achieved results in these case studies: (1) For national levels, Japan [10], Sweden [4], Norway [11], America [12], China [13], UK [14, 15], Italy [16] and some others. These studies analyzed energy and material flow and efficiency from a perspective of exergy, and assist the country's energy and resource to policy makers. (2) In the social sectorial level, Dincer and his group published a series of papers on transportation industry, and domestic, public and private sectors in Saudi Arabia [17-22] and Chen studied China [23] to assess the ‘‘resource content’’ of social input as well as environmental emissions [24, 25]. Chen and his group studied kinds of resource and different industries of Chinese society from exergy perspective, and proposed some suggestions which can improve the exergy efficiency of China to policymakers [6, 26-32]. Their results show the usefulness of exergy in solving environmental problems and progression toward sustainable development of human society.

Reistad's way only quantifies the exergy of energy carriers in an economy. Wall quantifies the exergy content of energy carriers and other materials such as metals, minerals, biomass as well as the waste emissions further. Sciubba adds the capital and labor in the quantification of exergy on Wall's approach.

Following Wall's approach, we measure the four series (copper, aluminum, lead and zinc, tin) input and output efficiency in the smelting process of nonferrous metals using Data envelopment analysis (DEA) method from the exergy perspective.

There are lots of papers studying the undesirable factors in the DEA framework and they are divided into the four perspectives.

First, undesirable variables are treated as inputs and both inputs and undesirable outputs should be decreased [33]. Second, in some papers good outputs are expanded and undesirable outputs are reduced simultaneously [34]. This approach has received considerable attention. Watanabe and Tanaka [35] examined the effects of undesirable output in different Chinese provinces. Zhou [36] discussed environmental DEA technologies that exhibit non-increasing returns to scale (NIRS) and variant returns to scale (VRS). Third, Seiford and Zhu [37] recommended the data transformation approach which integrates undesirable outputs into DEA models through the classification invariance property. Yeh [38] employed the approach to assess energy efficiency between Mainland China and Taiwan from 2002 to 2007, in which two non-desirable outputs are showed. Fourth, Sueyoshi [39] divided the operational and environmental performance into two aspects using a measure of efficiency referred to as the range-adjusted measure (RAM). DEA with RAM models can simultaneously maximize outputs and minimize inputs.

This study presents an application of data envelopment analysis approach with considering the undesirable outputs, and examines exergy efficiency of Chinese smelting of nonferrous metals sector in 2010. The output directional distance function is used, which explicitly expands desirable outputs and simultaneously reduces undesirable outputs.

We organize our paper as follows. In the next section we explain our method for transforming nonferrous metal ores, nonferrous metals and energy carriers into exergy. Two inputs oriented DEA models and potential exergy saving are adopted, which is based on the environmental DEA technology under different returns of scale. We report our results in the third section. Finally we summarize our work in the last section.

2. Methodology and data

2.1 Data resources

The data on amounts of energy carriers, ores, and refined metal products for the current study were obtained from the CNMY [40]. The quantities of ores consumed in the smelting and pressing of nonferrous metals are the production of domestic ore plus the import and minus the export. The quantities of CO_2 come from the U.S. Energy Information Administration (http://www.eia.gov/cfapps/ipdbproject/). Different kinds of energy produce different quantity CO_2. Based on the proportion of different energy consumption we obtain the quantity CO_2 in the smelting process of the nonferrous metals sector. For the data of pressing of nonferrous metals being unavailable, we choose the process of smelting process of the five main metals in this study because they are able to represent the whole smelting sector [7, 13].

2.2 Calculating the exergy of the ferrous metal ores

When the environment is determined, the exergy of a system is determined as well. For the exergy of kinds of ores, metals and CO_2 accounts, it is reasonable to select a global standard environment to illustrate in the series of works on standard chemical exergy of some elements and compounds that facilitate further exergy calculations [8, 9, 41].

The chemical exergy content of different material resources are represented in detail by some papers [3, 42]. The exergy of substances and materials is given as:

$$E_x = \sum_i n_i(\mu_i - \mu_{i0}) + RT_0 \sum_I n_i \ln \frac{c_i}{c_{i0}}, \qquad (1)$$

where T_0 is the temperature of the environment; n_i the ith mole number; μ_i the chemical potential of substance i in its present state; μ_{i0} the chemical potential of substance i in its environmental state; c_i the chemical concentration of substance i in its present state and c_{i0} is the chemical concentration of substance i in its environmental state.

In this paper, the material and energy flows are all assigned extended exergetic content given by its raw state exergy presented by Morris and Szargut [9,44].

Some researchers calculate exergy of the metals and minerals on the standard environment [9, 43-45]. With relatively low grade of the ore output in China (aluminum 40%, copper 0.57%, lead

2.46%, zinc 4.09% and tin 0.87%), the exergy contents of the aluminum, copper, lead, zinc and tin are estimated to be 0.3, 0.026, 0.021, 0.046 and 0.0002 MJ/kg, respectively [13]. The exergy contents of the aluminum, copper, lead, zinc and tin are estimated in the same way to be 32.9, 2.1, 13, 5.4 and 3.4MJ/kg [7].The exergy of CO_2 is 0.45 MJ/kg [46].

Thermophysical exergy of the materials is ignored as negligible for it is much smaller than the chemical exergy. With respect to a fuel, the exergy transformation factor is equal to the product of the lower heating value (LHV) on average, which is often adopted by energy statistical yearbooks, and the exergy–energy ratio [13, 47].

2.3 DEA methodology

In the Zhou's paper [48] it based on the environmental DEA technology under constant returns of scale (CRS), which means the inputs and outputs with constant efficiency. We employ non-increasing returns of scale (NIRS) meaning linearly scale the inputs and outputs without increasing efficiency and variant returns of scale (VRS) meaning linearly scale the inputs and outputs with increasing or decreasing efficiency to evaluate the exergy efficiency under different development stages.

The basic DEA model of assumes constant returns to scale (CRS), i.e. if all inputs increase with factor a then all outputs will increase with factor a as well. A DMU_k is efficient if and only if, in the dual optimal solution, θ = 1, which means DMU_k is scale efficient. If θ = 1, DMU_k is scale inefficient. Otherwise, when efficiency score θ is smaller than 1, DMU_k is inefficient.

2.3.1 Exergy efficiency performance under CRS

The joint production technology under CRS can be represented as:

P={ $(x^o, x^e, y^d, y^u) : (x^o, x^e)$ can produce (y^d, y^u) }, which satisfies the properties (P1) below.

(1) Outputs are weakly disposable, i.e, if $(x^o, x^e, y^d, y^u) \in P$ and $0 \le \delta \le 1$, then $(x^o, x^e, \delta y^d, \delta y^u) \in P$.

(2) Desirable outputs and undesirable outputs are null-joint, i.e., if $(x^o, x^e, y^d, y^u) \in P$ and $y^u = 0$, then $y^d = 0$.

$$EPIndex\ (CRS) = \min \frac{1}{L} \sum_{l=1}^{L} \theta_{l0}$$

s.t.

$$\sum_{j=1}^{J} \lambda_j x_{kj}^{o} \le x_{k0}^{o}, \quad k = 1,...,K \, , \tag{2}$$

$$\sum_{j=1}^{J} \lambda_j x_{lj}^{e} \le \theta_{l0} x_{k0}^{e}, \quad l = 1,...,L \, , \tag{3}$$

$$\sum_{j=1}^{J} \lambda_j y_{mj}^{d} \ge y_{m0}^{d}, \quad m = 1,...,M \, , \tag{4}$$

$$\sum_{j=1}^{J} \lambda_j y_{nj}^{u} = y_{n0}^{u}, \quad n = 1,...,N \, , \tag{5}$$

$$\lambda_j \ge 0, \quad j = 1, 2,..., J \, , \tag{6}$$

where the subscript "0" represents the DMU to be evaluated, and J is the DMUs whose exergy efficiency are to be measured, for the jth DMU, $x_j^o = (x_{1j}^o, x_{2j}^o,..., x_{kj}^o)$ represent exergy inputs of ores. $x_j^e = (x_{1j}^e, x_{2j}^e,..., x_{kj}^e)$ represent exergy inputs of energy carriers, $y_{mj}^d = (y_{1j}^d, y_{2j}^d,..., y_{Mj}^d)$ denote desirable outputs, and $y_{nj}^u = (y_{1j}^u, y_{2j}^u,..., y_{Nj}^u)$ represent undesirable outputs.

$EPIndex\ (CRS)$ measures total average of efficiency allocated to exergy inputs of energy carriers. It allows non-proportional adjustments for exergy inputs of energy carriers.

2.3.2 Exergy efficiency performance under NIRS

The NIRS exergy efficiency performance index can be formulated by imposing the restrictions of intensity variables on the CRS exergy efficiency performance index.

$$EPIndex\ (NIRS) = \min \frac{1}{L} \sum_{l=1}^{L} \theta_{l0} \, ,$$

s.t. (2), (3), (4), (5), and (6)

$$\sum_{j=1}^{J} \lambda_j \le 1 \, , \tag{7}$$

2.3.3 Exergy efficiency performance under VRS

Different to CRS and NIRS, the joint production technology under VRS should be made some modifications [36]

P={ $(x^o, x^e, y^d, y^u) : (x^o, x^e)$ can produce (y^d, y^u) }, which satisfies the properties (P2) below.

(1) Outputs are weakly disposable, i.e, if $(x^o, x^e, y^d, y^u) \in P$ and $0 < \delta \le 1$, then $(x^o, x^e, \delta y^d, \delta y^u) \in P$.

(2) Desirable outputs and undesirable outputs are null-joint, i.e., if $(x^o, x^e, y^d, y^u) \in P$ and

$y^u \to 0$, then $y^d \to 0$.

$$EPIndex\ (VRS) = \min \frac{1}{L}\sum_{l=1}^{L}\theta_{l0},$$

s.t. (2), (3), (4), (6), and

$$\sum_{j=1}^{J}\lambda_j y_{mj}^d \ge \alpha_0 y_{m0}^d, \quad m = 1,\dots,M, \tag{8}$$

$$\sum_{j=1}^{J}\lambda_j y_{nj}^u = \alpha_0 y_{n0}^u, \quad n = 1,\dots,N, \tag{9}$$

$$\sum_{j=1}^{J}\lambda_j = 1, \tag{10}$$

$$\alpha_0 \ge 1, \tag{11}$$

3. Results and discussion

3.1. Overview of input and output of smelting of nonferrous metals

The exergy of energy carriers occupied the most of the investment compared to the exergy of ores accounting the 98% of the total investment. The exergy of energy carriers are much bigger than the desirable output and undesirable output. In the output, the desirable output is 2.84 times than the undesirable output.

In these four series, the aluminum dominates the most parts from the exergy view. The aluminum accounts the 82.22%, 86.55%, 85.28% and 83.31% from exergy of energy carriers, ores, desirable out and undesirable output. The lead and zinc occupies the second part in the input and output except the ores and it is far behind the aluminum 11.19%, 1.86%, 13.11% and 10.58%.

In the exergy of energy carriers investments of the smelting of the nonferrous metals electricity accounts for the 20.62% in the total exergy investment and the coal accounts for the 27.92%. Coke, fuel oil, diesel oil, gas, and natural gas account for 4.27% in the smelting process.

In these four series the aluminum maintains the most of the exergy investment, accounting the 86.59% of the electricity, 85.5% of the coal. The lead and zinc account the 8.2% of the electricity and the 10.62% of the coal.

3.2. DEA results

All DEA models are solved by LINDO. The results are summarized in Table 1.

Table 1 DEA results of EPIndex(CRS) EPIndex(NIRS) EPIndex(VRS)

	CRS	NIRS	VRS
copper	0.9075	0.8120	0.8120
lead and zinc	1.0000	0.9640	0.9640
tin	1.0000	0.9554	0.9554
aluminum	1.0000	1.0000	1.0000

As shown in Table 1 the observations for EPIndex(CRS), EPIndex(NIRS), EPIndex (VRS)

(1) In EPIndex(CRS), copper is lowest efficiency in the four series and it is lower than 19.25% than the other three series. The lead and zinc, tin and aluminum have the higher efficiency 100%.

(2) In EPIndex(NIRS), copper is the lowest efficiency in the four series and it is lower than 18.8% than the aluminum series. Lead and zinc series has higher efficiency to 96.4% compared to the 95.54% of the tin series. The efficiency of aluminum is the highest and it reach to 100%.

(3) In EPIndex(VRS), copper is the lowest efficiency in the four series and its efficiency is 81.2%. Lead and zinc series has higher efficiency to 96.4% while the efficiency of tin series is 95.54%. The aluminum series has the highest efficiency 100%.

Exergy is considered as a goal function and adopted to identify the status, and trend of ecosystem growth and development [49–51]: the idea is that ecosystems will survive that are capable of storing amount of exergy than others or of being able to keep themselves in a permanent far-from-equilibrium state [52–54].

The relative exergy efficiency is higher there is less environmental impaction. The relative exergy efficiency of aluminum series is the highest one and this series emits the smallest CO_2 relatively while the copper series emits the maximum mount CO_2 relatively.

The consideration of exergy mix effect for the four series, the aluminum series generally performed better than the Lead and zinc, tin and copper. The Lead and zinc was better than the tin and the copper is the worst. Producing aluminum consumes plenty of electricity and electricity is the most effective energy compared to others. The electricity consumed in aluminum series is the high proportion 21.71% and the efficiency of aluminum series is the best one.

3.3. Exergy efficiency performance of different series

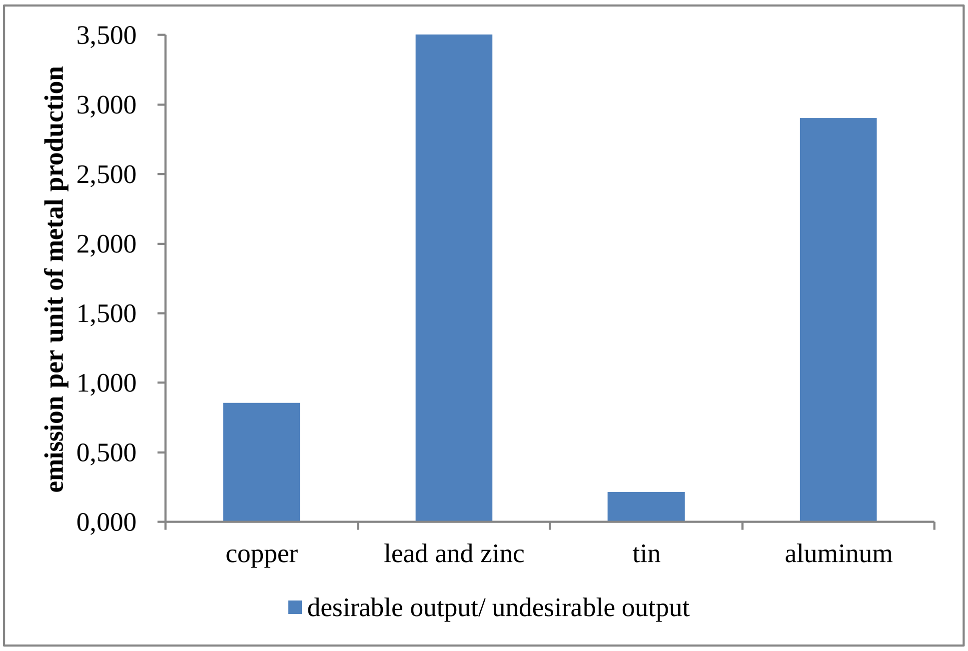

Figure 1 emission per unit of metal production

We divided the desirable out and undesirable output to analysis the CO_2 emissions per unit of metal production from exergy view. We found that smelting one unit lead and zinc made the largest contribution to CO_2 emissions in Fig 1. The aluminum, copper and tin were the second, the third and the fourth. That is to say, in order to smelting one unit lead and zinc we have to emit more CO_2 than aluminum, copper and tin which is not the same conclusion with the Shao[55].When we divided the desirable out and the energy carriers from exergy view we found that smelting one unit lead and zinc consumed 0.181 unit energy, higher than the aluminum 0.16, much higher than the copper 0.043 and tin 0.011. That is to say the lead and zinc series is the highest energy consumption in the four series.

Exergy, defined as the maximum work performed by a system in the process of reaching equilibrium with its reference environment while undergoing only reversible processes and interacting solely with the environment itself, is widely used in the fields of process optimization, resource accounting and environmental impact assessment, because it provides a rational and rigorously founded thermodynamic quantification of the consumption of natural resources, environmental losses.

The concept of exergy, or useful work, is able to unify different forms of material and energy. In our paper we are able to recalculate the input and output from the view of exergy unifying the kinds of materials and energy to get some new conclusions.

4. Conclusions

The current study presents an application of data envelopment analysis approach, and considers the undesirable outputs to benchmark the exergy efficiency performance of four series in Chinese smelting of nonferrous metals 2010. The output directional distance function which expands desirable outputs and reduces undesirable outputs is employed According to the exergy efficiency indexes, we found that the lowest efficient series was copper and the highest was aluminum.

The CO_2 emissions of the aluminum industry made the largest contribution to the total CO_2 emissions. The lead and zinc industry contributed the second highest CO_2 emissions. The copper and tin contributed the third and the fourth. While in order to get one unit desirable output we have to consume more energy and have more emissions in lead and zinc series than other series.

The high aluminum, lead and zinc production levels and the high energy consumption made the largest contribution to CO_2 emissions. Although Wang and Chandler [56] pointed out that the energy consumption of aluminum production in China had decreased, it remains high. The aluminum, lead and zinc industry therefore is the key target for environmental control. The aluminum industry should be guided towards low-carbon practices and the electrolytic aluminum industry should be phased out raising the environmental protection.

Furthermore, the following policy areas should be targeted: the utilization smelting of nonferrous metal industries; to upgrade industrial technological; to improve the competitiveness of energy-intensive industries. Finally, as a large energy consumer, the production of nonferrous metals should be controlled and supply of electricity and heat would have a decisive influence on the carbon emissions from the smelting of nonferrous metal sector. The coal consumption in the energy proportion should be reduced in order to raise the efficiency of energy.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (Grant No. 71173199) and Ministry of Education, Humanities and Social Sciences Planning Fund (Grant No. 10YJA630001).

References

1. CSY, *China Statistical Yearbook.* China Statistical Publishing House, Beijing, 2012.
2. CSY, *China Statistical Yearbook.* China Statistical Publishing House, Beijing, 2011.
3. Wall, *Exergy —a useful concept within resource accounting.* Research Report no.77–42 Go¨teborg, Sweden: Institute of Theoretical Physics, 1977.
4. Wall, *Exergy conversion in the Swedish society.* Resources and Energy, 1987. **9(1):55–73**.

5. Ertesvåg, I.S., *Energy, exergy, and extended-exergy analysis of the Norwegian society 2000.* Energy, 2005. **30**(5): p. 649-675.
6. Chen, G.Q. and B. Chen, *Extended-exergy analysis of the Chinese society.* Energy, 2009. **34**(9): p. 1127-1144.
7. Chen, G.Q. and Z.H. Qi, *Systems account of societal exergy utilization: China 2003.* Ecological Modelling, 2007. **208**(2-4): p. 102-118.
8. Szargut, J., Morris, D.R., Steward, F.R.,, *Exergy Analysis of Thermal, Chemical and Metallurgical Processes.* Hemisphere Publishing Corporation, New York., 1988.
9. Szargut, J., *CHEMICAL EXERGIES OF THE ELEMENTS.* Applied Energy, 1989. **32**(4): p. 269-286.
10. Wall, *EXERGY CONVERSION IN THE JAPANESE SOCIETY.* Energy, 1990. **15**(5): p. 435-444.
11. Ertesvåg, I.S. and M. Mielnik, *Exergy analysis of the Norwegian society.* Energy, 2000. **25**(10): p. 957-973.
12. Ayres, R.U., L.W. Ayres, and B. Warr, *Exergy, power and work in the US economy, 1900-1998.* Energy, 2003. **28**(3): p. 219-273.
13. Chen, B. and G.Q. Chen, *Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system.* Energy, 2006. **31**(8-9): p. 1115-1150.
14. Gasparatos, A., M. El-Haram, and M. Horner, *Assessing the sustainability of the UK society using thermodynamic concepts: Part 2.* Renewable & Sustainable Energy Reviews, 2009. **13**(5): p. 956-970.
15. Gasparatos, A., M. El-Haram, and M. Horner, *Assessing the sustainability of the UK society using thermodynamic concepts: Part 1.* Renewable & Sustainable Energy Reviews, 2009. **13**(5): p. 1074-1081.
16. Wall, G., E. Sciubba, and V. Naso, *EXERGY USE IN THE ITALIAN SOCIETY.* Energy, 1994. **19**(12): p. 1267-1274.
17. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Energy and exergy use in public and private sector of Saudi Arabia.* Energy Policy, 2004. **32**(14): p. 1615-1624.
18. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Energy and exergy utilization in transportation sector of Saudi Arabia.* Applied Thermal Engineering, 2004. **24**(4): p. 525-538.
19. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Energy and exergy use in the industrial sector of Saudi Arabia.* Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy, 2003. **217**(A5): p. 481-492.
20. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Analysis of sectoral energy and exergy use of Saudi Arabia.* International Journal of Energy Research, 2004. **28**(3): p. 205-243.
21. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Energy and exergy use in residential sector of Saudi Arabia.* Energy Sources, 2004. **26**(13): p. 1239-1252.
22. Dincer, I., M.M. Hussain, and I. Al-Zaharnah, *Energy and exergy utilization in agricultural sector of Saudi Arabia.* Energy Policy, 2005. **33**(11): p. 1461-1467.
23. Chen, B., G.Q. Chen, and Z. Yang, *Exergy-based resource accounting for China.* Ecological Modelling, 2006. **196**(3-4): p. 313-328.
24. Dincer, I., *The role of exergy in energy policy making.* Energy Policy, 2002. **30**(2): p. 137-149.
25. GQ, C., *Scarcity of exergy and ecological evaluation based on embodied exergy.* Communications in Nonlinear Science and Numerical Simulation, 2006: p. 11(4):531–52.
26. Chen, G.Q. and B. Chen, *Resource analysis of the Chinese society 1980-2002 based on exergy - Part 1: Fossil fuels and energy minerals.* Energy Policy, 2007. **35**(4): p. 2038-2050.
27. Chen, B. and G.Q. Chen, *Resource analysis of the Chinese society 1980-2002 based on exergy - Part 2: Renewable energy sources and forest.* Energy Policy, 2007. **35**(4): p. 2051-2064.
28. Chen, B. and G.Q. Chen, *Resource analysis of the Chinese society 1980-2002 based on exergy - Part 3: Agricultural products.* Energy Policy, 2007. **35**(4): p. 2065-2078.
29. Chen, B. and G.Q. Chen, *Resource analysis of the Chinese society 1980-2002 based on exergy - Part 4: Fishery and rangeland.* Energy Policy, 2007. **35**(4): p. 2079-2086.

30. Chen, G.Q. and B. Chen, *Resource analysis of the Chinese society 1980-2002 based on energy - Part 5: Resource structure and intensity.* Energy Policy, 2007. **35**(4): p. 2087-2095.
31. Chen, B. and G.Q. Chen, *Modified ecological footprint accounting and analysis based on embodied exergy - a case study of the Chinese society 1981-2001.* Ecological Economics, 2007. **61**(2-3): p. 355-376.
32. Zhang, B. and G.Q. Chen, *Physical sustainability assessment for the China society: Exergy-based systems account for resources use and environmental emissions.* Renewable & Sustainable Energy Reviews, 2010. **14**(6): p. 1527-1545.
33. Korhonen, P.J. and M. Luptacik, *Eco-efficiency analysis of power plants: An extension of data envelopment analysis.* European Journal of Operational Research, 2004. **154**(2): p. 437-446.
34. Chung, Y.H., R. Färe, and S. Grosskopf, *Productivity and undesirable outputs: A directional distance function approach.* Journal of Environmental Management, 1997. **51**(3): p. 229-240.
35. Watanabe, M. and K. Tanaka, *Efficiency analysis of Chinese industry: A directional distance function approach.* Energy Policy, 2007. **35**(12): p. 6323-6331.
36. Zhou, P., B.W. Ang, and K.L. Poh, *Measuring environmental performance under different environmental DEA technologies.* Energy Economics, 2008. **30**(1): p. 1-14.
37. Seiford, L.M. and J. Zhu, *Modeling undesirable factors in efficiency evaluation.* European Journal of Operational Research, 2002. **142**(1): p. 16-20.
38. Yeh, T.-l., T.-y. Chen, and P.-y. Lai, *A comparative study of energy utilization efficiency between Taiwan and China.* Energy Policy, 2010. **38**(5): p. 2386-2394.
39. Sueyoshi, T., M. Goto, and T. Ueno, *Performance analysis of US coal-fired power plants by measuring three DEA efficiencies.* Energy Policy, 2010. **38**(4): p. 1675-1688.
40. CNMY, *China nonferrous metal yearbook.* Beijing: China Statistical Publishing House, 2011.
41. Szargut, J., Morris, D.R, *Calculation of the standard chemical exergy of some elements and their compounds, based upon seawater as the datum level substance.* Bull. Pol. Acad. Sci. Technol, 1985: p. 33 (5–6), 292–305.
42. Wall, *Exergy-a useful concept.* Thesis. Go¨teborg, Sweden: Chalmers University of Technology, 1986.
43. Ayres, R.U., L.W. Ayres, and K. Martinas, *Exergy, waste accounting, and life-cycle analysis.* Energy, 1998. **23**(5): p. 355-363.
44. Morris, D.R. and J. Szargut, *STANDARD CHEMICAL EXERGY OF SOME ELEMENTS AND COMPOUNDS ON THE PLANET EARTH.* Energy, 1986. **11**(8): p. 733-755.
45. Finnveden, G. and P. Ostlund, *Exergies of natural resources in life-cycle assessment and other applications.* Energy, 1997. **22**(9): p. 923-931.
46. Dai, J., B. Fath, and B. Chen, *Constructing a network of the social-economic consumption system of China using extended exergy analysis.* Renewable & Sustainable Energy Reviews, 2012. **16**(7): p. 4796-4808.
47. Kotas, T.J., *The Exergy Method of Thermal Plant Analysis.* Butterworths, London, 1985.
48. Zhou, P. and B.W. Ang, *Linear programming models for measuring economy-wide energy efficiency performance.* Energy Policy, 2008. **36**(8): p. 2911-2916.

49 Jørgensen SE, Mejer H. *Ecological buffer capacity*. Eco Model1977;3(1):39–45.

50 Jørgensen SE. *The shifts in species composition and ecological modeling in hydrobiology*. Hydrobiologia1992;239:115–29.

51 Jørgensen SE. *Ecological modeling by Ecological modelling*. Eco Model 1997;100:5–10.

52 Fath BD, Patten BC, Choi JS. *Complementarity of ecological goal functions*. J Theor Biol2001;208:493–506.

53 Fath BD. *Network analysis applied to large-scale cyber-ecosystems*. Eco Model 2004;171:329–37.

54 Sciubba E. *Wate did Lokta really say? A critical reassessment of the maximum power principle* Eco Model 2011; 222(8):1347–53.

55. Shao, C.F., et al., *Performance analysis of CO2 emissions and energy efficiency of metal industries in China.* Journal of Environmental Management, 2014. **134**: p. 30-38.

56. Wang, Y.J. and W. Chandler, *The Chinese nonferrous metals industry-energy use and CO_2 emissions.* Energy Policy, 2010. **38**(11): p. 6475-6484.