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Extended exergy accounting for smelting and pressing of metals industry in China

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ABSTRACT

Rapid expansion, relative shortage resources supply and environmental impact threat the sustainable development of the smelting and pressing of metals sector. Fluxes of energy, materials, environmental remediation expenses, labor, and capital were quantified by Joules based on the second-law thermodynamics during years 1992–2015. The accounting method that quantifies the component of the extended exergy fluxes and the proportion in the total inputs was used to analyze this energy-intensive industry. Net per-capita exergy resource input and labor production efficiency are described the conversion of natural resource exergy to economic output and labor efficiency. The results showed the following: (1) the smelting and pressing of metals sector expands rapidly; the ferrous metals industry accounts the large part of the overall metals industry and the nonferrous metals industry grows faster than the ferrous metals industry. Natural resource exergy, especially energy exergy, dominates the investments of the metals industry. (2) Capital exergy and labor exergy decrease in the smelting and pressing of metals industry, while they increase in the nonferrous metals industry and decrease in the ferrous metals industry. Environmental exergy declines in both the nonferrous metals and ferrous metals industries. (3) The comparison of the nonferrous metals and ferrous metals industries with China as a whole, conducted by applying the two indicators for efficiency, shows that the two industries are exceeding the whole country in efficiency and have made great progress. In addition, the extended exergy analysis of smelting and pressing of metals industry is helpful in the identification of resource consumption and environmental cost in sustainable development view.

1. Introduction

The energy consumption of Chinese smelting and pressing of metals sector increased from 142.19 million tons of SCE (standard coal equivalency) (13% of total Chinese energy consumption) in 1992 to 846.53 million tons of SCE (20%) (NBSC, 1994–2017) expanding 4.95 times. Metals production increased from 229.3 million tons to 2705.6 million tons, enhancing 10.8 times (CSY, 1993–2016; YNMC, 1993–2016) with lots of industrial "three wastes" released into environment during those years. Since the continuous investments in infrastructure and the promotion of the consumption structure, the Chinese smelting and pressing of metals industry will confront resource and environmental problems in the future. It is necessary that we choose adequate tools to assess the extent of the resource shortages as well as estimate the ecological impact for both the scientific and broader communities for the further sustainable development of this sector.

Different from traditional research base on money (Schiavo et al., 2010; Wang and Feng, 2018) or quantity of materials (Zhang et al., 2019b) which not reflecting the energetic explanations of the resources, the "exergy" is able to unify kinds of substance and energy into joules according to how far the studied system is from thermodynamic equilibrium (Wall, 1977, 1987). Exergy accounting is a method to assess the usefulness of resources from physical point considering the second of thermodynamics law.

Wall (1987) employed exergy to calculate resource depletion in Sweden. Moreover, exergy has been used to judge the availability of different resources and the environmental effects of those resources (Chen and Qi, 2007; Jørgensen et al., 1995; Szargut, 2002; Valero et al., 2010; Zhang and Chen, 2010). In the next years, different nations and industries were discussed from an exergy view.

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(1) Wall analyzed Sweden (Wall, 1987), Japan (Wall, 1990) and Italy (Wall et al., 1994); with the help of their colleagues, Brockway, Chen and Li studied China (Brockway et al., 2015; Chen and Chen, 2006, 2007, 2009; Chen et al., 2006; Li et al., 2019); Ayres and his workmates researched the United States (Ayres et al., 2003; Warr and Ayres, 2010); then Norway (Ertesvåg and Mielnik, 2000), the UK (Gasparatos et al., 2009), Spain (Valero et al., 2014), and Colombia (Gabriel Carmona et al., 2015) also were investigated. Subsequently, parts of Denmark (Nielsen and Jørgensen, 2015) and Canada (Bligh and Ismet Ugursal, 2012), Latin America (Palacios et al., 2018) were studied through the exergy analysis.

(2) At the industry level, Dincer with his colleagues analyzed the exergy performance of the transportation and agriculture industries, among others, in Saudi Arabia (Dincer et al., 2003, 2004a, b, c, d, 2005). Some papers investigated the exergy efficiency of industries such as transportation systems (Dai et al., 2014; Ji and Chen, 2006; Ji et al., 2009) and agriculture (Chen et al., 2009; Zhang et al., 2019a) in China; the residential-commercial sector (Utlu and Hepbasli, 2005) and transportation (Ediger and Çamdalı, 2007; Seckin et al., 2013; Utlu and Hepbasli, 2006) in Turkey; the utility and commercial sectors (Saidur et al., 2007) and agriculture (Ahamed et al., 2011) in Malaysia; energy-intensive industries in Denmark (Bühler et al., 2016); residential and industrial sectors in Greece (Koroneos et al., 2011); and transportation in Jordan (Jaber et al., 2008).

(3) This system of research has also expanded to global levels and exergy efficiency has been compared across countries (Ertesvåg, 2001; Perryman and Schramski, 2015; Warr et al., 2010).

All these studies have illustrated the utility of exergy in solving problems related to the environment in the progression of societal development. These researches studied the exergy conversion for different countries and sectors, uncovering the potential production capacity of societies from the thermodynamic view and making suggestions to improve exergy efficiency. In short, the aim of these exergy accounting papers is to make sure the priorities of developing sectors and to build more reasonable pattern. Exergy analyses realize the aim by calculating the exergy depletion of resources and by suggesting methods to increase the conversion efficiency in thermodynamic view from spatial and temporal scale.

We are able to classify these studies into three main categories, such as Reistad's classification that focuses on the exergy depletion of energy carriers only: OECD/non-OECD (Nakicenovic et al., 1996), Saudi Arabia (Dincer et al., 2005), and USA (GM, 1975); On the basis of Reistad's research, Wall supplements our knowledge of the exergy content of materials including different kinds of metals and minerals for Japan (Wall, 1990), China (Chen et al., 2006), Italy (Wall et al., 1994), and Norway (Ertesvåg and Mielnik, 2000); Sciubba is in consistent with this method and adds currency and labor force into the exergy accounting: China (Chen and Chen, 2009; Dai et al., 2012; Yang and Chen, 2014), Norway (Ertesvåg, 2005), Turkey (Seckin et al., 2012) and Italy (Milia and Sciubba, 2006).

Extended exergy accounting (EEA) is a tool measuring the total exergy resource equivalent consumption (Sciubba, 2003; Sciubba et al., 2008). Being an extension of exergy analysis, it includes labor and capital costs in terms of Joules. EEA had been revised and published in theoretical research and applications issue (Ptasinski et al., 2006). The intrinsic measurement of extended exergy accounting is the amount of primary exergy expressed in Joules that being cumulatively used over the total process. EEA includes five parts in this paper: (1) the exergy equivalent of energy carrier (2) the exergy equivalent of material, (3,4) the exergy equivalent of labor and capital, and (5) environmental remediation costs. It is easier and more meaningful to compare different commodities and production processes by EEA within Joules from the second thermodynamics law (Sciubba, 2011). Furthermore, this kind of measure of natural-social-environmental impacts may be considered as the "ecological cost'' of different resources including material, energy, human labor, capital, and environmental costs related to one system. Therefore, EEA bridges the gap about the 'production of value' which separates economics and biophysical-based approaches (Chen and Chen, 2009).

Being the largest developing country with the huge population and improving urbanization and industrialization, Chinese government has to face the fact that the smelting and pressing of metals sector continues to play a fundamental role. The energy-intensive industry has undergone dramatic change in the background of rapid growth of China. Some scholars have performed a series of studies on exergy accounting of the Chinese society covering the smelting and pressing of metals sector (Chen and Chen, 2006, 2009; Chen et al., 2006; Chen and Qi, 2007). Nevertheless, it remains to be systematically revealed over decade years.

To fill this gap, an overall extended exergy accounting for the smelting and pressing of metals sector in China from 1992 to 2015 will be presented to determine the role of materials and energy consumption, social and economic input, and the environmental impact in order to increase the resource efficiency in conversion processes and to promote sustainable development. As the smelting and pressing of metals sector consists of nonferrous metals and ferrous metals industries, there may be differences between the subsectors. A comparison between the ferrous metals and nonferrous metals industries is offered based on extended exergetic metrics. The paper is organized as follows: the introduction in the first section, the second section presents the methodology and data, and the third section is our results of Chinese smelting and pressing of metals industry. Section four introduces the discussion and our work in next stage.

2. Methodology and data

2.1. Methodology

Measuring the materials and energy resources, the labor, capital inputs and environmental remediation costs all expressed in energetic units (joules) is the particular characteristic of EEA. Based on the previous studies (Chen et al., 2014; Dai et al., 2012, 2014), the calculation is formulated as follows:

$$EE = CEC + E_K + E_L + E_R \tag{1}$$

where CEC represents the cumulative exergy consumption of energy and material flows, E_K is the exergy equivalent of capital flows, E_L is the exergy equivalent of human labor, and E_R is the environmental impact.

In Eq. (1), CEC expresses the cumulative exergy consumption (including both primary resources consumption and material input). From a consumption viewpoint, CEC consists of two portions: E_E meaning "energetic" natural resources input (coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, electricity), and E_M standing kinds of materials which are quantified by their respective transformation factors (listed in Table 1) (Chen and Chen, 2006; Chen and Qi, 2007; Ertesvåg and Mielnik, 2000).

2.1.1. Natural resource exergy depletion in the industry

In Eq. (1), CEC is the total net input of resources including energy carriers (coal, coke, oil, petroleum productions, natural gas, and electricity) and materials (iron ore, copper ore, lead ore, zinc ore, lead ore, tin ore, bauxite and alumina) measured in Joules. Exergy factors of energy were obtained from (Kotas, 1985). Based on previous research (Chen and Qi, 2007; Zhang et al., 2018), copper, aluminum, lead, zinc, and tin were chosen to represent the overall nonferrous metals industry though it included the copper, aluminum, lead, zinc, nickel, tin, antimony, mercury, magnesium, titanium, tungsten, and molybdenum, etc. In the same method, pig iron, crude steel, ferroalloy and finished steel were chosen to indicate the overall ferrous metals industry as it comprised iron, chromium and manganese.

Table 1
The value of the raw exergy of each component.

Item	Value	Unit
Coal	22.16	PJ/Mt
Coke	29.86	PJ/Mt
Natural gas	4.13	PJ/10^8m^3
Electricity	0.36	PJ/10^8 kWh
Oil/petroleum product	44.32	PJ/Mt
Iron ore	0.42	PJ/Mt
Iron concentrate	0.84	PJ/Mt
Copper ore	0.026	PJ/Mt
Copper concentrate	1.1	PJ/Mt
Lead ore	0.021	PJ/Mt
Zinc ore	0.046	PJ/Mt
Tin ore	0.0002	PJ/Mt
Bauxite	0.3	PJ/Mt
Alumina	2	PJ/Mt
Iron/steel	6.8	PJ/Mt
Copper	2.1	PJ/Mt
Aluminum	32.9	PJ/Mt
Lead	13	PJ/Mt
Zinc	5.4	PJ/Mt
Tin	3.4	PJ/Mt

2.1.2. Labor and capital exergy calculation

Based on the previous studies (Chen et al., 2014; Dai et al., 2012, 2014; Sciubba, 2011), E_L and E_K value are respectively calculated as follows:

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

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

The α and β describe the process and the relationship with different parameters, and E_{in} represents the exergy influx to the society.

The calculation expressions of α and β were summarized as:

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

$$\beta = \frac{M2}{s \times N_w \times W} \tag{5}$$

We got E_L and E_K

$$E_L f \times e_{surv} \times N_h \tag{6}$$

$$E_K \frac{M2 \times f \times e_{surv} \times N_h}{s \times N_w \times W} \tag{7}$$

where f represents a factor related to the living standard of one social system ($f = HDI/HDI_0$; HDI is the Human Development Index published by the United Nations every year); e_{surv} is the necessary exergy consumption for one person, which is to say 10^7 J/(person × day); N_h is the population in China; M2 represents the money stock in one year (In China, a large part of M2 is deposits, which is different from monetary circulation in Western banking systems, and checks are not cashed freely, as in Western countries. Therefore, we had to take the GDP as the monetary circulation indicator.); s is the average wage one year in China; N_w is the number of workers one year in China; and W is the average workload one year in China.

Based on previous studies (Chen et al., 2014; Chen and Chen, 2009), 2000 h was chosen as the yearly workload. Similarly, the percentage of the working population in the industry was used to allocate the available work hours. After we calculated the E_K in China, then we got the E_L and E_K of smelting and pressing of metals industry according the average wage and the number of workers in the energy intensive industry (Chen et al., 2014).

2.1.3. Exergy of environmental remediation calculation

In EEA method, the exact amounts of different emissions have to be clear with the chemical composition in the total system. For some data are partly absent, we selected an effective way that been used in previous research (Chen et al., 2014): (1) compute the rate of current investment in environmental management, comprising wastewater, waste gas and solid waste, and (2) transform the monetary value into equivalent exergy with the EEA.

2.1.4. Equivalent exergy indicators of labor and capital

The net input of resource exergy per capita (IEPC) and labor production efficiency (LPE) are indexes that capture the capability from materials to currency and the efficiency of labor as defined by the EEA approach (Chen et al., 2014). The mathematical representation is expressed as:

$$IEPC(J/USD) = \frac{CEC}{E_cO} \tag{8}$$

$$LPE(J/wh) = \frac{CEC}{Wh} \tag{9}$$

where EcO is the financial output of exergy utility; Wh is the work hour invested in the process of exergy consumption.

2.2. Data

In this study, the data of materials consumption were collected from China Steel Yearbook (CSY, 1993–2016) and the Yearbook of Nonferrous Metals Industry of China (YNMC, 1993–2016). Data of energy carriers depletion, population, average salary in China, the number of workers and GDP extracted from the China Statistical Yearbook (NBSC, 1994–2017). The employed population and the average salary in the smelting and pressing of metals sector from China Labor Statistical Yearbook (CLSY, 1993–2016). The pollution remediation and the data of wastewater, waste gas and solid waste emissions were available in the Environmental Statistics Yearbook (CEY, 1993–2016).

3. Results

The variation of extended exergy in smelting and pressing of metals industry from 1992 to 2015 is shown in Fig. 1.

3.1. Structural transformation of extended exergy in the industry

Fig. 1 display the changes in the five extended exergy constituents (material equivalent, energy equivalent, capital-equivalent, labor-equivalent and environmental remediation equivalent) in the smelting and pressing of metals industry in China from 1992 to 2015. The overall extended exergy has changed greatly during the 24 years considered. The growth rate of the sector decreased in four years only (1996, 1997, 1998 and 2015), and it reached 20.4% in 2003. Firstly, material exergy and energy exergy investments in this industry improved from 125 PJ and 4594 PJ respectively in 1992–2134 PJ and 26131 PJ, respectively, in 2015, increasing 16.1-fold and 4.7-fold. Secondly, the values of labor exergy, capital exergy and environmental exergy decreased from 1600 PJ, 1.21 PJ and 16.1 PJ, respectively, in 1992 to 1138 PJ, 0.78 PJ and 3.37 PJ, respectively, in 2015, accounting for 71.1%, 64.8% and 21.1% of their values in 1992. Due to its large population, China contains several sectors with labor-intensive productions. In the smelting and pressing of metals industry, the extended exergy accounting of labor is decreasing, as well as the exergy of capital and environmental cost.

In this paper, extended exergy declines with small fluctuations in the labor and capital components and a decrease with violent fluctuations in the environmental remediation component are characteristics of the trend in the industrial structure over these 24 years, as is the conversion to intensive economic growth from extensive growth, and requires fewer

Fig. 1. Inter-annual variation of extended exergy in Smelting and Pressing of Metals sector.

human beings. With the progression of Chinese society, its productivity has increased. From 1992 to 2015, the sector has developed along urbanization and industrialization as well as upgrading of the consumption structure in China with expanded scale. Demand for energy of the sector remains at a high level. The sector is the basic industry of China with features of high energy consumption and pollution. Facing the serious situations, the Chinese government has made decision to reduce emissions and energy conservation. The capital and labor became less important as before, and technical progress began to be the key factor.

In conclusion, natural resources including the energy and material contributions to the smelting and pressing of the metals industry development have played an important role. At the same time, more attention should be focused on materials investments that heavily depend on those from abroad. The proportion of materials imported accounting to the whole materials depletion was 18.5% in 1992, while it increased to 43.9% in 2015, an increase of approximately 237%.

As shown in Fig. 2(a), in the smelting and pressing of metals sector, although the nonferrous metals industry grew faster than the ferrous metals industry, its scale was much smaller than that of the ferrous metals industry. For example, the growth rates for nonferrous metals and ferrous metals were 32.6% and 7.3%, respectively, in 2010, while the overall growth rate for metals was just 10.3%. Therefore, the whole sector was dominated by the ferrous metals industry.

In the smelting and pressing of metals sector, coal, coke and electricity were the main sources of energy exergy depletion, accounting for 93.76% in 1992 and 98.96% in 2015, as shown in Fig. 3. The proportion of coal declined steadily, while the proportion of electricity and coke increased constantly from 1992 to 2015. Since the coke being made of coal and thermal power accounting for a large proportion of the power output in China, coal consumption is still high in the metals industry.

3.2. Inter-annual variation of extended exergy in the sector and the two industries

The variation of extended exergy in the sector investments was exploited from the energy, material, capital, labor, environmental remediation and yield respectively in this paper.

3.2.1. Energy exergy

In the smelting and pressing of nonferrous metals and ferrous metals industries, energy exergy input was the dominant exergy input, with inputs increasing in both industries and with percentages varying from 58.27% to 90.53% and 74.43%–88.42% from 1992 to 2015, respectively. Similarly, in the overall metals sector, the proportion of energy exergy to total exergy input increased from 72.5% to 88.86%, as shown in Fig. 4.

The E_E in the ferrous metals industry climbed to 20548 PJ in 2015 from 4155 PJ in 1992 with some decline in 1996, 1998, 1999, 2000 and 2015. In contrast to the ferrous metals industry, the E_E in the nonferrous metals industry increased from 439.31 PJ to 5582.28 PJ with some radical changes, especially from 2002 to 2015. The quantity of E_E in the ferrous metals dominated the overall E_E of the metals industry, so the growth rate of energy exergy in metals was more similar to the growth rate of energy exergy in ferrous metals shown in Fig. 2(b).

3.2.2. Material exergy

The E_M in the ferrous metals industry, including iron ore and scrap steel, climbed to 1946.97 PJ in 2015 from 119 PJ in 1992 with a slight decline in 1996, 1998, 2012 and 2015 shown in Fig. 2(c). In contrast to the ferrous metals industry, the E_M in the nonferrous metals industry, including copper ore, bauxite, alumina, lead ore, zinc ore, tin ore and scraps, increased from 5.64 PJ to 187.3 PJ with radical changes over the same period. The growth rate of material exergy in ferrous metals was relatively milder than that of nonferrous metals. For the quantity of E_M in the ferrous metals industry being so much greater than that in the nonferrous metals industry, the growth rate of material exergy in the overall metals industry followed the growth rate of material exergy in ferrous metals.

As shown in Fig. 5, the three components of material exergy—domestic, imported and scrap—increased from 90.3 PJ, 23.1 PJ and 11.6 PJ in 1992 to 604.9 PJ, 936.7 PJ and 592.7 PJ in 2015. The proportion of each component changed from 72.2%, 18.5% and 9.3% in 1992 to 28.3%, 43.9% and 27.8% in 2015. For the 198.6 PJ scrap-steel inputs in 2000, the growth rate climbed to 99.4%, and it declined slightly in 1996, 1998, 2012 and 2015 only. It is worth noting that dependence on imported material exergy is climbing in the smelting and pressing of metals sector.

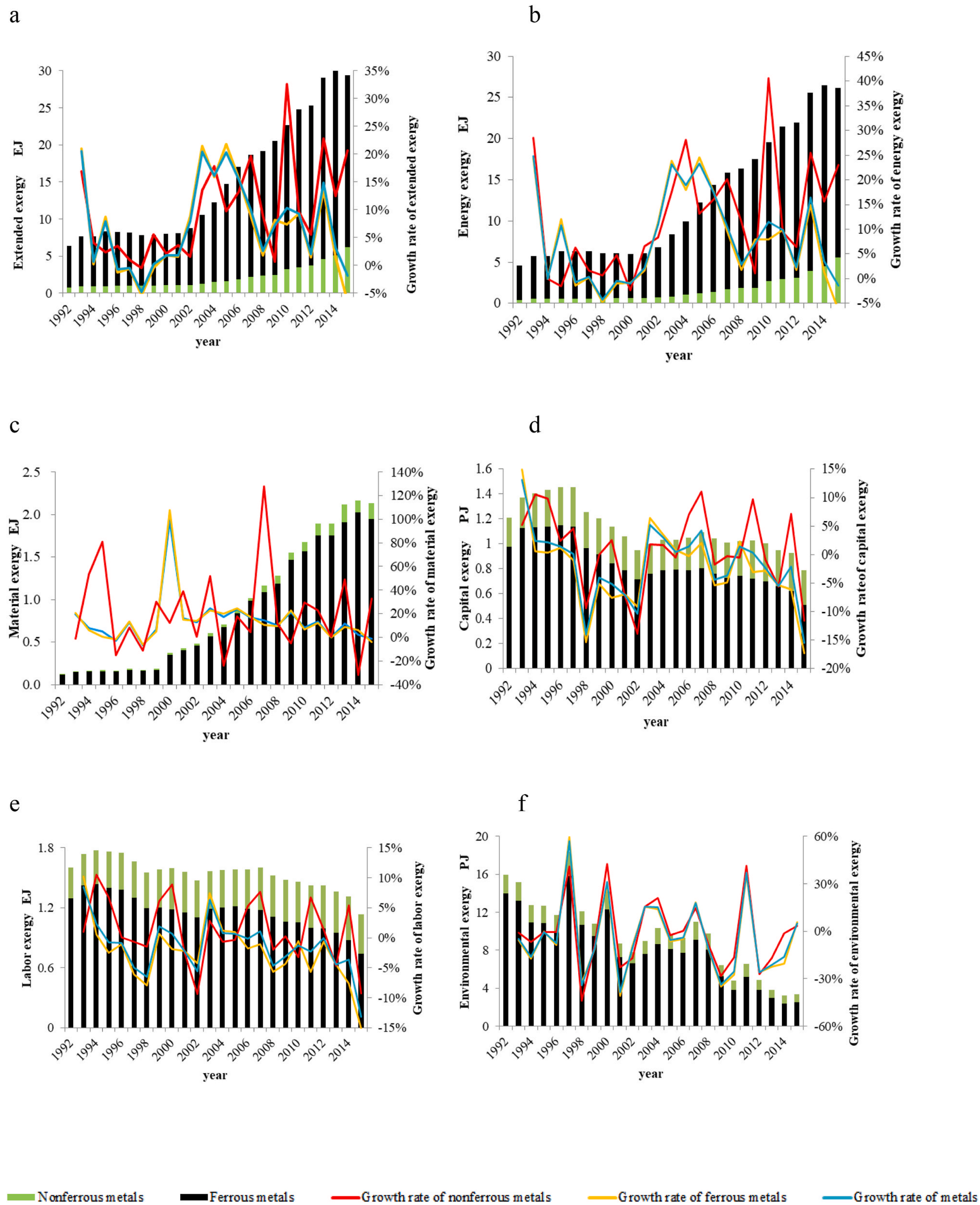

Fig. 2. (a) Extended exergy investment in ferrous and nonferrous metals industry; (b) Energy exergy investment in ferrous metals and nonferrous metals industry; (c) Material exergy investment in ferrous metals and nonferrous metals industry; (d) Capital exergy in ferrous metals and nonferrous metals industry; (e) Labor exergy in ferrous metals and nonferrous metals industry; (f) Environmental exergy in ferrous metals and nonferrous metals industry.

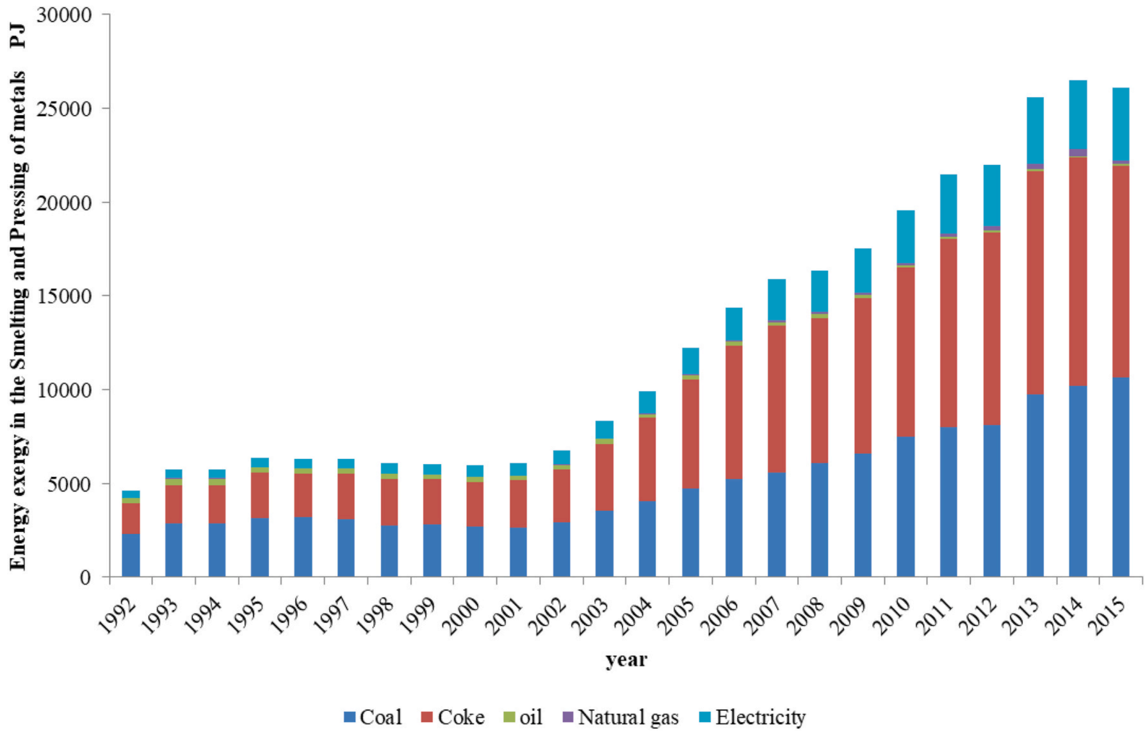

Fig. 3. Energy exergy investments in the Smelting and Pressing of metals sector.

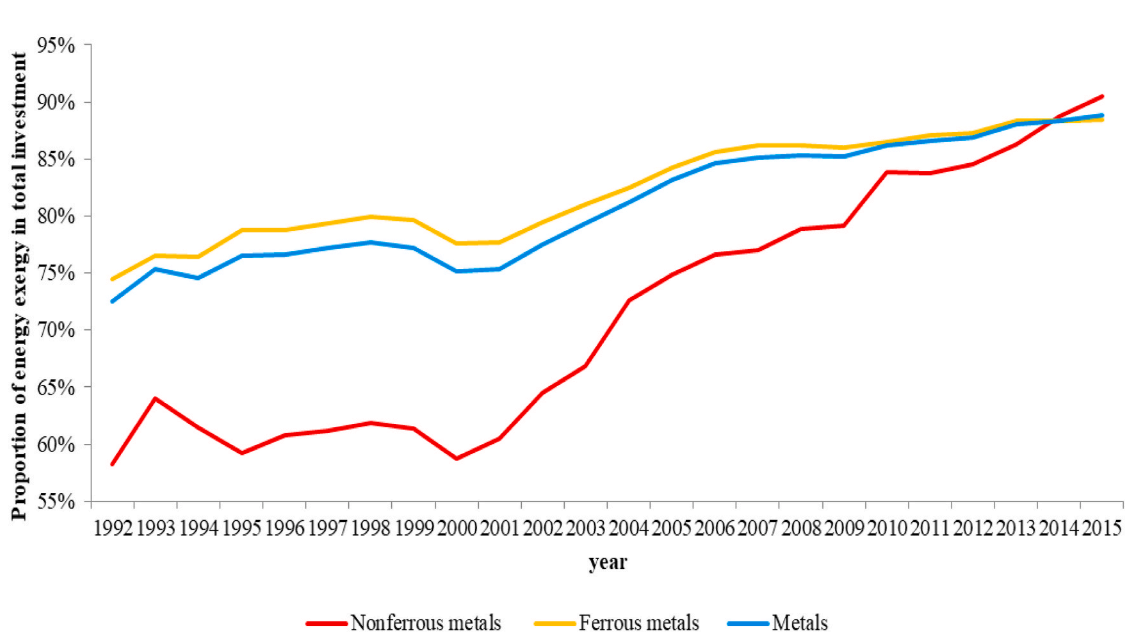

Fig. 4. Proportion of energy exergy in extended exergy investment.

3.2.3. *Capital exergy and labor exergy*

The role of E_K in the ferrous metals industry declined to 52.28% from 0.979 PJ in 1992 to 0.512 PJ in 2015, with fluctuations as shown in Fig. 2(d). The E_K in the nonferrous metals industry increased to 117.40%, from 0.232 PJ to 0.273 PJ in the same period. Similar to that of the E_K, the role of E_L in the ferrous metals industry declined to 52.07% from 1293 PJ in 1992 to 742 PJ in 2015 with fluctuations, and the E_L in the nonferrous metals industry increased to 127.7%, from 307 PJ to 395 PJ shown in Fig. 2(e). The E_K and E_L in the overall metals industry declined to 64.77% and 65.56%, respectively, from 1992 to 2015.

Meanwhile, the percentages of E_K and E_L both declined, which meant that the use of capital and labor were not as important as before, and technical progress was the key factor and Feng et al. (2019) supported this view also.

3.2.4. *Environmental exergy*

The role of E_R in the ferrous metals industry declined to 17.8% from 13.99 PJ in 1992 to 2.49 PJ in 2015 with fluctuations, and the E_R in the nonferrous metals industry declined to 44.49%, from 1.97 PJ to 0.88 PJ over the same period, as shown in Fig. 2(f). The E_R in the overall metals industry declined to 21.1% from 1992 to 2015.

The E_R of the nonferrous metals industry was 1.97 PJ, comprising

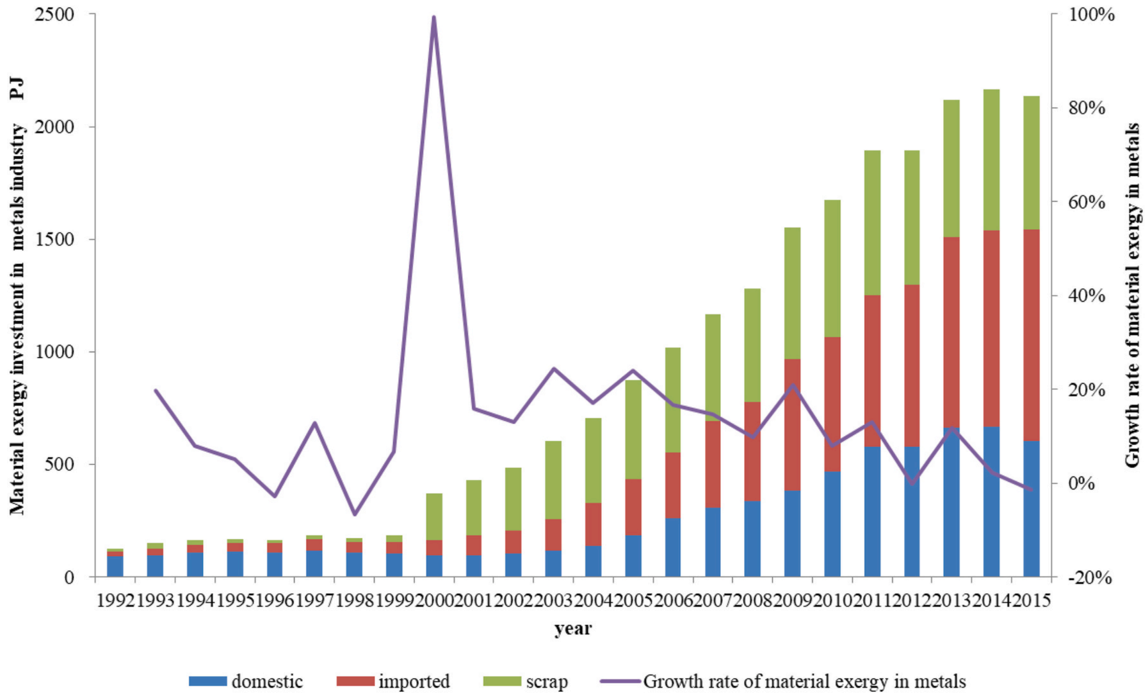

Fig. 5. Material exergy investments in metals sector.

wastewater (1.97 PJ), waste gas (22.3 GJ) and solid waste (1.26 TJ). The E_R of the ferrous metals industry was 13.9 PJ, also comprising waste water (13.9 PJ), waste gas (0.23 TJ) and solid waste (6.1 TJ) in 1992; therefore, the E_R of waste water dominated the overall E_R in both the ferrous and nonferrous metals industries. Moreover, the decline of the E_R reveals positive outcomes resulting from concerns and actions related to the environmental pollution from the smelting and pressing of metals sector. This pollution decreased due to the management of the Chinese government according to data from the statistical yearbooks. The wastewater should be paid more attention by the government.

3.2.5. *Yield of products*

In the smelting and pressing of ferrous metals industry, the main products include pig iron, crude steel, ferroalloy and finished steel, and the exergy output increased from 1539.7 PJ in 1992–18056.7 PJ in 2015, an enhancing 10.7 times over. The growth rate for output was positive, with fluctuations over the 23 years studied; the lowest growth rate was −1.62% in 2015. During this period, the proportion of pig iron in total output declined from 33.53% to 26.04%; crude steel remained almost stable, decreasing from 35.7% to 30.27%; and finished steel increased significantly from 29.56% to 42.31%.

In the smelting and pressing of nonferrous metals industry, the main products included copper, aluminum, lead, zinc and tin, and the output increased from 46.22 PJ in 1992 to 1144.76 PJ in 2015, increasing 23.77 times over. The growth rate of the output was positive with fluctuations over the 24 years studied, except in 2009, with −0.67% (the only negative rate), and the highest rate was 30.37% in 2007. During this time, the proportions of copper, lead, zinc and tin in total output declined from 2.99%, 10.29%, 8.4%, and 0.29% in 1992 to 1.46%, 5.02%, 2.88%, and 0.05% in 2015, respectively, while aluminum accounted for most of the output, and its share continuously increased from 78.02% to 90.58%.

Fig. 6(a) shows the output of the smelting and pressing of metals industry increased from 1585.93 PJ to 19201.46 PJ, an 11.1-fold increase. The output of the nonferrous metals industry was much less than that of the ferrous metals industry, to the point that the output of nonferrous metals had no influence on the growth rate of the overall metals sector. The growth rates of the two industries had different trends in eight years (1994, 1995, 2005, 2006, 2007, 2009, 2010, and 2014) and the same trend for fourteen years (from 1996 to 2004, 2008, from 2011 to 2013 and 2015).

3.3. *Comparison between exergy and extended exergy by the nonferrous metals and ferrous metals industry*

Fig. 6(b) reveals the distinction between exergy and extended exergy in the two industries. The industries have mainly provided products to society by relying on natural resources. The ratio of extended exergy to exergy in ferrous metals decreased from 1.31 in 1992 to 1.03 in 2015, and it declined from 1.69 to 1.07 in nonferrous metals at the same time, showing that the nonferrous metals industry demands more capital and labor than the ferrous metals industry. The ratio declined to 79% and 63% from 1992 to 2015 in the ferrous metals and nonferrous metals industries, respectively, indicating that the nonferrous metals industry had greater progress than the ferrous metals industry.

In Fig. 6(c), USD measures the value of industry output in the two industries. The meaning of Exergy/USD may be understood as the quantity of exergy consumption from one unit of economic output. In other words, a larger numerical value implies lower efficiency. As Chen selected GDP in USD as overall output (Chen et al., 2014), the value-added of the industry corresponding to GDP was selected as the industry output. The results show that the conversion efficiency of the nonferrous metals industry was always higher than that of the ferrous metals industry, with 404 MJ/USD and 172 MJ/USD in 1992 and 129 MJ/USD and 30.2 MJ/USD in 2007. The conversion efficiency of the two industries followed the same trend: they first increased, then declined over the next few years, reaching their lowest point in 1999, and then increased again.

Since some data on the value-added of industry in the nonferrous metals and ferrous metals industry from 1992 to 2015 are unavailable, we may try to employ the difference between revenue and cost as our output measure from 1992 to 2015 (NBSC, 1994–2017) to check the trend of the exergy consumption for unit of output shown in Fig. 6(d). The results show the same trends as for the exergy consumption for one unit of output value as measured by the value-added of the industries. The nonferrous metals industry was more efficient than the ferrous

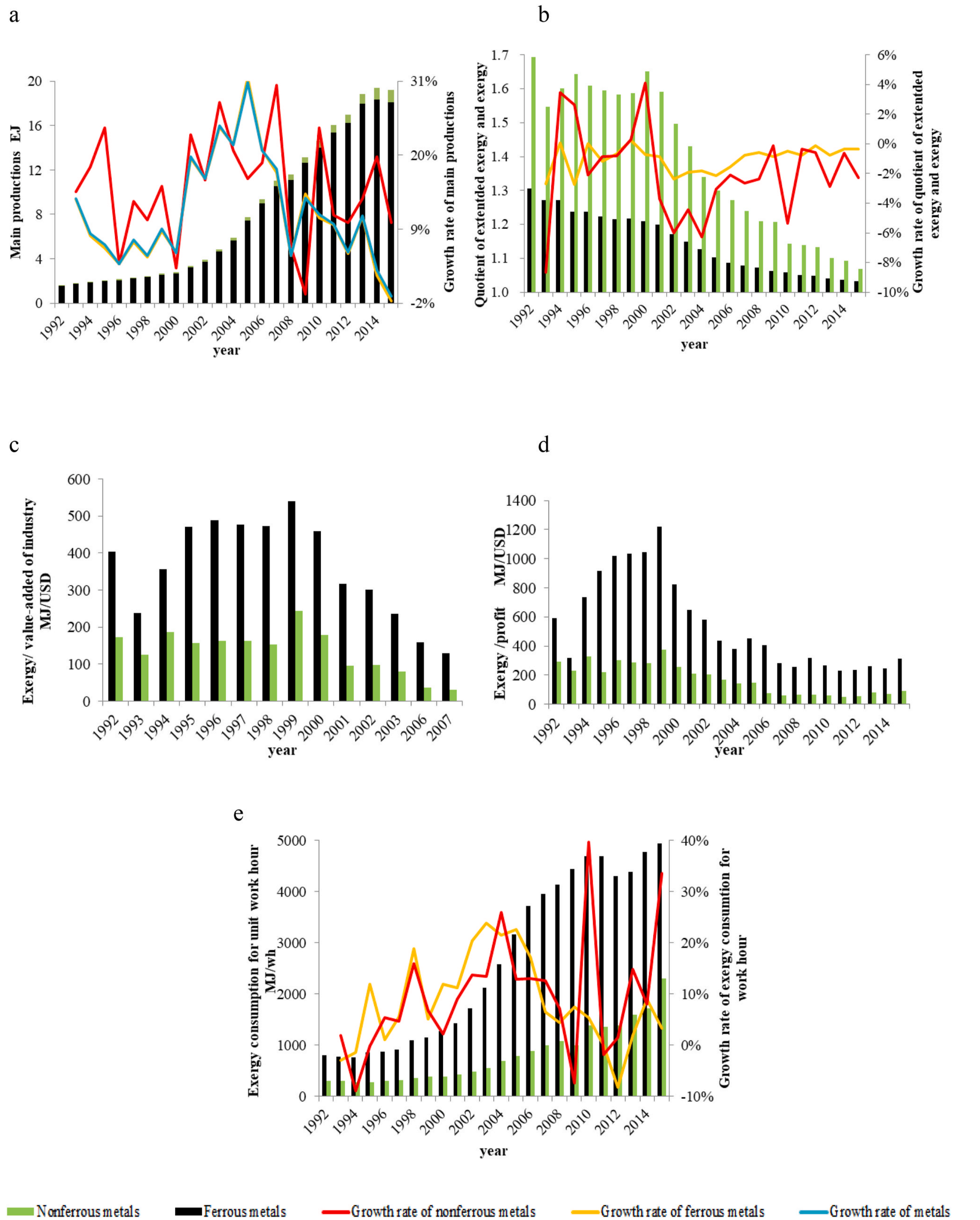

Fig. 6. (a) Contrast the products in ferrous and nonferrous metals industry; (b) Quotient of Extended exergy and exergy in ferrous and nonferrous metals industry; (c) Exergy consumption for unit output value in value-added of industry; (d) Exergy consumption for unit output value in profit; (e) Exergy depletion for unit work hour in ferrous and nonferrous metals industry.

metals industry from two different viewpoints.

3.4. Equivalent exergies of labor and capital in the smelting and pressing of metals industry

By EEA method, we calculated the quantity of natural resource exergy and labor input in the smelting and pressing of metals industry during 1992–2015 shown in Fig. 6(e). Labor production efficiency grew from 696 MJ/wh (wh is the abbreviation for work-hours) in 1992–3702 MJ/wh in 2015, increasing 4.3 times over. During the 23 years studied, efficiency always increased except in 1993, 1994, 2011 and 2012.

Contrasting the two industries, the exergy of labor in the ferrous metals industry is much higher than that in the nonferrous metals industry. In the ferrous metals industry, exergy per work-hour climbed from 803 MJ/wh in 1992–4777 MJ/wh in 2015, while in the nonferrous metals industry, it increased from 305 MJ/wh to 1720 MJ/wh, augmenting 5.9 and 5.6 times over, respectively. The growth rate of exergy consumption per work hour in the nonferrous metals industry was larger than that in the ferrous metals industry in the last few years.

As shown in Table 2, the labor production efficiency in China was 51.9 MJ/wh and 76.3 MJ/wh in 2000 and 2007 (Chen et al., 2014), while labor production efficiency in the ferrous metals industry and nonferrous metals industry increased from 1282.48 MJ/wh and 394.77 MJ/wh to 3955.65 MJ/wh and 1004.08 MJ/wh, respectively. It increased 308% and 254% from 2000 to 2007 in the ferrous metals industry and nonferrous metals industry, respectively, as compared with the whole country expanded to 147%, showing that the labor production efficiency of these energy-intensive industries exceeded that of the whole country.

The ratio of the value of economic output and exergy depletion is used as an index to assess the connection between exergy resources and the economy. This index expresses the capability transform materials into currency, meaning the efficiency of resource consumption. The value of this index was 41.8 MJ/USD in 2000 and decreased to 22.8 MJ/USD in 2007 in China (Chen et al., 2014) while its value in the ferrous metals industry and nonferrous metals industry declined from 458.79 MJ/USD and 178.42 MJ/USD to 129.1 MJ/USD and 30.18 MJ/USD, respectively. Great improvements took place in the ferrous metals and nonferrous metals industries. The index value decreased to 28% and 17% from 2000 to 2007, in comparison with the index value for the whole country declining to 55%, indicating great progress in improving the efficiency with which materials are transformed into economically valuable output in the energy-intensive industries, which exceeded that of the country as a whole. In the future, China will continue to carry out the urbanization and industrialization as well as upgrading of the consumption structure. Therefore, the demand of metals will keep on growing. Owing the large population and the relatively resources shortage, only the increasing of labor production efficiency and resource consumption efficiency can meet the demand of metals of China.

Table 2
Comparison of the Smelting and Pressing of Ferrous metals, Nonferrous metals industry and China on Exergy/wh and Exergy/USD.

year	Exergy/wh (MJ/wh)			Exergy/USD (MJ/USD)		
	labor production efficiency			net input of resource exergy per capita		
	China	Ferrous metals	Nonferrous metals	China	Ferrous metals	Nonferrous metals
2000	51.90	1282.48	394.77	41.8	458.79	178.42
2001	53.90	1426.12	430.55	40.2	316.63	95.85
2002	57.00	1716.98	489.38	39.2	300.21	97.77
2003	62.00	2126.09	555.30	38.1	236.80	80.60
2004	67.40	2584.51	699.00	35.6		
2005	71.50	3170.43	789.42	32.4		
2006	74.50	3716.09	891.86	28.6	158.77	36.06
2007	76.30	3955.65	1004.08	22.8	129.10	30.18

4. Discussion

4.1. Conclusions

Through the use of extended exergy accounting, this paper investigates natural resource consumption in the smelting and pressing of metals industry from 1992 to 2015 in China. EEA provides a scientific method for measuring energy, material, labor, capital and environmental remediation costs, expressed in joules. It measures the exergy depletion and efficiency of an energy-intensive sector from the second law of thermodynamics in order to promote the sustainable development of the sector.

Though the growth rate of nonferrous metals was faster than the ferrous metals industry, the quantity of exergy input in ferrous metals industry was so much greater than that of the nonferrous metals industry. Therefore, the overall metals industry followed the growth rate of in ferrous metals.

The extended exergy of resource consumption in the smelting and pressing of metals sector in China increased at a fast rate. The enhancing labor production efficiency and declining net input of resource exergy per capita indicates that the sector made great progress. In 1992, as to 100 units of metals yield, there were about 400 units of resource input including 0.076 units exergy of capital, 100.9 units exergy of labor, 7.9 units of exergy of materials, 289.7 units exergy of energy, 1 unit exergy of environmental cost. While in 2015, as to 100 units of metals yield, there were about 153 units of resource input including 0.004 units exergy of capital, 5.9 units exergy of labor, 1.1 units of exergy of materials, 136.1 units exergy of energy, 0.018 units exergy of environmental cost. The ratio of input and output declined to 38.3%, indicating the great progresses of the energy intensive sector.

In the sector, energy input dominated the overall input, and increased continuously from 72.5% to 88.86%. Especially, energy consumption varied with percentages from 58.27% to 90.53% in the nonferrous metals industry. The materials input increased 16.12 times in metals sector. So much resources depletion had pressure on the Chinese society and environment. On one hand, for the largest population in global, China faces lower per capita resource still. On the other hand, large resources consumption produce “three wastes” especially the waste water accounting large part of the environmental impact in the smelting and pressing of metals sector. For the smelting and pressing of metals sector consuming so many resources, it is hard to rely only on domestic resource extraction; thus, more attention should be concentrated on resources from abroad.

Since this sector absorbs many workers, if some manufacturing is moved to other countries, some workers will become unemployed. In particular, the nonferrous metals industry has been growing faster than the ferrous metals industry, producing more emissions and using more labor to produce one unit output. For the Chinese smelting and pressing of the metals industry to become sustainable, it is necessary to either restrict the scale of this sector in Chinese territories or move some of its production capacity to other countries with high exergy ores.

The nonferrous metals and ferrous metals industries have both relied on the exergy of energy and materials at an increasing rate from 1992 to 2015, particularly the ferrous metals industry. The nonferrous metals industry depends on more factors such as capital, labor and environmental remediation than those of the ferrous metals industry according to the extended exergy accounting. Therefore, the nonferrous metals industry should try to imitate the ferrous metals industry, improving the proportion of exergy from energy and materials.

Because of the conversion efficiency of the nonferrous metals industry being always higher than that of the ferrous metals industry, the ferrous metals industry has extensive room for improvement in profits per unit of exergy consumption relative to the nonferrous metals industry.

In this paper, we found that increase of the labor production efficiency and the decrease of the net input of resource exergy pro-capite in the smelting and pressing of metals industry and the same situation appeared in China (Chen et al., 2014). The capital and man power input assumed a greater significance in China (Chen et al., 2014) while they fell off in the smelting and pressing of metals industry. In the transportation sector, natural exergy and environmental exergy were the two major contributors with 42.16% and 41.74%, respectively (Dai et al., 2014). The environmental exergy accounted much larger proportion than the smelting and pressing of metals industry. Contrasting Chinese agriculture consuming more environmental resource and producing larger waste emissions (Zhang et al., 2019a), the smelting and pressing of metals sector consumed large environmental resource also and generated less waste emissions. For nonferrous metals industry, energy consumption in the extraction is much less than that of the smelting and pressing. Shao (Shao et al., 2014) thought that the energy consumption rate of China's nonferrous metal industries showed a declining trend. Different with the point, we considered that the exergy of energy investment in the smelting and pressing of nonferrous metals did not decline and increased fast.

4.2. Policy implications

Considering that coal has dominated the exergy energy of the sector, the Chinese government should improve the energy structure by restricting coal consumption to achieve sustainable development. Moreover, to prevent overexploitation, it is necessary to make changes to policies in a targeted manner, for example, by raising the threshold for output in new mines or restricting production from small-scale mines. Being important part of energy investment in the energy intensive sector, considerable part of the electricity comes from thermal power. That is to say, the smelting and pressing of metals sector has generated large emissions indirectly. For sustainable development, Chinese government may strive to develop renewable energy, such as: wind energy and solar energy, etc.

In terms of the metal ore trade, the non-homogenous distribution of metal ore resources globally and the strong demand in China have led China to import large amounts of ore in recent years. In particular, iron ore, bauxite and copper ore have been the major exergy minerals leading to increasing dependency on resources from abroad in the smelting and pressing of metals sector of China. The exergy content of these mineral ores in China is much lower than that overseas. China could strengthen its relationship with countries producing high exergy resources or exporting large amounts of scrap metal, broadening the number of countries from which it imports to reduce the risk of disruption due to policy changes in the resource-exporting countries. Since the iron ores and bauxite accounting for large part of ores, import these ores with high exergy content from Australia or Brazil may be an option to make the sector develop more sustainability. In the materials exergy investment, the scraps grew rapidly. Since scraps saving much energy than the ores, Chinese government may import more scrap to reduce emissions.

The upgrading life standards and industry construction consumed kinds of metals resources. Moreover, China faces the embarrassing situation of using large quantities of resources while having low per-capita quantities of those resources. Therefore, to resolve resource shortages, the Chinese government has to improve the efficiency of resource use and exploit renewable energy.

Extended exergy analysis is an effective method to reflect the resources quality in conversion process (Chen and Chen, 2009). The comparison of resource accounting between different industries is able to determine the efficiency of production process, assess environment impact, and show the utilization structure of resource in different time and location. EEA is a tool measuring the amount of material or immaterial resources "used up" (Milia and Sciubba, 2006), indicating the comprehensive necessary and environmentally cost.

As the product of the smelting and pressing of metals industry, metals have different density. Since the EEA theory measure the degradation of resources in conversion process based on the second thermodynamic law, the density of metals is obliterated. For instance, the density of iron and aluminum is 7.87 g/cm^3 and 2.7 g/cm^3, and the exergy value of iron and aluminum is 6.8 PJ/Mt and 32.9 PJ/Mt, respectively. Similar to this, theory of EEA cannot reflect the physical properties such as: mass, conductor of electricity, chemical properties and other properties of resources.

In one word, EEA is an appropriate tool to assess resource and foundation to adjust resource policies of the industry based on the second-law of thermodynamics. The estimation of the E_R has some drawbacks, as it was contained in the CEC. We know that many pollution and ecological problems cannot be evaluated based on capital investment only. Appropriately calculating the EEA-based E_R will be pursued in future studies. In the future, we may also continue to calculate the exergy of other industries or not energy-intensive industries in China, such as the tertiary industry, or compare energy-intensive industries in other countries.

Author statement

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