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Emergy-based environmental accounting of gold ingot production in China

Wei Chen[a], Yong Geng[a,b,c,*], Xu Tian[a], Shaozhuo Zhong[a], Cuixia Gao[d], Wei You[a], Shun Li[e]

[a] School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China
[b] China Institute of Urban Governance, Shanghai Jiao Tong University, No. 1954, Huashan Road, Shanghai, 200030, PR China
[c] Shanghai Institute of Pollution Control and Ecological Security, Shanghai, 200092, PR China
[d] Institute of Applied System Analysis, Jiangsu University, Zhenjiang, 212013, PR China
[e] Environmental Protection Bureau of Haixi Prefecture, Delingha, 817099, PR China

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ABSTRACT

Gold production has brought serious environmental impacts on the natural ecosystem. Thus, it is critical to evaluate such impacts so that appropriate mitigation measures can be initiated. Derived from thermodynamics and systems ecology, emergy synthesis is one evaluation method widely used for environmental accounting. This study employs emergy-based indicators to evaluate gold ingot production based on regional data so that the holistic environmental performance of gold production in China can be examined. Sensitivity analysis on gold concentration, dominant contributors, labor & services is conducted so that more reliable results can be obtained. Results show that the total emergy (without labor & services) used for per gram gold ingot production was 9.63E + 13 sej, in which energy and chemicals were the dominant contributors. Specially, the unit emergy value of gold in the ground based on local gold enrichment was 3.67E + 12 sej/g. Results also indicate that gold production is extremely unsustainable because it's heavily dependent on nonrenewable resources during its whole production life cycle. Finally, several recommendations were proposed to mitigate its overall environmental impacts by considering the local realities.

1. Introduction

Rapid industrialization resulted in the degradation of natural ecosystem worldwide (Yang, 2015). Metal resources are indispensable for economic development due to their important roles on meeting with the special functional requests of different products and household consumption. However, the development of metallurgic industry has caused many environmental issues (Chen et al., 2018a). Gold is one kind of precious metals and has a unique role on modern industries and global economic system. However, the processes of gold mining have adverse impacts on the local environment and public health (Jeronimo et al., 2015; Akpalu and Normanyo, 2017). Although the construction of green mines has been promoted in China, problems such as water and soil contamination and vegetation destruction still exist (MIIT, 2012). China has been the largest gold producer since 2007 (CGA, 2018). But China's gold production decreased by 6.03% in 2017, which is the first sharp decline (more than 5%) since 1974 (CGA, 2018). With the strict enforcement of environmental regulations, many Chinese gold mine enterprises reduced their production, which eventually resulted in the reduction of China's gold production (CGA, 2018). It is crucial to promote green mining so that the overall environmental impacts from gold production can be minimized. In this regard, it is necessary to assess the environmental performance of gold production so that more appropriate mitigation measures can be raised.

Emergy synthesis is one systematic method for quantifying the work previously required to generate a product or service (Odum, 1996). It seeks to integrate the work of nature and the value of natural capital into human decision-making (Odum, 1996; Rugani and Benetto, 2012). In addition, it enables the comparison of flows with various quality by transforming them into a common energy metric (Odum, 1996; Chen et al., 2017a). Derived from thermodynamics and systems ecology, emergy synthesis can help us better understand the importance of ecological network for supporting economic activities (Zhang et al., 2010), while other thermodynamic methods (e.g., exergy) can hardly reflect energy requirements underlying environmental processes (Ukidwe and Bakshi, 2004; Ingwersen, 2011). In recent years, studies on Emergy Accounting (EMA) have experienced a rapid growth with the improvement of Unit Emergy Values (UEVs) database (Chen et al., 2017a). For example, emergy synthesis has been used to evaluate environmental performance of agricultural systems (Wang et al., 2017), solid waste management (Liu et al., 2017; Wang et al., 2018), international trade (Tian et al., 2018; Geng et al., 2017; Tian et al., 2017),

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[*] Corresponding author.
E-mail address: ygeng@sjtu.edu.cn (Y. Geng).

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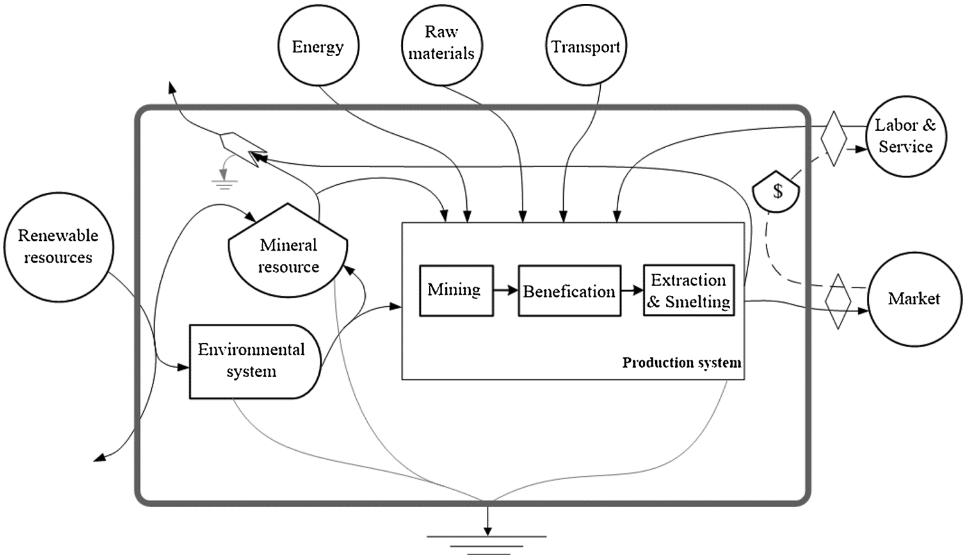

Fig. 1. Emergy system diagram of gold ingot production.

and regional economic systems (Restrepo and Morales-Pinzón, 2018; Geng et al., 2013; Sun et al., 2016; Chen et al., 2017b, 2018c). Specially, EMA has been extensively applied in industrial sectors (Corcelli et al., 2018; Chen et al., 2016). With the novel algorithm for calculating the UEVs of different wastes, the overall sustainability of one industrial park was also evaluated so that feasible strategies for industrial parks' sustainable management can be raised (Geng et al., 2010, 2014). Chen et al. (2018a) found that the impact on resources category had a significant contribution to the total environmental burden generated from gold production. Thus, it's particularly important to evaluate the environmental impacts for gold production activities. To the best of our knowledge, no EMA-based studies on gold production have been conducted in China. Internationally, the only available literature is that Ingwersen (2011) evaluated the total emergy used for gold production based on the life cycle inventory (LCI) of one gold mine in Peru. However, the UEVs of flows associated with gold production in Ingwersen (2011) were not stated clearly. The environmental support for mineral formation significantly varies with corresponding ore grades (Cohen et al., 2007), which means that the total emergy used for gold production varies with different gold resource endowments. China's gold production has ranked the first in the world since 2007 (CGA, 2018). Consequently, it is urgent to undertake an EMA-based evaluation on China's gold production so that environmental performance of gold production can be evaluated and appropriate mitigation policies can be prepared.

To fill such a research gap, this study focuses on evaluating the overall environmental performance of gold ingot production in China by employing an EMA approach. Specially, the UEV of gold in the ground is evaluated based on the local gold enrichment. Also, emergy-based indicators are established to assess the overall sustainability of gold production so that more specific suggestions can be prepared. Finally, sensitivity analysis on gold concentrations, dominant contributors, and labor & services (L&S) is performed so that results can be more reliable and valuable for decision-makers. The whole paper is organized as below. After this introduction section, Section 2 depicts research methods and data sources. Section 3 presents research results and Section 4 discusses policy implications. Finally, Section 5 draws research conclusions.

2. Methods and data sources

2.1. Emergy synthesis

Defined as the total amount of available energy needed directly and indirectly to make one product or service, emergy synthesis emerged in the 1980s and gradually received global attentions (Odum, 1996; Chen et al., 2017a). By quantifying the work of nature to generate and concentrate resources as well as the work of humans to manufacture them by adopting a common energy metrics (usually solar energy), this method can present the holistic aspects of one investigated system in an integrated way (Odum, 1996; Lou and Ulgiati, 2013). According to Odum (1996), the total emergy used for one product can be calculated by using Eq. (1):

$$U = \sum_{i=1}^{n} U_i = \sum_{i=1}^{n} f_i \times UEV_i \tag{1}$$

where i is one individual flow associated with the investigated system; U_i represents the emergy used for supporting the investigated system in terms of flow i; f_i represents the amount of the individual flow of i and is expressed in the unit of grams (g), joule (J), or money ($); and UEV_i is the amount of emergy required for generating one unit of the individual flow of i, expressed in the unit of sej/unit (i.e., sej/g, sej/J, and sej/$).

Emergy-based indicators (Odum, 1996; Chen et al., 2017b) have been widely employed to assess the sustainable level of an investigated system. In this study, commonly used indicators, including Emergy Investment Ratio (EIR), Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), and Emergy Sustainability Index (ESI), are applied to quantify the environmental performance and the overall sustainability of gold ingot production. Detailed information of those indicators are available in the supplemental material of this paper.

2.2. Emergy flows of gold ingot production

Fig. 1 illustrates the emergy system diagram of gold ingot production. The system boundary considered in this study is set up by using a cradle-to-gate approach, in which the gold consumption and final disposal are excluded. Key flows for gold ingot are considered, such as gold ore, steel, electricity, etc. These inflows can be further classified into renewable resources (R), local nonrenewable resources (N), and inputs into the studied system from outside (F). The direct renewable resources provided by the nature enter from left, whereas the gold product exits from right. All the flows associated with the investigated system should be drawn in a clockwise pathway based on their corresponding UEVs.

The emergy used for minerals formation have been detailed in Cohen et al. (2007) and Martínez et al. (2007). In this study, the UEV of gold in the ground is calculated based on a universal model (listed in Eqs. (2) and (3) for estimating the emergy of minerals in the ground.

$$UEVc = UEVave \times ERc \tag{2}$$

$$ERc = OGgold \div CCgold \tag{3}$$

where UEV_c is the UEV of gold in the ground with the concentration of c; UEV_{ave} is the UEV of average crustal minerals (i.e., 12.00E + 24 sej/yr ÷ 9.36E + 15 g/yr = 1.28E + 09 sej/g); ER_c is the enrichment ratio of gold with the concentration of c; OG_{gold} is the ore grade used for gold production; and CC_{gold} is crustal background concentration of gold.

2.3. Data sources

In this study, material and energy flows associated with gold ingot production are derived from a previous study conducted by the authors (Chen et al., 2018a). The LCI of gold ingot production was established based on annual monitoring data of a gold production company locating in Haixi prefecture of Qinghai province, northwest China. The specific LCI data for the processes of mining and beneficiation were obtained from the Chinese process-based LCI database (CPLCID), in which international reviewed process-based LCI of China is covered (Qi et al., 2017; Hong et al., 2017). Detailed data of used LCI are available in the supplemental material of this study. Most of UEVs adopted in this study are taken from international peer-reviewed publications, but the UEV of gold ore at the mine and the UEV of gold concentrate are calculated by using the local data. Furthermore, updated global emergy baseline with the value of 12.00E + 24 sej/yr (Brown et al., 2016) was used for all the emergy calculations involved in this study. Correspondingly, UEVs based on other baselines were all revised by multiplying a coefficient in order to obtain a consistent baseline (Chen et al., 2016). Detailed data of used energy and material flows and corresponding UEVs are shown in Table 1. The supplemental material of this paper provides detailed calculation procedures.

3. Results

In this study, the UEVs of gold in the ground, gold ore at the mine (gold ore after mining process), gold concentrate (gold ore after beneficiation process), and gold ingot (gold product) are all calculated. Since labor is not considered in the LCI database, emergy of L&S is not considered in this study. However, EMA of L&S is discussed in Section 3.4 in order to assure the integrity of this study.

3.1. EMA of gold ore

With the gold content of 4.3 g/t (Chen et al., 2018a) and a crustal background enrichment of 1.5 mg/t (Frimmel, 2008; Valero et al., 2010), the UEV of gold in the ground in this study is 3.67E + 12 sej/g (based on Eqs. (2) and (3).

The UEV of gold ore at the mine is also calculated. Results show that the emergy of per gram gold ore at the mine is 3.67E + 12 (3.6694E + 12) sej, in which the emergy of gold in the ground is the dominant contributor, with the value of 3.6693E + 12 sej. Such results indicate that emergy inputs of renewable resources and external inputs are negligible for gold ore mining process. The UEV of gold concentrate is also calculated in this study, with a value of 4.22E + 12 (4.2214E + 12) sej/g. Such a result indicates that gold ore at the mine is the dominant contributor to the total emergy used for gold concentrate. The LCI of mining and beneficiation processes are available in the supplemental material of this study.

3.2. EMA of gold ingot

Table 2 lists the major emergy flows used for supporting gold ingot production, including renewable resources, local nonrenewable resources, and external inputs into the process. Results show that total emergy used for per gram gold ingot production is 9.63E + 13 sej (without L&S). Contributions of individual flows to the total emegy used for gold production (without L&S) are shown in Table 2.

For renewable resources, emergy from solar radiation, geothermal heat, rainfall (chemical and geopotential), and wind are included, while emergy from wave and tide are not considered because this company locates in the Qinghai-Tibet highland, far away from the ocean. According to Brown and Ulgiati (2016), the largest one among primary, secondary, and tertiary renewable resources should be selected as the emergy of renewable resources to avoid double accounting. With such a consideration, the emergy of primary renewable resources is calculated, with a value of 7.41E + 08 sej for per gram gold production.

In this study, the indigenous nonrenewable resource is the gold ore used for gold ingot production. As shown in Table 2, the emergy input of gold ore is 4.15E + 12 sej for per gram gold ingot production, accounting for 4.30% of the emergy used (without L&S) for gold ingot production.

The emergy of external inputs associated with gold ingot production is 9.22E + 13 sej (without L&S), including energy and materials associated with gold ingot production and the delivery of used raw materials. Table 2 shows that the emergy of external inputs is the major part to the total emergy used for gold ingot production, with the proportion of 95.70%. Specifically, the emergy inputs of energy, raw materials, and delivery of materials for per gram gold ingot production are 2.10E + 13 sej, 7.06E + 13 sej, and 6.42E + 11 sej, respectively.

With regard to the total emergy used for gold ingot production, emergy of external inputs is the major part (> 90%), followed by indigenous nonrenewable resources (4.30%), while emergy of local renewable sources is very marginal (< 0.01%). For the emergy of external inputs, emergy of raw materials associated with gold ingot production is the largest, followed by emergy of energy, and delivery of raw materials. With regard to energy, electricity is the largest contributor, accounting for 19.06% of total emergy used for gold ingot production. With regard to raw materials, ferric sulfate, sodium cyanide, sodium metabisulfite are the major raw materials emergy inputs, with proportions of 31.27%, 12.62%, and 7.49%, respectively. Such results are similar to those from Ingwersen (2011) and Chen et al. (2018a), reflecting that it is necessary to improve the efficiency of resource utilization (energy and materials) for gold production.

3.3. Emergy-based indicators

Table 3 lists the results of emergy-based indicators. The values of UEV (without L&S), EIR, and EYR of gold ingot production are 9.63E + 13 sej/g, 22.23, and 1.04, respectively. These results indicate that gold production process induced serious environmental impacts on the local ecosystem, particularly due to its nonrenewable resources-based production process.

In addition, the value of ELR in this study is higher than other metallurgy processes, while the value of ESI is lower than other metallurgy processes, such as steel (Zhang et al., 2009; Pan et al., 2016). This is because the element enrichment of gold is much lower than that of iron. Chen et al. (2018a) also found that the environmental burden generated from gold production is higher than that of zinc and lead given the fact that ore grades of lead and zinc are usually several orders of magnitude higher than that of gold. In general, these studies all demonstrate that metallurgic industry can bring serious environmental impacts on the natural ecosystem. Therefore, more efforts should be made in order to mitigate such impacts.

Table 1
Data used for emergy accounting of per gram gold ingot production.

Note	Item	Amount	Unit	UEV (sej/unit)	Reference for UEV
Local renewable resource					
Primary sources					
1	Sunlight	6.56E+07	J	1	Odum (1996)
2	Geothermal heat	1.55E+04	J	4.37E+04	After Brown and Bardi (2001)
Secondary and tertiary sources					
3	Rain, geopotential	1.51E+04	J	3.54E+04	After Brown and Bardi (2001)
4	Rain, chemical	3.36E+03	J	2.31E+04	After Brown and Bardi (2001)
5	Wind, kinetic energy	3.65E+04	J	1.90E+03	After Brown and Bardi (2001)
Local nonrenewable resource					
6	Gold, in ore at the mine (4.3 g/t)	1.13	g	3.67E+12	This study
Inputs from outside					
Imported energy					
7	Electricity	1.08E+08	J	1.69E+05	After Lou et al. (2015)
8	Coal	2.18E+07	J	7.67E+04	After Brown et al. (2011)
9	Gasoline	1.26E+06	J	1.48E+05	After Brown et al. (2011)
10	Diesel	5.18E+06	J	1.43E+05	After Brown et al. (2011)
Imported raw materials					
11	Limestone	1.66E+03	g	1.27E+09	After Brown and Buranakarn (2003)
12	Steel	3.44E+02	g	9.80E+09	After Brown et al. (2012)
13	Gold, in gold concentrate (13.2 g/t)	9.14E-02	g	4.22E + 12	This study
14	Sulfur concentrate	8.02E+02	g	5.79E+09	After Rugani et al. (2011)
15	Xanthate	7.42E+01	g	6.11E+10	After Rugani et al. (2011)
16	Sodium cyanide	1.99E+02	g	6.11E+10	After Rugani et al. (2011)
17	Sodium metabisulfite	1.18E+02	g	6.11E+10	After Rugani et al. (2011)
18	Copper sulfate	9.44E+01	g	6.11E+10	After Rugani et al. (2011)
19	Ferric sulfate	4.93E+02	g	6.11E+10	After Rugani et al. (2011)
20	Water	2.26E+05	g	1.26E+06	After Brown et al. (2012)
Transport of raw materials (assumption 100 km)					
21	Transport (truck)	8.43E-01	t·km	7.61E+11	After Brown and Buranakarn (2003)
Labor & service					
24	Labor & service	2.48E+02	RMB	2.12E + 13	After Chen et al. (2018c)

Table 2
Material and energy flows for gold ingot production. Values were presented as per gram gold production.

Note	Item	Solar Emergy (sej)	% (sej/sej)
Local renewable resource			< 0.01
Primary sources			
1	Sunlight	6.56E+07	
2	Geothermal heat	6.76E+08	
Sum of primary sources		7.41E + 08	
Secondary and tertiary sources			
3	Rain, geopotential	5.35E+08	
4	Rain, chemical	7.76E+07	
5	Wind, kinetic energy	6.94E+07	
Largest of primary, 2nd and 3rd sources		7.41E + 08	< 0.01
Local nonrenewable resource			***4.30***
6	Gold, in ore at the mine	4.15E + 12	4.30
Inputs from outside			***95.70***
Imported energy			
7	Electricity	1.84E+13	19.06
8	Coal	1.67E+12	1.73
9	Gasoline	1.87E+11	0.19
10	Diesel	7.41E+11	0.77
Imported raw materials			
11	Limestone	2.11E+12	2.19
12	Steel	3.37E+12	3.50
13	Gold, in gold concentrate	3.86E+11	0.40
14	Sulfur concentrate	4.64E+12	4.81
15	Xanthate	4.53E+12	4.71
16	Sodium cyanide	1.22E + 13	12.62
17	Sodium metabisulfite	7.21E+12	7.49
18	Copper sulfate	5.77E+12	5.99
19	Ferric sulfate	3.01E+13	31.27
20	Water	2.84E+11	0.30
Transport of raw materials (assumption 100 km)			
21	Transport (truck)	6.42E + 11	0.67
Total emergy input			
Total (without labor & service)		9.63E + 13	

Table 3
Emergy-based indicators for per gram gold production.

Category	Expression	Amount
Renewable sources	R	7.41E + 08 sej
Indigenous nonrenewable resources	N	4.15E + 12 sej
Inputs from outside	F	9.22E + 13 sej
Unit emergy value (without labor & service)	UEV	9.63E + 13 sej/g
Emergy investment ratio	EIR = F/(R + N)	22.23
Environmental loading ratio	ELR = (N + F)/R	> 100
Emergy yield ratio	EYR = U/F	1.04
Emergy sustainability index	ESI = EYR/ELR	< 0.01

3.4. EMA of labor & services

Ulgiati and Brown (2014) differentiated labor and services for emergy synthesis. Labor is the direct input of human work calculated by using the money paid for wages, whereas services are considered as indirect labor calculated by using prices of all inputs associated with the investigated system (Ulgiati and Brown, 2014). L&S can be calculated as a combined input through multiplying the price of the final product by regional emergy to money ratio (EMR) when detailed data are unavailable (Ulgiati and Brown, 2014). Thus, L&S is considered as a combined input in this study because the prices of all inputs are not available. Since the research area locates in Qinghai Province, the EMR of Qinghai is employed in this study. The emergy of L&S for per gram gold ingot production would be 5.26E + 15 sej when using the EMR result of Qinghai from Chen et al. (2018c). The EMR of Qinghai Province is much higher than those of most Chinese provinces (Li and Luo, 2015; Chen et al., 2018c). In this regard, if the EMR result of China in 2009 from Lou and Ulgiati (2013) is employed, then the emergy in term of L&S for per gram gold ingot production is reduced to 2.14E + 14 sej.

Table 4
Various UEVs of gold in the ground.

Item	C1 (g/t)	C2 (mg/t)	UEV (sej/g)	Baseline (sej)	Reference
1	0.87	4.0	3.65E + 11	15.83E+24	Ingwersen (2011)
2	15	1.8	1.40E + 13	15.83E+24	Martínez et al. (2007)
3	1.2	4.0	5.04E+11	15.83E+24	Cohen et al. (2007)
4	4.3	1.5	3.67E + 12	12.00E + 24	This study

C1: grade ore for mining.
C2: crustal background enrichment.

3.5. Sensitivity analysis

3.5.1. Gold concentration

A comparison study on the UEV of gold in the ground is conducted. Table 4 lists the results, showing that the UEV obtained from this study (3.67E + 12 sej/g) is within the range of previously published results (3.65E + 11 sej/g to 1.40E + 13 sej/g). Results also show that the differences in background concentration, grade ore, and baseline have contributions to the variation of UEV.

The UEV of gold in the ground in this study is 3.67E + 12 sej/g based on a crustal background enrichment of 1.5 mg/t (Frimmel, 2008; Valero et al., 2010) and an ore grade of 4.3 g/t. Jiang et al. (2017) found that gold enrichment was 0.58 g/t for Zijinshan Cu-Au deposit, the largest gold mining company in China. Zhang et al. (2017) found that the average ore grade was 5.6 g/t for Axi deposit, the largest low sulfidation epithermal gold deposit in the northwest China. Frimmel (2008) summarized the ore grades of several gold deposits in the world and found that ore grade varies from 0.3 g/t to 10 g/t. In addition, Huang and Zhao (2015) found that the mean value and median value for gold abundance in Yunnan Province of China was 2.33 g/t and 1.50 g/t, respectively. In fact, the value of mineral abundance in continental crust varies with tectonics and analytical methods (Gao et al., 1998). As shown in Table 4, gold concentration (i.e., background enrichment and grade ore for mining) is the major contribution to the variation of UEV. In order to further investigate the impact of gold concentration to the variation of UEV, sensitivity analysis of gold concentration is performed in this study. As shown in Fig. 2, if the value of 2.33 g/t for gold abundance is considered, the UEV for gold in the ground will be reduced to 2.3622E + 12 sej/g. Correspondingly, the UEV for gold ore at the mine, gold concentrate, and gold ingot production (without L&S) will be reduced to 2.3623E + 12 sej/g, 2.72E + 12 sej/g, and 9.47E + 13 sej/g, respectively.

3.5.2. Dominant contributors

The total emergy used for gold ingot production is influenced by various factors (e.g., production technology, energy and resource efficiency). It is necessary to conduct a sensitivity analysis so that the impacts of different factors can be better evaluated. As shown in Fig. 3a 5% decrease of ferric sulfate, electricity, and sodium cyanide could lead to 1.59%, 0.96%, and 0.63% reduction in the total emergy input, respectively. Fig. 3 also illustrates the results for the rest factors. These results suggest that it would be crucial to improve the utilization efficiency of ferric sulfate, electricity, and sodium cyanide.

3.5.3. Labor & services

The EMR value is region-specific (Ulgiati and Brown, 2014). In this study, the investigated enterprise locates in Qinghai Province, thus the EMR value of Qinghai Province is used. According to Chen et al. (2018c), the EMR of Qinghai Province fluctuated from 1.41E + 13 sej/RMB in 2002 to 2.12E + 13 sej/RMB in 2015, with the highest value of 2.91E + 13 sej/RMB in 2007. In addition, the price of gold is also variable. In this study, the price of final gold product (248.08 RMB/g) is taken from the report of the investigated enterprise. This report also introduced that the gold price varied from 169.13 RMB/g in 2007 to 235.09 RMB/g in 2015, with a highest value of 338.81 RMB/g in 2012. L&S is calculated based on the price of the final gold product and regional EMR value (Section 3.4). Fig. 4 illustrates the environmental support in terms of L&S for gold ingot production.

4. Policy implications

Gold mining and refining process has been considered as one of the most destructive anthropogenic activities with enormous environmental problems (Zhu et al., 2016). As the largest gold producer in the world, China's gold production has resulted in increasing environmental concerns. In the 19th National Congress of the Communist Party of China, President Xi (2017) proposed that the Chinese governments will establish a legal and policy framework to promote green production and consumption. Under such a circumstance, it is crucial to make appropriate suggestions to improve the overall performance of gold production.

EMA on gold production was performed in this study to help understand the environmental support for gold production so that potentials for improving its environmental performance can be identified by considering the local conditions. Results show that energy and chemicals are the major contributors to the total emergy used for gold ingot production (without L&S). Life cycle assessment of gold production uncovered that energy and ore consumption are the key factors on inducing the environmental burden generated from gold production (Chen et al., 2018a). The 13th Eco-environment Protecting Plan issued by the Chinese government emphasized the importance of implementing cleaner production in metallurgical industry (The State Council and The People's Republic of China, 2016). Therefore, it is critical to implement cleaner production in gold production industry so that environmental emissions can be reduced and energy consumption can be minimized.

In this study coal-based electricity was considered given its dominance in China's power grid. However, if hydropower is considered, the total emergy input for gold ingot production would be reduced by at least 17%. Chen et al. (2018a) found that the environmental impacts on climate change, terrestrial acidification, human toxicity, particulate matter formation, marine ecotoxicity, and fossil depletion, would be reduced by at least 64%, 43%, 58%, 49%, 22%, and 68%, respectively, if hydropower is applied for gold production. Also, Xi (2017) highlighted the importance of establishing clean, low-carbon, safe, and efficient energy sector. Locating at the upper stream of three major rivers, including Yangtze river, Yellow river and Mekong river, Qinghai Province is abundant with water resources and should actively promote the application of hydropower. Meanwhile, Qinghai has a special advantage on promoting solar power due to its longer sunshine time. In addition, Qinghai is also rich in terms of wind power. Thus, it is critical to promote clean energy by fully utilizing local resource endowment. Although several hydro-photovoltaic power plants have been operated in Qinghai, more efforts should be initiated so that its abundant renewable resource endowment (e.g., solar energy, hydropower, and geothermal power) can be further applied.

In addition, MIIT (2016) proposed to improve the exploration and utilization of gold in its 13th Five-Year Plan. Also, the Chinese government has actively promoted ecological civilization, with circular economy (CE) as the key strategy (Geng et al., 2013; Chen et al., 2018b). Qinghai Province has been selected by the Chinese central government as one key region to implement the concept of circular economy. However, the effectiveness of these policies highly depends on the enforcement of local government. Although several measures such as the establishment of provincial CE fund and financial subsidies on promoting CE have been taken, further efforts need to be made so that all the stakeholders can join these efforts, such as more capacity-building activities on improving the general public's environmental awareness, promoting cleaner production in all the mining enterprises, transferring advanced technologies from other regions, and establishing an information platform so that potential byproducts users can identify

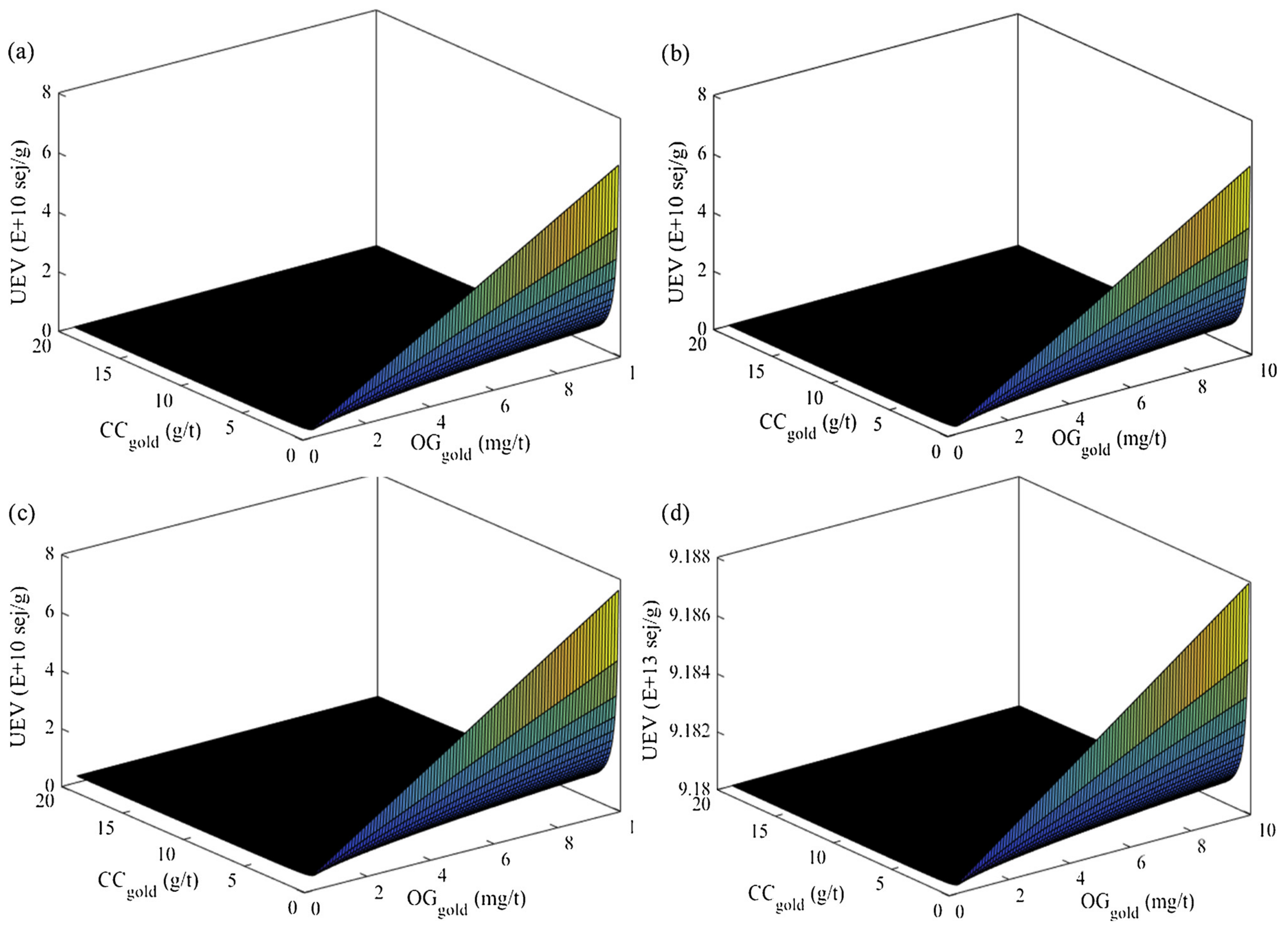

Fig. 2. Sensitivity analysis of gold concentration. (a) UEV of gold in the ground; (b) UEV of gold ore at the mine; (c) UEV of gold concentrate; (d) UEV of gold ingot.

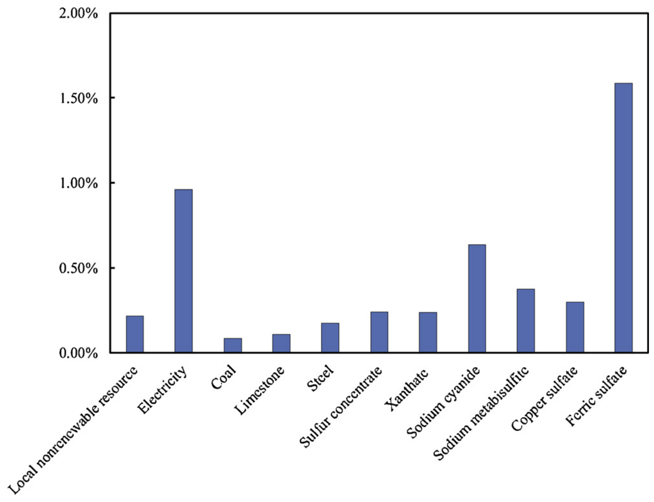

Fig. 3. Sensitivity analysis of dominant contributors.

the possible industrial symbiosis opportunities or more energy/water cascading activities can occur.

Finally, mining activities lead to water pollution and soil erosion, which may degrade the functions of ecological service (Asner and Tupayachi, 2017). Therefore, ecosystem restoration is vital for mining industry. In this regard, ecological compensation is an effective approach to address such a problem since it uses a market-based instrument to adjust the costs and benefits among different stakeholders (Zhen and Zhang, 2011). However, effective ecological compensation is based upon rational evaluation of natural ecosystem. Without a scientific determination of appropriate ecological compensation standard, such a measure will not function well. Normally, the price of one good or service is determined by the consumer demand in a market. However, environmental externalities are always excluded from such a price, leading to that stakeholders pay less attention on environmental protection. Consequently, it is necessary to include the value of ecosystem service into the final determination of one product or service's final price (Campbell and Tilley, 2014). Emergy synthesis has been applied for the resource value evaluation by converting the biophysical flows into emergy-based "currency equivalents" (Franzese et al., 2017; Vassallo et al., 2017). However, its application is still facing both theoretical and practical barriers, such as a lack of UEVs on different items and a unified and updated international database (Geng et al., 2016). Therefore, it is critical to conduct more studies so that appropriate ecological compensation standard can be determined and accepted based upon EMA.

5. Conclusions

Gold production has resulted in severe environmental challenges. China is the largest producer on gold production and has to seek a sustainable approach on improving its gold production. Under such a circumstance, environmental accounting on gold production was performed to provide a holistic picture of its environmental performance by employing an emergy synthesis method. Results show that the total emergy input for per gram gold ingot production was 9.63E + 13 sej (without L&S), dominated by ferric sulfate, electricity, and sodium cyanide. In addition, the UEV of gold in the ground obtained from this study was 3.67E + 12 sej/g, within the range of previously published

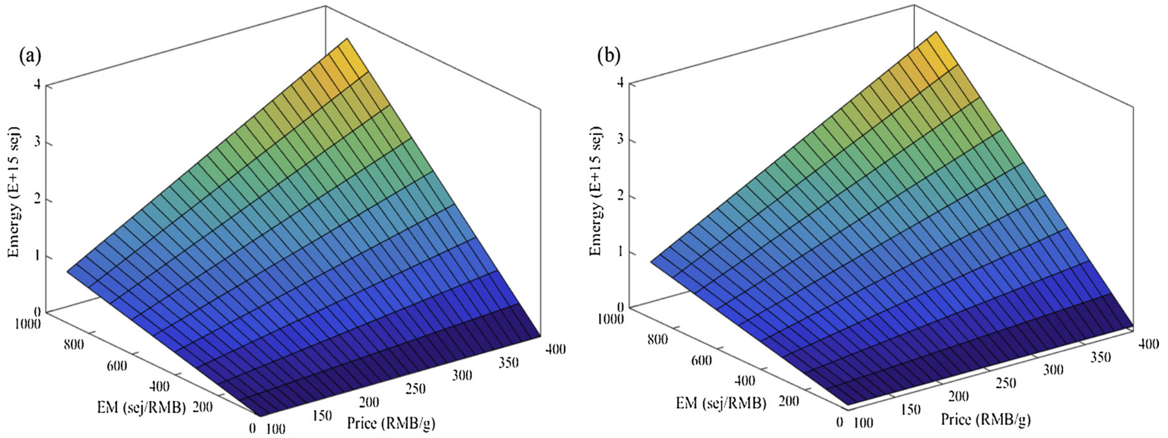

Fig. 4. Sensitivity analysis of labor & service. (a) emergy of labor & service for per gram gold product; (b) emergy of per gram gold product with labor & service.

results. Emergy-based indicators show that gold industry is unsustainable with a low value of ESI, particularly due to its chemical and energy intensive nature. Sensitivity analysis of gold concentration was also conducted since resource endowment varies among different regions. Also, the discussion of L&S was conducted separately because the EMR used for L&S evaluation is highly region-specific. Finally, policy suggestions are raised by considering the local realities, including the implementation of cleaner production, energy structure optimization, resource efficiency improvement through circular economy and the application of ecological compensation. In general, this study provides valuable insights to gold production industry so that the overall performance of this industry can be minimized.

However, this study has several limitations. EMA on gold production was conducted based on a case study, thus results obtained from this study can hardly represent the overall gold industry in China. In addition, the UEVs of most inputs were referred to different sources, which may add the uncertainty of results. The EMR value is region-specific and varies greatly within different regions. Thus, establishing a China-specific UEV database in which UEVs with L&S and without L&S are distinguished is crucial. In addition, standardizations for EMA should be established so that EMA-based results can be more acceptable for policy-makers.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.12.021.

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