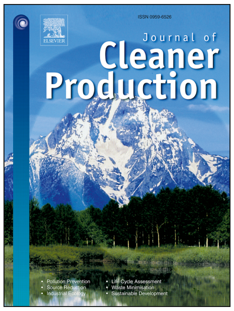

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Life cycle environmental and economic assessment of alumina recovery from secondary aluminum dross in China

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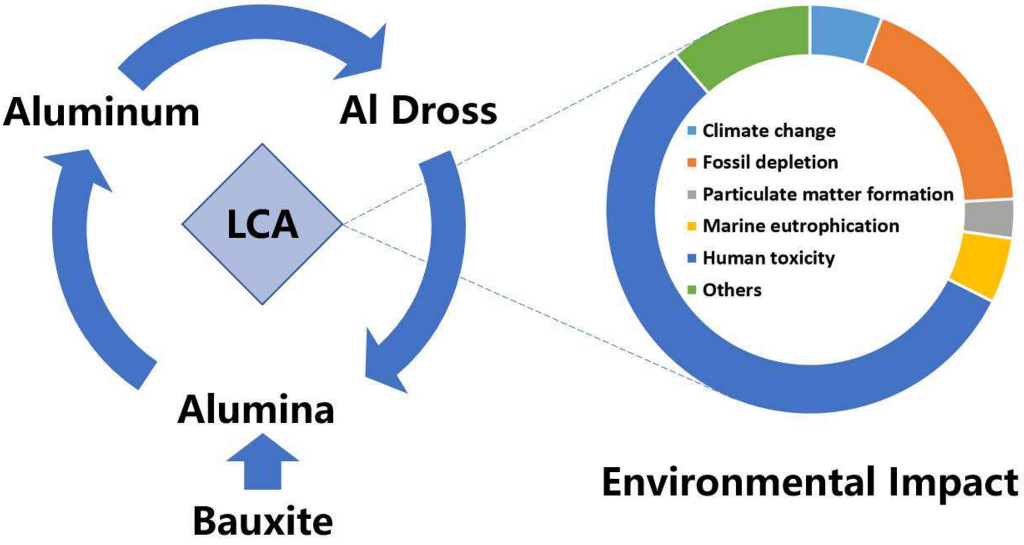
Highlights

- Coupled LCA and LCC showed that producing alumina from secondary aluminum dross had lower environmental impacts and economic costs than dross process.
- Steam, sodium hydroxide and electricity contributed most to impact values.
- Suggestions for dross transportation and aluminum industry migration in China were proposed.

Word Count: 6623

Abstract

Secondary aluminum dross is regarded as a hazardous solid waste in many countries. A coupled life cycle assessment and life cycle costing method was used to evaluate the environmental impact and economic cost of two processes for producing alumina from bauxite and secondary aluminum dross. The results showed that the total normalized midpoint value of the dross process is 32.16% lower than that of the bauxite process. The cost of producing 1 t alumina by dross process is 130.01 $, accounting for only 49.54% of that of bauxite process. Ammonium sulfate as a by-product also brought in a profit of 22.18 $. These findings could be attributed to the decrease in energy and raw material consumption (i.e., steam, sodium hydroxide, electricity) and the relatively low cost of secondary aluminum dross. Adjusting raw materials for steam production and optimizing electricity structure could reduce the overall environmental impact of secondary aluminum dross recovery. Based on the forecast of environmental impact and policy adjustment in the future, inter-provincial dross transportation and southwest aluminum industry migration in China could be feasible solutions.



Keywords Life cycle assessment; Secondary aluminum dross; Recovery; Bauxite;

1.Introduction

In recent years, China has become the world's largest aluminum producer. During the process of producing 1 t aluminum, more than 40 kg of aluminum dross is generated (Meshram and Singh, 2018). In 2017, China produced 32.3 million tons of primary aluminum, which means that the output of aluminum dross exceeded 1.29 million tons (National Bureau of Statistics of China, 2018). The component of aluminum dross is determined by its source, usually containing aluminum metal, aluminum oxide, iron oxide, silicon dioxide, aluminum nitride, aluminum carbide and other metal oxides, chlorides and fluorides (Mahinroosta and Allahverdi, 2018b). According to the number of times of aluminum dross recovery and the metal aluminum content in dross, aluminum dross is usually divided into two categories: primary aluminum dross and secondary aluminum dross. Secondary aluminum dross has a low metal aluminum content of about 5-10 wt%, high oxide and salt content, whereas primary aluminum dross contains a high metal fraction of about 30 wt% and small amounts of oxide and salt compounds (Mahinroosta and Allahverdi, 2018).

Secondary aluminum dross is regarded as a hazardous waste in many countries. In humid environment, secondary aluminum dross easily reacts with water, forming flammable or toxic gases such as methane, hydrogen, and ammonia. Direct landfill may let heavy metals such as Cd, Cr and Pb in the dross penetrate through soil and water, causing harm to animals and plants (Mahinroosta and Allahverdi, 2018b). Besides, the aluminum metal and aluminum oxide in the secondary aluminum dross are both components with recovery value. The alumina resources contained in 1 t secondary aluminum dross are generally equivalent to that from 1.8 t bauxite. Therefore, the accumulation of aluminum dross not only causes environmental pollution, but also causes loss of valuable materials.

At present, primary aluminum dross recovery technology is relatively mature in various countries around the world. However, secondary aluminum dross recovery technologies are still in the stage of laboratory exploration. Hiraki et al. (2005) used aluminum dross to produce hydrogen but ignored its economic utility. Murayama et al. used aluminum dross to make specific materials such as $AlPO_4$-5 type zeolitic materials (Murayama et al., 2006) and Zn–Al type layered double hydroxides (Murayama et al., 2012). Nevertheless, these methods cannot solve the practical problem of massive dross accumulation. Mahinroosta et al. (2018a) successfully extracted alumina from secondary aluminum dross in a low-energy and safe process. However, the purity of alumina is hard to reach the standard. In a nutshell, these existing secondary aluminum dross recovery processes have shortcomings such as high cost, small scale, and low value. Fortunately, our research group successfully recovered alumina from secondary aluminum dross by using sodium hydroxide, which not only had good yield but also met the national quality standard (Li et al., 2019; Jin et al., 2019; Song Ming, 2018).

In order to evaluate the environmental and economic superiority of our process, life cycle assessment (LCA) coupled with life cycle costing (LCC) method is used, which is an effective method to quantify the energy and materials invested in a process and analyze the economic and environmental burdens caused by the process (Hong et al., 2018). Unfortunately, there are very few LCA studies on aluminum dross. Nakajima et al. (2007) conducted LCA of hydrogen production from aluminum dross. However, the output only included waste and carbon dioxide emissions. Hong et al. (2010) compared the resource consumption and waste discharge of aluminum-silicon alloys production and alumina production from aluminum dross. Nevertheless, no common LCA model was used to characterize the inventory, making their LCA results lack systematicity and comparability. In conclusion, current LCA studies on aluminum dross have serious limitations.

Since the process for recovering alumina from secondary aluminum dross is promising and its environmental impact remains unknown, this study aims to use the LCA coupled with LCC method evaluating the environmental impact and economic cost of this innovative process. For comparison, the currently widely used process for extracting alumina from bauxite through Bayer method was chosen as a baseline scenario. The results are expected to provide data support for the industrialization of secondary aluminum dross recovery. Based on the prediction of industrial adjustment for China's aluminum industry, suggestions for process optimization and site selection of dross recovery industry in China were proposed.

2. Methodology

2.1 Goal and scope

This study chose Bayer process as a baseline scenario to compare the environmental impact and economic cost of recovering alumina from secondary aluminum dross. The production of 1 t alumina was selected as the functional unit, which was the base for life cycle inventory comparison. All materials, energy consumption, emissions, waste disposal and economic costs were based on this functional unit (International Organization for Standardization, 2006).

System boundaries were set by applying a cradle-to-gate approach, which only focused on industrial production in the entire life cycle of alumina. Since the composition of aluminum dross is close to bauxite from the perspective of resource attribute, dross and bauxite were set as the start of the system boundary in two scenarios. Figure 1 shows the system boundary for two processes. Since the transportation of the two processes is similar and its impacts in alumina production accounts for less than 1%, transportation was not included in this study.

For baseline scenario, bauxite is the raw material for producing alumina with Bayer method. Under high temperature and high pressure, bauxite can be dissolved in a solution of high concentration sodium hydroxide. After precipitation and filtration, sodium aluminate solution and red mud are obtained respectively. Due to the chemical nature, sodium aluminate will gradually transform into aluminum hydroxide crystals through dilution and stirring. The remaining alkaline solution can be recycled after evaporation and concentration. Aluminum hydroxide will be converted into alumina after calcination.

For dross scenario, secondary aluminum dross is the raw material. The additional process is ‘gas production’, in which metal aluminum, aluminum carbide and aluminum nitride react with sodium hydroxide at 90 ℃, producing hydrogen, methane and ammonia. Ammonia is absorbed by sulfuric acid to obtain ammonium sulfate in another unique ‘acid absorption’ unit. Hydrogen and methane are used as fuel for ‘calcination’ unit, achieving energy recovery. Other processes in these two scenarios were similar, in which dosage or condition may be slightly different. The alumina from dross is dissolved by sodium hydroxide at 250 ℃. After filtration and dilution, clear sodium aluminate solution would be obtained. After being diluted 2.5 times and stirred at room temperature for 72 hours, sodium aluminate solution will precipitate out aluminum hydroxide. The remaining alkaline solution can also be recycled after evaporation and concentration. After calcination, aluminum hydroxide will be converted to alumina. Under the above conditions, the recovery rate of alumina in secondary aluminum dross can reach 88.20% (Li et al., 2019). The entire process will produce dust, wastewater, and filter residue.

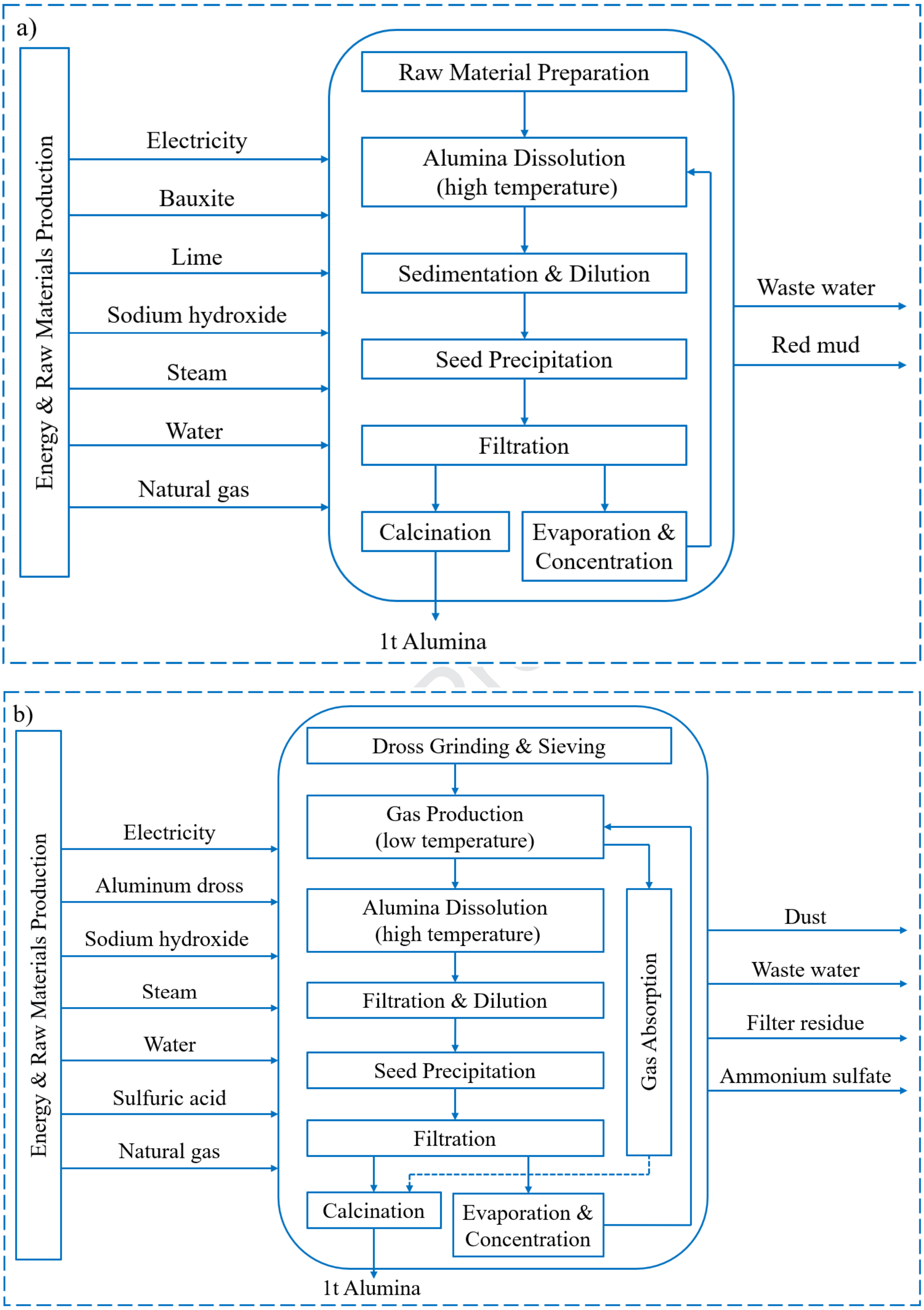


Fig. 1. System boundary of two processes: a) bauxite scenario, b) dross scenario.

2.2 Life cycle inventory

Life cycle inventory data for the bauxite process was from the average data of relative industries in China. Data for the secondary aluminum dross process was mainly from the average data of our experimental results (Li et al., 2019; Jin et al., 2019; Song Ming, 2018). Since some processes of two scenarios were identical, some data for energy consumption and emissions also referred to bauxite scenario. The electricity type in this study was a hybrid electricity based on China's national conditions (70.99% thermal power, 18.59% hydropower, and 10.42% other forms of power) (Yu Chongde, 2018). The steam used in this study was coal based. In addition, the environmental impact data was from the latest version 3.6 Ecoinvent database integrated in GaBi 6.0 software. The cost of raw materials referred to market prices.

According to EN ISO 14040 standard, the life cycle inventory is an inventory of the input/output data of the processes (International Organization for Standardization, 2006). Table 1 displays the inventory of two scenarios.

Table 1

Life cycle inventory

	Materials	Bauxite scenario	Dross scenario	Units
Resources (Input)	Bauxite	2.48×10^{3}	0	kg
	Secondary aluminum dross	0	1.42×10^{3}	kg
	Lime	3.20×10^{1}	0	kg
	Sodium hydroxide	6.15×10^{1}	5.70×10^{1}	kg
	Steam	2.43×10^{3}	2.21×10^{3}	kg
	Water	2.00×10^{0}	1.24×10^{0}	t
	Electricity	1.69×10^{2}	2.14×10^{2}	kwh
	Natural gas	7.25×10^{1}	2.34×10^{1}	m³
	Sulfuric acid	0	3.01×10^{2}	kg
Emissions (Output)	Waste water	7.91×10^{2}	3.13×10^{2}	kg
	Filter residue	7.58×10^{2}	2.89×10^{2}	kg
	Dust	2.90×10^{-1}	1.58×10^{-2}	kg
	Ammonia	1.25×10^{-2}	8.93×10^{-2}	kg
	Chromium	1.32×10^{-3}	1.32×10^{-3}	kg
	Bromine	1.15×10^{-3}	1.14×10^{-3}	kg
	Carbon monoxide	1.16×10^{0}	8.60×10^{-1}	kg
	Hydrogen fluoride	1.57×10^{-3}	1.47×10^{-3}	kg
	Hydrogen sulfide	6.44×10^{-3}	3.57×10^{-3}	kg
	Sulfur dioxide	3.41×10^{0}	2.77×10^{0}	kg
	Propane	2.52×10^{-2}	1.99×10^{-3}	kg
	Xylene	9.17×10^{-2}	9.16×10^{-2}	kg

Particulate matters 10	1.61×10^{-1}	3.74×10^{-6}	kg
Particulate matters 2.5	1.03×10^{0}	9.90×10^{-1}	kg
Biochemical oxygen demand	9.52×10^{-3}	1.39×10^{-3}	kg
Chemical oxygen demand	2.60×10^{-1}	2.60×10^{-1}	kg

2.3 Impact assessment

On the one hand, since secondary aluminum dross is an emerging issue in recent years, there is no industrialized treatment process currently. The process of recovering alumina from secondary aluminum dross is promising, but it is still in the early stage. Therefore, the LCA of dross process in this study is an ex-ante type. On the other hand, the bauxite process is very mature and most units and materials of both processes are the same, which helps to estimate the data of dross process based on industrial scale. Overall, in order to evaluate the energy consumption and emissions of the two processes, the comparative LCA study of the two processes is an attributional type.

The LCA results were calculated at midpoint level using the version 1.08 of ReCiPe 2008 model, which is one of the most authoritative approaches in LCA analysis, including eighteen representative environmental impact categories. The characterization factors were based Ecoinvent database 3.6 integrated in GaBi 6.0 software. The reference values for normalization were the global midpoint values for ReCiPe 2008 model, in which the normalization factors were updated in December 2014 (Goedkoop et al., 2014; Sleeswijk et al., 2008). The costs of two processes were assessed through LCC method. The LCC method is similar to LCA, wherein the evaluation considers the cost of energy and raw materials listed in the inventory instead of the environmental impacts. Since the gap of costs of labor in the raw material, energy production and manufacture stages between two processes is small, those costs were not included in this paper. The LCC results were calculated based on the price and amount of materials.

2.4 Interpretation

Main contributing processes and key substances were identified through life cycle interpretation. In dross scenario, since the environmental impact and economic cost caused by alumina production accounted for more than 95% of the entire process, the allocation of environmental and economic burden from ammonium sulfate production was not considered for the convenience of this work. In section 4.3.1, the benefit of using natural gas based steam was discussed. Two new scenarios were assumed: (1) Using natural gas as raw material to produce steam at 85% efficiency; (2) Using natural gas as raw material to produce steam at 95% efficiency. In section 4.3.2, the adjustment of electricity structure was proposed. Since Henan and Shandong, the two largest alumina production provinces in China, strongly depend on thermal power, the power structure of Qinghai Province (24.8% thermal power, 53.9% hydro power, 18.3% solar power, 2.9% of wind power) was taken as an example to analyze the reduction of environmental impacts. In section 4.4.1, inter-provincial dross transportation was proposed and its benefits and impacts were discussed. In section 4.4.2, suggestion for the south and southwest migration of the aluminum industry in China was discussed.

3. Results

3.1 LCA midpoint results

Table 2 shows the midpoint results of life cycle impact assessment pointing out the contribution of most significant processes. For both scenarios, steam consumption represented dominant contribution in most categories (usually over 50%), indicating that alumina production is an energy-intensive industry. Furthermore, the dross scenario had less potential impact in all categories and the improvements in most categories was over 30%, which was mainly due to different alumina content in bauxites and dross. Concretely speaking, the aluminum in bauxite is relatively less than secondary aluminum dross, resulting in higher material input and energy consumption during the extraction. In addition, the characteristic value of metal depletion category in secondary aluminum dross process was -0.257. That’s because the dross process uses industrial residual as a raw material, avoiding the consumption of bauxite. Another interesting point was that electricity was not found to dominate the environmental impact, for example, its contribution to climate change was only 17.52%. That was because the amount of electricity used in both processes was much lower than the amount of steam. Thus, steam replaced electricity as the main contributor to the climate change category.

Table 2 ReCiPe midpoint results for two processes

Categories	Units	Bauxite scenario		Dross scenario		Improvement %
		Results	Main contributing process	Results	Main contributing process	
Climate change	kg CO_2 eq	1.09×10^{3}	Steam (55.5%) + NaOH (23.1%)	7.36×10^{2}	Steam (68.1%)	32.48
Terrestrial acidification	kg SO_2 eq	2.16×10^{0}	Steam (47.8%) + NaOH (21.2%)	1.52×10^{0}	Steam (52.4%) + H_2SO_4 (31.2%)	29.63
Freshwater eutrophication	kg P eq	1.60×10^{-3}	NaOH (88.1%)	2.86×10^{-4}	NaOH (46.9%) + H_2SO_4 (29.7%)	82.13
Ozone depletion	kg CFC-11 eq	3.13×10^{-10}	NaOH (87.5%)	3.09×10^{-10}	NaOH (39.6%) + H_2SO_4 (37.9%)	1.28
Fossil depletion	kg oil eq	4.26×10^{2}	Steam (55.0%)	3.21×10^{2}	Steam (52.5%)	24.65
Freshwater ecotoxicity	kg 1,4-DB eq	1.55×10^{-1}	NaOH (71.0%)	4.87×10^{-2}	Steam (34.2%) + NaOH (24.4%)	68.58
Human toxicity	kg 1,4-DB eq	7.86×10^{1}	Steam (48.1%)	6.29×10^{1}	Steam (77.8%)	19.97
Ionizing radiation	U235 eq	2.62×10^{1}	NaOH (92.0%)	1.92×10^{1}	H_2SO_4 (47.9%) + NaOH (40.3%)	26.72
Marine ecotoxicity	kg 1,4-DB eq	6.74×10^{-2}	Steam (34.6%) + NaOH (35.9%)	4.23×10^{-2}	Steam (55.0%)	37.24
Marine eutrophication	kg N eq	7.40×10^{-1}	Steam (50.3%) + NaOH (27.1%)	5.10×10^{-1}	Steam (68.4%)	31.08
Metal depletion	kg Fe eq	6.46×10^{1}	Bauxite (91.3%)	-2.57×10^{-1}	Dross (100.0%)	100.40
Particulate matter formation	kg PM_{10} eq	1.53×10^{0}	Steam (36.6%) + Bauxite (28.2%) + Electricity (22.8%)	5.90×10^{-1}	Steam (61.9%)	61.44
Photochemical oxidant formation	kg NMVOC eq	2.11×10^{1}	Steam (52.2%) + NaOH (23.8%)	1.43×10^{1}	Steam (65.1%)	32.23
Terrestrial ecotoxicity	kg 1,4-DB eq	4.03×10^{-2}	Steam (54.7%)	3.39×10^{-2}	Steam (79.7%)	15.88
Water depletion	m^3	6.11×10^{2}	NaOH (78.6%)	5.24×10^{2}	NaOH (35.7%) + Electricity (36.5%)	14.24

3.2 Normalized LCA midpoint results

In order to compare the differences between various categories, characteristic values need to be normalized. As shown in Figure 2, human toxicity accounted for the largest proportion in the normalized value of both processes, which was caused by a variety of reasons: (1) Both processes produced particulate matters and harmful gases such as hydrogen sulfide, sulfur dioxide, etc. (2) Harmful components such as chromium and xylene were present in the waste water. (3) The amount of solid waste was considerable, especially the red mud from bauxite process. (4) Alumina extraction required high consumption of electricity, steam, and natural gas. During the production of these energy, various toxic and hazardous substances were produced, which was the hidden and main cause of high human toxicity value. Compared with the proportion of 47.6% in bauxite scenario, the normalized human toxicity value of dross process accounted for 63.0% of the total value. However, the actual human toxicity normalization value was lower than that of the bauxite process, indicating that the total values of all categories in dross scenario was significantly lower.

In addition, the normalized values of the two processes in the fossil depletion category were apparently different. Fossil depletion was mainly caused by electricity and steam consumption. Since the alumina that can be recovered from per unit mass of dross was higher than that from per unit mass of bauxite, the energy requirement of dross scenario was relatively low under the same output. Furthermore, according to the dross process proposed by our group, hydrogen and methane generated by aluminum and aluminum carbide was used as fuels in the calcination unit, which made up part of the energy demand.

Overall, the total normalized values of bauxite process and dross process were 1.99 and 1.35 respectively, indicating that producing alumina by dross process had better environmental benefits.

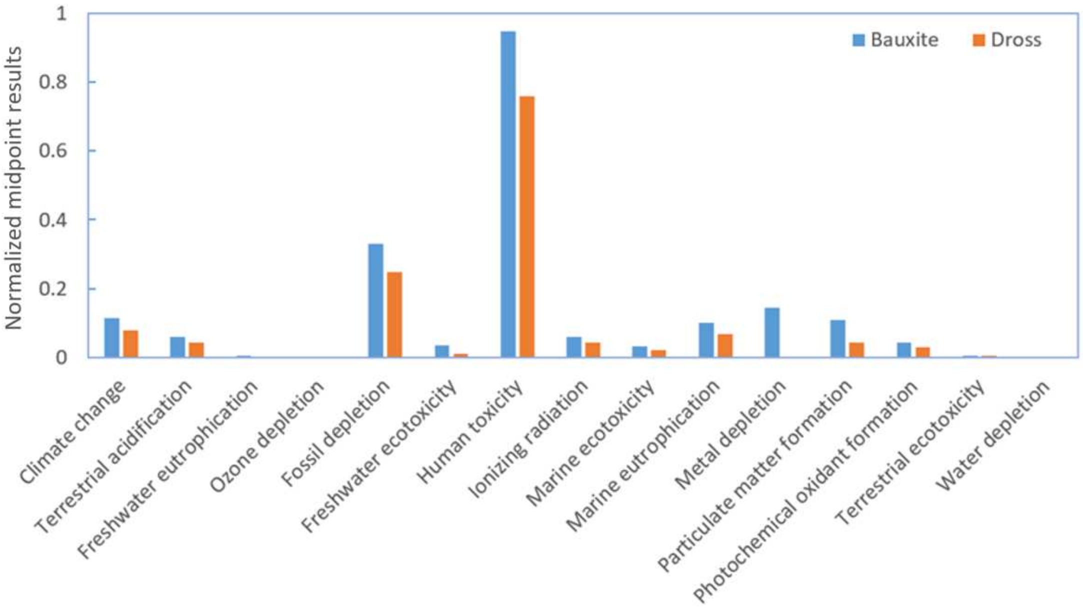


Fig. 2. Normalized midpoint results

3.3. Sensitivity analysis

Figure 3 presented the sensitivity analysis results of main contributors (steam, sodium hydroxide, and sulfuric acid) for both processes. The amounts of these main contributors were reduced by 5%.

For bauxite scenario, despite the high sensitivity of sodium hydroxide in freshwater eutrophication, ozone depletion, ionizing radiation, and water depletion, steam showed the highest sensitivity in other categories. For dross scenario, due to the reduced use of sodium hydroxide and the introduction of sulfuric acid, the sensitivity of sodium hydroxide to the above categories was reduced absolutely by 1% to 3%, partly replaced by sulfuric acid. Steam showed the highest sensitivity in 12 categories. However, this highlight was not due to the amount of steam but the decrease in the sensitivity of other materials. While the consumption of other resources reduced, steam consumption still accounted for 90.9% of the consumption in bauxite process, making its sensitivity more pronounced. As for electricity and water, neither of the two scenarios showed high sensitivity. Therefore, reducing steam demand or using renewable energy is the key to reducing the overall environmental impact of dross process.

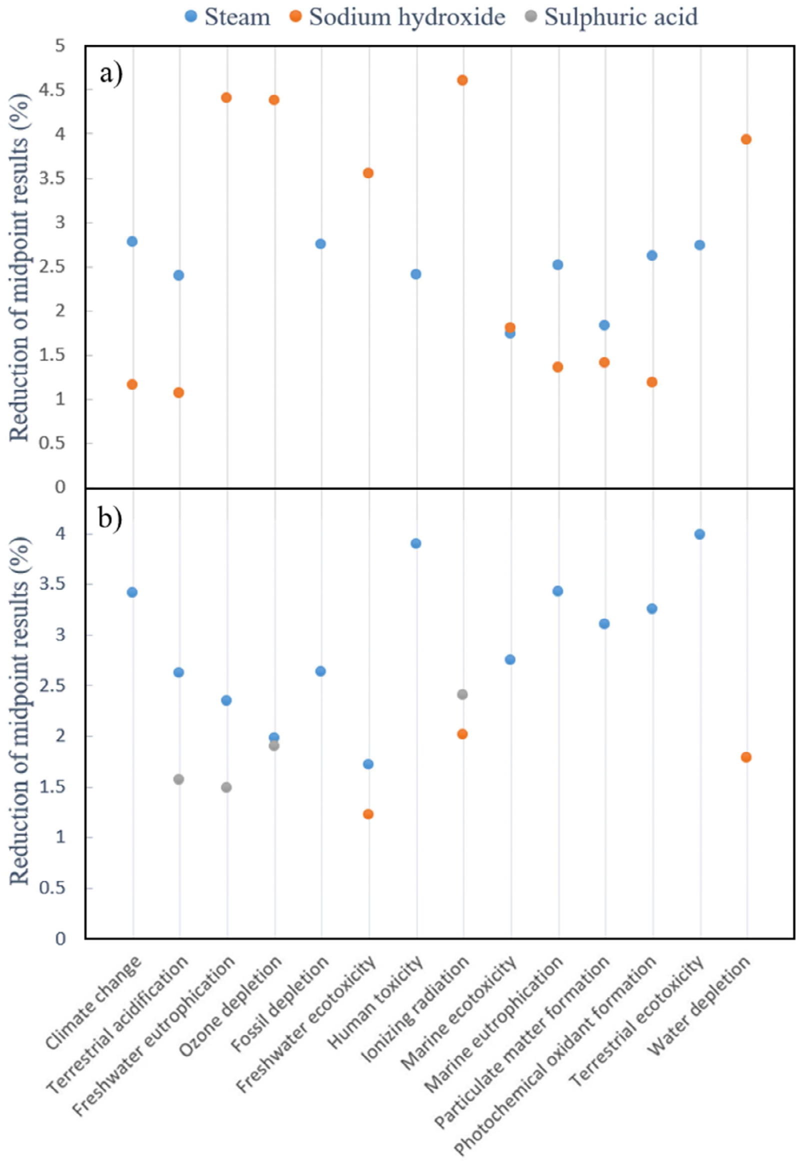


Fig. 3. Sensitivity analysis: a) bauxite scenario, b) dross scenario.

3.4 LCC results

The LCA results proved that the environmental impact of dross process is less than that of bauxite process. In order to find out whether dross process is also superior in economic term, the raw material cost and energy cost of two processes were compared in Table 3. In the calculation, the exchange rate of USD to RMB is set to 1 $ equal to 7.136 ￥.

The total cost of producing 1 t alumina from bauxite was 262.46 $, while the cost of dross process was 130.01 $, accounting for only 49.5% of the bauxite scenario. This gap was mainly caused by the difference in raw material prices. Since secondary aluminum dross was regarded as an industrial solid waste and the dross used in the experiment was freely donated by the enterprise, the price of the secondary aluminum dross was set as 0 $. In fact, due to the dangerous properties of secondary aluminum dross, ordinary companies do not have the processing qualifications (Meshram and Singh, 2018), and even need to spend money to ask other qualified organizations to properly handle the dross. In addition, when producing 1 t alumina, dross process obtained 406 kg ammonium sulfate as a by-product, with a profit of 22.18 $, which was higher than the cost of sulfuric acid, water, and electricity. The absorption of ammonia by sulfuric acid not only reduced its pollution to the atmosphere, but also achieved economic benefits.

Table 3

LCC results of two processes

Materials	Price	Units	Cost [$]	
			Bauxite scenario	Dross scenario
Bauxite	52.971	$/t	131.37	0
Secondary aluminum dross	0	$/t	0	0
Lime	11.911	$/t	0.38	0
Sodium hydroxide	197.590	$/t	12.15	11.26
Steam	28.728	$/t	69.81	63.49
Water	0.392	$/t	0.78	0.49
Electricity	0.149	$/kWh	25.10	31.79
Natural gas	0.315	$/m3	22.86	7.38
Sulfuric acid	51.850	$/t	131.37	15.61
Total			262.46	130.01

Figure 4 shows the environmental impact coupled with economic costs of the key material used in dross process. The Y axis shows the economic cost of water, sodium hydroxide, sulfuric acid, electricity, and steam. The X axis represents the sum of normalized values of all environmental impact categories for each material. As can be seen, the polyline continues to extend to the upper right, meaning that for dross scenario, the environmental loads of materials are proportional with the economic costs. The use of steam brought the largest environmental impact and consumed highest economic costs. Environmental pollution and economic costs caused by electricity cannot be ignored neither. Therefore, reducing the use of steam and electricity or using clean energy could be the key to reducing the environmental impacts as well as economic costs of secondary aluminum process.

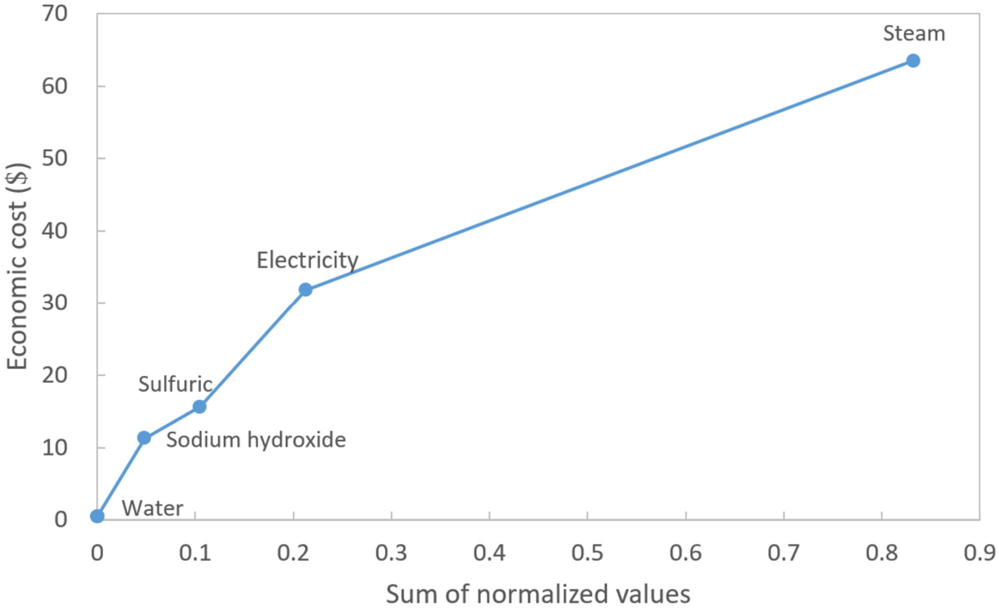


Fig. 4. Environmental impact coupled with economic costs analysis for dross process

4.Discussion

4.1 Unit analysis

Due to the differences in the partial process of two scenarios, the gas production unit and the gas absorption unit are unique in dross process. To further optimize the environmental benefits of the dross process, it is necessary to identify the environmental impact of these two units. Figure 5 shows the ratio of the LCA midpoint values of these two units to the total values of the entire process.

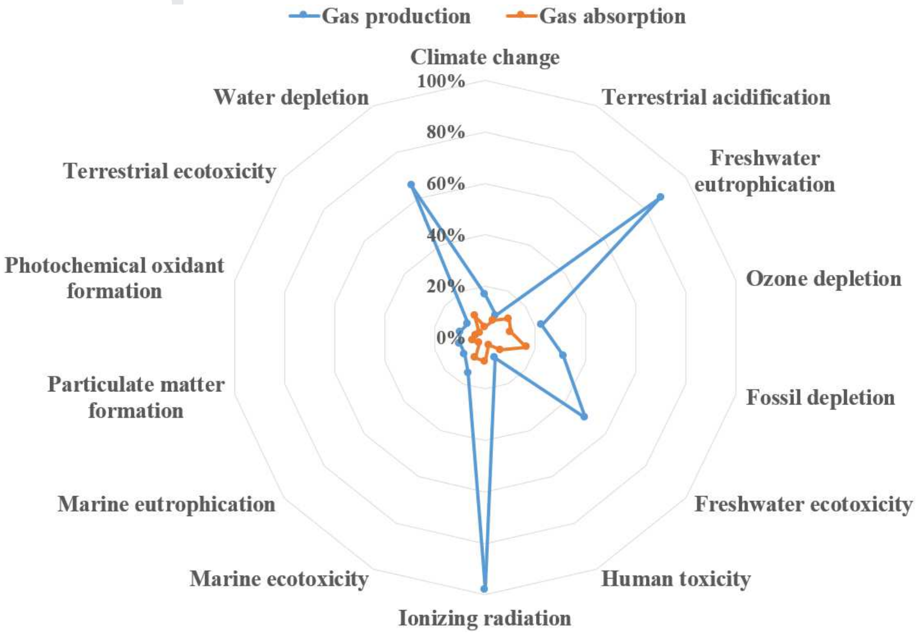


Fig. 5. Proportion of the characteristic values of two unique units

In the gas absorption unit, the proportion was relatively small because of the low material and energy input in this unit. Fossil depletion had the highest proportion of 16%. As the main input of this unit, sulfuric acid used in the process was produced from pyrites. During the production of pyrites, high-temperature processing and catalytic heating reaction were required, leading to high energy consumption (Yuan and Wang, 2012). Together with the input of electricity and water, fossil depletion accounted for the largest proportion.

In the gas production unit, freshwater eutrophication, freshwater ecotoxicity, ionizing radiation, water depletion and fossil depletion accounted for a large proportion of the total characteristic values. The characteristic value of ionizing radiation in gas production unit accounted for 98.0% of that value of the whole process, which was mainly caused by the consumption of sodium hydroxide for dissolving secondary aluminum dross. In addition, sodium hydroxide also exacerbated freshwater eutrophication and ecotoxicity to some extent. Furthermore, in order to prepare the sodium hydroxide solution and reach the reaction temperature, this unit also consumed a large amount of water as well as electricity, resulting in large proportion of water and fossil depletion. However, despite of the environmental hazards caused by sodium hydroxide in dross process, the bauxite process also required large amounts of sodium hydroxide, which was even 8% higher (Zhang et al., 2016).

4.2 Key substances identification

Identifying key substances emitted by the two processes is beneficial to better analysis of their environmental impact. Figure 6 shows the key substances produced by two processes that mostly affecting the climate change and fossil depletion. Since carbon dioxide is the main cause of global warming, the key substances of climate change for both processes were identified as carbon dioxide, with a proportion over 92%. Methane and Nitrous oxide accounted for about 2% of the contribution. Although the distributions of key substances in two scenarios were similar, the characteristic value of dross process was lower, therefore resulting less greenhouse gas emissions. Additionally. the key substances of fossil depletion in two scenarios were quite different. On the one hand, high energy consumption of bauxite process led to the high proportion of natural gas. On the other hand, secondary aluminum dross process consumed 44.86 kWh more electricity than the bauxite process when producing 1 t alumina, leading to higher contribution of coal based on China's current power generation mode. As the backward small power plants gradually shutting down, the energy source of electricity will be much cleaner (Cui et al., 2012; Wang et al., 2019). Furthermore, it can be reasonably inferred that if dross process can be industrialized after years, electricity consumption and overall energy demand will be significantly reduced (Zhang et al., 2015). Technology development will bring 50% reduction in greenhouse gas emission factors after 10 years (Liu et al., 2016).

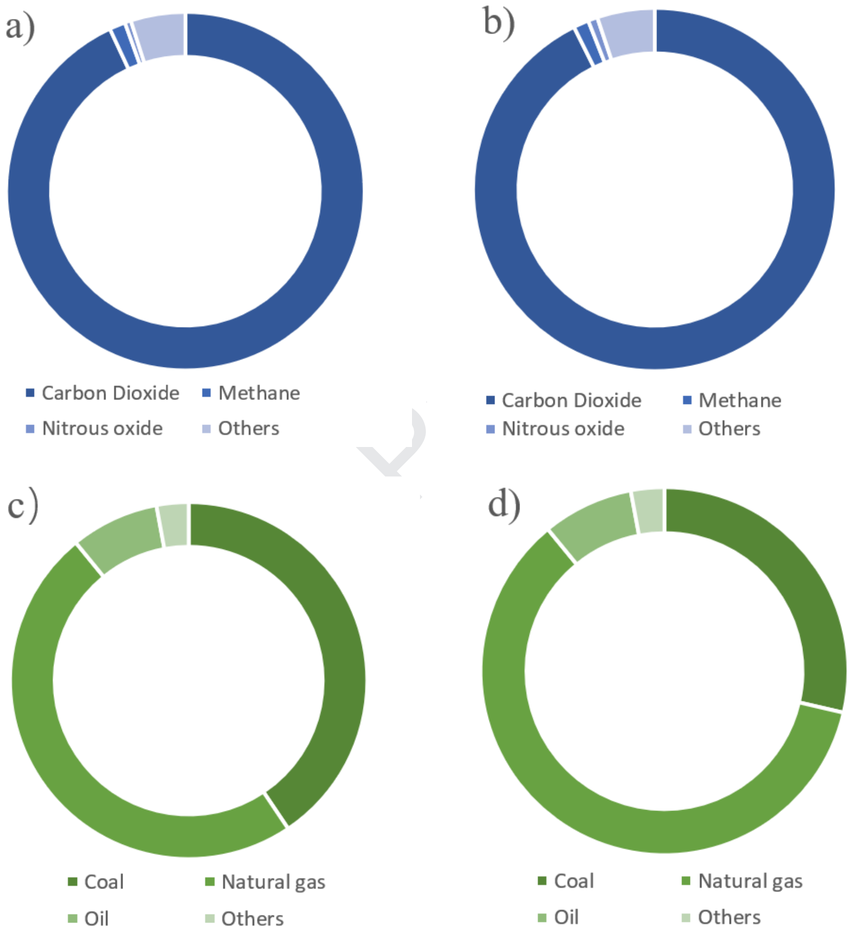


Fig. 6. Contribution of significant substances to the midpoint score: a) Climate change from dross scenario, b) Climate change from bauxite scenario, c) Fossil depletion from dross scenario, d) Fossil depletion from bauxite scenario.

4.3 Scenario analysis

Compared with the bauxite scenario, dross scenario represents lower economic costs and higher environmental benefit in all categories. According to the coupled LCC and LCA in Figure 4, the environmental and economic burden of dross scenario was mainly due to the strong dependence on steam and electricity. In order to further reduce the environmental impact caused by dross process, adjusting its energy structure was proposed.

4.3.1 Steam material replacement

Table 2 identified the key processes in most categories as steam, which was produced from coal at 95% efficiency in the original calculation. As mentioned in section 2.4, two new scenarios using natural gas based steam were proposed. Table 4 shows the changes of characteristic values of 10 categories that are most affected by steam.

When using natural gas as raw material to produce steam at 85% efficiency, the characteristic values of all environmental categories except fossil depletion significantly decreased. When utilization rate increased from 85% to 95%, the characteristic values were further decreased. Human toxicity, particulate matter formation and terrestrial ecotoxicity showed the largest decline, all of which exceeded 50%. Since the characterization factor of natural gas in the fossil depletion category is slightly higher than that of coal (Steubing et al., 2016), fossil depletion showed a small increase of 9.91%. However, denying the use of natural gas based on only one indicator is unreasonable. From other evaluation indicators of the ReCiPe model (Goedkoop et al., 2014; Sleeswijk et al., 2008), the small increase in fossil depletion was followed by a tremendous improvement in the environment and human health. Obviously, the advantages of using natural gas as the steam material outweighed the disadvantages. Besides, if the utilization efficiency of steam is improved, the characteristic value of fossil depletion may also decrease. Furthermore, changes in steam production materials will also lead to changes in economic costs. Producing 1 t steam at 95% efficiency consumes about 75.82 m^3 natural gas, 21.62 kWh electricity, and 0.17t water (Althaus et al., 2007). Based on the production of 1 t alumina, compared with the original steam cost of 63.49 \$, the cost of producing steam with natural gas would be 60.05 \$. Therefore, while the environmental impact was greatly reduced, the economic cost also reduced by 2.65%.

Table 4

Changes of characteristic values in new scenarios

Categories	Changes of Characteristic Values/%	
	85% Natural Gas	95% Natural Gas
Climate change	-14.65	-20.20
Terrestrial acidification	-42.00	-43.00

Fossil depletion	19.44	9.91
Freshwater ecotoxicity	-27.20	-27.92
Human toxicity	-76.70	-76.80
Marine ecotoxicity	-49.08	-49.69
Marine eutrophication	-31.34	-35.20
Particulate matter formation	-53.85	-54.95
Photochemical oxidant formation	-30.98	-34.51
Terrestrial ecotoxicity	-76.85	-76.95

4.3.2 Electricity structure adjustment

In dross scenario, the environmental impact of electricity ranked second only to steam. Henan, Shandong and Qinghai are the three provinces with the highest primary aluminum production in China (Hao et al., 2016). As mentioned in section 2.4, assuming the electricity composition of dross recovery follows the example of Qinghai, the reduction in environmental impacts is shown in Table 5.

Table 5

Improvement of characteristic values under electricity structure adjustment

Categories	Reduction /%
Climate change	12.58%
Terrestrial acidification	9.94%
Freshwater eutrophication	4.34%
Ozone depletion	14.34%
Fossil depletion	10.07%
Freshwater ecotoxicity	7.70%
Human toxicity	14.30%
Ionizing radiation	5.75%
Marine ecotoxicity	10.76%
Marine eutrophication	13.60%
Metal depletion	0.19%
Particulate matter formation	11.42%
Photochemical oxidant formation	12.83%
Terrestrial ecotoxicity	14.36%
Water depletion	10.60%

After adjusting the electricity structure, all environmental categories showed a certain degree of improvement, mostly over 10%. The reason why the improvement of metal depletion is extremely slight was because the main process in this category is aluminum dross. Since the recovery of second aluminum dross has already achieved environmental benefits in metal depletion, the current result is acceptable. Therefore, if these high aluminum production provinces want to recover alumina from secondary aluminum dross, increasing the proportion of hydro power could be an effective way to solve environmental problems. However, since the aluminum industry is already mature, it is not easy to change the local electricity structure. In this case, dross transportation could be a feasible solution.

4.4 Industrial recommendations

4.4.1 Dross transportation

Transporting secondary aluminum dross from nearby provinces that heavily rely on thermal power to hydropower-type provinces for further recovery could also be a beneficial suggestion. Figure 7 shows the power structure of each province in China. As can be seen, Qinghai could be the transport destination for aluminum dross in Xinjiang and Ningxia, which are also two provinces with high aluminum production. Hubei could be the transport destination for aluminum dross in Henan and Shandong.

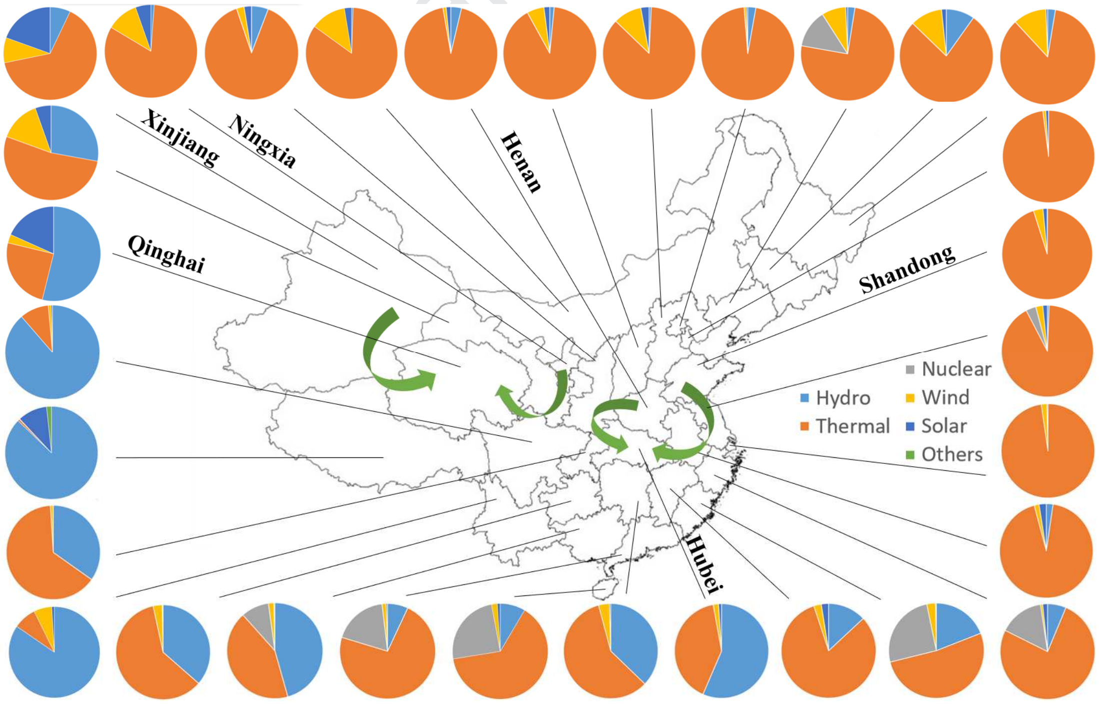


Fig. 7. The power structure of each province in China

Long-distance transportation may cause additional environmental problems, especially climate change and particulate matter formation (Zhang et al., 2016). Transportation distance is the most important factor (Fan et al., 2018). For the case of dross transportation, as the distance increases, the greenhouse gas emissions will gradually increase, eventually exceeding the environmental benefits brought by hydropower. According to the power structure of Qinghai and Ningxia (Yu Chongde, 2018), hydropower replacement can reduce the characteristic value of climate change by 107.7 kg CO_2 eq when producing 1 t alumina. As shown in Figure 8, when dross is transported over 664 kilometers, electricity structure adjustment will no longer be a wise choice. Similarly, when the distance exceeds 945 kilometers, the particulate matter discharged from transportation exceeds the improvement from electricity structure adjustment (0.2646 kg PM10 eq).

Furthermore, Qinghai Province has the lowest industrial electricity price in China at 0.053 \$/kWh. The industrial electricity price in Hubei is similar to that in Shandong and Henan (Yu Chongde, 2018). If using the average hydropower price in Hubei and Qinghai as the standard, the electricity cost can be reduced by 5.64 \$ when producing 1 t alumina. According to trucks' general energy consumption and diesel prices in China (Ministry of Transport of the People's Republic of China, 2018), the cost of 100 km transportation is about 0.717 \$/t. When the transportation distance exceeds 554 kilometers, the economic cost of dross transportation will exceed the original plan. Therefore, from the perspective of economic cost, transporting the dross to Qinghai and Hubei has limited benefits but acceptable.

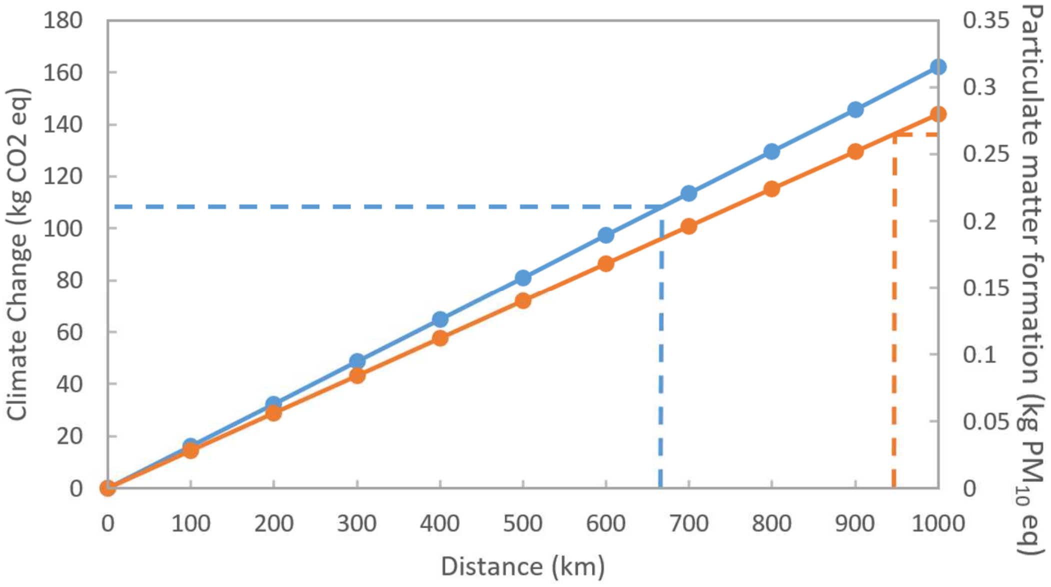


Fig. 8. Relationship between environmental impact and transportation distance

4.4.2 Industry migration

According to bauxite and alumina statistics information from United States

Geological Survey (United States Geological Survey, 2019), compared with other countries, China is facing a dilemma of low reserves and high demand for bauxite. Such situation requires China to increase the utilization of bauxite, which means that the aluminum industry must pay attention to the recovery of million tons of tailings such as secondary aluminum dross. Since dross recovery is the end industry of aluminum production and it has not been industrialized, the site selection should particularly focus on the future trends of aluminum industry.

Previous analysis showed that hydropower could bring significant environmental benefits for dross recovery. Therefore, hydropower-type provinces will be suitable construction sites. Similar perspectives were obtained according to the LCA of China’s aluminum industry (Guo et al., 2019; Hao et al., 2016). At the provincial level, industry migration to south and southwest areas (hydropower-type provinces) was reasonable from the perspective of environmental pollution.

According to the mineral resources report from Ministry of Natural Resources of China (Ministry of Natural Resources of the People’s Republic of China, 2019), as the demand for bauxite increases year by year, Henan and Shanxi, which provides bauxite for Shandong, is facing shortage of resources and decline in the bauxite quality. Evaluation of China's bauxite potential indicated that more than 100 million tons high quality laterite type bauxite was discovered in Guangxi Province in recent years. Other southern provinces such as Yunnan, Guizhou and Guangdong were believed having huge exploration potential. The distribution of bauxite shows that aluminum industry will likely migrate from traditional industrial provinces such as Henan and Shandong to southern provinces in the future.

Both policy and environmental factors suggest the south and southwest migration of the aluminum industry. Based on a comprehensive forecast of environmental impact and policy adjustment, Yunnan and Guangxi are the most suitable destinations for the aluminum industry migration and secondary aluminum dross recovery.

5.Conclusion

In this paper, LCA method is used to compare the environmental impacts and economic costs of two processes for producing alumina from secondary aluminum dross as well as bauxite. Both characteristic values and normalized values of all environmental impact categories of the secondary aluminum dross process are lower than the bauxite process. LCC results showed that dross process could reduce the cost of 132.45 $ by producing 1 t alumina compared to bauxite process. The characteristic value caused by sodium hydroxide accounts for the largest proportion of the unique gas production unit in dross scenario, while it’s still 8% lower than bauxite scenario.

The LCA coupled with LCC results showed that the use of steam and electricity were the keys to reducing the environmental impacts as well as economic costs of dross process. Using natural gas as raw material to produce steam instead of coal can significantly reduce the environmental impact of the whole dross process. Increasing the use of hydropower in China’s high aluminum production provinces can generally bring 10% environmental benefits for dross process. Dross transportation within 591 km or south and southwest migration of aluminum industry could be feasible solutions in China.

This study provides data support for the industrialization of secondary aluminum dross recovery. However, the current study has several limitations. Some data of the dross process were based on experiments, which might be small changes in actual industrial production. Some background data were selected from the European database, which may have slight difference from the actual situation in China. Thus, further research on secondary aluminum dross recovery is necessary.

Author Contributions

Jin.Q. and Zhu.X. performed the experiments and designed the life cycle assessment. All authors collected and analyzed the data. Zhu.X. wrote the manuscript with contributions of all the coauthors. All authors have given approval to the final version of the manuscript.

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Qiang Jin: Conceptualization, Methodology, Data curation, Writing- Reviewing and Editing, Supervision

Zhen Ye: Data curation, Writing- Reviewing and Editing

Declaration of interests

☑ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: