Technical Assessment of Industrial Solid Waste Recycling Process Based on the Willingness-to-Pay LCIA Model

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Technical Assessment of Industrial Solid Waste Recycling Process Based on the Willingness-to-Pay LCIA Model

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Abstract. The recycle and reuse of solid waste must consider both the economic and environmental respect. For most of the present environmental technologies, the biggest obstacle for their practical implementation is the economic barrier. For some cases, even the technical process demonstrates the good performance in energy-saving, emission-reduction etc., but it is still hard to be applied due to the high operating cost. For most of the technology assessment and comparison, they are carried out only from the environmental or the economic perspective, and rarely combine the two respects. For assessing the recycle and reuse of solid waste in a more comprehensive manner, the present paper adopted the monetized LCIA method based on the Willingness-to-Pay theory. Based on the proposed method, a LCIA case study on the production process of sintered brick with coal fly ash was carried out. Through monetizing the environmental impact during its production process, it was found that the environmental cost resulted from the production of sintered brick is 8.76E-3Yuan/kg, namely, 8.76 Yuan/ton. The major environmental impact category is global warming, followed by the acidification and suspended particulate matter. In contrast, due to the reuse of industrial wastes as raw materials, the consumption of natural resources only accounts for a minor part of the entire environmental impacts. Therefore, the control of GHG emissions shall be prioritized for the technical optimization.

1. Introduction

Recycle and reuse of the solid waste are effective ways to tackle down the current resources and environmental crisis in China. The solid wastes recycled as the raw materials for production can replace natural resource, but it may also pose extra pollutions to the environments and threats the human health. Therefore, it is necessary to access and optimize the solid waste recycling process from the comprehensive perspective, so as to make full use of the resource properties and avoid the occurrence of secondary pollution.

At present, life cycle assessment (hereinafter referred to as "LCA") is the well-accepted method for the measurement of the environmental burden. According to the definition of United Nations Environment Programme, "LCA is a tool to assess environmental impacts associated with all the stages of a product system's life cycle from raw material extraction through materials processing, manufacture, packaging, marketing, use, reuse and maintenance, and disposal or recycling." Although different institutes and organizations may have slightly different understandings about LCA, the general LCA procedure follows similar framework. According to the ISO 14040 standards, a Life Cycle Assessment is carried out in four inter-correlated phases, namely, goal and scope definition, inventory analysis, impact assessment and interpretation, as illustrated in Figure 1 [1]:

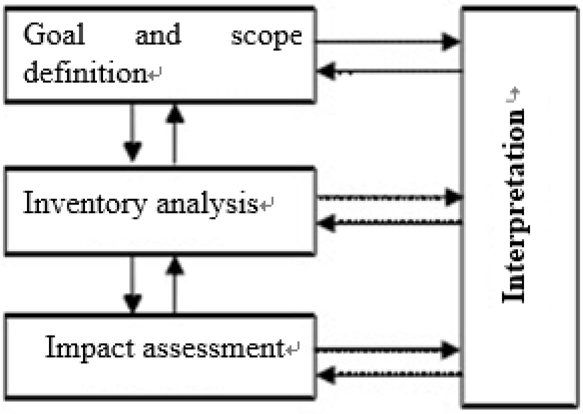

Figure 1. Technical Framework of LCA

Theoretically, the assessment of industrial solid waste recycle process shall follow the LCA framework as shown in Figure 2. However, due to the substitution of conventional materials with solid wastes, the waste recycle process must be taken into consideration. The extra transportation and energy required due to the usage of the solid wastes also need to be included as shown in Figure 2. It is also important to note that these processes usually do not occur in sequence or go on simultaneously. Instead, they are interrelated and exist in the very complex manner, while the boundaries of all links are not clear. Therefore, sometimes, appropriate hypothesis and simplification shall be made for the relevant system during the assessment process.

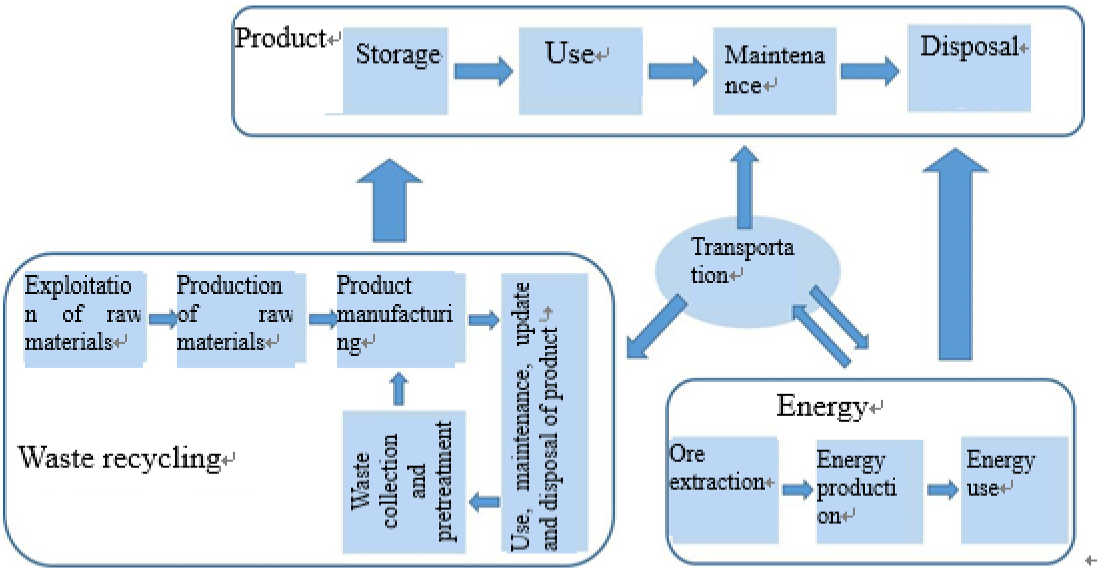

Figure 2. Life Cycle of Industrial Solid Waste Recycling Product

LCA study needs to define the system boundary in accordance with the purpose. To ensure the completeness of assessment, the indispensable processes must be incorporated. However, the scope mustn't be overextended. The collection of solid waste, for instance, can be excluded, whereas the pretreatment of the wastes specifically for the production must be taken into consideration. The consistency matter and energy flow also need to be ensured throughout the entire system.

For the case study, the present research analyzed the production process of sintered bricks with coal fly ash. China has always been the major producer of bricks, with the annual output of more than 800 Billion bricks. With the emerging resources problem in recent years, the production of sintered solid bricks is subject to certain restrictions, while the percentage of hollow bricks is gradually rising every year. Waste slag, coal fly ash and other solid wastes are also commonly used to replace the natural resources. This study intends to calculate the environmental impacts posed by the typical sintered brick production, so as to provide the suggestions for the technical improvement of sintered bricks.

2. Study Method

The relevant study and application of LCA in China has been lag behind compared to the developed countries and regions. On the basis of the ISO 14040 series standards, China enacted the GB/T 24040 *Environmental Management - Life Cycle Assessment - Principles and Framework* [2], GB/T 24042 *Environmental Management--Life Cycle Assessment - Life Cycle Impact Assessment* [3], and GB/T 24043 *Environmental Management - Life Cycle Assessment- Life Cycle Interpretation* in 1999 [4]. At present, China also has a few LCA databases [5,6], which incorporate the background LCA data in terms of energy [7,8,9], iron & steel [10,11], non-ferrous metals & building materials [12,13,14], high polymer materials [15,16] and other basic products. In recent years, China has also gradually carried out the LCA study on cars, TVs, Air Conditioners, and other complex products. The inventory allocation method, data quality, uncertainty analysis and other methodology research have also been conducted [17, 18, 19].

For the life cycle impact assessment, there are three models have been proposed in China, namely, target distance model, willingness-to-pay model and expert choice model. The major differences among them are the weighting basis.

2.1. Target Distance Model

Based on the concept framework at the LCA impact assessment of SETAC & ISO, Yang et al established the assessment model as shown in Figure 3. This method firstly converts the inventory data into the environmental impact categories via the characterization, and then standardizes the environmental impacts with the national per capita index (or unit space indicator) of all environmental impacts as the reference value, and obtains the relative value. The weight of different impact categories are determined by the target distance method. The severity of certain environmental effects shall be demonstrated by the distance between the current level and target level (standard or capacity) of such effect [20], which is shown in Table 1.

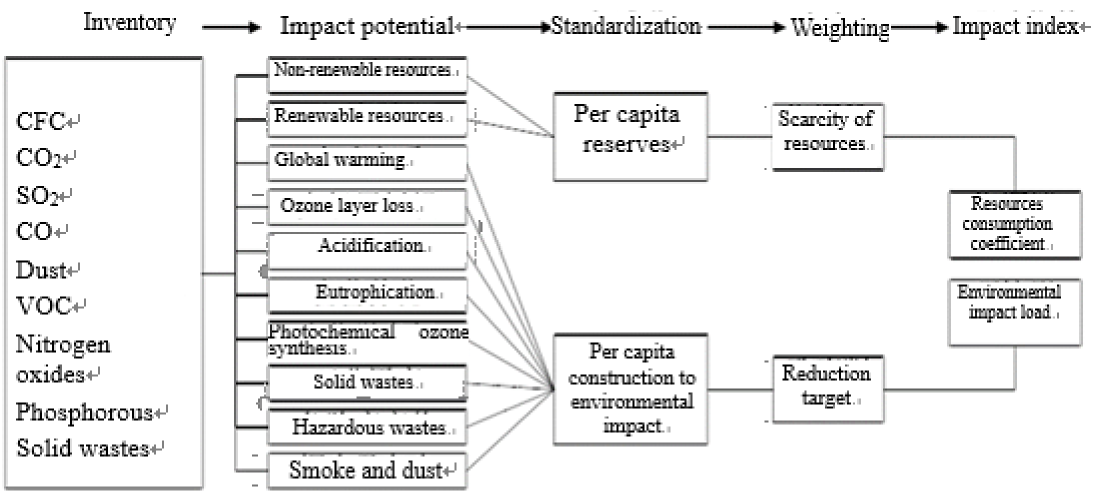

Figure 3. Target Distance Model of Environmental Impact Assessment

Table 1. Environmental Impact Weight Determined by the Target Distance Method

Impact Category	Global Warming	Ozone Layer Loss	Acidification	Eutrophication	Photochemical Ozone Synthesis	Solid Wastes	Hazardous Wastes	Smoke & Dust
Weight	0.83	2.7	0.73	0.73	0.53	0.62	0.45	0.61

Table 2. Resources Weight Determined by the Target Distance Method

Resources	Service Life (a)	Weight	Resources	Service Life (a)	Weight
Oil	43	0.023	Copper	36	0.027
Coal	172	0.006	Nickel	52	0.019
Lignite	387	0.003	Manganese	86	0.012
Natural Gas	61	0.016	Lead	21	0.049
Iron	119	0.008	Antimony	30	0.034
Aluminum	195	0.005	Timber Production Forest	16	0.063
Zinc	20	0.051	Water	1	1.000

2.2. Willingness-to-Pay Model

Zhang et al construct their assessment model as shown in Figure 4. In the weighting process, the significance of environmental impacts is represented with the economic cost that shall be paid to mitigate the ecological damage resulted from such impact. Such method is based on the willingness-to-pay theory in the environmental economics, where the environmental tax and resources tax are used as the evidence to determine the weight [21].

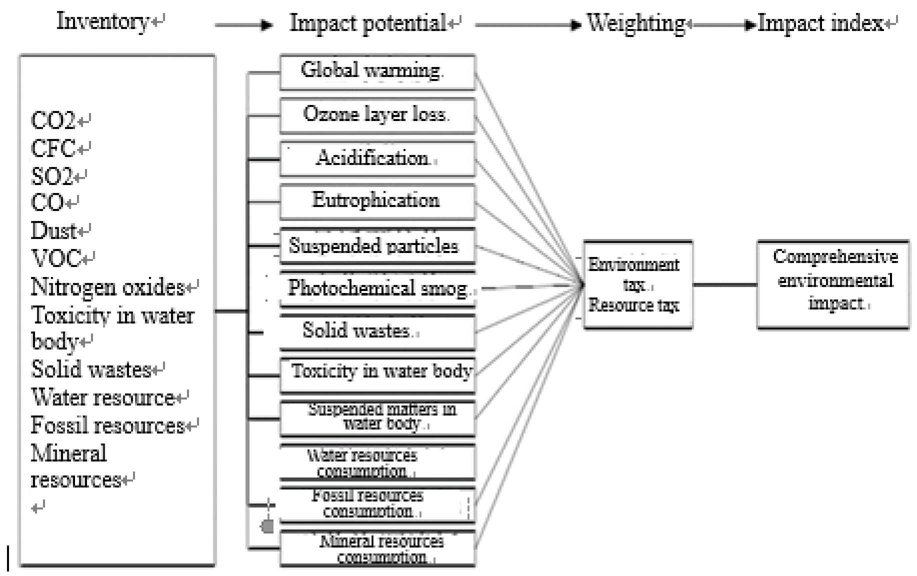

Figure 4. Willingness-to-Pay Model of Environmental Impact Assessment

For the project that does not determine the environmental tax and resources tax, the calculation process of its weighting indicator is as shown in the equation below:

$$w_i = \sum_j (e_{ij} \cdot c_{ij}) \quad (i,j = 1,2,3\ldots\ldots) \tag{1}$$

Where, w_i refers to the weight factor, while c_{ij} refers to currency factor, namely, the discharge fee of such pollutant, but its unit of measurement shall be measured with the impact factor (for instance, the unit of measurement for the currency factor of SO_2 is RMB/ kgeq.SO_2); Besides, e_{ij} refers to the overall impact potential coefficient of pollutant number j under the environmental impact number i. Obviously, it is not only related to the contamination capacity of pollutant, but also related to the total discharge amount of such pollutant. An environmental impact may be resulted from variable pollutants. Therefore, during the weight calculation process, only several typical pollutants will be selected for an impact category. For instance, only SO_2, NO_x & NH_3, these three substances are selected for the acidification calculation. The calculation method of impact potential coefficient is as shown in the equation below:

$$e_{ij} = \frac{f_j \cdot a_j}{\sum_j (f_j \cdot a_j)} \text{ (i,j = 1,2,3……)} \quad (2)$$

Where, f_j refers to the unit impact potential coefficient of pollutant number j, while a_j refers to the annual discharge amount of pollutant number j. Partial environmental impact and resources consumption category weight taken from the aforesaid method is as shown in Table 3. Such weight has the dimension, while its demonstration is the price of unit environmental impact. The unit of integrated environmental impact calculated and taken from such method is Yuan or RMB.

Table 3. Environmental and Resources Weight (Partial) Determined by Willingness-to-Pay Method

Impact Factor	Weight (RMB/kg)	Impact Factor	Weight (RMB/kg)
Global Warming (CO_2 Equivalent)	0.01	Water Resources	Regional Variety
Ozone Layer Loss (ODP Equivalent)	15.36	Iron Ore	0.0171
Acidification (SO_2 Equivalent)	0.74	Limestone	0.002
Eutrophication (NO_3^- Equivalent)	0.58	Bauxite	0.02
Suspended Particles	0.19	Zinc	0.003
Solid Wastes	0.06	Copper	0.0014
Photochemical Pollution (C_2H_4 Equivalent)	3.41	Manganese	0.002
Toxicity of Water Body (Pb Equivalent)	6.04	Kaolin	0.003
Suspended Matter in Water Body	0.175	Fluorite	0.02
Fossil Energy (Standard Coal Equivalent)	Regional Variety	Saline Rock	0.025

2.3. Expert Choice Model

Gu adopts the endpoint damage model to quantify the environmental impact, as shown in Figure 5 [22]. This method selects four endpoint environmental impact categories, namely, resource depletion, energy depletion, human health damage and ecological damage. When the mineral resources consumption is calculated, this method defines the scarcity factor of iron ore as 1, while the scarcity factor of other depletable resources is the relative value comparing to the iron ore. For the farmland, forest and water resources which are theoretically renewable but extremely scarce at present, their scarcity factors are independently analyzed. The resource scarcity factors in this method are as shown in Table 4. The resource depletion amount is the sum product of weight of all resources and their scarcity factors. This method makes a difference between the fossil energy and normal mineral resources. When the consumption of fossil energy is calculated, it defines the energy quality coefficient, namely, the specific value of energy's ability to do work and its total energy, as shown in Table 5. The depletion amounts of all energies are jointly calculated and taken as per their caloricity and energy quality coefficient, which not only considers the caloricity variation of different energies, but also considers the quality difference of different energies. Then, after conducting the questionnaire survey to 130 plus experts from the relevant fields, it determines the weight of four categories of endpoint environmental impact, as shown in Table 6, while the integrated assessment indicator, namely, environmental load is further taken via weighting, and its unit of measurement is defined as point (hereinafter referred to as "pt").

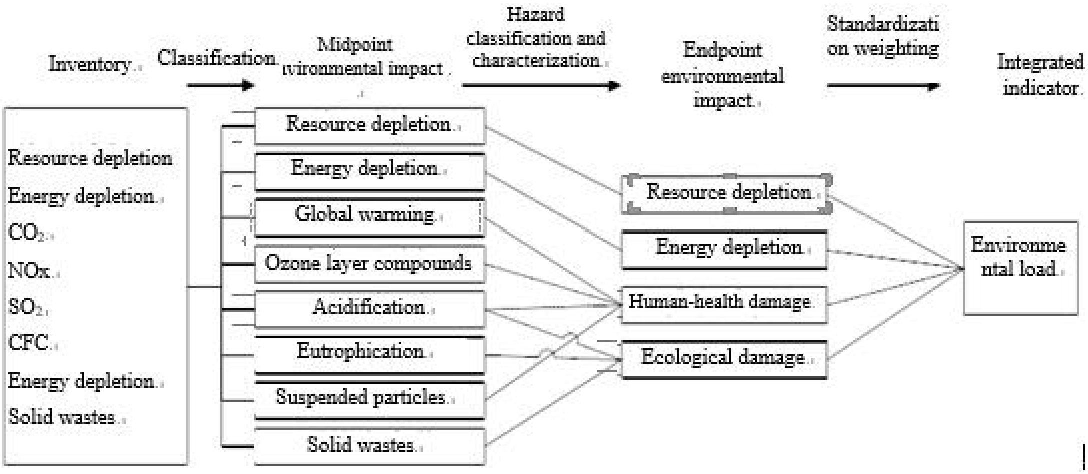

Figure 5. Expert Marking Model of Environmental Impact Assessment

Table 4. Environmental and Resources Weight Determined by Willingness-to-Pay Method

Resource	Service Life (a)	Weight	Resource	Service Life (a)	Weight
Iron Ore	190	1.00	Cement Limestone	500	0.38
Manganese Ore	64	2.98	Glass Silica Gel	434	0.44
Zinc Ore	94	2.02	Fluorite	500	0.38
Tin Ore	84	2.25	Gypsum	500	0.38
Copper Ore	76	2.51	Marble	500	0.38
Bauxite	345	0.55	Farmland	43	4.37
Saline Rock	500	0.38	Forest	-	3.84
Kaolin	500	0.38	Water Resources	-	0.0075

Table 5. Energy Quality Coefficient of Three Fossil Resources

Resource Category	Coal Ore	Oil	Natural Gas
Energy Quality Coefficient	0.35	0.46	0.52

Table 6. Weight of Four Endpoint Environmental Impacts

Endpoint Impact	Resource Depletion	Energy Depletion	Human Health Damage	Ecological Damage
Weight	0.27	0.28	0.22	0.23

All abovementioned three methods are developed based on China's context. The Target-Distance and willingness-to-pay models have more environmental impact categories and it is hard to weight, but the quantitative mechanism is much simpler. Whereas, the third method makes the secondary category. Therefore, there is less endpoint environmental impact number, and it is easy to determine the weight, but the quantitative mechanism is very complex. For weight decision, the target distance method may be related with the national policy and highlight the key social problems at present. However, the environmental policies generally have much stronger phased and regional characteristics and are prone to be affected by the non-environmental factors. Once any change occurs to the target, great changes may occur to the results. As mentioned above, for the expert marking method, its biggest problem is that it has much higher requirements upon the expert's personal quality and requires the experts to have the much stronger ability of macroscopically handling the interdisciplinary or multidisciplinary problems. Therefore, this method also has a certain limitation or controversy for its application. Combined with the reality of China's industrial solid waste recycling, this paper finally selects the willingness-to-pay method as the LCIA method, which has the advantages and disadvantages as shown in Table 7.

Table 7. Advantages & Disadvantages of Conducting the LCIA of Industrial Solid Waste Recycling Product with the Willingness-to-Pay Model

Pro	Con
1. It directly introduces the economic indicator in the form of weight, while it is the only one with the dimension among all three methods. Besides, it is simple and intuitive to assess the environmental impact in currency unit, which can be directly correlated with the cost, revenue and other data of the product; 2. It has many data sources, such as environmental tax, energy tax, resource tax, pollution discharge fee. Meanwhile, it has multi-layers within the temporal and spatial scope, such as the worldwide/ nationwide/ within the province, city or region and even the industry; 3. It has the timeliness property, which can demonstrate the current hot-spot issues of concern, especially regarding resource consumption. It can directly reflect the market impact. Therefore, the obtained assessment results is much easier to be accepted by the market; 4. It is featured in simple structure and low technical threshold. Relatively speaking, it is the easiest manner to realize the modularization and software-based operation among all three analysis methods, easy to be promoted and convenient to be applied.	1. China's environmental tax and resource tax system is still not perfect. Especially for environmental tax, many environmental impacts are still not levied with taxes. Meanwhile, the existing environmental tax amount is generally much lower, while the environmental tax is often subject to the macro-control policy and cannot completely equal to "economic cost required for environmental recovery". 2. It is difficult to reflect the priority relationship of all environmental factors in a long-term and objective manner. Instead, it is much suitable to solve the current short-term prominent problems. However, when the long-term planning problem is encountered, it will be subject to the much larger temporal and spatial restrictions; 3. Compared with the other two methods, willingness-to-pay method lacks the professional theoretical support (experts do not participate during the whole process.)

3. LCA Analysis of Sintered Brick with Coal Fly Ash

3.1. Scope of Study

The determination of study scope is to define the system boundaries of LCA assessment. Theoretically, the life cycle assessment shall include the whole process of the assessment object, from its cradle to its grave, namely from extraction of raw materials to final disposal of wastes. However, due to time and data source limitations, generally, a certain definition shall be made for the system boundaries. This study defines the scope of study as the production process of sintered brick. Therefore, the system boundary starts from extraction of raw materials and ends with the termination of production process, as shown in Figure 6. Compared with other materials, the production process of sintered brick is much simpler, while the process flow is much shorter. The raw materials involved in the production mainly include the shale, coal gangue, coal fly ash, slag, etc. Meanwhile, the consumed fuels mainly include the coal and electricity, while a certain amount of CO_2, SO_2 and other environmental pollution gases are excluded.

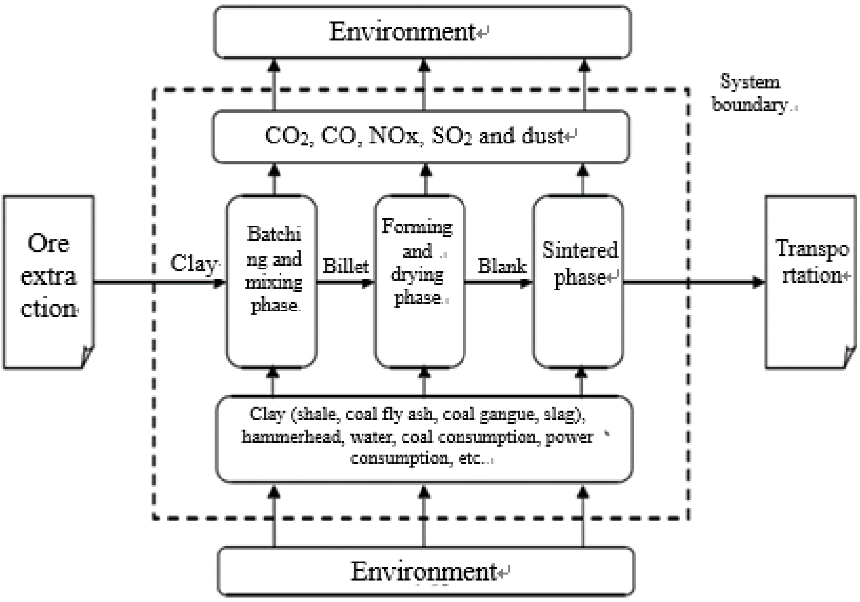

Figure 6. System Boundary of LCA Assessment in the Sintered Brick Manufacturing with Coal Fly Ash

3.2. Inventory Analysis

During the manufacturing process of sintered bricks, the energy and resources are consumed, while all sorts of environmental discharge will also be followed. These variable environmental impacts shall be accounted for. The relevant data in the case study mainly comes from 30 plus varying-scale sintered brick manufacturers located in different regions, such as Inner Mongolia, Sichuan, Guizhou, Guangxi, Hunan, Shandong, Henan, Lanzhou, Tianjin, Jilin and etc. After the data supplement and correction, it can almost reflect the present production level and energy consumption level of China's sintered wall materials. The study period, namely, the data acquisition period was in 2007.

3.2.1. Energy Consumption Analysis. The sintered wall brick industry not only consumes a great amount of natural resources, but also consumes a great amount of fossil energies during its production process, which may have impacts upon China's coal, power and other energy industry. In recent years, due to the introduction of "prohibition of solid bricks and restrictions of clay use" and other acts, China's sintered wall materials enterprises have paid more attention to the recycling of coal fly ash, coal gangue and other calorific wastes, which leads to the reduction of coal and power consumption in 2007. The integrated energy consumption was reduced from the 988kgce/ 1×10^4 standard bricks in 2000 to 900kgce/ 1×10^4 standard bricks in 2005, and then to 812kgce/ 1×10^4 standard bricks in 2007, decreased by 8.9% & 9.7% respectively. Anyhow, due to the great output of China's sintered brick, the absolute amount of energy consumption is still very frightening. As per the statistics, the energy consumption of wall materials industry accounts for about 5% of the national process energy consumption, while the sintered wall materials industry is also the major energy consumer of wall materials. As per the typical survey and integrated measurement, and with reference to the calculation methods in the national resource consumption estimates, the major energy consumption details of sintered brick & tile industry in 2007 is taken as shown in Table 8.

Table 8. Major Energy Consumption Conditions of Sintered Brick Manufacturing with Coal Fly Ash

Energy Consumption Items	Coal (kg/kg Brick)	Electricity (KWh/kg Brick)	Fuel (kg/kg)
Amount	7.61E-03	4.36E-02	9.31E-05

3.2.2. Resource Consumption Analysis. During the entire manufacturing process of sintered bricks, totally 7 major raw materials are consumed, as shown in Table 9.

Table 9. Major Raw Materials Consumption Conditions of Sintered Brick Manufacturing with Coal Fly Ash

Resource Item	Shale	Coal Gangue	Coal Fly Ash	Slag	Hammerhead
Amount (kg/kg)	1.30E+00	2.92E-01	1.49E-01	1.25E-01	2.71E-04

Among which, the hammerhead is one of the steel crushing tool used during the raw materials crushing process, while its damage is the consumption of iron resources in fact. For the hammerhead manufacturing process inventory, please refer to the iron & steel manufacturing process mentioned in the master thesis of ZHOU Hemin, while its resource consumption and discharge inventory is as shown in Table 10.

Table 10. Functional Resource Inventory of Hammerhead Manufacturing

Impact Category	Resource Item	Amount (kg/kg Hammerhead)
Resource Consumption	Dolomite	8.52×10^{-2}
	Fluorite	1.80×10^{-2}
	Steel Scrap	1.72×10^{-1}
	Iron Ore	2.05
	Limestone	1.78×10^{-1}
	Manganese Ore	4.64×10^{-2}
	Silicon Ore	9.90×10^{-4}
Energy Consumption	Coal	2.59
	Fuel Oil	1.25×10^{-3}
Pollutant Emission	CO_2	2.42
	SO_2	3.69×10^{-3}
	NOx	8.63×10^{-4}
	CO	2.05×10^{-4}
	Industrial Dust	5.67×10^{-3}

3.2.3 Pollutant Emission Analysis. The emissions resulted from the enterprise production process mainly *include* the SO_2, HF, NOx, CO_2 and others contained in solid waste dust, smoke dust and flue gas. Due to the variable raw materials & coal quality and equipment level used by enterprises, and the different emission amount, as well as the imperfect surveillance mechanism, there are some sintered brick manufacturers without providing the emission data and the emission amount of their manufacturing wastes is unknown. The emission amount of the relevant wastes is herein estimated with the empirical formula, as shown in Table 11.

Table 11. Pollutant Emission Conditions of Sintered Brick Manufacturing with Coal Fly Ash

Pollutant Emission	CO_2	SO_2	NOx	CO	CH_4	Industrial Dust
Amount (kg/kg)	9.61E-02	3.41E-04	5.43E-05	3.20E-05	1.84E-05	8.38E-04

After combining the resource consumption, energy consumption and pollutant emission of all the aforesaid processes, the life cycle inventory of sintered brick manufacturing process is taken, as shown in Table 12. Among while, the relevant data of shale extraction, power generation process and coal production come from Gu's *Studies on the Environmental Impact of the Building Industry in China*

Based on the Life Cycle Assessment [23] and Di's *Several Fundamental Researches in the Life Cycle Assessment for Mineral Resources and Materials* [24].

Table 12. Input & Output Inventory during the process of Sintered Brick Manufacturing with Coal Fly Ash (kg/kg Brick)

	Sintered Brick Manufacturing	Shale Extraction	Hammerhead Production	Coal Production	Power Generation	In Total
Shale	1.30E+00					1.30E+00
Coal Gangue	2.92E-01					2.92E-01
Coal Fly Ash	1.49E-01					1.49E-01
Slag	1.25E-01					1.25E-01
Dolomite			2.31E-05			2.31E-05
Fluorite			4.88E-06			4.88E-06
Steel Scrap			4.66E-05			4.66E-05
Iron Ore			5.55E-04			5.55E-04
Limestone			4.82E-05			4.82E-05
Manganese Ore			1.26E-05			1.26E-05
Silicon Ore			2.68E-07			2.68E-07
Coal		3.97E-04	7.01E-04	5.63E-03	3.79E-03	1.05E-02
Oil		9.17E-07	3.39E-07	4.47E-06	8.82E-05	9.39E-05
Natural Gas		3.33E-05		2.67E-10	6.59E-05	9.92E-05
CO_2	9.61E-02	3.56E-03	6.55E-04	3.22E-05	7.28E-03	1.08E-01
SO_2	3.41E-04	7.86E-06	9.99E-07	3.88E-08	4.14E-05	3.91E-04
NOx	5.43E-05	1.60E-05	2.34E-07	2.23E-07	4.34E-05	1.14E-04
CO	3.20E-05	5.85E-06	5.55E-08	2.69E-08	1.10E-05	4.89E-05
Dust	8.38E-04	2.56E-06	1.54E-06	4.43E-08	1.81E-05	8.60E-04
Industrial Wastes			3.58E-06	2.56E-04		2.60E-04
CH_4	1.84E-05	4.91E-06		4.54E-05	2.20E-05	9.07E-05
COD			2.59E-09		4.99E-07	5.02E-07

As shown from the life cycle inventory results, the major resources consumption during the manufacturing process of sintered brick with coal fly ash is shale consumption, with the amount of 1.30kg/kg brick, while the major energy consumption is raw coal, crude oil and natural gas, and the major gas emission is CO_2, with the amount of 0.129kg/k brick. If analyzed as per each production phase, the sintered brick manufacturing and power generation process are the major source of pollutants during the whole life cycle. It is noteworthy that the water consumption is not incorporated into this inventory, due to the great variation of relevant data and the extensive application of recycling water or intermediate water in all processes. Therefore, this paper temporarily does not consider the water resources consumption during the life cycle of sintered bricks.

4. Monetized Life Cycle Impact Assessment (LCIA)

The inventory analysis results only reflect the environmental consumption amount and pollutant emission amount involved in the life cycle of sintered brick. In order to more clearly demonstrate the environmental problems related to the energy & resources consumption and pollutant emission of sintered brick manufacturing, it is required to allocate the inventory results into the variable environmental impact categories and characterize the selected environmental problems, characterize the use category parameters, and also interpret the life cycle inventory results.

4.1. Classification

As the technical framework of the LCA specifies, it is required to incorporate the resources consumption and pollutant emission inventory data into the variable environmental impact categories. This paper adopts the internationally almost generally accepted impact category, category parameters and environmental load category. Meanwhile, it also adopts the equivalent assessment model extensively applied in the LCA at present, and classifies the resources and pollutants involved in the inventory of sintered bricks into the twelve environmental impact categories determined in the aforesaid Willingness-to-Pay model, while the results are as shown in the Table below.

Table 13. Environmental Impact Category at the Life Cycle Phases of Sintered Brick with Coal Fly Ash

Environmental Impact Category	Environmental Load Item	Environmental Impact Category	Environmental Load Item
Global Warming	CO_2,CH_4	Solid Waste	Industrial Solid Waste
Ozone Layer Loss	N/A	Toxicity in Water Body	N/A
Acidification	SO_2,NOx	Suspended Matters in Water Body	N/A
Eutrophication	COD	Water Resources Consumption	Water (not considered temporarily)
Suspended Particles	Industrial Dust	Fossil Resources Consumption	Coal, Oil & Natural Gas
Photochemical Smog	CO	Mineral Resources Consumption	Dolomite, Iron, and etc.

4.2. Characterization

As per the properly classified environmental impact category and selected computational model, the relevant data of life cycle inventory are converted into the corresponding environmental impact indicators, which are known as characterization. Herein, the characterization method adopts the effect equivalent factor mentioned in Yang's *Methodology and Application of Life Cycle Assessment*. Take acidification as an example. The pollutants with the acidification effect in the life cycle of sintered brick are SO_2 & NO_X, while the characterization indicator of acidification is SO_2 equivalent. As shown in Yang's *Methodology and Application of Life Cycle Assessment*, the equivalent indicator of NOx is 0.7kgSO_4eq./kg. Therefore, the overall acidification and characterization results in the life cycle of coal fly ash can be calculated, as shown in Table 14.

Table 14. Acidification Characterization Results at the Life Cycle Phases of Sintered Brick with Coal Fly Ash

Emission	Emission Amount a (kg/kg Brick)	Characterization Factor b ($kgSO_2eq./kg$)	Characterization Results a*b ($kgSO_2eq./kg$ Brick)
SO_2	3.91E-04	1.00E+00	3.91E-04
NOx	1.14E-04	7.00E-01	7.99E-05
In Total			4.71E-04

As per the similar process, the characterization calculation may be made for environmental impact at all phases of life cycle, while the results are as shown in Table 15. Among which, the environmental impact of shale is demonstrated in the form of energy consumption and pollutant emission during its extraction process. The steel scrap, coal gangue, coal fly ash and slag belong to waste recycling. Therefore, their consumption is not incorporated into the scope of environmental impact assessment. Due to the adoption of willingness-to-pay method, the weight of dolomite, fluorite and other minerals may be directly taken from environmental tax. Therefore, during the characterization process, they are not converted into the form of single equivalent indicator.

Table 15. Characterization Results at the Life Cycle Phases of Sintered Brick with Coal Fly Ash (/kg Brick)

Environmental Impact Category	Unit	Sintered Brick Manufacturing	Shale Extraction	Hammerhead Production	Coal Production	Power Generation	In Total
Acidification	$kgSO_2eq.$	3.79E-04	1.91E-05	1.16E-06	1.95E-07	7.18E-05	4.71E-04
Eutrophication	$kgNO_3eq.$			5.96E-10		1.15E-07	1.15E-07
Solid Waste	Kg			3.58E-06	2.56E-04		2.60E-04
Photochemical Smog	$kgC_2H_4eq.$	9.60E-07	1.76E-07	1.67E-09	8.07E-10	3.30E-07	1.47E-06
Global Warming	$kgCO_2eq.$	1.02E-01	5.13E-03	6.55E-04	1.46E-02	1.43E-02	1.37E-01
Suspended Particles	Kg	8.38E-04	2.56E-06	1.54E-06	4.43E-08	1.81E-05	8.60E-04
Fossil Resources	kgSCEeq.		3.29E-04	5.01E-04	4.03E-03	2.92E-03	7.78E-03
Mineral Resources	Dolomite (kg)			2.31E-05			2.31E-05
	Fluorite (kg)			4.88E-06			4.88E-06
	Iron Ore (kg)			5.55E-04			5.55E-04
	Limestone (kg)			4.82E-05			4.82E-05
	Manganese Ore (kg)			1.26E-05			1.26E-05
	Silicon Ore (kg)			2.68E-07			2.68E-07

5. Conclusions

During the characterization process, the environmental load value of all environmental impact categories are taken, but they only represent the absolute total amount. In order to further demonstrate the comparability of variable impact category data, it is required to integrate the characterization results. When the determined weighting coefficient is adopted for normalization calculation, all environmental impact results during the life cycle process of sintered bricks may be taken. When calculated as per China’s environmental tax items, the weight of dolomite is RMB 0.003 /kg. When the quartz sand is counted, the weight of silicon ore is RMB 0.003 /kg. The calculation results are as shown in Table 16.

Table 16. Normalization Results at the Life Cycle Phases of Sintered Brick with Coal Fly Ash (RMB/kg Brick)

Environmental Impact Category	Sintered Brick Manufacturing	Shale Extraction	Hammerhead Production	Coal Production	Power Generation	In Total
Acidification	2.69E-04	1.35E-05	8.26E-07	1.38E-07	5.10E-05	3.35E-04
Eutrophication			3.34E-10		6.43E-08	6.46E-08
Solid Waste			2.15E-07	1.54E-05		1.56E-05
Photochemical Smog	3.27E-06	5.98E-07	5.68E-09	2.75E-09	1.13E-06	5.01E-06
Global Warming	6.12E-03	3.08E-04	3.93E-05	8.74E-04	8.59E-04	8.20E-03
Suspended Particles	1.59E-04	4.86E-07	2.93E-07	8.42E-09	3.44E-06	1.63E-04
Fossil Resources		1.25E-06	1.90E-06	1.53E-05	1.11E-05	2.95E-05
Mineral Resources			9.83E-06			9.83E-06
					In Total	8.76E-03

As shown from the normalization results, the environmental impact resulted from the sintered brick manufacturing process is RMB 8.76E-3 /kg, namely, RMB 8.76/ton. Among which, the environmental impact dominated by global warming, namely, CO_2 emissions, followed by acidification and suspended particles. In contrast, due to the adoption of a great amount of industrial wastes as the raw materials, the consumption of mineral resources only accounts for a minor part of the entire environmental impact. This shows that it is the key task of next-step ecological design to control the GHG emissions, especially, reducing the generation of carbon dioxide during the sintered brick manufacturing process.

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