The assessment of eco-design with a comprehensive index incorporating environmental impact and economic profit

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Abstract. Eco-design is an advanced design approach which plays an important part in the national innovation project and serves as a key point for the successful transformation of the supply structure. However, the practical implementation of the pro-environmental designs and technologies always faces a dilemma situation, where some processes can effectively control their emissions to protect the environment at relatively high costs, while others pursue the individual interest in making profit by ignoring the possible adverse environmental impacts. Thus, the assessment on the eco-design process must be carried out based on the comprehensive consideration of the economic and environmental aspects. Presently, the assessment systems in China are unable to fully reflect the new environmental technologies regarding their innovative features or performance. Most of the assessment systems adopt scoring method based on the judgments of the experts, which are easy to use but somewhat subjective. The assessment method presented in this paper includes the environmental impact (EI) assessment based on LCA principal and willingness-to-pay theory, and economic profit (EP) assessment mainly based on market price. The results from the assessment are in the form of EI/EP, which evaluate the targeted process from a combined perspective of environmental and economic performance. A case study was carried out upon the utilization process of coal fly ash, which indicates the proposed method can compare different technical processes in an effective and objective manner, and provide explicit and insightful suggestions for decision making.

1. Introduction

It is widely acknowledged that China's economic miracle has been achieved at the expense of its natural capital and environment. In order to deal with this problem, sustainable development has been chosen as a national policy. With growing concerns related to industrial pollution, environmental regulations have been getting more stringent in China while efficient use of resources is gaining more importance. Industries are under continuous pressure to improve the environmental performance of manufacturing processes based on waste hierarchy principle, which prioritize pollution prevention and waste minimization over end-of-pipe treatment techniques. Eco-design as a modern design approach which integrates the humankind and nature is regarded as a pathway towards more advanced and pro-environmental economic growth. In 2013, guideline for the implementation of eco-design of industrial products was jointly issued by Ministry of Industry and Information Technology, National Development and Reform Commission and Ministry of Environmental Protection. It clearly states in the document that the central and local government will encourage the practical application of eco-

design in different industrial sectors by providing positive incentives such as subsidy, tax deduction, governmental procurement and so forth. Therefore, as a precondition, how to assess the innovation features and performances of the design plans become a relative and pressing issue.

From the viewpoint of practical application, the identification and selection of the promising manufacturing process always faces a dilemma situation, where some technologies can effectively control their emissions to protect the environment at relatively high costs, while others pursue the individual interest in making profit by ignoring the possible adverse environmental impacts [1]. Thus, the assessment of the eco-design process must be carried out based on the comprehensive consideration of economic and environmental aspects. LCA methodology is the well-known tool for evaluating the environmental performance of the targeted process. Because it quantifies the material requirements, energy consumption and gaseous and waste emissions throughout the life cycles of the products, the results of LCA thus provide in-depth and objective reference for the technology comparison [2]. Gnansounou et al assessed four different scenarios of the sugarcane-based biorefineries using LCA and techno-economic assessment, which determined the configurations of the best economic performance and lowest environmental impact. But the study evaluated the economic and environmental performances separately without the further integration of the assessment results [3].

The mostly accepted assessment index which combines the environmental and economic thinking is eco-efficiency proposed by the World Business Council for Sustainable Development (WBSD). It evaluates the resource-use efficiency and the impact of human activities on the environment. The framework of eco-efficiency developed by the WBCSD offers enough flexibility for various applications. A set of subject-wise indexes has also been provided, which are normally defined as the ratios between the environmental impacts and outcomes of production such as production cost, market profit and GDP etc [4]. Tichavska and Tovar assessed the eco-efficiency performance of Las Palmas port by calculating the external cost of the exhaust pollutants (NO_x, So_x, VOC, CO and PM) with respect to passenger, cargo, ship call and port revenue. However other environmental impacts such as the consumption of resource and energy were not considered [5]. Korol et al compared the eco-efficiency performances of the plastic pallets made by different materials. The relative values of eco-efficiency were calculated accordingly, which showed the selection of environmental impact categories had significant influence on the eco-efficiency assessment [6].

This paper aims to develop an assessment model which combines the advantage of LCA on environmental impact assessment and the comprehensive thinking of eco-efficiency. To facilitate the practical implementation and support decision-making, it requires the model to produce in-depth, objective and comparable results. The features of the proposed model are presented as follows:

- The environmental impacts (EI) including waste emission, resource and energy consumption are assessed based on LCA principles.
- Willingness-to-pay (WTP) theory was used to valuate and integrate different environmental impacts. Green tax and resource compensation fee are introduced as weighting factor to produce the EI results in monetary form [7, 8] .
- Market factors (e.g., prices of the materials and products) are taken into account in the assessment framework. The economic profit (EP) of each process is associated with corresponding monetary EI to create a comprehensive index, which is called EI per unit EP (EI/EP). This index evaluates the targeted processes from a combined perspective of environmental friendliness and economic performance.

2. Assessment framework
The proposed model is intended to provide decision makers with a reference for the identification of more environmental-friendly manufacturing process. Meanwhile, the economic factor cannot be ignored either. Thus both the assessments of environmental impact (EI) in relation to the production process and economic profits (EP) of the products are incorporated in the framework of the model (Fig. 1).
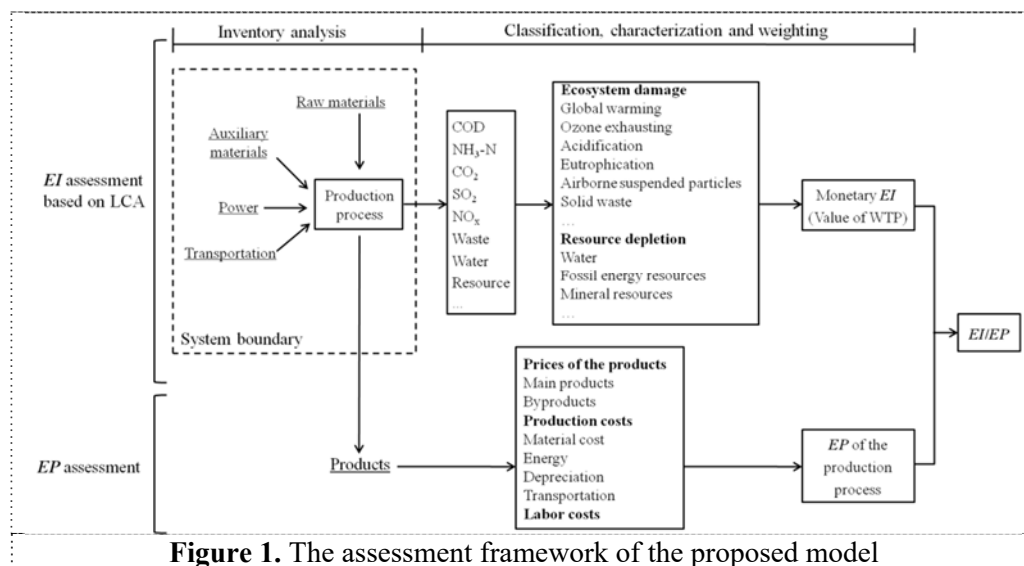
Figure 1. The assessment framework of the proposed model

2.1 EI assessment

The LCA methodology was used in order to capture the multiple environmental impacts of the assessed design or process. The main advantage of using LCA is the possibility of assessing the environmental performance of products throughout their life cycles with a comprehensive perspective. The well-accepted LCA procedure has been specified by ISO14040, which can be divided as goal and scope definition, data collection, inventory analysis, environmental impact assessment and interpretation. The purpose of the assessment model is to compare different technologies and processes so to select the better one for production. Therefore the scope of LCA can be defined as "from cradle to gate", meaning the process from the material acquisition till the products are ready for distribution must be covered. The functional unit must be chosen in accordance to the purpose and practical situation. Normally a complete set of product including the product, the package and necessary accessories can be used as the functional unit for LCA.

2.1.1 Inventory analysis. To carry out inventory analysis, field data and background data need to be collected. As the framework presents, the inventory data should at least cover the production process, the raw and auxiliary materials, power production and transportation. The first hand field data are always recommended if they are available. However the lack of inventory background data has always been a problem that inhibits the implement of LCA in China [9]. Some efforts have been committed to the construction of the Chinese life cycle inventory (LCI) database, and among which China National Institute of Standardization and Sichuan University took part in the International Reference Life Cycle Data System (ILCD) project initiated by the Joint Research Centre of the European Commission [10]. Because the LCA data have very strong regional characteristics, the LCIA analysis in the Chinese context should be conducted to ensure the credibility of the assessment.

2.1.2 Classification and characterization. The impact analysis is aimed at evaluating the significance of potential environmental impacts using the inventory analysis results. The inventory data are associated with specific environmental impact categories and category indexes, thereby attempting to understand these impacts. Three sub-steps including classification, characterization and weighting were carried out sequentially in order to obtain the environmental impact result.

In the step of classification, the mid-point impact categories were selected based on the problem-oriented consideration in the proposed model. As can be seen in Fig.4, the impact categories normally include global warming, acidification, eutrophication, photo-chemical smog, suspended particles, solid waste, wastewater, depletions of water, fossil energy and minerals and so forth. The choice of impact category must be according to the actual situation of assessed target.

The characterization step involves the conversion of LCI results to common category indexes and the aggregation of the converted results (index results) within the same impact category. Yang et al investigated the pollutant emissions and calculated the regional environmental burden in China [11]. His value-choices for the impact potentials of the typical pollutants are partially comprised in Table 1.

Table 1. Typical pollutants and their impact potentials

Impact category	Index	Index unit	Impact potentials of typical pollutants
Ecosystem damage			
Globe warming	CO_2	$kgeq.CO_2$	$CH_4=21kgeq.CO_2/kg…$
Ozone depletion	CFC-11	ODP	
Acidification	SO_2	$kgeq.SO_2$	$NO_x=0.7kgeq.SO_2/kg$, $NH_3=1.88kgeq.SO_2/kg$
Eutrophication	NO_3	$kgeq.NO_3$	$NH_3=4.01kgeq.NO_3/kg$, $TP=32kgeq.NO_3/kg$
Solid waste	Solid waste	kg	
Photochemical smog	C_2H_2	$kgeq.C_2H_2$	$CO=0.03kgeq.C_2H_2/kg$, $VOC=0.5kgeq.C_2H_2/kg$
Resource depletion			
Depletion of water	Water	m^3	-
Depletion of fossil energy	Standard coal	kgeq.SCE	Natural gas=$1.33kgeq.SCE/m^3$, Petroleum=$1.429kgeq.SCE/kg$
	Iron	kg	-
Depletion of mineral resource	Aluminum	kg	-
	Limestone	kg	-
	…		

2.1.3 Weighting and integration. Weighting is the process that the seriousness of the different impact categories is compared and valuated, in which the inventory analysis results across the impact categories are converted and aggregated using numerical factors. Weighting approaches can be either quantitative or qualitative. This paper considered to adopt the quantitative one. According to Lindeijer, the quantitative weighting approaches can be further classified into the groups as proxy, technology, panels, monetization, and distance-to-target [12]. Some specific information about the quantitative weighing approaches is given in Table 2.

Table 2. Description and comparison of the quantitative weighting approaches

Approach	Description	Application	Pro	Con
Proxy	Use a few quantitative measures, stated to be indicative for the total environmental impact		This approach picks one or a few factors instead of weighting between all different types of environmental impacts, so it is easy to apply.	This approach cannot be exactly described as a weighting method because no inter-effect weighting is included.
Technology	Use the technology which is used to abate	Ecological Footprint	The local technology	The assessment results are

	the impact to represent the environmental impact. In most cases, it is combined with some other measure, for example costs to reduce the burdens.		readiness level is considered.	depended on the choice of technology. It is arguable that if such human activities should be included in weighting.
Panel	People are asked to judge seriousness across categories subjectively and empirically through questionnaires or face-to-face, and be done in the Delphi or AHP process.	Eco-index 99	The approach is of high flexibility and easy to be applied in small-scale and specific cases.	Results are sensitive to how the questions are being asked. The interpretation of the questions is also of great influence.
Distance-to-target	For each impact category, an administrative or "sustainable"target is defined and the distance from the current level to the target is used as the weighting factor	EDIP, Eco-Index 95	Both the target and the actual levels related to a given region or country are considered. No classification/char acterization is needed to be performed	The approach is based on the assumption that all targets are equally important and only reveals the inner-seriousness within a category instead of the inter-seriousness across categories.
Monetizati on	The seriousness across categories is measured and presented by money. Several methods have been developed based on this thinking such as willingness-to-pay (WTP), Market price, Abatement cost, Budget constraint etc..	EPS-system, Tellus system, EVA/impac t pathway analysis, DESC-method, Ecotax	It converts the social and biophysical impacts on non-market goods into monetary units, which then can be compared against each other and against the costs and benefits already expressed in monetary units.	LCA accounts for "potential" rather than "actual" impacts. Thus the choice of link between a specific emission and its impact in monetary form can be rather intrigue.

As the comparison among the different weighting approaches show, monetization weighting is the most fitting approach for the purpose of the study. Firstly, the monetary EI result can be easily associated with the economic performance indexes. Secondly, environmental tax is about to be enacted in China, which can be used as the weighing references. Wu et al carried out a study of the environmental impacts based on the concept of "green tax" which are levied on emissions and natural resources and are calculated based on social willingness-to pay. Both potentials of the pollutants and tax rates were taken into account to calculate the weighing factors as

$$e_{ij} = \frac{f_i \cdot a_j}{\sum_j (f_j \cdot a_j)} \tag{1}$$

Where, e_{ij} is the potential coefficient of pollutant j in impact category i; f_j the polluting potential per unit of pollutant j, measured by each category's indicator unit; a_j the annual emission volume of pollutant j. Then, the weighting factor of an impact category can be defined as

$$w_i = \sum_j (e_{ij} \cdot c_{ij}) \tag{2}$$

Where, w_i is the weighting factor of impact category i; c_{ij} the tax rate of pollutant j in impact category i, measured by the each category's indicator unit for consistency.

Some of the calculated values of the factors are directly used in the model development of the present study. However, with more attention paid to the conservation of environment and resource during the last ten years, lots of new policies have been implemented in China. Thus some modifications to the weighting factors were also made. In Wu's paper, the weighting factor of global warming was taken based on the annual GDP loss due to greenhouse gas emission, which was estimated by Fankauser [13]. In recent years, carbon tax has caused extensive concern nationwide. To balance between environmental protection and economic growth, the central government is intent to start with a relatively conservative tax rate of 10 Yuan/t-CO_2, which can be accepted by most of the companies [14] and also effective for the initial phase [15]. The solid wastes discharged from the processes are Ca-Si based slag and coal combustion residues, which can be classified as non-hazardous wastes. The weighting factor referring to them is taken based on the investigation of municipal solid waste disposal cost by Yang and Dong [16]. The water resource fee in China is regionally different, so the value choice for water use must be depended on the local policy. The latest natural resource compensation fees are adopted for the depletion of fossil energy resources and mineral resources. The choices of values for the weighting factors and their sources can be seen in Table 3.

Table 3. Weighting factors for the impact categories

Category	Weighting factor	Unit	Source
Ecosystem damage			
Global warming	0.01	Yuan/kgeq.CO_2	[14] and [15]
Acidification	0.74	Yuan/kgeq.SO_2	[7]
Eutrophication	0.58	Yuan/kgeq.NO_3^-	[7]
Solid waste	0.015	Yuan/kg	[16]
Airborne suspended particle	0.26	Yuan/kg	[7]
Photochemical smog	3.41	Yuan/kgeq.C_2H_2	[7]
Waterborne suspended substance	0.175	Yuan/kg	[7]
Resource depletion			
Water resource	Regionally different	Yuan/kg	Local policy
Fossil energy	0.0032	Yuan/kg. coal	MOF P.R.China

resource	0.225	Yuan/kg. petroleum	
	0.01	Yuan/m^3. natural gas	
	0.003	Yuan/kg. limestone	
Mineral resource	0.025	Yuan/kg. halite	MOF P.R.China
	…	...	

*2.2 EP assessment and associate with EI*
Compared with the environmental performance assessment, the assessment on economic performance is more straightforward. WBCSD proposed costs as a possible indicator of product or service value [17]. But the net economic profit is the more fitting index especially when the outputs of the compared processes are different. The net economic profit can normally be defined as the sum of the sell prices of the products including both the main products and byproducts reducing the total costs during the production. The total cost is comprised of material costs and operational costs which can be further divided into the depreciation of the machinery, maintenance fee, labor cost etc.. It needs to be noted that the economic performance results of the assessed targets are sensitive to the ever-changing market. Thus the latest data are always recommended if they are available. Then the obtained EP result is associated with EI and form the indicator EI/EP, which is indicative of the environmental efficiency of the economic gain.

3. Application to technology comparison

3.1 The assessed case
With the established assessment framework, this paper attempts to assess and compare the environmental efficiencies of three fly ash utilization pathways based on their environmental and economic performances. The selected case for the study is a high-Al content fly ash (HAFA) comprehensive utilization project located in Inner Mongolia. In the particular type of fly ash, the contents of silica and alumina together make up almost 90wt% of the total weight. Because of the high Al_2O_3 content, HAFA is considered as a potential source for alumina recovery. A number of processes for recovering alumina have been reported, which can be grouped into three types: the sintering process, the acid leaching process and HiChlor process [18]. HAFA can also be used to prepare different industrial products, e.g., foam materials [19], zeolite [20], glass ceramics [21], and mullite ceramics [22]. Mullite ceramics have high refractoriness and creep resistance, suitable strength and fracture toughness, which make it amenable to various applications [23]. Therefore the preparation of mullite ceramics from HAFA attracted much attention.

The conventional methods for preparation mullite from fly ash normally require the addition of high Al_2O_3 content materials such as Al_2O_3 powder or bauxite [24]. Lin et al developed an effective method which uses HAFA as the only Al_2O_3-containing material and produces high performance mullite ceramics via consecutive steps of alkaline and acid leaching and sintering process [25]. All the three scenarios in the case study have incorporated this method and the flow diagram is presented by Fig.2 [26, 27, 28].
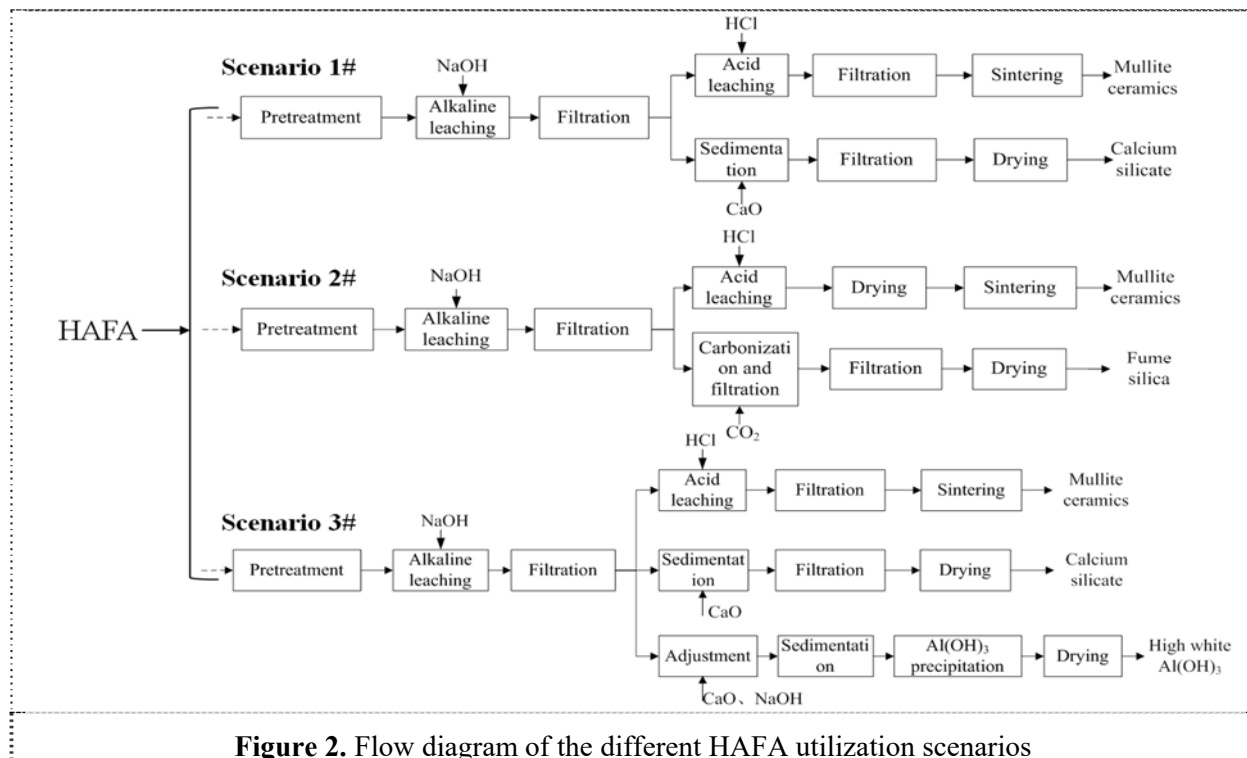
Figure 2. Flow diagram of the different HAFA utilization scenarios

3.2 Data collection

The three technical processes in the case study are all characterized by the comprehensive utilization of HAFA. Scenario 1# and 2# have similar steps which both produce mullite ceramics as the main output but with different by-products (calcium silicate ($CaSiO_3$) and fume silica (SiO_2)). HAFA undergo more sophisticated process in scenario 3# so to produce the high-value-added high white $Al(OH)_3$. The data of the input, output and major pollutant emissions of the three scenarios are presented by Table 4. In LCA, the use of 1000 kg HAFA was selected as the functional unit and the data have been transformed accordingly. The solid waste in the table refers to the integration of tailings from the production processes and bottom ashes from boilers for the provision of heat. These two substances are treated indiscriminately in this case, so they are counted and assessed together regarding their environmental impacts.

Table 4. The input, output and waste emissions in the three scenarios

		unit	Scenario 1#	Scenario 2#	Scenario 3#
Input	HAFA	kg	1000.00	1000.00	1000.00
	NaOH	kg	190.41	190.41	126.15
	HCl (31v/v%)	kg	513.70	506.85	265.02
	CO_2 (100v/v%)	kg		165.07	
	CaO	kg	254.79	210.96	308.48
	Fresh water	Kg	2800.68	2786.99	4770.32
	Electricity	KWh	68.49	82.19	204.95
	Coal	Kg	500.00	360.27	684.81
Output	Mullite ceramics	Kg	684.93	684.93	353.36
	$CaSiO_3$	Kg	479.45		247.35

		Unit			
	Fume silica	Kg		205.48	
	HWAH	Kg			353.36
	COD	g	21.23	21.92	37.46
	CO$_2$	kg	1143.84	821.92	1566.78
Emission	SO$_2$	kg	0.11	0.08	0.15
	NO$_x$	kg	0.11	0.08	0.16
	Solid waste	kg	450.00	821.92	758.30

The market prices of the products and the inputs including the ancillary materials, water, coal, electricity and the operational costs are obtained from surveys and comprised in Table 5.. Scenario 1# and scenario 2# have very similar technical processes, so the operation costs of the two are about the same. Scenario 3# cost the most during operation, because a comparably more complex process is carried out in this case. It needs to be noted that all the processes in the case study are pilot programs, which are run on small scale and haven't yet been optimized. Therefore the operation costs may be relatively high in current stage.

Table 5. The market prices of the products and the corresponding costs

	Price or cost	Unit
Product		
Mullite	2200	Yuan/t
CaSiO$_3$	2000	Yuan/t
Silica	3500	Yuan/t
HWAH	3500	Yuan/t
Input		
NaOH	2500	Yuan/t
HCl (31v/v%)	400	Yuan/t
CO$_2$ (100v/v%)	500	Yuan/t
CaO	300	Yuan/t
Fresh water	1.5	Yuan/t
Electricity	0.3	Yuan/Kwh
Coal	200	Yuan/t
Operation cost		
Scenario 1#	1185	Yuan/t·HAFA
Scenario 2#	1200	Yuan/t·HAFA
Scenario 3#	1500	Yuan/t·HAFA

3.3 Assessment and comparison

With the field data in Table 4 and the background data in the database of GreenIN, the inventory analysis was carried out. The inventory results of the three HAFA utilization scenarios are exhibited in Table 6.

Table 6. The environmental profiles of the three HAFA utilization scenarios (/t·HAFA)

	Unit	Scenario 1#	Scenario 2#	Scenario 3#
Pollutant emissions				

CO_2	kg	1976.7	1728.8	2421.4
SO_2	kg	2.13	2.36	3.30
NO_x	kg	0.88	1.00	1.37
COD	kg	0.22	0.27	0.45
Solid waste	kg	1826.1	2528.9	1821.8
Consumption of natural resource				
Water	kg	10372.4	11862.9	15878.8
Coal	kg	683.3	582.9	871.4
Natural gas	m^3	76.1	110.7	56.2
Oil	kg	30.6	30.6	21.7
Limestone	kg	510.9	427.7	606.6
Halite rock	kg	321.5	320.3	193.4

With environmental profiles listed in Table 6, the environmental impacts of the reference scenarios were investigated and the results are exhibited by Table 7. As the calculation reveals, scenario 3# imposes the greatest environmental impact compared with the other two. It can be seen that the momentary EI results obtained by the proposed method are easily comprehendible, and can provide useful insights for the decision making, especially when the concept and accounting method for environmental cost is still controversial in China [29]. It needs to bear in mind that the results here can only be used for comparison, which in this case shows us scenario 1# is a more "green" process. But it cannot conclude that the fly ash user who practically implement scenario 1# must pay 97.67Yuan/t·HAFA for the right of using environment. Firstly, the environmental impact does not entirely originate from the production process. Secondly, arguments still exist that the current resource compensation fees and other relevant tax rates in China are unable to reflect the reality.

Table 7. The environmental impact of the three HAFA utilization scenarios (Yuan/t·HAFA)

Impact category	Scenario 1#	Scenario 2#	Scenario 3#
Global warming	19.77	17.29	24.21
Acidification	2.03	2.26	3.15
Eutrophication	0.03	0.04	0.06
Solid waste	27.39	37.93	27.33
Water resource	29.04	33.22	44.46
Fossil energy resource	9.84	9.86	8.24
Mineral resource	9.57	9.29	6.65
Total	97.67	109.89	114.11

The economic performances of the three scenarios in the case study are showed in Table 8. All the three HAFA utilization methods are proven to be profitable. The market favors the products from scenario 3# the most. However due to the highest operation cost, its profit turns out to be the second in the three. Scenario 1# is with the biggest economic profit and least environmental impact, so the EI/EP of scenario 1# is the smallest one. Therefore the process in scenario 1# is the most recommended approach for HAFA utilization by the proposed assessment model. On the contrary, the EI/EP of

scenario 2# is 1.09, which indicates the economic profit of the process may be not enough to compensate the damage it causes to the natural, so it is the least recommended for practical implementation.

Table 8. The economic profit (Yuan/t·HAFA) and EI/EP of the three HAFA utilization scenarios

	Scenario 1#	Scenario 2#	Scenario 3#
Input cost	882.69	925.48	719.52
Operation cost	1185.00	1200.00	1500.00
Price of Products	2465.75	2226.03	2508.83
Economic Profit (EP)	398.06	100.55	289.31
Environmental impact (EI)	97.67	109.89	114.11
EI/EP	0.25	1.09	0.39

4. Conclusion

This paper has developed a method for the eco-design assessment. Compared with other assessment method, the proposed method considers both the environmental and economic performances of the assessed targets. Therefore the promising processes or technologies recognized by the presented model need to be both environment-friendly and economically feasible. To combine with economic assessment results, willing-to-pay theory was adopted in the LCA and the environmental tax rates were introduced as the weighting factors in order to converse the environmental impact results into monetary form. The application of tax rates as weighting references is controversial in the studies of LCA with some augments being raised that the tax rate reflects political consideration rather than individual WTP. However, the primary concern of the paper is the method rather than the choice of weighting factors. Other monetization approaches can also use economic loss, remediation costs, costs of evasive behaviour, etc. as the weighting references if they fit the purpose and context of the assessment. As long as the environmental impact result is in monetary form, then it can be associated with the economic result. As the case study of the paper shows, the proposed method is able to provide straightforward and definitive results for the technology comparison. The indicator of EI/EP can also be used for technical optimization, which we believe can greatly facilitate the implementation of eco-design.

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