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Comparative study of municipal solid waste incinerator fly ash reutilization in China: Environmental and economic performances

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ABSTRACT

Harmless disposal and reutilization of municipal solid waste incinerator fly ash (IFA) attract growing interests due to the gap between increasing IFA generation and limited landfill space. Therefore, an economical-affordable and environmentally friendly approach to deal with IFA is required. Herein, major IFA reutilization technologies in China (IFA-to-cement, glassy slags, rock wool, and ceramsite) were evaluated and compared with the landfill using life cycle assessment (LCA) and environmental life-cycle costing (eLCC). Prior to assessments, material flow analysis (MFA) was used to establish a heavy metal transfer coefficient model. LCA results indicate IFA-to-cement and IFA-to-ceramsite outperform others while eLCC results show that IFA-to-ceramsite and IFA-to-rock wool are preferred, breaking even at years 3 and 5 compared to IFA-to-cement (new plant) at year 11. To reveal true costs of reutilization technologies, whole life costing (WLC) was applied to include externality costs via monetizing emissions. Major pollutants contributed to externality costs of these technologies were identified. IFA-to-ceramsite and IFA-to-rock wool technologies remain preferred with payback time as 4 and 6 years respectively. A scenario analysis suggests that replacing sintering aids with polluted soil and Sec-FA recovery could further improve the overall performance of IFA-to-ceramsite option. Policy scenario analysis reveals that corporate income tax and environmental protection tax have negligible impacts but waste disposal subsidy is vital for IFA reutilization technologies being economic feasible even without externalities.

1. Introduction

Due to the rapid increase of municipal solid waste (MSW) generation and incineration, the amount of incinerator fly ash (IFA) grows significantly and reached over 10 million tonnes per year in China by 2019 (Wang and Fan, 2020). IFA, collected from air pollution control devices (APCDs) after MSW incineration, was a hazardous waste because it contains heavy metals and dioxins. Mismanagement of IFA would pose risks to the environment and human health. On the other hand, IFA contains a good amount of silica, calcium, and aluminum. This gives it the potential of being reutilized, such as construction materials (Quina et al., 2018; Rehman et al., 2020).

Currently, most IFA in China is disposed of in landfills after water washing and cement solidification as they can be implemented easily at a relatively low cost (Ma et al., 2019). However, landfill disposal consumes a significant amount of cement and occupies a large area (Ma et al., 2017). Other drawbacks also include potential leaching risks of heavy metals and dioxins, and missed opportunities of turning IFA to the resource as a practice of circular economy thinking (Assi et al., 2020; Wang et al., 2019).

In China, the most widely used IFA reutilization technology is cement kiln co-processing (IFA-to-cement). Emerging sintering technology (IFA-to-ceramsite) has been demonstrated at the industrial scale whilst plasma melting technologies (IFA-to-glassy slags and IFA-to-rock wool) are at the pilot-scale (Guo et al., 2017; Ma et al., 2019; Peng et al., 2020).

IFA-to-cement could enable the excellent stability of heavy metals, providing relative long-term environmental safety benefits (Guo et al., 2015). However, the IFA addition ratio is limited (mostly<10%, sometimes<2%) because the higher IFA content will worsen the cement quality and a part of the existing cement manufacturing capacity needs

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Abbreviation of description

Abbreviation	
municipal solid waste	MSW
incinerator fly ash	IFA
air pollution control devices	APCDs
secondary fly ash	Sec-FA
life cycle assessment	LCA
environmental Life-cycle costing	eLCC
net present value	NPV
whole Life costing	WLC
China renewable energy outlook	CREO
life-cycle costing	LCC
environmental performance	EP

to co-treat coal fly ash, etc. Therefore, the existing cement kiln can only co-treat approximately 6% of the total amount of IFA generated in China (Qian conference report, 2020a) but requires a large amount of water to remove chlorides as a pre-step to control the quality of cement (Clavier et al., 2020).

Demonstrated industrial-scale IFA-to-ceramsite and pilot-scale plasma melting technology could cope with a larger proportion of IFA in their processes. Both technologies could well stabilize most heavy metals in IFA, facilitate volatile heavy metal transferring and concentration, and decompose organic pollutants. Final emissions after APCDs can meet the required standard in China (Ministry of Environmental Protection, 2000) (Ma et al., 2017; Wang et al., 2008; Zhao et al., 2020). IFA-to-ceramsite could eliminate the water-washing step while heavy metals and chlorides would be concentrated in the second fly ash (Sec-FA) (Peng et al., 2020). Field experiments supported that both heavy metals and crystal salts in the Sec-FA could be recycled (Wang et al., 2018b). Therefore, IFA-to-ceramsite with Sec-FA reuse could realize almost full resource utilization of IFA and ultra-clean emission of flue gas. Traditional plasma melting technology (IFA-to-glassy slags) converts IFA to glassy slags but requires a water-washing step. Its operational process is energy-intensive and the facility requires heavy maintenance (Ma et al., 2017). An emerging pilot plasma melting technology IFA-to-rock wool assessed in this study could avoid the water-washing step, reduce energy consumption and improve the lifetime of the melting facility while turn IFA to a higher value-added insulation material, i.e. rock wool. These reutilization technologies decompose most dioxins in IFA, produce valuable products with potentially more resources consumed and pollutants emitted. Nevertheless, whether these technologies are environmentally friendly and economically viable remains a question.

The life cycle assessment (LCA) approach, which has been widely used to quantify environmental impacts and identify the potential weak points during the manufacturing process, could provide improvement insights to their environmental performances and enable the comparison of IFA management options from an environmental perspective (Istrate et al., 2020; Khandelwal et al., 2019; Naves et al., 2019; Rugani and Benetto, 2012; Wang et al., 2012). The environmental life-cycle costing (eLCC) approach, which used to account for budget costs (i.e. capital cost and operational cost), transfer costs (i.e. taxes, subsidies, and fees, etc.), and sales incomes (Edwards et al., 2018), could estimate the life cycle costs and profits of technology/product supply chains (Hoogmartens et al., 2014). Results by the eLCC assessment, in terms of net present value (NPV) and break-even years, could provide insights for investors and policymakers by incorporating multiple stakeholders' views. But the focus of eLCC remains on the internalized or expected to be internalized real cash flows (Hoogmartens et al., 2014). Both LCA and eLCC have been used worldwide to compare different waste treatment options. However, one of the challenges the comparison faces is the aggregation of environmental and economic perspectives. Thus whole life costing (WLC), defined in BSI ISO 15686–5 (2008), was applied to integrate the two aspects by taking into account the externality costs (representing monetized values of environmental pollution emissions) (Martinez-Sanchez et al., 2017; Naves et al., 2019). It has been widely used and recognized as a useful way to support decision making though it is imperfect. First, externality cost estimates could provide a dollar value as a means of comparing different inventory metrics based on their relative importance to one another. Second, the monetized emissions estimates provide guidance as to what governments may wish to pay in order to avoid undesirable externalities in the future and spot major risk contributor (Hauschild et al., 2018; Hoogmartens et al., 2014) (BSI ISO 15686–5 (2008)).

With regard to IFA disposal, several existing studies have evaluated the IFA neutralization, stabilization, carbonation, and thermal treatment before landfill disposal using LCA approach (Fruergaard et al., 2010; Guinee et al., 2011; Huber et al., 2018; Margallo et al., 2019). Several IFA reutilization technologies were also assessed by LCA methods, such as COSMOS-rice husk technology to produce biologically safe materials (Tomasoni et al., 2015), heavy metal recovery technologies (Boesch et al., 2014; Tang et al., 2018), and our newly published ceramsite production technology (Zhao et al., 2020).

Huang et al. applied both LCA and cost-benefit analysis to evaluate IFA-to-landfill, cement, bricks, and alkali (Huang et al., 2017). But it lacks the aggregation of environmental and economic performances. Huber and Fellner analyzed the economic performances of IFA treatment technologies i.e. metal recovery, water-washing pretreatment followed by landfill disposal, and cement production from the investor's view. Their study performed the integration of economic and environmental performance by monetizing endpoint LCA indicators based on a willingness-to-pay survey in Japan (Huber and Fellner 2018). But the Japan-based monetization method of externality costs does not apply to China due to the different economic development stages and cultural backgrounds between countries (Itsubo et al., 2012). Instead, China Renewable Energy Outlook (CREO) 2017 released estimated externality costs of major emissions, which is approximate to the societal valuation calculated by reducing economic loss associated with per unit of pollutants. These externality costs, together with monetization values per unit emissions in Edwards et al.'s study as a gap filler for missing emissions in CREO, were applied in this study to estimate externality costs (Edwards et al., 2018).

To support the development of IFA management enterprises, environmental protection tax, aiming to reduce pollutant emissions, is exempted provisionally by policymakers in China (Hu et al., 2019) (Environmental Protection Tax Law of China 2018). Financial incentives, i.e. IFA disposal subsidy (USD 73.5–734.8) are provided by the government (National Development and Reform Commission, PRC, 2020). The Chinese government also reduces the corporate income tax to help IFA reutilization enterprises competing against the traditional landfill. Changes in these currently implemented policies may pose significant impacts on the economic performance of IFA management options and therefore be studied in scenario analysis.

Variations in inventories or LCC (including eLCC and WLC) accounting parameters would lead to different evaluation results (Jiao et al., 2019; Yan and Crookes, 2009). Therefore, a sensitivity analysis was performed to identify the improvement potential of relevant parameters on LCA and LCC results for each technology.

In summary, the research objectives of this study are as follows:

- Establish material and cash flow inventories of the five IFA management technologies. Explore heavy metal distribution and transfer efficiency during IFA treatment process.
- Evaluate the environmental impact of IFA reutilization methods (i.e. IFA-to-glassy slags, cement, rock wool, and ceramsite) and compare them with the landfill option.

- Compare the NPVs of five IFA treatment technologies. Analyze the influence of policy changes (including environmental protection tax, corporate income tax, and waste disposal subsidy) on their economic performances from an eLCC perspective.
- Apply WLC where externality costs are included in IFA management systems. Compare their NPVs to provide insights for policymakers.
- Analyze the externality costs comprehensively. Identify the contaminants contributing mostly to externality costs for each technology to guide technology improvements and government decisions.

2. Methodology

2.1. Goal and scope definition

The goal of this study is to evaluate the environmental and economic performances of four IFA reutilization technologies and to compare them with the conventional landfill (baseline case). The functional unit is processing 10,000 t of IFA. The system boundary started from the transportation of IFA collected from the APCDs after MSW incineration to the discard of IFA products after their use for each technology. The system includes mining and pretreatment of raw materials used in all unit processes, transportation, product processing, product use, and waste discard. Final products (i.e. cement, glassy slags, rock wool, and ceramsite) generated in IFA management processes were considered to replace the traditional and similar commodities on the market in full. To treat any by-products (i.e. crystal salts and Sec-FA), system expansion was also applied to avoid allocation (Fig. 1).

2.2. Technology description

IFA-to-landfill is a traditional IFA treatment method. IFA is water washed first, stabilized with cement in the ratio of cement: IFA=1:1, and finally landfill disposed of. Energy and material consumption mainly include water and cement. Heavy metals leached to the underground water account for the major emissions in the whole process (Huang et al., 2017).

IFA-to-cement involves IFA water washing and drying, material mining, calcining (800–1300 °C), clinker milling, cement use, and discard. Coal combustion and IFA drying processes contribute to the main pollutants. IFA: limestone is equal to 1.3% according to engineering practice. The cement quality complies with standards GB30485–2013, GB30760–2014, and HG662–2013.

IFA-to-glassy slags is a plasma melting technology. Water washed IFA and 20% silica sand are mixed and fed into a furnace over 1500 °C to produce glassy slags, which can replace traditional shale stones. Sec-FA is landfill disposed of and flue gas is emitted after APCDs. Electricity is the main consumption and flue gas emissions are the major pollutant source.

IFA-to-rock wool is another plasma melting technology. IFA is directly vaporized, molten over 1500 °C, and transferred into a vitreous state together with 8% of basalt. Then rock wool is produced after the direct draw process in the furnace. The produced rock wool is in line with the relevant standards (GB/T 1549–2008, GB/T 3284–2015, and GB/T 5480–2017). Sec-FA is re-injected back to the furnace and flue gas is emitted after APCDs. A carbon rod, as the major consumable material, is used to replace the traditional graphite electrode. Electricity is a major consumption. The prime pollutants are flue gas emissions.

IFA-to-ceramsite is a sintering technology with IFA: additives = 2:1 at 1150–1350 °C (Peng et al., 2020). After sintering, dioxins can be detoxified (Zhao et al., 2020) and the generated Sec-FA is landfill disposed of. The produced ceramsite is in line with the standard DB12T779–2018 and can replace conventional ceramsite mainly used as roadbed materials (Peng et al., 2020). Emissions from the rotary kiln and coal combustion after APCDs are the major pollutants (Fig. S1).

2.3. Data source and life cycle inventory

Life cycle inventories for IFA-to-cement, glassy slags, rock wool, and ceramsite were collected from enterprises in Zhejiang, Sichuan, Henan, and Tianjin, via plant investigation. Life cycle inventories for the

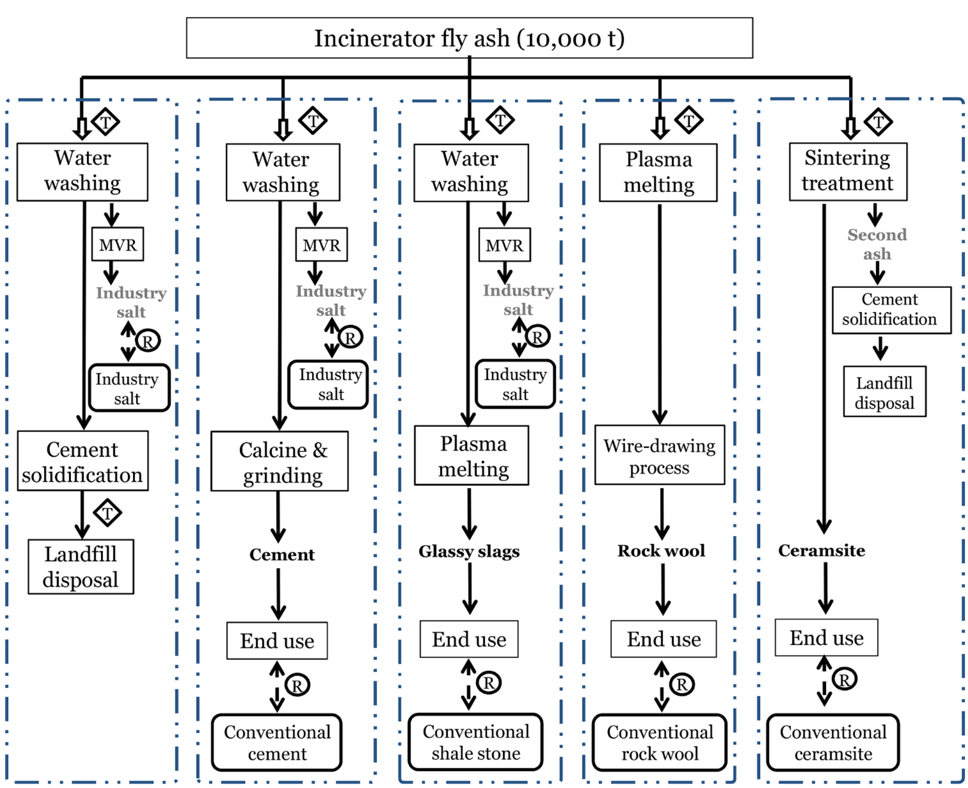

Fig. 1. Comparative systems for IFA management technologies (i.e. IFA-to-landfill, cement, glassy slags, rock wool, and ceramsite).

replaced main products and byproducts referred to the background database in eFootprint. The socioeconomic circumstances, technology applied for MSW incinerator, and different MSW compositions may pose a significant impact on the environmental and economic assessment results. Therefore, each IFA from different MSW incinerators needs to be evaluated on a case-by-case basis (Huber and Fellner, 2018). To perform a comparative study, composition and loss on ignition (represents the percentage of the mass reduced by burning residues at a certain temperature in the original incineration residue mass) of IFA were unified (Table S1) (Peng et al., 2020). Heavy metal content represents the average values of those of MSW incineration power plants in 16 cities in China (Qian conference report 2020b). Heavy metals transfer coefficient model was established based on the original mass balance in collected inventory data to track the whereabouts of major pollutants (Supplementary materials-sheet B). Heavy metal content in polluted soil mentioned in Section 3.5 was obtained by field research in Tianjin (Table S2). Fig. 2 illustrates the material flows of five technologies calculated by proportionally scaling up or down of the collected inventory data.

Economic data about budget costs were from enterprise investigations and their environmental impact assessment reports. Commodity prices were obtained from enterprise or public domain reflecting their market prices in 2019. IFA disposal subsidy is the average of 16 cities from a report in the public domain (National Development and Reform Commission, PRC, 2020). The sales incomes represent all incomes from product sales. To calculate the capital cost, the scaling exponent coefficient was used to scale up or down capital cost from the original data (0.7 is chosen in this study) (Jones. et al., 2013). Operational costs in this study mainly included transportation, feedstock, energy consumption, and labor costs. Transportation distance was unified as 100 km. Transfer costs in this study included enterprise income taxes and potential environment protection tax. Enterprise income tax for IFA utilization technologies is exempted in the 1st three years and halved in the 2nd three years (12.5%) (Enterprise Income Tax Law, 2000). The data sources of externality cost estimation were mainly from CREO 2017. For missing data in CREO, monetization values of per unit total emissions in Edwards et al.'s study were used (Supplementary Materials-sheet H). The discount rate for budget costs and externality costs were 10% and 4% (Huysegoms et al., 2018). The major life cycle inventories for the 5 pathways are presented in Table 1. Relevant prerequisites and assumptions, the life cycle inventories, and LCC inventories of IFA management technologies including the avoided debts are shown in Supplementary material-sheet A, C, and F.

Notes: (1) PCA-polymeric chloride aluminum; PAM-polyacrylamide; MVR-mechanical vapor recompression; APCDs- air pollution control devices; t-tonnes.

(2) "Loss" represents the mass loss of raw materials during the thermal process; The image source for glassy slags is from Ma (Ma et al., 2017).

2.4. Environmental and economic evaluation

To quantitatively compare the environmental performances, LCA was performed using eFootprint software, an online LCA software that featured a built-in Chinese Life Cycle Database (CLCD) and developed by IKE Environmental Technology Co., Ltd Jiao et al., 2019; Zhao et al., 2020). In this study, seven characteristic indicators related to potential environmental impacts of technology processes were selected, i.e. primary energy consumption (PED, MJ), water use (WU, kg), global warming potential (GWP, kg CO_2 eq), acidification (AP, kg SO_2 eq), respiration inorganics (RI, kg $PM_{2.5}$ eq), eutrophication (EuP, kg PO_4^{3-} eq), and photochemical ozone formation (POFP, kg NMVOC eq) (Cao et al., 2021). The impact assessment methods CML 2002 (for AP and EuP), IPCC 2013 (for GWP), IMPACT 2002+ (for RI), and ReCiPe 2016 Midpoint (H) (for POFP) was used in this study. The total calorific value for primary energy (i.e. coal, petroleum, and natural gas) and the water consumption are directly used to denote the indicators "PED" and WU according to eFootprint. To include emissions from coal combustion, the emission factor of coal combustion from GREET® 2018 model was used (Argonne National Laboratory, 2018). The total environmental performance (EP_{total}) represents EP of each indicator for each technology. EP_{avoid} represents the environmental credits from products substituting the same amount of conventional products; EP_{net} is calculated by formula ((1)

$$EP_{net} = EP_{total} - EP_{avoid} \tag{1}$$

To present LCA results more concisely, EP_{total} and EP_{avoid} were normalized according to the characterization result of each technology. The normalized basis was set as the EP_{total} of IFA-to-cement due to its being the biggest share among all the indicators (as seen in Fig. 3).

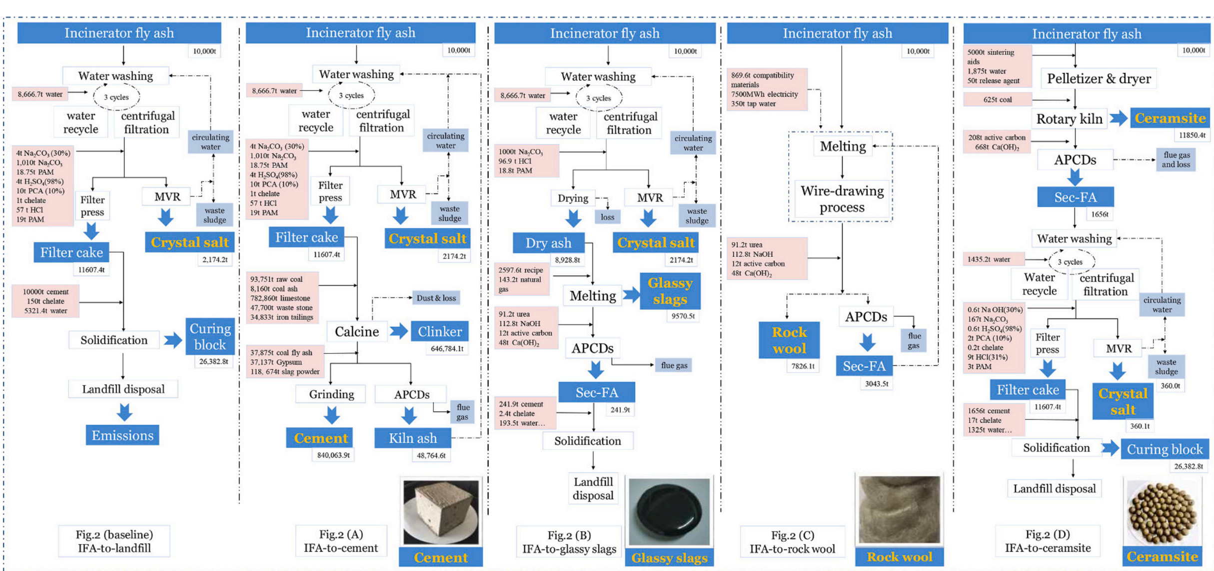

Fig.2. Material flow analysis of IFA disposal and reutilization technologies

Notes: (1) PCA-polymeric chloride aluminum; PAM-polyacrylamide; APCDs- air pollution control devices; MVR-mechanical vapor recompression; Sec-FA represents second fly ash recycled with APCDs.
(2) Loss represents the vapor loss of raw materials during the thermal process (for example, raw coal, waste stone, and limestone contain with 12%, 7%, and 1.5% of water, respectively).

Fig. 2. Material flow analysis of IFA disposal and reutilization technologies.

Table 1
Major life cycle inventories of IFA disposal and reutilization technologies.

Major inputs	Unit	IFA-to-landfill	IFA-to-cement	IFA-to-glassy slags	IFA-to-rock wool	IFA-to-ceramsite
incinerator fly ash	t	10,000	10,000	10,000	10,000	10,000
water	t	16666.7	150225.7	8860.2	350	4635.0
electricity	kWh	12380.9	140,625,000	24055905.7	7,500,000	34041.7
coal	t		93751.0			625
Na_2CO_3	t	1009.5	1000	1067.3		167.2
HCl (31%)	t	57.1	96.9	538.3		9.5
cement	t	10,000		241.9		1656
diesel	t	467.5		11.3		77.4
NaOH (30%)	t	3.8		89.8	89.8	0.6
$Ca(OH)_2$	t			48.1	48.1	668.1
compatibility materials	t			2603.1	869.6	
urea	t			91.4	91.4	
active carbon	t			12.0	12.0	208.0
soil	t	1260.0		30.5		208.7
chelating agent	t	101.0		2.4		0.2
aluminum polychloride (10%)	t	9.5				1.6
polyacrylamide	t	19.0				3.2
steam	t	19.0				3.2
limestone	t		782859.3			
copper slags	t		34833.3			
sintering aids	t					5000
natural gas	t			144.3		
clay	t	1260				

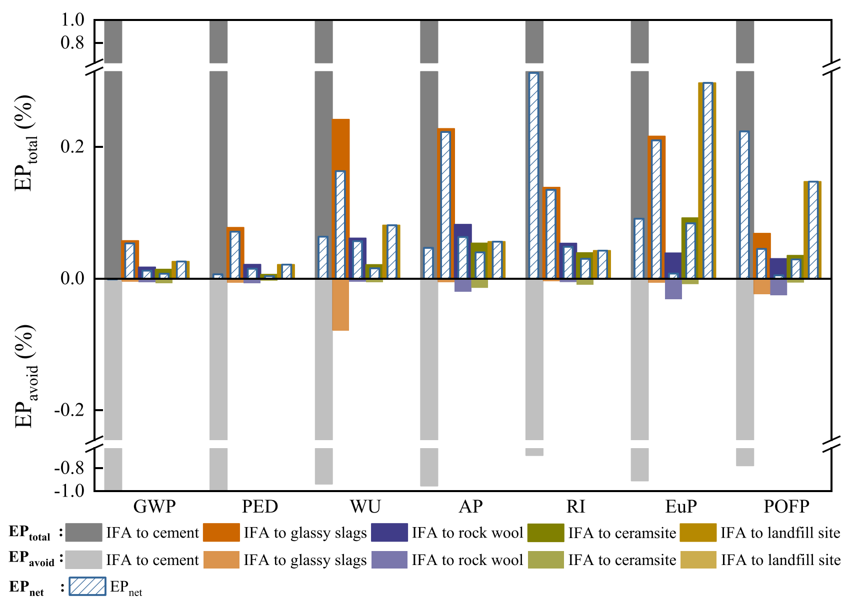

Fig. 3. Environmental assessment results for IFA management technologies.

To assess the economic feasibility of each technology, LCC was performed with results indicated by net present value (NPV) and break-even years. NPV_i refers to the difference between cash inflow (C_I) and cash outflow (C_O) generated by different IFA treatment technologies in the year i after a discount rate of 10% applied (formula (2)). C_{I_i} is the sum of the cash inflow, i.e. waste disposal subsidy, main product and byproduct incomes of each technology. C_{O_i} represents the sum of cash outflow, i.e. capital cost, operational cost, and working capital of each technology (Supplementary Materials-sheet F & sheet G). If $NPV_5>0$, the IFA reutilization technology would be commercially feasible with higher NPV preferred according to market experiences in China. In this study, NPV_i of the five technologies were analyzed and compared in the context of eLCC. Break-even year represents the first year when $NPV_i>0$.

$$NPV_i = \sum_{i=0}^{n} (C_{I_i} - C_{O_i})(1+10\%)^{-i} \tag{2}$$

$$\text{Externality costs}_j = \sum_{j=0}^{5} t_j \cdot \sum_{j,k} e_{j,k} \cdot P_k \tag{3}$$

To integrate the environmental and economic performances, WLC including eLCC and externality costs were applied according to the standard BSI ISO 15,686–5. Externality costs were estimated with formula (3) by Ecotax 2002 method in Sweden Martinez-Sanchez et al., 2017; Wu et al., 2005). The t_j represents one of the five IFA management technologies. The $e_{j,k}$ is the emission amount of pollutant k for technology j. The P_k represents per unit price of pollutant k for technology j. Whilst, "price-per-pollutant" data aligned with EP_{total} instead of the EP_{net} was used in the context of reflecting the 'true cost' of emissions from projects. Therefore, NPV_i for technologies in the context of WLC could be calculated with formula (2) whilst estimated externality costs in formula ((3) were included in C_O. The exchange rate in this study is "1USD = 6.804RMB". The money unit used in Supplementary Materials is ten thousand yuan.

To further identify the major pollutant contribution to externality costs, the total externality costs were grouped into four comprehensive impact categories, i.e. water quality, human health, climate change, and indeterminate (Edwards et al., 2018; Martinez-Sanchez et al., 2017). The monetized value of heavy metals (i.e. Sb, Ba, Co, Mn, Mo, Ni, Se, Ag, Zn, Sn) and ammonium, nitrite, phosphate emitted to water makes up the total water quality contribution to externality costs. The monetized value of heavy metals (i.e. As, Pb, Cd, Cr, Cu, Hg) emitted to water, and emissions to air (i.e. NO_x, Hg, Cd, Pb, dioxins, $PM_{2.5}$, VOC, CO, PM_{10}, and dust) constitutes the human health contribution to externality costs. Externality costs of climate change represent the monetized value of CO_2, N_2O, and CH_4. The monetized value by other pollutants is the indeterminate contribution to externality costs (Edwards et al., 2018; Martinez-Sanchez et al., 2017).

Land use of each technology was also estimated according to the occupation area of each plant, their capacities and life times.

2.5. Sensitivity analysis

Sensitivity analysis is of great importance for LCA and LCC to detect model robustness and identify the key contributors to results to perform focused improvements for each technology. Sensitivity analysis results for LCA and LCC were calculated with the formula (4) (Liao et al., 2020). The effect on LCA and LCC was assessed with a one-at-a-time approach by varying 10% of each environmental factor (i.e. inventory feedstock) or economic factor (i.e. capital cost, operational cost, sales income, and scaling exponent) according to Edwards (Edwards et al., 2018). As a result, sensitivity ratios of LCA and LCC assessment were obtained (Liang et al., 2012; Wang et al., 2018).

$$Sensitivity\ ratio = \frac{\Delta result/result}{\Delta factor/factor} \tag{4}$$

2.6. Scenario analysis

In addition to the baseline scenario of IFA-to-ceramsite mentioned in Fig. 2 and Table 1, another two scenarios were proposed representing potential improvements according to the enterprise investigation as shown in Fig. S1. In the baseline case, Sec-FA was landfill disposed of. In scenario 1, heavy metals were recovered from Sec-FA after acid washing, mechanical vapor recompression, and heavy metal concentration (Wang et al., 2018). In scenario 2, heavy metals were recovered, sintering aids were replaced by polluted soil, and environmental performance of polluted soil remediation was avoided (Huysegoms et al., 2018) (Fig. S1). The experiment has been carried out previously to demonstrate the technical feasibility (Liu, 2019). The potential of scaling up the use of polluted soil was also confirmed via enterprise consult. Detailed LCA and LCC inventories are shown in Supplementary Materials- sheet C, F, and G.

3. Results

3.1. Material flow analysis

Material flow diagrams for five technologies are shown in Fig. 2. Data demonstrated that 10,000 t of IFA for each reutilization technology could respectively produce 9570.5 t of glassy slags, 7826.1 t of rock wool, and 11850.4 t of ceramsite. For IFA-to-cement, the ratio of IFA: limestone is equal to 1.3% and IFA could replace 7990.5 t of limestone. With water washing pretreatment and MVR technology, 2174.2 t of crystal salts were recycled for IFA-to-cement and IFA-to-glassy slags. While recycled crystal salts for IFA-to-ceramsite were 360.1 t because the incomplete volatilization of chlorides during the sintering process could reduce chloride content in Sec-FA (Peng et al., 2020). Different amounts of Sec-FA were generated during IFA-to-glassy slags (241.9 t), IFA-to-rock wool (3043.5 t), and IFA-to-ceramsite (1656 t). This is due to the differences in water washing and thermal treatment sequence, as well as chloride content in Sec-FA from different technologies.

Heavy metal distributions after IFA treatment shown in Supplementary Materials- sheet B indicated that heavy metals in IFA finally transferred and distributed in the main products (i.e. cement, glassy slags, rock wool, and ceramsite), emitted flue gas after APCDs, wastewater (if any), and byproducts (i.e. Sec-FA or crystal salts). Data demonstrated that 100% of Hg, 10.7% of As, and 5.1% of Ni in IFA would be leached out to water for IFA-to-landfill. However, after IFA thermal treatment, higher than 63.4% of Ni, Cr, and Mn were solidified in the main products, lower than 1.52% of heavy metals were emitted to environment. The remaining heavy metals were transferred either to wastewater or Sec-FA, being two new focal points of potential heavy metal pollution after thermal treatment. Wastewater was circularly reused and Sec-FA concentrated with heavy metals was landfill disposed of. While for IFA-to-cement and IFA-to-rock wool, Sec-FA (or kiln ash) was all reinjected into the system for reutilization. Data in Supplementary Materials- sheet B revealed that higher than 96.9% of Hg was transferred to Sec-FA for IFA-to-cement and IFA-to-rock wool. This may raise concerns about heavy metal volatilization instead of solidification during a new reinjection cycle, especially Hg. Water washing pretreatment resulted in better dechlorination and facilitated subsequent crystal salt recycling for IFA-to-cement and IFA-to-glassy slags. However, the water washing process led to a redistribution of heavy metals in outputs. Higher than 4.1% for each heavy metal was transferred to the wastewater and crystal salts, especially Cd (35.0%) and As (20.0%), which would be mainly transferred to Sec-FA otherwise.

3.2. Environmental performances

Fig. 3 shows the environmental performances (i.e. EP_{total}, EP_{avoid}, and EP_{net} mentioned in Part 2.4) of each IFA treatment technology. The highest EP_{total} was observed for IFA-to-cement mainly ascribed to the lowest IFA blend ratio and the largest consumption of limestone, water, electricity, and coal. EP_{total} of IFA-to-glassy slags was approximately twice as large as that of IFA-to-landfill, rock wool, and ceramsite due to its larger consumption of electricity, natural gas, and chemicals, such as Na_2CO_3, HCl, and NaOH (Table 1). Compared with IFA-to-glassy slags, IFA-to-rock wool eliminated the water-washing step thus saving significant environmental burdens (Huber and Fellner, 2018). EP_{total} of IFA-to-landfill was higher than that of IFA-to-ceramsite because a larger amount of cement, diesel, and water were consumed.

EP_{avoid} represents life cycle environmental burdens resulted from replacing the same amount of conventional products with IFA products. EP_{avoid} of IFA-to-cement was the biggest because the energy consumption of producing traditional cement is similar to producing the same amount of cement with IFA (Supplementary Materials-sheet C). EP_{avoid} of IFA-to-landfill was the lowest because only a small amount of recycled salts were substituted. EP_{avoid} of IFA-to-glassy slags was similar to that of IFA-to-ceramsite but lower than that of IFA-to-rock wool except for WU.

Overall, IFA-to-glassy slags presented the highest EP_{net} in most categories apart from RI, EuP, and POFP. On the other hand, IFA-to-ceramsite shared the lowest EP_{net} in category PED, WU, AP, and RI except for EuP and POFP where IFA-to-rock wool outperformed. GWP category for IFA-to-cement presented the lowest. Therefore, IFA-to-ceramsite, cement, and rock wool have the potential to substitute the traditional landfill option from an environmental perspective.

Analysis when IFA-to-landfill is replaced by IFA-to-ceramsite, cement, and rock wool is shown in Table S3. Under this situation, comprehensive EP_{net} could reduce more than 17.0% for IFA-to-ceramsite, especially CO_2 eq (104.5%). Although the water consumption during IFA-to-cement is higher than the traditional cement production process, IFA-to-cement could still reduce 21.2% for WU indicator compared with IFA-to-landfill, eliminating the concern about water consumption by water washing pretreatment mentioned by

(Clavier et al., 2020). For IFA-to-ceramsite, higher than 66.3% of indicators for comprehensive EP_{net} could be improved apart from RI (25.7%) and AP (25.0%) by replacing IFA-to-landfill with the reutilization options. For IFA-to-rock wool, EP_{net} of AP and RI increased by 12.4% and 13.6%, contributing to extra emissions of SO_2 eq and $PM_{2.5}$ eq to the earth when IFA-to-landfill is replaced by IFA-to-rock wool. This is mainly ascribed to the comprehensive higher electricity consumption during rock wool production. Therefore, the comprehensive substitutability for IFA-to-rock wool is questionable and needs further demonstration (seen in Section 3.3.4).

Land occupation of the five IFA management technologies are shown in Table S4. Results indicated that IFA reutilization could release up to significant amount of land area from landfill. IFA-to-landfill occupies the largest land area (3172 m^2/ 10, 000 t of IFA) compared to IFA-to-ceramsite (204.2 m^2/ IFA 10, 000 t), IFA-to-cement (new plant) (2000 m^2/ IFA 10, 000 t), IFA-to-glassy slags (72 m^2/ IFA 10, 000 t), and IFA-to-rock wool (95 m^2/ IFA 10, 000 t), respectively.

3.3. Economic performances

3.3.1. eLCC assessment

The economic performances of the five technologies were analyzed by eLCC method. The calculation process is documented in Supplementary Materials-sheet F. IFA-to-ceramsite, rock wool, cement, and landfill technologies become NPV positive in years of 3, 5, 11, and 13, respectively (Table 2). The economic performance of IFA-to-ceramsite is found to be the best mainly due to the lowest capital investment compared with IFA-to landfill and IFA-to-cement. Although sales income of glassy slags is higher than that of cement and ceramsite, the net NPV of IFA-to-glassy slags is the lowest because of its larger capital cost and operational costs (Supplementary Materials-sheet F). Fig. 4(a) presents contributions from incomes and costs to the NPV_1. Both IFA-to-glassy slags and IFA-to-rock wool are plasma melting technology. While the latter one is an industry chain extension of the former one. Result indicates that IFA-to-rock wool paid back in 5 years but IFA-to-glassy slags could not break even. This is because the sales income of IFA-to-rock wool is approximately 2.5 times higher than that of IFA-to-glassy slags. The break-even year is 2 for IFA-to-cement when co-treating IFA with an existing cement plant. Nevertheless, the break-even year is 11 if a new plant is required and being economically unviable, which has not been studied to our best knowledge (Clavier et al., 2020).

To further recognize the key operational costs and provide improvement suggestions, the operational costs of four IFA reutilization technologies were analyzed in Fig. 4(c). Results demonstrate that over 75% of the total operational costs of IFA-to-ceramsite is the raw material cost where sintering aids are the major contributors. For IFA-to-glassy slags and IFA-to-rock wool, the energy cost, i.e. coal and natural gas, is the major contributor, and therefore their economic performances could benefit from improving energy use efficiency (Fig. 4(c)). While for IFA-to-cement, large operational costs are mainly caused by feedstock and labor costs. This is because the water washing step needs more workers and consumes more raw materials and energy compared with other reutilization technologies. Therefore, the improvement for IFA-to-cement should mainly focus on reducing consumptions during the water washing process.

3.3.2. Policy scenario analysis of eLCC assessment

Based on findings in Section 3.3.1, enterprises could have their investment paid back sooner by producing ceramsite or rock wool from IFA. However, results could be influenced by the potential changes in relevant government policies. Therefore, we examined the economic trajectories of IFA management technologies in the following scenarios:

(1) Policy scenario baseline: IFA disposal subsidy (USD 173.3 per tonne IFA) was provided, corporate income tax was exempted in the 1st three years and halved in the 2nd three years. The environmental protection tax was exempted.
(2) Scenario 1: No exemption and a 50% reduction in corporate income tax.
(3) Scenario 2: No exemption of the environmental protection tax.
(4) Scenario 3: No waste disposal subsidy.

Results in Table 3 show that exemption or 50% reduction in corporate income tax has a negligible impact on break-even years for each technology. If environmental protection tax becomes mandatory, IFA-to-landfill enterprises will not survive but it would pose no distinct threaten to other reutilization technologies. If a waste disposal subsidy is not provided by the government, all the five IFA management technologies will be difficult to break even in 30 years. By accounting, waste disposal subsidies were respectively 123.2, 167.7, 205.3, 249.4, and 388.1 in USD for IFA-to-ceramsite, rock wool, landfill, cement, and glassy slags when NPV_5=0 in treating 10,000 t of IFA. This could provide a flexible subsidy reference for policymaking of different IFA management technologies to survive. Nevertheless, changes in current government policies would have a universal impact on the IFA reutilization industry chain, but IFA-to-rock wool and IFA-to-ceramsite are more resilient.

3.3.3. WLC assessment

LCA results demonstrate that IFA-to-cement and IFA-to-ceramsite are preferred from an environmental perspective. Whilst eLCC results indicate that IFA-to-ceramsite and IFA-to-rock wool outperform from an economic perspective. The WLC method, which includes externality costs and eLCC categories, was performed to integrate the environmental and economic performances and reveal the true cost during IFA treatment processes.

Externality costs of IFA-to-landfill are the largest among all technologies because most heavy metals and dioxins would be leached out to underground water in 100 years (Fig. 4(b), Table 4, Supplementary Materials-sheet G and H). As a result, the landfill option was unprofitable from a WLC perspective. IFA-to-cement also might not be a favorable alternative because the break-even year is over 30 years even with a subsistent cement plant. The conclusion is inconsistent with Huber's due to the differences of IFA to limestone ratios and the used accounting method of externality costs (Huber and Fellner, 2018). Non-uniform accounting ways of externality costs could bring about variations in WLC results (Huysegoms et al., 2018). However, due to the lack of universally accepted guidelines, the influence of method choice is not in the scope of this paper. The WLC results also show that externality costs have a smaller impact on the break-even years' determination for IFA-to-ceramsite and IFA-to-rock wool due to their relatively lower emissions compared to emissions from IFA-to-landfill and IFA-to-cement options.

Table 2
NPVs and break-even years of five IFA management technologies from the eLCC perspective (Function unit: treatment of 10,000 t of IFA, unit of $NPV_{i:}$ USD).

Items	IFA-to-landfill	IFA-to-cement	IFA-to- glassy slags	IFA-to- rock wool	IFA-to-ceramsite
NPV_1	−3.31E+05	−8.92E+05	−8.91E+05	−8.67E+05	−1.13E+05
NPV_5	−1.77E+05	−4.23E+05	−1.20E+06	3.25E+04	2.81E+05
NPV_{10}	−4.44E+04	−2.62E+04	−1.43E+06	7.62E+05	6.07E+05
Break-even year	13	11	>30	5	3

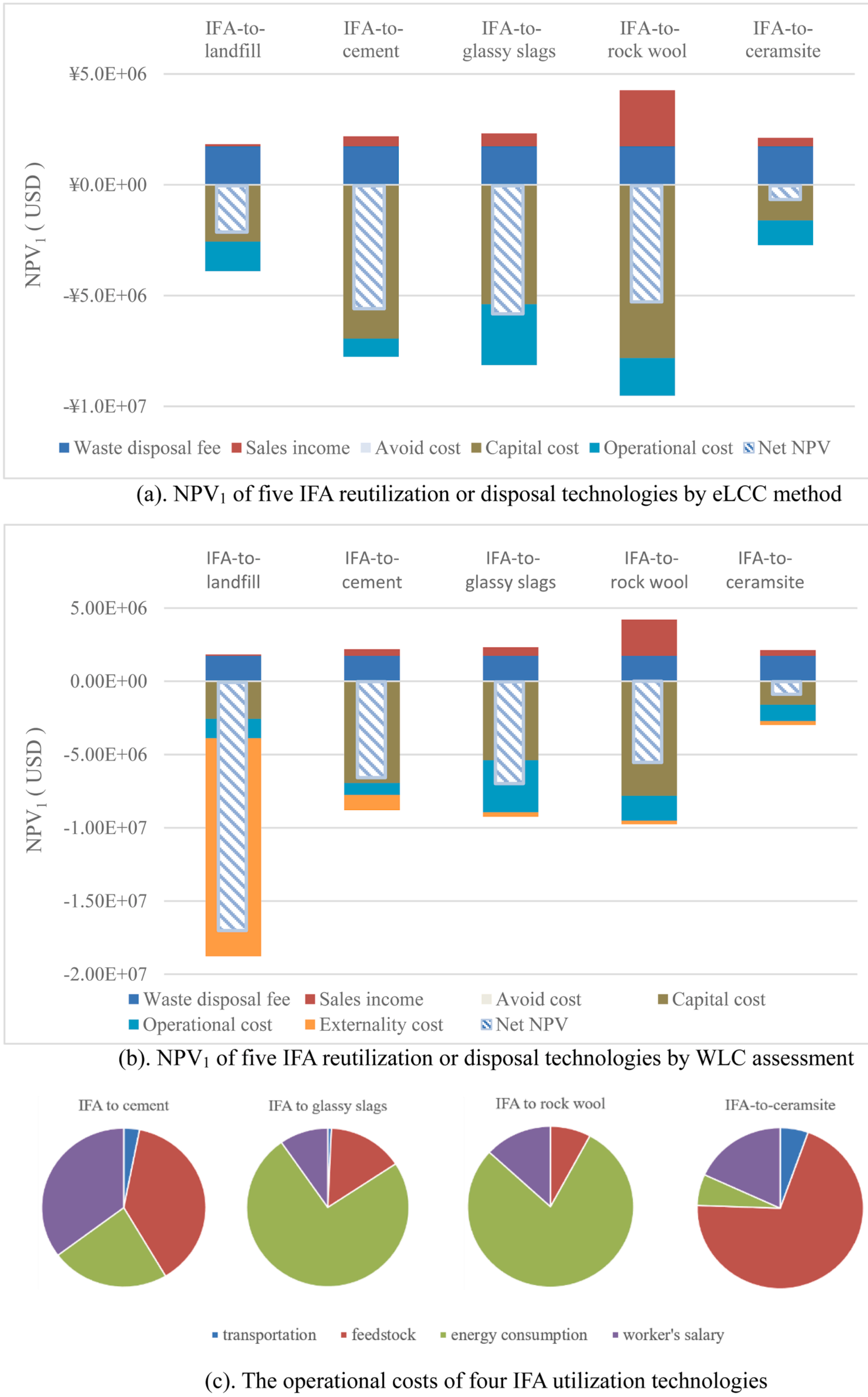

Fig. 4. NPV_1 of IFA treatment technologies by eLCC and WLC assessment and operational costs of IFA utilization technologies. (a). NPV_1 of five IFA reutilization or disposal technologies by eLCC method, (b). NPV_1 of five IFA reutilization or disposal technologies by WLC assessment, (c). The operational costs of four IFA utilization technologies.

3.3.4. *Contribution analysis of emissions to externality costs*

To identify the major pollutant contributions to externality costs, overall externality costs were grouped into 4 comprehensive impact categories (Edwards et al., 2018; Martinez-Sanchez et al., 2017) (Fig. 5). Total externality costs for IFA-to-landfill are two orders of magnitude higher than those for other thermal treatment technologies. Externality costs for IFA-to-ceramsite and IFA-to-rock wool are lower than those for others, demonstrating their lower potential pollutants-induced costs to society and eliminating the environmental impact concern of IFA-to-rock wool mentioned in Section 3.2. However, for the four IFA reutilization technologies, climate change costs are higher than those for IFA-to-landfill due to their higher consumption of coal and natural gas,

Table 3
Policy impact on the technology selection of IFA reuse for investors.

Technologies	Policy scenario Baseline	No exemption and a 50% reduction in corporate income tax	No exemption of environmental protection tax	No waste disposal subsidy
IFA-to-landfill	13	13	>30	>30
IFA-to-cement (new plant)	11	11	11	
IFA-to-glassy slags	>30	>30	>30	
IFA-to-rock wool	5	5	5	
IFA-to-ceramsite	3	3	3	

indicating that climate change caused by IFA reutilization should be better controlled.

Major contaminants, as significant contributors to externality costs, are identified for each technology (Supplementary Material-sheet H). Dioxins and mercury are the biggest contributors to human health while ammonium discharged into water is mainly responsible for water quality issues for the landfill option. 95% of the externalities for IFA-to-cement came from human health-related emissions due to sulfur dioxides and nitric oxides from the cement calcination process. Results for IFA-to-glassy slags and IFA-to-rock wool are similar except climate change due to their higher natural gas combustion. Externality costs for IFA-to-ceramsite are mainly caused by sulfur dioxides, nitric oxides, and lead, which are the major sources of human health and climate change costs. More efforts should be paid to reduce these emissions during the IFA-to-ceramsite process to reduce their potential risks to society.

3.4. Sensitivity analysis

3.4.1. Environmental analysis

Sensitivities of major input parameters on EP_{net} in Section 3.2 are shown in Fig. 6. Electricity, coal, and limestone rank in the top three for IFA-to-cement. For IFA-to-glassy slags and IFA-to-rock wool, electricity is the most sensitive parameter. For IFA-to-ceramsite, PED, AP, EP, and PI are sensitive to coal mining and combustion (42.9%), SO_2 (53.5%), Na_2CO_3 (47.9%), and calcium hydroxide (42.9%), respectively. POFP, GWP, and WU are sensitive to cement consumption and their sensitivities are all higher than 27.8%. In general, parameters related to energy consumption (i.e. electricity, coal, and natural gas) affect the environment most for IFA-to-glassy slags (81.0%), IFA-to-rock wool (115.0%), and IFA-to-cement (82.2%), which should be the major improvement directions. For IFA-to-landfill, the raw materials, i.e. cement and chelating agent, are the most sensitive parameters.

3.4.2. Economic analysis

Sensitivities of the major parameters on eLCC and WLC results corresponding to NPV_5 in Section 3.3 are shown in Table 5. Prices of the main products, feedstock, and labor costs are the most sensitive parameters for IFA-to-cement (newly built plant), and 10% variation of the three parameters could result in 46.8%, 39.3%, and 38.0% of NPV_5 changes, respectively. Energy consumption and the price of main products ranked in the top two for IFA-to-glassy slags and IFA-to-rock wool, especially the latter one because of the higher selling price of rock wool (USD 323.4 per tonne). For IFA-to-ceramsite, the price of main products and feedstock are the most sensitive parameters for both the eLCC and WLC results. For WLC, sensitivity analysis of externality cost was analyzed and found externality cost is the most sensitive factor for IFA-to-cement and IFA-to-landfill compared with other factors from a WLC perspective.

3.5. Scenario analysis

IFA-to-ceramsite is the most preferred technology according to WLC results. Sensitivity analysis results of IFA-to-ceramsite demonstrate that Sec-FA landfill contributes to the most environmental impact for IFA-to-ceramsite because of cement consumption. While, sintering aids, as one of the feedstock, account for over 75% of the total operational costs (Fig. 4(c)). To further improve IFA-to-ceramsite option, a scenario analysis was performed using LCA, eLCC, and WLC methods as follows. Detailed information of baseline case and two scenarios is described in Section 2.6.

3.5.1. Environmental analysis

Results in Fig. S2 show that scores in all environmental impact categories are reduced by more than 16.9% in scenario 1 and scenario 2 compared with the baseline case. This is mainly due to the elimination of cement consumption to stabilize Sec-FA before landfill disposal in the baseline case. Also, recovering salts and heavy metals enlarge the $EP_{a\text{-}void}$. Compared with scenario 1, a significant reduction in PED (184.0%) is observed in scenario 2. This is because the replacement of clay with polluted soil could eliminate the environmental impact of traditional polluted soil in-situ remediation and clay mining. Overall, recycling Sec-FA to recover resources (i.e. salts and heavy metals) could improve its environmental performance. Replacing clay with polluted soil could lead to further improvement. As a result, scenario 2 performs better than the other four IFA reutilization technologies from an environmental aspect (Supplementary materials-sheet D).

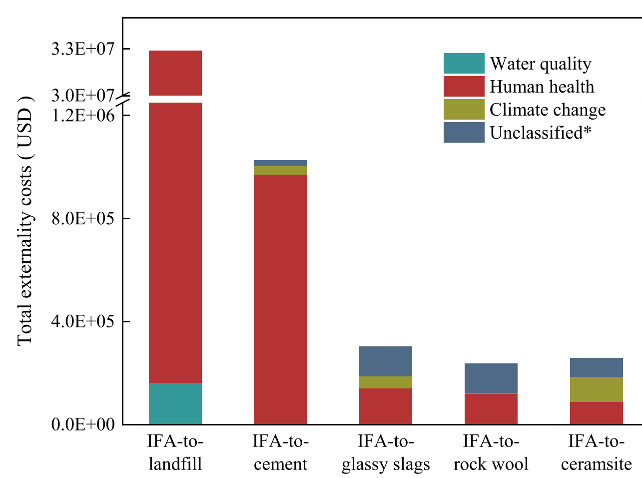

Fig. 5. Contribution of environmental emissions within four categories to externality costs. (Note: Unclassified * represents externality costs of the remaining unclassified emissions).

Table 4
NPV of five IFA management technologies calculated by WLC assessment (Function unit: treatment of 10,000 t of IFA, unit of NPV_i: USD).

Items	IFA-to-landfill	IFA-to-cement	IFA-to-glassy slags	IFA-to-rock wool	IFA-to-ceramsite
NPV_1	−4.86E+05	−1.31E+06	−1.31E+06	−1.27E+06	−1.66E+05
NPV_5	−2.61E+05	−6.22E+05	−1.76E+06	4.77E+04	4.12E+05
NPV_{10}	−6.52E+04	−3.84E+04	−2.10E+06	1.12E+06	8.93E+05
Break-even year	>30	>30	>30	6	4

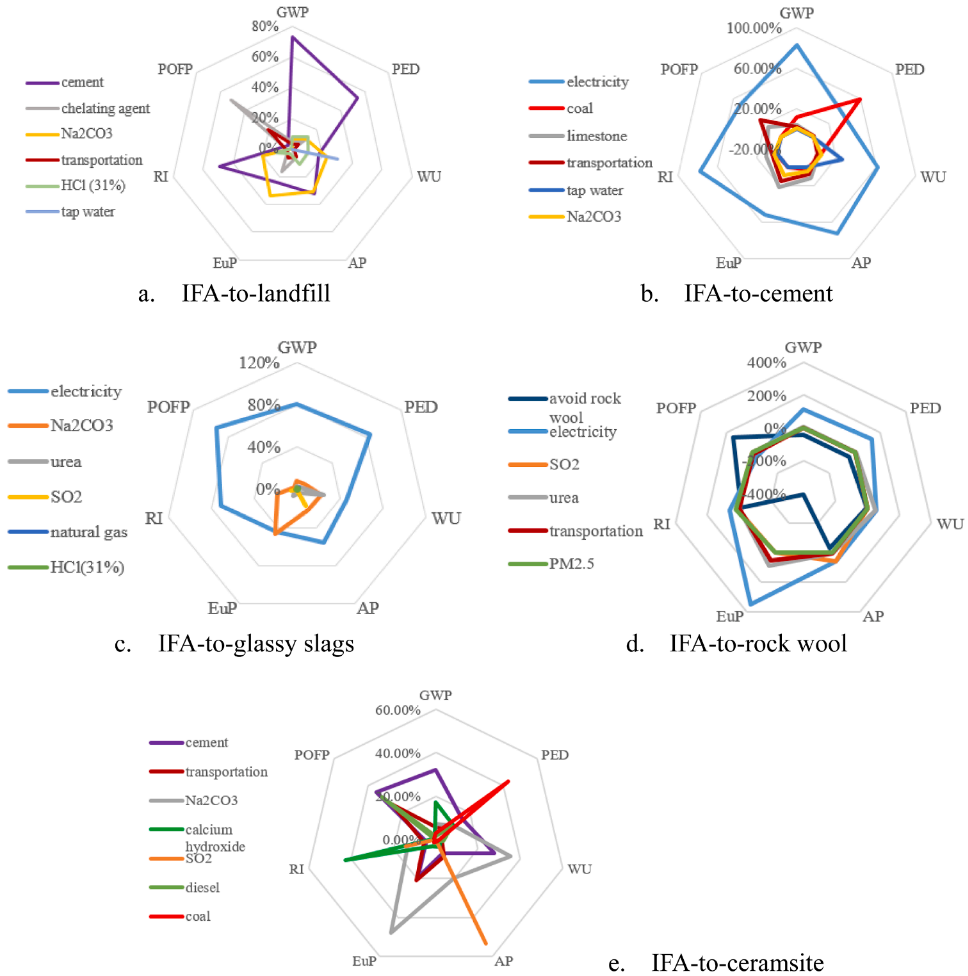

Fig. 6. Sensitivity analysis of LCA results for the five IFA reutilization or disposal technologies. A. IFA-to-landfill. B. IFA-to-cement. C. IFA-to-glassy slags. D. IFA-to-rock wool. E. IFA-to-ceramsite.

Table 5
Sensitivity analysis of economic results of the four IFA reutilization technologies.

Items	Sensitivity ratios		IFA-to-cement	IFA-to-glassy slags	IFA-to-rock wool	IFA-to-ceramsite	IFA-to-landfill
Incomes	price of the main products	eLCC	46.8%	22.9%	4160.8%	76.6%	0%
		WLC	20.0%	20.1%	1354.9%	157.0%	0%
	price of byproducts	eLCC	12.2%	4.3%	/	3.05%	29.1%
		WLC	5.2%	3.8%	/	6.2%	0.6%
Traditional costs	transportation	eLCC	3.1%	0.9%	0.6%	10.4%	8.6%
		WLC	1.3%	0.8%	0.2%	21.2%	0.2%
	feedstock	eLCC	39.3%	19.3%	216.1%	118.5%	/
		WLC	16.7%	16.9%	70.4%	242.8%	/
	energy consumption	eLCC	27.1%	95.5%	2175.2%	11.4%	/
		WLC	11.5%	83.7%	708.3%	23.4%	/
	labor costs	eLCC	38.0%	12.4%	362.5%	29.2%	/
		WLC	16.2%	10.9%	118.0%	59.8%	/
Externality costs		eLCC	/	/	/	/	/
		WLC	57.5%	12.4%	132.6%	104.9%	97.9%

3.5.2. *Economic analysis*

Economic analysis results by eLCC and WLC methods for IFA-to-ceramsite scenarios are shown in Table S5. NPV results for eLCC and WLC results at year 1 (Figs. S3 and S4) show a similar trend except the externality costs added in WLC results. Both results indicated that sales income increases while cost decrease in scenario 1 and 2. The operational costs for scenario 1 and scenario 2 are reduced by 11.9% and 58.1% than the baseline case. The waste disposal subsidy in scenario 3 is relatively higher because the polluted soil disposal subsidy was included as an income. Besides, the co-processing of IFA with polluted soil avoided the soil remediation, so the avoided treatment cost of polluted soil was also included as an income. As a result, both scenario 1 and scenario 2 break even ahead of schedule compared with the baseline case, indicating that improvements are promising from eLCC and WLC perspectives. Nevertheless, the break-even year of the WLC results for each scenario was delayed for 1 year compared with that of the eLCC results due to introducing the externality costs.

4. Discussion

The newly released standard "Technical specification for pollution control of MSW IFA (HJ 1134-2020)" is one of the most important milestones in China to motivate IFA reutilization development. To promote IFA reuse, comprehensive information on their environmental impacts and economic performances could support policymakers' decisions. Our results indicate that the demonstrated IFA-to-ceramsite and IFA-to-rock wool technologies could be potential candidates to substitute the industrial IFA-to-landfill and as an alternative/addition to the current widely used technology IFA-to-cement. Despite the risk of leaching heavy metals and dioxins, IFA-to-landfill would still occupy a large market share temporarily due to the lack of mature IFA reutilization technologies and its relatively longer industrial cycle. IFA-to-cement presents better environmental performance because the added IFA replaces a good amount of limestone in conventional cement production. Our economic analysis suggests that a retrofit of an existing cement plant for IFA co-treatment instead of a new cement kiln could be an option. However, the existing cement plant could only cover 6% of the total IFA amount in China. On the other hand, our analysis results raise certain concerns for the economic viability when a new IFA-to-cement plant is built, and the further treatment of heavy metals and salts transferred into the wastewater. Emerging IFA-to-glassy slags could release land occupations. However, both environmental and economic analysis results do not support its industrialization potential. We recommend an extension of the industrial chain to produce higher value-added and more environmentally-friendly main products (i.e. rock wool being 6 times higher value than the glassy slags), and to eliminate the water-washing step potentially due to the pollutants' transfer. IFA-to-ceramsite and IFA-to-rock wool technologies performed better than other technologies from a WLC perspective. The end use of ceramsite and rock wool as construction materials offers a larger market potential than glassy slags. Even so, product quality still needs more authentication because the incomplete volatilization of chlorides during IFA-to-ceramsite process and chlorine-contained Sec-FA reinjection during IFA-to-rock wool may lead to a higher content of chlorides being transferred into the main products. Our scenario analysis of IFA-to-ceramsite supports the recommendation of the environmental and economic benefits by using polluted soils as sintering aids and Sec-FA reutilization in the literature (Zhao et al., 2020). Electricity, as the major contributor to IFA-to-rock wool technology's inputs, is the key factor to be improved. We suggest an on-site IFA reutilization in the MSW incineration plant to produce rock wool by using electricity from the MSW incineration plant via co-location rather than sourcing from coal and natural gas. Scenario analysis on policy changes raise the concerns for the heavy dependence of IFA treatment businesses on government supports, but IFA-to-ceramsite and IFA-to-rock wool show better resilience. The estimated waste disposal subsidy when $NPV_5=0$ could provide a break-even subsidy indicator for policymakers for each technology. The analysis of pollutants' contribution to externality costs inspires policymakers of stricter control of the "climate change" indicator during the technological transition of IFA management. Nevertheless, as IFA is a hazardous waste, policymakers should take the social benefits from its management as the guidance to minimize the environmental impact of IFA management, to restrain enterprises from the excessive pursuit of economic benefit, to prevent the vicious competition among enterprises. Specific measures should be developed to strengthen the supervision over the IFA illegal transfer, IFA disposal subsidy, and the end use of IFA product.

There are uncertainties and limitations in this study. We make assumptions to unify the functional unit of systems, the IFA composition, transportation distances, and facility depreciation in different technologies. The prerequisites are given to avoid some unnecessary interference (Supplementary Material-sheet A). Results and conclusions are based on the compiled LCA and LCC inventories from enterprise investigation. The universality may be influenced and restricted by the complexity of IFA composition and the quality of IFA products.

5. Conclusions

Material and cash flow models for four IFA reutilization technologies (i.e. IFA-to-glassy slags, cement, rock wool, and ceramsite) and one IFA-to-landfill technology in China were established. Heavy metal distribution and transfer efficiency during the IFA treatment process were analyzed by material flow analysis. The environmental and economic performances of these five technologies were performed and compared by LCA and eLCC methods. To aggregate LCA and eLCC results, WLC was performed by extending the eLCC scope to include externality costs. The major contribution of pollutants to externality costs was identified to flag potential damage caused by pollutant emissions for IFA management technologies. The impact of policy changes on technology selection were examined in the context of eLCC. Scenario analysis of IFA-to-ceramsite was executed for a technology improvement.

Environmental impact results indicate that IFA-to-cement and IFA-to-ceramsite are superior to IFA-to-landfill and IFA-to-glassy slags. Economic analysis results denoted by NPV values show that IFA-to-ceramsite and rock wool, cement (new plant), and landfill could achieve break-even points at years 3, 5, 11, and 13. The LCA results of IFA-to-cement (new plant) and IFA-to-rock wool presented inconsistency with the eLCC result. The WLC analysis integrates both aspects and demonstrates that IFA-to-ceramsite and IFA-to-rock wool technologies have the potential to substitute the traditional IFA-to-landfill and IFA-to-cement, to improve the economic and environmental benefits from the whole industrial chain of IFA management in China. Policy scenarios show that changes in corporate income tax and environmental protection tax have little effect on the economic performances but waste disposal subsidy is a compulsory for all five technologies to be economically feasible from the eLCC perspective. Results of pollutants' contribution to externality costs demonstrate that major pollutants in IFA-to-landfill were dioxins, mercury, and ammonium. While sulfur dioxides, nitric oxides, lead, etc. were dominators for IFA reutilization technologies from the WLC perspective. Results for land use assessment indicate that IFA reutilization technologies could release significant amount of land from landfill treatment.

Future research should focus on incorporating other factors in assessing the performance of IFA reutilization technologies (i.e. different transportation radius, different city characteristics, the site area occupation, the market demand for IFA products, as well as risk assessment of products based on different application scenarios), to achieve the overall environmentally friendly, economically feasible and resilient reutilization of IFA.

CRediT Author Statement

Fang Liu: Basic conceiving, investigation, data collection, data analysis, methodology, model building, original draft writing.

Hanqiao Liu: Collecting data, technology analysis and guidance, enhancing scenario analysis and discussion.

Na Yang: Reviewing the original draft, enhancing methodology.

Lei Wang: Comprehensive conceptualization, collecting data, overall guidance, model building, funding acquisition, reviewing the original draft.

All authors contributed to discussing the results and writing the paper.

Declaration of Competing Interest

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105541.

Appendix A

Supplementary data

Content of Supplementary Materials		
1	Sheet A	Prerequisites and assumptions
2	Sheet B	Material Flow Analysis (MFA)
3	Sheet C	Life cycle inventory
4	Sheet D	Life cycle impact assessment
5	Sheet E	Sensitivity analysis-LCA
6	Sheet F	Economic performance
7	Sheet G	Integrated analysis (WLC)
8	Sheet H	Externality costs
9	Sheet I	Supplementary tables and figures

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