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Exergetic assessment of municipal solid waste management system in south Beijing

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ABSTRACT

The exergetic analysis model of municipal solid waste (MSW) was established to study the MSW management system in south Beijing. The materials and energy inventory of different processes, including transport, mechanical separation, compost, incineration and landfill, were analyzed. Based on the inventory analysis, the exergetic efficiencies of different unit technologies and management systems were studied, and the main results were: (1) the exergetic efficiency of compost and incineration is 5.98% and 14.23%, higher than landfill, 2.92%; (2) mechanical separation increases the exergetic efficiency of unit technologies, from 2.92% to 4.33% of landfill and from 14.23% to 15.59% of incineration; and (3) integrated treatment increases the comprehensive exergetic efficiency of the MSW management system, exergetic efficiency of MSW management system in south Beijing increased from 2.91% to 4.57% because the processes of mechanical separation and compost were introduced, furthermore, when the incineration facility is applied to treat the plastic and paper, exergetic efficiency of the system will increase to 13.95%. According to the exergetic analysis, HRRIS aims (harmless, recycling, reductive, industrializing and socializing) of MSW management system were put forward, and scavenger management, charging mechanism and integration of technologies were discussed.

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1. Introduction

Municipal solid waste (MSW) management system is a complex system that contains social economic and environmental factors (Banar et al.). Different materials and energies were inter-transformed through processes, and the harmless, recycling, reductive, industrializing and socializing aims were expected to be completed. Thus methods of systemic assessment are essential to research the MSW management.

Life cycle analysis (LCA) method was widely practiced for systemically assessing MSW management systems. Life cycle inventory analysis of resources, energies and pollutants emissions is the first phase to determine the emission patterns within the system; some studies also involved economic and welfare factors into the life cycle inventory (Eriksson et al., 2005). And then the environmental impact potentials of global warming, acidification, nutrient enrichment and ecotoxicity are calculated (Banar et al.; Xu et al., 2000; Eriksson et al., 2005; Chen and Lin, 2008). Some LCA models with friendly human–computer interface have been developed to assist the decision-making of MSW management and proved successful, such as Integrated Waste Management

(IWM) model, Waste Reduction Model (WARM), Organic Waste Research model (ORWARE) and WASTED model (Diaz and Warith, 2006; Oeler et al., 2006). Analytic hierarchy process (AHP) model, multi-decision making model and geography information system (GIS) were used to overcome the difficulties of temporal and spatial analysis of LCA (Shmelev and Powell, 2006; Contreras et al., 2008). Though such useful improvements were made, there are still some difficulties of LCA method, for example, comparison among environmental impacts, cost and social benefits may be determined by subjective weights. The environmental impact potential of LCA does not have any physical signification, and analyzing the benefits of resource recovering was found to be difficult (Brown and Buranakarn, 2003).

Emergy and exergy analyses are used to assess the resources' transforming efficiency and sustainability, and they are always integrated with life cycle inventory analysis (Li and Wang, 2009). Emergy analysis has been introduced in researching the recycling processes of municipal solid waste and demolition waste. Emergies, materials, labors and investments are unified into solar emergy joules (sej) by their emergy transformity to research systemic efficiency (Lei and Wang; Brown and Buranakarn, 2003; Marchettini et al., 2007). Dewulf assessed waste recycling processes with exergy method to quantify the systemic sustainability in industrial ecology perspective (Dewulf and Langenhove, 2002, 2005). Both emergy and exergy can reflect the quality of energy inhered in the

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resources, thus can unify different types of resources and used as a systemic assessing tool. Nevertheless, emergy is appropriate to study the large scale systems, such as ecological and urban systems, while exergy is appropriate to study comparatively small scale processes, such as power plants and bio-ethanol productions (Sciubba and Ulgiati, 2005). Improvements of exergy analysis have been made to study more complex systems, for example, extended exergy accounting including externalities of exergy resources, thus providing possibility to study the biodiversity, ecological services and social-economic-natural complex ecological systems (Dewulf et al., 2000, 2001; Nielsen, 2007; Jogensen, 2010; Petrovskaya et al., 2006).

The exergy analysis model was studied to assess MSW management system in south Beijing. Inputs and outputs of exergy resources of different processes were listed in the inventory and calculated the exergy consumption, such as materials (food waste, paper, plastic, methane, compost, etc.), energies (coal, electricity, diesel, etc.) and labors. The exergetic efficiencies of MSW management systems and unit treatment technologies (landfill, compost and incineration) were studied; moreover, the impacts on systemic exergetic efficiency due to the social phenomena of rubbish collectors (scavengers) and relative policies were discussed.

2. Methods

2.1. Exergy analysis

The second law of thermodynamics says every process has a degradation toward entropic, in other words, the quality of energy decreases. Exergy is the maximum work that can be obtained from materials, so it can be expressed as “useful energy” and reflect the quality of energy. The implication of exergy is expressed in forum (1).

$$e_1 = h_1 - h_0 - T_0(s_1 - s_0) \quad (1)$$

where: e_1 , exergy; h_1 , h_0 , specific enthalpy; T_0 , temperature; s_1 , s_0 , specific entropy.

Cumulative exergy consumption (CExC) derived from the concept of exergy. It can be quantified that the exhausted resources and energy to obtain some products or service, and the CExC of different resources and energies are additive. Procedure for exergy accounting is: (1) define the control boundary; (2) draw a detailed flow chart of the system; (3) establish a library of CExC of each process and classify the useful and useless products; (4) define the thermodynamic state; (5) perform a mass and energy balance; (6) study the exergy balance of each process; (7) compute the exergetic efficiency of each process or system (Sciubba and Ulgiati, 2005), that is the ratio of all the exergy outputs and inputs. The method to compute exergetic efficiency of the MSW management system was shown in forum (2).

$$\eta = \frac{\sum_{\text{useful}} O_k}{\sum_j I_j} = \frac{O_{\text{methane}} + O_{\text{compost}} + O_{\text{heat}}}{I_{\text{waste}} + I_{\text{energy}} + I_{\text{labour}}} \quad (2)$$

2.2. Study area

There are two important parts of municipal solid waste management: (1) the commercial department is in charge of the recyclables' collection, recycling and remanufacturing; (2) the municipal administration committee is in charge of the transport, separation, compost, incineration and landfill of the municipal solid waste, which is deemed to be useless and only has a small part of recyclables. Materials flow of MSW management system is

Fig. 1. Flow of MSW treatment system.

shown in Fig. 1. The exergy inputs of the MSW management systems include solid wastes, energy and labor, while the exergy outputs include methane, heat and compost.

MSW management system in south Beijing (Xuanwu District and Fengtai District) is studied. These two districts produce about 1900 tons of waste/day. Currently, there are three MSW treatment facilities: Majialou transfer and separation station with capacity of 1100 tons/day, Nangong compost facility with capacity of 600 tons/day, and Anding landfill with capacity of 1300 tons/day; and an incinerator with capacity of 1000 tons/day has been planned. The Majialou transfer and separation station was built in year 2002 and designed to separate solid waste into three categories by their diameters: (1) <15 mm, the main composition is dirt, ash and a small part of organics; (2) from 15 to 60 mm, most of this part is organics; (3) more than 60 mm, the main composition is plastic, paper and organics. Currently, solid waste with the diameter from 15 to 60 mm (226 tons/day) was sent to the Nangong compost facility, while other parts (874 tons/day) were sent to the Anding landfill. According to the MSW treatment plan, when the incinerator is used, solid waste larger than 60 mm is supposed to be incinerated, the combusted ash and solid waste smaller than 15 mm are disposed in Anding landfill (149 tons/day). Exergetic transforming efficiency of different MSW management systems in south Beijing was researched: S1 is the system before year 2002, solid waste was disposed in landfill without mechanical separation and compost; S2 is the system at present, solid waste was mechanically separated, and medium sized solid waste was composted; and S3 is the proposed system, where an incinerator will be introduced to treat large sized solid waste.

2.3. Numerical model of treatment process

W is the weight of processed solid waste (W_T , transport; W_S , separation; W_L , landfill; W_C , compost; W_I , incineration), c_i , d_i and w_i are proportion, degradable organic component (DOC) and moisture of different kinds of composition, where $i = 1, 2, 3, 4, 5, 6, 7$ refers to food waste, paper, plastic, glass, dirt and ash, metal and wood.

- (1) Transport and mechanical separation: exergy inputs are electricity, diesel and labor, no exergy output.
- (2) Landfill: main product is methane, calculated with formula (3) (IPCC, 2000, 2001) and (4). About 80% of methane could be collected in the landfill site.

$$W_{\text{methane}} = W_L \times \text{MCF} \times \text{DOC} \times \text{DOC}_F \times F \times \frac{16}{12} \quad (3)$$

$$\text{DOC} = \sum c_i \cdot d_i \cdot (1 - w_i) \quad (4)$$

where W_L = total MSW disposed to landfill sites; MCF = methane correction factor (1.0 for sanitary landfill); DOC = degradable organic carbon; DOC_F = fraction DOC dissimilated ($0.014T + 0.28 = 0.77$, $T = 35$); F = fraction of methane in landfill gas (default 0.5).

- (3) Incineration: main product is heat, calculated with formula (5) and (6) (Rand et al., 2000).

$$E_{\text{heat}} = \varepsilon \cdot \sum W_i \cdot C_i \cdot \text{LHV} \quad (5)$$

$$\text{LHV}_i = \text{HHV}_i \cdot C_i - w_i \cdot 2445 \quad (6)$$

where E_{heat} = heat recovered from the incineration facilities; ε = efficiencies of energy recover systems (80%, system only recover heat); LHV_i = low heat value of different waste; HHV_i = high heat value of different waste; C_i = combustibles of different waste (%).

- (4) Compost: main product is compost, which could be calculated with formula (7).

$$W_{\text{compost}} = \alpha \cdot W_C \quad (7)$$

where W_{compost} = the weight of compost; α = transfer efficiency from organic waste to compost (25% in practice).

2.4. Cumulative exergy consumption

Extraction of resources out of the ecosphere, transport and labor are considered in order to compute the total cumulative exergy consumption (CExC) for solid waste recycling and treatment. A library of the CExC of materials and energies and their reference are given in Table 1. Fresh water has been selected as the reference state of zero exergy content.

3. Results

3.1. Input and output of CExC

The inputs and outputs of exergy resource were calculated (see Table 2). The exergetic transforming process is determined by the characteristics of solid waste. The composition, moisture, DOC and high heat value of different sized solid waste in south Beijing were mentioned in Appendix A. The main productions of solid waste treatment processes were determined by formula (4)–(7). According to the calculation, the most important exergetic input was solid waste, which accounts for 95.8–99.6% of the total exergetic inputs. The exergetic input of plastic is about 15,000 GJ, which is the highest among all the components of solid waste; the exergetic inputs of food waste and paper are 7413.2 GJ and 1240.9 GJ, which are lower than plastic; the exergetic inputs of glass, dirt and ash, metal and wood are <500 GJ, which are much lower than plastics, food waste and paper.

When the different unit technologies, mechanical separation, compost, incineration and landfill, were integrated and the systems were improved from S1 to S2 and S3, the output of exergy increased from 743.2 GJ to 1173.6 GJ and 3699.8 GJ, though the accessorial exergy inputs of transport, energies and labor increased from 65.4 GJ to 236.4 GJ and 1120.3 GJ in the same time. In the view of exergetic resource recovering, these improvements are totally worthy because the accessory inputs are much lower than the exergetic output of solid waste.

3.2. Exergetic efficiency of different treatment systems

When mechanical separation, compost, incineration and landfill were integrated and the systems were improved from S1 (landfill) to S2 (separation, compost and landfill) and S3 (separation, compost, incineration and landfill), the exergetic efficiency of different systems increases (see Fig. 2). As shown in Fig. 2, the main results are: (1) the exergetic efficiency of S1 was the lowest among these three systems, only 2.92%. (2) S2 separated 15–60 mm sized organics from solid waste and composted, the organics can be recycled in a more efficient way, thus the exergetic efficiency of S2 increase to 4.57%. Although other solid waste were separated into 15 mm undersized and 60 mm oversized, they were mixed again and landfilled because of lacking further treatment facilities; (3) S3 adds an incinerator to S2, solid waste larger than 60 mm (most of them are plastic, paper and food waste) is combusted, the energy inherent in plastics and papers can transform to heat, which is then transformed into electricity. Thus the exergetic efficiency will increase to 13.95% in the future.

3.3. Exergetic efficiency of different processes

Three main processes, landfill, compost and incineration, are considered. The exergetic efficiency of different solid waste treatment processes is impacted by the characteristics of solid waste. Each process is best suited for certain kind of solid waste in the view of exergetic transformation. In the south Beijing's case, solid waste has separated into three different sizes; the exergetic efficiency of each process treating different sized solid waste is shown in Table 3. Landfill with mixed solid waste obtain a lowest exergetic efficiency of 2.92%, but when the medium sized (15–60 mm) solid waste was separated, the exergetic efficiency of landfill increased to 4.33%. If the solid waste larger than 60 mm is separated from landfill process, the exergetic efficiency increases to 10.90%. This is because that most of this part is plastics and papers, which have very high cumulative exergy consumption but have little impact on methane production in the landfill process. The same result comes to incineration processes of different kinds of solid waste. Comparing the incineration of mixed solid waste and the

Table 1
Resources and utilities required for the MSW treatment system.

I/O	Material and energy	CExC	Unit	Reference
Input	Food	15.5	MJ/kg	Wall (1986)
	Paper	69.16	MJ/kg	Finnveden et al. (2005)
	Plastic	86	MJ/kg	Dewulf and Langenhove (2002)
	Glass	33.4	MJ/kg	Szargut et al. (1988)
	Stone and ash	1.1	MJ/kg	Dewulf et al. (2001)
	Metal	45.9	MJ/kg	Szargut et al. (1988)
	Wood	13.3	MJ/kg	Wall (1986)
	Electricity	11.27	MJ/kWh	Szargut et al. (2002)
	Coal	22.6	MJ/kg	Szargut et al. (2002)
	Diesel	53.2	MJ/kg	Wall (1986)
	Transport	4.33	MJ/km	Dewulf et al. (2001)
	Labor	52.7	MJ (man – 1 h) – 1	Sciubba (2001)
	Compost	4.36	MJ/kg	Dewulf et al. (2001)
	Methane	51.98	MJ/kg	Szargut et al. (1988)
Output	Electricity	11.27	MJ/MJ	Szargut et al. (2002)

Table 2
Summary of exergy input and output of different MSW treatment systems.

I/O	Materials and resources	CExC of S1 (GJ)			CExC of S2 (GJ)			CExC of S3 (GJ)			Separation (1100 tons)	Total (1100 tons)
		Landfill (874 tons)	Transport (1100 tons)	Total (1100 tons)	Landfill (874 tons)	Compost (226 tons)	Separation (1100 tons)	Total (1100 tons)	Landfill (149tonstons)	Compost (226 tons)		
Input	Food	7413.2			4209.6	3201.7			231.0	3201.7	3977.0	
	Paper	1240.9			913.1	328.2			0.0	328.2	912.6	
	Plastic	15492.1			15147.3	359.6			0.0	359.6	15138.6	
	Glass	375.1			193.8	181.2			0.0	181.2	193.7	
	Stone and ash	424.6			420.0	4.5			147.5	4.5	272.7	
	Metal	166.7			156.5	10.4			0.0	10.4	156.4	
	Wood	293.0			293.3	0.0			0.0	0.0	293.1	
	Electricity	18.6			14.8	19.4	43.4		2.5	19.4	0.0	43.4
	Coal	0.0			0.0	0.0			0.0	0.0	819.3	
	Diesel	29.3			23.2	0.0			4.0	0.0	69.4	
Output	Transport	0.0	39.7		6.3	1.6	39.7		1.1	1.6	5.2	39.7
	Labor	17.5			13.9	15.9	58.2		2.4	15.9	38.2	58.2
	Total input	25470.9	39.7	25510.6	21391.8	4122.4	141.3	25655.5	388.4	4122.4	21876.2	26528.3
	Compost	0.0			0.0	246.3			0.0	246.3	0.0	
	Methane	743.2			927.3	0.0			42.3	0.0	0.0	
	Electricity	0.0			0.0	0.0			0.0	0.0	3411.1	
	Total output	743.2		743.2	927.3	246.3		1173.6	42.3	246.3	3411.1	3699.8

2000). According to recent estimation, there are 130,000 scavengers in Beijing city. Most of them belong to the floating population and live on collecting and selling recyclable resources.

We have studied separating processes of scavengers in the community, and the main results are: (1) recyclable resources that could be collected/inhabitant/day by scavengers are: cardboard, $10.57 \text{ kg } 10^{-3} \text{ capita}^{-1} \text{ d}^{-1}$; newspaper, $7.27 \text{ kg } 10^{-3} \text{ capita}^{-1} \text{ d}^{-1}$; plastic, $0.83 \text{ kg } 10^{-3} \text{ capita}^{-1} \text{ d}^{-1}$; (2) average separating efficiency of a scavenger is $0.64 \text{ kg (waste) capita}^{-1} \text{ min}^{-1}$. According to these experiment datum, we could estimate that the recyclable resources collected by scavenger in south Beijing is 21.1 tons of cardboard, 14.5 tons of newspaper and 1.66 tons of PET plastic bottles, and the population of scavengers is about 6.2 thousand.

Dewulf has computed that the exergetic efficiencies of remanufacturing cardboard, newspaper and PET plastic are 36.1%, 47.1% and 83.5%, respectively (Dewulf and Langenhove, 2002). The exergy input of manual separation of scavengers is estimated of 326.7 GJ (6.2 thousand people's daily labor, $8 \text{ h capita}^{-1} \text{ day}^{-1}$). Even considering the labor inputs, the exergetic efficiency of collecting and remanufacturing cardboard, newspaper and PET plastic is expected to reach 50.0%, which is much higher than the incinerating processes (cardboard and newspaper, 7.1%; plastic, 18.7%). Although scavengers could assist the remanufacturing system to obtain higher exergetic efficiency, there are still many disadvantages, such as poverty, lacking medicare and unemployment insurance, crime and environmental pollution. Scavengers always live in the suburb and are hard to govern.

Suggestions are: (1) reserve a reasonable population of scavengers in the city; (2) standardize the management of scavengers and support the small or middle sized enterprises to organize scavengers to separate solid waste into three or more categories (combustible, compostable and recyclable waste), compensate for the extra works of scavengers; and (3) integrate the scavengers into the "venous industry" and extend the recycling industrial chain, establish relative policies, criterions, standards and the regulations of supervision, inspection, assessment and encouragement to manage the whole society participating solid waste recycling.

4.2. Charge for producing solid waste

Exergy can be used as an index to charge and compensate for producing solid waste. For example, reduction of solid waste and controlling the pollutants of the process of recycling do not have any profit, but the exergetic efficiency of the whole system may be increased due to these operations. It is helpful to establish indices to compare different kinds of contributions or impacts on solid waste management systems, thus exergy can be used as an index and integrated with other indices, such as cost, weight or pollution. Charging or compensating mechanism between different processes and departments (source, collection, transport, recycling, treatment and disposal) should be established to integrate the management of the whole system.

4.3. Integration of technologies at the end

According to the exergy analysis, integrating technologies increase the exergetic efficiency at the end of MSW management system. Separation and terminal treatment should be matching and planned holistically. Separation of solid waste is expected to be promoted through developing relative policies, propaganda and education, thus a multifunctional integration of unit technologies should be constructed at the end. there are some considerations in south Beijing's case: (1) some policies have been made to promote safe recycling of restaurant's food waste with higher moisture and oil content, thus a food waste treating factory should be constructed; digestion or biodiesel technologies could be chosen;

(2) it is hard to find a new landfill site around Beijing, exploiting old landfill sites can both reuse the landfill space and recycle manure, metals and plastics in the old sites, thus screening and separating technologies of old landfills should be applied; (3) the biological processes can be accelerated in bioreactor landfill with leachate recirculation or aeration, thus relative facilities should be constructed; and (4) an MSW management system should be constructed at the end with technical integration of landfill, compost, incineration, digestion, biodiesel, screening and separation, bioreactor landfill, etc.

5. Conclusion

- (1) Exergetic analysis could be used as a scientific tool to objectively and comprehensively assess the MSW management systems.
- (2) Exergetic analysis could explain the hierarchy in the MSW management; prevention and separation are on the top of the hierarchy.
- (3) Integration of different technologies (separation, recycle, compost, incineration and landfill) could increase the systematic exergetic efficiency.
- (4) According to the exergetic analysis, HRRIS aims (harmless, recycling, reductive, industrializing and socializing) of MSW management system were put forward, and scavenger management, charging mechanism and integration of technologies were discussed.
- (5) This paper focused on the exergetic assessment of resource transforming; some researches using the exergy method to reflect the environmental impact have been done recently. Hence, a comprehensive exergetic index that integrated different systematic aims could be further discussed.

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Appendix A

Tables 4 and 5

Table 4

Component of different diameters of separated municipal solid waste (Rong et al., 2004).

Waste	<15 mm	15–60 mm	>60 mm	<15 mm and >60 mm	All mix
Food	10.00%	91.40%	35.39%	31.07%	43.48%
Paper	0.00%	2.10%	1.82%	1.51%	1.63%
Plastic	0.00%	1.85%	24.28%	20.15%	16.38%
Glass	0.00%	2.40%	0.80%	0.66%	1.02%
Stone and ash	90.00%	1.80%	34.20%	43.69%	35.09%
Metal	0.00%	0.10%	0.47%	0.39%	0.33%
Wood	0.00%	0.00%	3.04%	2.52%	2.00%
Battery	0.00%	0.35%	0.00%	0.00%	0.07%

Table 5

Parameters for calculating the low heat value of MSW.

Waste	d_i	HHV (kJ/kg)	w_i	C_i
Food	0.444	17,000	0.66	0.21
Paper	0.356	16,000	0.47	0.47
Plastic	0.000	33,000	0.29	0.63
Glass	0.000	0	0.03	0.00
Stone and ash	0.000	0	0.10	0.00
Metal	0.000	0	0.06	0.00
Wood	0.000	17,000	0.35	0.60

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