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Life cycle assessment of the municipal solid waste management system in Hangzhou, China (EASEWASTE)

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Abstract: With the purpose of assessing the environmental impacts and benefits of the current municipal solid waste management system and two modified systems, EASEWASTE, a life-cycle-based model, was used to evaluate the waste system of Hangzhou city in China. An integrated model was established, including waste generation, collection, transportation, treatment, disposal and accompanying external processes. The results showed that CH_4 released from landfilling was the primary pollutant contributing to global warming, and HCl and NH_3 from incineration contributed most to acidification. Materials recycling and incineration with energy recovery were important because of the induced savings in material production based on virgin materials and in energy production based on coal combustion. A modified system in which waste is transported to the nearest incinerators would be relatively better than the current system, mainly due to the decrease of pollution from landfilled waste and the increase in energy production from waste avoiding energy production by traditional power plants. A ban on free plastic bags for shopping was shown to reduce most environmental impacts due to saved oil resources and other materials used in producing the disposal plastic bags. Sensitivity analysis confirmed the robustness of the results. LCA methodology and a model like EASEWASTE are very suitable for evaluating the overall environmental consequences, and can be used for decision support and strategic planning in developing countries like China where pollution control has become increasingly important with the rapid increase of waste generation as well as the increasing public awareness of environmental protection.

Keywords: Life cycle assessment (LCA), solid waste, environmental impacts, waste management modelling, EASEWASTE

Introduction

Waste management has become a key issue in environmental protection and urban management in China as it has in many rapidly developing economies (Wang & Nie 2001a, Wang & Nie 2001b). Main challenges include the collection of data describing the existing waste management system and developing a rational assessment of potential improvements in the system. The purpose of this paper is to introduce LCA-modelling (Life Cycle Assessment) as a holistic and systematic methodology for environmental evaluation of waste management systems in developing countries so that the information collection, technology development and waste management system improvements can be introduced in a scientific and efficient way.

The paper presents the results of an assessment of environmental impacts of the municipal solid waste system in the City of Hangzhou, China. The assessment includes the current municipal solid waste management system and two potential improvements: (1) optimizing the waste collection system so that the waste is transported to the nearest treatment facilities, and (2) avoiding the use of free shopping bags made of non-recyclable plastic and introducing reusable bags made of recyclable plastic.

LCA accounts for all uses of resources and all emissions from the system accumulated through the whole ‘lifetime’ of the waste (Hansen *et al.* 2006a, Christensen *et al.* 2007). In this study we used the EASEWASTE model (Environmental Assessment of Solid Waste Systems and Technologies), which has been developed by the Technical University of Denmark for environmental assessment of waste systems. EASEWASTE is able to compare different waste management strategies, waste treatment methods and waste treatment technologies by quantitatively evaluating environmental impacts and resource consumptions (Kirkeby *et al.* 2006a). The model contains default data for waste composition and source segregation efficiencies as well as for most technical processes: collection, transport, material recycling facilities, thermal treatment, composting, digestion, landfilling, recycling processes, use-on-land of organic waste, material utilization and energy utilization, as well as external processes that may occur either upstream or downstream of a solid waste management system, such as energy production and consumption processes. The model calculates emissions to air, water and soil and any consumption of resources. The life cycle impact assessment (LCIA) method from EDIP 1997 (Wenzel *et al*. 1997) was applied to translate the emissions into environmental impacts (Kirkeby *et al.* 2006b). The model is a framework and all the necessary data in each category can be defined by the users, including that of the LCIA method. EASEWASTE has been used in the evaluation of waste management systems, such as application of treated organic solid waste on agricultural land (Hansen *et al.* 2006a, Hansen *et al.* 2006b), solid waste landfill (Kirkeby *et al.* 2007), solid waste incineration (Riber *et al*. 2008) and for assessing the solid waste management system in the municipality of Aarhus, Denmark (Kirkeby *et al.* 2006b).

Materials and Methods

For the Hangzhou case study, data have been collected mainly from local municipal and environmental departments, local waste treatment plants, associated references and bibliographies. Some data which are of less importance or lacking under Chinese conditions were taken from the default database in EASEWASTE and the articles mentioned above. EASEWASTE was utilized to represent a life cycle inventory, a characterization of impacts, a normalized impact profile and finally a weighted impact profile.

Scope of waste management system

Hangzhou is a mega city in east of China and approximately 2 775 800 inhabitants lived in the City of Hangzhou in 2006, not including the inhabitants living in suburbs (Li *et al*. 2007). The housing is dominated by apartment buildings. The unit generation rate of waste was 1.17 kg per person per day, and the total amount of municipal solid waste was approximately 3 247 tonnes per day, equal to 1 185 269 tonnes per year. The composition of solid waste used in this paper is shown in Table 1 (Nie 2000).

Table 1 Typical composition of MSW in China (%) (Nie 2000)

Fractions	Percentage by wet weight	DS (%)	Element percentage by weight (%DS)				
			C	H	O	N	S
Vegetable food waste	45	28	48.0	6.4	37.6	2.6	0.4
All kinds of paper	15	85	43.5	6.0	44.0	0.3	0.2
Yard waste, flowers	12	55	47.8	6.0	38.0	3.4	0.3
All kinds of glass	8	95	0.0	0.0	0.0	0.0	0.0
Cardboard	4	75	44.0	5.9	44.6	0.3	0.2
Ash	4	90	26.3	3.0	2.0	0.5	0.3
All kinds of plastics	3	92	60.0	7.2	22.8	0.0	0.0
Other metals	3	95	0.0	0.0	0.0	0.0	0.0
Wood	2	70	49.5	6.0	42.7	0.2	0.1
Textiles	2	90	55.0	6.6	31.2	4.6	0.15
Aluminium containers	1	95	0.0	0.0	0.0	0.0	0.0
Rubber, etc	0.5	90	78.0	10.0	0.0	2.0	0.0
Shoes, leather	0.5	90	60.0	8.0	11.6	10.0	0.4
total	100	56.8	41.25	5.41	32.16	1.81	0.27

The total amount of solid waste was 1185 269 tonnes per year, of which 271 427 tonnes per year was individually collected waste, including 106 674 tonnes of waste paper, 66 375 tonnes of waste glass and 98 378 tonnes of other individual collections such as plastic bottles, aluminium containers and so on. The individual collection aims at the valuable fractions to be recycled by individual, unorganized transportation. These activities were modelled as part of waste separation at the source. The recycle percentages of the waste are shown in Table 2 (Tian *et al*. 2007).

Table 2 Recycle percentages of different fractions in MSW (Tian *et al*. 2007)

Fractions	Collecting Percentage (%)
All kinds of plastics	20
Rubber, etc	50
All kinds of paper	60
Cardboard	80
Textiles	60
Shoes, leather	60
Other metals	60
Aluminium containers	90
All kinds of glass	70

The rest of the municipal solid waste, which was approximately 913 842 tonnes per year, was collected by the municipal collection system and transported to the treatment plants after material recycling, with about 18 654 tonnes of waste recycled annually. In terms of the capacity of each treatment plant, 32 945 tonnes per year was taken to incinerator A, 210 907 tonnes per year was taken to incinerator B which is close to the material recycling facilities, 122 638 tonnes per year was taken to incinerator C, and the residuals were directed to the landfill which is outside the city. The transport distances are average distances from each material recycling facility and transfer station to the corresponding treatment plant. The integrated solid waste system of the city is represented in Figure 1.

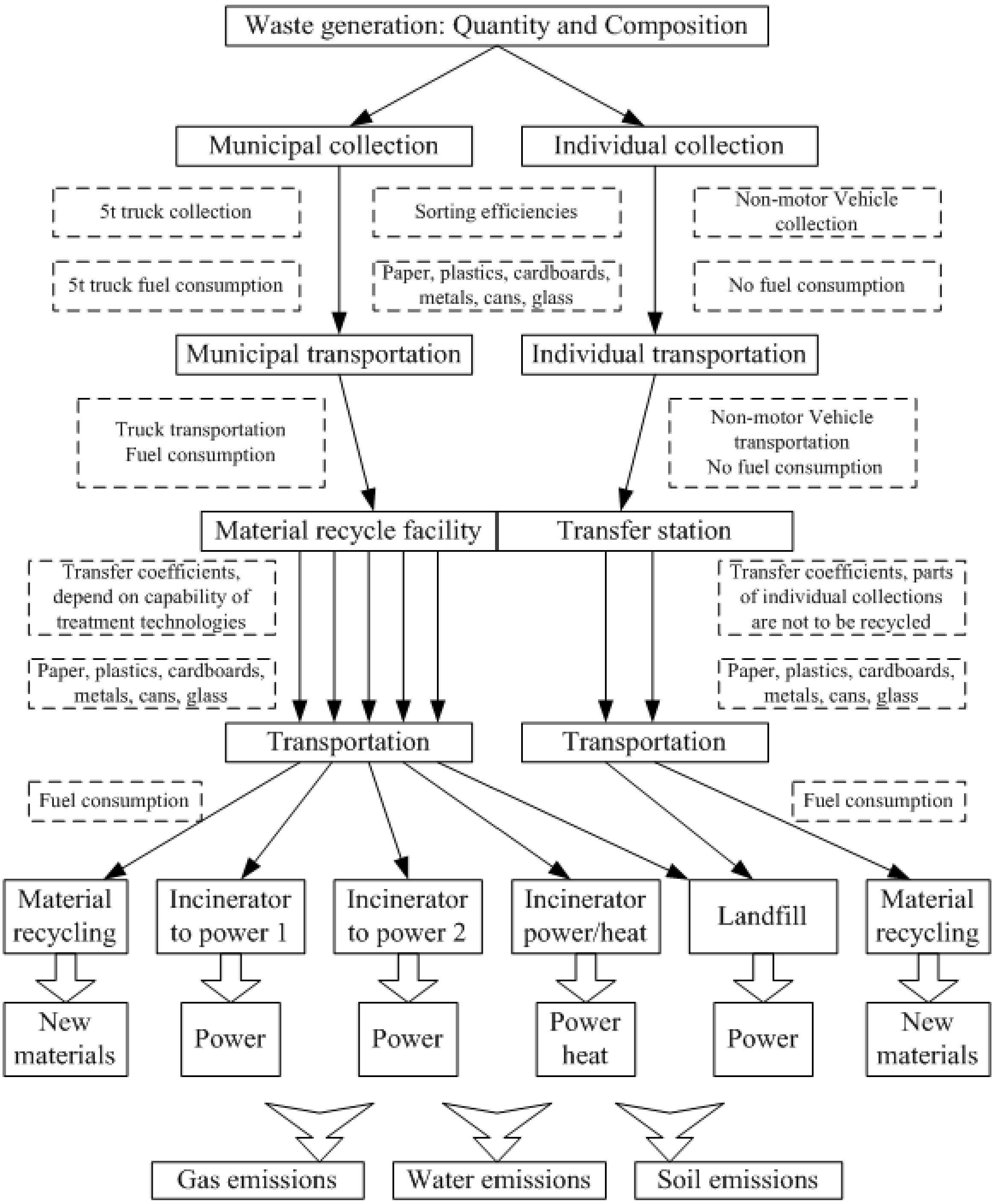

Fig. 1 Municipal solid waste system of Hangzhou City, China

Technologies

The technologies contained in the waste system model can be classified into two types. One is the waste treatment and disposal technologies including material recycling facilities (MRFs), incineration, landfill and material recycling as shown in Figure 1. The other is external processes. External processes represent the environmental impacts from material production and energy production which are used in the waste system. The following is an overview of some of the most important technology parameters for the study.

The collection trucks in the study were 5 tonne collection trucks with an average fuel consumption of 1.28 l per tonne collected (Li *et al*. 2007), and they were assumed to have a combustion technology corresponding to Euro3 standards. Electricity for all processes was mainly based on coal production (Li *et al*. 2007) and this is also the process used for substituting the energy production from the incinerators. The energy recovery efficiency for all 3 incinerators was set to be 23% (from default database). All residual waste products leaving the 3 incinerators were sent to Tanziling sanitary landfill. The recycling processes were all from the EDIP database and the following substitution percentages were used: Paper recycling 82 %; Plastic recycling 81 %; Cardboard recycling 85 %; Iron recycling 100 %; Aluminium recycling 79 %; and Glass recycling 96 %. The residual waste was sent to the same mixed waste landfill. The landfill has a limited collection of methane for energy recovery, 29 % of the methane is collected for energy recovery with a combustion efficiency of 30%. Another 8% of the methane is collected and flared. The remaining 63 % of the potential methane is assumed to be either oxidized in the top cover or released to the atmosphere. 95% of the leachate is assumed collected and sent to a waste water treatment plant.

Scenarios

The environmental assessment is based on three scenarios, where the first two (Scenario A and B) addresses the waste distribution to the treatment facilities. For the sake of the global environment, free shopping bags made of non-recyclable plastic are forbidden in China after June 1st, 2008. So Scenario C assesses the environmental impacts from substitution of non-recyclable disposable bags with reusable plastic bags made from recycled plastic. A deposit on the bags has been introduced to increase the reuse of the bags.

Scenario A is the current waste management system in Hangzhou, in which the mixed waste after recycling is sent to incineration and landfill averagely in terms of the capacity of the treatment plants.

Scenario B is based on an optimization of waste collection and transportation, according to which solid waste generated from multi-family houses is collected and transported preferentially to the nearest thermal treatment facility, and the waste exceeding the capacity of the current facilities is sent straight to the landfill.

Scenario C considers recyclable plastic bags as the substitution and the consumption of plastic bags will be reduced by 2/3. Furthermore, about 50% of the plastic bags discarded can be recycled.

Results

The scenarios gave the following material flows as seen in Table 3 separated into individual collection and municipal collection.

Table 3 Treatment and disposal of waste and residues in all scenarios (tonnes)

	Scenario A	Scenario B	Scenario C
Individual collections	271 427	271 427	271 427
Plastic recycling	7 112	7 112	7 112
Paper recycling	106 674	106 674	106 674
Cardboard recycling	37 929	37 929	37 929
Steel recycling	21 335	21 335	21 335
Aluminium recycling	10 667	10 667	10 667
Glass recycling	66 375	66 375	66 375
Residues (Landfill)	21 335	21 335	21 335
Municipal collections	913 842	913 842	896 063
Plastic recycling	3 023	3 023	4 800
Cardboard recycling	1 896	1 896	1 896
Steel recycling	7 453	7 453	7 453
Aluminium recycling	593	593	593
Glass recycling	5 689	5 689	5 689
Incinerator A	32 945	54 741	53 545
Incinerator B	210 907	292 005	285 629
Incinerator C	122 638	164 265	160 678
Landfill	528 698	384 177	375 780
Total	1 185 269	1 185 269	1 167 490

The results for all three scenarios are calculated as normalized potential impacts according to the normalized environmental impacts potential reference of China (Li *et al.* 2007), which are different from the default LCIA method, EDIP 1997 (Wenzel *et al.* 1997), as shown in Table 4. Normalization provides a relative expression of the environmental impact or resource consumption compared to the impact from one average person. The yearly contributions from the defined system are divided by the normalization reference, which are the yearly total emission (global/regional/local) per person (worldwide/regionally/locally). This yields a normalized impact potential in the unit ‘person equivalent’, PE for short (Hansen *et al.* 2006b). In the EASEWASTE software, a positive value of normalized impact potential means a contribution to the impact, and a negative value indicates that the system in the scenario leads to avoidance of the impact or resource consumption due to an avoided production of external virgin materials or energy such as electricity, district heating, paper and glass (Kirkeby *et al.* 2006b). When these products are substituted, the emissions to air, water and soil that would have occurred during their manufacturing are subtracted from emissions occurring in the waste management system.

Table 4 Environmental normalized potential impacts reference in China and EDIP 1997* (Li et al. 2007 & Wenzel et al. 1997)

Environmental Impacts	Standard Unit	Normalization Reference	
		China	EDIP 1997
Global warming (GW100)	$kgCO_2\ eq \cdot a^{-1}$	8700	8700
Stratospheric Ozone Depletion (OD)	$kgCFC\text{-}11\ eq \cdot a^{-1}$	0.20	0.103
Acidification (AC)	$kgSO_2\ eq \cdot a^{-1}$	36	74
Nutrient Enrichment (NE)	$kgNO_3\ eq \cdot a^{-1}$	62	119
Photochemical Ozone Formation (POF)	$kgC_2H_4\ eq \cdot a^{-1}$	0.65	25

Figure 2 shows the environmental impacts caused by scenario A where it can be seen that most of the impacts are more or less avoided in total except stratospheric ozone depletion which shows an infinitesimal negative value. Materials recycling, especially aluminium recycling and paper recycling are the main contributors to the savings of emissions of photochemical ozone formation, acidification and greenhouse gases. Incineration of waste can save the impacts mentioned above as well. The released methane from the landfill is the main pollutant source of global warming and photochemical ozone formation, and consumption of electricity in the MRFs and transfer stations contributes with the maximum impacts of acidification. Furthermore, over 75% of the contribution to global warming is caused by the release of landfill gases.

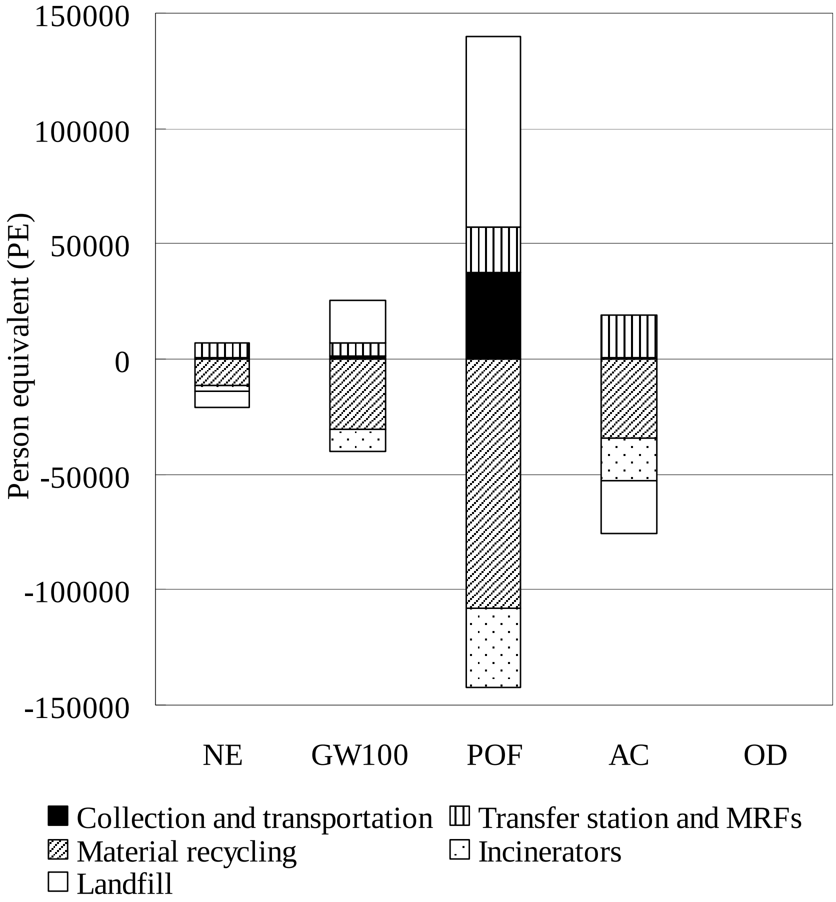

Fig. 2 Normalized potential impacts for scenario A

The differences in environmental impacts from scenario A and scenario B, which are shown in Table 5, are relatively large in most impacts due to an additional 16% of the overall waste mass, approximately 900 000 tonnes, is lead to incineration instead of the landfill (Table 3). The potential impacts for global warming from scenario A is greater than that from scenario B due to more methane release from landfill in scenario A, though the total normalized impacts are both negative because of energy recovery from waste incineration and biogas. The high values of savings for the acidification impact indicate that recycled material production and electricity from the incinerated waste contribute to the avoidance of pollution deriving from virgin materials and energy production (Figure 3). For photochemical ozone formation, scenario B is significantly better than scenario A. This is because the emissions from transportation and landfill counteract almost all the avoidance from recycling and incineration in scenario A, whereas in scenario B, the pollution from landfill decreases and the avoidance from incineration increase. Nonetheless, in the whole waste system, the methane released from the landfill is a pollutant of primary importance to global warming and photochemical ozone formation, and the hydrogen chloride from incineration and ammonia from the landfill are the two main substances contributing to acidification.

Table 5 Environmental impacts from scenario A and B

Impacts	Scenario A PE	Scenario B PE	Difference in PE	Comments
Global warming	–14338	–23116	–8778	Scenario B better
Stratospheric Ozone Depletion	–19	–25	–6	Scenario B better
Acidification	–56617	–57730	–1113	Scenario B marginally better
Nutrient Enrichment	–13813	–13062	751	Scenario A marginally better
Photochemical Ozone Formation	–2785	–40871	–38086	Scenario B significantly better

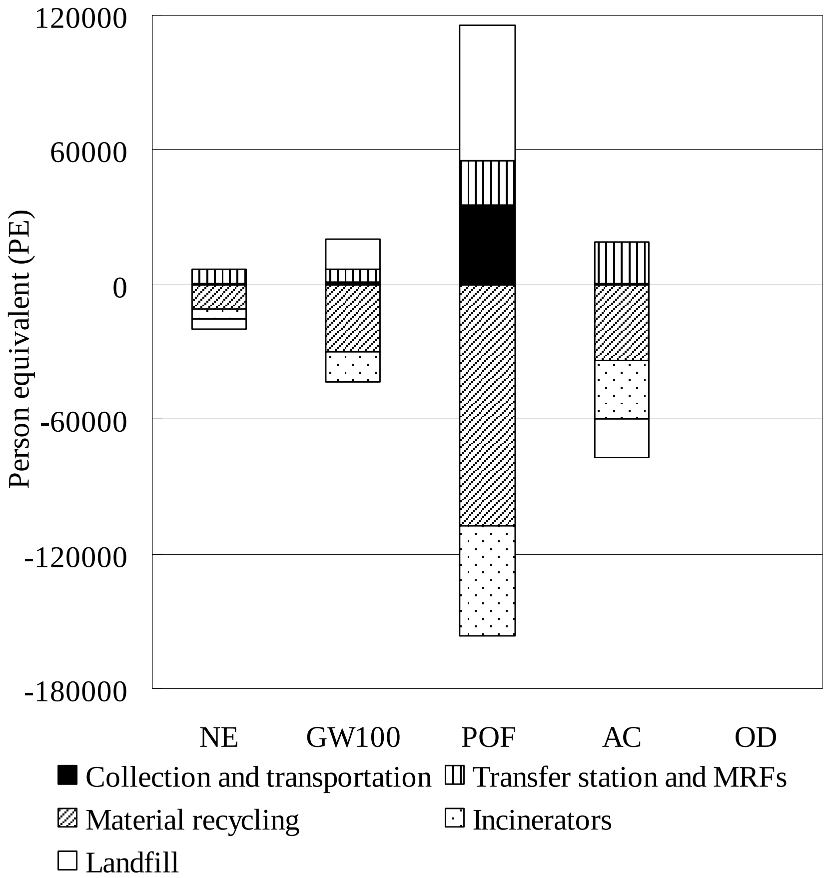

Fig. 3 Normalized potential impacts for scenario B

Results from scenario C (Table 3 and Figure 4) show that approximately 18 000 tonnes of waste is avoided per year after the free shopping bags made of non-recyclable plastic were forbidden. The difference between scenario B and C is not as significant as that between scenario A and B, but still impacts are saved in all the categories investigated. In scenario C, about 1 800 tonnes of additional plastic per year is going to be recycled due to the enhancement of the recyclable proportion. It will make a great contribution to reducing nutrient enrichment, greenhouse gases, photochemical ozone and acidification. On the other hand the decrease of plastic waste will lead to less power production from incineration and thus less substitution of electricity generation from coal. Therefore, scenario B has apparent advantages in most impacts in comparison with scenario C without including the impacts avoided from less plastic production. Greenhouse gases for instance, are mainly caused by gas released from the landfill and the use of fossil fuel, as shown in Table 6. But meanwhile, the incineration can save the impacts of greenhouse gases because of the energy production which is the substitution of fossil fuel energy. In theses instances, there is marginally less transportation and less biogas in scenario C because of less waste generation, and also less substitution of energy. As a result. Scenario C seems not as good as scenario B if the avoided impacts from less plastic production are not included. However, the potential impacts of material production can be calculated in EASEWASTE as well. There are 3781 PE avoided from avoided production of plastic bags and it means more benefit to the global warming impact due to saved oil resources and other materials for plastic production. The same conclusion can be obtained in the analysis of nutrient enrichment and acidification impacts.

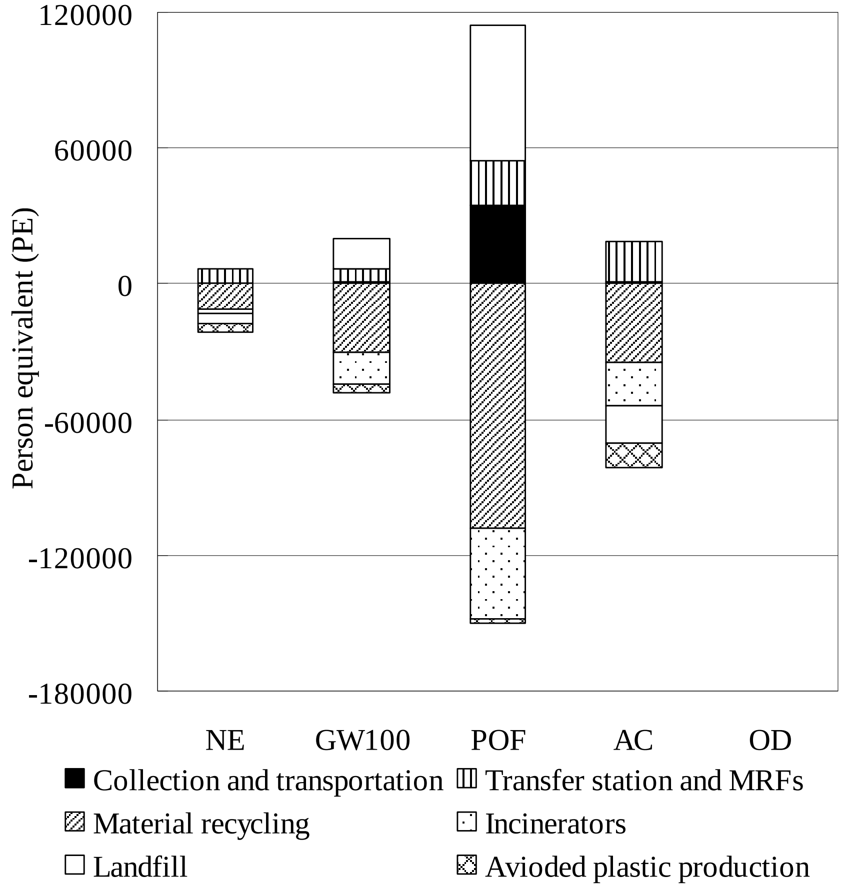

Fig. 4 Normalized potential impacts for scenario C

Table 6 Impacts of global warming from scenario B and C

Technologies	Scenario B PE	Scenario C PE	Difference in PE	Comments
Collection and transportation	1103	1084	–19	No significant difference
Transfer stations and MRFs	5973	5856	–117	Scenario C marginally better
Material recycling	–30277	–30413	–136	Scenario C marginally better
Incinerators	–13216	–13729	–513	Scenario C marginally better
Landfill	13301	13294	–7	No significant difference
Avoided plastic production	0	–3781	–3781	Scenario C significantly better
Total	–23116	–23908	–792	Scenario C better

Sensitivity analysis

There was a significant degree of uncertainty in some data utilized in the scenarios above, so it wss necessary to perform a sensitivity analysis to assess the robustness of the results and the conclusions. With this purpose a series of alternative scenarios, in which some of the parameters in scenario A and B which had been found uncertain or interesting, were constructed to evaluate the importance of these parameters. The sensitivity scenarios are mainly based on scenario C, and compared with scenario C. The sensitivity parameters are described below and all the results are aggregated in Figure 5.

Scenario C1: The decrease of plastic waste is 1/2 instead of 2/3

The decrease in plastic waste is an uncertain value because it will be related to the implementation of the policy, the acceptance of the public, the cost of shopping bags and many other factors. It was assumed that 2/3 of non-recyclable plastic waste will be avoided after the free shopping bags were forbidden in scenario C and the proportion was changed to 1/2 in this scenario. The result shows a small difference with that of scenario C. The avoidance of nutrient enrichment, global warming and acidification is a little less than that of scenario C due to the pollution from 4 445 tonnes more plastic produced per year.

Scenario C2: The recycling proportion of plastic bags reduced to 35% from 50%

The plastic recycling percentage depends on technology, properties of waste, utilization of recycled waste and so on. It even varies with the labour market as well. Therefore, 35% of recycling proportion of plastic bags is considered as a more conservative estimation compared with 50% as used in the original scenario. The results show that the saving of impacts is of little difference with that of scenario C, which indicates that the recycling proportion of recyclable plastic bags is not a sensitive parameter in the system with incineration.

Scenario C3: The reduced plastic bags are substituted by the same quantity of paper bags

It may affect the convenience of consumers at the beginning that the free plastic bags were banned, so the substitutions of non-recyclable plastic bags are probably put on schedule very soon. Paper bags are an alternative option due to its decomposability, recycling ability and low cost, and it is also discussible because of the consumption of resources, low strength and its non-watertight quality. This scenario evaluates the difference between plastic bags and paper bags in the sense of environmental impacts. The results in figure 5 show that the impacts of global warming, nutrient enrichment and photochemical ozone formation are significantly worse in scenario C3 due to the pollution and resource consumption from more paper production and application. Though more paper waste leads to more power recovery in incinerators, the saved impacts can not compensate for the impacts from paper production.

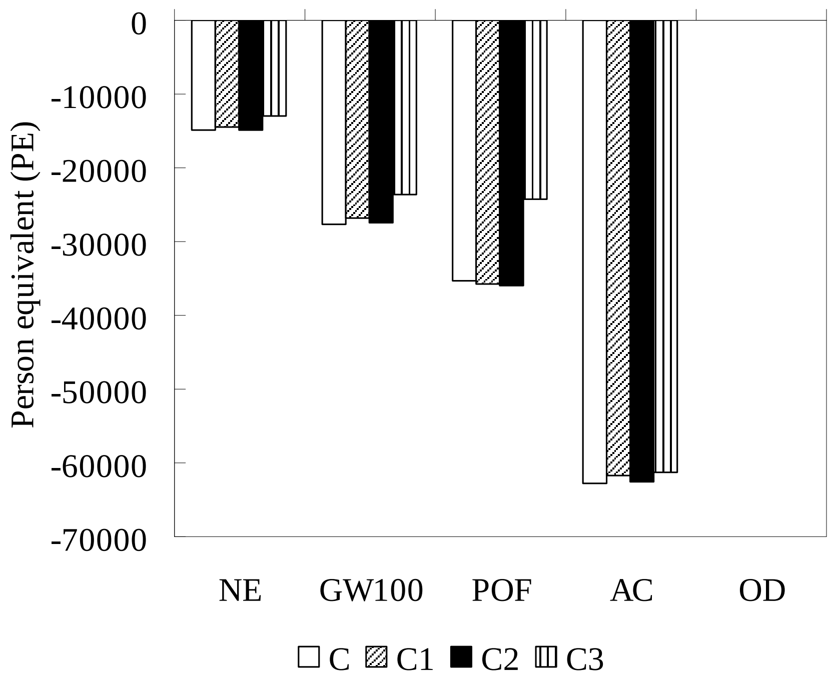

Fig. 5 Normalized potential impacts for sensitivity scenarios

Discussion

The scenarios depend on a large set of data which all cannot be collected satisfactorily. The data were collected from local municipal and environmental departments, local waste treatment plants, associated references and bibliographies, but were also taken from the default database in EASEWASTE. In this instance, it is necessary to assess the reliability and source of the data. Some of the main problems in the waste system are related to the waste composition, transportation, treatment, and evaluation method.

Waste generation

The waste quantity in Hangzhou system is in accordance with the population in the centre of the city. A number of inhabitants living in the suburbs, where the waste system is not as sound and holistic as that in the city, are not included in the scenarios. The waste composition which is taken from a bibliography is based on the average waste composition in cities of China. However, the compositions varies within cities and local cultures, for instance, 3%

(weight) of waste is plastic waste in the municipal solid waste in Beijing while plastic waste amounts to approximately 7% in Shanghai. Furthermore, the chemical compositions of each material fraction were not complete for Chinese material fractions, and the missing data are taken from the EASEWASTE default database from fraction with similar characteristics.

Collection and transportation

The waste collection and transportation in the cities of China are implemented in a specific way. Most recyclable and valuable fractions in the waste such as glass bottles, plastic bottles, cardboard and metals are collected by individuals and then sold to the transfer stations. So it has been named ‘individual collections’ in this paper and non-motor vehicles are utilized to transport the waste. It can be considered as a kind of source-separation and there is no emission or impact to the environment because no fuel is consumed, except for the production of the non-motorized vehicles which are considered negligible in this study. But individual collections are unorganized and data on the amounts collected are hard to obtain.

Technologies

The main treatment technologies in Hangzhou system are incineration and landfill. As shown in the above results, the landfill leads to more emissions than incineration due to the different standards of operation. Therefore, the waste management system can probably benefit if more incinerators come in service in the future instead of landfills. Moreover, because of many reasons including economy, technique, society and culture, there is no source separation for organic waste, and therefore, there is no biotechnological utilization in the treatment system. This situation may lead to many problems. Firstly, the organic waste, which usually has a high water content, does not burn very well. Secondly, the organic waste poses many problems in landfill such as leachate, gas release and land use. Thirdly, composted or digested organic waste could constitute a source of nutrients if applied to land as fertilizer. Therefore , for organic waste alternatives to incinerators and landfills should be investigated in order to develop a sound and systematic waste management strategy.

LCA method

LCA provides a detailed and complete assessment method for waste management and the models such as EASEWASTE make the calculation and evaluation much easier. The methodology is versatile, whereas the normalization references and weighting factors are different in different regions (except the global impacts). So it is a crucial and desirable job to construct corresponding standard methods with particular and convincing data worldwide, regionally and locally.

Conclusion

The results from the environmental assessment of the solid waste system in the City of Hangzhou showed that the optimized strategy in which waste is transported preferentially to the nearest thermal treatment facilities is relatively better than the current system, mainly due to the decrease of pollution from landfilled waste and the increase in energy production from waste avoiding energy production by traditional power plants. In the whole system, the methane released from the landfill is a primary pollutant to global warming and photochemical ozone formation, and the hydrogen chloride and ammonia contribute the most to acidification. Materials recycling and incineration are of importance because of the avoided impacts.

There were significant differences in most of the potential environmental impacts before and after the free shopping bags made of non-recyclable plastic were prohibited. It is evident that approximately 18 000 tonnes of waste is avoided per year after the free shopping bags were forbidden, and about 1 800 tonnes more plastics per year is going to be recycled due to the enhancement of recyclable proportion. This makes a great contribution to reducing greenhouse gases and impacts of nutrient enrichment and acidification. Moreover, it is also advantageous that the material and resource consumption for the production of bags is avoided. The results of the sensitivity analysis indicate that the amount of avoided plastic bags affected the environmental impacts a little bit and the proportion of plastic recycling showed to be of no consequence. However, it showed a large influence on nutrient enrichment, global warming and photochemical ozone formation if the recyclable plastic bags were substituted by paper bags due to the pollution and material consumption in paper production.

LCA methodology provides a systematic and holistic method to evaluate the environmental impacts and benefits from solid waste systems and their upstream and downstream related activities. EASEWASTE, which is a model based on LCA, can be used as a tool for supporting decisions regarding solid waste management systems and strategies, wherever in worldwide, regional or local level. It demonstrates that LCA methodology and the model of EASEWASTE can be of great help for waste management optimization, especially for the investigation and development of a strategy for waste management in developing countries.

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