EVALUATION OF WASTE TREATMENT STRATEGIES IN CHINESE CITIES FROM VIEWPOINTS OF GHG EMISSION

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Recent years have witnessed increased attention being given to the evaluation and selection of alternative waste treatment strategies from the view of reduction of greenhouse gas (GHG) emissions. However, a long period of waste records is necessary for getting acceptably accurate results, especially in calculating GHG emission from disposal site. Therefore, in this paper, applying the systematic approach we have developed in the previous work, the back-casting and ex-post forecasting of the waste quantity by composition in the past is conducted. Then, current GHG emissions in five Chinese metropolitan cities are investigated and analyzed; thereafter, a scenario analysis is carried out in Shanghai based on the forecasts of waste generation and the corresponding waste category in 2015. Methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O) are mainly taken into account in GHG emission due to significant amount emitted from waste treatment. The results confirm that the per capita CO₂ emission factor (kg CO₂-eq/kg waste-treated) in Shanghai, Guangzhou, Hangzhou, Wuhan and Chengdu in 2007 is 0.48, 0.59, 0.57, 0.41 and 0.48 respectively, thereby demonstrating that economic growth is the main driving force of GHG emissions currently observed in Chinese cities. Further, through the scenario analysis, composting and integrated waste management are considered as effective attempts at reducing GHG emissions in Shanghai.

Key Words: GHG emission, Chinese metropolitan cities, scenario analysis, waste forecasts, composting

1. INTRODUCTION

Greenhouse gas (GHG) emitted from municipal solid waste (MSW) treatment is given increasing concern due to the non-ignorable contribution to the global warming¹-³. As in the cases of Canada and USA, amount of GHG emitted from waste treatment accounted for about 4% in 2001 and 1999, respectively, including waste disposal, incineration and biological treatment rather than involving the emissions from waste collection and transportation⁴-⁵. In 2009, the Chinese State Council talked over and decided to reduce the carbon dioxide (CO₂) emission per unit gross domestic product (GDP) by 40%-45% until 2020 as compared to the value in 2005. The reduction from waste treatment is considered as an effective consideration in China as it is one of the biggest generators of MSW in the world⁶. Further, the effective implementation of the plan needs the good understanding of GHG emission in current and future waste treatment systems.

In the IPCC guideline for calculating methane emission (CH₄) in disposal site, disposal data over a time period of 3 to 5 half-live is suggested in order
to achieve acceptably accurate results\textsuperscript{7}. However, the waste records in a majority of Chinese cities are far from enough, especially for waste composition. In addition, the accurate forecast of MSW generation of each category is prerequisite for designing successful waste treatment system in the future, considering reducing GHG emission. Thus, a model capable of forecasting the waste generation by composition in the past and future years becomes necessary. Yang et al. has developed a systematic approach to estimate MSW generation by composition from the consumption of goods and applied into five Chinese cities\textsuperscript{8}. Applying the approach, not only the back-casting data in past years beyond the periods of available waste records, but also the forecasts of waste generation until 2015 can be conducted.

A large number of research have attempted to take a broad view in comparing different waste treatment strategies from the perspective of the reduction of GHG emission\textsuperscript{9-12}. Zhao et al. analyzed the solid waste management (SWM) with regard to GHG emissions by lifecycle assessment (LCA) in Tianjin, China and designed a scenario analysis for evaluating different integrations of waste treatment\textsuperscript{10}. However, little research has been done based on the back-casting or future forecasting of MSW generation by composition.

Therefore, in this paper, go along with the previous research, firstly, GHG emissions in five metropolises with distinct economic levels are investigated and analyzed; thereafter, a scenario analysis is carried out in Shanghai to evaluate alternative waste treatment options, based on the forecasts of waste generation and the corresponding waste category. Five cities are: from the eastern region, Shanghai, Guangzhou and Hangzhou; from the central region, Wuhan; and from the western region, Chengdu.

2. PREVIOUS RESEARCH ON FORECASTING MSW GENERATION

As mentioned above, the research flow of the systematic approach in previous work is illustrated as Fig. 1. Firstly, individual total household consumption expenditure is estimated by using ordinary least squares (OLS) simultaneously taking into account economic growth and socioeconomic indicators (Model 1); then, household consumption pattern is estimated using an extension of the linear expenditure system (LES), with lifestyle factors attributed as explanatory variables (Model 2); thereafter, per capita MSW generation by composition is quantitatively expressed in terms of the expenditure for consumption category and waste management policies by using OLS method (Model 3); finally, overall MSW generation by composition is obtained integrated with the projection of total population. In this paper, MSW generation is defined as amount of waste collected and transported. The detailed information regarding the development of Models 2 and 3 can be found in the previous work\textsuperscript{8}. However, as the improvement, saving rate towards consumption, rather than aggregated saving deposits in previous research, and natural growth rate (NGR) are considered to be two important variables that significantly affect consumer behaviour in Chinese cities.

Therefore, the waste quantity by composition beyond the period of waste records in the past is estimated by using back-casting and ex-post of the MSW generation model (Model 3), based on the known consumption expenditure in each city. Fig. 2 depicts the change in waste composition in Wuhan as an example. In which, the data from 1989 to 1993 is obtained by back-casting estimation of model 3; values from 1994 to 2005 denote actual records and data regarding the period of 2006-2007 is conducted.
Further, the future MSW generation is forecasted by extrapolating the models as ex-ante forecasts. As future GDP growth is forecasted merely in Shanghai by using Shanghai macro-economic model in previous work, the scenario regarding alternative waste treatment strategies is thus carried out in Shanghai as an example. Further, as demonstrated in previous work, in Shanghai, household size is more influential as compared to NGR as it is an advanced metropolitan city. Therefore, in a target year, with the assumed explanatory variables in each model as well as the continued influence of waste management policies, the forecasts of MSW generation by composition can be obtained. Predicted GDP growth rate and the assumptions of involved explanatory variables in 2010 and 2015 are summarized in Table 1; the values between the years are determined by interpolation method. Moreover, Table 2 tabulates the forecasts of MSW generation by waste category until the year of 2015 in Shanghai. Based on the forecasted results, the fraction of each type of waste will continue experiencing a significant change during the next decade. The fraction of potential recyclable items including paper, plastic, textile, glass and metal will increase from 35.02% to 43.11% as we move from 2005 to 2015. However, even with a marked increase in recyclable items, food waste will still make up over 50% of the waste stream in 2015, greatly affecting the waste treatment options.

### Table 1 Assumption of explanatory variables in each model

| Year | Growth rate of GDP, % | Population, millions | Saving rate, % | Household size, person |
|------|-----------------------|----------------------|----------------|------------------------|
| 2010 | 10.15 (2006—2010)     | 10.61                | 37.80          | 3.0                    |
| 2015 | 8.88 (2010—2020)      | 10.75                | 27.50          | 2.9                    |

Note: The total population is predicted referring to 2002 Population and Family Planning Yearbook of Shanghai and the urban population is assumed to be 75% of total population based on historical records.

### Table 2 Forecasts of waste quantity and composition in Shanghai

| Year | Quantity of MSW (million tons) | Waste composition (%) |
|------|--------------------------------|-----------------------|
|      |                                | food | plastic | paper | textile | glass | metal | ash & wood |
| 2011 | 7.61                           | 57.00| 24.20   | 10.88 | 1.83    | 3.04  | 0.54  | 2.5        |
| 2012 | 8.12                           | 56.30| 24.87   | 11.02 | 1.80    | 2.99  | 0.53  | 2.5        |
| 2013 | 8.68                           | 55.63| 25.50   | 11.15 | 1.77    | 2.94  | 0.53  | 2.5        |
| 2014 | 9.28                           | 54.99| 26.09   | 11.27 | 1.74    | 2.89  | 0.52  | 2.5        |
| 2015 | 9.92                           | 54.39| 26.66   | 11.38 | 1.71    | 2.85  | 0.51  | 2.5        |

### Fig. 2 Change in waste composition in Wuhan, %

LCA is wildly used as an environment management tool to compare the environmental impacts of a product or service. It is applied herein to evaluate the waste treatment strategies in terms of GHG emissions. Further, in order to make comparisons of GHG emissions among the cities, the functional unit is set as both per ton and total quantity of waste. The system boundary includes treatment and final disposal, as incineration plant, composting and landfill, not covering the collection and transportation system. However, even back-casting estimation method is cited to extend the periods of waste records; the data before 1986 in some cities is difficult to be obtained. Further, most of the waste in China was treated by open dumping before 1986 due to the deficiency of landfill sites. Moreover, the emissions from the substitutions of thermal power are considered as well, indicated by negative values. In addition, CO₂ equivalent value (CO₂-eq) is calculated and used for meaningful comparison. On the basis of Fourth Assessment Report (FAR) published by IPCC, the global warming potential (GWP) of CH₄

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3. METHODOLOGY FOR GHG EMISSION
and nitrous oxide (N\textsubscript{2}O) is 25 and 298 during 100-year time horizon (http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf). Thereafter, a scenario analysis based on the waste forecasts in 2015 is carried out in Shanghai.

(1) GHG Emission from waste treatment plants

a) Solid waste disposal site (DS)

Significant amounts of CH\textsubscript{4}, biogenic CO\textsubscript{2} and smaller amounts of N\textsubscript{2}O are emitted from DS. It is evaluated that about 60% CH\textsubscript{4} and 40% CO\textsubscript{2} is generated with other trace gases in DS in Taiwan\textsuperscript{(16)}. However, CO\textsubscript{2} is of biogenic origin not included in the national totals. N\textsubscript{2}O is also assumed to be negligible due to the tiny content. CH\textsubscript{4} emission is calculated using the Microsoft Excel spreadsheet model named IPCC_Waste_Model, based on the First Order Decay (FOD) method.

b) Incineration plant

More and more emphasis has been given for reducing waste volume and producing energy by combusting waste in Chinese cities. Related gases emitted from process of combustion and open burning include CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O, and CO\textsubscript{2} is the most important one. The calculation method is in accordance with the guidance of IPCC (2006).

i. CO\textsubscript{2}

Water content and total carbon content of each type of waste category refer to the actual values investigated in Hangzhou, as tabulated in Table 3. Further, the fraction of fossil carbon in the total carbon is provided based on the IPCC guideline, as shown in the table as well.

ii. CH\textsubscript{4} and N\textsubscript{2}O

Based on the IPCC guideline, the default values of aggregate CH\textsubscript{4} and N\textsubscript{2}O emission factor are cited, as 30 kg and 4 kg per TJ on the net calorific basis (NCB), respectively.

c) Composting plant

Biological treatment of solid waste is common for treating organic waste not only in developed countries, but also in developing countries. It comprises composting, anaerobic digestion (AD) and mechanical-biological (MB) treatment. The main gases considered in this process are CH\textsubscript{4} and N\textsubscript{2}O. However, among the cities, only 8.5% of MSW in Shanghai was treated by composting in 2007, not a key treatment option. Therefore, the emission in composting process is calculated using default emission factors. The default factors for CH\textsubscript{4} and N\textsubscript{2}O emissions are 4g CH\textsubscript{4}/kg waste and 0.3g N\textsubscript{2}O/kg waste on a wet weight basis, respectively.

(2) Scenario analysis

Forecasts of waste quantity and composition of Shanghai until 2015 are conducted as input files of scenario analysis. Further, based on Eleventh-five year Environmental Plan of Shanghai, there is no simple disposal expected in Shanghai until 2015 and the ratio of harmless waste treatment will achieve 100%. Two scenarios concerning the same treatment options in accordance with that in 2007 are noted as baseline scenarios. In which, landfill equipping landfill gas (LFG) recovery system is noted as S\textsubscript{LFG} (energy scenario) and the scenario without energy recovery is set as S\textsubscript{BAU} (BAU scenario). Moreover, the ratio of simple disposal is merged into sanitary landfill in each scenario.

In addition, four scenarios are designed with different percentage share of each kind of treatment option, as shown in Fig. 3. In which, S denotes each scenario. Scenario 1 (S\textsubscript{1}, incineration scenario) is set up for comparing GHG emissions in waste-to-energy plant (WTE) and sanitary landfill both equipping with electricity producing system. Apart from that 8.5% of waste is composted, all other MSW is sent for combustion producing energy instead of landfill. In S\textsubscript{2} (composting scenario), 50% of food waste is assumed to be composted. The remaining waste is treated in WTE plant for producing electricity. S\textsubscript{3} (recycling scenario) is designed to explore the reduction effect of recycling prior to the waste treatment. Based on the report in China-Japan Joint Conference\textsuperscript{(17)}, 50% of the recyclable items is expected to be reclaimed in 2015. The remaining part has the same treatment options with S\textsubscript{BAU}. Integrated waste treatment is set as S\textsubscript{4} (integrated scenario) with 50% of recyclable items being recycled and 50% of food waste being composted, the remaining part is sent to WTE plant. In each scenario, the residues from incineration plant (20%) are assumed to be sent to DS without GHG emission. For simplicity, waste composition keeps unchanged in each scenario.

| Table 3 Water content, total carbon and fossil carbon by waste category, % |
|-----------------|--------------|--------------|--------------|
| Waste category  | Water content | Total carbon in the dry matter | Fossil carbon |
| Food            | 72           | 48           | 0            |
| Plastic         | 6            | 60           | 100          |
| Paper           | 30           | 44           | 1            |
| Textile         | 30           | 55           | 20           |
| Wood            | 45           | 49           | 0            |
| Glass           | 2            | 0            | 0            |
| Ash             | 2            | 4.7          | 100          |
| Metal           | 30           | 26.3         | 0            |
4. TARGET CITIES

(1) Climate variations in each city

Decomposition of organic component in DS is greatly affected by local climate. Thus, prior to calculating GHG emissions, it would be very helpful to investigate the climate conditions of each city, including mean annual temperature (MAT), average relative humidity (H), potential evapotranspiration (PET) and mean annual precipitation (MAP) (Table 4). Based on 2006 IPCC guideline, the moisture content of a DS that affects anaerobic decomposition and CH$_4$ emission is considered to be proportional to MAP in the location of DS or to the ratio of MAP and PET. when MAT $\leq$ 20°C and MAP/PET $>$ 1, the climate is defined as wet climate in Boreal and Temperate zone (W). On the other hand, when MAT $>$ 20°C and MAP $\geq$ 1000mm, it belongs to moist and wet climate in Tropical zone (M); the decomposition of organic matter in a DS is rapid in this condition$^{[19]}$. There is no available information on PET values in Wuhan and Chengdu. However, the two cities locate in the same latitude with Hangzhou and Shanghai, thereby considered as W climate as well.

Table 4 Climate condition in each city in 2007

| Parameter        | Shanghai | Hangzhou | Guangzhou | Wuhan   | Chengdu |
|------------------|----------|----------|-----------|---------|---------|
| MAT (°C)         | 18.2     | 18.4     | 23.2      | 18.5    | 16.8    |
| H (%)            | 68.8     | 71.3     | 70.8      | 66.8    | 76.7    |
| PET (mm)         | 813.8    | 1 150 – 1 400 | –      | –       | –       |
| MAP (mm)         | 1 290.4  | 1 378.5  | 1 370.3   | 1 023.2 | 624.5   |
| MAP/PET          | >1       | >1       | –         | –       | –       |
| Climate zone     | W        | W        | M         | W       | W       |

Source: respective 2008 Statistical Yearbook of each city; ‘—’ denotes no available information

Table 5 General characteristics and solid waste treatment options in each city

| Parameter                             | Shanghai | Guangzhou | Hangzhou | Wuhan   | Chengdu |
|---------------------------------------|----------|-----------|----------|---------|---------|
| Area (km$^2$)                         | 2007     | 6 340     | 7 434    | 16 596  | 8 494   | 12 390  |
| Population (million)                  | 1990     | 12.83     | 5.94     | 5.75    | 6.70    | 9.19    |
|                                        | 2007     | 13.79     | 7.73     | 6.72    | 8.28    | 11.12   |
| Average increase rate of overall MSW(%)| 2000 – 2005 | 4.77 | 5.76 | 5.81 | 7.65 | 5.49 |
| MSW generation per capita per day (kg) | 1990 | 0.59 | 0.81 | 0.86 | – | – |
|                                        | 1995 | 0.64 | 1.11 | 1.21 | 0.42 | 0.55 |
|                                        | 2004 | 1.30 | 1.08 (2003) | 1.59 | 1.01 | 0.81 |
| Percentage share of each treatment option in 2007 (%) | Sanitary landfill | 54.63 | 71.47 | 683 | 54.05 | 92.63 |
|                                        | Compost | 8.50 | 0 | 0 | 0 | 0 |
|                                        | Incineration | 15.64 | 10.88 | 32 | 0 | 3.42 |
|                                        | Simple disposal | 21.23 | 17.65 | 0 | 45.95 | 3.95 |

Note: 1) ‘—’ denotes no available information; 2) Original data is obtained from Department of Integrated Finance Ministry of Construction and has been recalculated by the author; 3) Data in Hangzhou is obtained from field investigation.
(2) Waste quantity and composition

Waste information is obtained from the local Municipal Sanitation Bureau (MSB) of each city that is leded by local Environmental Protection Agency (EPA). Prior to further investigation, the general characteristics of each city are tabulated in Table 5. The increase rates of quantity of MSW generated in the urban area from 2000 to 2005 and per capita waste generation in different years are also summarized in the table. It is confirmed that amount of waste collected and transported has experienced a sharp increase in each city during the last decade.

Further, waste composition has also experienced significant change during the past decade in each city. Chinese cities have high proportion of organic waste (over 50% in selected cities) with high moisture content, thereby seriously affecting compost quality. Further, the fraction of ash waste is gradually decreasing\(^{20}\), for example, from 57.26% to 5.65% in Guangzhou as we move from 1986 to 2003. On the other hand, the fractions of recyclable items are increasing and larger in eastern cities than in central and western cities. Taking Shanghai as an example, the fraction of paper waste has increased from 4.01% in 1990 to 9.23% in 2005. Moreover, eastern cities have higher proportion of organic compounds and lower proportion of ash waste than Wuhan and Chengdu. The fraction of ash waste in Shanghai, Guangzhou and Hangzhou was 1.4%, 5.65% and 5.63%, respectively in 2003, while the value in Wuhan and Chengdu was 16.87% and 17.66%, respectively.

(3) Waste treatment options

Adequate understanding of the characteristics of current waste management is effective for the improvement of SWM system. The waste treatment strategies in Chinese cities mainly consist of incineration, composting and landfill. In which, landfill is the most common method and accounted for 81% of harmless treatment options in 2007\(^{21}\). Further, the open dumping or simple disposal accounts for a big share. The waste treatment options in each city in 2007 are summarized in Table 5 as well. The first formal incineration plant in Shanghai called Yuqiao plant was put into operation in 2002. Another plant named Jiangqiao plant opened in 2005. Incinerators in two plants are both grate furnaces with continuous operation and electricity-generating system (Germany Steinmuller). All the waste was supposed to be sent to landfill sites or open dumping sites before 2002 in Shanghai. Further, one of the main disposal sites — phase IV Laogang DS was transformed and opened again in 2005 capable of processing over 8000 t/d of waste and producing about 160 kWh electricity per ton waste\(^{22}\).

In Hangzhou, the biggest DS for disposing most of waste in urban area is Tianziling DS. The site opened in 1992 in strict accordance with stratified operation unit and the basic flow is level-compact-cover. Further, the landfill gas (LFG) recovery system was in use from 1998. On the other hand, incineration plant equipping with fluidized bed with treatment capacity of \((2 \times 300t/d + 200t/d)\) started to operate around the year 2002. Another plant was built in July 2004 with 7.5MW turbo generator and gas removing system. Fly ash and incineration residues account for 18—20% of the waste, usually sent to cement plants and for construction materials, respectively. Therefore, before the year of 2002, all the MSW was supposed to be sent to DS or simple disposal site as the case in Shanghai.

The formal incineration plant in Guangzhou operated from 2005. Further, the ratio of incineration will be up to 62.5% in 2010 with 29.3% of landfill and 8.2% of composting, as described in the new government plan\(^{23}\). Further, in Wuhan, currently all the waste is sent to DS with a high rate of open dumping or simple disposal. On the other hand, a small amount of MSW (3.42% in 2007) is incinerated in Chengdu.

5. RESULT AND DISCUSSION

(1) GHG emission from waste treatment plants

a) CH\(_4\) emissions from DS of each city

Fig. 4 depicts per capita CH\(_4\) emission from DS in each city until 2007. In 2007, per capita emission in Shanghai, Guangzhou, Hangzhou, Wuhan and Chengdu is 217.69, 399.62, 320.49, 164.00 and 162.53kgCO\(_2\)-eq/yr, respectively. The emissions in eastern cities are larger than in central and western cities. Guangzhou belongs to wet climate (W) that greatly accelerates the waste decomposition rate in DS, thereby leading to a big contribution to GHG emissions. Further, the landfill site in Hangzhou is sanitary landfill fully managed, merely comprising two types of landfill structure as anaerobic and semi-aerobic (2006 IPCC guideline), thereby producing much CH\(_4\) from a given amount of waste than other site types. On the other hand, the CO\(_2\) emission factors in landfill are 0.51, 0.60, 0.64, 0.41 and 0.48 kg CO\(_2\)-eq/kg waste-treated in Shanghai, Guangzhou, Hangzhou, Wuhan and Chengdu, respectively, having the similar tendency with per capita CO\(_2\) emission. It confirms that eastern cities have higher emission levels than central and western cities.

Moreover, Fig. 5 describes the emission from each type of waste in Shanghai from 1990 to 2007, taking into account the overall CH\(_4\) emission. In this case, the year of 2007 was the last year for MSW disposal; CH\(_4\) emission thus achieves a peak in 2008. From the
figure, it is easily to found out that food waste makes the biggest contribution to CH$_4$ emission followed by paper waste; the total gas emissions from these two items accounted for 94.44% in 2007. Further, with the change in waste composition, the amount of CH$_4$ emitted from food waste is decreasing while the amount emitted from paper waste is increasing. The share from food waste has reduced from 93.33% in 1992 to 78.89% in 2007 and the share from paper is up to 15.56% in 2007. Therefore, with the increasing fraction of recyclable items in MSW, recycling of recyclable items prior to waste treatment will be an effective consideration to reducing CH$_4$ emission.

Further, even though no more MSW will be sent to DS from the year of 2007, the emissions will continue a long time and total amount of CH$_4$ emission will be 19Gg/yr in 2020.

b) Emission from incineration plants
The average lower heating value of MSW in Shanghai is obtained from Shanghai Academy of Environmental Sciences (AES). It was 5488.3kJ/kg in 2005, and it is supposed to be 6812kJ/kg in 2015 based on a regression analysis of historical records, with the prediction model as $heating\ value = 126.177 \times (year - 1990) + 3702.35$ (Adjusted $R^2 = 0.97$, $F = 202.531$, and $p$ < 0.05). The emission factors of CH$_4$ and N$_2$O are calculated and shown in Table 6. Further, Table 7 tabulates the per capita CO$_2$-eq emission by waste category in incineration plants of several cities in 2007. In which sum0 denotes the sum of CO$_2$ emissions from each waste category; CH$_4$-CO$_2$ and N$_2$O-CO$_2$ stand for the CO$_2$-eq from CH$_4$ and N$_2$O emissions. Energy producing is not considered in this part for simplicity. Several points are addressed. Firstly, CO$_2$ emissions are much greater than CH$_4$ and N$_2$O emissions in combustion process. Secondly, plastic waste represents the waste type with the highest fossil carbon fraction and contributes the greatest share of CO$_2$ emission among the components. The share is up to 97.91% in Shanghai in 2007. Thirdly, the contribution of ash waste into T-sum is reducing with the decreasing fraction in MSW, from 7.15% in 2002 to 3.99% in 2007 in Hangzhou as an example.

c) Emission from composting plant
According to Table 5, only 8.5% of MSW in Shanghai was sent for composting in 2007 and the per capita CO$_2$-eq emission was 9.00kg/yr.

Then, making a sum of emissions from each type of treatment option in each city, it is found out that per capita CO$_2$-eq emission in Shanghai, Guangzhou, Hangzhou, Wuhan and Chengdu is 266.85, 446.92, 419.70, 164.00 and 167.12kg/yr and the CO$_2$ emission factor is 0.48, 0.59, 0.57, 0.41, and 0.48kgCO$_2$-eq/kg waste-treated, respectively. The factors in eastern cities are higher than those in central and western cities, thereby demonstrating that economic growth is one of the main driving forces of GHG emissions currently observed in Chinese metropolitan cities. On the other hand, considering the population, the total CO$_2$ emission in each city is 2754.08, 2845.69, 912.18, 1358.27 and 1064.16GgCO$_2$-eq/yr in 2007, respectively.

| Default emission factor | 2005 | 2015 |
|-------------------------|------|------|
| CH$_4$ (g/kg waste)     | 30 (kg GHG per TJ on the NCB) | 0.163 | 0.185 |
| N$_2$O (g/kg waste)     | 4 (kg GHG per TJ on the NCB) | 0.022 | 0.025 |
(2) Scenario analysis

Based on the default technical parameter, the recovery efficiency of LFG is assumed as 40% with energy producing efficiency being 20%\(^2\). Further, disposing one ton waste produces about 160kWh electricity in DS\(^2\). Combusting one ton waste produces about 200-250kWh electricity in WTE plant, and the latter value is adopted. In the composting process, based on the survey that has been done in Okayama, Japan, the product producing rate is assumed to be 20% and the CO\(_2\) emission rate is 0.504kg-CO\(_2\)/kg product (Environmental burden basic unit based on IO table, Architectural Institute of Japan, 1990). Moreover, as noted in the report of Japan\(^2\), the CO\(_2\) emission factor in generating electricity by using thermal power was 0.8kg-CO\(_2\)/kWh in 2005 in Shanghai. The value is supposed to be fixed in 2015. In addition, emissions from recycling process are not involved because no relative information is available.

The CO\(_2\)-eq emissions from different scenarios are tabulated in Table 8, in which, change ratio denotes that the change in GHG emissions in scenarios S\(_1\)-S\(_4\) compared with the value in S\(_01\). Further, the total CO\(_2\)-eq emission from 2000 to 2015 in Shanghai is depicted in Fig. 6.

Under S\(_01\), the GHG emission factor will increase from 0.47 in 2007 to 0.59kg CO\(_2\)-eq/kg waste-treated as a result of increasing volume of total waste generation and fraction of paper waste. However, the emission factor will decrease to 0.36 when LFG recovery system is considered in DS, as represented in S\(_{01}\). Further, compared to S\(_{01}\), the GHG emissions have the varying extent of reduction in each scenario. Scenario 1 (S\(_1\)) regarding that MSW is sent to WTE will diminish the GHG emissions. It will reduce the CO\(_2\) emission by 40% than S\(_{00}\). However, compared with S\(_{01}\), no apparent advantage is represented than landfill with LFG recovery, with only 1% of the reduction of GHG emission. Further, 12% of GHG emissions will be reduced in S\(_2\) (composting scenario) than S\(_{01}\) when 50% of food waste is composted. Moreover, S\(_3\) scenario concerning 50% of recyclable items being sent to recycling center will reduce the GHG by 43% than S\(_{00}\) and 6% than S\(_{01}\), showing significant effect on reducing GHG emissions as well. Finally, S\(_4\) scenario designed as integrated waste management system makes the biggest contribution to reducing GHG emissions, as 34% compared to S\(_{01}\). The high fractions of organic compounds and recyclable items in 2015 determine that composting and recycling prior to waste treatment have greater influence on the reduction of GHG emissions in Shanghai, rather than combustion. Moreover, if the efficiency of LFG

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**Table 7 CO\(_2\)-eq emissions from incineration plant in 2007, Gg/yr**

| Scenario | Plastic (Gg) | Paper (Gg) | Textile (Gg) | Ash (Gg) | CH\(_4\)-CO\(_2\) (Gg) | N\(_2\)O-CO\(_2\) (Gg) | T-Sum (Gg) |
|----------|--------------|------------|--------------|---------|------------------------|----------------------|------------|
| Shanghai | 38.41        | 0.10       | 0.49         | 0.23    | 39.23                  | 0.36                 | 0.57       | 40.16     |
| Hangzhou | 91.33        | 0.23       | 1.18         | 3.96    | 96.69                  | 0.97                 | 1.55       | 99.21     |
| Guangzhou| 44.55        | 0.08       | 1.19         | 0.50    | 46.32                  | 0.38                 | 0.60       | 47.30     |
| Chengdu  | 4.09         | 0.02       | 0.07         | 0.29    | 4.48                   | 0.05                 | 0.09       | 4.62      |

**Table 8 CO\(_2\)-eq emissions in alternative waste treatment strategies in Shanghai in 2015, Gg/yr**

| Scenario | DS (TWh) | WTE Energy recovery (TWh) | Compost Energy recovery (TWh) | CO\(_2\)-eq in recovery | Total CO\(_2\)-eq emission | Change ratio (%) |
|----------|----------|---------------------------|-------------------------------|-------------------------|---------------------------|------------------|
| S\(_01\) | 4 850.00 | 887.49                    | 159.73                        | 0.87                    | -404.19                  | 3 553.02         |
| S\(_1\)  | 5 192.15 | 159.73                    | 2.27                          | -1 832.62               | 3 142.75                 | 12               |
| S\(_2\)  | 4 130.47 | 511.05                    | 1.81                          | -1 498.76               | 2 751.25                 | 6                |
| S\(_3\)  | 4 750.00 | 696.20                    | 0.68                          | -317.25                 | 3 354.25                 | 6                |
| S\(_4\)  | 2 908.17 | 511.05                    | 1.27                          | -1 071.34               | 2 347.88                 | 34               |
recovery attains to 50%, the emission factor in S_{SI} will be 0.31 kg CO_{2}-eq/kg waste-treated.

On the other hand, from the viewpoint of energy recovery, S_{S} generates the most electricity power (2.27 TWh), followed by S_{I} and S_{R}. Therefore, comprehensively considering the GHG emissions and energy benefit, composting of food waste and the integrated waste management are the better selections to waste problems than other waste treatment strategies in Shanghai.

6. CONCLUSION

GHG emissions from waste treatment have been one of important considerations when evaluating waste treatment strategies. In order to get the acceptably accurate GHG emissions in current and future waste treatment system, it is indispensable to use long waste records. In this paper, applying the approach that we developed in the previous research, the waste generation by composition in the past years beyond the available waste records is obtained by using the back-casting and ex-post forecasting. The quantity of waste and composition until 2015 is predicted as well by ex-ante forecasting. Then, based on the forecasted waste generation, this paper made its own effort to calculate the GHG emission in five Chinese metropolitan cities under current waste treatment options and carry out a scenario analysis in Shanghai for evaluating the integration of alternative waste treatment strategies in 2015.

The meaningful comparison among the five cities demonstrates that the emission factors are higher in eastern cities than in central and western cities. Further, scenario analysis has clarified that composting, integrated waste management and recycling are the effective ways to reduce the GHG emissions in Shanghai due to high fractions of organic waste and recyclable items. The result has the ability to provide effective reference for the local authorities to select the appropriate waste treatment method comprehensively considering environmental loads in terms of GHG emissions. However, although back-casting forecasting of waste generation and citing the data from treatment plants lessen the uncertainties in calculation, the underestimation of GHG emissions from DS may be unavoidable. Accurate plant-specific activity data is strongly desired for further research.

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