Development of Improved Environmental Cost Efficiency (IECE)

Indicator for Municipal Waste Management

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In most developing countries, eco-efficient strategy is increasingly demanded in municipal solid waste management industry. The traditionally Eco-efficiency indicator is argued to be inappropriate for MSWM industry which usually employs End-of-Pipe (EOP) technology. Environmental Cost Efficiency (ECE) was previously introduced by other researchers to assess the eco-efficient of the EOP technologies in MSWM industry. This paper is to introduce Improved Environmental Cost Efficiency (IECE) as an eco-efficient indicator derived from ECE but it includes the factor of treatment load into the calculation of eco-efficiency of EOP. Two eco-efficiency indicators are compared through case studies of various EOP technologies (sanitary landfill, incinerator, composting and anaerobic digestion) employed in Tianjin, China. Life Cycle Inventory (LCI) of the case studies was obtained from the previous paper whereas this paper only focuses on the eco-efficiency assessment. The assessment is carried out through comparison of incinerator (T2-T1), composting (T3-T1) and anaerobic digestion (T4-T1) over the existing sanitary landfill. Generally from the case studies, both ECE and IECE show similar pattern of eco-efficiency indicator with T2-T1 exhibits negative value which means incinerator is not favorable over sanitary landfill in term of both environmental and economical aspects. T3-T1 shows higher ECE (5.56) and IECE (0.91) values compared to the ECE (1.03) and IECE (0.34) of T4-T1. Both ECE and IECE show that composting is preferable to divert kitchen waste out from sanitary landfill in view of the environmental and economical dimensions. This paper advocates the compatibility of IECE in assessment of eco-efficiency in EOP technologies employed by MSWM industry. However, due to the factor of treatment load accounted in IECE, the eco-efficiency value of T3-T1 and T4-T1 reduce with increase of treatment load in different rate. T3-T1 becomes not preferable (determined by the IECE value) after the “equivalent point” and thus T4-T1 (anaerobic digestion) becomes the preferred option in diverting the kitchen waste from sanitary landfill. From the study, we conclude that IECE could provide more comprehensive information as decision-making-reference which takes in account the influence of treatment load towards the environmental impacts and financial aspects.

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Keywords: Environmental Cost Efficiency, Improved Environmental Cost Efficiency, End-of-Pipe, Municipal Solid Waste Management, Treatment Load, Eco-efficiency.

1. INTRODUCTION

Investors and stakeholders increasingly demand the companies or organizations to pursue eco-efficient strategies in order to reduce damage to the environment while increasing or at least maintain the shareholder value. (Muller, 2000) The eco-efficiency concept developed by the World Business Council on Sustainable Development is commonly used by different industrial players to pursue different environmental strategies with their own methods and standards. Unfortunately, this creates confusion to the public and undermines the advantages of EEIs. (Olsthoorn et al., 2001) This approach is based on gate-to-gate analysis where input and output of a considered boundary are taken into account by integrating LCA approach. EEIs can be applied as a decision-making tool to improve SWM industry in both economy and environmental aspects.

The main user of this tool are policy makers in the SWM industry, who will use the EEIs across the industry sub-sector, or industry as a whole, or across country, to develop environmental policies and programs in regard to SWM industry. EEIs can also be used for efficiency initiatives to monitor the result from any measures being implemented. Besides, the government particularly from the developing countries, can compare and monitor every SWM industry company by using this standardized framework and methodology, determine preference within a few SWM options, and monitor the performance of the existing SWM companies over time with respect to the resources consumption and environmental impacts associated to the processes and activities of the companies. However, typical EEIs are not appropriate for SWM industry which employs End-of-Pipe (EOP) technologies (Hellwed S. et.al., ). EOP technologies are used to improve the environment by removing the already formed pollutants from air, water, waste and products. SWM industry normally employs EOP technologies as the last stage process to treat the waste before it is disposed and generates adverse impacts to the environment. Hellwed S. et.al. argued that traditional definition of eco-efficiency does not hold with regards to EOP technologies because there is no financial benefit to be expected and secondly, EOP technologies are meant to reduce environmental impact. Hence, Hellwed S. et.al., proposed a modified indicator to integrate the economical and environmental dimension of EOP technologies in SWM industry. The modified indicator is called Environmental Cost Efficiency (ECE)

2. ENVIRONMENTAL COST EFFICIENCY OF END-OF-PIPE TECHNOLOGIES

The ECE quantifies the environmental benefit of a technology over another technology per additional cost. Prior separate financial and environmental assessment of two different technologies is required before they are quantified in ECE. Annuity method is recommended for the economic assessment. The measuring unit is monetary (e.g. USD per functional unit) whereas the environmental assessment can be performed with LCA. ‘Ecopoints’ or ‘CO₂-equivalents’ can be the possible units of the impact.

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potential depending on the method applied and question to be studied. (Hellwed S. et.al.).

\[
E_{CE_{A,B}} = \frac{NEB_{A} - NEB_{B}}{AC_{A} - AC_{B}} = \frac{NEB_{A} - NEB_{B}}{NC_{A} - NC_{B}} = \frac{(-IP_{B}) - (-IP_{A})}{NC_{A} - NC_{B}}
\]  

(1)

\[
NPV_{x} = \sum_{t} ((B_{x,t} - C_{x,t}) * \frac{1}{(1 + r)^t})
\]

(2)

\[
A_{x} = \frac{NPV_{x} * (1 + r)^T * r}{(1 + r)^T - 1}
\]

(3)

**ECE** :Net environmental benefit of Technology A over B

**AC** : Additional financial costs of implementing Technology A instead of B

**IP** : Environmental impact potential of Technology X per tonne of waste

**NC** : Net cost of Technology X per tonne of waste (determined with Equation 3)

**B** : Benefit of Technology X at time, t

**C** : Cost of Technology X at time, t

**r** : Discount rate

**t** : Time index

**T** : Lifetime of Technology X

**NEB** : Environmental benefit of EOP Technology X

3. IMPROVED ENVIRONMENTAL COST EFFICIENCY (IECE)

ECE proposed by Hellwed S. et.al. is appropriate for EOP technologies by quantifying the ratio between net environmental benefits and the difference in costs. It is well designed to solve the problem to quantify efficiency associated with EOP which focuses on improving environmental condition by treating the existing pollutants before they further degrade the environment. However, there is still one aspect need to be considered in order to get better result of efficiency comparison. The aspect we propose is the treatment load of each EOP technology. Treatment load plays a very significant variable in assessing their efficiency. For example, an incinerator with 0.118 Eco-indicator points per tonne of waste has less environmental impact compared to sanitary landfills with impact potential of 0.172 Eco-indicator points per tonne of waste. However, this statement is not appropriate when we compare a sanitary landfill with tipping load of 20 tonne per day with incinerator with treat 100 tonne of waste per day. From this comparison, the potential impact of incinerator is greater than that of sanitary landfill. Hence, this paper highlights the influence of treatment load upon the impact potential of the EOP waste treatment technology.

\[
E_{CE_{A,B}} = \frac{NEB_{A} - NEB_{B}}{NC_{A} - NC_{B}} = \frac{(-IP_{B})(C_{A}) - (-IP_{A})(C_{B})}{NC_{A} - NC_{B}^{(A,B)}}
\]

(4)

**ECE** :Net environmental benefit of Technology A over B

**IP** : Environmental impact potential of Technology X per tonne of waste

**NC** : Net cost of Technology X per tonne of waste (determined with Equation 3)

**B** : Benefit of Technology X at time, t

**C** : Cost of Technology X at time, t

**r** : Discount rate

**t** : Time index

**T** : Lifetime of Technology X

**NEB** : Environmental benefit of EOP Technology X

In ECE (Equation 1), Technology A is defined as the environmentally superior technology. This indicates that IPB is always bigger than IPA. Therefore the numerator of Equation 1 is always positive. ECE will show negative sign if the net cost of Technology B is higher than that of
Technology A. In this case, ECE is not required as both environmental and economical aspects already point to the same direction and hence the favorable one would be the option. If the financial costs of Technology A are higher than B, there is a trade-off between financial and environmental aspects. In this case, a high ECE shows a high cost-efficiency. (Hellwed S. et.al.).

However, in Equation 4, Technology A is not necessary environmentally superior than Technology B. Environmental impacts of both technologies are influenced by the load of the treatment technology proposed and therefore the numerator of Equation 4 is not always positive. Similarly to Equation 1, negative sign of IECE shows that no IECE needed to be conducted when a comparison between to technology to be made as both financial cost and environmental goal point to the same direction. If there is trade-off between financial and environmental goals, high value of IECE indicates high environmental-efficiency with consideration of the treatment load. Figure 1 and Figure 2 illustrate the typical ECE of technology A over technology B with environmental impact and financial cost as variables respectively.

** Technology B with fixed environmental impact and cost

Figure 1: Effect of environmental impact of Technology A upon ECE with fixed cost

** Technology B with fixed environmental impact and cost

Figure 2: Effect of financial cost of Technology A upon ECE with fixed cost

4. APPLICATION IN DECISION-MAKING

In most developing countries, solid waste management is not as advanced as those in far developed countries. Some developing countries particularly rely mainly on landfills without much waste minimization. For instance, average waste generation in the capital of Malaysia, Kuala Lumpur is recorded to be about 2,200 tonne/day. (Solid Waste Disposal Sdn Bhd, 2010) Out of these waste collected, all are transported and disposed at sanitary landfills without much significant recovery activities. In Malaysia itself, there are 170 landfills throughout the country yet on 6 of them are sanitary landfills. (National Solid Waste Management Department, 2010). In 2006, the Malaysian government decided to expedite the finalization of the draft bill and in 2007 the Cabinet approved full privatization at the peninsular Malaysia to take and place as soon as the Solid Waste and Public Cleansing Management Act 2007 came into force. (Yahaya N. B., & Larsen I.B., 2008). Like other developing countries, new policy is restructured and streamlined to achieve the following objectives:
a. To establish a SWM system that conserves resources and protects the environment and public health

b. to establish a comprehensive, integrated and efficient SWM system from generation to final destination

c. to establish a cost-effective SWM system

Obviously, the planning in national level particularly does not focus only in environment but also includes the financial aspect in decision making process. In approval process on SWM facilities, IECE can be used as decision-making-reference for the government to assess the feasibility of proposed new EOP technology. Examples of EOP technology for SWM are listed:

a. Biogas facility

b. Communal or commercial composting facility

c. Material recovery facility

d. Refuse derived fuel facility

e. Thermal treatment plant

f. Transfer station

g. Sanitary landfill

h. Inert landfill

5. SELECTION OF SUITABLE GENERIC ENVIRONMENTAL ITEMS AS INDICATORS IN SWM INDUSTRY

The environmental benefit indicators used in IECE are flexible depending on the region and objective of analysis and comparison. Hellwed S. et al. proposed fully aggregating LCIA method, i.e. Eco-indicator 99 and Swiss Method of Ecological Scarcity to be used as the environmental items in efficiency analysis. However, in addition to highly aggregated indicators, IECE can be used for detailed separate environmental and economical analysis such as global warming potential, carbon emission, energy consumption and eutrophication potential depending on the objectives of analysis.

We have defined some relevant EEIs associated to SWM industry that address the most significant environmental impact for an environmental reporting framework which is standardized, simple and most importantly integrate financial aspect into environmental figure. The environmental items used as indicators are proposed as:

a. Energy use

b. Generation of greenhouse gases (GHGs)

c. Water consumption

d. Wastewater production

ECE and IECE are suitable for SWM industry which mostly employs EOP technology. EOP technology is employed to reduce the existing environmental impacts resulted from the solid waste. In order to get the environmental benefit from each EOP technology, their environmental impacts inventory is obtained. Therefore, the environmental benefits are put in negative sign which reflect the environmental impacts created from the EOP technology. Technology with less environmental impacts is considered to have more environmental benefits.

6. CASE STUDY
6.1 Goal and Scope Definition

The goal of this study is to analyze and compare the eco-efficiency of different EOP technology for MSW industry in Tianjin, China. The comparison analysis is made by using IECE through scenario studies.

6.1.1 Functional Unit

The functional unit is defined as the total amount of MSW collected by the central district of Tianjin city in year 2006. The total amount of waste discarded is about 909,160 tons (55% of MSW generated in whole Tianjin City) (Zhao W. et.al., 2009).

Table 1: Fraction composition and elementary composition of MSW in Tianjin

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Amount</th>
<th>Moisture</th>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen waste</td>
<td>537,230</td>
<td>55%</td>
<td>6.4</td>
<td>37.6</td>
<td>0.4</td>
<td>0.6</td>
<td>5</td>
</tr>
<tr>
<td>Bag and rags</td>
<td>105,475</td>
<td>10%</td>
<td>5.1</td>
<td>4.1</td>
<td>0.1</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>Paper</td>
<td>10,340</td>
<td>2%</td>
<td>4.8</td>
<td>4.1</td>
<td>0.1</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>653,045</td>
<td>100%</td>
<td>5.1</td>
<td>4.1</td>
<td>0.1</td>
<td>0.6</td>
<td>6</td>
</tr>
</tbody>
</table>

Source: (Zhao W. et.al., 2009)

6.1.2 Scenarios

This study compares 4 different EOP technology used in MSW industry. Zhao W. et. al. (2009) proposed seven scenarios in their studies of GHGs emissions evaluation. However, in this IECE case study, we only study four scenarios from Zhao W. et. al. (2009). The four technologies considered in our studies are:

T1: Sanitary landfill with LFG utilization
T2: Incineration (all MSW is assumed to be treated in the MSW-to-energy plant. This scenario tests the benefit from incineration with energy recovery instead of LFG utilization. It is assumed that 90% of the total waste is incinerated generating 10% of fly ash on weight. Disposal of inert fly ash in landfill is assumed to be stable and will not generate any adverse impact to the environment in term in GHG emission.
T3: Centralized composting. This composting plant is assumed to treat only the kitchen waste from the whole waste stream. Kitchen waste is assumed to be separated at source and collected.
T4: Anaerobic digestion. This composting plant is assumed to treat only the kitchen waste from the whole waste stream. Kitchen waste is assumed to be separated at source and collected.

6.1.3 System boundary

![System definition and boundary adapted and modified from Zhao W., et.al. 2009](image_url)

6.1.4 Selected Result

The results of the inventory analysis are obtained from Zhao W. et.al., (2009). Since the purpose of the study is to show the integration of the environmental and economic analysis, we focus on the impact assessment result, particularly the GHG emission and do not discuss...
the inventory in details.

Table 2: References of LCI for the EOP technology in SWM industry

<table>
<thead>
<tr>
<th>Technology</th>
<th>GHGs Emission</th>
<th>Reference</th>
<th>Financial cost</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanitary landfill</td>
<td>156.19 g CO2 eq/ton</td>
<td>(Zhao W. et al., 2009)</td>
<td>40 CNY/ton</td>
<td>World Bank, (2005).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Zhao W. et al., 2009)</td>
</tr>
<tr>
<td>Incinerator-T2</td>
<td>296.98 g CO2 eq/ton</td>
<td>(Zhao W. et al., 2009)</td>
<td>167 CNY/ton</td>
<td>World Bank, (2005).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Zhao W. et al., 2009)</td>
</tr>
<tr>
<td>Composting-T3</td>
<td>100.55 g CO2 eq/ton</td>
<td>(Zhao W. et al., 2009)</td>
<td>50 CNY/ton</td>
<td>TCAEEDI, 2007</td>
</tr>
<tr>
<td>Anaerobic Digestion-T4</td>
<td>94.69 g CO2 eq/ton</td>
<td>(Zhao W. et al., 2009)</td>
<td>100 CNY/ton</td>
<td>TCAEEDI, 2007</td>
</tr>
</tbody>
</table>

Global warming potential for a 100-year time horizon (GWP100) was used as the characterization factor. Contribution of GHG emission is estimated by allocation of economic partitioning. The data inventory is shown in figure 4 and figure 5.

7. RESULT AND DISCUSSIONS

7.1 Environmental-Economical Analyses

In this session, analysis on eco-efficiency will be carried out upon the four different EOP technologies in SWM industry. Initially, the structure if financial cost and environmental impacts are compared separately. Different from the normal Eco-efficiency indicators developed by World Business Council, environmental benefit is displayed in negative as the GHG emission is assessed for each EOP technology. The lower the GHG emission, the greater the environmental benefits generated from the EOP technology which is employed to reduce the existing environmental
bepurs in SWM industry. Financial costs obtained are mainly driven by operational cost (opex). Analysis on comparison will be carried out by using IECE with consideration of treatment load. Comparison will be made in 3 different pairs namely T2-T1, T3-T1 and T4-T1. EOP technologies are compared with sanitary landfills as sanitary landfills are the compulsory waste disposal facility in every country. All SWM include final disposal in landfills regardless of sanitary or non-sanitary. (Fauziah S.H., 2003). Fly ash from incinerator and digested matter from Composting or anaerobic digestion plant are needed to be disposed if they are not fully utilized and reused as fertilizer. Moreover, comparison of other SWM technology with sanitary landfill is suitable for developing countries which mainly rely on disposal of MSW in landfill without effort of waste minimization. Hence IECE could be suitable and used as decision-making-reference for policy makers towards implementing waste treatment process or waste minimization process prior to final disposal of MSW in landfills. IECE is also useful as reference for decision making in waste diversion strategy. Comparison of SWM technology with sanitary landfill with higher value of IECE shows higher environmental efficiency.

Figure 6: IECE of comparison among different EOP technologies in MSWM industry

In figure, we calculate the IECE for all three combinations of technology. Average costs and the total emission of GHG from each technology were used and compared. IECE with negative value shows that no IECE is required for combination T2-T1 as both environmental goal and financial cost favours the sanitary landfill. There is no trade-off between environmental and economy aspects in T2-T1 combination of EOP technology. For combinations of T3-T1 and T3-T1, comparison is made is such a way that kitchen waste is diverted out from the existing landfill. Hence, the load of landfill is reduced by the total weight of kitchen waste which is assumed to be fully diverted and treated with either composting or anaerobic digestion. The construction of kitchen waste diversion and treatment technology shows high eco-efficiency with higher IECE value. Zhao W. et. al. (2009) showed that incinerator is a good option technically, with slightly higher GHG emission that sanitary landfill. However, IECE does not reveal the same result. Incinerator is not encouraged as it generates more environmental impact while the financial operating cost is higher compared to sanitary landfill with LFG recovery facilities. This information can be referred by any policy makers or government in MSWM strategy. Report from Zhao W. et. al. (2009) shows anaerobic digestion technology is more environmental-friendly but it is more
financial costly in term of operation compared to composting technology. There is a trade-off between environmental goal and financial aspect. If a decision has to be made to choose only one technology for MSWM with stringent environmental goal and financial constraint, IECE could play its role in providing information as reference. This study revealed that combination of T3-T1 has higher value of IECE compared to T4-T1 which means composting plant is preferred to divert 57% (517,130 ton of kitchen waste) from total waste 909,160 ton generated in 2006 in Tianjin. Hence, the composting technology is shown the most cost-efficient, environmentally superior alternative to other EOP technology proposed. The second most efficient alternative to sanitary landfill is followed closely by anaerobic digestion technology. Incinerator is not encouraged at all in view of its higher environmental impacts generated and operating cost.

Besides, IECE can be used to analyze eco-efficiency of EOP technology with different treatment load. Figure 8 shows that IECE for T3-T1 is always greater than that of T4-T1 if their treatment load of composting plant and anaerobic digestion plant are less than 550,000 ton/year (equivalent point). This means that if both technologies’ treatment load exceeds 550,000, the eco-efficiency of T3-T1 is less than that of T4-T1 and thus anaerobic digestion technology is more preferable. This information is very useful for policy makers in planning MSWM strategy.

![Figure 8: IECE for comparison of EOP technologies with different treatment load](image)

8. CONCLUSION AND RECOMMENDATION

The case study in Tianjin MSWM (Zhao W. et. al., 2009) illustrates that Improved Environmental Cost Efficiency (IECE) is capable of resolving trade-offs between environmental and financial aspects of EOP technology employed in MSWM industry. Like ECE, IECE is one of the indicators used to quantify eco-efficiency in MSWM industry which normally employ EOP technologies. However, IECE incorporates an additional element of treatment load into the assessment of EOP technology. From the study, we conclude that IECE could provide more comprehensive information as decision-making-reference which takes in account the influence of treatment load towards the environmental impacts and financial aspects.

The case study shows that the environmental items can be of anything from aggregated to non-aggregated results of the environmental assessment. Hellwed S. et al., 2005 used eco-indicator 99 and Method
of Ecological Scarcity in the assessment of ECE. In this study, we used non-aggregated environmental impact for assessment of IECE. GHGs emission criteria is used for IECE assessment. From the study above, the IECE may help to decide which of the three technologies should be implemented if the goal is to mitigate the most GHGs emission per unit of money invested. The same methodology can be applied to other environmental items for assessment depending on the objective of the study.

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