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# Developing An Integrated Environmental Assessment Model of Waste Management and Resource Circulation

## A Progress Report



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## 1. Introduction

Waste management is the key stage that links anthroposphere and ecosphere. An ill-designed waste management system may lead to pollution and resource misuse. Furthermore, waste management involves LULU (Locally Unwanted Land Use) facilities, such as landfills and incinerators, and thus becomes a highly controversial public issue. Nowadays, the novel management paradigm called Integrated Waste Management (IWM) had been proposed to replace the traditional waste hierarchy. The main features of IWM are substituting the residue treatment by resource management, and it aims to optimize the total environmental benefit by combining different treatment technologies. In this sense, the 3Rs (reduce, reuse and recycle) is an approach for IWM. As the paradigm shifts toward more integrated management, a more integrated environment assessment method is emerging to support the strategy formulation.

An integrated environmental assessment (IEA) can be defined as “an interdisciplinary process of identification, analysis and appraisal of all relevant natural and human processes and their interactions which determine both the current and future state of environmental quality and resources...thus facilitating the framing and implementation of policies and strategies.” (EEA) Applying IEA to waste management requires the utilization of life cycle approach to quantify the multiple environmental impacts of waste treatment technologies and a new approach to link material consumption and waste generation (Monkhouse and Farmer, 2003).

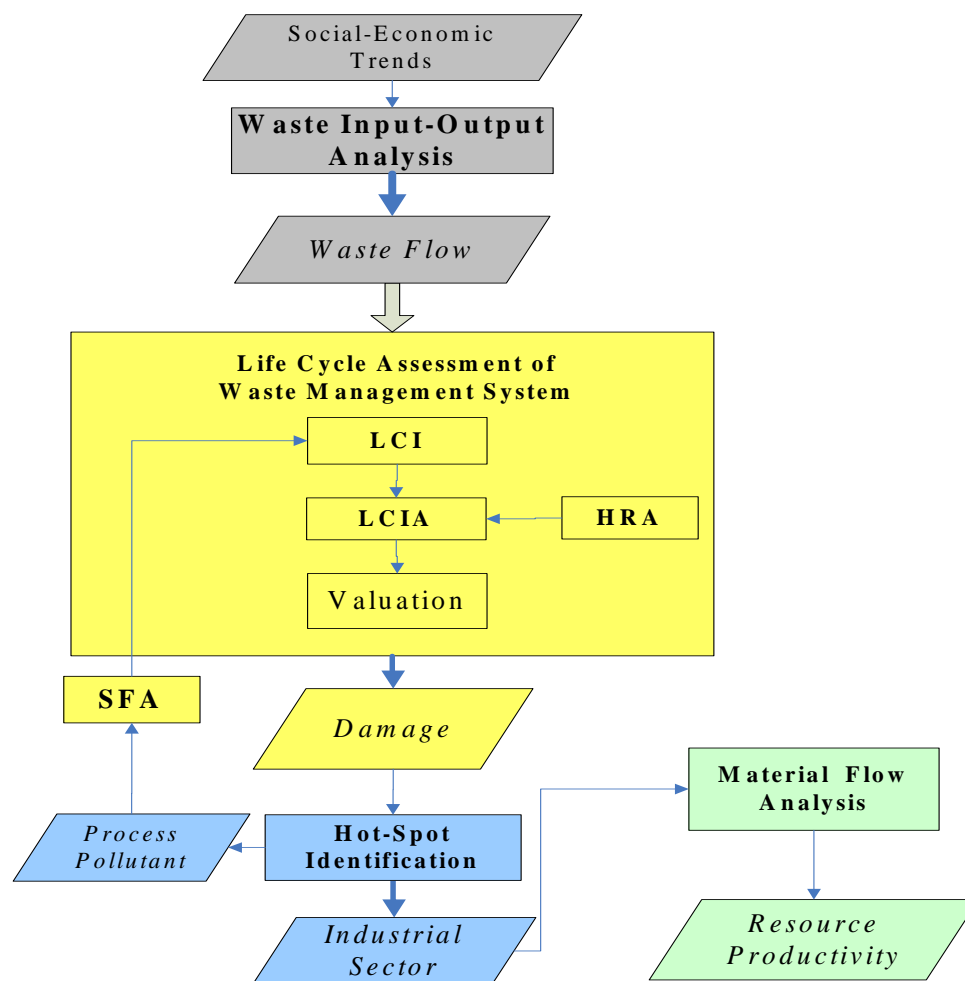
Life Cycle Assessment (LCA) had been widely applied in waste management since mid-90's, and are viewed as a key tool to provide environmental information under the multi-criteria decision making (MCDM) framework. However, three issues during this application are identified: credibility of inventory analysis, limitation of waste stream projection and scenario analysis, and omission of site-dependent information of impact assessment. As a result, in order to maximize the science robustness of evaluation, integrating other environmental assessment tools to overcome the above limitations, such as waste input-output analysis (WIO), health risk assessment (HRA) and material flow analysis (MFA), is an indispensable task to construct an integrated environmental assessment model.

The organization of this paper is as follows. Section 2 provides a conceptual framework to integrate the key assessment tool. The operational details of each component will then be introduced with the basic theory and data source in Section 3.

In order to verify the usefulness of this IEA model, Section 4 introduces an illustrative example to exhibit the challenges and key concerns of Taiwan future WM/3R policy based on the future industrial structure and consumption patterns. Finally, this paper will be concluded with a discussion to explore the importance of IEA model during the decision making process of WM/3R policy.

## 2. The conceptual methodological framework of Integrated Environmental Assessment Model

By combining assessment tools such as MFA, HRA, and LCA to fulfill the requirement of modern WM/3R policy evaluation, an integrated model TWMIEA (Integrated Environmental Assessment model for Taiwan Waste Management) is developed as sketched in Figure 1.



**Figure 3** The conceptual framework of IEA of WM/RC

In this framework, in order to establish the linkage between industrial structure and consumption patterns with waste stream, Waste Input Output Analysis (WIO) is also developed to estimate the direct and indirect waste generated by each industrial sector,

which enables the simulation of the influence of industrial structure on the flow of waste. After WIO is used to improve the applicability on waste prognosis and resource productivity estimation, the impact incurred during waste treatment stage are still the determinant factors of policy making; therefore the limitation of WM-LCA, such as credibility of inventory and site dependency of impact assessment, should be addressed.

The credibility of evaluation module is improved by two innovations. The first is substituting the traditional deterministic assessment by probabilistic inventory databases. The approaches of assigning probability distribution forms are mainly based on statistic results for local survey (such as air pollutants emitted by incinerators) and subjective probability transformation by data quality indicators (such as emissions from recycling process). The second innovation is integrating substance flow analysis (SFA) to trace the distribution of toxic substance for hot-spots. Once the first tier evaluation is finished, the SFA should be executed to modify the emission factors of major contributors to the impact. Since the human health impact is the key concern of waste management and treatment facilities, the fate and exposure models of HRA are integrated with the existing life cycle impact assessment method to enhance the health impact assessment.

While the above steps focus on constructing an overall picture of the distribution of waste flow and potential environmental impact resulting from a high level WM/3R policy, material flow analysis would be useful to evaluate the material/resource productivity of key sectors so as to formulate the suitable mitigation strategies and quantify the effectiveness of resource circulation initiatives.



### 3. Constructing the TWMIEA model

#### 3.1 Establishing Taiwan WIO table for waste flow prognosis

The waste input-output model (WIO) originated from the environmental input-output model developed by Leontief (Nakamura, 2002). It is capable of characterizing the flow of wastes under a life cycle thinking perspective. Especially, the waste generated by industry could be modeled through inter-industry relationship and the mechanism of various economic demands. Figure 3 shows the framework of WIO. The upper left area is an intermediate transaction matrix to model flow of good and service from industries to industries. The rectangle underneath refers to the flow of waste generated by each industry. The demand of treatment capacity is placed over the region on the right to intermediate transaction. WIO modeling adopts a mechanism similar to input-output analysis linking environmental intervention with economic demands such as household consumption, government expenditure, export and etc. Therefore the waste generation could be predicted as responses to various market demands.

Based on Japan WIO framework, we also developed a Taiwan WIO (TW-WIO) table in 2008. Benefiting from a dedicated industrial waste registry system, a complete database has been obtained to facilitate the WIO compilation. The information about Taiwan compilation is listed in Tables 1.

	sectors			Waste treatment	Final demand	
Sectors				Data for G Multiplier		
		$X_{ij}(\$)$			X	
Wastes				Data for S Allocation matrix	Waste from household	
		$W_{ki}(\text{mass})$				
Environ. load	Air Emission Water Emission Resource Consumption					
Value added						

Figure 4 The Structure of WIO table

**Table 1** Specification of Taiwan WIO and data source

	Classification	Fiscal year
Input-output table	<b>52</b> and <b>166</b> sectors	2004, 2006
Industry classification of waste registry	<b>758</b> industries or processes or services	2002~2008
Waste classification	<b>199</b> General wastes <b>191</b> Hazardous wastes	2002~2008
Treatment classification	<b>28</b> General wastes <b>19</b> Hazardous wastes	2002~2008

## **3.2 Quantifying the environmental intervention through Life Cycle Inventory**

### **3.2.1 Scope and Goal Definition**

Since the main function of waste management is to treat the waste effectively and thus the capacity of each management subsystem should be taken into consideration, the amount of municipal solid waste per year is chosen as the functional unit in this model.

The system boundary are designed based on the future scheme of Taiwan municipal solid waste management policy, thus the collection/transportation, MRF sorting, bio-waste treatment, recycling, thermal treatment (mass burn and RDF), ash treatment, landfill are included. For the industrial waste management subsystem, owing to the large variety of treatment technologies, this model presently only covers the 12 subsystem that represent 65% of total general industrial waste and 55% of hazardous industrial waste. The system boundary is shown as Figures 3 and 4.

### **3.2.2 Inventory Analysis**

One major difference between LCA of product and LCA of waste management system is the consideration of avoided environmental burden. This characteristic implies that during the inventory analysis of waste management system, including the ratio of resource recycling and energy recovery and information of pollutants emitted through raw material and energy production systems is inevitable. Therefore, the conceptual equation of inventory analysis is represented by following equation.

$$E_{wm,i,j} = \sum \left[ Q_{m,j} \times (EF_{m,i} + En_{en,m} \times EF_{en,i}) - Q_{m,j} \times (RR_{m,j} \times EF_{m,j} + ER_{m,j} \times EF_{en,i}) \right] \text{ Eq 1}$$

$E_{wm}$ : Total emission and resource consumption of the whole waste management system;  $Q$ : The amount of waste treated by a certain process;  $EF$ : Pollutants emission (or resource consumption) factor ;  $En$ : Energy consumption factor;  $RR$  : Resource recycling ratio;  $ER$  : energy recovery ratio;  $i$  : pollutant or resource type ;  $m$  : treatment subsystem ;  $en$  : type of energy consumed or recovered during the treatment process ;  $rw$  : type of raw material replaced

As shown in Figure 3 and 4, about 20 subsystems are included in the TWMIEA model; therefore establishing a complete inventory database is a highly data-intensive task. The data sources of each parameter presented in the equation above include local survey, literature, existing WM-LCA models, and LCA inventory databases.

### 3.3 Evaluating the potential damage with best practice LCIA method

In order to increase the practicability and credibility of TWMIEA model, this study tries to design a method that could reflect the best available practice and the issue of spatial differentiation. Therefore, the existing LCIA methods are compared to explore the suitable approach for the new impact assessment. The detail of impact assessment will be introduced from the impact and damage categories, the characterization models selection, to the characterization factors localization as follows along with Table 2.

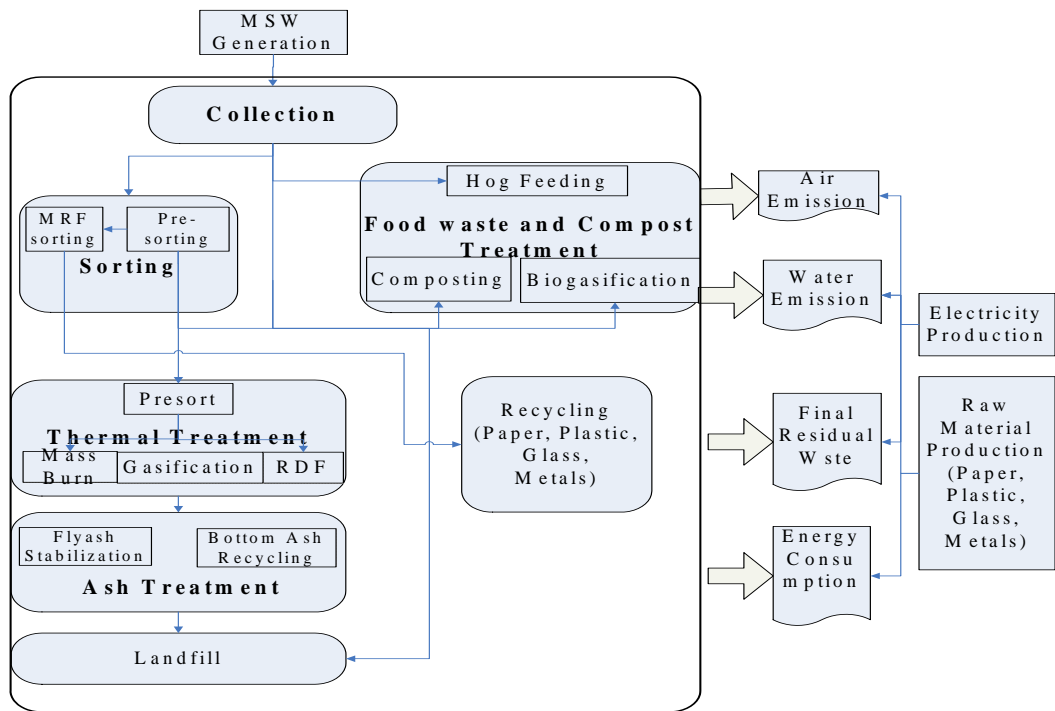


Figure 5 The System boundary of TWMIEA (for municipal waste)

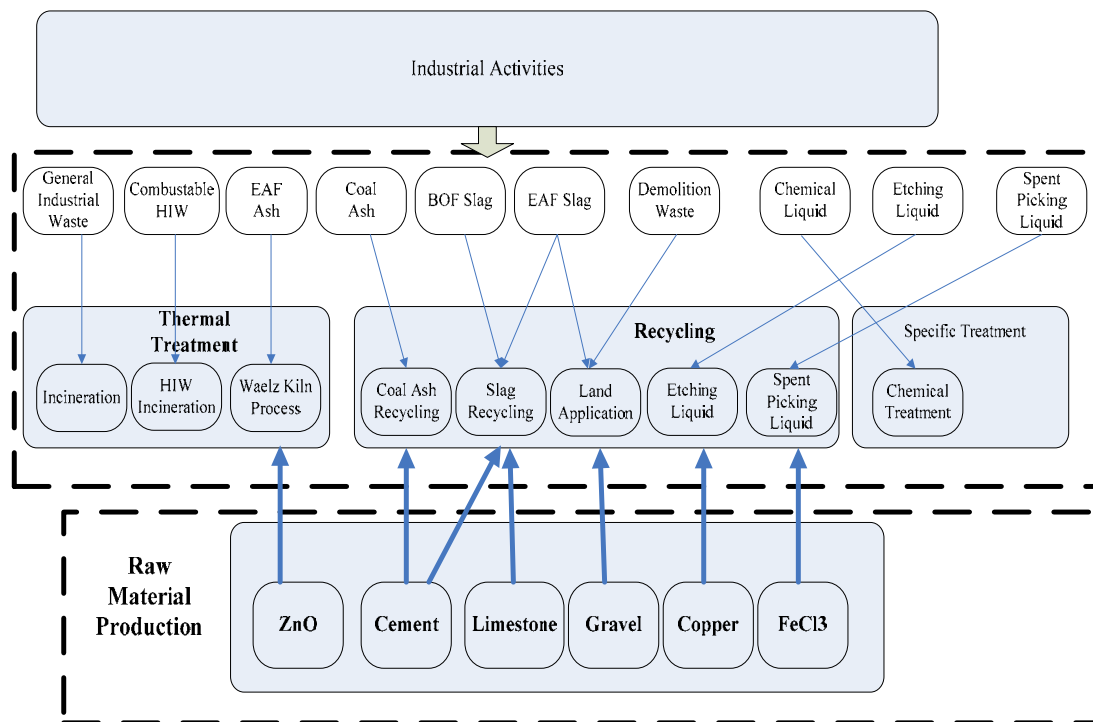


Figure 6 The System Boundary of TWMIEA (for industrial waste)

### **3.3.1 Impact and Damage Categories Identification**

First of all, this study reviews the main consideration of environmental impact and impact categories included in the other WM-LCA. Therefore, 12 impact categories are chosen, including: human toxicity (carcinogenic effect), human toxicity (non-carcinogenic), respiratory effect, photochemical smog, aquatic ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication, terrestrial acidification, global warming, metal depletion, water depletion and fossil depletion. The impact categories can be further aggregated into three damage categories: human health, ecosystem, and resource. Those three areas of protection are recommended by the latest combined LCIA method, ReCiPe, developed by Dutch experts (Goedkoop et al, 2009 ).

### **3.3.2 Characterization Models Selection**

The impact categories include site-generic impact and other site-dependent impact. They are dealt with different selection principles.

Site-generic impact categories include global warming, metal depletion, and fossil depletion. Because the characterization models of those impacts are well-developed and hold high degree of consensus, the latest CFs can be adopted directly. In the meantime, as suggested by the international expert in the ILCD report, the ReCiPe method provides the most comprehensive characterization model for those impact categories. Therefore, the CFs from ReCiPe are adopted.

The site-dependent impact categories, such as human toxicity, acidification, eutrophication, photochemical smog, and eco-toxicity, should consider the fate analysis and receptor sensitivity. Here, the best available characterization models are chosen based on the recommendation of ILCD panel, and further modified with local parameters. At this point of time, only human toxicity and ecotoxicity are localized in this version of TWMIEA. Human Toxicity Impact is one of the greatest concerns of the waste management system. Therefore, air dispersion modeling, multimedia risk assessment modeling, and population exposure are integrated to develop “Site-Dependent Human Toxicity Potentials (sd-HTPs)”. The sd-HTPs for the heavy metal and dioxins emitted from every incinerator in Taiwan are calculated (Chao et al, 2006).

### 3.3.3 Damage Factor Derivation

In order to aggregate the impact equivalent into potential damage, this study uses ReCiPe framework. The ReCiPe method provides the CFs that link the elementary flows to the endpoints. Hence, we adapt the CFs at the endpoints for each reference substance of the impact categories. Then the impact equivalents can be converted into disability-adjusted loss of life years, loss of species during a year, and increased cost, respectively.

**Table 2** LCIA method of TWMIEA

Damage	Damage Indicators	Impact Categories	Category Indicator	Characterization Model
Human Health	DALYs	Human toxicity	kg-eq Benzene <sub>air</sub> (carcinogenic) kg-eq Toluene <sub>air</sub> (non-carcinogenic )	CalTOX with local parameters
		Respiratory	kg-eq PM2.5 <sub>air</sub>	TRACi
		Photochemical oxidation	kg-eq NOx <sub>(air)</sub>	TRACi
		Global warming	kg-eq CO2 into air	IPCC(2007)
Ecosystem Diversity	Species	Aquatic ecotoxicity	kg-eq 2,4-D <sub>(water)</sub>	CalTOX + IMPACT2002+
		Terrestrial ecotoxicity	kg-eq 2,4-D <sub>(soil)</sub>	CalTOX + IMPACT2002+
		Aquatic eutrophication	kg-eq PO <sub>4</sub> <sup>-</sup> limited	IMPACT2002+
		Aquatic acidification	kg-eq SO <sub>2</sub>	IMPACT2002+
		Fossil depletion	MJ	CED by Ecoinvent
Resource Availability	Increased cost	Metal depletion	kg/kg	Distant-to-target
		Land use	Land Use Index Quantity of land use	TRACi
-	-	Water consumption	m <sup>3</sup> / m <sup>3</sup>	Distant-to-target

### 3.4 Material/Resource Productivity Evaluation

WIO and LCA are combined to quantify the overall impact of specific WM/3R policy; in addition, the hot-spots which contribute to the major impact are also identified. The hot-spot identification specifies the key sector from following principles:

- a. Contribution of total industrial waste
- b. Sensibility of forward and backward linkage
- c. Magnitude of potential environmental impact and benefit

For the waste management system, there are two main mitigation measures: minimizing the emission factor and maximizing the recycling ratio. By using material flow analysis, the material productivity of key sectors can be evaluated.

According to the definition by OECD (2008), “material productivity is defined as the quantity of output produced per unit of materials inputs used in the production of the output.” Two material flow indicators are used to examine the trend of material productivity of key industrial sectors, Material Use Efficiency (MUE) and Waste Output per Service (WOPS). MUE establishes the physical relationship between the material input and waste output of industrial activities; the major difference of MUE from traditional waste generation factors or recycling ratios is the consideration of upstream and indirect effect. WOPS are developed based on the concept of material input per service (MIPS); the trend of the indicator can be used to examine the decoupling effect of industrial sector on waste stream.

By using these two indicators, the historical trend of material productivity of hotspots is analyzed. It will provide a valuable reference to formulate suitable mitigation strategies.

$$MUE = 1 - \frac{TWO}{TMI} \quad \text{Eq 2}$$

**MUE: Material Use Efficiency;**  
**TWO: Total Direct and Indirect Waste Generated by Sector**  
**TMI: Total Direct and Indirect Material Input of Sector**

$$WOPS = \frac{TWO}{PV} \quad \text{Eq 3}$$

**WOPS: Waste Output per Service**  
**TWO: Total Direct and Indirect Waste Generated by Sector**  
**PV : Production Value of Sector**

## **4. Case Study – Evaluating the challenge and environmental effect of future WM/3R policy**

This section aims to illustrate the application of TWMIEA model to assessing the environmental implication embedded in the overall waste flow in 2007.

### **4.1 Waste Flow Prognosis**

With WIO modeling, we have identified the contribution of several driving forces. From the perspective of demand and supply, both domestic market demand and export are motivating the industrial activities. The domestic demand could be further analyzed for government expenditure, stock change, and household.

When the focus is placed on the garbage discarded from household only, Taiwan has shown a great success to reduce the garbage per cap per day to be less than 0.6 kg. But, if the indirect industrial waste driven by household demand is taken into consideration, the overall waste generated by household expenditure is up to 3.415 kg/cap-day in 2007.

Analyzing the contribution of each driver on industrial waste generation, Figures 5 shows that more than 40% of mandatory reusing waste and corrosive waste are generated to meet export, especially the export of electronics and leather products. Furthermore, as shown in Figure 6, based on analysis on family expenditure on different goods and service, the household consumption of other service, such as medical and infrastructure, had the largest embodied waste footprint. For the waste with larger toxicity potential, such as leachable toxics, PCB containing waste and PCDDs/PCDFs containing waste, consumption on clothing, transportation and other service cause the main burden. Therefore with the application of TW-WIO, the waste flow can be interpreted in the sense of “footprint”.



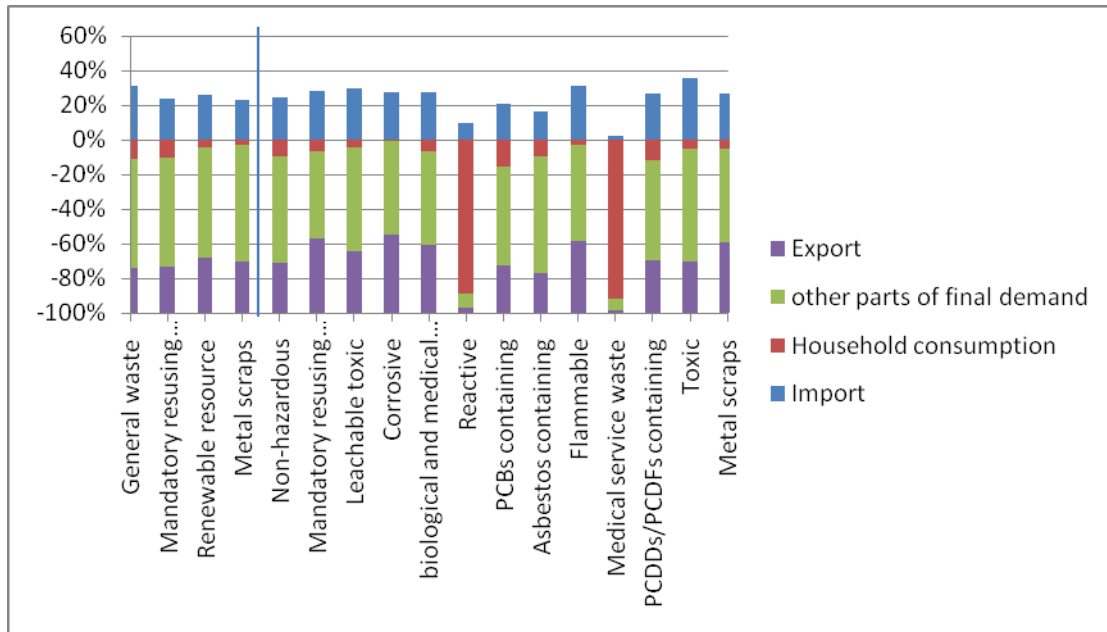


Figure 7 Contribution of the final demands on various types of industrial waste production

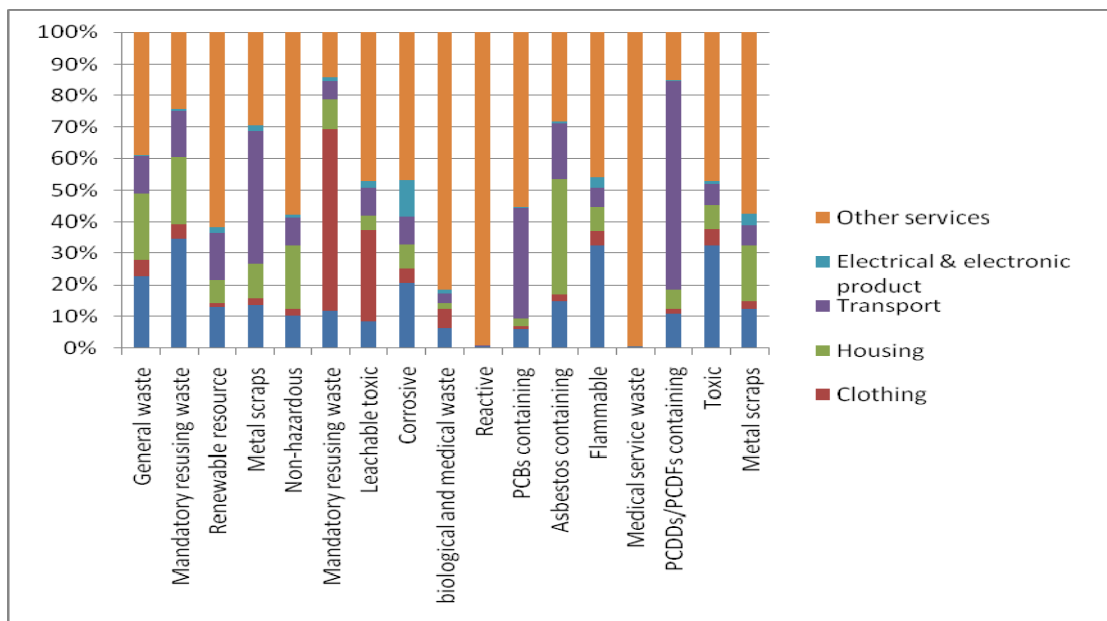


Figure 8 Contribution of different categories of household consumption on industrial waste production

## 4.2 Environmental Impact Assessment

### 4.2.1 MSW

With the amount and distribution of MSW in 2007, the environmental impact of the waste management system estimated by the TWMLCA model is shown in Table 3. It

indicates that even when the avoided burden is included, there is still net impact on human toxicity, photochemical smog, global warming and eutrophication. On the other hand, the energy recovery and resource recycling provide a significant offset on the impact categories related to the resource and ecosystem. As a result, the damage assessment implies that the overall MSW management system causes 2.59E+03 DALYs in 2007; the hot-spots of this category is the CO<sub>2</sub> and lead emitted to the air during MSW incineration, and lead emitted to the water by recycled paper production. However, energy recovery avoids coal consumption of electric power supply, saving the majority of the 5.7 billion dollar surplus cost on resource exploitation. For the ecosystem diversity, Al and tin recycling avoid the potential aluminum emitted to water, reducing the rate of species extinction by 44 species.

**Table 3** Damage and Impact Assessment Result of MSW in 2007

Damage Assessment		Impact Assessment	
Categories	Result	Categories	Result
Human Health	2.59E+03 DALYs	Carcinogenic effect	1.02E+06 kg-eq Bezene <sub>air</sub>
		Non- carcinogenic	2.62E+09 kg-eq Toluene <sub>air</sub>
		Respiratory	-3.65E+05kg-eq PM2.5 <sub>air</sub>
		Smog	2.06E+06 kg-eq NO <sub>x(air)</sub>
		Global warming	8.41E+08 kg-eq CO <sub>2</sub>
Ecosystem Diversity	-4.36E+01 Species	Aquatic ecotoxicity	-1.98E+07 kg-eq 2,4-D <sub>(water)</sub>
		Terrestrial ecotoxicity	-5.76E+08 kg-eq 2,4-D <sub>(soil)</sub>
		eutrophication	2.07E+06 kg-eq PO <sub>4</sub> <sup>-</sup> limited
		Aquatic acidification	-3.26E+05 kg-eq SO <sub>2</sub>
Resource Availability	-5.72E+09 Increased cost	Fossil depletion	-3.56E+08 kg-eq Crude Oil
		Metal depletion	-1.54E+08 kg-eq Fe
-	-	Water consumption	-4.19E+08 m <sup>3</sup> water

#### 4.2.2 Industrial Waste

With the amount and distribution of industrial waste in 2007, the environmental impact of the waste management system estimated by the TWMLCA model is shown in Table 4. Even when the avoided burden is included, there is still net impact on human toxicity and eutrophication. Therefore, the whole industrial waste treatment system causes 4.34E+04 DALYs. According to inventory data obtained from TEDS

7.0, one of the hotspots is the etching liquid recycling process that emits huge amount of lead to the air. On the other hand, BOF slag and coal ash recycling replace the production of concrete and cement and therefore reduces GHGs emissions and fossil fuel consumption significantly. The evaluation of this study shows that the existing resource circulation program saves more than 7.4 billion dollars on resource consumption in addition to saving 140 species from extinction. The results demonstrate the benefit of industrial waste circulation as well as provide information on the side effects; for example, the side effect of etchant recycling should be further investigated to ensure the public health.

**Table 4** Damage and Impact Assessment Result of Industrial Waste in 2007

Damage Assessment		Impact Assessment	
Categories	Result	Categories	Result
Human Health	4.34E+04 DALYs	Carcinogenic effect	3.87E+06 kg-eq Bezene <sub>air</sub>
		Non- carcinogenic	8.63E+10 kg-eq Toluene <sub>air</sub>
		Respiratory	-1.22E+06 kg-eq PM2.5 <sub>air</sub>
		Smog	-5.96 E+06 kg-eq NOx <sub>(air)</sub>
		Global warming	-4.10 E+09 kg-eq CO2
Ecosystem Diversity	-1.46E+02 Species	Aquatic ecotoxicity	-2.02E+07 kg-eq 2,4-D <sub>(water)</sub>
		Terrestrial ecotoxicity	-1.31E+09 kg-eq 2,4-D <sub>(soil)</sub>
		eutrophication	4.35 E+04 kg-eq PO <sub>4</sub> <sup>-</sup> limited
		Aquatic acidification	-5.85E+06 kg-eq SO <sub>2</sub>
		Resource Availability	-7.47E+09 Increased cost
		Metal depletion	-1.14E+08 kg-eq Fe
-	-	Water consumption	-6.29E+09 m <sup>3</sup> water

### 4.3 Material Productivity Evaluation

For example, according to the TW-WIO model, the coal ash and mixture of fly ash and bottom ash generated from electric supply industry contributes to 15% of general industrial waste. Moreover, the waste flow forecasting also indicates that the power supply industry is the main driver of industrial waste generation. Regarding to environmental impact, the coal ash recycling plays a significant role to offset GHGs emission, energy consumption. Therefore, the electric supply industry is selected as a

key sector to illustrate further examination.

In order to monitor the progress of resource productivity, this study collects the coal ash generation and coal consumption of this sector during 2002 and 2008. The trend of material use efficiency (MUE) (Figure 7) shows that there is no stable improvement on this sector. The latest MUE decrease from 95.4% to 93.9%, which implies the generation of coal ash will continuously increase. By examining the trend of MIPS and WOPS of this sector (Figure 8), it signals that there is no reduction on MIPS and WOPS, which implies that the material productivity of the power supply industry has not been improved under existing management strategies. Although 96% of coal ashes are recycled and reused, the majority of existing facilities licensed to treat coal ashes is sand & gravel companies, which lack of ability to monitor the leaching of heavy metal in the coal ashes. As a result, the capacity and suitability of coal ash recycling will be a key issue

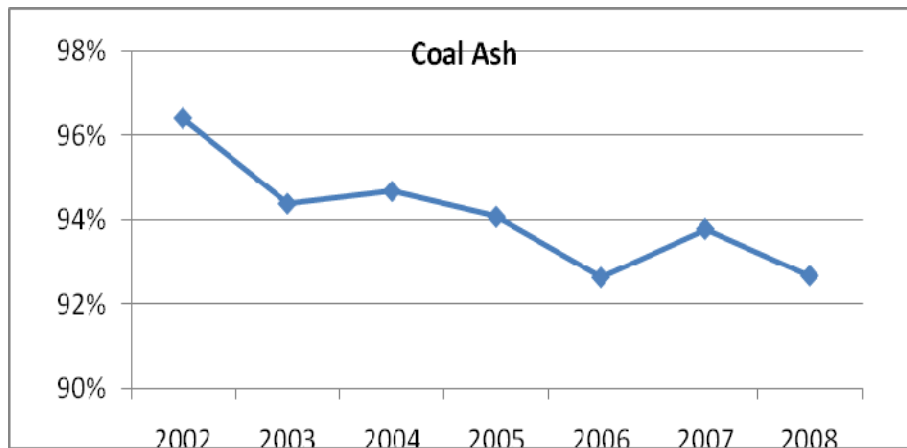


Figure 9 The trend of MUE of Electricity Supply Industry

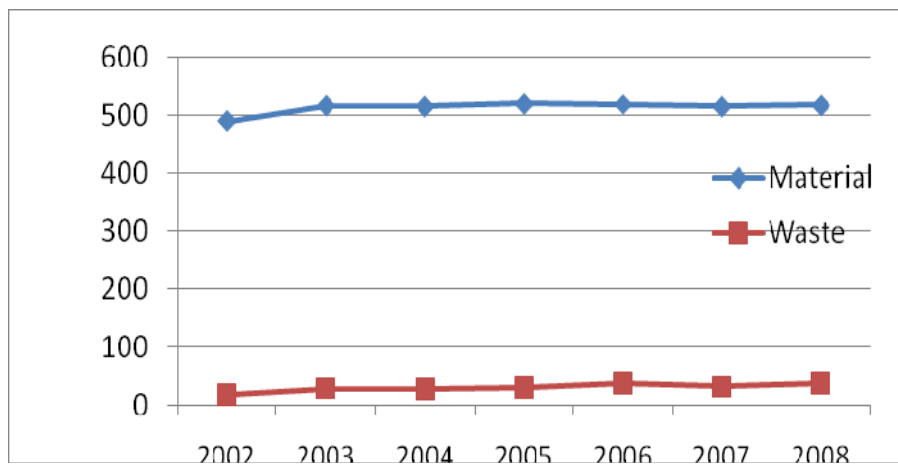


Figure 10 The trend of MIPS and WOPS of Electricity Supply Industry

## 4.4 Discussion

Compared with the existing environmental assessment tools, the TWMIEA model attempts to provide the following advantages:

**a. Footprint Concept:** Existing waste flow statistics ignores the relationship between household consumption and industrial waste generation. The TWMIEA utilizes waste input-output analysis to estimate waste embedded in and contributed by various consumption patterns.

**b. Industrial Linkage:** Waste generation factors have been employed to forecast the future waste flow traditionally; however the upstream and downstream influences are omitted in general. The TWMIEA overcomes this defect by WIO analysis to enhance the credibility of waste flow prognosis.

**c. Comprehensive coverage on waste categories and treatment technologies:** While the existing WM-LCA models cover the MSW system only, this study not only incorporate the industrial waste management system to enlarge coverage of waste categories, but also include several novel treatment technologies, such as gasification, RDF, and bottom ash recycling.

**d. Higher robustness of impact assessment:** Adopting an existing LCIA method is the general practice for environmental impact assessment, under which the limitation of LCIA is overlooked. This study follows recommendations of best available LCIA methods and derives local CFs to reflect site-dependency. In particular, a method called sd-HTP is developed to improve human toxicity assessment based on the integration of LCIA and HRA.

**e. Decision supporting for Resource Circulation policy:** Without the information of resource productivity, decision support system of sustainable waste management will lack of its ability to express actual benefits of resource circulation initiatives. This study performs resource productivity evaluation on key sectors in terms of material flow indicators. The assessment result would offer a basis to identify the effect of existing strategies and refine the waste flow prognosis.

## **5. Conclusion: Future Development and Application in ARCR project**

The objective of this study is to establish an integrated impact assessment method to address multiple benefits of the 3Rs policy and support governance for 3R implementation in the developing Asia. The accomplishment of the first year is the construction of the TWMIEA model. The utility and applicability of the model will be explored subsequently by analyzing individual 3R policies in Taiwan. In order to extend the applications of this model in the Asian region, the following future tasks are needed:

- a. Introducing the conceptual framework to apply the IEA model in WM/3R issues.
- b. Extending single region WIO table to multi-regional WIO table to address the waste transfer issue among Asian regions and the effect of regional economic growth on waste generation.
- c. Establishing a common inventory database:
  - Gathering the possible policy transition pathways to identify the soundness of treatment technologies.
  - Designing a common inventory framework for supporting participant countries to establish their own database.

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