Modeling and Scenarios Analysis of Environmental Sustainability in Waste Management

Qizhen Yang[1] and Zhiqi Shen[2*]

[1]Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075
qyang@simtech.a-star.edu.sg
[2]Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798
zqshen@ntu.edu.sg

Abstract

Environmental sustainability is a critical issue in waste management. Comprehensive sustainability models and scenarios analysis are needed for waste treatment decisions. This study develops information models to quantify and evaluate the environmental sustainability of industrial waste recycling practice. Environmental sustainability factors such as greenhouse gas emissions, material efficiency, and energy consumption are assessed based on the recycling system parameters and environmental regulative requirements. Model-enabled scenario analyses are conducted to predict the impacts of different recycling technologies and practices from environmental sustainability perspectives. The sustainability models have been tested in a case study for secondary metal recovery from waste catalysts. The results show that these models are able to provide comprehensive and reliable emission, waste and efficiency related information under changing process conditions to support sustainable waste management and recycling.

Keyword: Environmental sustainability model, scenarios analysis, waste management, material recovery from industrial wastes.

I. Introduction

In the sustainable waste management practice, the focus of waste treatment is shifting from a general disposal processing to a more specific utilization of wastes by such as recycling, reuse, recovery or

* Corresponding author

remanufacturing. Such a shifting requires more comprehensive sustainability information to support waste treatment decisions and to evaluate consequences from the selected treatment methods. Research and development of environmental sustainability models and scenarios analysis is therefore needed to enable sustainable waste management.

In this study, the concept of sustainability and means of information modeling are applied to environmental sustainability formulation and scenarios analysis in waste management, specifically for industrial waste recycling and recovery. One of the challenges in the sustainable recycling technology development is how to integrate the sustainability concepts and methods into the technological innovation processes. This requires a balanced consideration of the environmental impacts of new recycling technologies while they are still under development. It also requires scenarios analysis of new technology options using scientific, quantitative methods in order to identify and select the most sustainable EOL (end-of-life) solutions under given constraints. Take the EOL treatment of waste catalysts from the oil refinery industry as an example. Several studies [1-3] highlighted the necessity for the development of economically viable methods without posing risks of environmental hazards in recovering metals from waste catalyst materials. Another study by Singh [4] argued that the choice of treatment options, such as regeneration, recovery or disposal of spent catalysts should depend on economic factors coupled to environmental factors. Although the efforts above addressed the economic and environmental issues in catalytic wastes processing to certain extend, they are more focused on the investigation of technical feasibilities rather their sustainability. This situation motivates us to conduct more focused environmental sustainability studies to support sustainable waste recycling and recovery.

This paper is focused on the formulation of information models to quantify and evaluate the environmental sustainability of industrial waste recycling technologies and practices. An environmental impact assessment model is built to estimate the greenhouse gas emissions from the EOL processing. Material efficiency and energy efficiency at EOL are analyzed through a composite indicator [5]. An assessment case study on secondary nickel recovery from waste catalysts in the palm oil refining industry is used to test these sustainability models. The results have provided the sustainability knowledge for further maturity and commercialization of a new nickel recovery technology. The results also help potential technology adopters in evaluation and selection of sustainable methods and processes in industrial waste processing.

II. Model Development for Environmental Sustainability

The environmental sustainability of a waste recycling solution can be evaluated in many aspects, such as carbon footprint (weighted sum of GHG emissions [6] concerned), waste reduction at source, energy consumption, etc. This section discusses the carbon footprint modeling for material recovery from industrial wastes.

A carbon footprint is a quantitative measure of the amount of GHG emissions directly or indirectly induced by an activity, a product or a service. Carbon footprint is calculated based on the climate-change impact of emissions from the six types of the Kyoto Protocol greenhouse gases [7]. These include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). Carbon footprint is expressed in carbon dioxide-equivalent (CO2e) which is obtained by multiplying the mass emissions of each GHG by its Global Warming Potential (GWP). GWP is the ability of each greenhouse gas to trap heat in the atmosphere relative to carbon dioxide, which serves as the reference gas [10]. Table 1 lists the six Kyoto Protocol GHGs and their GWP factors from IPCC [11].

Table 1 The six Kyoto Protocol gases and their GWP factors [11].

Greenhouse Gas	**GWP (100 years)**
Carbon dioxide (CO2)	1
Methane (CH4)	25
Nitrous oxide (N2O)	298
Hydrofluorocarbons (HFCs)	124~14,800
Perfluorocarbons (PFCs)	7,390~12,200
Sulfur hexafluoride (SF6)	22,800

The following sections compare and select available emissions quantification methods and describe our carbon footprint model derived. Our modeling process follows the general emission estimation principles and guidelines in the Climate Leaders Greenhouse Gas Inventory Guidance [10] from the USEPA.

A. *Carbon Footprint Quantification Method*

There exist several GHG emission quantification methods. The most commonly used ones include:

- Direct measurement of GHG emissions over a period of time for a specified industrial facility or process;
- Site data sampling for calculation of GHG emissions from an industrial site where the data are sampled;
- Mass balance methods to compare the total amount of mass entering a process to that leaving the process for emissions estimation; and
- Emission factor methods that use the emission factors derived from the averaged industry-wise or country-wiser emission measurements and experiments for emissions calculation.

The choice of an emission quantification method depends on the availability of resources needed, the degree of accuracy required, and the way of the estimates to be used. In this study, an emission factors method is selected for estimating carbon footprint in material recovery processes, mainly because of its ease of use and relative low cost for carbon footprint estimation.

B. *Carbon Footprint Modeling Process*

The objective of emissions modeling here is to identify, estimate and compare the carbon footprint associated with each process step in waste recycling/recovery. Our modeling process is in accordance with the EPA's overall guidance [10]. It mainly covers: defining inventory boundaries; identifying GHG emission sources; compiling emission factors and activity data; and calculating GHG emissions.

(1) Inventory boundary setting

Boundary setting specifies which activities are assessed for their emissions, what input/output data are required, and what emissions are considered. In our case, the inventory boundary is determined by the purpose of the study: to estimate and analyze the GHG emissions performance of material recovery processes, in order to select low-emission process/material options and to identify the carbon footprint reduction potentials. As such, the assessment boundary is set to include the whole material recovery operations involving mainly chemical processes, together with all important mass and energy flows (input-output) of the operations. Within this boundary, the CO2e emissions associated with the involved process activities are identified and categorized into direct, indirect and optional emissions according to the Design Principles guidance [10].

(2) Emission sources analysis

Direct emissions in this study encompass those emitted from processing activities for material recovery and from production transport. Indirect emissions include those from the generation of electricity consumed for material recovery. Optional emissions cover the emissions from the production of raw materials used in the recovery processes. Such emissions are the consequences of the activities in the recovery processes, but occurred from sources at the upstream raw material production. The Guidance [10] termed them as optional that can be included in or excluded from the carbon footprint analysis for an assessed process. From the analysis above, the emission sources of material recovery from wastes can be identified. They are: process activities for material recovery; production transportation; energy consumed in the process; and materials/chemicals used in waste-sourced material recovery.

(3) Compilation of emission factors and activity data

As mentioned earlier, this study uses an emission factors method to quantify carbon footprint. The method requires collection/calculation of emission factors and activity data. According to EPA, an emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant [12]. The quantitative measure of this activity is referred as *activity data*. In general, activity data are collected from real recovery processes and empirical studies. However compared to the acquisition of activity data, the compilation of emission factors is more challengeable. Although EPA, IPCC, EU and many countries maintain compilations of emission factors that can be used in various emission estimates, there still are emission factors not readily available, such as those for some chemicals. In these cases, the factors need to be calculated based on chemical reaction equations and the available data in literature, together with additional assumptions. Besides calculation-based methods, emission factors can also be acquired by literature survey and direct testing methods.

(4) GHG emissions calculation

The calculation depends on the compiled emissions data in (3) above and the emissions model to be detailed below.

C. *Emissions Model Construction*

A general equation for emission estimation is available from EPA [12], as shown in Eq. (1):

$$E = A \times EF \times (1 - ER/100) \quad (1)$$

where E = emissions; A = activity data; EF = emission factor, ER = overall emission reduction efficiency.

Applying Eq. (1) to the carbon footprint assessment of material recovery processes, we have developed individual models for estimating the direct, indirect and optional CO2e emissions of the assessed processes.

(1) Direct emission of CO2e from transport

The direct emission E_i from three GHGs: CO2, CH4, N2O is calculated separately based on Eq. (1), using $ER = 0$ for baseline scenario assessment. The calculation formula is given by:

$$E_i = EF_i \times \sum_j A_j^T \quad (2)$$

where E_i is the i^{th} direct emission; i = (CO2, CH4, N2O); EF_i the i^{th} emission factor; A_j^T the transport activity data at the process step j.

The CO2, CH4 and N2O emissions calculated from Eq. (2) are converted to carbon footprint (CO2e emissions) by use of the following formula:

$$CF_{direct} = \sum_i (E_i \times GWP_i) \qquad (3)$$

where CF_{direct} represents the direct CO2e emissions composed of CO2, CH4 and N2O emissions (E_i) in transport; E_i is derived from Eq. (2); GWP_i is the i^{th} GWP factor (i = CO2, CH4, N2O) given in Table 1.

(2) Indirect CO2e emission from the use of electricity

Assume the energy used for material recovery is electricity. The emission factor of purchased electricity for each country/region is usually compiled based on a measure of kg CO2e per kWh. Using this factor, the indirect CO2e emission can then be calculated by:

$$CF_{indirect} = EF_e \times \sum_j A_j^e \qquad (4)$$

where $CF_{indirect}$ is the total indirect CO2-eq emissions from using purchased electricity; EF_e the emission factor of electricity; A_j^e the activity data of electricity consumed at process step j.

(3) Optional CO2e emission from the use of materials/chemicals

Similar to the indirect emission calculation in Eq. (4), the optional CO2e emissions from the use of materials and chemicals can be accounted by:

$$CF_{optional} = \sum_n (EF_n \times \sum_j A_n^j) \qquad (5)$$

where $CF_{optional}$ is the optional CO2e emissions induced from the use of materials/chemicals in an assessed process; EF_n the emission factor of the n^{th} type of material; A_n^j the activity data of material n used at the j^{th} process step.

(4) Total carbon footprint calculation

From the above equations (2)-(5), the core direct, indirect and optional CO2e emissions can be estimated. The total carbon footprint of an assessed case is then computed as a summation of these emissions by:

$$CF_{total} = CF_{direct} + CF_{indirect} + Opt(CF_{optional}) \qquad (6)$$

where CF_{total} represents the total carbon footprint of a material recovery process; $Opt(\cdot)$ denotes an optional summation operator.

III. Energy and Material Efficiency Indicator

In the present study, the energy and material efficiency in waste processing is measured with a metrics model, a resource use efficiency indicator. It is a composite indicator to quantitatively describe the efficiency in the use of energy and raw materials/chemicals including process waters in waste recycling and recovery processes. The resource efficiency indicator is defined by:

$$Eff = 1 - \sum_i \sum_j [(u_{ij} - U_{ij}) / u_{ij}]\ (1/N_i)\ W_i \qquad (7)$$

where *Eff* is the composite indicator for resource use efficiency of a waste processing option; W_i the weight of the i^{th} resource type; i = (material, energy, water); u_{ij} the measured consumption of the j^{th} resource under the i^{th} resource type; j = (material_1, material_2, …, material_n) for the "*material*" resource type and j = (electricity, natural gas, fuel oil, steam, other forms of energy) for the "*energy*" resource type; U_{ij} the expected consumption (best achievables under a given production condition) of the j^{th} resource under the i^{th} resource type; N_i the total number of the resources under the i^{th} resource type.

The resource use efficiency metrics model in Eq. (7) will be used in a case study in Section VI to measure and compare the usage efficiencies of resources in waste treatment by using different material recovery technologies.

IV. Case Study

A case study for nickel recovery from hazardous waste catalysts in palm oil hydrogenation was conducted to test the environmental sustainability models developed in the previous sections, which is summarized as follows.

A. *Metal Recovery Processes Used in the Case Study*

The case study examined two nickel recovery processes developed by Qi et al for a closed-loop process and an open-loop option [8]. Fig. 1 shows a simplified process flow for the closed-loop process.

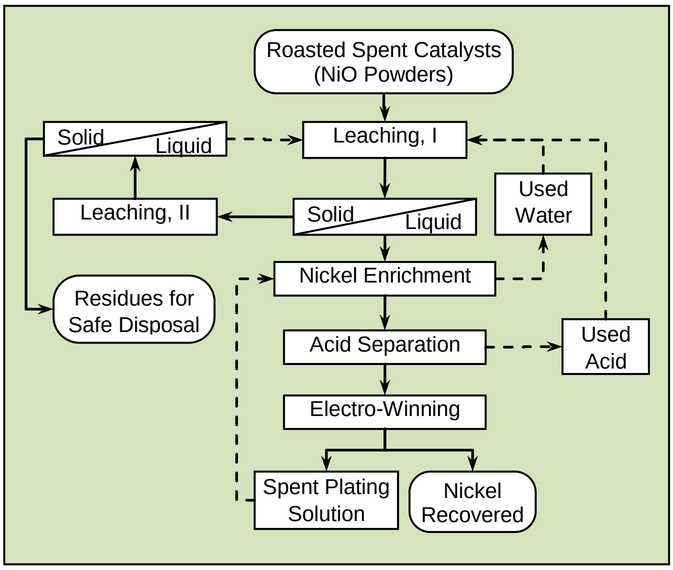

Fig. 1 A closed-loop nickel recovery process

The closed-loop process concept refers to the practice to reduce the amount of wastes generated at each sub-process before being recycled or discharged with external systems. The waste reduction is implemented by reusing unconsumed materials in the same process instead of directing them to a waste stream, known as in-process recycling. The nickel recovery process in Fig. 1 uses such a closed-loop concept with the characteristics of a two-staged sulfuric acid leaching procedure, an effective acid separation and nickel enrichment technique, and an electro-winning operation at high current efficiency, as shown in Fig. 1. On contrary, an open-loop cycle does not implement the in-process recycling techniques. It thus cannot use the recycled water, acid and spent plating solution as the closed-loop process does.

B. *Carbon Footprint Estimation*

The carbon footprint of the studied process in Fig. 1 is estimated using Eqs. (3-6) derived in Section II.C. The emission factors and activity data used in this assessment are listed in Table 2 for a baseline scenario that uses the existing process parameters and experimental measures for activity data. The results are shown in Table 3.

Table 2 Emission data used in the case study.

Emission Source		**Emission Factor**	**Unit**	**Reference**	**Activity Data** (Baseline Scenario)	**Unit**
Material Use	Sulfuric Acid	0.244	kg CO2e/kg	[14]	1.62	kg/kg
	Additive_1	2.732	kg CO2e/kg	[15]	0.27	kg/kg
	Additive_2	4.619	kg CO2e/kg	[15]	0.27	kg/kg
	DI Water	0.005	kg CO2e/kg	[14]	30.6	l/kg
Energy Use	Electricity	0.576	kg CO2e/kWh	[13]	21.84	kWh/kg
Transport	Truck travel	1.066	kg CO2/km	[16]		
	Truck travel	0.0032	g CH4/km	[16]	0.39	km/kg
	Truck travel	0.003	g N2O/km	[16]		

Table 3 Carbon footprint of the studied case.

Emission Source	**Emission Category**	**Quantity (kg CO2e/kg Ni)**	**% of Total**
Material use	Optional emission	2.53	16.3%
Energy use	Indirect emission	12.58	81.0%
Transport	Direct emission	0.42	2.7%
Total		15.53	100%

To date, there are no published carbon footprint data found in the literature for secondary nickel from catalytic wastes. Even for the primary nickel, a recent report [9] revealed that significant global variability exists in GHG emissions from nickel production. The difference could be as high as 70-100 fold [9]. As such, it would be not feasible to directly benchmark the carbon footprint estimated in this study. Instead, our results were sent to waste nickel catalyst recyclers who are interested in adopting the nickel recovery technology being assessed here. The results have been reviewed by them.

C. *Resource Efficiency Assessment*

The resource consumption data of materials, energy and processing water for an open-loop scenario, a baseline scenario and an optimal scenario of the studied process are given in Table 4 with the specified weight factors for each resource type. The optimal scenario is used as the best achievable scenario under the pilot-scale settings. The resource use efficiencies for these scenarios are calculated by Eq. (7). The results are also reported in Table 4.

Table 4 Parameters used in resource use efficiency calculation and the results derived.

Resource Type (*i*)	**Resource (*j*)**	**Resource Consumption in Optimal Scenario (U_{ij})**	**Resource Consumption in Baseline Scenario ($u_{ij}^{Baseline}$)**	**Resource Consumption in Open-loop Scenario ($u_{ij}^{Open\text{-}loop}$)**	**Weight Factor (W_i)**	**Number of Resources (N_i)**
Material	NiO	1.94 (kg/kg)	1.98 (kg/kg)	2.00 (kg/kg)	0.4	4
	Sulfuric acid	1.19 (kg/kg)	1.62 (kg/kg)	8.16 (kg/kg)		
	Additive_1	0.26 (kg/kg)	0.27 (kg/kg)	0.27 (kg/kg)		
	Additive_2	0.26 (kg/kg)	0.27 (kg/kg)	0.27 (kg/kg)		
Energy	Electricity	17.47 (kWh/kg)	21.84 (kWh/kg)	21.84 (kWh/kg)	0.3	1
Water	DI water	3 (l/kg)	30.6 (l/kg)	49.12 (l/kg)	0.3	1
Resource Efficiency		1	0.663	0.562		

Compared to the open-loop scenario, the baseline scenario of the closed-loop process demonstrated higher resource use efficiency, because of its implementation of in-process recycling techniques. This feature is fully reflected in the calculated results in Table 4.

V. Conclusion

A set of environmental sustainability models for industrial waste recycling and recovery has been established in this study. The models have also been tested by a nickel recovery case study for the assessment of the key sustainability properties, including carbon footprint, energy and material efficiency. The assessment results were consistent with the measured or recognized data from the experiments and from the waste recycling industry. Our next target is to conduct more case studies for recovery of other materials from different industrial wastes, thus to further improve the models and scenarios analysis to support the sustainability information needs in industrial waste recycling and recovery.

Acknowledgment

The authors would like to thank Dr. G.J. Qi, Mr. H.C. Low, and Mr. R.S. Ng from SIMTech for their domain knowledge sharing and the process/inventory data support in the case study. Thanks are also due to Ms. D.N. Xu from NTU for her contribution to emission data collection for the case study.

References

[1] M. A. Khalilzadeh, A. Jamshidi, A. Hosseini, "Factors affecting the recovery of nickel from refinery spent NiO/Al2O3 catalysts", in proceedings of the 12th EuCheMS International Conference on Chemistry and the Environment, Stockholm, Sweden, 2009.

[2] N. M. Al-Mansi, N. M.Abdel Monem, "Recovery of nickel oxide from spent catalyst", Waste Management (2002), vol. 22, No. 1, pp. 85-90.

[3] M. Wladyslawa, M. Beata, A. Szymczycha, "Kinetics of nickel leaching from spent catalyst in sulphuric acid solution", International Journal on Mineral Processing (2005), vol. 77, No. 4, pp. 231-235.

[4] B. Singh, "Treatment of spent catalyst from the nitrogenous fertilizer industry – A review of the available methods of regeneration, recovery and disposal", Journal of Hazardous Materials (2009), vol. 167, No. 1-3, pp. 24-37.

[5] M. Nardo, M. Saisana, A. Saltelli, S. Tarantola, A. Hoffman, E. Giovannini, "Handbook on constructing composite indicators: methodology and user guide", OECD Statistics Working Paper, 2005.

[6] International Organization for Standardization (ISO), "ISO/CD 14067-1: Carbon footprint of products – Part 1: Quantification," Geneva, Switzerland: ISO, 2010.

[7] International Organization for Standardization (ISO), "ISO 14064-1: Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals", Geneva, Switzerland: ISO, 2006.

[8] G.J. Qi, H.C. Low, Y.P. Zhang, “Process development for recovery of nickel from oxide powders”, SIMTech project report, 2009.

[9] M.J. Eckelman, “Significant global variability in a facility-level greenhouse gas assessment of primary nickel”, in proceedings of 2010 IEEE International Symposium on Sustainable Systems and Technology, Arlington, VA, 2010, pp. 1-4.

[10] U.S. Environmental Protection Agency (EPA,) “Climate leaders greenhouse gas inventory protocol design principles”, 2005.

[11] Intergovernmental Panel on Climate Change (IPCC), Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report, Solomon SD and Qin M (eds.), Geneva, Switzerland: IPCC, 2007.

[12] U.S. Environmental Protection Agency (EPA), Emissions factors and AP-42, available at http://www.epa.gov/ttn/chief/ap42/index.html (accessed in Dec 2010).

[13] National Environment Agency (NEA) of Singapore, “Leaching test - Recommended acceptance criteria for suitability of industrial wastes for landfill disposal”, NEA, 2009.

[14] PE International, GaBi - Life cycle assessment software system, available at: http://www.gabi-software.com/international/software/gabi-4/, (accessed in Dec 2010).

[15] Q.Z. Yang, R.S. Ng, G.J. Qi, H.C. Low, “Economic and environmental impact evaluation of nickel recovery process”, SIMTech Technical Report (2009), vol. 10, No. 4, pp. 244-249.

[16] U.S. Environmental Protection Agency (EPA), “Direct emissions from mobile combustion sources”, EPA 430-K-08-004, 2008.