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Realizing CO_2 emission reduction through industrial symbiosis: a cement production case study for Kawasaki

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Abstract

This article is one effort to examine the present and potential performances of CO2 emission reduction though industrial symbiosis by employing a case study approach and life cycle CO2 analysis for alternative industrial symbiosis scenarios. As one of the first and the best-known eco-town projects, Kawasaki Eco-town was chosen as a case study area. First, the current industrial symbiosis practices in this area are introduced. To evaluate the potential of reducing the total CO2 emission through industrial symbiosis, alternative industrial symbiosis scenarios are then designed based on a questionnaire survey of 57 major local industries, to which 35 companies appropriately responded. The main focus of this paper is to calculate the total CO2 emission for different scenarios by adopting a life cycle CO2 analysis method. We then present recommendations on further improvement with consideration of the local realities. Our findings are that industrial symbiosis practices in Kawasaki Eco-town still have room for improvement in that greenhouse gas emissions can be further reduced and natural resources conserved through effective material exchanges, not only between companies, but also with the surrounding area. To encourage material exchanges between the municipality and industry, the city government should introduce a detailed separation program for garbage collection so that wastes can be effectively reused. In addition, the Waste Disposal and Public Cleaning Law needs amending so that industries can effectively use municipal solid waste in their manufacturing.

Keywords: industrial symbiosis, greenhouse gas, co-processing, alternative fuel and raw material, life cycle CO2 analysis.

1. Introduction

The Intergovernmental Panel on Climate Change Fourth Assessment Report issued in late 2007 clearly states the "*very likely*" relation between human-induced greenhouse gas (GHG) concentrations and most of the observed increase in the global average temperature since the mid-20th century (IPCC, 2007), which might shape a series of negotiations toward a new international framework referred to as a post-Kyoto agreement. Annex I parties of the Kyoto Protocol are facing even greater pressures to fulfill their commitment to GHG reduction as they enter the first commitment period of the Kyoto Protocol (2008–2012). One such challenge is to reduce GHG emissions from industry, one of the greatest contributors to the anthropogenic GHG concentration. For instance, more than 90% of the total CO_2 emissions in Japan come from fuel combustion, of which about 30% is from industries as the largest source (Greenhouse Gas Inventory Office of Japan, 2008). Various measures have been suggested to reduce industry GHG emissions, ranging from energy efficiency to fuel switching to CO_2 sequestration (Metz and Davidson et al., 2007). Among them, the utilization of waste as alternative fuels and raw materials is one of the best solutions as it is an innovative method to both reduce total CO_2 emissions and alleviate waste management pressures (Metz and Davidson et al., 2007). The cement industry, for example, has a long history of utilizing various wastes as fuels and raw materials (Hendrik and Padovani, 2002), which is now recognized as one opportunity for reducing CO_2 emissions (Battelle, 2002a; Holcim and GTZ, 2006). The use of such an approach can also be seen in the steel industry. New technologies in the steel industry allow coke ovens and blast furnaces (BFs) to use plastic wastes as alternative fuels and feedstock (Ziebek and Stanek, 2001; Okuwaki, 2004). Generally, such an approach is termed as “co-processing”, and it is a sustainable and efficient way of managing industrial by-products, off-spec wastes, out-of-date products and other waste materials that are unable to be recycled by traditional methods (Holcim and GTZ, 2006; Mutz et al., 2007).

In this context, the philosophy of industrial symbiosis (IS) would contribute to the further development of such efforts as IS promotes the exchange of resources such as wastes and by-products across multiple industries by taking advantage of geographical proximity of co-located industries (Chertow, 2000). Practically, IS encourages the establishment an eco-industrial park (EIP) so that more synergy opportunities can be identified within a certain industrial cluster. EIPs have been developed, often backed by national initiatives, not only in developed countries (Heeres et al., 2004; Mirata, 2004; Beers et al., 2007) but also in industrializing countries (Global Environment Centre Foundation, 2005; Fang et al., 2007). By working together, firms operating as a community within an EIP and engaging in IS collaborations should realize greater benefits collectively (such as GHG emission reductions through by-product exchanges and thermal recovery) than they would if each business optimized its performance in isolation; however, further case studies examining regional IS practices are required (Harris, 2007).

Eco-towns (a Japanese term for EIPs) have been developed as a national program of the Japanese Ministry of Environment and Ministry of Economy, Trade and Industry (METI) since 1997. The primary aim of this program was to cope with a serious shortage of landfill sites and to revitalize local stagnating industries at the same time. By March 2005, 47 recycling plants had been constructed and, in total, 732,000 t of waste was reused or recycled in 23 Eco-towns (METI, 2006). In 2005, METI established a special committee to deliberate the future direction of the eco-town program. After a series of discussions, the committee issued a report indicating that the eco-town program should also address global warming issues (METI, 2005). By 2006, there were 26 Eco-towns developed across the country. Recent study of all the 26 Eco-towns identified that approximately 1.65 billion USD was invested in 61 recycling projects across the country which attracted government subsidy of 36% on average. Such investment also spurred the construction of at least 107 other recycling facilities in their vicinity without government subsidy and has contributed the development of environmental industries in Japan (Van Berkel et al., 2009a).

The goal and scope of this study is to analyze the potential of CO_2 emission reduction through IS by employing a case study approach. As one of the most well known eco-town projects, Kawasaki Eco-town was chosen for our case study. In this article, an anchor industry of Kawasaki Eco-town is identified by investigating existing material flow. To obtain a detailed picture of the material flow, a questionnaire survey of 57 major industries located in and around the eco-town was conducted, for which 35 companies appropriately responded. The survey items include the types and quantity of resources such as virgin materials, by-products and wastes. Based on the anchor company, alternative IS scenarios are designed. The anchor tenant approach has been employed to design alternative scenarios (Lowe, 1997; Côté and Rosenthal, 1998). The main focus of this paper is to calculate the total CO_2 emission for different scenarios by adopting life cycle CO_2 ($LCCO_2$)

analysis. Finally, recommendations on further improvement are presented and discussed by considering the local reality.

2. The Kawasaki Eco-town project

2.1. Basic information on Kawasaki Eco-town

Kawasaki Eco-town is located in the coastal area of the city of Kawasaki, between Tokyo and Yokohama (**Fig. 1**). Several large petrochemical and steel companies have been established since the 1950s. Kawasaki city has now become the center of the Keihin Industrial Area, the largest industrial area in Japan. However, owing to the collapse of the bubble economy in the early 1990s and increasing competition from rapidly industrializing economies, companies in this area greatly suffered from continuous economic stagnation. To revitalize this area, the Japanese government chose the waterfront industrial area as one of the first four national eco-town projects in 1997. 227 million USD of subsidies were provided for constructing new recycling facilities, including one waste plastic recycling plant (producing BF feed for steel production), one waste plastic recycling plant (producing raw materials for concrete formwork production), one paper recycling plant (recycling hard-to-recycle papers such as coated papers) one waste plastic recycling plant (producing raw materials for ammonia production) and one PET-to-PET recycling plant. While the waste plasic recycling plants for BF feed production and for ammonia production were constructed to produce raw materials for existing steel and ammonia production processes as supplemental facilities, others were constructed as an independent, brand-new recycling plant. Besides these five plants, several other recycling plants, such as an electric appliance recycling plant and a cement production plant with recycling processes, were constructed as part of the eco-town, but without any subsidies from the government. Currently, more than 70 companies are operating in Kawasaki Eco-town; major industrial sectors include steel, chemical, cement, nonferrous metal processing and paper making sectors. Recent study indentified that there are seven major by-product and waste exchanges, contributing to 565,000 t of waste diversion from incineration or landfill and estimated economic opportunity of more than 13.3 billion JPY (~130 million USD) (Van Berkel et al., 2009b).

<insert figure 1 here>

2.2. Material flow analysis within Kawasaki Eco-town

Kawasaki Eco-town consumed 21.6 million tonnes of different materials in 2004, comprising of virgin materials (89.7%), by-products and wastes (10.3%). **Fig. 2** depicts the current IS network within the Kawasaki Eco-town, in which we can see that IS takes place both at an individual company level and between different companies.

<insert figure 2 here>

A typical example of innovative companies participating in IS practice is the JFE Steel Corporation, one of the leading steel companies in the world. Within this company, plastic wastes are processed in the household appliance recycling plant and then delivered to the BF feed production plant for further treatment. The processed materials are then consumed both as reducing agents and fuels in the BF during steel production. Some of the plastic waste from the household appliance recycling plant is delivered to another plant operated by JFE Kankyo (Kankyo literally means "environment") as raw materials for making concrete formwork.

In terms of IS efforts between different companies, several by-product exchanges have been established. For instance, BF slag from JFE Steel Corporation, paper sludge from a paper recycling company, and incineration ash from the local incinerators are used as alternative raw materials for cement production by a local cement company, D.C. Cement Company. Plastic wastes are also reused by D.C. Cement Company as alternative fuels. Waste metals collected through the paper recycling process are used by JFE Steel Corporation in their steel production. With regard to water recycling, treated wastewater from the local sewage treatment facility is consumed by the cement company for cooling and manufacturing purposes.

Among all companies participating in IS networks, the key anchor company is D.C. Cement, which produces 348,000 t of Portland cement and 272,000 t of BF cement, as well as other related products such as concrete admixtures. The company's innovative approach means it can use both virgin materials (such as limestone and coal) and various wastes and industrial by-products for making Portland cement. Moreover, sewage sludge, slag, surplus soil from construction sites, as well as soot dust and burnt residue can be utilized as clay substitutes, while plastic wastes and waste tires are mainly used as fuel alternatives to coal.

In terms of the production process, no virgin clay is used as it is completely substituted by different wastes. Plastic wastes are sorted to remove impurities and then crushed to serve as alternative fuels. Alternative fuels and raw materials (AFRs) are put into a rotary kiln through a preheating facility to improve combustion efficiency. Crushed plastic wastes are directly used as fuels. The rotary kiln is operated at a temperature of more than 1400°C to produce cement clinker. Combustion residues of coals and wastes used as AFRs are also put into the rotary kiln; thereby no wastes are generated in the production process. The produced cement clinker, after being mixed with gypsum and other additives, is finely ground to become Portland cement (**Fig. 3**). Then, part of Portland cement produced is mixed with the fine-powder of blast furnace slag to produce BF cement. Estimated amount of the BF slag utilized in this process for the year 2006 is 123,000 t, all of which is transported from the neighboring steel mill operated by JFE Steel.

<insert figure 3 here>

In total, the cement plant uses about 390,000 t of wastes and by-products to produce their products in 2006, of which 250,000 t were clay substitutes such as sludge and surplus soil and 7,000 t were plastic wastes as coal alternatives. The practices of utilizing different wastes in cement production process has been known for quite a long time (Battelle, 2002b; Hendrik and Padovani, 2002, 2003), thus, the cement industry is a typical example of “scavenger” in industrial ecology (Reijnders, 2007).

3. Design and evaluation of alternative material exchange scenarios

3.1. Alternative material exchange scenarios

Based upon the case for D.C. Cement Company, we designed four alternative material exchange scenarios for its Portland cement production process so as to examine the present IS performance and evaluate the potential for further IS practices in Kawasaki Eco-town. Our analysis set the amount of Portland cement production at the current level (348,000 t a year) for all four scenarios and change the amounts of virgin materials and wastes and by-products used in production (**Table 1**).

<insert Table 1 here**>**

Scenario 1: No IS activities

Scenario 1 is our baseline scenario, in which the cement production process only uses virgin materials, such as limestone, clay and coal.

Scenario 2: Current IS efforts

Scenario 2 represents current cement production process, in which all clay and some coal is substituted by wastes from the city of Kawasaki and surrounding areas.

Scenario 3: Improved IS at the industrial cluster level

Keeping the same total input of AFRs, this scenario assumes the flow of the wastes from outside Kawasaki is replaced by industrial wastes generated in the Kawasaki Eco-town area. Thus, Scenario 3 involves shorter transportation distances for AFRs.

Scenario 4: Broader IS initiatives at the regional level

According to the waste management report of the Kawasaki city government, 56,000 t of annual municipal solid waste (MSW) is plastic waste (City of Kawasaki, 2007), most of which is incinerated. However, the D.C. Cement Company can potentially use 20,000 t of plastic waste per year to replace coal. The city of Kawasaki generated about 490,000 t of MSWs to be incinerated in 2006, of which 49,700 t was plastic wastes. Thus, we presume that for Scenario 4, all plastic waste collected within the city of Kawasaki is delivered to the cement company as alternative fuel.

Assumptions and formulas for evaluation are described below and CO_2 emission factors used in calculations are given in **Table 2**. Emission factors are mainly taken from the Act on Promotion of Global Warming Countermeasures (MoE, online) and from the manual of the Mandatory Greenhouse Gas Accounting and Reporting System (MoE and METI, 2008), both of which are developed for statutory GHS Accounting and Reporting obliged to high volume GHG generators. In regard to alternative fuels, there are two materials for coal substitutes, namely industrial plastic wastes and municipal plastic wastes. The emission factor of industrial plastic wastes and of municipal plastic wastes are the value of direct incineration and are slightly different each other due to their carbon content. Recycling of plastic wastes is not taken into account in these factors (MoE, online).

<insert Table 2 here**>**

3.2. Evaluation process

The annual CO_2 emission Q_i under each scenario is composed of seven parts:

$$Q_i = QTv_i + QTiwr_i + QTmswr_i + QM_i + QTiwd_i + QTmswd_i + QWd_i \text{ - (1)}$$

where

i: index number of a scenario (from 1 to 4)

QTv_i [t-CO_2/y]: CO_2 emissions from transportation of virgin materials,

$QTiwr_i$ [t-CO_2/y]: CO_2 emissions from transportation of industrial wastes to be recycled,

$QTmswr_i$ [t-CO_2/y]: CO_2 emissions from transportation of MSWs to be recycled,

QM_i [t-CO_2/y]: CO_2 emissions from cement production,

$QTiwd_i$ [t-CO_2/y]: CO_2 emissions from transportation of industrial wastes to be disposed of,

$QTmswd_i$ [t-CO_2/y]: CO_2 emissions from transportation of MSWs to be disposed of,

QWd_i [t-CO_2/y]: CO_2 emissions from waste disposal.

QTv_i: CO_2 emissions from transportation of virgin materials.

Coal, limestone and clay are delivered by ships with different capacities. Hence, CO_2 emission from virgin material transportation for scenario i is

$$QTv_i = \alpha_1 \cdot \left(\frac{Wc_i}{S_1}\right) \cdot \left(\frac{Dc_i}{v_1}\right) \cdot \beta + \alpha_2 \cdot \left(\frac{Wl_i}{S_2}\right) \cdot \left(\frac{Dl_i}{v_2}\right) \cdot \beta + \alpha_3 \cdot Ws_i \cdot Ds_i \text{ - (2)}$$

where

$QTvi$ [t-CO_2/y]: CO_2 emissions from virgin material transportation for scenario i,

α_1 [t-fuel/day/ship]: daily fuel consumption for a 100,000 t tanker,

α_2 [t-fuel/day/ship]: daily fuel consumption for a 10,000 t tanker,

α_3 [t-CO$_2$/t/km]: CO$_2$ emission factor for domestic shipping,

β [t-CO$_2$/t-fuel]: CO$_2$ emission factor for heavy crude oil consumption,

v_1 [km/day]: average speed of a 100,000 t tanker,

v_2 [km/day]: average speed of a 10,000 t tanker,

S_1 [t/ship]: maximum load of a 100,000 t tanker,

S_2: [t/ship]: maximum load of a 10,000 t tanker,

Wc_i [t/y]: weight of coal used in scenario i,

Wl_i [t/y]: weight of limestone used in scenario i,

Ws_i [t/y]: weight of clay used in scenario i,

Dc_i [km]: transportation distance for coal in scenario i,

Dl_i [km]: transportation distance for limestone in scenario i,

Ds_i [km]: transportation distance for clay in scenario i.

$QTiwr_i$: CO$_2$ emissions from transportation of industrial wastes to be recycled.

All industrial wastes are transported by 10 t trucks. Weight-averaged distances between supply areas and the cement production plant are used as transportation distance in the calculation (Figure 3). CO$_2$ emissions from this process are described by

$$QTiwr_i = \gamma \cdot (Wipw_i \cdot Dcs_i + Wcs_i \cdot Dss_i) \text{ - (3)}$$

where

$QTiwr_i$ [t-CO$_2$/y]: CO$_2$ emissions from transporting industrial waste to be recycled,

γ [t-CO$_2$/t/km]: CO$_2$ emission factor for transportation by a 10 ton truck,

$Wipw_i$ [t/y]: weight of industrial plastics wastes used,

Wcs_i [t/y]: weight of clay substitutes used,

Dcs_i [km]: transportation distance for industrial plastic wastes used,

Dcs_i [km]: transportation distance for clay substitutes used.

$QTmswr_i$: CO_2 emissions from transportation of MSWs to be recycled.

CO_2 emissions discharged through collection and transportation of MSWs are calculated using the following formula. Here, MSWs are assumed to be transported to the cement production plant by 10 t trucks.

$$QTmswr_i = \gamma \cdot Wmsw_i \cdot Dmsw_i \text{ - (4)}$$

where

$QTmswr_i$ [t-CO_2/y]: CO_2 emissions of transporting MSWs to be recycled,

γ [t-CO_2/t/km]: CO_2 emission factor for a 10 ton truck,

$Wmspw_i$ [t/y]: weight of MSW plastic wastes used,

$Dmsw_i$ [km]: transportation distance for MSWs plastic wastes used.

QMi: CO_2 emissions from cement production

CO_2 emissions from cement production comprise three parts: emissions from the consumption of electric power for the entire production process, emissions from the combustion of coal and plastic waste, and emissions from the calcination of limestone.

$$QM_i = \delta \cdot E_i + \omega_1 \cdot C_i + \omega_2 \cdot Wipw_i + \omega_3 \cdot Wmspw_i + \omega_4 \cdot Wl_i \text{ - (5)}$$

where

QM_i [t-CO$_2$/y]: CO$_2$ emissions from cement production,

δ [t-CO$_2$/kWh]: CO$_2$ emission factor for electric power consumption,

E_i [kWh]: electric power consumption,

C_i [t/y]: weight of coal used,

$Wipw_i$ [t/y]: weight of industrial plastic wastes used,

$Wmspw_i$ [t/y]: weight of MSW plastic wastes used,

Wl_i [t/y]: weight of limestone used,

ω_1 [t-CO$_2$/t]: CO$_2$ emission factor for coal combustion,

ω_2 [t-CO$_2$/t]: CO$_2$ emission factor for industrial plastic wastes combustion,

ω_3 [t-CO$_2$/t]: CO$_2$ emission factor for MSW plastic wastes combustion,

ω_4 [t-CO$_2$/t]: CO$_2$ emission factor for limestone calcination.

$QTiwd_i$: CO$_2$ emissions from transportation of industrial wastes to be disposed of.

CO$_2$ emissions discharged from transporting industrial wastes for their treatment by 10 t trucks are derived as

$$QTiwd_i = \gamma \cdot Wiwd_i \cdot Diwd_i \text{ -(6)}$$

where

$QTiwd_i$ [t-CO$_2$/y]: CO$_2$ emissions of transporting industrial wastes to be disposed,

γ [t-CO$_2$/t/km]: emission factor for transportation by a 10 t truck,

$Wiwd_i$ [t/y]: weight of industrial wastes to be disposed of (t/y),

$Diwd_i$ [t/y]: transportation distance for industrial wastes to be disposed of.

$QTmswd_i$: CO_2 emissions from transportation of MSWs to be disposed of

Data from the Report on Green House Gas Emissions of Kawasaki is used to calculate CO_2 emissions discharged from the transportation of MSWs for their treatment.

QWd_i: CO_2 emissions from waste disposal

The following formula is used to calculate the CO_2 emissions generated by the incineration of those wastes not used in production.

$$QWd_i = \omega_2 \cdot Wiwd_i + \omega_2 \cdot Wmswd_i \text{ - (7)}$$

where

QWd_i [t-CO_2/y]: CO_2 emissions discharged by waste disposal,

ω_2 [t-CO_2/t]: CO_2 emission factor for industrial plastic waste combustion,

ω_3 [t-CO_2/t]: CO_2 emission factor for MSW plastic wastes combustion,

$Wiwd_i$ [t/y]: weight of industrial plastic wastes to be disposed of,

$Wmswd_i$ [t/y]: weight of municipal plastic wastes to be disposed of.

4. Results and discussion

Comparing with Scenario 1 in which no AFRs are used, the current IS practice described by scenario 2 reduces CO_2 emissions by about 41,300 t per year while saving about 272,000 t of virgin materials per year (**Table 3**). Scenario 3, in which the current IS practices are expanded to reuse or recycle local wastes and encourage by-product exchanges rather than transporting original materials from remote areas, can reduce CO_2 emissions by about 43,100 t per year. The difference between Scenario 2 and Scenario 3, a further reduction of CO_2 emissions of about 2,000 t per year, is achieved by shorter transportation distance for the AFR procurement. Three major processes with a potential CO_2 emission reduction of with more than about 20,000 t per year are combustion in cement production, MSW disposal and industrial waste disposal. The use of plastic wastes in cement production as coal substitutes will result in an overall significant reduction in CO_2 emissions. Such CO_2 emission savings originates from the reduced coal consumption in cement production and avoided plastic waste incineration in waste management. The life cycle assessment considers the final waste disposal of both industrial and municipal solid wastes, and it is clear that the recycling of these wastes, rather than their incineration, can significantly reduce total CO_2 emissions. It is true that the CO_2 emission reduction depends strongly on the assumed emission factors of the alternative fuels, or plastic wastes. For instance, if the emission factor of industrial and municipal plastic wastes increase by 10%, the overall CO_2 emissions increase by 10,600 t for Scenario 1, by 8,900 t for Scenario 2 and 3 and by 5,300 t for Scenario 4, compared to the original settings. Similarly, 10% decrease in the emission factor of industrial and municipal solid wastes results in the overall CO_2 emissions reduction of 10,600 t for Scenario 1, 8,900 t for Scenario 2 and 3 and 5,300 ts for Scenario 4. In this manner, changes in the emission factors of plastic wastes do not have influence on the relative performance of four scenarios but have influence on the total CO_2 emissions of the scenarios.

<insert Table 3 here>

Comparing with other scenarios, Scenario 4 has by far the highest potential for CO_2 emission reduction and can further conserve virgin materials (Table 3). This means that IS at a broader level, let's say at the regional level, can significantly reduce both virgin material consumption and CO_2 emissions. The realization of Scenario 4 could provide comprehensive economic, environmental, and societal benefits. For instance, resource costs, solid waste treatment costs, and environmental liability and insurance costs are related to solid waste issues, and could be reduced. Additional financial benefits of developing eco-towns include increased revenues from the sale of wastes, increased sales due to 'green' and niche marketing and more competitive production methods, and the avoidance of regulatory penalties for waste discharge. Furthermore, IS systematically considers the various types of solid waste, including industrial and municipal waste, as well as all stakeholders' concerns; therefore, various environmental benefits could be gained, such as conserving natural resources and reducing the solid waste volume and thus reducing the burden on local landfills. Moreover, the case of Kawasaki indicates that some societal benefits could be achieved, such as improved public awareness by encouraging IS, and improved public health by reducing solid and hazardous wastes. This system also encourages collaboration among different companies and between companies and the city government, as well as with the local community.

To encourage material exchanges between municipalities and industries in Japan, city governments should introduce a detailed separation program for garbage collection so that wastes collected can be effectively recycled. In addition, the Waste Disposal and Public Cleaning Law needs to be amended so that industries can utilize MSWs in their manufacturing. Under the current legal framework, the responsibility for waste management is twofold; industrial companies are responsible for managing their industrial wastes, while municipal governments are responsible for managing municipal solid wastes. By transferring MSWs to industries, city governments could reduce their financial burden regarding waste management; for example, by reducing the costs involved in the construction and operation of incineration plants and landfill sites. As such, if we properly design an IS network, an eco-town project would have both economic and environmental benefits, such as a greater return from increasing recycled materials, waste reduction, and CO_2 emission reduction. Because our analysis focused solely on the performance of Portland cement production; further research to comprehensive methods to quantify and environmental benefit of the cement production plant is warranted to improve the collective understanding of the relative performance of the individual industrial symbiosis.

5. Conclusion

With increasing concerns about global warming, many countries are now seeking innovative approaches to reform their industries. IS characterizes relationships between businesses by analyzing their economic and environmental performance. By encouraging IS, industrial systems can minimize environmental impacts by mimicking the circular flow of energy and materials as demonstrated by natural ecosystems (Geng and Côté, 2007). One of the significant impacts of IS is the reduction of carbon emissions, thus alleviating global warming.

This paper examines the feasibility of IS by employing a case study approach. From the case of Kawasaki, we can see the value of encouraging IS at the broader level. A cement producer, as the anchor company for IS in Kawasaki Eco-town, reduced CO_2 emissions by 43,000 tons per year using recycled materials rather than virgin materials. In addition, the study showed that IS practices have the potential to achieve further reductions in GHG emissions and conserve natural resources thorough effectively aligning material exchanges not only between companies but also with local governments. If the growing concerns of global warming urge local governments to reduce CO_2 emissions from their activities, Kawasaki could change its attitudes toward current MSW management practice, or waste incineration. Similarly, with increasing concerns on natural resource scarcity and continuous price rises for virgin materials, the use of AFRs would become more economically viable.

Our approach provides a basic framework to identify various benefits brought by IS practices such as potential CO_2 emission reductions. The framework would be useful in quantitatively evaluating CO_2 emission reduction potential for other EIDs. It would be useful for practitioners designing material exchanges on a regional scale, making best use of local resources, so that EIDs minimize CO_2 emission while reducing the use of virgin materials. For governments, the framework would be useful in evaluating the CO_2 emission reduction potential of different EIDs and in determining which type of EID should be promoted. Therefore, our approach could help develop and enhance IS practices and thus serve in the development of a low carbon society.

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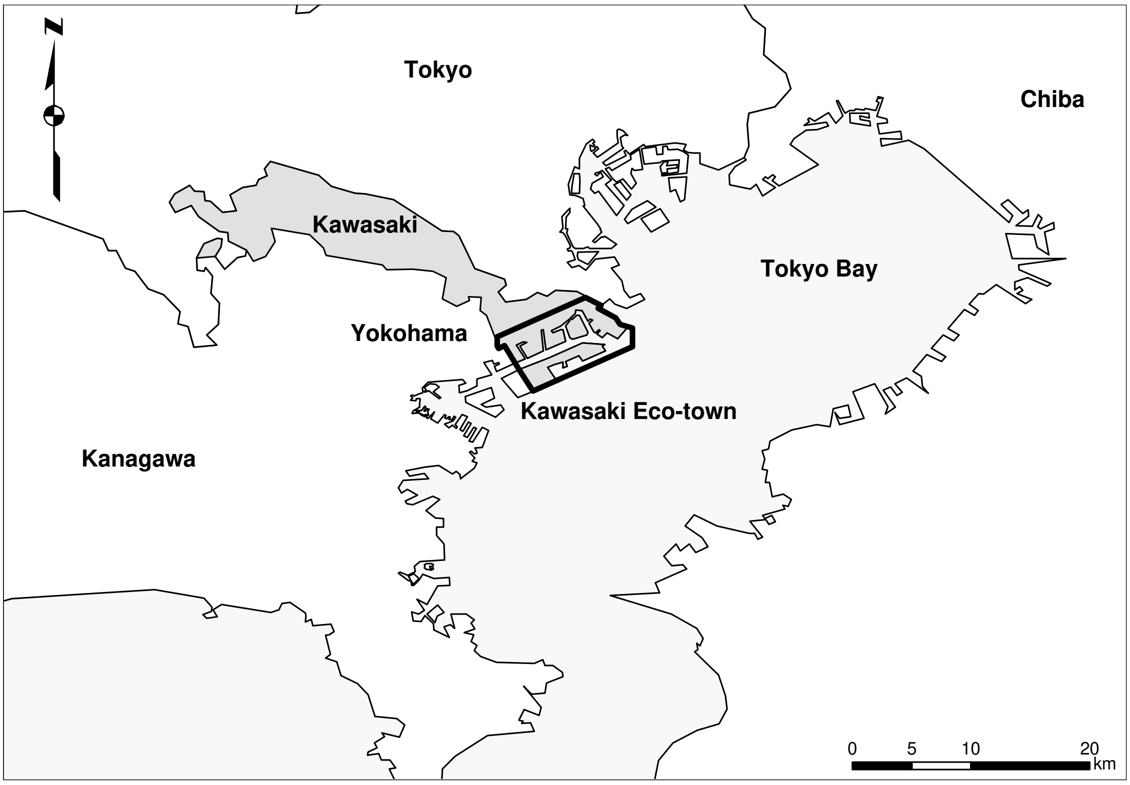


Fig. 1 Location of Kawasaki Eco-town denoted by a heavy line

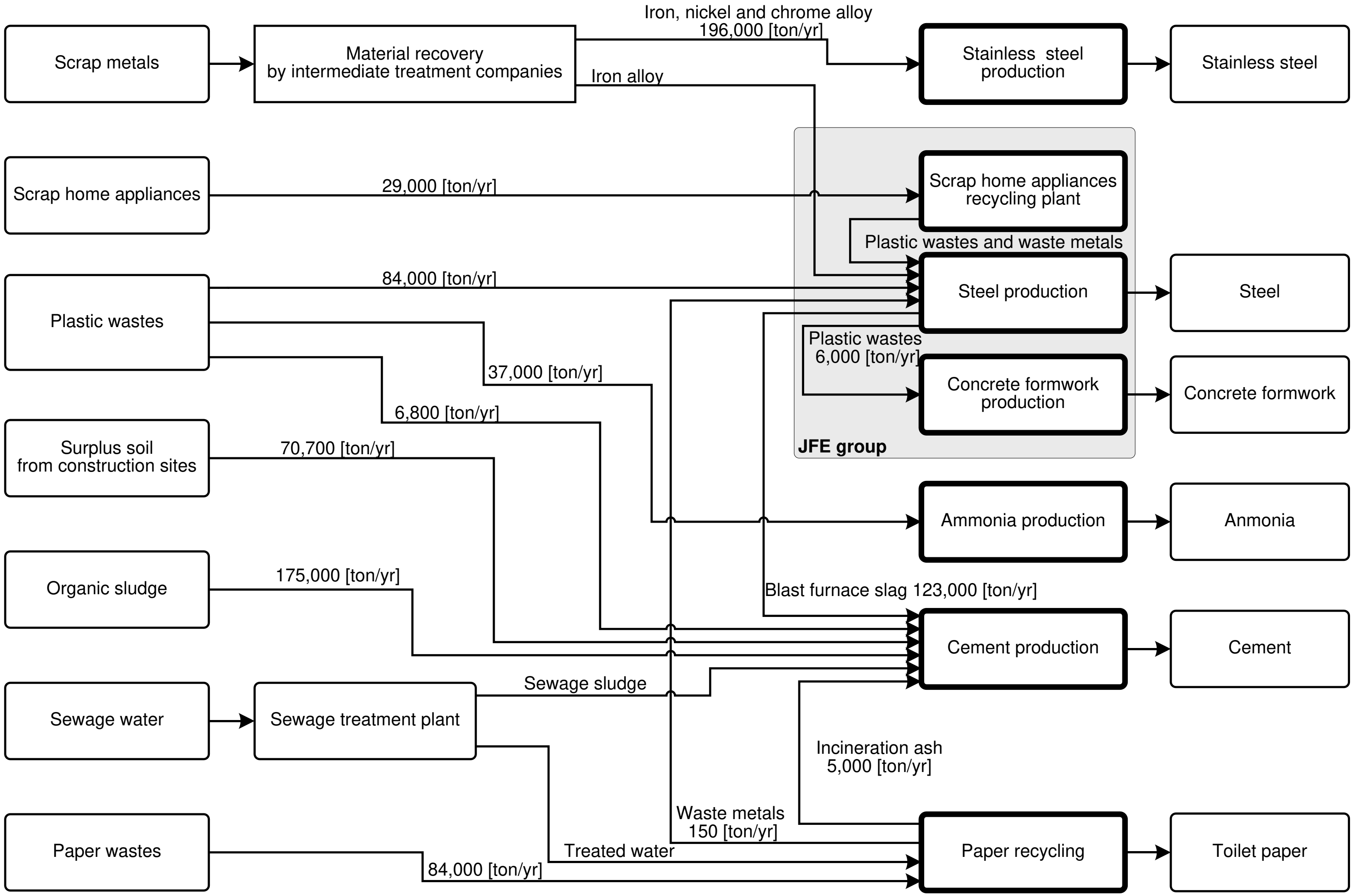


Fig. 2 Overview of present material exchanges in Kawasaki Eco-town

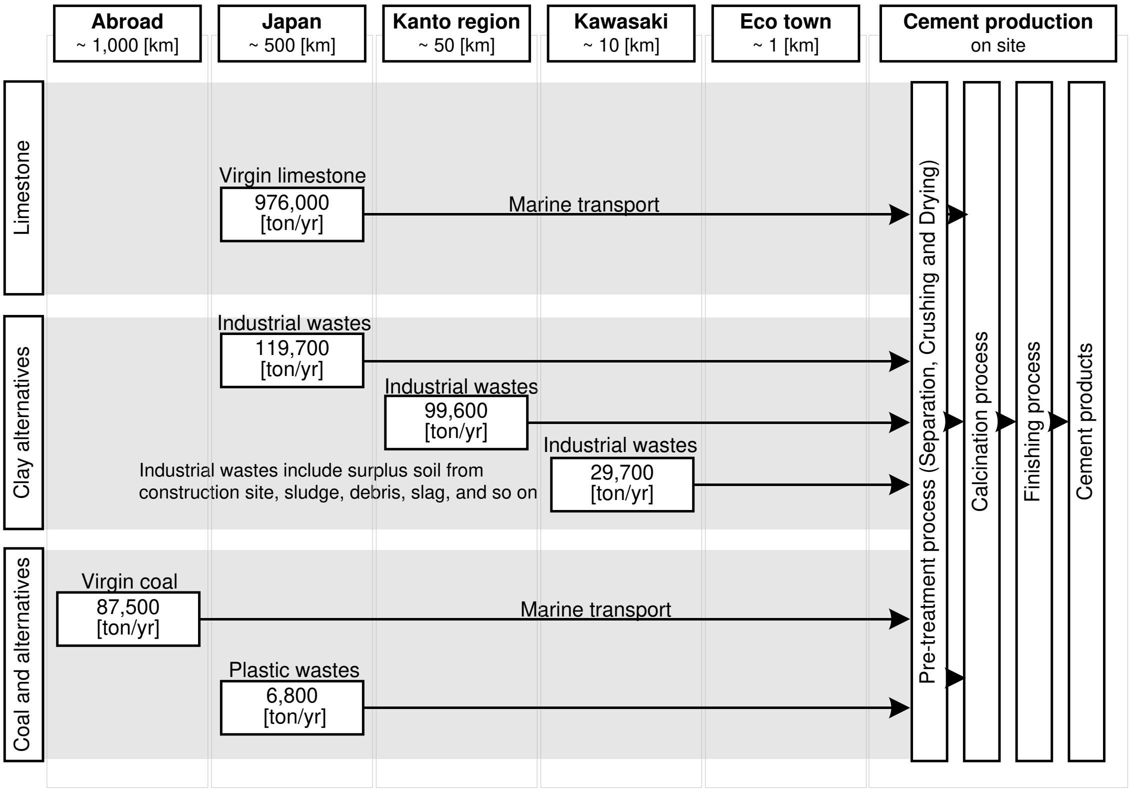
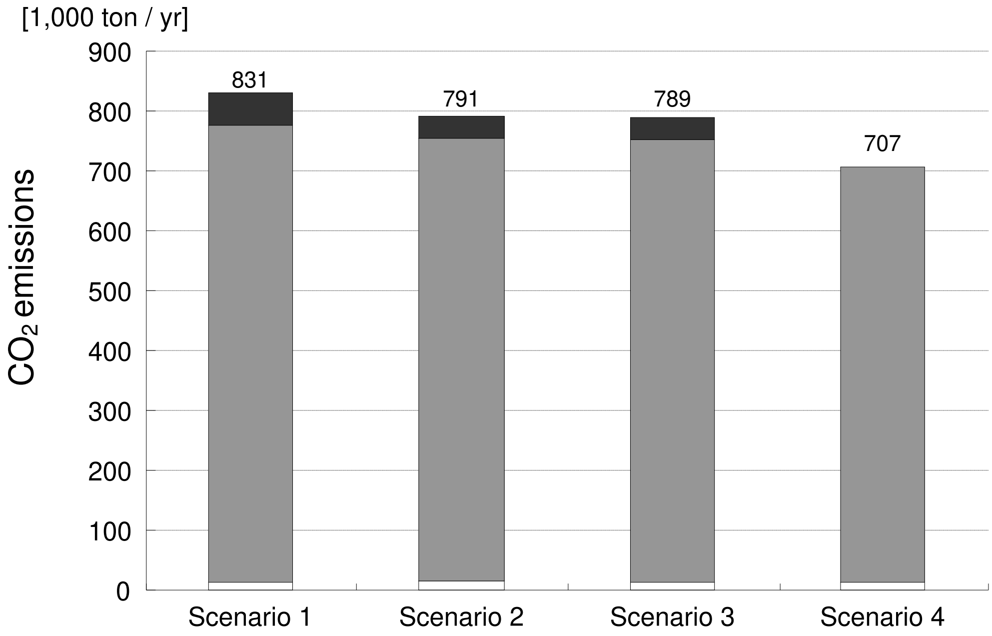


Fig. 3 Material flow in Portland cement production



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
■ Waste disposal	55	36	36	0
▨ Cement production	762	739	739	693
□ Transportation of AFRs	14	16	14	14

Fig. 4 Breakdown of annual CO_2 emissions for the scenarios [1,000 t/y]

Table 1 Material balances of the alternative cement production scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Input materials for cement production (t/y)	Limestone	976,000	976,000	976,000	976,000
	Clay	263,000	0	0	0
	Clay substitutes	0	249,900	249,900	249,900
	Coal	96,600	87,500	87,500	69,800
	Coal substitute (industrial plastic wastes)	0	6,800	6,800	6,800
	Coal substitute (municipal plastic wastes)	0	0	0	13,200
Disposed wastes (t/y)	Clay substitutes	249,900	0	0	0
	Industrial plastic wastes	6,800	0	0	0
	Municipal plastic wastes	13,200	13,200	13,200	0

Table 2 Emission factors and parameters used in the life cycle assessment

Emission factors and parameters used in the LCA			Reference
α_1	: Daily fuel consumption by 100,000 t tanker	17 [t-fuel/day/ship]	OPRF (2001)
α_2	: Daily fuel consumption by 10,000 t tanker	42 [t-fuel/day/ship]	OPRF (2001)
α_3	: CO_2 emission factor for domestic shipping	0.04 [t-CO_2/t/km]	MLIT (2002)
β	: CO_2 emission factor for Bunker C consumption	2.98 [t-CO_2/ton-fuel]	NIES (online)
γ	: CO_2 emission factor for transportation by 10 t truck	0.078 [t-CO_2/t/km]	BRI (2004)
δ	: CO2 emission factor for electric power consumption	0.000555 [t-CO_2/kWh]	MoE and METI (2008)
v_1	: Average speed of 100,000 t tanker	578 [km/day]	OPRF (2001)
v_2	: Average speed of 10,000 t tanker	489 [km/day]	OPRF (2001)
η	: CO_2 emission factor for gasoline consumption	2.32 [t-CO_2/kl]	MoE (online)
ω_1	: CO_2 emission factor for coal combustion	2.58 [t-CO_2/ton]	MLIT (2002)
ω_2	: CO_2 emission factor for industrial plastic waste combustion	2.567 [t-CO_2/t]	MoE (online)
ω_3	: CO_2 emission factor for MSW plastic waste combustion	2.442 [t-CO_2/t]	MoE (online)
ω_4	: CO_2 emission factor for limestone calcination process	0.44 [t-CO_2/t]	NIES (online)

Table 3 CO_2 emissions for the alternative scenarios by process

Process segmentations		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Transportation process [t/y]	Virgin materials	14,500	14,000	14,000	13,400
	AFRs	0	2,000	100	200
Manufacturing process [t/y]	Calcination	425,900	425,900	425,900	425,900
	Combustion	302,300	278,800	278,800	233,200
	Electric power consumption	34,100	34,100	34,100	34,100
Disposal process [t/y]	Industrial wastes	19,300	0	0	0
	MSWs	35,900	35,900	35,900	200
Total		832,000	790,700	788,900	707,000
Reduction from Scenario 1		0	-41,300	-43,100	-125,000