Possibility of developing low-carbon industries through urban symbiosis in Asian cities

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Abstract

Energy and resource consumption has been expanding quickly with the rapid growth of Asian cities, which has resulted in increased greenhouse gas emission and waste generation. The promotion of low-carbon industries is an urgent global issue that extends to Asia as well. To reduce carbon dioxide emission substantially, industries must not only introduce energy-saving technologies but also use low-carbon raw materials and fuel, such as recyclable wastes and carbon-neutral biomass. This paper presents the concept of a “hybrid industry,” that is, an industry whose processes utilize not only fossil resources but also recycled and renewable resources as much as possible. This study examines the feasibility of hybrid industries through the promotion of urban symbiosis in cities in three Asian countries with different circumstances: Kawasaki in Japan, Ulsan in Korea, and Shenyang in China. Asian cities are in the midst of shifting from dumping wastes to incineration. However, in view of the carbon reduction effect of recycling as well as the cost for recycling and appropriate treatment of wastes, the potential of hybrid industries that use combustible municipal wastes as input should be considered. In this study, the potential for carbon dioxide reduction as well as the costs of promoting hybrid industries are evaluated. The results highlight that promoting hybrid industries generates significant environmental benefits for the three cities, and there are important factors that affect the cost-effectiveness of hybrid industries, including the spatial density of waste generation, composition of wastes, relative labor cost for collection and pre-treatment of wastes compared with construction cost of an incinerator and avoided costs through product and fossil resource substitution, and the willingness of citizens to separate wastes. Finally, key drivers for promoting hybrid industries through urban symbiosis in Asian cities are discussed.

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wastes, energy, and by-products among industrial facilities (Chertow, 2000; Chertow and Lombardi, 2005) and is an effective approach for reducing industrial CO₂ emissions (Tseng, 2011; Tseng and Lin, 2009). As an extension of this concept, "urban symbiosis" (Geng et al., 2010; van Berkel et al., 2009) promotes the use of municipal recyclable wastes in industries and industrial waste heat in cities (Togawa et al., 2014). In this way, the effective use of wastes by industries can result in the reduction of both fossil resource use and the final disposal amount (a co-benefit perspective). Industrial and urban symbiosis has promoted successfully in EU (e.g., Kalundborg in Denmark) and Japan (waste recycling and urban symbiosis) (Jacobsen, 2006; van Berkel et al., 2009), realized significant fossil fuel reduction and CO₂ mitigation, but promoting this strategy to developing Asia countries is a challenge due to various socioeconomic condition.

Come to Japan, municipal solid waste (MSW), especially most of the combustible MSW (e.g., mixed plastics and paper), is incinerated (JEC, 2010). Although many incinerators have electric power generation facilities, their generation efficiencies (gross efficiencies) are limited from several percent to around 20%, which is much less than the generation efficiencies of electric thermal power plants (around 40% in a coal-fired power plant and around 60% in a gas-fired power plant). Therefore, the CO₂ reduction effect of incineration is worrisome from the viewpoint of effective use of wastes. Also, the burden associated with the huge investment for construction and operation has prohibited the use of incinerators in other Asian countries.

Industries, especially material industries, have a furnace and treatment facility for exhaust gas and waste water, although these are insufficient in developing Asia countries (JEC, 2010). Economical and environmentally friendly MSW treatment would be possible by utilizing existing industrial facilities. In addition, the recycling of combustible MSW by using industrial facilities is much more efficient than using purpose-built facilities for waste treatment, such as incinerators and methane fermentation plants (Fujii et al., 2011). Especially when a mixture of different kinds of plastics are used, the CO₂ reduction effect of chemical recycling in the steel, chemical, paper, and cement industries is in the same range or greater than that of mechanical material recycling (Japan Containers and Packaging Recycling Association, 2007).

This study evaluated the feasibility of promoting urban symbiosis in cities of three Asian countries with different circumstances: Kawasaki, Japan; Ulsan, Korea; and Shenyang, China. In Japan, a mature developed country, MSW treatment has been largely dependent on incineration. Due to the population decline (because of the falling birth rate) and aging incinerators, a major shift in the recycling and waste treatment policy may be required. As a pilot for an Eco-Town project, several environmental evaluations have been done for the urban symbiosis of Kawasaki, focusing on recycling activities (Berkel et al., 2009; Geng et al., 2010; Hashimoto et al., 2010). In Korea, another mature developed country, the rate of incineration is low and, as a result, recycling and landfill are the dominant means of MSW treatment. Urban symbiosis may help to increase recycling and decrease landfill in an economical manner. Recent studies of Ulsan mainly focused on the symbiotic network in industrial parks (e.g., heat network) (Behera et al., 2012; Park et al., 2008), whereas little research on urban symbiosis has been conducted. Finally, China is a country with a rapidly growing economy. In 2010, it was the world’s top CO₂ emitter from fossil fuel combustion and some industrial processes (Carbon Dioxide Information Analysis Center, 2010). In a country’s dominant method of MSW treatment is landfill, but local governments have plans to install incinerators. However, in view of the cost performance, urban symbiosis may be more attractive than expensive incinerators. To date, apart from a Life cycle assessment (LCA) on plastic recycling (Chen et al., 2011), no studies on urban symbiosis in Shenyang have been done.

Few studies have conducted cost–benefit analyses of hybrid industries and comparative analyses of urban symbiosis in multiple cases. Japan, Korea, and China have different economic conditions, ranging from developed to developing countries, and as a result, their environmental management strategies also differ. Performing a comparative study will provide critical insights into their promotion of regional eco-industrial development and shed light on other Asian countries.

The remainder of the paper is structured as follows: Section 2 presents the features of hybrid industry, which holds great potential to support low-carbon industry, and the related key supporting technologies; Section 3 describes the methodology; Section 4 reviews the current status of waste disposal and potential of hybrid industry implementation in Japan, Korea, and China; Section 5 analyzes the feasibility of promoting hybrid industry, with a discussion of the incineration strategy, as well as a cost–benefit analysis; and finally, Section 6 presents conclusions and future concerns. The results of our analyses will be critical for industrial planning policy in the three countries and shed light on their low-carbon transformation.

2. Promotion of low-carbon industries

2.1. Hybrid industries: a system for transitioning to low-carbon industries

In Japan, high standards for energy conservation measures have been introduced, but the energy efficiencies to produce a unit weight of steel, cement, and paper have not been improved in recent years. In 2010, the comparable energy consumption index required to produce 1 t of steel in Japan, Korea, and China were 100 (energy consumption per unit ton of steel in Japan set as “100”), 104, and 117, respectively, whereas the energy saving potentials in the cement industry if best available technologies were introduced were 0.4, 1.3, and 0.9 GJ/t in Japan, Korea, and China and those in the paper industry were 0.3 GJ/t in Japan and 3.0 GJ/t in the world (Keidanren, 2013). Thus, significant carbon reduction only by saving energy is difficult in Japan, and the same can be said of other countries after installing best available technologies. Therefore, it is essential to promote the use of low-carbon raw materials and fuel.

A hybrid industry is an industry whose processes use not only fossil resources but also recycled and renewable resources to the highest extent possible. For example, the cement industry has been accepting a large amount of wastes and renewable resources, such as incineration ash (used as kiln matrix to substitute raw materials such as clay, shale, and limestone), waste tires, waste plastics, wood (which has significant calorific value and is used as a substitute for fossil fuel in cement kilns), and slag (used with cinder to produce cement). However, there is much room to expand the use of combustible MSW in industries, both in cities as waste generators and industries as potential waste users. Fig. 1 illustrates the differences and linkages between the current system, a hybrid industry, and an ideal future low-carbon industry. Accepting MSW from cities means that industries also serve the function of waste treatment. Thus, a hybrid industry has multiple functions: not only the original function to manufacture a product, but it also has additional functions such as waste treatment and supplying energy for surrounding residential areas. Compared with separate industrial processes and waste incineration (the current trend in many Asian countries), the promotion of hybrid industries (combined with urban symbiosis, in which municipal waste can be utilized as a resource in industries) can be a system innovation to improve the resource and energy efficiency of the whole system, thereby
reducing the fossil fuel input. The future ideal system is expected to utilize more renewable resources (e.g., biomass) and make the best use of resources from waste, so as to minimize the fossil resource input. Such an economical system will likely be encouraged to spread. Therefore, hybrid and multi-functional industries are expected to be a transitional system that will promote low-carbon industries in the future.

2.2. Available technologies for the promotion of hybrid industries

In Japan, chemical recycling technologies (i.e., feedstock recycling of waste plastics) have been developed along with enforcement of the Law for the Promotion of Sorted Collection and Recycling of Containers and Packaging (often referred to as the Containers and Packaging Recycling Law), which was enacted in 1997 (Plastic Waste Management Institute, 2013). In the cement and paper industries, solid recycled fuel—so-called refuse paper and plastic fuel (RPF), which is composed of mixed paper and plastics that are difficult for material recycling in terms of quality—has been used as a means of energy recovery. To expand the use of mixed paper to chemical recycling, more technological development is required; in practice, however, a small amount of paper is recycled by chemical recycling processes as an impurity of waste plastic.

Examples of chemical recycling technologies include blast furnace feedstock recycling, coke oven chemical feedstock recycling, gasification, and liquefaction, and they can help to reduce CO₂ emission from the steel and chemical industries (Plastic Waste Management Institute, 2013). In every chemical recycling technology, waste plastic is fed into a furnace after light pre-treatments, such as removal of foreign matter, shredding, and molding. In a blast furnace, plastic materials act as a reducing agent for iron ore reduction and help to decrease the consumption of coke or pulverized coal. In a coke oven, plastic is converted into 40% oil, 40% gas, and 20% coke through the pyrolysis reaction. The resulting oil is used as chemical feedstock, such that the coke oven serves the role of pre-treatment in preparation for further reactions to produce various chemical products. The gas is used in the factory as fuel for steel production processes, and part of it is fed to a combined cycle gas-fired power plant. Therefore, a part of the recycling process functions as an integrated gasification combined cycle of waste plastic to produce electricity with high efficiency. In the gasification process and liquefaction process, an additional furnace is required for pyrolysis, but the resulting intermediate materials can be used in existing reactors in common with those made from virgin fossil resources. In this way, the pre-treatment function of chemical recycling technologies will help to expand the application of wastes and enhance the efficiency of recycling.

For energy recovery, chlorine content must be restricted in order to prevent the corrosion of furnace or boiler tubes and avoid the loss of quality in some products. Although polyvinyl chloride, which is the main source of chloride, can be removed by an optical sorter (Japan Containers and Packaging Recycling Association, 2014), increasing the mixing rate of paper can help to dilute chlorine in recycled fuel. A cement kiln has a chlorine bypass system to remove chlorine from the kiln.

The use of mixed plastics and paper from MSW in industries results in a decrease of the lower heating value of the rest of the combustible MSW, making it difficult to incinerate. To cope with this problem, a combination of incineration and methane fermentation is effective because the latter can recover energy as methane gas from kitchen wastes, which contain considerable moisture.

2.3. Efficiency of hybrid industries

Wastes must be treated appropriately, but at the same time they contain valuable resources. Therefore, the recycling method should be highly efficient. To judge the quality of a recycling method, comparison with the theoretical maximum efficiency of recycling (Fujii et al., 2011) would be helpful. Here the recycling efficiency is defined as the fuel reduction per unit of waste recycling. Accordingly, the maximum efficiency in terms of energy efficiency is achieved when 1 kg of waste can substitute for 1 kg of the virgin form of the same material with no additional energy input. Fig. 2 reveals the utilization efficiency of the cases, such as the gasification of plastic containers, blast furnace reducing agent, chemical materials recycled from coke oven, and raw fuels recycled from cement (energy recovery in a cement kiln uses those plastics and paper), as well as the efficiency of waste power generation by incinerators. The efficiencies are compared with the theoretical
maximum efficiency. It is noted that in the figure all of the efficiencies are converted into power generation efficiency equivalent (Fujii et al., 2011).

Although the actual efficiency of recycling by utilizing the industrial facilities is lower than the theoretical maximum efficiency, in the case of cement and steel which possesses a large share, it has achieved a high utilization efficiency by about 30–40%. This is absolutely higher comparing to the waste incineration power generation, of which the average efficiency in Japan is around 11%. Thus, in terms of utilization efficiency, industrial facilities are concluded to have a sufficient capacity. On the other hand, since the recycling in industries is intended to use the energy of the recyclables as a fuel in place of fossil resources, it cannot save the energy for production of materials which can be saved by material recycling. As a result, the efficiency of recycling in industries is lower than the theoretical maximum efficiency. However, because plastic containers and packaging are a mixture of various kinds of plastics and even contain foreign matter such as paper, laminated aluminum, and food, it is difficult to achieve efficiency close to the maximum value. In consideration of this, hybrid industries (recycling in industry) are considered to have sufficiently high efficiencies. In particular, they are much better than the average efficiencies of waste power generation by incinerators in Japan and better or comparable with that of the most-advanced incinerator.

3. Methodology

This section briefly describes the analytical methodology of this study. In this paper a previously developed model (Fujii et al., 2012) was applied to several Asian cities to contribute to model generalization, using updated parameters.

Unit CO2 emission \((E, \text{t-CO}_2/\text{t})\) in hybrid industry scenario is calculated based on the waste collection process \((E_1, E_2, \text{and } C_1)\), the activity of a pre-treatment plant (recycling center) to produce recycled fuel \((E_3 \text{ and } C_2)\), substitution of fossil fuel in industrial process \((E_3 \text{ and } C_3)\), transport of waste to industries \((E_4 \text{ and } C_4)\) and a part of waste to incinerator \((E_5 \text{ and } C_5)\). Eq. (1) shows the equation. For the Unit cost \((C, \text{USD/t})\) calculation, it is in similar procedure (Eq. (2)).

Detail information of the system and function of SRC is presented in (Fujii et al., 2012). In such an integrated waste management system, waste is collected first, then waste has two recycling routes: (1) it is incinerated; (2) used for industrial process. For the former, we only consider the incineration process with power generation, for the later, parameters related to various area served by the recycling center are simulated (served areas will affect the scale of recycling center).

\[
E = E_1 + E_2 + E_3 + E_4 + E_5
\]

\[
C = C_1 + C_2 + C_3 + C_4 + C_5
\]

For the waste collection process, the collection distance, corresponding fuel consumption, labor cost (working hours and salary), and number of trucks are key factors. Based on this, unit emission and cost can be calculated. In this paper, they are estimated by using the Grid City Model (Fujii et al., 2006; Ishikawa, 1996) under conditions of different population densities and areas served by recycling centers in three cities.

For the pre-treatment plant, according to the regional diagnosis on the waste generation, population density and so on, several various scales recycling centers are set, and related parameters are set and calculated accordingly based on regional condition in three cities (e.g. electricity/fuel consumption, cost and related emissions). With the sample data of specific scales’ recycling centers, regression is made to simulate the relationship of CO2 emissions and cost with area served by recycling center. With Eqs. (3) and (4), recycling center related unit emission and cost can be gained.

Unit CO2 emissions under different waste recycling scenarios (e.g., different collection area, waste amount) is simulated by using equation (3):

\[
Y_{CO2} = a \times X^b,
\]

where \(Y_{CO2}\) is the unit CO2 emissions (kg-CO2/kg); \(X\) represents the scale of facilities (waste treatment amount) (t/day); and \(a \text{ and } b\) are correction factors (obtained through regression of the process data).

Similarly, unit cost under different waste recycling scenarios is simulated by using equation (4):

\[
Y_{cost} = c \times X^d,
\]

where \(Y_{cost}\) is the unit cost (JPY/kg); \(X\) represents the scale of facilities (t/day); and \(c \text{ and } d\) are correction factors (obtained through regression of the process data). The values of \(a \text{ to } d\) for the three cities are summarized in Table 1.

For the parameters related to substitution in industrial process, transport and incinerator, as well as other key parameters related to hybrid industries, are summarized in Table 2. With above, the difference of unit CO2 emission and cost between hybrid industries scenario and traditional mixed collection can be calculated.

### Table 1

<table>
<thead>
<tr>
<th>Parameters for process unit CO2 emission and cost calculation.</th>
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<tr>
<td>Parameters</td>
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<tr>
<td>Unit process CO2 emission</td>
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<tr>
<td>(a)</td>
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<td>(b)</td>
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<td>Unit process cost</td>
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<td>(c)</td>
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<td>(d)</td>
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4. Current status of waste disposal and potential for hybrid industries in the three countries

4.1. Waste disposal

4.1.1. Japan

Understanding the current status of MSW generation from cities and disposal conditions is important for examining the feasibility of hybrid industries through urban symbiosis. Kawasaki City, with a population over 1.4 million, is located between Tokyo and Yokohama and is home to steel, chemical, cement, and paper industries. In 2012, annual MSW generation was 0.37 million t (0.26 t/person/year), and the amount including general wastes from business activities was 0.48 million t (0.34 t/person/year), and the amount including general wastes from business activities was 0.48 million t (0.34 t/person/year) (MOEJ, 2014). Recycling has been actively implemented, but 79% of MSW is still burned in incinerators, although they have power generation systems. Among the wastes that go to incinerators, those with high quality in terms of heat value and lack of corrosive contaminants can be used for hybrid industries.

In Japan, several recycling laws have been enacted, including the Container and Packaging Recycling Law, Home Appliance Recycling Law, and End-of-Life Vehicle Recycling Law. These have helped to enhance separate collection of wastes generated in cities and promoted the use of waste plastics and paper as industrial inputs. However, only about 10% of waste plastics and mixed paper is collected separately from other combustible MSW, with the majority being incinerated (Fujii et al., 2012). As a result, it is difficult to reduce the number of incinerators and associated cost for construction and operation while maintaining an equivalent capacity for waste treatment. Thus, the main challenges for realizing hybrid industries in Japan are achieving a substantial increase in the use of MSW as an input for industries and decreasing the number of incinerators to reduce the cost.

4.1.2. Korea

Ulsan City has more than 1.1 million residents and a large industrial sector composed of chemical industry, paper industry, and automotive industry. The annual MSW generation was 0.43 million t (0.38 t/person/year) in 2011 (Ulsan City, 2013). The incineration rate of MSW was around 16% in 2005 (JEC, 2010). Although Korea has not succeeded in reducing waste volume, the percentage of total waste volume recycled has increased significantly. In 1999 51.6% of MSW was landfilled and 38.2% was recycled, whereas in 2012 15.8% was landfilled and 59.1% was recycled (MOEK, 2013). However, film-based packaging materials are not being separated when disposed of because of the insufficient recycling capacity of several local governments (CSD, 2009). The Korean government adopted the “Measures Concerning Waste Resource and Biomass Energy” in 2008. To maximize the waste-to-energy effect, the Korean government is planning to expand and centralize waste-to-energy facilities and to create an environmental energy town in every district (CSD, 2009). For such a purpose, the hybrid industry system would partly contribute to maximize the energy efficiency.

4.1.3. China

In China, there are many large cities whose population exceeds 5 million. Among them, Shenyang City has more than 7 million residents and has a sister city relationship with Kawasaki City, Japan. These two cities cooperate in the areas of environment and waste management. Annual MSW generation in Shenyang was 1.9 million t (0.24 t/person/year) in 2009 (NBS, 2010). Combustible MSW has been disposed of at landfill sites, but the city government has a plan to build incinerators. Although polyethylene terephthalate bottles and some other plastics and paper with high quality that are easily recycled by mechanical recycling are collected separately, the separation of wastes at generation sites is generally unfamiliar to residents. A part of the resulting unseparated MSW could be used in industries. However, compared to the wastes in Japan and Korea, the MSW in Shenyang contains more kitchen waste and less paper (Table 3). As a result, the percentage of MSW that can be used in industries will be smaller than in Kawasaki City and Ulsan City. The MSW in Beijing contains less kitchen wastes and more paper compared with Shenyang, but the fraction that could be used in industries is still smaller than those in Japan and Korea.

4.2. Potential use of MSW in industries

4.2.1. Japan

As noted in Section 2.2, recycling of some combustible MSW in industries, especially the material industries, is in practical use in Japan. However, industries cannot procure enough wastes for their capacity. Japan Iron and Steel Federation set a voluntary action plan to utilize 1 million t of waste plastics annually in their steel production process; however, in fact, the use of plastic has been limited to around 0.4 million t (Japan Iron and Steel Federation, 2013). In the paper industry, recycled fuel from wastes accounted for 9% of

<table>
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<th>Table 2</th>
<th>Key parameters in the three case cities.</th>
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<tr>
<td>Unit Kawasaki</td>
<td>Ulsan (three districts)</td>
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<tr>
<td>Approximate population density</td>
<td>persons/km²</td>
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<tr>
<td>Area</td>
<td>km²</td>
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<tr>
<td>Waste generation</td>
<td>kg/person/y</td>
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<tr>
<td>Collection rate for industrial use within plastic and paper</td>
<td>%</td>
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<tr>
<td>Labor cost for waste collection</td>
<td>JPY/person/d</td>
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<tr>
<td>Labor cost for pre-treatment</td>
<td>JPY/person/d</td>
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<tr>
<td>Relative construction cost*</td>
<td>%</td>
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<tr>
<td>Transportation cost†</td>
<td>USD/t</td>
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<tr>
<td>Recycled fuel production</td>
<td>kg/person/y</td>
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<td>Coal substitution by recycled fuel</td>
<td>kg/person/y</td>
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<td>Incineration</td>
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<tr>
<td>Electricity consume</td>
<td>kWh/kg</td>
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<tr>
<td>CO₂ emission/kWh</td>
<td>kg-CO₂/kWh</td>
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<tr>
<td>Incineration amount</td>
<td>kg/person/y</td>
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<tr>
<td>CO₂ emission from power consume</td>
<td>kg-CO₂/kg</td>
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<tr>
<td>Cost</td>
<td>JPY/kg</td>
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<tr>
<td>Transport CO₂ emission</td>
<td>kg-CO₂/t/km</td>
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* Relative construction costs were set considering the difference of construction costs for incinerators in each country (Aoyama, 2004).
† Transportation costs were set considering trucking costs and proximity between residential area and industries.
total fuel consumption (Japan Paper Association, 2013); because fossil fuels accounted for around 50% of total energy consumption (i.e., 9 million coal equivalent t/year), there is room to replace more. Across the entire industrial sector in Japan, there is also high potential to utilize recyclable waste. Coal, which can be easily replaced by wastes, accounted for 120 million t, but the amount of plastic and mixed paper in MSW was only 9 million coal equivalent t (Fujii et al., 2011). Therefore much more combustible MSW can be used in industries. In addition, if it is used widely, combustible MSW can be used at low concentrations mixed with a large amount of fossil resources to minimize any negative influence on the facilities and products that may be caused by impurities in recycled material and fuel (IEC and Geo Partner AG, 2007). In Kawasaki City, the presence of several material industries within the city is an advantage in terms of the transportation of recycled raw material and fuel. Many other large cities in Japan are also located close (e.g., less than 50 km) to candidate factories. Because the capability to supply materials from cities to industries is limited, it will be essential to expand the target material from MSW to industrial wastes and biomass as well.

The Japanese government has promoted the Eco-Town projects since 1997. Eco-Town projects aim to promote a zero-emission society at local and national levels, focusing on establishing new environmental cities/towns and implementing advanced resource and waste recycling technologies (METI, 2007). In total, 26 areas including Kawasaki City and Kitakyushu City were approved. In some areas, however, factory operation is infrequent due to the decrease of waste supply or demand for recycled products. To improve this situation, the Ministry of the Environment started a project in 2010 to advance Eco-Towns, and some of the authors of this paper were committee members for the project. In the new project, several model projects aimed at creating efficient procurement of MSW and expansion of the application of MSW were conducted in Eco-Towns in Kawasaki, Kitakyushu, Hokkaido, Akita, and Osaka. For example, in Kawasaki Eco-Town, a demonstration experiment designed to increase both procurement volumes to RPF and demand for the RPF was conducted. These projects also help to promote hybrid industries.

4.2.2. Korea

In 2005, Korea initiated a 15-year, three-phase eco-industrial park (EIP) project and a total of eight demonstration regions were selected. Ulsan City was selected as one of the regions, and the Ulsan EIP center has played a pivotal role in the implementation of symbiosis in the national industrial complex. In the designed symbiosis networks, an economic benefit of 68.52 million USD/year and environmental benefits in terms of emission reductions of 227,363 t/year of CO2, and 3682 t/year of other air pollutants (SOx, NOx, and CO) were achieved (Behera et al., 2012).

Within the symbiotic networks in Ulsan, for example, a waste incinerator supplies steam to a petrochemical company. Compared to the generation of electricity with low efficiency in an incinerator, providing steam to industries that was originally combusting fossil fuels can result in a much greater CO2 reduction. Incinerators can burn miscellaneous wastes that have low heating values, including kitchen waste. Therefore, the steam supply can help to broaden the utilizable wastes for hybrid industries, although the temperature of steam produced in an incinerator must not exceed about 400 °C to prevent the corrosion of tube walls in the boiler. In this case, construction of an incinerator is unavoidable, but the generator can be reduced or omitted in the incinerator.

Thus, to promote hybrid industries, a filtering function to purify wastes is necessary to make the wastes an acceptable form for industries (Fig. 3). Roughly speaking, there are two patterns for the filtering function: the separation and pre-treatment of waste (filtering function A) and the conversion of wastes to cleaner forms of energy (filtering function B). Because both patterns have advantages and disadvantages, either one can be used depending on the situation.

4.2.3. China

China is now the world’s top industrial country. For instance, in 2013 China produced 48.5% of the world’s crude steel (World Steel Association, 2014) and 57.5% of the cement (U.S. Geological Survey, 2014). China’s industrial sectors account for more than 60% of final energy use (NBS, 2013) and more than 80% of China’s total CO2 emission in recent years (Chen, 2010). Therefore, in order to significantly reduce global CO2 emission, carbon reduction from Chinese industries is absolutely critical. In China, industrial and urban symbiosis is promoted under the national strategy of circular economy and mainly in the form of EIPS. By 2010, 60 industrial parks had been selected as national pilot EIPS (Zhang et al., 2010). In the waste management area, regulating and expanding the waste trade market and building a venous industrial park should increase the productivity and economic benefit of the resource recovery industry (Su et al., 2013).

In China, the percentage of coal (in solid form) consumption is around 70% of the national energy consumption mix (NBS, 2013), which is higher than those of Japan and Korea, so there are greater opportunities to utilize solid recycled raw material and fuel.

Compared with developed countries, China’s MSW management is still at its early stage. At present in China, more than 80% of the MSW is treated as landfill, followed by composting (Zhang et al., 2010). Little MSW is reused in industries. However, with the promotion of a circular economic strategy and EIP projects, there is great potential for China’s industries to utilize MSW. In China’s 12th five-year plan (2011–2015) on national circular economic development, resource utilization of MSW is one key aspect (Ministry of
One important advantage for China to promote the utilization of MSW in industries is the large-scale integrated industrial system, particular process industries like iron/steel and cement plants. Their manufacturing process (with furnaces) provides an ideal place for the co-processing of waste, which has great potential for symbiotic construction (Dong et al., 2013). Large-scale waste plastics, tires, and sludge could be processed in the furnaces of steel and cement plants. In addition, the central government is promoting the construction of large-scale incineration plants for garbage and sludge. According to national planning, by 2015 incineration should account for 35% of the total amount of city garbage treatment (General Office of the State Council, 2012). High costs and potentially toxic emissions can be avoided through the promotion of hybrid industries.

5. Feasibility study of hybrid industries

5.1. Comparison with incineration

The feasibility of developing hybrid industries in Japan, Korea, and China through urban symbiosis using filtering function A (Fig. 3), which will bring greater change in cost than filtering function B with the requirement of incinerators, was examined in terms of economic cost. For the Tama area of the Tokyo metropolitan region, Fujii et al. (2014) analyzed the cost of recycling mixed plastics and paper contained in combustible MSW by utilizing industries in comparison with the case of incineration. Here, that model was modified and applied to three cities, each of which was approximated as a square region with the same area and population size as Kawasaki, Ulsan, and Shenyang, respectively, with uniform population density.

As described in Section 2.2, technologies have been developed to utilize some combustible MSW in industries, although continuous improvement is required, and this research has verified the relatively high efficiency of recycling in industries. One rather important step is the collection and pre-treatment of potential waste in MSW as industrial input in an economically feasible manner. In the study by Fujii et al. (2014), the case corresponding to promotion of hybrid industries in this paper was set to collect mixed plastic and paper and use them as raw material and fuel in industries after processing in a pre-treatment plant (e.g., separation of foreign matter and molding); this case is referred as the hybrid industry scenario. CO2 emission and cost were examined. In this scenario, other combustible MSW such as remaining plastics and paper, kitchen waste, and fibers are collected and burned in incinerators equipped with a power generation system (net generation efficiency, namely, transmission end efficiency is 12%). The number of incinerators (if capacity of an incinerator is constant) is reduced in proportion to the decrease of waste for incineration. The baseline scenario was set to mixed collection of other combustible MSW with mixed plastics and paper and then incineration with power generation (net generation efficiency is 12%), reflecting the fact that incineration is the most common treatment in Japan and is expanding in China. In the Japanese case, the current level of recycling of plastic containers and packaging continues in the baseline scenario. The final disposal of ash in MSW was omitted from the analysis because it is common in both scenarios.

Six parameters significantly affect the economic cost in both scenarios: (1) spatial density of waste generation (higher density leads to higher efficiency of collection); (2) scale of facilities, that is,
the incinerator and pre-treatment plant (greater scale leads to lower unit cost for construction and operation); (3) cost of construction and maintenance (different among countries or cities); (4) labor cost (different among countries or cities); (5) transportation cost of recycled raw material and fuel (different among cities); and (6) price of electricity (in both scenarios) and fossil resources (coal in the hybrid industry scenario) substituted by recycling or energy recovery (prices may change in the future).

In Kawasaki, the population density, which influences the density of waste generation, is around 10,000 persons/km² across the whole city. In Ulsan, 70% of the population lives in three districts (i.e., Dong District, Jung District, and Nam District) and the population density there is around 5000 persons/km². However, that in Shenyang is around 25,000 persons/km² in the central five districts where more than half of the city’s population lives. Although the price of electricity and fossil resources may be different due to taxes or subsidies and national or local policies, the price (excluding transport cost) is expected to converge with an international standard price. On the other hand, labor cost differs significantly among countries and cities and, as a result, the construction cost also varies widely. The monthly labor cost in Kawasaki was set as 3900 USD, that in Ulsan as 1900 USD, and that in Shenyang as 300 USD according to a previous investigation (Japan External Trade Organization, 2012). Although such a great difference will significantly influence the cost of recycling and disposal of wastes, the labor cost in developing countries shows a rising trend as economies expand. Important parameters are summarized in Section 3.

Fig. 4 illustrates the difference in unit CO₂ emission per 1 t of combustible MSW between the two scenarios in Kawasaki, Ulsan, and Shenyang. A negative value represents CO₂ emission including the avoided CO₂ release through the substitution of electricity and the use of less coal in the hybrid industry scenario. Because the spatial scale of recycling and the density of waste generation greatly affect the performance of recycling and waste treatment, the figure shows the estimation under a variety of those conditions, namely, the horizontal axis (the same for following Figs. 5–10) shows the area (km²) served by recycling center and three curves for the different population densities are shown. The various area will affect the recycling waste distance, scale of recycling center and corresponding parameters, like fuel consumption. They were estimated under conditions of different population densities and areas served by recycling centers. It is noted that, there are sorted collection of wastes from waste generation sites to the recycling center and transportation of recycled fuel from the recycling center to industries. The “area” is related only to the recycling center. If the...
In section 5.1, hybrid industries were compared with waste power generation by incinerators. In Asian countries, however, landfill is still the dominant waste disposal method. Therefore, this paper tests the economic feasibility of hybrid industries by comparing the cost for collection and pre-treatment of a part of the combustible MSW and the price of coal substituted in industries. As shown in Fig. 8, the cost for collection and pre-treatment exceeds the value of coal in a city like Kawasaki because both the labor cost and fuel substituted for coal as primary energy. Likewise, processed products have more added value than the values of raw material and fuel. Because electricity is secondary energy, electricity has a higher price than the recycled raw material and fuel substituted for coal as primary energy. In reality, however, the production of electricity by an incinerator leads to profit decline of the local electric company. When the cost analysis of recycling and waste treatment is done within the boundaries of the municipality and recycling company, sometimes the scenario that produces a product with a higher degree of processing is estimated to have an economic advantage. However, this does not reflect the cost balance of the entire society; rather, the calculation only considers the recycling promoter’s point of view. Such a calculation condition may underestimate the merit of hybrid industries that utilize wastes through a simple filtering function.

### 5.2. Cost–benefit analysis of hybrid industries

In section 5.1, hybrid industries were compared with waste power generation by incinerators. In Asian countries, however, landfill is still the dominant waste disposal method. Therefore, this paper tests the economic feasibility of hybrid industries by comparing the cost for collection and pre-treatment of a part of the combustible MSW and the price of coal substituted in industries. As shown in Fig. 8, the cost for collection and pre-treatment exceeds the value of coal in a city like Kawasaki because both the labor cost and construction cost for a pre-treatment facility are expensive in Japan. These findings highlight that if the collection and pre-treatment are done in a densely populated area with an appropriate scale, the cost difference is about 30%. Such a relative
difference may change if the price of fossil resources rises in the future.

In a city like Ulsan (Fig. 9), the cost is comparable with the benefit. Alternatives to reduce GHG emissions tend to be expensive. Therefore, the result around the break-even point can be attractive to the stakeholders such as governments and companies who are responsible for the reduction of carbon emissions.

In a city like Shenyang (Fig. 10), the cost structure is substantially different because the current labor cost and construction cost are much lower in China than in Japan. Substitution of coal through the promotion of hybrid industries, which has a large CO₂ reduction effect but small added value, still has a great cost advantage in China, although this situation may change if labor and construction costs increase in the future.

6. Conclusion and discussion

Here our established recycling model was generalized to analyze the cost and benefit of hybrid industry promotion in three Asian cities: Kawasaki, Japan; Ulsan, Korea; and Shenyang, China.

The potential for CO₂ reduction as well as the costs and benefits of promoting hybrid industries were evaluated. Our results highlight that promoting hybrid industries generates significant environmental benefits for the three cities, and there are important factors that affect the cost-effectiveness of hybrid industries, including the spatial density of waste generation, composition of wastes, relative labor cost, avoided costs through product and fossil resource substitution, and the willingness of citizens to separate wastes.

Regards to an in-depth discussion on cost-benefits and related parameters, this research presents characteristics and disparity for three Asian cities. All three cities are densely populated and located with heavy industries, which means the additional cost of sorted collection and pre-treatment to produce recycled raw material and fuel is relatively low, therefore recycling utilizing existing industrial facilities, which leads to the reduction of incinerators, can have an economic benefit. Compared with cases in Japan and Korea, rapidly developing China generates larger amount waste and with lower labor cost, thus properly utilize hybrid industries is able to make higher benefit with advanced technology transformation. What is more, investigation on mutual interaction of cost-benefit and factors like labor cost, spatial density and location, provide insights to future optimal recycling route and facilities location to minimize the cost. Finally, waste composition difference will cause uncertainty when consider technology transformation. For example, due to food culture, Chinese food waste usually have lower calorific value, leading to possible extra technology cost. Therefore, local oriented feasibility analysis is necessary and this study can shed a light for this point.

Our analysis provided critical insights for future policy making and implementation. In Japan, incinerators are getting older, while tighter budgets of local governments are expected for waste management due to the increase in social welfare expenses as the population ages and the birth rate declines. As a result, a major revision of the waste management plan is required, including the elimination and consolidation of inefficient incinerators. Hybrid industry, in which recycling and waste treatment utilize existing industrial facilities, has the potential to be an economically attractive solution, especially in large cities and surrounding regions near industrial complexes. In spite of the difficulty of achieving further energy savings, industries must reduce fossil fuel consumption in preparation for possible price increase of fossil resources and the introduction of caps or penalties for CO₂ emissions. Under such difficult conditions, fossil resource substitution and resulting CO₂ reduction through the promotion of hybrid industries can be favorable.

In Korea, the construction of incinerators has been difficult due to the objections of residents, and recycling has been prompted as an alternative means of waste treatment. Because urban citizens are supportive of waste separation, Korea has grounds to promote hybrid industries. However, the use of filtering function B is not easy. Therefore, it may be better to improve technologies for effective waste separation and advance the social system to increase the collection volume of target wastes in order to strengthen filtering function A.

In China, organized waste separation and sorted collection, which is an important part of filtering function A for the promotion of hybrid industries, is not common. Filtering function B does not require source separation of wastes, but investment in the construction and operation of incinerators is required. To reduce the investment in incinerators, it is important to raise awareness among residents about waste separation through environmental education and other such activities.

The development of hybrid industries through urban symbiosis also represents an attempt to optimize the use of existing industrial facilities while seeking greater efficiency of recycling. Such activities will help to build a robust recycling and waste treatment system in the face of changing external factors (e.g., population, economic situation, and technological innovation) through the restriction of redundant facility investment (Fujii et al., 2014). Therefore, hybrid industry may be a CO₂ reduction system that can be adapted to Asian countries under different situations, including Japan, which is in an active phase of population decline; Korea, whose population is projected to decrease (Matsue, 2012); and China and other countries, which are expanding their material consumption.

Finally, this study had several limitations. First, it will be important to investigate the sensitivity of the variation in the waste composition and waste properties. In addition, feasibility studies should be conducted on the transformation of waste to products, and dynamic modeling of changes in the supply–demand chain with the variation in waste composition is needed. Such future research will help to further improve the utilization efficiency of recycled resources.

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References


