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The potential environmental gains from recycling waste plastics: Simulation of transferring recycling and recovery technologies to Shenyang, China

Xudong Chen [a,b,c,*], Fengming Xi [a], Yong Geng [a,1], Tsuyoshi Fujita [b,c]

[a] Institute of Applied Ecology, Chinese Academy of Sciences, No. 72 Wenhua Road, Shenyang 110016, PR China
[b] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[c] Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya City 464-8601, Japan

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ABSTRACT

With the increasing attention on developing a low-carbon economy, it is necessary to seek appropriate ways on reducing greenhouse gas (GHG) emissions through innovative municipal solid waste management (MSWM), such as urban symbiosis. However, quantitative assessments on the environmental benefits of urban symbiosis, especially in developing countries, are limited because only a limited number of planned synergistic activities have been successful and it is difficult to acquire detailed inventory data from private companies. This paper modifies and applies a two-step simulation system and used it to assess the potential environmental benefits, including the reduction of GHG emissions and saving of fossil fuels, by employing various Japanese plastics recycling/energy-recovery technologies in Shenyang, China. The results showed that among various recycling/energy-recovery technologies, the mechanical waste plastics recycling technology, which produces concrete formwork boards (NF boards), has the greatest potential in terms of reducing GHG emissions (1.66 kg CO_2e/kg plastics), whereas the technology for the production of refuse plastic fuel (RPF) has the greatest potential on saving fossil fuel consumption (0.77 kgce/kg-plastics). Additional benefits can be gained by applying combined technologies that cascade the utilization of waste plastics. Moreover, the development of clean energy in conjunction with the promotion of new waste plastics recycling programs could contribute to additional reductions in GHG emissions and fossil fuel consumption.

1. Introduction

In the past decade, global warming attracted increasing attention internationally. Whereas European countries and Japan are playing their leading roles in mitigating global warming, the newly industrialized countries, especially those that have large populations and rapid economic growth, such as China and India, need to be involved in international actions to mitigate global warming. In the 2009 United Nations Climate Change Conference, held in Copenhagen, Denmark, China pledged to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40–45 percent compared with the level of 2005, and to increase the proportion of non-fossil fuels in its primary energy consumption to approximately 15% by 2020 (Xinhua News Agency, 2009).

With the increasing attention on developing a low-carbon economy, it is necessary to seek appropriate ways on reducing greenhouse gas (GHG) emissions through innovative municipal solid waste management (MSWM), such as urban symbiosis. Attempts have been made to identify environmentally sound methods and technologies for municipal solid waste management (MSWM) (e.g., Feo and Malvano, 2009; Geng et al., 2007; Hellweg et al., 2005; Horio et al., 2009; Khoo, 2009; Manfredi and Christensen, 2009; Moberg et al., 2005; Schmidt et al., 2007; Wong et al., 2008; Zhao et al., 2009). In addition to the conventional methods for MSWM, novel approaches on the use of byproducts (waste) from cities (or urban areas) as alternative raw materials or energy sources for industrial operations, known as urban symbiosis, have been shown to be a robust model in Japanese eco-towns (Geng et al., 2010; Hashimoto et al., 2010; van Berkel et al., 2009a,b). The eco-town program has demonstrated that environmental protection and economic revitalization can be compatible with each other. It was originally designed to both stimulate the development of new industries and solve problems of waste management, rather than to reduce emissions of GHG (van Berkel et al., 2009b). However, the low-carbon effect is concomitant with these synergistic activities. According to the results of a recent survey

* Corresponding author at: National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan. Tel.: +81 29 850 2809; fax: +81 29 850 2584.

E-mail addresses: chen.xudong@nies.go.jp (X. Chen), gengyong@iae.ac.cn (Y. Geng).

[1] Tel.: +86 24 8397 0371; fax: +86 24 8397 0372.

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conducted by the Ministry of Environment of Japan (MOE, 2009), 93 (of 170) projects in Japanese eco-towns recycled and recovered 2010 kt of wastes in 2007 (92% of the total waste input), eliminating the need to landfill 1022 kt of waste, and reducing greenhouse gas emissions by an equivalent of 424 kt of CO_2 (CO_2e) compared with the conventional production relying only on virgin materials. Similar environmental benefits have also been achieved in the other cases of industrial and urban symbioses (Chertow and Lombardi, 2005; Eckelman and Chertow, 2009; Jacobsen, 2006; van Berkel et al., 2009a). However, few quantitative assessments have been made of the environmental benefits of industrial and urban symbiosis, especially in developing countries, because only a limited number of planned synergistic activities are being undertaken, and it is difficult to acquire detailed inventory data from private companies.

In developing countries, such as China, data on the MSWM are usually inadequate and even fewer quantitative assessments have been made on potential industrial and urban symbioses than in developed countries. Yet, the demand for more efficient MSWM systems is particularly intense in China, as the country is the world's largest generator of MSW and is undergoing rapid urbanization with a continuous increase in the amount of MSW generated (Chen et al., 2010). Moreover, inappropriate management of wastes and informal recycling activities are not rare, causing severe pollution incidents of pollution and risks to public health (Mo et al., 2009). Meanwhile, China also has a considerable potential for waste recycling and recovery. In economic terms, the World Bank estimated that a US $600 million market exists for MSWM in China (The World Bank, 2005). This market could be even larger if innovative recycling technologies that could yield more added value than do conventional waste treatment technologies were adopted. Industrial and urban symbiosis, or generally eco-industrial development, are appropriate for addressing waste problems in China if the ever-increasing pressures on resources and the environment are taken into consideration (Geng et al., 2007). Consequently, it is crucial to have more studies on identifying the potential environmental gains through recycling various wastes, so that more businesses can engage in such activities.

This paper is one effort towards such a target. It employs a case study approach to quantitatively assess industrial and urban symbiosis in China. Owing to the limited amounts of data available, this paper focused on simulating the potential environmental gains in terms of the potential of GHG emission reduction and fossil fuel saving in the city of Shenyang by the adoption of various Japanese waste plastics recycling/energy-recovery technologies. Waste plastics can be converted through mechanical recycling, chemical recycling, or energy-recovery processes into products that substitute virgin materials such as plastic resins, wood lumbers, and fossil fuels. These recycling approaches are effective in reducing GHG emissions (Al-Salem et al., 2009; Astrup et al., 2009; JCPRA, 2007). Other technologies can be used to convert waste plastics directly into feedstocks for industrial production (JCPRA, 2007). For example, waste plastics can be used as a reductant in blast furnaces for the iron/steel production. The selection of Shenyang for the case study was made because the city is the largest city in northeast China, where a large amount of waste plastics are collected, pretreated, and frequently delivered elsewhere over long distance for recycling.

The framework of this paper is as follows: after the introduction, the second section provides the background information on Shenyang and its current status regarding waste management. The third section elaborates the methodology employed. The fourth section presents our result, and the fifth section elaborates the discussion. Conclusions are drawn in the final section.

2. Background information on Shenyang

Shenyang city is the capital city of Liaoning Province and is located in the central part of northeastern China (41° 11′ 45″–43° 2′ 13″ N, 122° 25′ 9″–123° 48′ 24″ E) (Fig. 1). The total administrative area of Shenyang is 12,980 km^2. The urban area consists of nine districts (Heping, Shenhe, Dadong, Huanggu, Tiexi, Sujiatun, Dongling, Yuhong, and Shenbei), while the rural area consists of four counties (Xinmin, Liaozhong, Faku, and Kangping). In 2009, the population was 7.8 million, and the gross domestic product (GDP) was 436 billion RMB (approximately 63.8 billion US dollars at an exchange rate of 6.83 RMB/US$) (Shenyang Municipal Government, 2010). The Shenyang Sanitation Research Institute reported that about 3 million tons of MSW were generated in Shenyang in 2008, of which 2.13 million tons were generated within the urban area (Sun et al., 2008). The total amount of MSW doubled between 2002 and 2008. Landfill is currently the major method of disposal of MSW. In the urban area, 1.85 million tons of MSW were landfilled in 2008 (Shenyang Statistical Yearbook, 2009). The remainder (0.28 million tons) was recycled, sold to the secondhand market, or dumped illegally. The composition of the landfilled wastes is shown in Fig. 2 (Sun et al., 2008). Taken together, plastics and rubber form the second largest category next to food waste, accounting for 15% of the waste to be landfilled.

According to the *Law of the PR China on the Prevention of Environmental Pollution Caused by Solid Waste*, the local Infrastructure and Construction Bureau (ICB) shall take the responsibilities for the cleaning of waste collection points and collection, storage, transportation, and final disposal of MSW in the city (Chen et al., 2010). In addition to the Shenyang ICB, the Renewable Resource Administration Office, which is part of the Shenyang Supply and Marketing Cooperative Association (SMCA), has administrative responsibility for waste plastics and other recyclable wastes. The SMCA is a governmental division that manages the supply and procurement of commodities in cities in the planned economy regime, and which is now in charge mainly of managing supplies for agricultural production (such as fertilizers and pesticides) and procurements of agricultural products, as well as managing recyclable solid wastes.

Because recyclable wastes have been largely collected by the informal sector in China, data on the total amounts and characteristics of recyclable wastes are difficult to be obtained (Chen et al., 2010). To improve its management of renewable resources, the Shenyang SMCA undertook a comprehensive survey and an on-site investigation on renewable resources in Shenyang in 2009. The investigation (Wang et al., 2009) showed that about two thousand itinerant junk-buyers registered to the Shenyang SMCA for waste collection. In addition, 2116 waste-redemption centers are scattered throughout Shenyang city, and two marketplaces were established for trading waste plastics. One marketplace is a formal one with 42 shops, while the other is informal with over 600 shops. The survey covered 27% of the registered junk-buyers, 94% of the redemption centers, 91% of the shops in the formal marketplace, and over 90% of shops in the informal marketplace (Wang et al., 2009).

The total amount of waste plastics produced in Shenyang in 2008 was 631 kt, of which 621 kt was traded in the two marketplaces and 10 kt was delivered to processors directly from redemption centers and junk-buyers (Fig. 3). About one third of these wastes plastics were polyethylene terephthalate (PET), 5% was polystyrene foam, and the remainder consisted of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and acrylonitrile butadiene styrene resin (ABS), etc. These waste plastics were collected from different sources. Local redemption centers and itinerant junk-buyers who collected plastics from

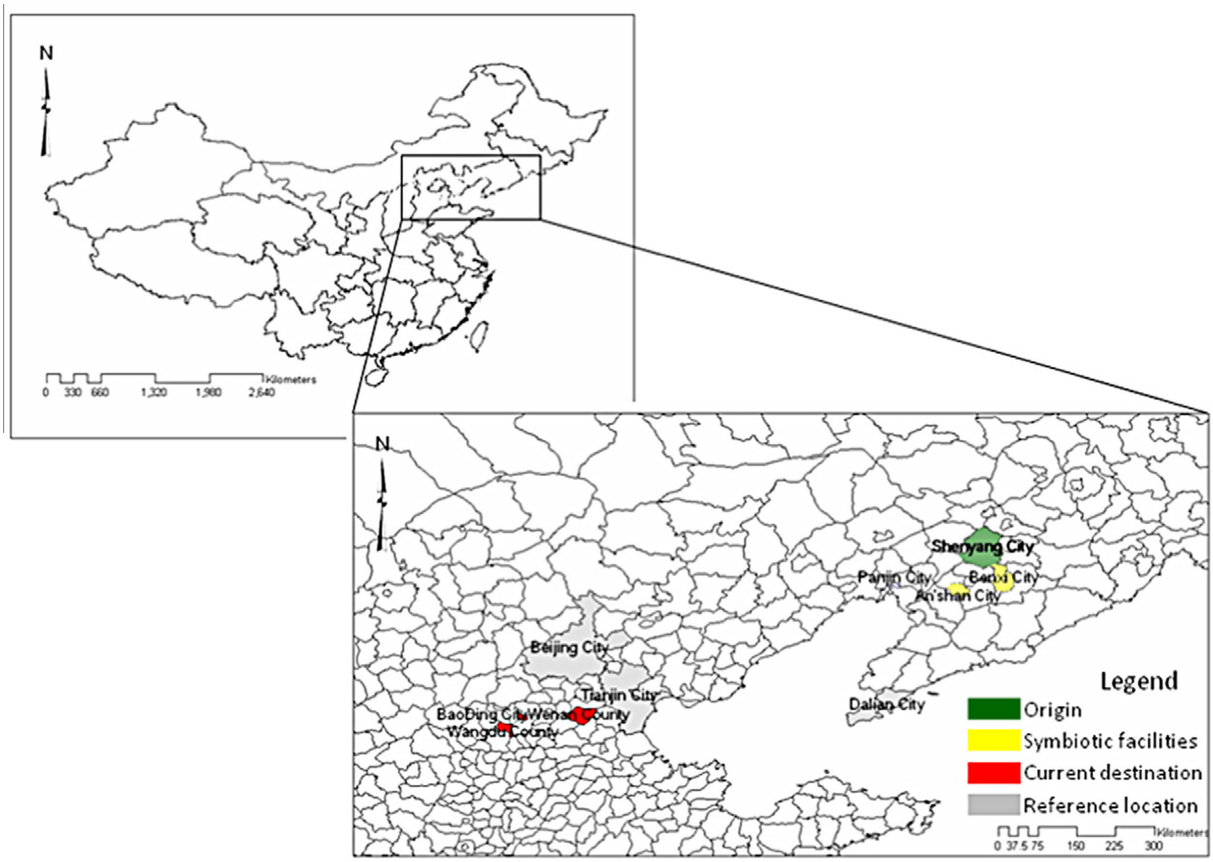

Fig. 1. The location of Shenyang and the major destinations for waste plastics.

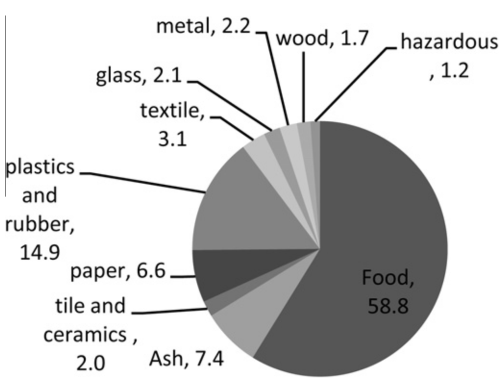

Fig. 2. The composition of MSW disposed in Shenyang. Source: Sun et al. (2008).

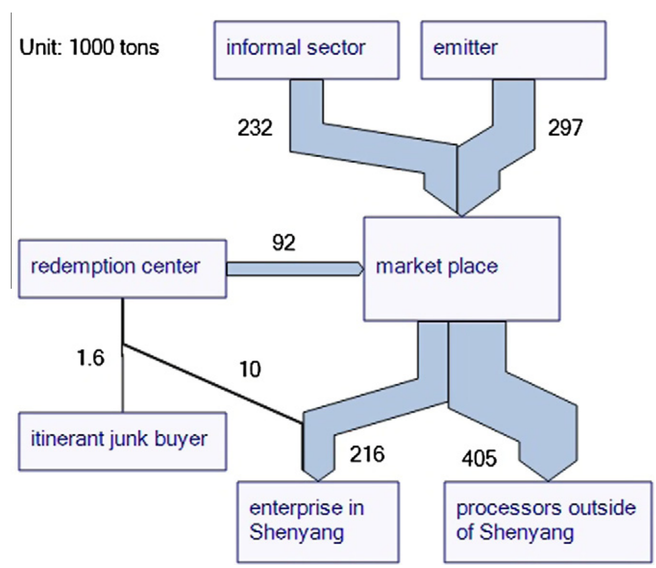

Fig. 3. Waste plastic flow in Shenyang. Source: Summarized by the authors from a survey conducted by the Shenyang SMCA (Wang et al., 2009).

local communities contributed only 15% of the total waste plastics traded in the marketplaces. A large proportion of the waste plastics was collected from outside Shenyang by the informal sector or came directly from emitters, including importers of waste plastics from foreign countries. According to the survey report, enterprises in Shenyang imported up to 41,200 tons of waste plastics each year from 2007 to 2009 (Wang et al., 2009). Collected waste plastics were usually manually separated, washed, and shredded or granulated to form pellets or granules. Most of such treatments were undertaken in small informal workshops without any controls over emissions. Approximately one third of the plastic pellets were utilized in Shenyang (Fig. 4). All the PET and over half the mixed plastics were transported to other provinces. Hebei province was the major destination, accounting for around 80% of the exported waste plastics (Fig. 1). The remainder was transported to Tianjin city and Shandong Province, or even as far as Zhejiang Province. Recycled PET was used mainly for casting and for fiber production. The other plastic wastes were used in the production of resins, packaging materials, and various plastic products, such as containers or ornaments.

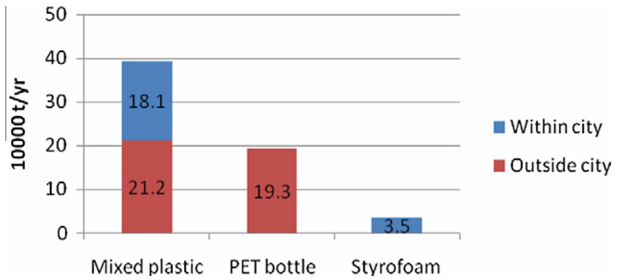

Fig. 4. Final destinations of waste plastics in Shenyang. Source: Wang et al. (2009).

3. Methodology

3.1. Model framework

In order to evaluate the potential environmental gains achievable by introducing new recycling and energy-recovery technologies in various policy scenarios, this paper employed the simulation system for urban environmental technology, which was developed by Fujita and his colleagues and has been applied in Kawasaki and the Tokyo Bay area in Japan (Fujita et al., 2007; Nagasawa et al., 2007; Wong et al., 2008). The model consists of three main parts: a database, a technology inventory, and various environmental policy options. To address technology transfer, the simulation system is modified into two steps in this paper: first, technology assessment that examines the potential environmental benefits of each technology in the context of Shenyang in terms of the composition of waste plastics, the energy structure, and emission factors; and second, scenario analysis that discusses the application of these technologies under various policies (Fig. 5).

The life cycle assessment (LCA) approach is adopted for the simulation in both steps. LCA has been widely used on waste management and similar issues (Banar et al., 2009; Buttol et al., 2007; Cherubini et al., 2009; Del Borghi et al., 2009; den Boer et al., 2007; Hellweg et al., 2005; Khoo, 2009; Moberg et al., 2005; Schmidt et al., 2007). This paper discusses two categories of impact: the global warming potential (GWP, or anthropogenic GHG emissions) and fossil fuel savings. These are the categories of effects upon which most studies have focused (Cleary, 2009) and which are covered in the declaration made by the Chinese government with regard to mitigating climate change (Xinhua News Agency, 2009).

3.2. Step 1: Technology assessment

3.2.1. Goals, definitions, system boundaries, and functional units

In Step 1, the aim was to evaluate the environmental impacts of individual technologies in the context of Shenyang. To differentiate the environmental benefits at various stages of the lifecycle of plastics, technologies were categorized into two types with slightly different boundary settings (Fig. 6). One is referred to as *open-loop recycling technologies*: these convert waste plastics into product(s) that substitute conventional products with equivalent functions. In such cases, the recycling process is different from the production process of the substituted products, and an equivalent function needs to be defined to determine the amounts of products that are replaced. Because the composition of the waste-derived products and the virgin-material-derived products may be different, the impacts of the disposal of these products are all included in the system boundary. In accordance with the current conditions in Shenyang, disposal is by landfill alone. The emissions of landfill gases (LFGs) were estimated based upon IPCC guideline 2006. In Shenyang, landfill sites are equipped with LFG collection facilities. From other LCA studies on MSW management in China (e.g., Zhao et al., 2009), 50% of the LFGs are assumed to be collected. The collected and purified LFGs are subsequently used in internal combustion engines for power production with an efficiency of 30%. Of the electricity generated, 20% is assumed to be consumed on-site for operations and maintenance. The second type of technologies is referred to here as *symbiotic technologies*, namely, converting waste plastics into feedstocks to replace virgin materials in producing the same product as produced exclusively from virgin materials. In such cases, part of the recycling process involves production processes with modified technologies and updated facilities. Our focus was on assessing the change in the inputs and outputs of the production process, as well as the yields of byproducts arising from the utilization of waste plastics. As the final products are the same, the disposal of these products is excluded from the system boundary.

The baseline scenario for all technologies is landfilling waste plastics without any utilization, where GWP and fossil fuel saving are considered to be zero. The functional unit in Step 1 was 1 kg of mixed waste plastic collected in Shenyang. The estimated composition of the targeted plastics waste, from interviews conducted by the investigators from Shenyang SMCA who performed the survey, is shown in Table 1.

3.2.2. Inventory data of technologies

In the current recycling process, or the business-as-usual (BaU) recycling process, waste plastics are shredded into pellets and granules. For the BaU technology, PP and PE were recycled to produce plastic resins (50% PP and 50% PE), and the remainder was assumed to replace wooden products. This recycling process is actually down-cycling and therefore a 10% material loss and 20% of quality loss were assumed (Astrup et al., 2009).

Four types of alternative treatment technologies were examined. The first was to recycle plastics to produce plastic boards

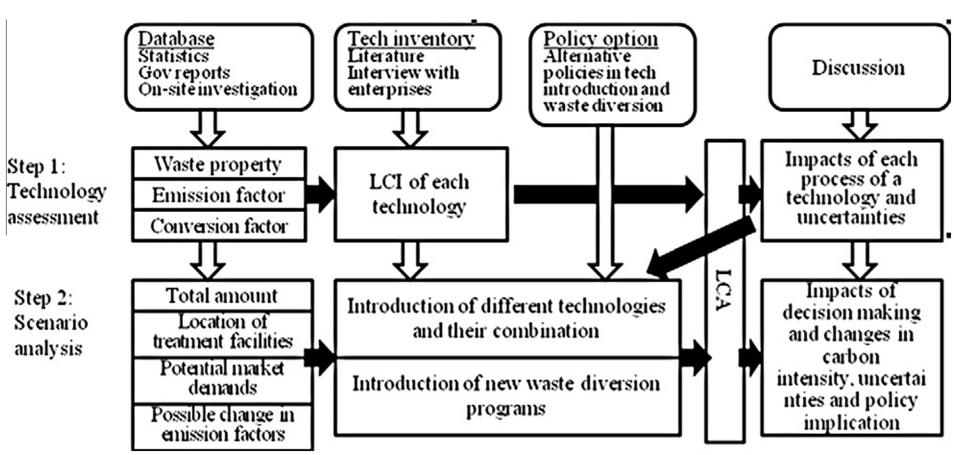

Fig. 5. The technical approach to the simulation system for urban environmental technology.

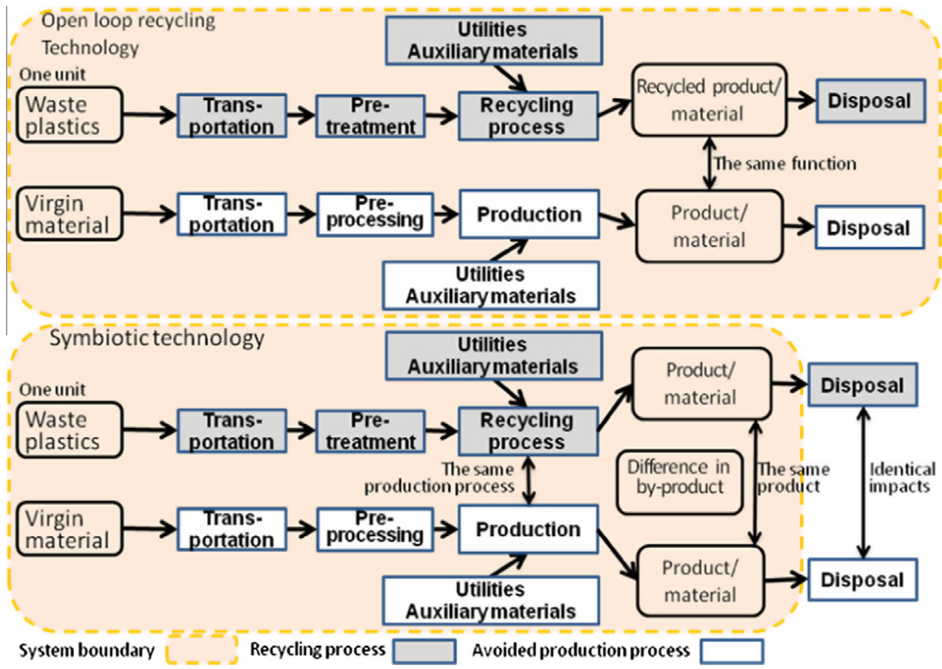

Fig. 6. Boundary setting for recycling and symbiotic technologies.

Table 1
The composition, LHV, and CO_2 emissions of waste plastics in Shenyang.

Composition	PE	PP	PS	PET	PVC	Other[a]	Moisture
Proportion	20%	20%	5%	0%	20%	30%	5%
LHV[b] (kJ/kg)	46,046	43,953	40,186	–	24,070	30,790	−2512
CO_2 (kg-CO_2/kg)	3.143	3.143	3.385	–	1.408	2.323	0

[a] As 'mixed various plastics' (Doka, 2009).
[b] See JCPRA (2007).

(known as *NF boards*) as replacement for wooden boards for concrete formwork. The second was to produce refuse plastic fuel (RPF) from shredded plastics as a source of energy to replace coal or other fossil fuels. The third technology was gasification of plastics to produce syngas to substitute natural gas for the production of ammonia. The final technology involves the use of waste plastics as a reductant in blast furnaces for the production of iron. The inputs and outputs for the major processes involved in each of these technologies and in the associated conventional production processes were calculated and listed in Tables 2–9. The original input/output data were acquired from a report written by the Japan Containers and Packaging Recycling Association (JCPRA, 2007). The data on all recycling/energy-recovery technologies and on the conventional technologies for the production of ammonia and iron were collected through surveys of Japanese companies

Table 2
Inventory data on the BaU technology.

Input/Output		Item	Amount	Units
Input	Material	Waste plastic	1	kg
		Electricity	0.575	kWh
	Utility	Water	0.435	kg
Output	Product	Plastic pellets	0.85	kg
	Residue	10% material loss, moisture	0.15	kg
Embodied GHGs in product	Product	Plastic resin	0.32[a]	kg
		Wood chips	0.36[a]	kg

[a] A 20% loss in quality is assumed.

Table 3
Inventory data on RPF production technology.

Input/Output		Item	Amount	Units
Input	Material	Waste plastic	1	kg
	Utility	Electricity	0.19	kWh
Output	Product	RPF (2% moisture)	0.67	kg
	By-product	Waste PVC	0.20	kg
	Residue	10% material loss, moisture	0.13	kg

and interviews with their personnel. The data on the production of wooden boards came from the Forestry Agency, which is part of the Ministry of Agriculture, Forestry, and Fisheries of Japan (JCPRA, 2007). The original data were adjusted to match the composition of waste plastics in Shenyang: only suitable compositions were diverted from the BaU route and to be processed by the recycling/energy-recovery technologies (Fig. 7). PE, PP, and PS are suitable for all the technologies; two thirds of the "other" plastics are assumed to be suitable only for use in energy-recovery and chemical-treatment technologies. The remaining one third (10% of the total) was considered material loss in the separation processes and landfilled together with other municipal solid wastes. Owing to the risk of synthesizing dioxins from chloride components, PVC is not recycled for the production of RPF and reductants and remains to be recycled through the BaU process. PVC is, however, treated through the gasification process. The lower heat value (LHV) and amount of CO_2 emitted by complete combustion of each type of waste plastic are listed in Table 1.

Table 4
Inventory data on NF board production technology.

Input/Output		Item	Amount	Units
Pretreatment process				
Input	Material	waste plastic	1	kg
	Utility	electricity	0.26	kWh
		light oil	0.001	L
		water	0.20	kg
Output	Product	plastic pellet (PP, PE, PS, 1% moisture)	0.46	kg
	By-product	mixed plastics	0.40	kg
	Residue	10% material loss, moisture	0.14	kg
Board production process				
Input	Material	Plastic pellet	0.46	kg
		PP	0.12	kg
	Auxiliary material	Inorganic compounds	0.03	kg
		Dye	0.003	kg
	Utility	Electricity	0.54	kWh
		Water	0.27	kg
Output	Product	NF board	0.61	kg

Table 5
Inventory data on wooden board production technology.

Input/Output		Item	Amount	Units
Board production process				
Input	Material	Wood	1.41	kg
	Auxiliary material	Glue	0.15	kg
	Utility	Electricity	0.18	kWh
		Heavy oil	0.02	L
		Light oil	0.00	L
		Wood chip	0.26	kg
Output	Product	Wooden board	1.56	kg
Landfill				
Input	Wooden board	Wood	1.41	kg
		Glue	0.15	kg

Table 6
Inventory data on the technology of gasification producing syngas for ammonia production.

Input/Output		Item	Amount	Units
Pretreatment: gasification process				
Input	Material	Waste plastic	1	kg
	Auxiliary material	Oxygen	0.86	Nm^3
		Caustic soda	0.005	kg
	Utility	Electricity	0.52	kWh
		Steam	1.29	kg
		Air	0.26	Nm^3
		Nitrogen	0.38	Nm^3
		Water	0.75	kg
Output	Product	Syngas	2.35	Nm^3
	By-product	Slag	0.04	kg
		Residue	0.03	kg
	Residue	10% material loss	0.10	kg
Ammonia production process				
Input	Material	Syngas	2.35	Nm^3
	Auxiliary material	Air	0.37	Nm^3
		Steam	1.167	kg
	Utility	Electricity	0.74	kWh
		City gas	0.18	Nm^3
Output	Product	Ammonia	0.79	kg
		Carbonic acid gas	1.14	Nm^3
		Hydrogen	0.02	Nm^3

For each recycled product, an equivalent function was determined for the amount of substituted products and the associated environmental impacts in their lifecycles. The equivalent function for NF boards was the area of concrete construction that is served. NF boards (9 kg/piece) are slightly lighter than wooden boards (9.2 kg/piece). Moreover, the service life of NF boards (about 10 use cycles per piece) is about 2.5 times that of wooden boards (about four use cycles per piece). For RPF, the equivalent function is the effective heat value that can be used. The inputs/outputs of the conventional production process were adjusted to yield products with the same function as the recycled products. In terms of the other two symbiotic technologies, the conventional production processes were manipulated to produce the same quantity of products as obtained by using the symbiotic technologies. The difference in byproducts is included in the process of "embodied GHGs in by-product". Additional residues from the process of producing ammonia by using waste plastics were considered to be treated and landfilled.

The localized emission factors of fossil fuels were estimated by means of Eqs. (1) and (2).

Table 7
Inventory data on conventional ammonia production technology.

Input/Output		Item	Amount	Units
Production process				
Input	Material	City gas	0.44	Nm^3
	Auxiliary material	Air	0.73	Nm^3
		Steam	2.10	kg
	Utility	Electricity	0.54	kWh
		City gas	0.18	Nm^3
Output	Product	Ammonia	0.79	kg
		CO_2	0.50	Nm^3
		Hydrogen	0.02	Nm^3
Embodied GHGs in product				
Output	Product	CO_2	0.64	Nm^3
	By-product	Slag	0.04	kg

Table 8
Concise inventory data on the technology using plastics as reductant for iron production.

Input/Output		Item	Amount	Units
Pretreatment: reductant production process				
Input	Material	Waste plastic	1	kg
	Utility	Electricity	0.29	kWh
		Coke over gas	0.01	Nm^3
		Kerosene	0.01	L
		Water	0.17	kg
Output	Product	Reductant	0.67	kg
	By-product	Waste PVC	0.20	kg
	Residue	10% material loss, moisture	0.13	kg
Iron production process				
Input	Material	Reductant	0.67	kg
		Cleaned coal	36.85	kg
Output	Product	Iron	67.00	kg
		Tail gas	387.04	MJ

Table 9
Concise inventory data on conventional iron production technology.

Input/output		Item	Amount	Units
Iron production process				
Input	Material	Cleaned coal	37.79	kg
Output	Product	Iron	67.00	kg
		Tail gas	385.64	MJ
Embodied GHGs in product				
Output	Product	Tailgas (steam)	1.40	MJ

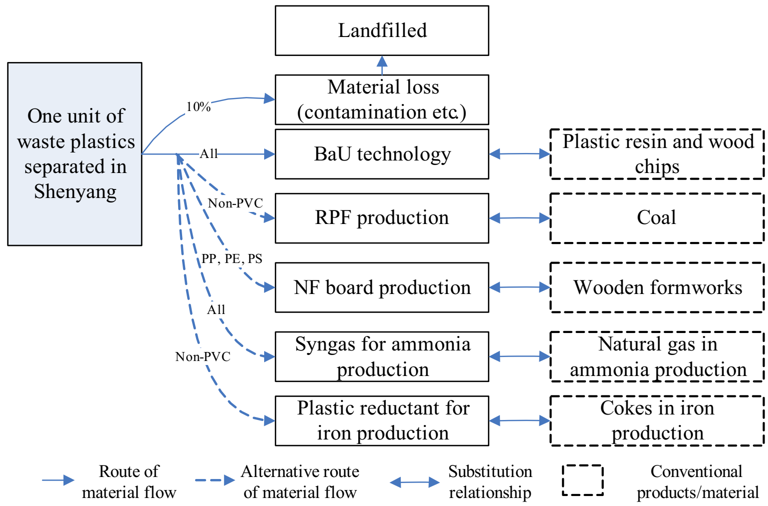

Fig. 7. Alternative routes of waste plastic flow for recycling technologies.

CO_2 emission factor

$$= \text{LHV} \cdot \text{Oxidation rate} \cdot \frac{\text{Carbon content}}{\text{LHV}} \cdot 44/12 \quad (1)$$

$CH_4(N_2O)$ emission factor

$$= \text{LHV} \cdot \text{Oxidation rate} \cdot \frac{CH_4(N_2O)\ \text{emissions}}{\text{LHV}} \quad (2)$$

LHVs, oxidization rates, and carbon contents per unit LHV were cited from the China Energy Yearbooks, Cai et al. (2009), and IPCC guideline (IPCC, 2006), respectively. The emission factors for electricity generation are referred to the marginal emission factors of coal-fired power plants in the Northeast China electricity grid, as published by the National Development and Reform Commission (NDRC, 2009) as the baseline for clean development mechanism (CDM) projects in 2009. Although the CDM baseline does not take into account the emissions from coal mining and transportation, it is considered a good estimation, because coal combustion accounts for a major proportion (over 93% in the US) of the life cycle GHG emissions of electricity generation (Spath et al., 1999). The emission factors for industrial water are estimated from the average energy consumption for water cleaning and supply from 2006 to 2008 in Shenyang (Table 10). CO_2, CH_4, and N_2O were regarded as GHGs. There are some debates on their GWP factors and time horizons (Gentil et al., 2009). Consistent with the IPCC's report, this paper employs the GWP factors of 1, 21, and 310 for CO_2, CH_4, and N_2O, respectively, based on a 100-year horizon (Gentil et al., 2009). The energy sources listed in Table 11 were taken into account with respect to saving of fossil fuels. The conversion factors to the unit of kilogram of coal equivalent (kgce) were taken from China Energy Yearbooks.

Deliveries of waste plastics are currently made by freight trucks. The average loading capacity of the trucks was 10 tons and their fuel efficiency was assumed to be 30 L-diesel/100 km. For the BaU technology, the major destinations of mixed waste plastics are Wen'an, Baoding, and Wangdu, all in Heibei province. For the recycling/energy-recovery technologies, Panjin was taken as the destination for the use of plastics in ammonia production, and Anshan and Benxi were taken as the destinations for iron production. The approximate distances from Shenyang to these cities are tabulated in Table 12.

Table 10
Emission factors of energy sources.

	CO_2	CH_4	N_2O	Units
Crude coal	1.82E+00	1.92E−04	2.88E−05	kg/kg
Cleaned coal	2.44E+00	2.58E−04	3.87E−05	kg/kg
Coke	2.83E+00	2.64E−04	3.96E−05	kg/kg
COG[a]	6.89E−01	1.55E−05	1.55E−05	kg/m^3
Natural gas	2.16E+00	3.85E−05	3.85E−06	kg/m3
Gasoline	2.14E+00	9.24E−05	1.85E−05	kg/L
Kerosene	2.44E+00	1.02E−04	2.04E−05	kg/L
Diesel	2.57E+00	1.04E−04	2.09E−05	kg/L
Fuel oil	3.06E+00	1.19E−04	2.37E−05	kg/L
Electricity	1.13E+00	1.19E−04	6.22E−08	kg/kWh
Water	5.50E−04	6.22E−08	9.35E−09	kg/kg

[a] COG: coke oven gas.

Table 11
Energy conversion factors to coal equivalents.

Fossil-Derived Energy	Conversion Factor	Unit
Crude coal	0.7143	kgce/kg
Cleaned coal	0.9000	kgce/kg
Coke	0.9714	kgce/kg
COG[a]	0.5714	kgce/m3
Blast furnace gas	0.1286	kgce/m^3
Natural gas	1.3300	kgce/m^3
Gasoline	1.0741	kgce/L
Kerosene	1.1771	kgce/L
Diesel	1.2094	kgce/L
Fuel oil	1.3715	kgce/L
Crude oil	1.4286	kgce/L
Electricity	0.4040	kgce/kwh

[a] COG: coke oven gas.

Table 12
Transportation distances to the major destinations for waste plastics.

Destination		Distance (km)	Note
For material recycling in BaU	Wen'an	771	
	Baoding	840	
	Wangdu	881	
Syngas for ammonia production	Panjin	160	Annual output 322 kt
Reductant for iron production	Anshan	110	Annual output about 16.1 million tons
	Benxi	80	Annual output about 7.4 million tons

3.3. Step 2: Scenario analysis

While Step 1 focused on the assessment of individual technologies, Step 2 addressed the potential effects of various decisions regarding the introduction of single or multiple technologies into Shenyang and the rolling out of new waste-recycling programs to reduce the total amount of mixed plastics sent to landfill and the carbon intensity of electricity, as indicated by GHG emissions per unit of electricity generated. Only the direct impacts of changes in the physical flows were taken into account; the rebound effects are not considered. The scenarios set in this paper were explorative scenarios (Höjer et al., 2008). They were designed to test the potential environmental gains by answering the question of "what can happen". Eight scenarios were designed to simulate the potential reductions in GHG emissions and savings in fossil fuel consumption by (1) the introduction of each individual technology, given the constraints of the market size (BaU and four scenarios for alternative technologies); (2) the introduction of two technologies that could cascade the utilization of waste plastics; (3) changes in the carbon intensity of electricity; and (4) the introduction of new waste plastic recycling programs to divert waste plastics from landfill sites (Table 13).

The functional unit in Step 2 is the mixed plastics that are currently used outside Shenyang and the mixed plastics in MSW that are currently landfilled. The total amount of the former is about 210 kt, and that of the latter was estimated to be about 185 kt based on the composition of the MSW being landfilled. The capacity of the adjacent symbiotic facilities (i.e. ammonia and iron production facilities) and the potential market demand for recycled products were taken into account in discussing the potential for substitution in each scenario. The NF boards were assumed to be used in the construction of buildings with concrete frameworks. New construction of buildings in Shenyang was considered the target market for the purpose of estimating the market potential. The annual average new construction area in Shenyang from 2006 to 2008 was approximately 48 million m^2 (Table 14). Each unit of floor area of new buildings requires roughly two unit areas of NF board (considering the floor area and the main walls), and each NF board can be reused ten times; the potential demand for NF boards is therefore 9.5 million m^2. Given the fact that the weight of each square meter of NF board is 9 kg, and taking into account the inventory data shown in Table 4, the potential market demand is equal to a capacity for recycling of up to 140 kt of waste plastics each year, which is less than the total amount of waste plastics currently collected in Shenyang. Therefore, in the 'NF scenario', the excess of waste plastics above the potential market demand remained to be treated as in the 'BaU scenario'.

RPF is suitable for replacing coal as a source of energy. The coal-fired power plants in Shenyang would serve as a potential market for RPF. In 2008, the total consumption of crude coal by these power plants was about 8.2 million tons, which is equivalent to 6.7 million tons of potential market capacity for RPF with the same heat value. For the production of ammonia and iron, large plants are located in surrounding cities. An ammonia plant with an annual output of 322 kt is located in Panjin, near the Liaohe oilfield (about 160 km southeast of Shenyang), and two iron plants with a total annual output over 2 million tons are located in Anshan (110 km from Shenyang) and Benxi (80 km). The demand of these large plants for recycled waste plastics exceeds the amount of waste plastics targeted in Step 2.

The 'NF board + RPF' scenario was designed to demonstrate synergies between various technologies. In this scenario, 90% of the used NF boards are assumed to be recycled for the production of RPF, and the remaining 10% (material loss in recycling) are landfilled as normal municipal solid waste. In the 'reduced carbon intensity' scenario, a 15% reduction in the carbon intensity of electricity was tested. In the "waste-recycling program" scenario, 50% of the landfilled waste plastics were assumed to be recycled for RPF production on top of the "reduced carbon intensity" scenario.

Table 14
Areas of new buildings in Shenyang.

Year	2006	2007	2008	Average
New building construction area ($10^6 \times m^2$)	34.6	50.2	58.0	47.6

4. Results

The results for GHG emissions and fossil fuel consumption for each of the treatment technologies are plotted in Fig. 8, in comparison with the BaU recycling technology. If 1 kg of waste plastics continues to be treated as at present, the recycling process could reduce 0.31 kg-CO_2e and 0.25 kgce compared with the zero baseline. The results of the four alternative recycling/energy-recovery technologies vary dramatically. The NF board production technology provides the most significant reduction in GHG emissions (1.66 kgCO_2e/kg-plastics), while the RPF production technology has the largest potential on fossil fuel saving (0.77 kgce/kg-plastics).

The reductions in GHG emissions for the individual processes of each technology are shown in Fig. 9. Emissions from transportation are relative small for all the technologies. Even for the BaU, where plastics are delivered about 900 km, the emissions from transportation account for only about 10% of the total emissions from the treatment process. Fig. 9 also illustrates the difference between open-loop recycling and symbiotic technologies in terms of the major processes that contribute to reductions in GHG emissions.

Table 13
Scenarios for introducing various technologies, changes in carbon intensity, and establishment of new recycling programs.

Scenario	Introduction of alternative technology	Carbon intensity of electricity	New recycling program
BaU	–	–	–
NF board	Recycling waste plastics to produce NF boards	–	–
RPF	Recycling waste plastics to produce fuel to replace fossil fuels	–	–
Syngas for ammonia	Gasifying waste plastics to produce syngas for ammonia production	–	–
Reductant	Recycling waste plastics to produce reductant for iron production	–	–
NF board + RPF	Recycling waste plastic to produce NF boards and producing fuel to replace fossil fuels from used NF boards	–	–
Reduced carbon intensity	As above	The carbon intensity of electricity is decreased by 15%	–
Waste-recycling program	As above	The same as in 'reduced carbon intensity' scenario	Rolling out new a recycling program to divert waste plastics from landfill

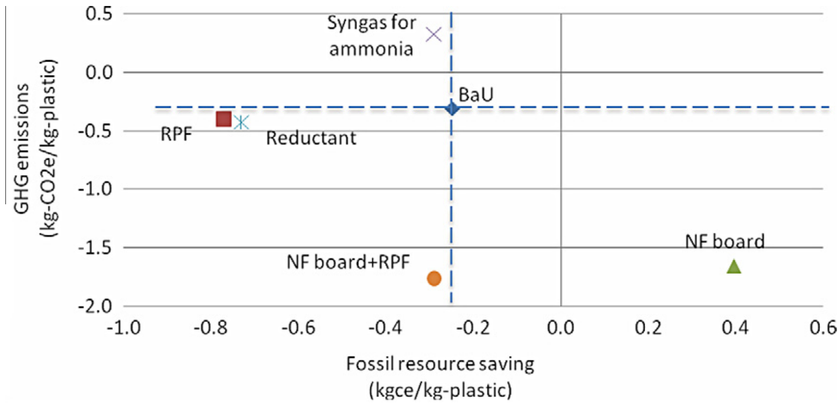

Fig. 8. GHG emissions and fossil resource consumption for each recycling technology.

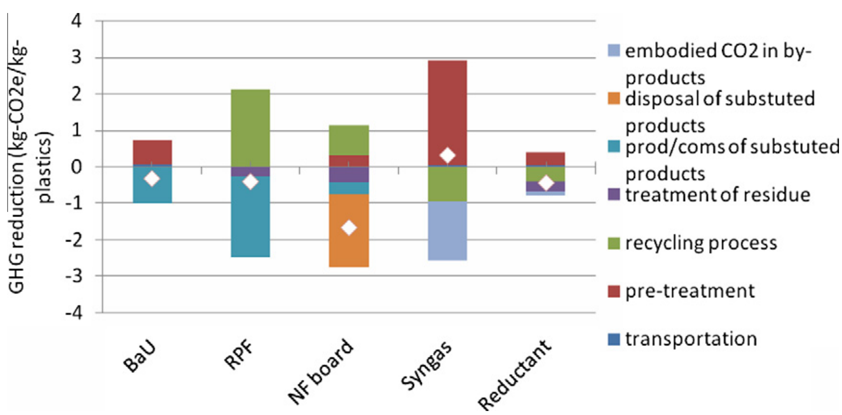

Fig. 9. GHG emissions by processes of each recycling technology.

The reductions from open-loop recycling technologies arise mainly from the avoidance of the production, consumption, and disposal of the substituted products, whereas most reductions from symbiotic technologies are realized in the production process and the yields of extra byproducts.

The results for eight scenarios are summarized in Fig. 10. Due to the large population and rapid urbanization of Shenyang and the existence of many large sized heavy industries located around Shenyang, all the technologies except for NF board production have the potential demands for the recycled products from the recycling of the 210 kt plastics. In spite of this the market constraint, the 'NF board' scenario still has the largest potential in terms of reducing GHG emission (254 ktCO_2e/year) among all the scenarios of applying a single technology. The synergy between various technologies could result in greater environmental gains. As shown in the 'NF board + RPF' scenario, the application of both the NF board and the RPF production technologies, which cascade the utilization of waste plastics, could bring greater reductions in GHG emissions than could any individual technology.

The last two scenarios tested the impacts of changes in the carbon intensity of electricity and the operation of new waste-recycling programs. These two factors are tightly related to the potential environmental gains that the technologies could achieve. In comparison with the 'NF board + RPF' scenario, a 15% reduction in the carbon intensity of electricity could lead to an additional 93 ktCO_2e/year (34%) reduction in GHG emissions and a 12 ktce/

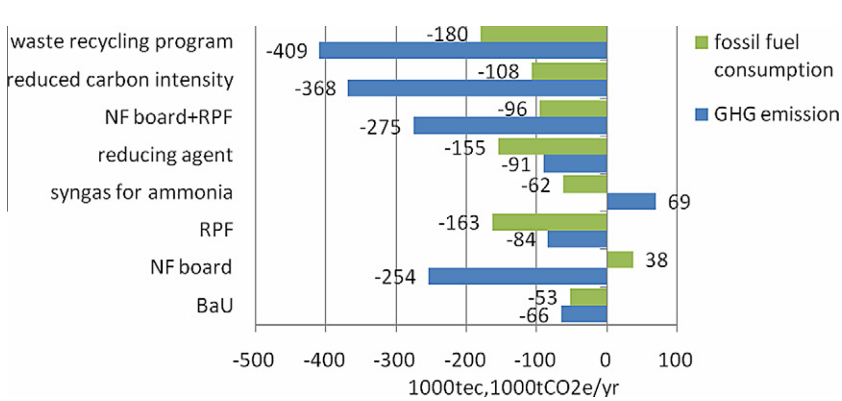

Fig. 10. GHG emissions and fossil resource consumption of scenarios.

year (12%) saving in fossil fuels. These results indicate a synergistic effect between clean energy and recycling/energy-recovery technologies. As an industrial activity, the recycling process itself consumes electricity. When the carbon intensity of electricity drops, both the 'cost' of recycling and the 'benefit' from collecting LFGs for electricity production decrease. The waste-recycling program could potentially divert 92 kt plastics from landfill to RPF production. This new recycling program would result in an additional 41 $ktCO_2e$/year (11%) reduction in GHG emission and a 72 ktce/year (68%) saving in fossil fuels.

5. Discussion

Although fossil fuels are the major source of GHG emissions, reductions in GHG emissions and savings in fossil resources were not correlated among the assessed technologies. Instead, the relationship between the reduction in GHG emission and savings of fossil resources is dependent mainly on how the waste plastics are treated and how the substituted products would be disposed off. Mechanical recycling technologies produce products such as plastic granules or NF boards from waste plastics, so that the carbon composed in the waste plastics is converted into a new product without being released to the atmosphere. The amount of reduction depends on the embodied GHG emissions and disposal methods of the substituted products. Since landfill is currently the only disposal method in Shenyang, replacing bio-decomposable (e.g., wooden) products would significantly reduce the generation of landfill gases, which contain methane. If combustible wastes were incinerated, fossil resource-derived wastes (e.g., plastics) would be converted into anthropogenic CO_2, whereas the incineration of wood would only release biogenic CO_2, so that replacing fossil resource-derived products would result in a considerable reduction in emissions of GHG. On the contrary, chemical-treatment and energy-recovery technologies treat waste plastics through a series of thermal reactions in which the carbon content of the plastics is finally converted into CO_2, provided that oxygen is present in abundance. Therefore, for the same saving in fossil fuels, mechanical recycling technologies tend to produce greater reductions in greenhouse gas emissions. Regardless of the difference in energy consumption between various recycling processes, the saving of fossil fuels depends heavily on the properties of the substituted products or materials. RPF and plastic blast furnace reductant, which replace coal and cokes, produce considerable savings in fossil fuels as, to a lesser extent, does gasification technology for producing syngas as a substitute for natural gas in the production of ammonia.

Another noteworthy result is the difference in the contribution to the reductions in GHG emissions of major processes in open-loop recycling and symbiotic technologies. When the reduction is contingent on the substitution taking place in the market, it becomes subject to a number of market factors (Ekvall and Weidema, 2004). In this paper, the recycled products are assumed to fully substitute conventional products with equivalent functions. The uncertainties in this assumption will be discussed in the section below. To obtain more credible results, further studies are needed that address the market effects and competitive products in simulations of open-loop recycling. In the case where waste plastics are taken as feedstocks for the production of ammonia or iron, the substitution takes place in the production process. The degree of uncertainty in the reduction in GHG emissions by symbiotic technologies is therefore with less uncertainty than that in open-loop recycling technologies.

Despite containing input and output data for all technologies, the model still has limitations and uncertainties. These limitations and uncertainties can be attributed to three main sources: data and technical limits, model inherent limits, and assumptions. Because of difficulties in obtaining data on technology inventories from Chinese companies, all the inventory data were taken from the report on Japanese technologies. The model therefore can not provide a full reflection of differences in conventional production processes and pretreatment processes between Japan and China. Furthermore, the LCA approach itself has several inherent limitations (Eriksson et al., 2007). This paper addressed some of these limitations, but others remain. First, in order to facilitate the comparison of various technologies and to aim at the total quantity of waste plastics, two functional units were chosen for the two steps of the simulation. The first step eases the management of inventory data across various technologies, while the second step allows for the discussion of both additional waste-recycling programs and constraints caused by limited market demand. Second, as the simulation tested the potential consequences of technology transfer, localized, and marginal emission factors were used wherever these were available. However, the model remained to be a static model that was not designed for time-series scenarios or with feedback loops.

Uncertainties also arise from several assumptions made in the simulation. As mentioned earlier, the recycled products from open-loop recycling technologies are assumed to fully substitute conventional products with the equivalent function and that the total demand in the market is constant and sufficient. In relevant assessment studies, particularly on the GWP of plastic recycling, as discussed by Astrup et al. (2009), market effects have generally not been taken into account. However, such an assumption requires that, for example, the production of wooden boards falls as soon as replacement plastic boards are available. Market effects and differences in the properties of the recycled and non-recycled products may lead to a substitution rate that is less than 100% (Ekvall and Weidema, 2004). Even if the new equilibrium between supply and demand in the market finally reaches the point of full substitution in the long term, the rate of substitute rate may be below 100% for a considerable time. In other words, supply is likely to exceed demand in the short term.

For the disposal of bio-decomposable wastes by landfill, 50% of LFGs are assumed to be collected for the generation of electricity. The actual rate of collection of LFGs is difficult to be estimated precisely, and this is often a relatively sensitive parameter in relation to GHG emissions from waste management (Zhao et al., 2009). In the 'waste-recycling program' scenario, 50% of the waste plastics that are currently landfilled were assumed to be diverted to produce RPF. Because there is no credible reference of the total recycling rate of waste plastics in formal recycling programs in China, the recycling rate is a tentative assumption with a high degree of uncertainty. In order to analyze the influence of these assumptions on the results, a sensitivity analysis is performed. Changes in the results for each scenario when the assumed values decrease by 10% are shown in Table 15. The assumption on the substitution rates is highly sensitive to the results in scenarios for the BaU and open-loop recycling technologies, because these reduce emissions mainly by avoiding consumption and by the production of the substituted products. A decrease in the substitution rate would result in a sharper drop in the reduction of emissions of GHG emission reduction than in savings of fossil fuel consumption. The 'BaU' and 'NF board' scenarios are also highly sensitive to the assumption on the LFG collection rate. The worse LFG collection is managed, the more environmental gains will be achieved in terms of both reducing GHG emission and savings in fossil fuel. In comparison with the other two parameters, changing the recycling rate has a relatively small impact on the results. Given that the collected waste plastics are well processed, a 10% drop in the recycling rate of the additional recycling program would only lead to about 1% and 4% decreases in the reduction in GHG emissions and savings in fossil fuels, respectively.

Table 15
Results of the sensitivity analysis.

Scenario	90% sub rate		45% LFG collection rate		45% recycling rate	
	GHG reduction (%)	Fossil fuel saving (%)	GHG reduction (%)	Fossil fuel saving (%)	GHG reduction (%)	Fossil fuel saving (%)
BaU	−33.1	−21.8	24.2	1.7	0.0	0.0
NF board	−15.8	7.8	22.1	−7.2	0.0	0.0
RPF	−56.3	−11.3	10.5	0.3	0.0	0.0
Syngas for ammonia	0.0	0.0	0.0	0.0	0.0	0.0
Reducing agent	−6.6	0.3	9.8	0.3	0.0	0.0
NF board + RPF	−27.7	−16.6	19.5	2.7	0.0	0.0
Reduced carbon intensity	−22.5	−15.0	3.3	2.0	0.0	0.0
Waste-recycling program	−25.3	−13.4	3.9	1.3	−1.0	−4.0

The results of the simulation showed the highest potential of each individual scenario. In reality, there is likely to be a mixture of several scenarios. To achieve the environmental benefits in any one of these scenarios requires an effective network for waste recycling and collection that can provide reliable supplies for the recycling business. Consequently, a public–private partnership should be developed so that the stakeholders, in this case, the local government and government-owned entities, should closely collaborate with the informal sector. Currently in Shenyang, most waste plastics are collected and treated by the informal sector. Government policies could play a key role in managing and maintaining this network. Recycling activities of the informal sector are basically profit oriented, because scavengers and junk-buyers are living on collecting and selling waste. Under such a circumstance, economic instruments should be adopted to help local recycling businesses to be more competitive, such as providing premium to those who deliver their waste plastics to local recycling businesses or subsidies to the local recycling businesses to reduce their costs. The results of the sensitivity analysis also imply that management of the demand side is crucial to realizing the potential environment benefits, especially for open-loop recycling technologies. If the recycled products are not competitive in the market, not only will the environmental benefits of recycling be much less than expected, but also the economic viability of the industry would be weakened. Policies to promote green purchase and green procurement would help develop the market for recycled products, and thus, need to be enacted and implemented by considering the local realities.

6. Conclusion

The achievement that the Japanese eco-towns have made with their innovative recycling and energy-recovery technologies has demonstrated a robust model for stimulating industrial development and addressing waste management issues simultaneously. As the world's biggest generator of MSW, together with efforts on waste reduction, China has a considerable potential to gain the environmental benefits associated with waste recycling and recovery. This paper evaluated the potential environmental gains of transferring advanced Japanese waste plastics recycling technologies to Shenyang. The results showed that among the four recycling and energy-recovery technologies, the mechanical recycling of waste plastics to produce NF boards has the largest potential in terms of reducing emissions of GHG, while the RPF production technology leads to the largest savings in the consumption of fossil fuels. More benefits could be gained by combining different technologies that cascade the utilization of waste plastics. The potential environmental gains of a given set of technologies depend on the technologies themselves and the local conditions, such as the energy structure and the carbon intensity of electricity. The development of clean energy, as well as the promotion of new waste plastics recycling programs could contribute to greater reductions in the emissions of GHG and larger savings in fossil fuel consumption. Moreover, the management of the demand for recycled products is of great importance in realizing the potential environmental benefits of open-loop recycling technologies.

The simulation on environmental technologies has shown the maximum potentials achievable through various management options, and the results can serve as a scientific reference for planning and policy making. However, the feasibility and viability of waste-recycling projects and the extent to which their potential can be achieved are subject to a variety of factors, such as economic costs and benefits, and cooperation between the various stakeholders in a particular project. Assessments from various perspectives may lead to more comprehensive results, to which models other than LCA, such as cost-benefit analysis, environmental technology assessment, environmental impact assessment, and environmental risk assessment, can contribute (Finnveden and Moberg, 2005; Hay and Noonan, 2002). Additional empirical studies are needed to analyze how the symbiotic network could be built and to analyze the dynamics and mechanisms of the synergistic activities so as to approach the full potential of applying innovative recycling and energy-recovery technologies.

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