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Life cycle assessment of integrated recycling schemes for plastic containers and packaging with consideration of resin composition

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Abstract Many life cycle assessment studies have evaluated and compared the environmental performance of various technologies for recycling plastic containers and packaging in Japan and other countries. However, no studies have evaluated the combination of recycling technologies in consideration of the resin composition in terms of the quantity of each recycled product so as to maximize their environmental potential. In this study, 27 scenarios of recycling schemes for household waste plastic containers and packaging are developed through integrating a conventional recycling scheme with additional recycling schemes. The conventional recycling scheme involves municipal curbside collection and either the material recycling or feedstock recycling of waste plastics. The additional recycling schemes are feedstock recycling in steel works of the residue from conventional material recycling processes, and corporate voluntary collection and independent material recycling of specific types of plastic trays. Life cycle assessment based on the modeling of recycling processes considering the resin composition in terms of the quantity of each recycled product is applied to evaluate and compare these scenarios from the viewpoints of fossil resource consumption and CO_2 emission. The results show that the environmental loads are reduced in all scenarios including the additional recycling schemes compared with the conventional recycling scheme. However, the independent plastic tray recycling scheme exhibits lower additional environmental savings when the residue recycling scheme is integrated with the conventional material recycling scheme. This is because both additional recycling schemes aim to utilize polystyrene and polyethylene terephthalate, which would otherwise be incinerated as residue from material recycling processes. The evaluation of the environmental loads of plastic recycling with consideration of the resin composition in terms of the quantity of each recycled product makes it possible to investigate recycling schemes that integrate different technologies to maximize their environmental potential.

Keywords Material recycling · Feedstock recycling · Residue recycling · Voluntary collection · Independent plastic tray recycling

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Introduction

Plastics are now used in countless applications including car parts, home products, mobile phones, containers and packaging. Containers and packaging remain the largest of these applications in Japan, accounting for 43.1% of all plastic products in 2008 [1]. The Law for Promotion of Sorted Collection and Recycling of Containers and Packaging (Containers and Packaging Recycling Law) was enacted in 1995 and enforced in 1997 in Japan. The

recycling of postconsumer plastic containers and packaging, other than beverage polyethylene terephthalate (PET) bottles, has been subject to the law since 2000 [2]. It is said that the law has contributed to the promotion of plastic recycling, at least in terms of the collection rate for recycling. However, many problems still remain unsolved, for example, the mismatch between the resin composition of collected waste plastics and the characteristics of recycling processes. Hence, almost half of the collected waste plastics become residue and are finally disposed of without material recovery in conventional material recycling [3]. To increase the utilization ratio of waste plastics, the feedstock recycling of residue from material recycling processes has been proposed [4]. In addition, recycled polyethylene (PE) and polypropylene (PP) mixed resin produced by conventional material recycling is sold at much lower prices than virgin PE or PP resin because of its reduced quality due to contamination from different types of resin and grime. A collection scheme for pure plastics is required to improve the quality of recycled materials, and specific types of plastic trays, foamed polystyrene (PS) trays and transparent PS and PET trays, are partly collected and recycled as voluntary activities by consumers, retailers and private recyclers independently from the conventional municipal curbside collection of waste plastics.

Many life cycle assessment (LCA) studies have evaluated and compared the environmental performance of various technologies for recycling plastic containers and packaging in Japan and other countries. Arena et al. [5] and Perugini et al. [6] compared the environmental performance between different technologies for recycling plastic containers in Italy. Similar comparisons have been carried out in Denmark [7], UK [8], Germany [9], Sweden [10, 11] and Japan [12–16]. In these studies, collected waste plastics and collection schemes were assumed to be identical among the evaluated scenarios, and they only focused on the difference between recycling technologies. The Japan Plastic Containers and Packaging Recycling Association (2007) [14] also evaluated the environmental performance of the combination of material recycling and energy recovery of residue from the material recycling processes considering the resin composition of waste plastics in terms of calorific value. Sekine et al. [17] investigated the potential reduction of CO_2 emission for feedstock recycling technologies in steel works for different types of plastic resin. Larsen et al. [18] demonstrated the environmental and economic potentials of the recycling of household waste including plastic packaging wastes in a full-scale waste management system and compared various collection schemes; however, the recycling technology was assumed to be identical regardless of the collection scheme. To the best of our knowledge, no studies have evaluated the combination of recycling technologies in consideration of the resin composition of

waste plastics in terms of the quantity of each recycled product.

In this study we aim to investigate recycling schemes for household waste plastic containers and packaging in which different technologies are integrated so as to maximize their environmental potential with consideration of the resin composition in terms of the quantity of each recycled product. First, we summarize the current plastic container and packaging recycling system in Japan based on our field surveys and a literature survey. Then, 27 scenarios are developed through integrating a conventional recycling scheme with a couple of additional recycling schemes. The conventional recycling scheme involves municipal curbside collection and either the material recycling or feedstock recycling of waste plastics. The additional recycling schemes are the feedstock recycling of the residue from the conventional material recycling processes, and corporate voluntary collection and independent material recycling of specific types of plastic trays. LCA based on the modeling of recycling processes considering the resin composition of waste plastics in terms of the quantity of each recycled product is applied to evaluate and compare these scenarios from the viewpoints of fossil resource consumption and CO_2 emission.

Plastic container and packaging recycling system in Japan

Conventional recycling schemes for plastic containers and packaging

Figure 1 shows the current recycling system for household waste plastic containers and packaging in Japan. Beverage PET bottles [19], which are collected and recycled separately from other plastic containers and packaging, are outside the scope of evaluation in this paper. Plastic containers and packaging include various types of plastic resin, for example, PE, PP, PS, PET and polyvinylchloride (PVC), and some containers and packaging are made from a single resin and some are made from a mixed resin such as laminated films. Municipalities collect household waste plastic containers and packaging, which consumers dispose of at the curbside, remove other undesirable materials, compact the remaining waste plastics as pretreatment, and then outsource their recycling to approved private recyclers. At this point, material recycling and several types of feedstock recycling, i.e., coke oven chemical feedstock recycling [20], blast furnace feedstock recycling, gasification and liquefaction [21, 22], are approved by the national designated recycling association.

Material recycling is categorized into two types. The first is material recycling producing mixed resin [referred

to as "material recycling (a)" below]. In this process, PE and PP mixed resin is produced; therefore, the other waste plastics, almost half of the collected wastes, become residue. Among the registered material recyclers in 2007, 92% of recyclers carried out material recycling (a) [2]. However, this resin is sold at much lower prices than virgin PE or PP resin because of its reduced quality due to contamination from different types of resin and grime, and its application is limited. The second is material recycling producing various types of single resin [referred to as "material recycling (b)" below]. In this process, various types of single resin, for example, high-density polyethylene (HDPE), low-density polyethylene (LDPE), PP, PS and PET, are produced. Eight percent of recyclers carried out material recycling (b) in 2007 [2].

Coke oven chemical feedstock recycling and blast furnace feedstock recycling are recycling technologies used in steel works. In coke oven chemical feedstock recycling, after PVC and polyvinylidene chloride (PVDC) are removed to maintain the chlorine content of the waste plastics placed in the coke oven below 2% [23], pelletized waste plastics are added to the coke oven with feedstock coals, and pyrolyzed to form cokes, coke oven gas (which is used to generate electricity) and hydrocarbon oil (which is decomposed to oil cokes, heavy oil, benzene, toluene and xylene). The rejected chlorine-containing resin fractions become residue. In blast furnace feedstock recycling, after all chlorine-containing resins are removed along with 11% of the other types of resin [14], pelletized waste plastics are added to the blast furnace and act as a reducing agent. The rejected chlorine-containing resins and 11% of the other types of resin become residue.

Independent plastic tray recycling scheme

In Japan, some postconsumer foamed PS trays and transparent trays are collected at retail points by the manufacturer independently from municipalities. Postconsumer foamed PS trays and transparent trays are voluntarily brought to the respective collection boxes at retail points by consumers, undesirable materials are removed by the retailers, then the trays are transported to recycling factories by the container wholesalers, where they are recycled through material recycling. This recycling system is also shown in Fig. 1. To decrease the mismatch between the resin composition of collected waste plastics and the characteristics of recycling processes, only specific types of plastic trays, which are made from a single resin and easily recognized by consumers, are selected as collection targets. In this paper, this recycling scheme is referred to as the "independent plastic tray recycling scheme".

In the case of foamed PS trays, both white trays and printed trays are collected and recycled separately. Pellets
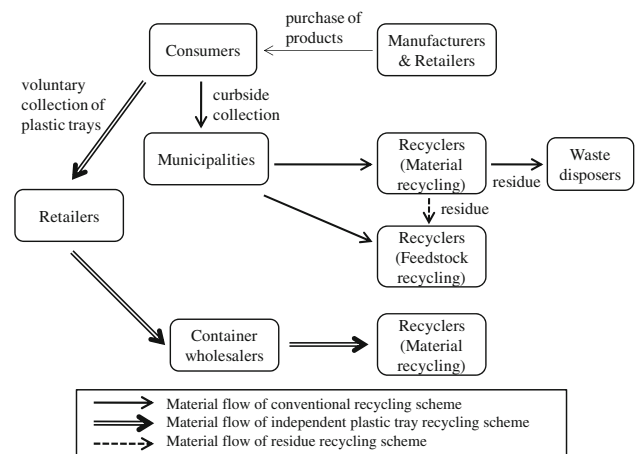
Fig. 1 Household waste plastic container and packaging recycling system in Japan

made from postconsumer white trays are recycled as a raw material of white trays along with virgin and preconsumer pellets. In the case of transparent trays, after printed trays and trays with attached adhesive tape and labels are removed, the remaining trays are separated automatically by near-infrared separation, and oriented PS trays and amorphous PET trays are extracted and recycled into foamed PS trays and PET trays, respectively.

Methods

Scenarios

Twenty-seven scenarios of recycling schemes for household waste plastic containers and packaging in Japan have been developed (see Table 1) through integrating (1) the conventional recycling scheme, which involves municipal curbside collection and either the material recycling or feedstock recycling of waste plastics, with two additional recycling schemes, i.e., (2) feedstock recycling in steel works of the residue from conventional material recycling processes (referred to as the "residue recycling scheme" below) and/or (3) corporate voluntary collection and independent material recycling of specific types of plastic trays (independent plastic tray recycling scheme). The above-mentioned material recycling (a) and (b) are considered conventional material recycling technologies, and coke oven chemical feedstock recycling and blast furnace feedstock recycling are considered feedstock recycling technologies. Moreover, scenarios in which waste plastics are collected along with combustibles and incinerated with energy recovery (power generation) are also developed for comparison.

In all the evaluated scenarios, the functional unit is the recycling or disposal of 1 kg of household waste plastic

Table 1 Evaluated scenarios of the management of postconsumer plastic containers and packaging

Scenario abbreviations	(1) Conventional recycling and disposal					(2) Residue recycling and disposal			(3) Independent plastic tray recycling	
	Material recycling (a)	Material recycling (b)	Coke oven chemical feedstock recycling	Blast furnace feedstock recycling	Incineration with power generation	Incineration with power generation	Coke oven chemical feedstock recycling	Blast furnace feedstock recycling	Foamed PS trays	Transparent trays
MaI-0	O					O				
MaI-1	O					O			O	
MaI-2	O					O			O	O
MbI-0		O				O				
MbI-1		O				O			O	
MbI-2		O				O			O	O
F1-0			O			O				
F1-1			O			O			O	
F1-2			O			O			O	O
F2-0				O		O				
F2-1				O		O			O	
F2-2				O		O			O	O
I-0					O					
I-1					O				O	
I-2					O				O	O
MaF1-0	O						O			
MaF1-1	O						O		O	
MaF1-2	O						O		O	O
MaF2-0	O							O		
MaF2-1	O							O	O	
MaF2-2	O							O	O	O
MbF1-0		O					O			
MbF1-1		O					O		O	
MbF1-2		O					O		O	O
MbF2-0		O						O		
MbF2-1		O						O	O	
MbF2-2		O						O	O	O

containers and packaging including 0.151 kg of undesirable materials other than plastics. The system boundary of the recycling system is shown in Figs. 2 and 3. In material recycling (a), PE and PP mixed resin is produced, and in material recycling (b), HDPE, LDPE, PP, PS and PET single resins are produced. Removed plastics and other materials, i.e., residue from material recycling and feedstock recycling processes, are incinerated with power generation in the scenarios other than those including residue recycling. In independent plastic tray recycling, foamed PS trays are made into PS single resin, and transparent PS and PET trays are made into PS and PET single resins, respectively. All foamed PS trays and transparent PS and PET trays are assumed to be collected at retail points. The environmental loads of the substituted system, which includes the production of equivalent products substituted by the recycled products, are subtracted from those of the recycling system.

Inventories

For each scenario, net fossil resource consumption was calculated by summing the amounts of fossil resources consumed in all the processes of the recycling system (see Fig. 2) and upstream processes for supplying relevant raw materials and fuels, and by subtracting those consumed for supplying the equivalent substituted products. Similarly, net CO_2 emission was calculated by summing the amounts
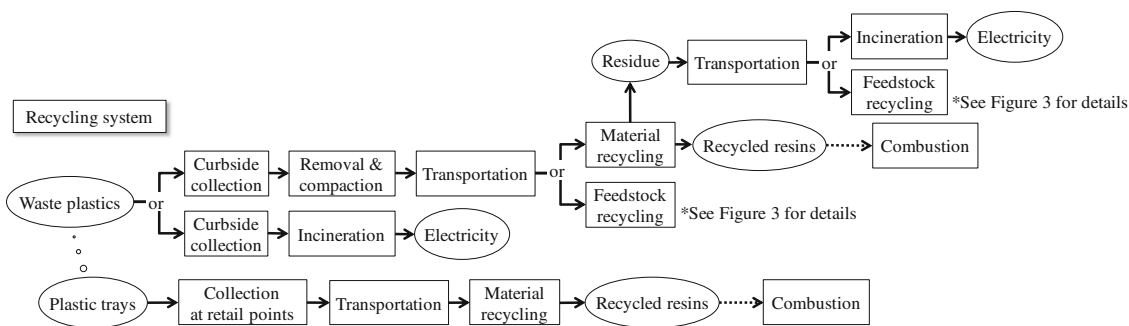
Fig. 2 System boundary of recycling system

of CO_2 emitted from all the processes of the recycling system, including the combustion of recycled products or waste plastics, and upstream processes, and by subtracting CO_2 emission for supplying and combusting the equivalent substituted products. The composition of waste plastics and the amounts of recycled and substituted resin in material recycling are shown in Fig. 4, which were obtained from modeling of the material recycling processes based on our field surveys and previous studies [2, 24, 25]. The amounts of recycled products and substituted products in coke oven chemical feedstock recycling and blast furnace feedstock recycling for each type of resin, obtained from the modeling of feedstock recycling processes based on previous studies [12, 14, 17], are shown in Tables 2 and 3, respectively. Power generation efficiency is assumed to be 20% for the energy recovery of household waste plastics in the I-0, I-1 and I-2 scenarios. For the energy recovery of the residue from material recycling and feedstock recycling processes, power generation efficiency is also assumed to be 20%.

A list of the inventories is shown in Table 4. The utility consumption of collection, transportation, coke oven chemical feedstock recycling, blast furnace feedstock recycling and incineration with power generation was quoted from published reports [14, 25–27] and databases [28]. For removal and compaction, and material recycling, utility consumption was obtained through our field surveys and databases [28]. The transportation distances of waste plastics between removal and compaction facilities and material recycling factories (a) and (b), between removal and compaction facilities and feedstock recycling factories, and between material recycling factories and incineration facilities are assumed to be 50 km.

In material recycling, the substitution rate of PE and PP mixed resin, produced by conventional material recycling (a), is assumed to be 50% (a substitution rate of 50% means that 100 g of recycled resin can substitute 50 g of virgin resin), which is the average value used in a published report [15]; that of PS and PET single resins, produced by independent material recycling, is assumed to be 75%,

which is calculated on the basis of the weight ratio between virgin and recycled foamed PS trays; and that of single resins, produced by conventional material recycling (b), is assumed to be 60%, which is the average value for PE and PP mixed resin and PS and PET single resins taking into consideration the recycling properties.

Results and discussion

The life cycle fossil resource consumption and CO_2 emission of the evaluated scenarios were calculated using the above-mentioned inventories. The results are shown in Fig. 5. Both indicators represent a similar tendency regarding relative overall environmental performances among the scenarios, except that CO_2 emission of recycling processes is comparably larger than that of the other processes in contrast to fossil resource consumption, because the former involves CO_2 emission due to combustion of the plastics themselves. It is found that the environmental loads of collection, removal and compaction, and transportation processes are much smaller than those of the other processes in all the scenarios. Net fossil resource consumption and CO_2 emission are smaller in all scenarios that include the recycling of household waste plastics compared with the I-0 scenario, which involves only energy recovery.

Scenarios including residue recycling

The MaF1-0 and MaF2-0 scenarios have smaller net environmental loads than the MaI-0 scenario. These results mean that the avoided environmental loads of production of the substituted products in the MaF1-0 and MaF2-0 scenarios are larger than those of the substituted grid electricity in the MaI-0 scenario, while the environmental loads of residue recycling in the MaF1-0 and MaF2-0 scenarios are slightly higher than those for the incineration of residue with power generation in the MaI-0 scenario. The same holds true for scenarios including material recycling (b); however, the differences in the net environmental loads

Coke oven chemical feedstock recycling

Blast furnace feedstock recycling
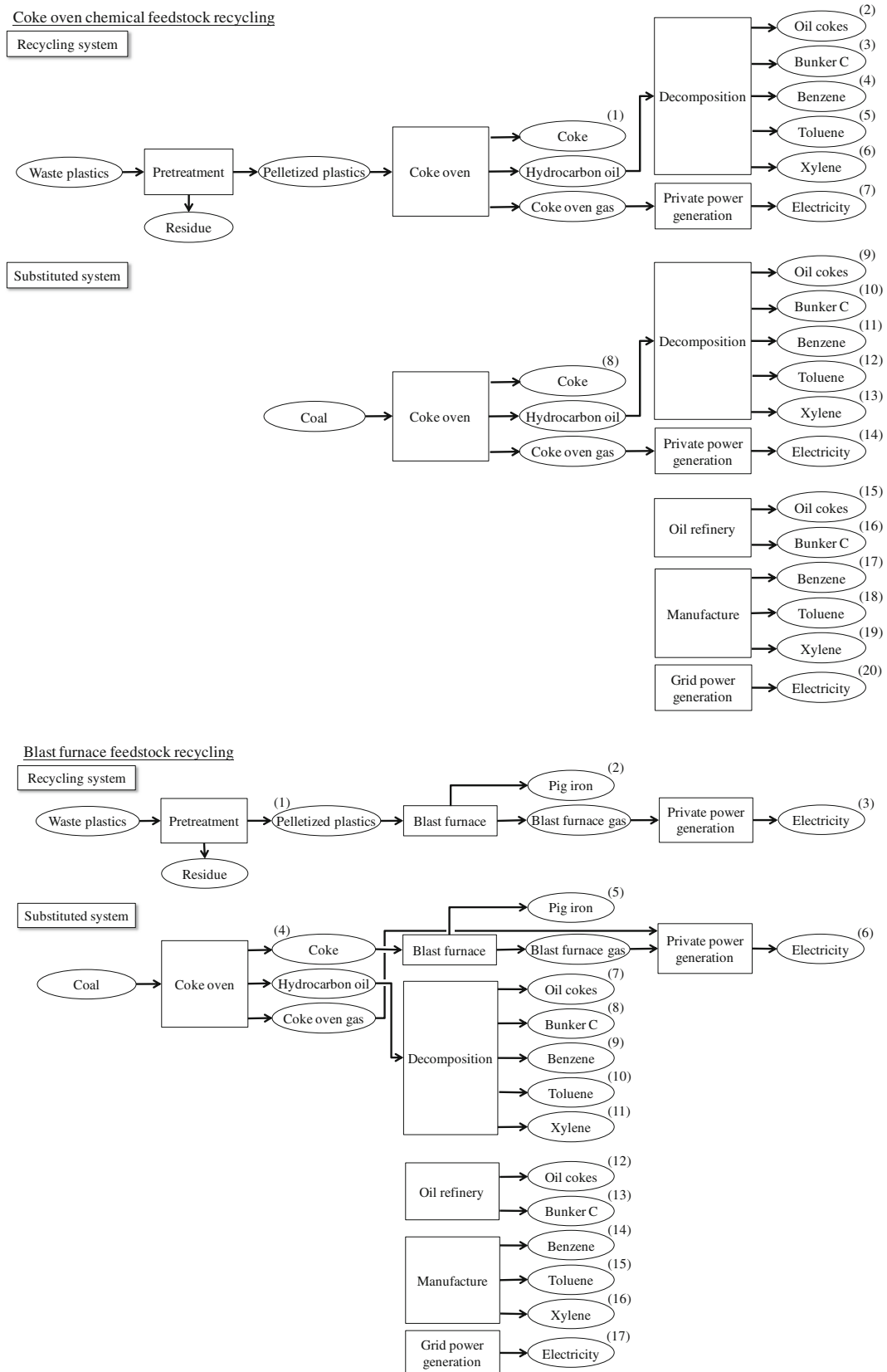
Fig. 3 Input and output products in recycling and substituted system in coke oven chemical feedstock recycling and blast furnace feedstock recycling. *Numbers* in parentheses correspond to those in Tables 2 and 3

Fig. 4 Composition of waste plastics, and types of recycled and substituted resin in material recycling (kg per 1 kg of waste plastics). *Values* in *italics* indicate recycled resins for independent plastic tray recycling and substituted virgin resins. The amount of substituted resin was calculated by multiplying the amount of corresponding recycled resin by the substitution rate. The waste plastic composition data was obtained from a composition survey of waste plastics by a specific material recycler [24]. The ratio of other materials was quoted from the Ministry of the Environment [25] and the Japan Plastic Containers and Packaging Recycling Association [14]. *LLDPE* linear low-density polyethylene, *PA* polyamide

Waste plastic composition		
HDPE		0.118
LDPE (LLDPE)		0.077
PE-PA		0.049
PE including aluminum		0.012
PE-PVDC, PET etc.		0.009
PP		0.114
PP including talc		0.036
PP including aluminum		0.025
PP-PET, PA etc.		0.033
PS	Foamed PS trays	0.068
	Transparent trays	0.016
	Others	0.098
Transparent PS		0.001
PS-PP		0.031
PS-PE etc.		0.020
PET	Transparent trays	0.021
	Others	0.044
PET-PE etc.		0.006
Other plastics		0.030
PVC, PVDC		0.042
Other materials		0.151

Recycled resin	MaI-0 / MaF1-0 / MaF2-0	MaI-1 / MaF1-1 / MaF2-1	MaI-2 / MaF1-2 / MaF2-2	MbI-0 / MbF1-0 / MbF2-0	MbI-1 / MbF1-1 / MbF2-1	MbI-2 / MbF1-2 / MbF2-2	Recycled resin
PE and PP mixed resin	0.472	0.472	0.472	0.118	0.118	0.118	HDPE
				0.126	0.126	0.126	LDPE
				0.150	0.150	0.150	PP
PS		*0.068*	*0.084*	0.234	0.166 *0.068*	0.150 *0.084*	PS
PET			*0.021*	0.071	0.071	0.050 *0.021*	PET

Substituted virgin resin	MaI-0 / MaF1-0 / MaF2-0	MaI-1 / MaF1-1 / MaF2-1	MaI-2 / MaF1-2 / MaF2-2	MbI-0 / MbF1-0 / MbF2-0	MbI-1 / MbF1-1 / MbF2-1	MbI-2 / MbF1-2 / MbF2-2	Substituted virgin resin
HDPE	0.059	0.059	0.059	0.071	0.071	0.071	HDPE
LDPE	0.059	0.059	0.059	0.076	0.076	0.076	LDPE
PP	0.118	0.118	0.118	0.090	0.090	0.090	PP
PS		*0.051*	*0.063*	0.140	*0.051* 0.100	*0.063* 0.090	PS
PET			*0.016*	0.043	0.043	*0.016* 0.030	PET

between the MbF1-0 or MbF2-0 scenario and the MbI-0 scenario are smaller than those between the MaF1-0 or MaF2-0 scenario and the MaI-0 scenario, because the amount of plastics included in the residue is larger in material recycling (a), 0.377 kg per 1 kg of household waste plastics, than in material recycling (b), 0.151 kg per 1 kg of household waste plastics. However, the F1-0 scenario has smaller net environmental loads than the MaF1-0 and MbF1-0 scenarios. The F2-0 scenario also has smaller net environmental loads than the MaF2-0 and MbF2-0 scenarios. The results indicate that the net environmental loads are reduced through coke oven chemical feedstock recycling or blast furnace feedstock recycling of residue from material recycling (a) or (b) processes, and that the additional environmental saving of residue recycling is maximized when it is integrated with conventional material recycling (a). However, the net environmental loads are smaller in scenarios where household waste plastics are directly utilized through coke oven chemical feedstock recycling in steel works.

Scenarios including independent plastic tray recycling

The net environmental loads in scenarios including the independent recycling of foamed PS trays are smaller than those in the corresponding scenarios without independent plastic tray recycling, and those in scenarios with the independent recycling of both foamed PS trays and transparent trays are even smaller. For example, the net environmental loads in the MaI-1 scenario are smaller than those in the MaI-0 scenario, and those in the MaI-2 scenario are even smaller. The differences in environmental loads among the I-0, I-1 and I-2 scenarios or the MaI-0, MaI-1, and MaI-2 scenarios are comparatively large, because foamed PS trays and/or transparent PS and PET trays, which would otherwise be incinerated as combustibles or residue from the material recycling (a) processes, are utilized through independent plastic tray recycling. On the other hand, the differences in environmental loads among the MbI-0, MbI-1 and MbI-2 scenarios, the F1-0, F1-1 and F1-2 scenarios, or the F2-0, F2-1 and F2-2 scenarios are comparatively small. This is because foamed PS trays and/or transparent PS and PET trays, which would be utilized through independent plastic tray recycling, are also utilized through conventional material recycling (b) or feedstock recycling. The results indicate that the net environmental loads can be reduced through independent plastic tray recycling, particularly through independent recycling of both foamed PS trays and transparent trays, and that the environmental load reduction through independent plastic tray recycling depends on the type of conventional recycling integrated with it. The additional

Table 2 Amounts of products in recycling and substituted system for each resin in coke oven chemical feedstock recycling (per 1 kg of waste plastics)

	PE	PP	PS	PET
Products in recycling system				
(1) Coke (kg)	0.110	0.136	0.187	0.068
(2) Oil cokes (kg)	X_{11}	X_{12}	X_{13}	X_{14}
(3) Bunker C (kg)	X_{21}	X_{22}	X_{23}	X_{24}
(4) Benzene (kg)	X_{31}	X_{32}	X_{33}	X_{34}
(5) Toluene (kg)	X_{41}	X_{42}	X_{43}	X_{44}
(6) Xylene (kg)	X_{51}	X_{52}	X_{53}	X_{54}
(7) Electricity (kWh)	X_{61}	X_{62}	X_{63}	X_{64}
Products in substituted system				
(8) Coke (kg)	0.110	0.136	0.187	0.068
(9) Oil cokes (kg)	$X_{11} - 0.050$	$X_{12} - 0.076$	$X_{13} - 0.109$	$X_{14} - 0.043$
(10) Bunker C (kg)	$X_{21} - 0.042$	$X_{22} - 0.063$	$X_{23} - 0.090$	$X_{24} - 0.036$
(11) Benzene (kg)	$X_{31} - 0.117$	$X_{32} - 0.179$	$X_{33} - 0.256$	$X_{34} - 0.102$
(12) Toluene (kg)	$X_{41} - 0.028$	$X_{42} - 0.043$	$X_{43} - 0.062$	$X_{44} - 0.025$
(13) Xylene (kg)	$X_{51} - 0.003$	$X_{52} - 0.005$	$X_{53} - 0.007$	$X_{54} - 0.003$
(14) Electricity (kWh)	$X_{61} - 2.654$	$X_{62} - 1.802$	$X_{63} - 0.619$	$X_{64} - 3.080$
(15) Oil cokes (kg)	0.050	0.076	0.109	0.043
(16) Bunker C (kg)	0.042	0.063	0.090	0.036
(17) Benzene (kg)	0.117	0.179	0.256	0.102
(18) Toluene (kg)	0.028	0.043	0.062	0.025
(19) Xylene (kg)	0.003	0.005	0.007	0.003
(20) Electricity (kWh)	2.654	1.802	0.619	3.080

Table 3 Amounts of products in recycling and substituted system for each resin in blast furnace feedstock recycling (per 1 kg of waste plastics)

	PE	PP	PS	PET
Products in recycling system				
(1) Pelletized plastics (kg)	0.849	0.849	0.849	0.849
(2) Pig iron (kg)	Y_{11}	Y_{12}	Y_{13}	Y_{14}
(3) Electricity (kWh)	Y_{21}	Y_{22}	Y_{23}	Y_{24}
Products in substituted system				
(4) Coke (kg)	0.994	0.858	1.087	0.484
(5) Pig iron (kg)	Y_{11}	Y_{12}	Y_{13}	Y_{14}
(6) Electricity (kWh)	$Y_{21} + 0.098$	$Y_{22} - 0.222$	$Y_{23} + 0.535$	$Y_{24} - 0.157$
(7) Oil cokes (kg)	0.005	0.004	0.005	0.002
(8) Bunker C (kg)	0.004	0.004	0.004	0.002
(9) Benzene (kg)	0.038	0.032	0.041	0.018
(10) Toluene (kg)	0.009	0.008	0.010	0.004
(11) Xylene (kg)	0.001	0.001	0.001	0.001
(12) Oil cokes (kg)	−0.005	−0.004	−0.005	−0.002
(13) Bunker C (kg)	−0.004	−0.004	−0.004	−0.002
(14) Benzene (kg)	−0.038	−0.032	−0.041	−0.018
(15) Toluene (kg)	−0.009	−0.008	−0.010	−0.004
(16) Xylene (kg)	−0.001	−0.001	−0.001	−0.001
(17) Electricity (kWh)	−0.098	0.222	−0.535	0.157

Table 4 List of the inventories

Unit process	Input	Output
Collection [25, 28]	Waste plastics 1.00 kg	Waste plastics 1.00 kg
	Diesel oil 0.032 L	CO_2 0.090 kg-CO_2
Removal and compaction[a] [28]	Waste plastics 1.09 kg	Waste plastics 1.00 kg
		Residue 0.09 kg
	Electricity 0.102 kWh	CO_2 0.069 kg-CO_2
	Diesel oil 0.008 L	
Transportation [12, 26–28]	Waste plastics 1.00 kg	Waste plastics 1.00 kg
	Diesel oil 0.010 L	CO_2 0.028 kg-CO_2
Material recycling (a)[a] [28]	Waste plastics 1.00 kg	Recycled resin: see Fig. 4
		Residue: see Fig. 4
	Electricity 0.494 kWh	CO_2 0.233 kg-CO_2
	Bunker C 0.002 L	
	Industrial water 0.002 m^3	
	Sodium hydroxide 0.009 kg	
Material recycling (b)[a] [28]	Waste plastics 1.00 kg	Recycled resin: see Fig. 4
		Residue: see Fig. 4
	Electricity 0.649 kWh	CO_2 0.304 kg-CO_2
	Bunker C 0.002 L	
	Industrial water 0.002 m^3	
	Sodium hydroxide 0.009 kg	
Material recycling of foamed PS trays[a] [28]	Waste plastics 1.00 kg	Recycled resin: see Fig. 4
		Residue: see Fig. 4
	Electricity 0.905 kWh	CO_2 0.425 kg-CO_2
	LPG 0.002 kg	
	Tap water 0.006 m^3	
Material recycling of transparent trays[a] [28]	Waste plastics 1.00 kg	Recycled resin: see Fig. 4
		Residue: see Fig. 4
	Electricity 0.748 kWh	CO_2 0.339 kg-CO_2
Pretreatment for coke oven chemical feedstock recycling [14, 28]	Waste plastics 1.00 kg	Pelletized plastics
		Residue
	Electricity 0.294 kWh	CO_2 0.133 kg-CO_2
Pretreatment for blast furnace feedstock recycling [14, 28]	Waste plastics 1.00 kg	Pelletized plastics
		Residue
	Electricity 0.291 kWh	CO_2 0.164 kg-CO_2
	Kerosene 0.008 L	
	Diesel oil 0.004 L	
Incineration [26–28]	Waste plastics 1.00 kg	CO_2 emitted by combustion
	Electricity 0.115 kWh	CO_2 0.056 kg-CO_2
	Bunker A 0.001 L	
Manufacture of HDPE [28]	Electricity 0.080 kWh	HDPE 1.00 kg
	Diesel oil 0.051 L	CO_2 1.39 kg-CO_2
	Bunker A 0.048 L	
	Bunker C 0.048 L	
	LPG 0.035 kg	
	Naphtha 1.55 L	
	NGL 0.041 kg	

Table 4 continued

Unit process	Input	Output
Manufacture of LDPE [28]	Electricity 0.301 kWh	LDPE 1.00 kg
	Diesel oil 0.070 L	CO_2 1.70 kg-CO_2
	Bunker A 0.065 L	
	Bunker C 0.065 L	
	LPG 0.038 kg	
	Naphtha 1.57 L	
	NGL 0.042 kg	
Manufacture of PP [28]	Electricity 0.159 kWh	PP 1.00 kg
	Diesel oil 0.055 L	CO_2 1.54 kg-CO_2
	Bunker A 0.051 L	
	Bunker C 0.051 L	
	LPG 0.039 kg	
	Naphtha 1.57 L	
	NGL 0.042 kg	
	Other fuel 2.07 MJ	
Manufacture of PS [28]	Electricity 0.133 kWh	PS 1.00 kg
	Diesel oil 0.065 L	CO_2 1.72 kg-CO_2
	Bunker A 0.061 L	
	Bunker C 0.061 L	
	LPG 0.037 kg	
	Naphtha 1.62 L	
	NGL 0.033 kg	
	Oxygen 0.012 kg	
Manufacture of PET [28]	Electricity 0.380 kWh	PET 1.00 kg
	Diesel oil 0.060 L	CO_2 1.69 kg-CO_2
	Bunker A 0.056 L	
	Bunker C 0.056 L	
	LPG 0.023 kg	
	Naphtha 1.29 L	
	NGL 0.006 kg	
	Oxygen 0.416 kg	
	Water 0.080 kg	
	LNG 0.014 kg	
Oil refinery for oil cokes[b] [14]	Energy 45.2 MJ	Oil cokes 1.00 kg
		CO_2 3.60 kg-CO_2
Oil refinery for bunker C [28]	Crude oil 1.00 L	Bunker C 1.00 L
	Electricity 0.0075 kWh	CO_2 3.11 kg-CO_2
Manufacture of benzene[b] [14]	Energy 51.7 MJ	Benzene 1.00 kg
		CO_2 3.95 kg-CO_2
Manufacture of toluene[b] [14]	Energy 51.7 MJ	Toluene 1.00 kg
		CO_2 3.91 kg-CO_2
Manufacture of xylene[b] [14]	Energy 51.7 MJ	Xylene 1.00 kg
		CO_2 3.88 kg-CO_2

[a] Inventories obtained from our field surveys

[b] Only energy consumption and CO_2 emission could be obtained

Fig. 5 Fossil resource consumption (1) and CO_2 emission (2) for each phase
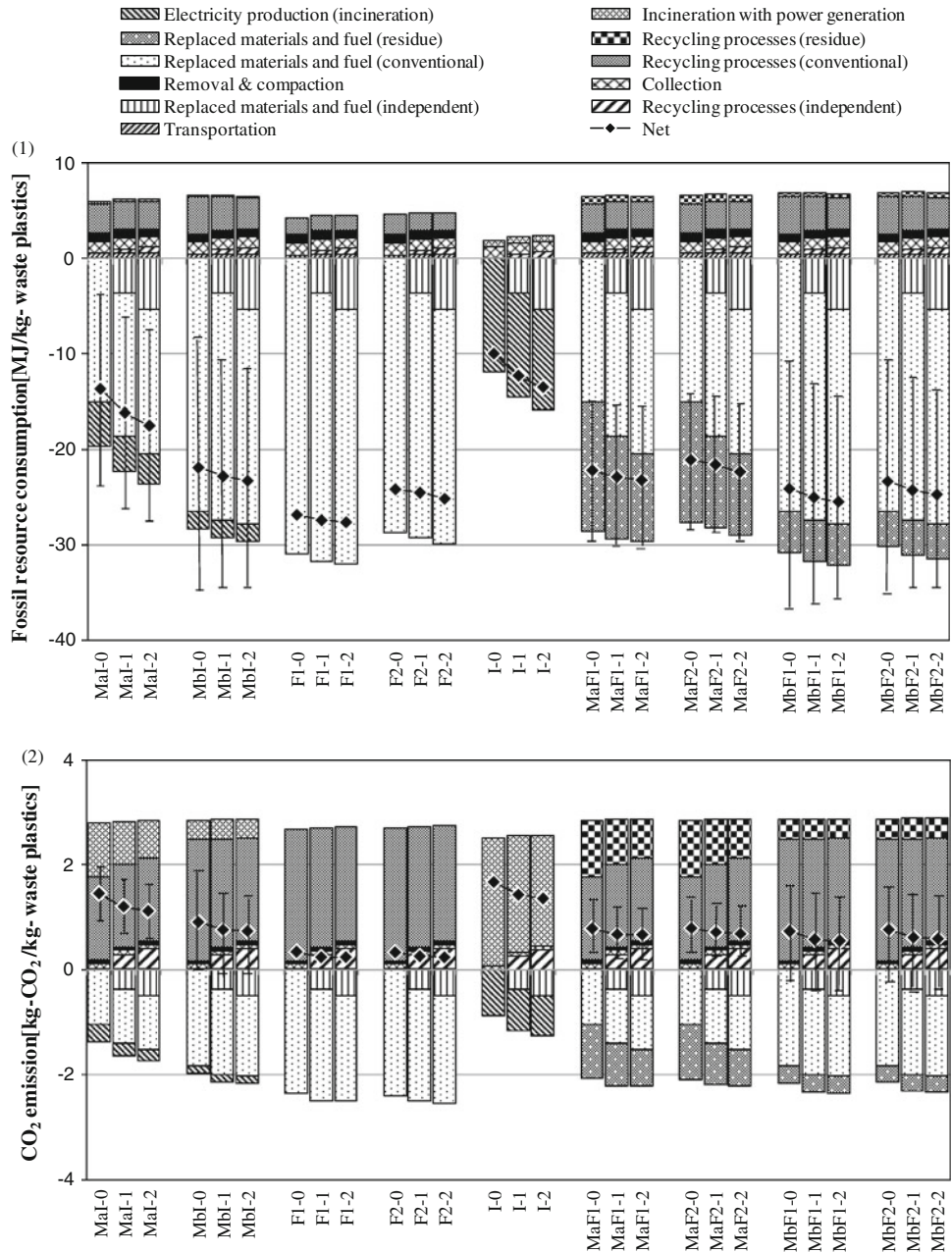
environmental saving of independent plastic tray recycling is maximized when it is integrated with conventional material recycling (a) or energy recovery.

Scenarios including both residue recycling and independent plastic tray recycling

Scenarios where both residue recycling and independent plastic tray recycling are integrated with conventional material recycling have smaller environmental loads than the corresponding scenarios without independent plastic tray recycling (the MaF1-0, MaF2-0, MbF1-0 and MbF2-0 scenarios). For the MaF1-1, MaF1-2, MaF2-1 and MaF2-2

scenarios, the plastic trays utilized through independent plastic tray recycling would otherwise be utilized through the feedstock recycling of residue in the MaF1-0 or MaF2-0 scenario. This results in a smaller additional reduction of environmental loads through independent plastic tray recycling compared with the additional recycling in scenarios where only independent plastic tray recycling is integrated with material recycling (a), i.e., the MaI-1 and MaI-2 scenarios. The results indicate that independent plastic tray recycling exhibits the lower additional environmental saving when residue recycling is integrated with conventional material recycling (a), because both additional recycling schemes aim to utilize PS and PET, which

would otherwise be incinerated as residue from the material recycling (a) processes.

Sensitivity analysis

Sensitivity analysis was conducted to examine the validity of the critical assumptions. The results showed that, in the range of plus or minus 50% for each parameter, both fossil resource consumption and CO_2 emission were the most sensitive to the substitution rate of recycled resins produced by conventional material recycling (a) and (b). Therefore, the results of sensitivity analysis for the substitution rate of recycled resins are indicated by error bars in Fig. 5.

Conclusions

In this study, we evaluated and compared recycling schemes for household waste plastic containers and packaging from the viewpoints of fossil resource consumption and CO_2 emission. Various scenarios were developed through integrating the conventional recycling scheme, which involved municipal curbside collection and either material recycling or feedstock recycling, with a couple of additional recycling schemes, i.e., feedstock recycling of the residue from conventional material recycling processes and/or independent material recycling of foamed PS trays and transparent trays.

Both indicators represented a similar tendency regarding relative overall environmental performances among the scenarios, except that CO_2 emission of recycling processes was comparably larger than that of the other processes in contrast to fossil resource consumption, because CO_2 emission of recycling processes involved CO_2 emission due to combustion of the plastics themselves. Among all scenarios, the net environmental loads were smaller in scenarios integrating independent plastic tray recycling with coke oven chemical feedstock recycling, and they were reduced in all scenarios including the additional recycling schemes compared with the corresponding scenarios that only involved conventional recycling or energy recovery. The residue recycling scheme and independent plastic tray recycling scheme maximized their additional environmental saving when they were integrated with conventional material recycling (a). On the other hand, independent plastic tray recycling exhibited a lower additional reduction when residue recycling was integrated with conventional material recycling (a), because both additional recycling schemes aimed to utilize PS and PET, which would otherwise be incinerated as residue from the material recycling (a) processes. The same was true of material recycling (b), and the overall environmental loads

in scenarios including material recycling (b) were smaller than those in scenarios including material recycling (a).

The practical implications obtained from this study are summarized below. In the case where no recycling schemes of waste plastics have yet been introduced, independent material recycling of foamed PS trays and transparent trays integrated with coke oven chemical feedstock recycling of the other waste plastics should be chosen from the viewpoints of reduction of the net environmental loads. In the case where conventional material recycling (a) or (b) schemes have already been introduced, independent material recycling of foamed PS trays and transparent trays integrated with coke oven chemical feedstock recycling of the residue from material recycling processes should be chosen, and if only one additional recycling scheme can be introduced, the addition of coke oven chemical feedstock recycling of the residue from material recycling processes can maximize the additional environmental saving.

In this paper, it was found that the additional environmental saving through the additional recycling schemes depended on the type of the conventional recycling scheme integrated with them. The results empirically indicated that evaluation of the environmental loads of individual recycling technologies, as conducted in previous studies, was insufficient to investigate recycling schemes that maximize the net environmental performance of the whole recycling system. In this paper, to evaluate and compare the overall environmental performance in scenarios including additional recycling schemes, LCA based on the modeling of recycling processes considering the resin composition of waste plastics in terms of the quantity of each recycled product was applied from the viewpoints of the whole recycling system, which made it possible to investigate recycling schemes that integrate different technologies to maximize their environmental potential. Evaluation from both bird's-eye and insect's-eye viewpoints is an essential step in investigating more desirable recycling systems.

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