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LCA OF WASTE MANAGEMENT SYSTEMS

Life-cycle assessment of domestic and transboundary recycling of post-consumer PET bottles

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Abstract

Background, aim, and scope In recent years, besides being recycled domestically, a part of Japanese post-consumer polyethylene terephthalate (PET) bottles have been exported to and recycled in mainland China. In this study, life-cycle assessment (LCA) was applied to compare domestic and transboundary recycling scenarios between Japan and China and disposal scenarios from the viewpoints of greenhouse gases (GHG) emission and fossil resource consumption.

Methods The following 10 scenarios based on our field surveys were evaluated: Japanese post-consumer PET bottles are (i) recycled into polyester staple in Japan, (ii) recycled into polyester filaments in Japan, (iii) recycled into polyester clothes in Japan, (iv) chemically decomposed and recycled into bottle-grade PET resin in Japan, (v) chemically decomposed and recycled into polyester filaments in Japan, (vi)–(vii) recycled into polyester staple via two different flows in China, (viii) recycled into polyester clothes in China, (ix) incinerated and partly recovered as electricity in Japan, and (x) directly landfilled in Japan. In all the evaluated scenarios, the functional unit is the recycling or disposal of 1 kg of Japanese post-consumer PET bottles. The system boundaries range from waste collection by municipalities to the manufacture of recycled products that can be regarded as substitutes for virgin products, and a credit for the avoided production of equivalent virgin products is given to each scenario. The inventories of both foreground and background processes in Japan were quoted from published reports and databases. The actual conditions of PET bottle recycling that were obtained through field surveys in China were reflected to some inventories of foreground processes in China. The inventories of public electricity supplies in China were based on the national statistics, and the inventories of petroleum products, industrial water supply, and waste treatment are based on our field surveys in China. Other unknown inventories in China were substituted by corresponding inventories in Japan.

Results and discussion The results showed that all the domestic and transboundary recycling scenarios had smaller GHG emissions and fossil resource consumptions than the incineration scenario and that the chemical recycling scenarios had larger GHG emissions and fossil resource consumptions than the other recycling scenarios. The landfilling scenario had the largest fossil resource consumption, while it was better than the incineration scenario and slightly better than the chemical recycling scenarios from the viewpoint of GHG emission. The robustness of the results was examined, and it was found that the differences in GHG emission and fossil resource consumption between the domestic and transboundary recycling scenarios, other than the scenarios including cloth-manufacturing processes in system boundaries, were sufficiently large to be robust against the variability of background parameters for electricity supplies. As for the

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variability against the substitutions between recycled products and virgin products, interchanging the producer countries of substituted virgin products decreases the GHG emissions and fossil resource consumptions of the domestic recycling scenarios, but increases those of the transboundary scenarios.
Conclusions When recycling systems between different countries are compared using LCA, it should be noted that the differences in background parameters have an impact on the environmental burdens of recycling and avoided manufacturing processes, and therefore, the result depends on the identification of the producer countries of the virgin products that are substituted by recycled products. However, it is practically impossible to identify in which country the manufacture of virgin products are avoided by recycling. Therefore, it is recommended that the results be presented according to the relationships between recycled and substituted virgin products as described in this paper.

Keywords Background parameter · China · Domestic recycling · Japan · Post-consumer PET bottle · Substituted virgin product · Transboundary recycling · Variability

1 Introduction

In Japan, the recycling of post-consumer polyethylene terephthalate (PET) bottles has been promoted under the national recycling law since 1997, and the collection rate for recycling purposes reached 87.7% in 2007 (Council for PET Bottle Recycling, Japan 2008). In Japan, collected post-consumer PET bottles are processed into recycled PET resin by mechanical operations such as shredding, washing, and melting (mechanical recycling) or by chemical operations where waste PET bottles are decomposed into monomers of PET, either purified terephthalic acid (PTA), dimethyl terephthalate (DMT), or bis (2-hydroxyethyl) terephthalate, and repolymerized into PET (chemical recycling). Mechanically recycled PET resin is used as raw materials for polyester filament and staple products, PET sheet products, and molded products. On the other hand, chemically recycled PET resin is used as raw materials for beverage PET bottles and polyester filament products.

In recent years, besides being recycled domestically, some Japanese post-consumer PET bottles are being exported to and recycled in mainland China. As shown in Fig. 1, among the total amount of PET bottles designated by the national recycling law of 573,000 tons in 2007, 270,000 tons were collected for domestic recycling purposes, whilst the amount of exported post-consumer PET bottles was estimated to be 295,000 tons (Council for PET Bottle Recycling, Japan 2008). The advantages and disadvantages of such transboundary recycling over domestic recycling are widely discussed.

Many life-cycle assessment (LCA) studies have evaluated the domestic recycling system of waste PET bottles in Japan (e.g., Fukushima and Hirao 1998; Tokai and Furuichi 2000; Sugiyama et al. 2006; Matsuda and Kubota 2008). Mechanical recycling systems of post-consumer plastics, including PET bottles, in other countries have also been evaluated (e.g., Arena et al. 2003; Perugini et al. 2005; Romero-Hernandez et al. 2009). However, to the best of our knowledge, there exist no studies on the evaluation and comparison of environmental burdens of domestic and transboundary recycling systems with consideration given to the differences in recycling processes and background parameters between countries.

In this study, LCA is applied to evaluate and compare the recycling and disposal scenarios of Japanese post-consumer PET bottles, including domestic and transboundary recycling between Japan and China, from the viewpoints of greenhouse gases (GHG) emission and fossil resource consumption. Those two impact categories were selected as environmental indicators of plastics recycling because plastics are typically made from fossil resources and therefore can be significant GHG, in particular CO_2, emission sources. In what follows, "domestic recycling" is defined as a recycling system of which all processes in the system boundary are located in Japan, and "transboundary recycling" is defined as a recycling system in which either process is located in China. The inventories of both foreground and background processes in Japan were quoted from published reports and databases, and those in China were based on the national statistics and our field surveys in China, or substituted by corresponding inventories in Japan. The robustness of the results is examined against the variability of background parameters for electricity supplies and against the substitutions between recycled products and virgin products.

2 Materials and methods

2.1 Evaluated scenarios

Ten scenarios presented in Table 1, based on our field surveys in Japan and China from 2006 to 2007, were evaluated. In these scenarios, Japanese post-consumer PET bottles are (i) recycled into polyester staple in Japan, (ii) recycled into polyester filaments in Japan, (iii) recycled into polyester staple and then clothes in Japan, (iv) chemically decomposed into PTA and then recycled into bottle-grade PET resin in Japan, along with polyester filaments obtained as coproducts, (v) chemically decomposed into DMT and then recycled into polyester filaments in Japan, (vi)–(vii) recycled into polyester staple via two different flows in China, (viii) recycled into polyester staple and then clothes

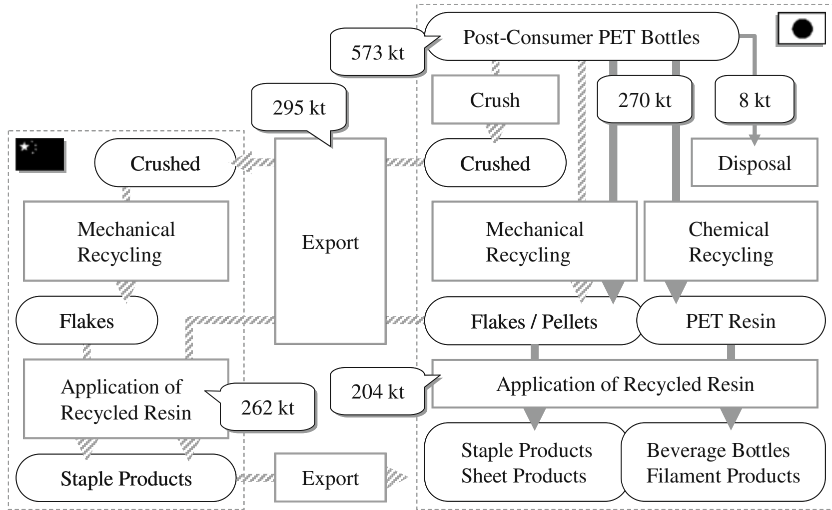


Fig. 1 Domestic and transboundary recycling flows of Japanese post-consumer PET bottles

Notes: Solid and dotted lines denote the domestic and transboundary recycling flows, respectively. Fine dashed lines denote the national borders of Japan and China. The source of the amounts of materials is Council for PET Bottle Recycling, Japan (2008).

in China, (ix) incinerated and partly recovered as electricity (power generation efficiency, 10%), and (x) directly landfilled in Japan. Those scenarios are named “domestic MR scenario A,” “transboundary MR scenario C,” “incineration scenario,” and so on (see Table 1). In other words, scenarios (i)–(iii) and (v) are categorized into “domestic open-loop recycling,” scenario (iv) falls under “domestic closed-loop recycling,” and scenarios (vi)–(viii) are “transboundary open-loop recycling.”

Among 204,000 tons of domestically recycled PET resin in 2007 (see Fig. 1), 41% was used as raw materials for fiber products corresponding to the domestic MR scenarios A, B, C, and CR scenario B, and 4% for beverage bottles corresponding to the domestic CR scenario A (Council for PET Bottle Recycling, Japan 2008). As for the transboundary recycling (295,000 tons were exported in 2007), our field surveys in China found that recycled PET resin was predominantly used as raw materials for polyester staple corresponding to the transboundary MR scenarios A and B, but could not identify recycled PET resin used for polyester clothes corresponding to the transboundary MR scenarios C.

In all the evaluated scenarios, the functional unit is the recycling or disposal of 1 kg of Japanese waste PET bottles. The system boundaries range from waste collection and pretreatment by municipalities, transportation including export to China, down to waste treatment or the manufacture of recycled products that can be regarded as substitutes for virgin products, and a credit for the avoided production of equivalent virgin polyester/PET products or public electricity in the same country as recycling processes is given to each scenario (system expansion). For example, the avoided production of 0.739 kg of virgin polyester staple in Japan, 0.557 kg of virgin polyester clothes in China, and 0.607 kW h of public electricity are credited in the domestic MR scenario A, the transboundary MR scenario C, and the incineration scenario, respectively.

2.2 Inventories

The inventories of both foreground and background processes in Japan were quoted from published reports and databases (Japan PET Bottle Association and Industrial Information Research Center 2004; Fujii et al. 2007; JLCA 2008). The actual conditions of PET bottle recycling that were obtained through field surveys in China were reflected in some inventories of foreground processes in China. For example, inventories of mechanical recycling processes in China were estimated with consideration given to modules that were found to be included in Chinese mechanical recycling processes and module-by-module inventories of Japanese mechanical recycling processes. Coal was assumed to be the heat source of recycling processes in China, whereas heavy oil was assumed for Japan. The inventories of public electricity supplies in China were based on the national statistics (National Bureau of Statistics and National Development and Reform Commission, People’s Republic of China 2007), and the CO_2 emission factor of Chinese coal was quoted from the statistics (IEA 1999). The inventories of petroleum products (mining and refinery processes), industrial water supply, waste treatment, and some chemicals (caustic soda and quick lime) are based on our field surveys in China and Kobayashi et al. (2008). Other unknown inventories in China were substituted by corresponding inventories in Japan. The details of inventories are given in Online Resource. GHG emission was evaluated in CO_2 equivalent

Table 1 Summary of the 10 evaluated scenarios: domestic mechanical recycling (D-MR), domestic chemical recycling (D-CR), and transboundary mechanical recycling (T-MR) scenarios

Scenario	Recycling/disposal process	Substituted virgin product
(i) D-MR A	Waste bottles: 1.000 kg>flakes: 0.768 kg>staple: 0.739 kg	Polyester staple in Japan, 0.739 kg
(ii) D-MR B	Waste bottles: 1.000 kg>pellets: 0.757 kg>filaments: 0.721 kg	Polyester filaments in Japan, 0.721 kg
(iii) D-MR C	Waste bottles: 1.000 kg>flakes: 0.768 kg>staple: 0.739 kg>clothes: 0.503 kg	Polyester clothes in Japan, 0.503 kg
(iv) D-CR A	Waste bottles: 1.000 kg>(PTA)>bottle-grade PET rein: 0.731 kg, and filaments: 0.083 kg	Bottle-grade PET resin in Japan, 0.731 kg and polyester filaments in Japan, 0.083 kg
(v) D-CR B	Waste bottles: 1.000 kg>(DMT)>fiber-grade PET rein: 0.874 kg>filaments: 0.832 kg	Polyester filaments in Japan, 0.832 kg
(vi) T-MR A	Waste bottles: 1.000 kg>[export]>flakes: 0.882 kg>staple: 0.818 kg	Polyester staple in China, 0.818 kg
(vii) T-MR B	Waste bottles: 1.000 kg>flakes: 0.768 kg>[export]>staple: 0.739 kg	Polyester staple in China, 0.739 kg
(viii) T-MR C	Waste bottles: 1.000 kg>[export]>flakes: 0.882 kg>staple: 0.818 kg>clothes: 0.557 kg	Polyester clothes in China, 0.557 kg
(ix) Incineration	Waste bottles: 1.000 kg>[incineration]> electricity: 0.607 kW h	Public electricity in Japan, 0.607 kW h
(x) Landfilling	Waste bottles: 1.000 kg>[landfilling]	(Nothing)

based on Global Warming Potentials with the time horizon of 100 years, 1, 23, and 296 for CO_2, CH_4, and N_2O, respectively (IPCC 2001).

3 Results

The life-cycle GHG emissions and fossil resource consumptions of the evaluated scenarios were calculated using the above-mentioned inventories. The results are shown in Fig. 2. It is found that GHG emissions and fossil resource consumptions of waste collection, pretreatment, and transportation including export and import are much smaller than those of the other processes in all the scenarios. All the domestic and transboundary recycling scenarios have smaller GHG emissions and fossil resource consumptions than the incineration scenario, which indicates the importance of recycling post-consumer PET bottles. The chemical recycling scenarios have larger GHG emissions than the mechanical recycling scenarios. The landfilling scenario had the largest fossil resource consumption, while it was better than the incineration scenario and slightly better than the chemical recycling scenarios from the viewpoint of GHG emission.

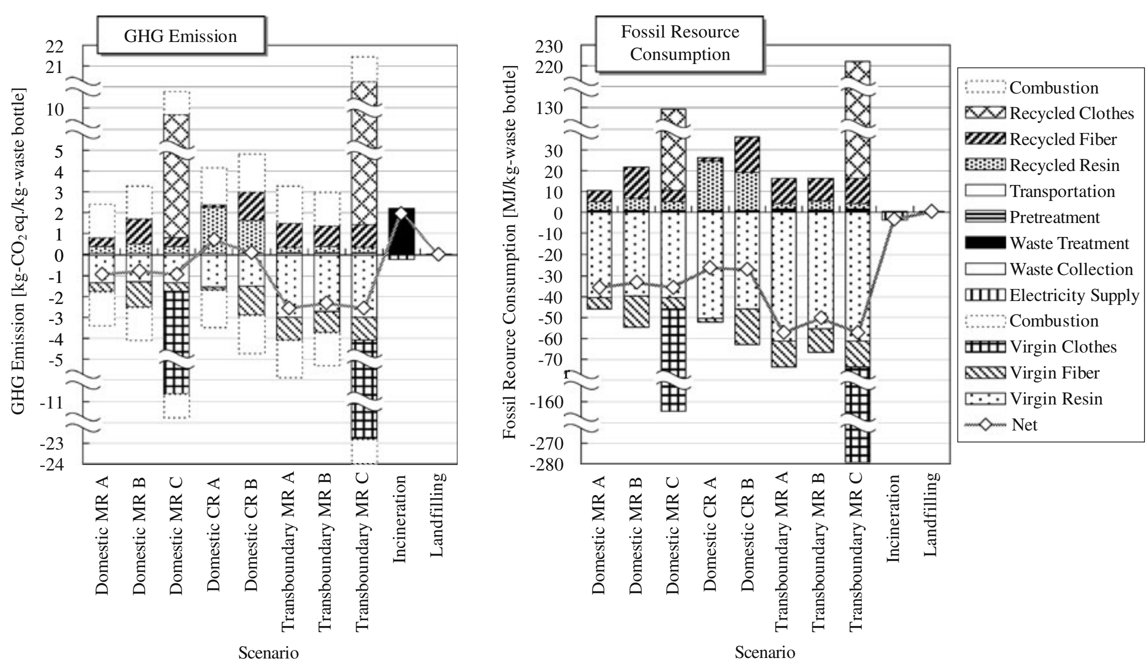


Fig. 2 GHG emissions and fossil resource consumptions of the evaluated scenarios

The domestic MR scenarios A and C, which have the smallest GHG emissions and fossil resource consumption among the domestic recycling scenarios, have larger GHG emissions and fossil resource consumptions than the transboundary MR scenarios A and C. This difference results from the relatively large impacts of the avoided manufacturing processes of virgin products in China. Critical factors are the differences in background parameters between Japan and China, particularly for electricity supplies (the life-cycle GHG emission and fossil resource consumption factors for 1 kW h of electricity are 0.40 kg-CO_2 eq. and 5.7 MJ in Japan and 1.01 kg-CO_2 eq. and 10.5 MJ in China, respectively) and naphtha production (those for 1 l of naphtha are 0.19 kg-CO_2 eq. and 37.7 MJ in Japan, and 0.71 kg-CO_2 eq. and 44.5 MJ in China, respectively).

The results show that the domestic MR scenario B (post-consumer PET bottles are recycled into polyester filaments) has slightly larger GHG emission and fossil resource consumption than the domestic MR scenario A (recycled into polyester staple). This is because the raw materials of the substituted virgin products are the same, that is, fiber-grade PET resin, in both scenarios, while the pelletizing process required for recycling into filaments requires additional energy input. Similarly, the domestic CR scenario A (recycled into bottle-grade PET resin) has larger GHG emission and fossil resource consumption than the domestic CR scenario B (recycled into fiber-grade PET resin) because the impacts of manufacturing processes do not markedly differ between virgin bottle-grade and fiber-grade PET resins, while the hydrolysis of DMT into PTA required for recycling into bottle-grade PET resin needs additional energy input. These results indicate that, as far as there are demands for relatively low-quality materials, the significance of the quality improvement of recycled materials is not necessarily reflected in the results of LCA.

For the domestic MR scenarios A (recycled into polyester staple) and C (recycled into polyester staple and then polyester clothes), although the impacts of recycling or manufacturing processes for substituted virgin products are much larger in the latter scenario, the net GHG emissions and fossil resource consumptions are identical between the two scenarios. Much the same is true for the transboundary MR scenarios A and C. This is because fuel consumptions and yield ratio of cloth-manufacturing processes, where polyester staple as a raw material is processed into clothes, are assumed to be identical regardless of whether the raw material is recycled or virgin staple (see Electronic supplementary materials). In such cases, the substitutions between recycled and virgin products, i.e., virgin staple is substituted with recycled staple, or virgin clothes are substituted with recycled clothes, have no effect on the results of LCA as long as recycled products are manufactured in the same country as the substituted virgin products.

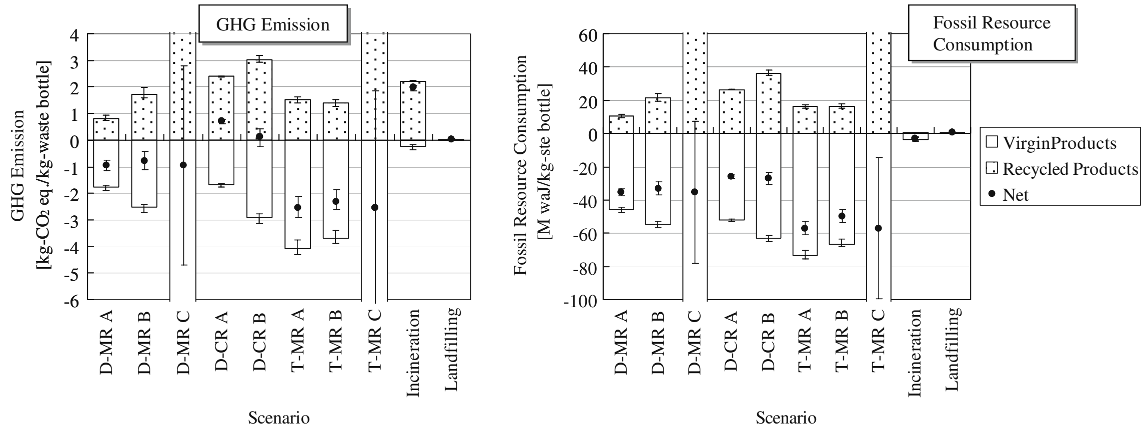
4 Variability analysis

4.1 Variability against background parameters

The robustness of the results was examined against the variability of background parameters for electricity supplies in both Japan and China. To estimate the district-by-district life-cycle GHG emission and fossil resource consumption factors of electricity supplies shown in Table 2, the compositions of the energy sources of the nine Japanese electric power companies (excluding Okinawa Electric Power) that supply electricity to their respective districts were compiled from their annual business reports, and those of electricity supplies in Shanghai, Jiangsu, Zhejiang, and Guangdong, where the recycling of post-consumer PET bottles imported from Japan was confirmed in our field surveys, were quoted from Chinese national statistics (National Bureau of Statistics and National Development and Reform Commission, People's Republic of China 2007). Thirty-six combinations of the nine sets of parameters in Japan and the four sets of parameters in China were applied to evaluate GHG emissions and fossil resource consumptions of the recycling and avoided manufacturing processes. The variability of GHG emission or fossil resource consumption was defined as the interval between its upper limit, i.e., a combination of the upper limit for the recycling processes and the lower limit for the avoided processes and its lower limit, i.e., a combination of the lower limit for the recycling processes and the upper limit for the avoided processes, in each scenario (Fig. 3). That is,

Table 2 Life-cycle GHG emission and fossil resource consumption factors of electricity supplies in Japan and China

	GHG emission [kg-CO_2 eq./kW h]	Fossil resource consumption [MJ/kW h]
Average in Japan	0.40	5.7
Hokkaido Electric Power	0.43	4.9
Tohoku Electric Power	0.42	5.9
Tokyo Electric Power	0.34	5.6
Chubu Electric Power	0.49	7.7
Hokuriku Electric Power	0.46	5.0
Kansai Electric Power	0.29	4.1
Chugoku Electric Power	0.60	7.5
Shikoku Electric Power	0.41	4.7
Kyushu Electric Power	0.35	4.8
Average in China	1.01	10.5
Shanghai Shi	1.04	9.9
Jiangsu Sheng	1.13	11.7
Zhejiang Sheng	0.83	8.8
Guangdong Sheng	0.86	9.2



Note: D-MR stands for domestic mechanical recycling, D-CR stands for domestic chemical recycling, and T-MR stands for transboundary mechanical recycling

Fig. 3 Variability against background parameters for electricity supplies

variability arises when the recycling and avoided processes are located in different districts of each country.

The results of the variability analysis showed that, except for the domestic MR scenario C and the transboundary MR scenario C, the variability was so small that all the recycling scenarios were superior to the incineration scenario from the viewpoints of GHG emission and fossil resource consumption. The differences between the domestic and transboundary recycling scenarios were sufficiently large to be robust against the variability of background parameters for electricity supplies. For the domestic and transboundary MR scenarios C, including cloth-manufacturing processes in the system boundaries, the variability was so large that they could be inferior to the chemical recycling and disposal scenarios. On the other hand, their GHG emissions and fossil resource consumptions could be much smaller than those of the other scenarios.

4.2 Variability against substitutions between recycled and virgin products

As mentioned in Section 3, the differences in GHG emissions and fossil resource consumptions between the domestic and transboundary recycling scenarios mainly result from the differences in the impacts of the avoided manufacturing processes of virgin products in China, rather than the differences in the impacts of recycling processes. In the analyses above, the avoided processes are assumed to be the production processes of equivalent virgin products in the same country as where recycling processes are located. Also, there are cases where recycled products manufactured in Japan substitute equivalent virgin products that would be imported from China, or conversely, recycled products manufactured in and imported from China substitute equivalent virgin products that would be manufactured in Japan. In view of such cases, the robustness of the results was examined against substitutions of recycled products and virgin products as follows.

The relationships between recycled products and substituted virgin products in the evaluated scenarios, along with the amounts of recycled products obtained by recycling 1 kg of waste PET bottles (see Table 1), are illustrated in Fig. 4. The GHG emission of each scenario is calculated by multiplying the difference between recycled products and substituted virgin products by the amount of recycled products that are obtained in each scenario. GHG emissions of product imports are considered in the scenarios where virgin products imported from China are substituted by recycled products manufactured in Japan and in the scenarios where recycled products imported from China substitute virgin products in Japan. Much the same is true for the fossil resource consumption of each scenario. For reference, the fossil resource consumption of the transboundary MR scenario A is calculated as $(20.0 - 90.0) \times 0.818 = -57.2$ MJ for 1 kg of waste bottles.

For the scenarios in which post-consumer PET bottles are recycled into polyester staple or clothes, the producer countries of substituted virgin products are interchanged, and such scenarios are named domestic MR scenario a and so on (see Fig. 4). Figure 5 shows the net GHG emissions and fossil resource consumptions of the corresponding scenarios. Interchanging the producer countries decreases the GHG emissions and fossil resource consumptions of the domestic recycling scenarios, but increases those of the transboundary scenarios. In particular, for the scenarios including cloth-manufacturing processes, the variability is so large that the transboundary MR scenario c is inferior to the chemical recycling and disposal scenarios.

As mentioned above, the results largely depend on the producer countries of virgin products substituted by recycled products. Similarly, as described in Section 4.1, variability against background parameters arises when recycled products and substituted virgin products are

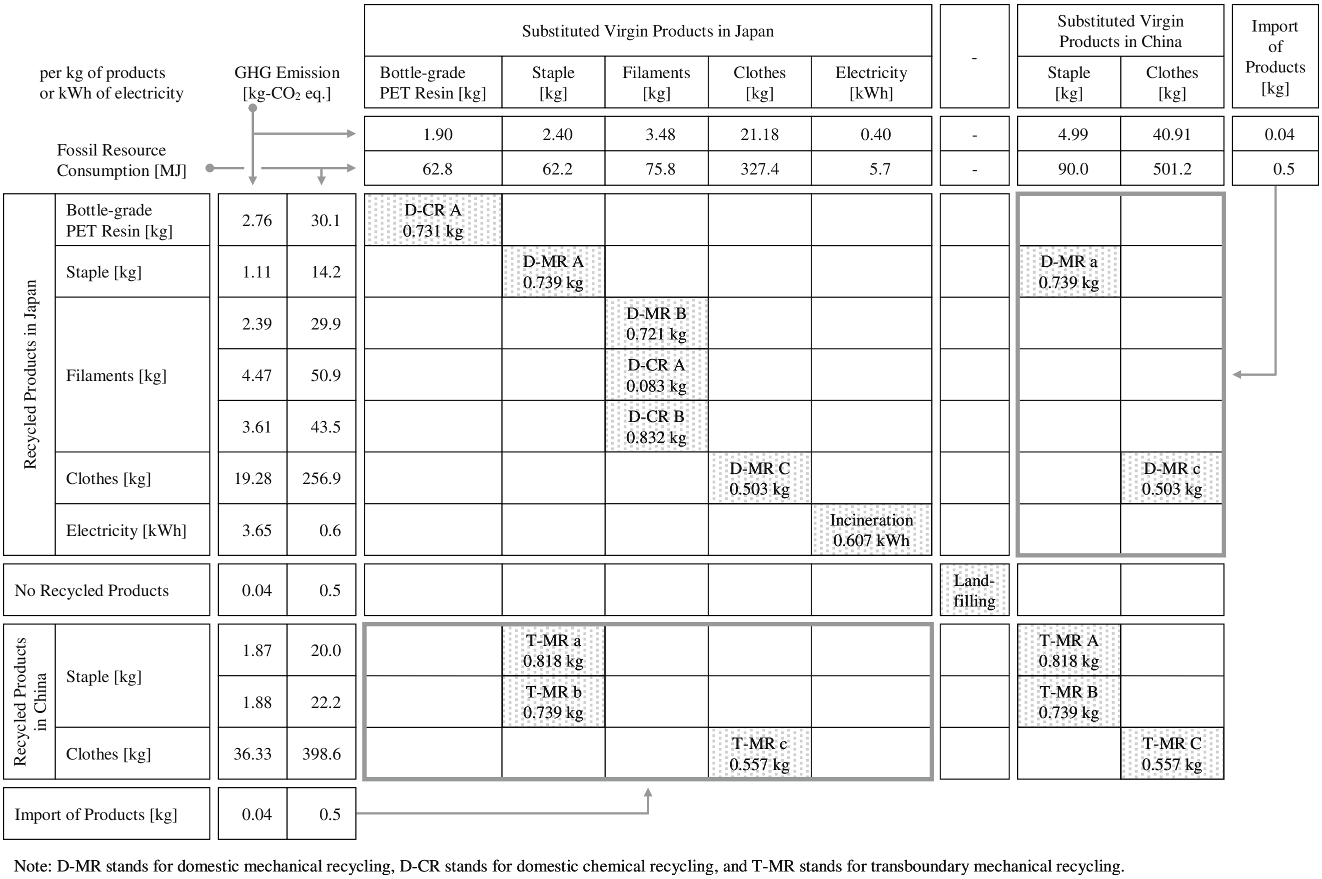


Fig. 4 Substitutions between recycled and virgin products in the evaluated scenarios

manufactured in different districts of each country. Identification of the producer countries (or districts) of substituted virgin products has an impact on environmental burdens of the recycling scenarios through the differences in the impacts of the avoided manufacturing processes between countries (or districts) depending on their differences in background parameters.

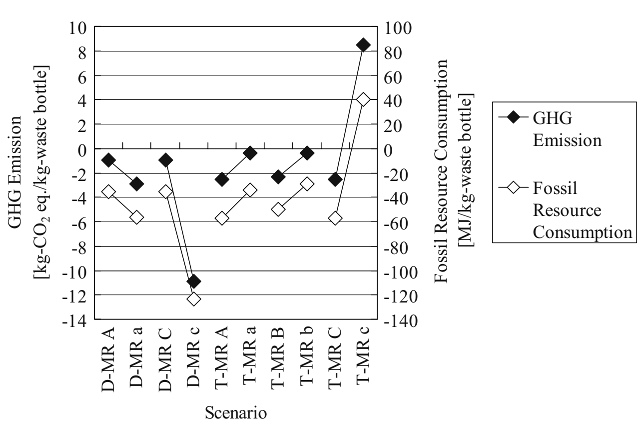


Fig. 5 Variability against substitutions between recycled and virgin products

5 Conclusions

In this study, LCA was applied to evaluate and compare the domestic and transboundary recycling between Japan and China and the disposal scenarios from the viewpoints of GHG emission and fossil resource consumption. The robustness of the results was examined against the variability of background parameters for electricity supplies and against substitutions between recycled products and virgin products.

The results showed that the differences in GHG emission and fossil resource consumption between the domestic and transboundary recycling scenarios, other than the scenarios including cloth-manufacturing processes in the system boundaries, were sufficiently large to be robust against the variability of background parameters for electricity supplies. For the variability against the substitutions between recycled products and virgin products, interchanging the producer countries of substituted virgin products decreases the GHG emissions and fossil resource consumptions of the domestic recycling scenarios, but increases those of the transboundary scenarios. In particular, for the scenarios including cloth-manufacturing processes, the variability was so large that the transboundary recycling scenarios could be inferior to the domestic recycling and disposal scenarios.

As indicated by Bjorklund and Finnveden (2005), the crucial factor in LCA for the recycling of nonrenewable materials including plastics is what material is substituted. Ekvall and Finnveden (2001) also indicated that the uncertainty regarding the substituted materials could be important for the LCA results for open-loop recycling. When recycling systems between different countries are compared using LCA, it should be noted that the differences in the background parameters have an impact on the environmental burdens of recycling and avoided manufacturing processes, and therefore, the result depends on the identification of the producer countries of virgin products substituted by recycled products. The variability of the result also depends on at which phase (e.g., PET flakes, polyester staple or clothes) recycled products can be regarded as substitutes for virgin products, and it increases according to the expansion of system boundaries. In terms of open-loop recycling, Ekvall (2000) presents a conceptual model to identify what processes are affected by recycling based on the price elasticity of the supply and demand of recycled material, and its simplified approach is suggested by Ekvall and Weidema (2004). Frees (2008) applied the approach in the context of primary and recycled aluminum. Presently, because of insufficient data for estimating the price elasticity of recycled and virgin polyester/PET products in both countries, it is practically impossible to identify in which country, and even up to which phase, the manufacture of virgin products is avoided by recycling. Therefore, it is recommended that the results should be presented, as described in this paper, according to the relationships between recycled and substituted virgin products.

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