LCA Evaluation of Industrial Plastic Waste

October 2022

Japan Initiative for Marine Environment　(JaIME)
Consignee: Plastic Waste Management Institute（Japan）

Introduction

The Japan Initiative for Marine Environment (JaIME) established in September 2018 recognizes the "prevention of plastic waste discharge" as a countermeasure to the marine plastic problem. In short, preventing the flow of plastic into rivers is the most important way of dealing with the marine plastic problem, and to this end, JaIME studies what measures would be globally effective and how the chemical industry can contribute to and execute those measures.

In March 2022, the United Nations Environment Assembly adopted the resolution "End Plastic Pollution: Towards an internationally legally binding instrument" that includes the marine plastic problem. This resolution stresses the need for waste management and evaluation by life cycle assessment (LCA) to prevent the discharge of plastic into the environment, and it includes content in agreement with JaIME's action policy.

The following three points summarize the activities undertaken at JaIME for preventing the discharge of plastic waste:

1) Support improvements in plastic waste management and processing in emerging countries in Asia
2) Support environmental awareness among consumers including the younger generation
3) Perform environmental load evaluations to help promote the recycling of plastic resources.

The project presented here was carried out as one of the above activities in relation to point 3), "perform environmental load evaluations to help promote the recycling of plastic resources." A working group was formed targeting the following two themes and the results of its work have been compiled into reports.

Theme I: Taking post-use plastic containers and packaging as input material, environmental load when effectively using and not effectively using plastic containers and packaging were calculated for each effective-use method. That difference was evaluated as the environmental load reduction effect and the results of this evaluation were presented in the survey report "Evaluation of Environmental Load Reduction Effect of Plastic Containers and Packaging Recycling Methods and Energy Recovery (LCA)" in March 2019.

Theme II: Taking plastic from industrial waste systems as input material, the above evaluation was performed for new recycling techniques such as chemical recycling (conversion to monomers, etc.) and the environmental load reduction effect was compared among those techniques. Results were presented in the survey report "LCA Evaluation of Industrial Plastic Waste" (this report) in October 2022.

Through the above surveys, we were able to provide useful data on selecting techniques for effectively using plastic including mechanical recycling, chemical recycling, and energy recovery. In addition, we brought up certain issues with regard to new techniques awaiting development and their evaluation methods as a first step toward the future. The following items (1) – (4) were carried out in Theme II (this survey).

(1) The survey "Evaluation of Environmental Load Reduction Effect of Plastic Containers and Packaging Recycling Methods and Energy Recovery (LCA)" conducted by JaIME in 2019 (hereinafter, "the JaIME survey") targeted plastic (plastic containers and packaging) focused on by the Containers and Packaging Recycling Law but did not target industrial plastic waste. This survey adds an evaluation of recycling techniques targeting industrial plastic waste in contrast to the 2019 JaIME survey.

(2) Chemical recycling (conversion to naphtha and monomers) that produces chemical materials and that is now being studied for commercialization is a highly important technique in an overall evaluation. At present, however, it is difficult to get hold of data on actual results, so we are collecting publicly available data and studying possible methods of evaluation. Nevertheless, compared to the other techniques addressed in this report, the amount of information is small, and in addition, there are many specific chemical-recycling techniques still in the development stage, so we leave LCA evaluation of chemical recycling as a topic for later study.

(3) In the 2019 JaIME survey, the only evaluation indices were "CO_2 emissions reduction effect" and "energy resource consumption reduction effect," but taking into account recent movements seeking a sustainable society and circular economy, we investigated an index that indicates "resource consumption reduction effect" and added it to the evaluation. We also examined evaluation from the viewpoint of resource circularity in which plastic waste is produced several times as chemical material or plastic through chemical recycling and adjusted our evaluation approach.

(4) There are movements in countries around the world to reassess evaluation indices with the aim of creating a zero-emissions society. In the evaluation taken up here, it was decided to incorporate as much as possible trends in Japanese policies toward a zero-emissions society in calculations. However, given that an overall image of a zero-emissions society has yet to be solidified, we inferred preconditions in calculations to the extent possible, and based on the results obtained, we adjusted recycling techniques and evaluation approach in a zero-emissions society though in a limited range.

Preparation of the report on this survey and evaluation results was consigned to Mizuho Information & Research Institute, Inc. We would like to extend our deep appreciation to those individuals who participated in the working group and to concerned companies for their valuable advice regarding LCA calculations and their gracious understanding in relation to this survey.

October 2022

Japan Initiative for Marine Environment (JaIME)
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Working Group on LCA Evaluation of Industrial Plastic Waste
(Period: November 2021 to July 2022)

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Report Summary

1. Purpose of evaluation

Objective 1: Study of environmental load reduction effect by recycling industrial plastic waste

This evaluation aims to objectively and quantitatively evaluate the environmental load reduction effect of mechanical recycling, chemical recycling, and energy recovery targeting industrial plastic waste.

Specifically, using the LCA evaluation report "Evaluation of Environmental Load Reduction Effect of Plastic Containers and Packaging Recycling Methods and Energy Recovery (LCA)" related to the processing of plastic (plastic containers and packaging) targeted by the Containers and Packaging Recycling Law released by the Japan Initiative for Marine Environment (hereinafter, "JaIME") in March 2019 (hereinafter, "the 2019 report") as a basis to work from, and taking up the case of performing such an evaluation for industrial plastic waste, the environmental load (CO_2 emissions and energy resource consumption) reduction effect of each processing method was calculated for 1 kilogram of plastic waste. In the case of industrial plastic waste, the processing of single-composition plastic after dismantling post-use products is common, and the situation is such that the composition of input plastic waste differs depending on the recycling processing method. For this reason, the objective here is not a simple comparison between different methods but rather to grasp the environmental load reduction effect of each processing method. Additionally, while this survey targets greenhouse gases overall in evaluating climate change effects, we denote this in terms of the amount of CO_2 emissions given that CO_2 is representative of greenhouse gases.

The techniques targeted for evaluation are listed below. Note that the techniques marked by the symbol Δ, while studied, were not evaluated due to the fact that information is still lacking.

Recycling processing method			Products obtained by recycling process	Evaluation target of industrial plastic waste			2019 report (plastic containers and packaging)
Class		Process		Resource consumption reduction	Energy reduction	CO_2 emissions reduction	
Mechanical recycling		Recycling	Recycled plastic	○	○	○	○
Chemical recycling	Liquefaction	Cracking	Fuel	○	○	○	○
			Naphtha (HiCOP)	○	○	○	○
			Styrene monomer	△	△	△	
	Gasification	Gas reduction	Hydrogen→ Ammonia	○	○	○	○
		Microbial fermentation	Ethanol→ Ethylene	△	△	△	
	Reduction	Blast furnace reduction	Pig iron	○	○	○	○
	Chemical reaction	Coke oven	BTX, etc.	○	○	○	○
Energy recovery		RPF use	RPF fuel	○	○	○	○
		Cement calcination	Cement	○	○	○	○
		Incineration with power generation	Power	○	○	○	○

Objective 2: Study of CO_2 emissions reduction effect through carbon-neutral recycling

A variety of measures are now being promoted around the world to achieve carbon neutrality for society on the whole. It has been confirmed that the recycling of plastic waste has contributed to a reduction in CO_2 emissions. However, if carbon neutrality in society continues to progress from here on, it can be assumed that conditions on the original-system side targeted for reduction comparison will change and that the effect of CO_2 emissions reduction by recycling will likewise change (for example, if the use of renewable energy for power continues to progress, it can be assumed that the CO_2 emissions reduction effect of incineration with power generation will become smaller). This survey, as a consequence, postulated future changes in society within a possible range, analyzed the CO_2 emissions reduction effects of recycling processing methods based on those changes, and proposed future directions in the study of plastic recycling.

Objective 3: Study of evaluation models toward new environmental load reduction

This evaluation analyzed the environmental load reduction effect of different recycling processing methods, but in studies conducted by the working group, it was recognized that evaluation methods that focus on resource circularity would be needed in the future when considering the appropriate introduction and implementation of recycling processing anticipating a reduction in the consumption of fossil fuels and a reduction in CO_2 emissions. Against this background, we drew up a proposal for quantitative evaluations based on a "carbon-balance model" that incorporates the use of carbon resources among sectors in society.

2. Study of CO_2 emissions reduction effect by recycling industrial plastic waste

(1) Evaluation of mechanical recycling (single-composition plastic waste)

For mechanical recycling, we evaluated single-composition plastic waste processing for polyethylene (PE), polypropylene (PP), polystyrene (PS). Regardless of the type of plastic, results showed that energy consumption and CO_2 emissions were less by the recycling system. In short, these results indicate that mechanical recycling is effective for reducing CO_2 emissions when collecting single-composition plastic waste.

Table 1. Evaluation results for mechanical recycling (recycling of single-composition plastic)

	Energy resource consumption [MJ]			CO_2 emissions [kg-CO_2]		
	Recycling system	Original system	Reduction effect	Recycling system	Original system	Reduction effect
PE	5.03E+01	1.64E+02	1.14+02	3.41E+00	8.31E+00	4.89E+00
PP	4.82E+01	1.60E+02	1.12+02	3.41E+00	8.32E+00	4.90E+00
PS	4.45E+01	1.65E+02	1.21+02	3.66E+00	9.83E+00	6.18E+00

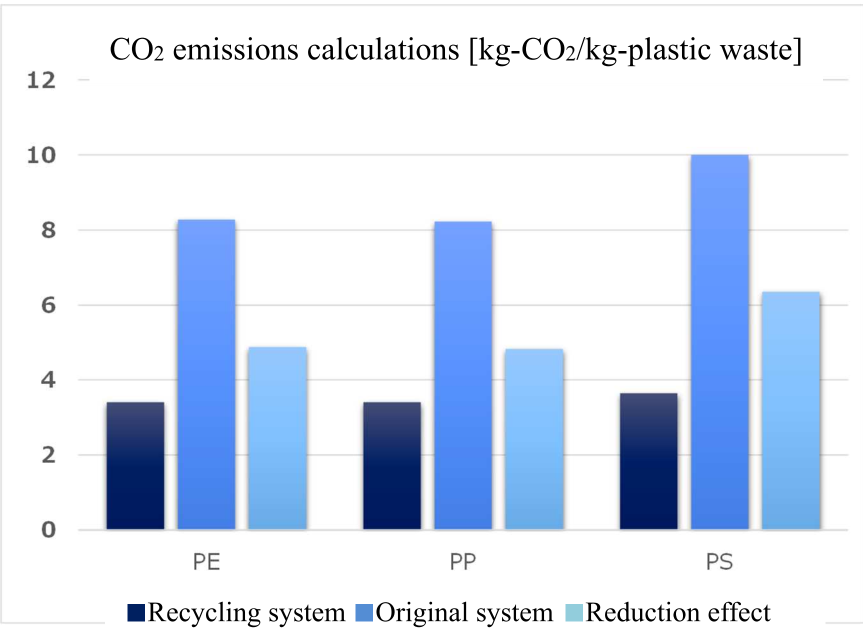


Figure 1. Evaluation results for mechanical recycling (CO_2 emissions)

(2) Evaluation of chemical recycling and energy recovery (processing of mixed plastic waste)

(a) Industrialized techniques

In the case of chemical recycling and energy recovery techniques that have already been industrialized, evaluation results show that energy consumption and CO_2 emissions were less for the recycling system based on either of these processing methods and that recycling was effective in reducing energy consumption and CO_2 emissions. It can also be seen from these results that a large CO_2 emissions reduction effect could be obtained by gasification, blast furnace reduction, coke-oven reduction, RPF use, and cement calcination compared with incineration with power generation.

Additionally, chemical recycling of slightly sorted mixed plastic waste was found to be effective. Looking to the future, we can expect an increasing demand for the recycling of mixed plastic waste and composite materials even if advances should be made in sorting technology and mono-material design. As a result, technology development continues to this day for chemical recycling having a comparatively broad range of allowable input material, so we can expect further reductions in CO_2 emissions through such process improvements.

Table 2. Evaluation results for industrialized chemical recycling and energy recovery (recycling of mixed plastic)

	Energy resource consumption [MJ]			CO_2 emissions [kg-CO_2]		
	Recycling system	Original system	Reduction effect	Recycling system	Original system	Reduction effect
Gasification (ammonia)	6.56E+01	1.21E+02	5.55+01	4.56E+00	6.24E+00	1.68E+00
Blast furnace reduction (substitute for coke)	1.32E+03	1.36E+03	3.26+01	1.20E+02	1.23E+02	2.99E+00
Blast furnace reduction (substitute for pulverized coal)	2.62E+02	2.87E+02	2.53+01	2.38E+01	2.61E+01	2.28E+00
Coke-oven chemical material	3.66E+01	8.51E+01	4.85+01	2.83E+00	6.10E+00	3.27E+00
RPF use	3.51E+01	6.96E+01	3.45+01	2.65E+00	5.83E+00	3.18E+00
Cement calcination	3.51E+01	7.03E+01	3.52+01	2.65E+00	5.90E+00	3.25E+00
Incineration with power generation (14.05% efficiency)	3.57E+01	4.89E+01	1.32+01	2.70E+00	3.53E+00	8.36E-01
Incineration with power generation (25% efficiency)	3.57E+01	5.92E+01	2.35+01	2.70E+00	4.15E+00	1.46E+00

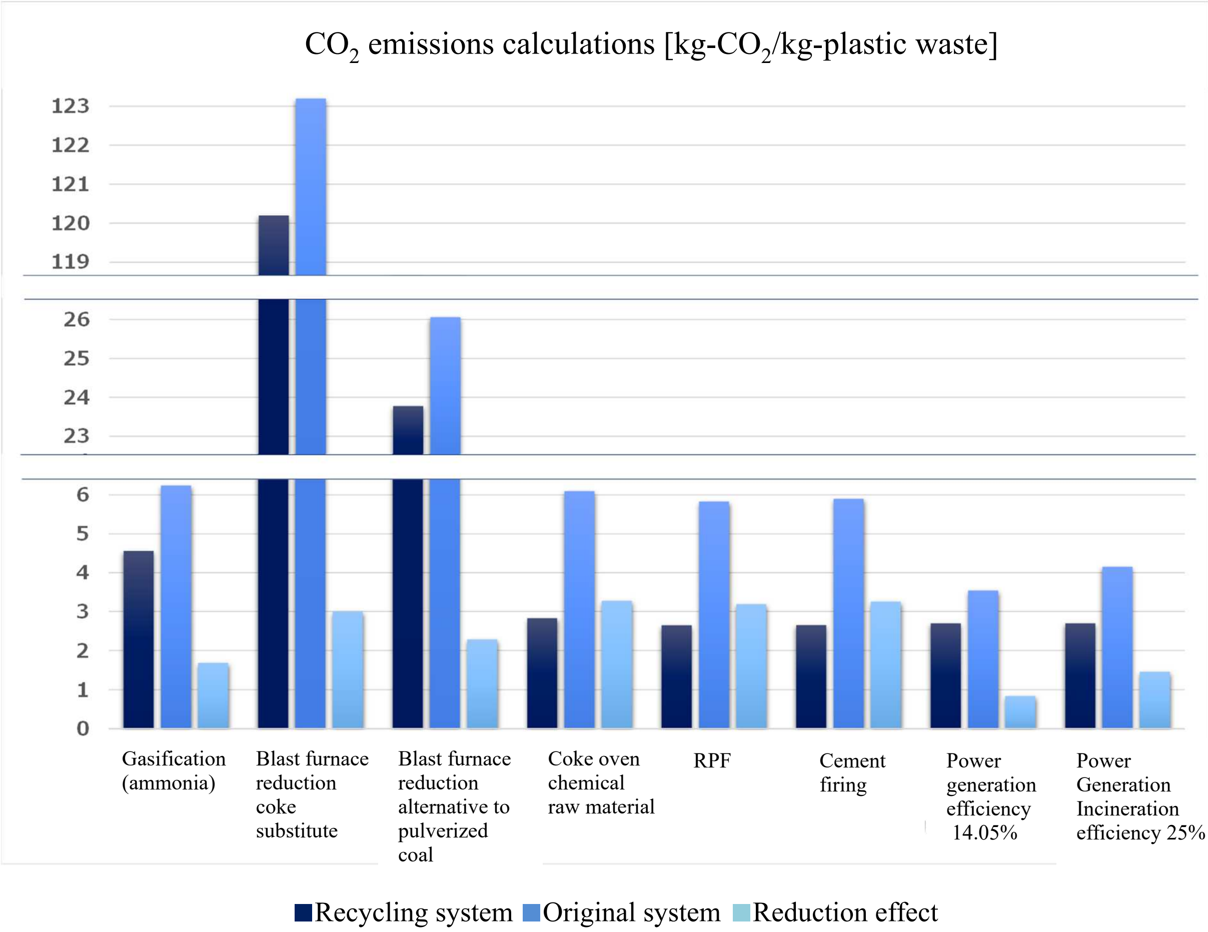


Figure 2. Evaluation results for recycling processing methods (industrialized) of mixed plastic waste

(b) Pre-industrialized techniques

For the case of chemical recycling (liquefaction) not yet industrialized, we were concerned that comparing it at this point in time with industrialized processes could lead to misunderstandings, so while we did not perform a comparison with industrialized techniques, it could still be seen that these pre-industrialized techniques could be associated with a reduction in CO_2 emissions throughout society.

Ongoing technology development of these techniques is expected to result in a further reduction in CO_2 emissions. Consequently, for these techniques that will continue to develop, an issue in the dissemination of this technology is how to quantitatively understand and verify the contribution to resource circularity by conversion to chemical fuel and the contribution to reduction in CO_2 emissions toward an even greater CO_2 emissions reduction effect.

Table 3. Evaluation results for non-industrialized chemical recycling (liquefaction) (recycling of mixed plastic)

	Energy resource consumption [MJ]			CO_2 emissions [kg-CO_2]		
	Recycling system	Original system	Reduction effect	Recycling system	Original system	Reduction effect
Liquefaction (fuel)	3.00E+01	5.00E+01	2.00+01	2.29E+00	3.78E+00	1.50E+00
Liquefaction (HiCOP)	3.61E+01	7.31E+01	3.69+01	2.65E+00	5.33E+00	2.68E+00

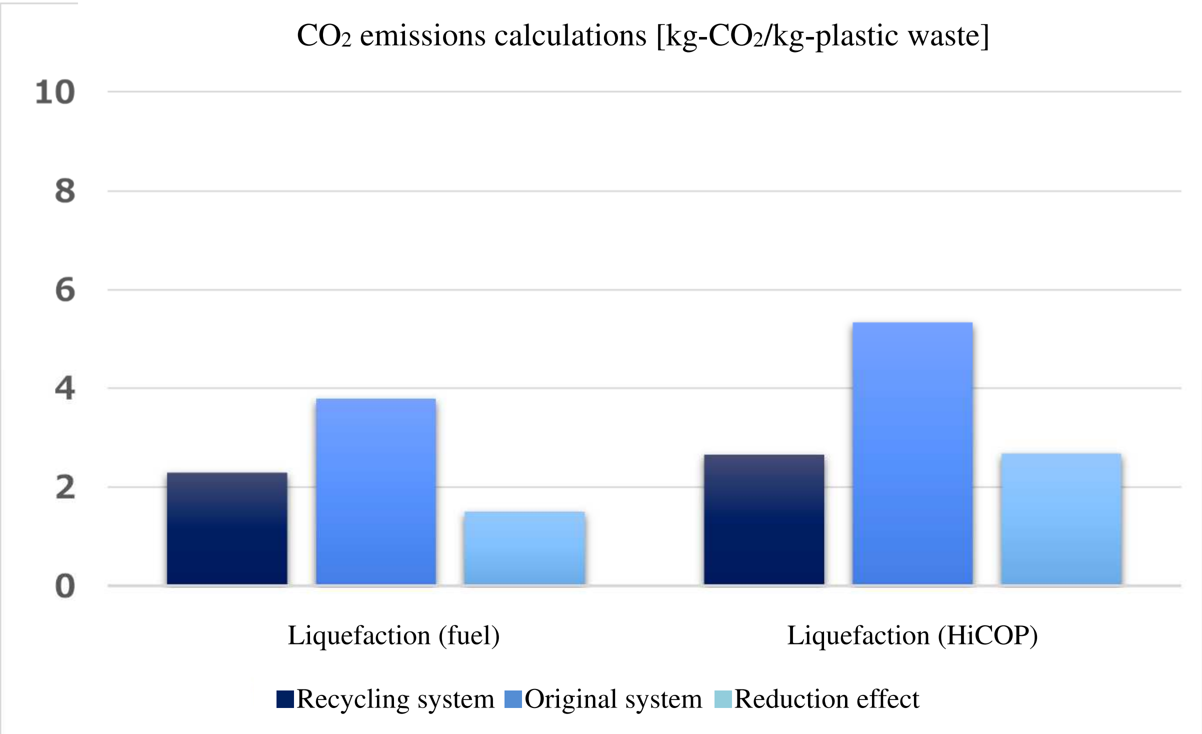


Figure 3. Evaluation results for recycling processing methods (pre-industrialized) of mixed plastic waste

3. Study of CO_2 emissions reduction effect by carbon-neutral recycling

(1) Description of analysis

In this survey, we inferred future changes in society to the extent possible, and based on those changes, analyzed the CO_2 emissions reduction effect of various recycling processing methods and studied how those changes might influence processing methods in the future. Main targets of evaluation are summarized below.

- Evaluation considering progress in the use of renewable energy as an energy source (evaluation when setting the CO_2 emission intensity of energy to 10% the current value)
- As for biomass resources, which appear to be affecting mechanical recycling already, there is much evaluation at the literature and research level, so we did not perform a quantitative analysis here but kept our evaluation to qualitative suggestions.

(2) Analysis results

(a) Effects on chemical recycling and energy recovery

As renewable energy is increasingly used for power and the use of fossil fuels decreases, the amount of emissions of energy recovery and chemical recycling (blast furnace reduction) will be nearly unchanged from that of original systems. That is, from the viewpoint of CO_2 reduction, these processing methods will approach simple incineration and their contribution to reducing CO_2 in society will greatly decrease. If coal usage should decrease toward carbon neutrality, the introduction of techniques like hydrogen reduction can be considered for blast furnace reduction and coke-oven chemical material, which could have the effect of eliminating them as candidates for destinations of plastic waste usage.

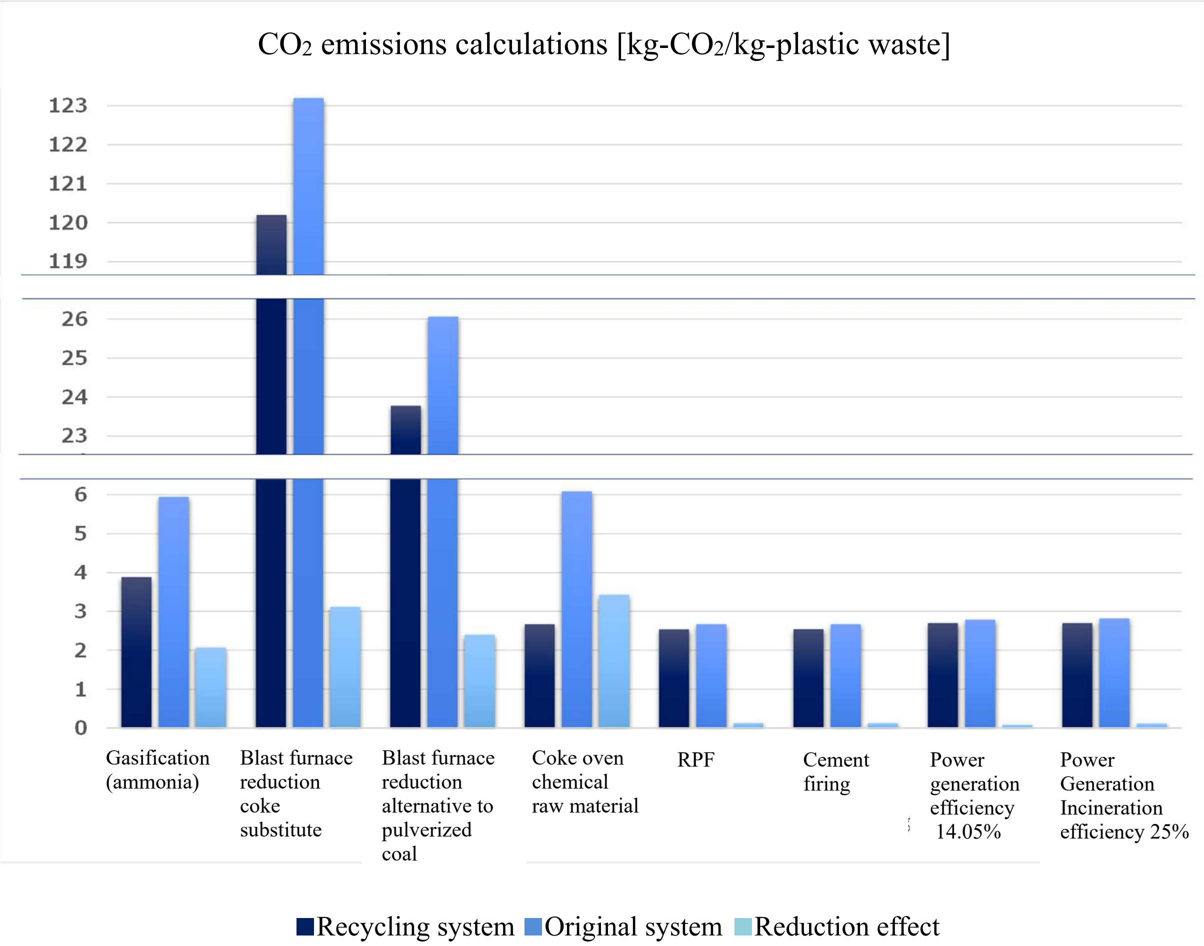


Figure 4. CO_2 emissions reduction effect in a carbon-neutral society (estimated under conditions established here)

(b) Effects on mechanical recycling

We consider that the trend toward the use of biomass as raw material could have an effect on mechanical recycling. Evaluations in relation to biomass as raw material are still in progress but some research results have appeared. It has been shown in the literature that the amount of CO_2 emissions when manufacturing biomass plastic (PE derived from sugar cane) decreases by 3.3 – 3.8 kg compared with plastic (PE) derived from fossil resources due to the effect of CO_2 fixation/absorption when growing sugar cane. On the other hand, the CO_2 emissions reduction effect due to mechanical recycling in this survey is about 4.9kg-CO_2, so if we were to treat biomass plastic as the original system, the CO_2 emissions reduction effect would significantly decrease to 1.2 – 1.7 kg-CO_2, though a certain amount of reduction would remain.

Yet, within a carbon-neutral society, a further decrease in the CO_2 emissions of biomass plastic can be considered. As a result, the CO_2 emissions reduction effect described above cannot be used to reflect the superiority of mechanical recycling in a carbon-neutral society. From here on, it will be important to analyze the amount of CO_2 emissions for both mechanical recycling and biomass resources and to scrutinize effective use by mechanical recycling.

(3) Directions in evaluation and study of recycling in a carbon-neutral society

The structure of a carbon-neutral society is still unclear, but along with the spread of renewable energy and biomass materials, the CO_2 emissions reduction effect brought about by plastic recycling is predicted from this evaluation to become increasingly smaller whatever the technique.

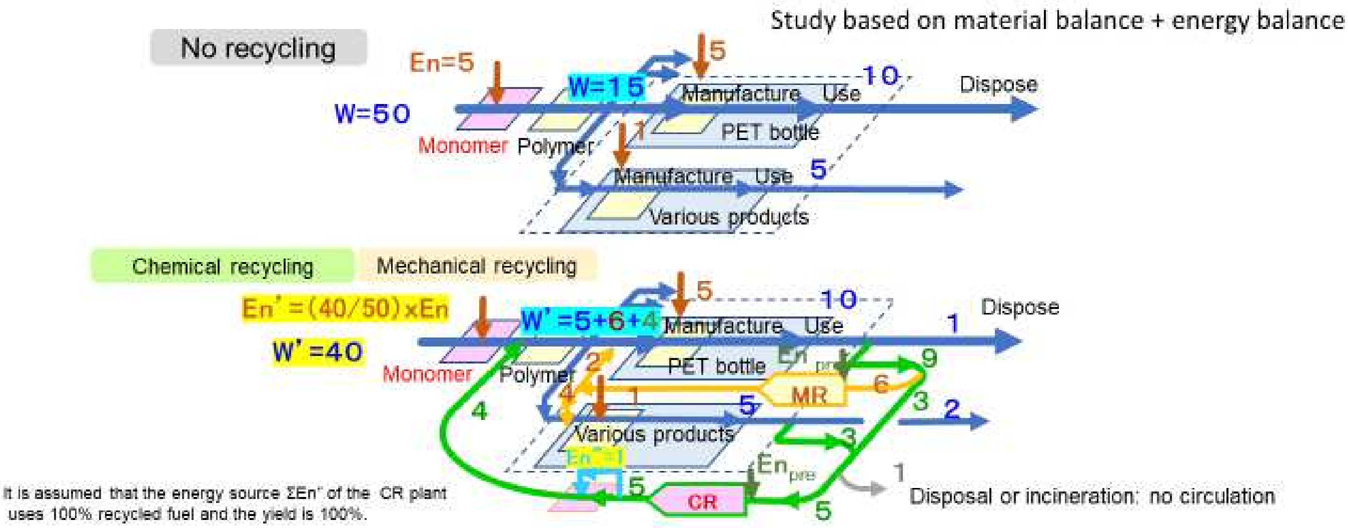
On the other hand, the extent to which the use of renewable energy and biomass materials may spread and the possibility of that spread are still unclear. Furthermore, considering that the effective usage of post-use biomass plastic is essential, we established the following directions in evaluation and study at this point in time.

<u>Future directions in evaluation and study of recycling</u>

1) Promoting the effective use of post-use plastic is necessary even in a carbon-neutral society.
2) Destinations of that usage should particular be sought out in fields that cannot be covered by renewable energy and biomass materials.
3) The following actions must therefore be taken going forward:
    1. Obtain a periodic understanding of trends in the use of renewable energy and biomass materials in assumed usage destinations
    2. Promote the development of recycling techniques that can expand the possibility of effective use
    3. Grasp environmental effects in the processes used by each recycling technique and disseminate that information

4. Approach to evaluations based on a carbon-balance model

Material balance in mechanical recycling + chemical recycling (combination)



	Input monomer Wo	Input fossil material W'	Total input fossil material	Monomer manufacturing energy En'	Product manufacturing enegy En	Recycling process input energy En"	Recycling preprocessing energy En_{pre}	Total input energy
No recycling	50	10+5	15	5	5+1	0	0	11
MR+CR	40	5	5	4.0	5+1	0	0.1+0.15	10.3
			Δ 10					Δ 0.7

In contrast to performing an evaluation for each recycling processing method as done in the survey described above, the aim of this technique is to analyze the minimization of the amount of input fossil resources in society overall based on a combination of multiple recycling processing methods. Here, the amount of input fossil resources is divided into energy use and chemical-material use. It can be assumed that the results of our survey will be incorporated in this model as numerical values corresponding to input/output of each recycling method, energy input to each process, etc.

Going forward, as Japan sets out to formulate policies and measures for reconstructing the social system toward a recycling-oriented society and zero-emissions society, the chemical industry as well is launching activities along these lines. A plastic-circulating system has yet to be completed, but plans are being drawn up for constructing plants based on new technologies toward the creation of a circulating system that can convert post-use plastic into monomers, naphtha, etc. The chemical industry must therefore make it possible to evaluate the degree of completion with regards to constructing a circulating system for carbon resources and to evaluate variations in system configuration by simulation.

We anticipate the use of simulation-based evaluations that combine a number of recycling techniques based on this "life-cycle carbon balance in the chemical industry." The following steps can be considered to this end:

(1) Incorporate specific values in this model (use the results of this survey)
(2) Refine the model itself by incorporating numerical values
(3) Use the model to analyze the appropriate amount of input fossil resources.

5. Overall summary

(1) CO_2 emissions reduction effect by recycling industrial plastic waste

- All recycling techniques targeted this time for evaluation were found to have a CO_2 emissions reduction effect.
- Although mechanical recycling is limited to single-composition plastic waste, a certain CO_2 emissions reduction effect can be obtained, so mechanical recycling can be considered effective in the case of single-composition plastic waste.
- The use of chemical recycling that allows for light sorting is beneficial for mixed plastic waste. In the future, demand for the recycling of mixed plastic waste and composite materials can be expected even if advances should be made in sorting technology and mono-material design. Consequently, for chemical recycling having a comparatively broad range of allowable input material, we can expect technology development and process improvements and further reductions in CO_2 emissions.

(2) Influence of carbon neutrality on CO_2 emissions reduction effect

- As renewable energy progresses and the use of fossil fuels decreases, the contribution of current energy-recovery and chemical-recycling methods to reducing CO_2 emissions in society is predicted to become significantly smaller.
- The introduction of techniques like hydrogen reduction toward carbon neutrality can be considered for blast furnace reduction and coke-oven chemical material, which could have the effect of eliminating these two processes as candidates for destinations of plastic waste usage.
- Progress in the use of biomass materials may also affect mechanical recycling and monomerization. In a carbon-neutral society, a further reduction in the CO_2 emissions of biomass plastic can be considered, so going forward, there is a need for analyzing CO_2 emissions in mechanical recycling and monomerization and in the use of biomass resources and to consider the effects of recycling.
- The extent to which the use of renewable energy and biomass materials may spread and the possibility of that spread are still unclear, and the effective usage of post-use biomass plastic is considered to be essential. From here on, the following three points are considered to be important in terms of the promotion and evaluation of recycling:

(1) Periodically grasp trends in the spread of renewable energy and biomass materials in usage destinations (determine usage destinations that can effectively contribute to a carbon-neutral society)
(2) Promote the development of recycling techniques that can expand usage destinations conducive to effective use (expanded demand for recycling through monomerization, etc.)
(3) Grasp environmental effects in the processes used by each recycling technique and disseminate that information (check whether individual techniques can contribute to a carbon-neutral society).

(3) Perform evaluations based on a carbon-balance model

- Activities in the chemical industry toward a future recycling-oriented society and zero-emissions society include plans for constructing plants based on new technologies such as those for converting post-use plastic into monomers, naphtha, etc. The chemical industry must therefore make it possible to evaluate the degree of completion in constructing a circulating system for carbon resources and to evaluate by simulation variations in system configuration.
- Based on the evaluation of individual recycling processing methods as done in this survey, we investigated a model that aims to analyze the minimization of the amount of input fossil resources in society overall based on a combination of multiple recycling methods.
- We consider the following activities to progress from here on: (1) incorporation of specific values in this model (using the results of this survey), (2) refining of the model itself by incorporating numerical values, and (3) using the model to analyze the appropriate amount of input fossil resources.