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Technology

Aiming to Become a Steelworks That Plays a Role in Recycling-oriented Society

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Abstract

The coke and blast furnace process has the potential to support a recycling-oriented society and economy in the region and the world. For example, we have been utilizing waste plastic and reducing CO_2 emissions inside and outside the steelworks by chemically decomposing and recycling waste plastics discharged in the area adjacent to the steelworks using coke ovens. In the future, by carbonizing and using landfill waste, we propose a method to reduce greenhouse gas emissions five times more effectively than using biomass charcoal. Furthermore, the scheme can be a meaningful initiative that will lead to the achievement of many SDGs such as environmental problems and job creation. By making full use of the technologies we have developed so far in the fields of steelmaking and environment, we aim to work toward building a sustainable, recycling-oriented society, both locally and globally.

1. Introduction

The steel industry of Japan has attained the No. 1 position in the world's steelmaking industry in terms of energy efficiency thanks to continuous improvement efforts made in the nearly 70 years that have elapsed since World War II. It is also promoting various measures to reduce the generation of global greenhouse gases: such measures include further decrease in the unit consumption of fuels and active participation in COURSE50 and other technical development projects to produce iron and steel through hydrogen reduction processes. It has to be noted, however, that as the word "global" implies, curbing the emissions of greenhouse gases is pointless by cutting their discharge only from inside the premises of steelworks, and it is necessary to take measures to decrease the emissions worldwide. In this sense, the industry should perform what it can by expanding the application of its specialty technologies that it has fostered in the fields of steelmaking and environment control to the regions outside the works and to the surrounding world. While decreasing the generation of global greenhouse gases is very important, this alone is not enough, and comprehensive efforts have to be made to attain as many of the 17 goals set forth in the Sustainable Development Goals (SDGs) as possible. The present paper focuses on the key phrase "recycling-oriented society," and examines the roles that the steel industry can play in the future.

2. Past Efforts toward Recycling-oriented Society—Chemical Recycling of Waste Plastics

2.1 Outline of efforts for recycling waste plastics

Global environmental issues such as biological effects caused by the influx of waste plastics into the ocean have been the focus of attention worldwide over the last few years. Nippon Steel Corporation focused on the pyrolysis process of coke ovens, which forms one of the main processes in steelworks, and has conducted research since 1997 aiming at recycling waste plastics using them. As a consequence, the facilities for plastic recycling started up at Nagoya Works and the Kimitsu Area of East Nippon Works in autumn 2000, and then the process was expanded to other steelworks, ending up with systems for collecting and recycling waste plastics being established to cover wide regions of the country (see **Fig. 1** [1]). This operation was not achieved by Nippon Steel alone, and the cooperation with the Ministry of the Environment, local governments and the Japan Containers and Packaging Recycling Association was essential.

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Fig. 1 Waste plastic processing system utilizing Nippon Steel's coke ovens[1)]

2.2 History of solving technical problems with recycling waste plastics (method for converting plastics into chemical raw materials in coke ovens)

Both plastics and coal are composed mainly of C, H and O, and it is easy to understand that when plastics are heated in coke ovens, they are converted into coke, tar, light oil, and coke oven gas (COG) in the same way as coal is. On the other hand, the important technical issues in recycling waste plastics using coke ovens were as follows: the product yields during dry distillation in the ovens; the effects of mixing them with coal on the coke quality; and the behavior of chlorine contained in them during the pyrolysis in the ovens. How these problems were solved is explained below.[2)]

2.2.1 Product yields at pyrolysis of waste plastics in coke ovens

Figure 2 shows the results of measuring product yields when various types of plastics were heated in a laboratory test oven (capacity 100 g, all the units herein are metric).[3)] As seen here, the yields of the products differ depending on the type of plastics. The graph also shows the product yields when volume-reduced pellets of waste plastics (to be explained later) were mixed with coal by 1 to 2% and the mixture was heated in commercial coke ovens.[3)] It was found that when waste plastics were carbonized together with coal, they turned into the following useful chemical products: 20% coke, 40% tar and light oil and 40% COG, approximately.

2.2.2 Effects of waste plastic addition on coke quality

Regarding the coke quality, when waste plastics were mixed with coal it was necessary to study the effects of the type, pellet size and addition ratio of the plastics. The effects of the pellet size and addition ratio on the cold strength of coke (DI^{150}_{15}, hereinafter referred to as the DI (drum index) in short) are described below.

Through the studies on the relationship between the plastic pellet size and DI, it was found that the DI was minimal with a certain pellet size as shown in **Fig. 3**, and that the drop of the DI decreased as the size became larger than that of the minimal DI.[4)] Since plastics are thermally decomposed in a temperature range lower than that in

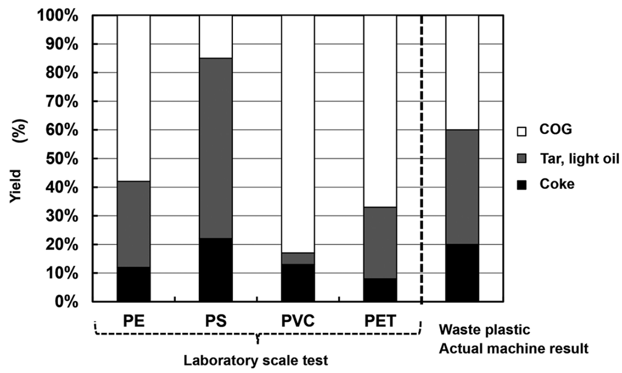

Fig. 2 Product yield when plastics are carbonized in a coke oven (PE: polyethylene, PS: polystyrene, PVC: polyvinyl chloride, PET: polyethylene terephthalate)

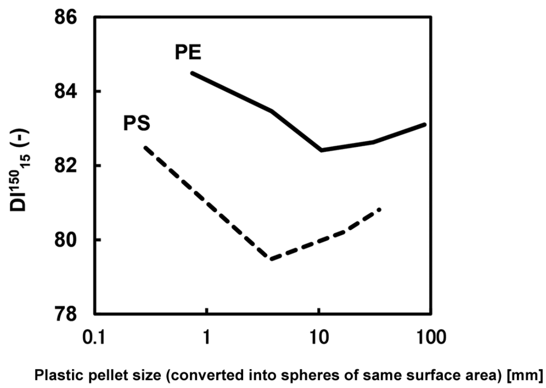

Fig. 3 Effect of plastic size on coke strength (PE: polyethylene, PS: polystyrene)

which coal is, they are decomposed before coal softens, melts and expands, and voids form in the space that the pellet occupied. As a result, the coal around the pellet expands freely into the voids, forming a fragile foamed portion of coke.

Assuming that the size of the fragile coke portion thus formed at the interface between the coal and the plastic pellets is constant regardless of the operation conditions and the position in the oven, the larger the pellet size, the smaller their total surface area becomes, the smaller the total volume of the fragile coke portion, and the less factors there will be to decrease coke strength. Based on these results and in consideration of the ease of handleability down to charging into the ovens, it was decided that waste plastics would be mixed with coal after forming them into volume-reduced solid pellets 20 to 30 mm in diameter. Through the tests of coke quality under the above condition in real coke ovens, it was found that as long as the mixing ratio of plastics was 1% or less, the DI was not adversely affected. The method of converting waste plastics into chemical raw materials using coke ovens has thus been verified as commercially feasible.

2.2.3 Behavior of chlorine in waste plastics during pyrolysis in coke ovens

Since waste plastics include chlorine-containing plastics such as polyvinyl chloride (PVC) and polyvinylidene chloride, we investigated the behavior of chlorine when waste plastics were heated in the coke ovens together with coal.[5,6] Waste plastics of a chlorine concentration of roughly 3% were added by 1 or 2% to the coal of a chlorine concentration of 450 ppm, the mixture was heated in the real coke ovens, and the chlorine concentrations in the products were measured. It became clear as shown in **Fig. 4** that the increase in the chlorine concentration in coke when plastics were added was very small. A close examination of the distribution ratios of the chlorine emitted from the waste plastics to the coke and the gas and the same of the chlorine from the coal revealed that whereas the chlorine from the waste plastics was distributed to the coke and the gas at a ratio of 7 to 93, that from the coal was at a ratio of 43 to 57. The distribution ratio of the former to coke is lower than that of the latter presumably because the existing form of chlorine is different: most of the chlorine in waste plastics comes from PVC, and the rate at which PVC is thermally decomposed in the ovens is higher than that at which chlorine in coal is released as a result of its thermal decomposition. In addition, most of the released chlorine is absorbed by ammonia liquor, which is flushed to hot COG coming

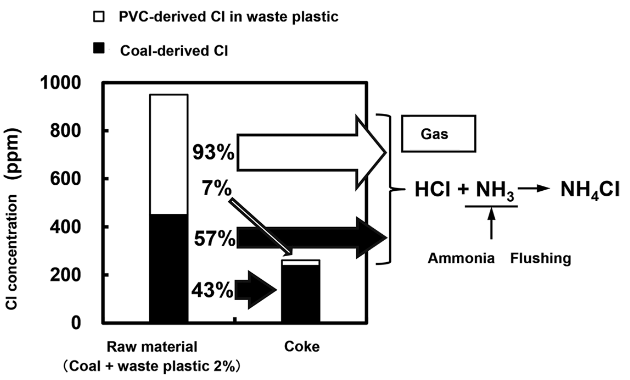

Fig. 4 Behavior of chlorine when coal and waste plastic are carbonized in a coke oven (Chlorine concentration in waste plastic 2.5%, chlorine concentration in coal 450 ppm, PVC: polyvinyl chloride)

from the ovens to cool it, and is fixed in the form of ammonium chloride by the chemical reaction of $HCl + NH_3 = NH_4Cl$. The chlorine in the waste plastics is finally distributed to the coke, ammonia liquor and COG at a ratio of 7:92:1, and the chlorine in coal at a ratio of 43:56:1. Considering the fact that the origin of ammonia is N contained in coal, the pyrolysis of coal and waste plastics in coke ovens is an exquisite process wherein N coming from coal, a natural resource, serves to capture chlorine in waste plastics.

2.3 Process flow of waste plastic recycling

The process flow of the waste plastic recycling using coke ovens is explained below in more detail (see **Fig. 5**[7]).

(1) Collection of waste plastics

Local residents sort and discharge waste of plastic containers and packaging according to municipalities' guidance, and the local governments roughly sort them out to remove foreign substances, and for ease of storage and transportation, compress and pack them with a press into bales, which are then transported by trucks to Nippon Steel's steelworks. Municipalities and the company have devised a framework to continuously improve the quality of waste plastics through the exchange of information on matters such as foreign substances possibly causing fire that the works have identified as such through years of operation.

Since residents' cooperation in the classified discharge is very important, Nippon Steel works with local governments and the related organizations to enhance their understanding of plastic recycling on the occasions of environmental events and the like. It is essential for the recycling of plastic containers and packaging, in which 1 108 municipalities participate as of fiscal year 2019 (from April to March next year, FY in short), that residents, local governments and Nippon Steel as the recycling process operator work in close communication.

(2) Pretreatment

As waste plastic containers and packaging collected for recycling are a mixture of various types of plastics (PE, PP, PS, etc.), they are in miscellaneous shapes, and substances of different chemical compositions are included. In addition, even if the residents sort and local governments roughly classify them, it is impossible to completely eliminate the inclusion of metals and inorganic substances such as stones. In consideration of this and to avoid adverse effects on the facilities for forming and thermal decomposition, foreign substances are removed by wind separation or the like. After that, they are crushed to around 20 mm in size, and then formed into pellets tens of millimeters in size to reduce volume and make them as easy to handle as coal in the transportation and charging into the ovens.

(3) Pyrolysis in coke ovens

The plastic pellets formed as above are charged together with coal into the coking chambers of the coke ovens. Inside the chambers, the plastics and coal are shielded from the outside air, heated indirectly through the brick walls on both sides, and decomposed without burning. In a reducing atmosphere at a maximum of 1 100 to 1 200°C, the plastics are thermally decomposed into 40% oil, 40% COG and 20% coke, approximately, all of which are used as valuable raw materials.

The oil mainly consists of tar and light oil, which are transported to chemical plants and manufactured into chemical products such as plastics and paints. The gas, mainly composed of hydrogen and methane, has a high calorific value, and is used for power generation, etc. It is expected to be used also as a reducing agent in blast furnaces in the future. The balance, i.e., solid coke, is used in blast

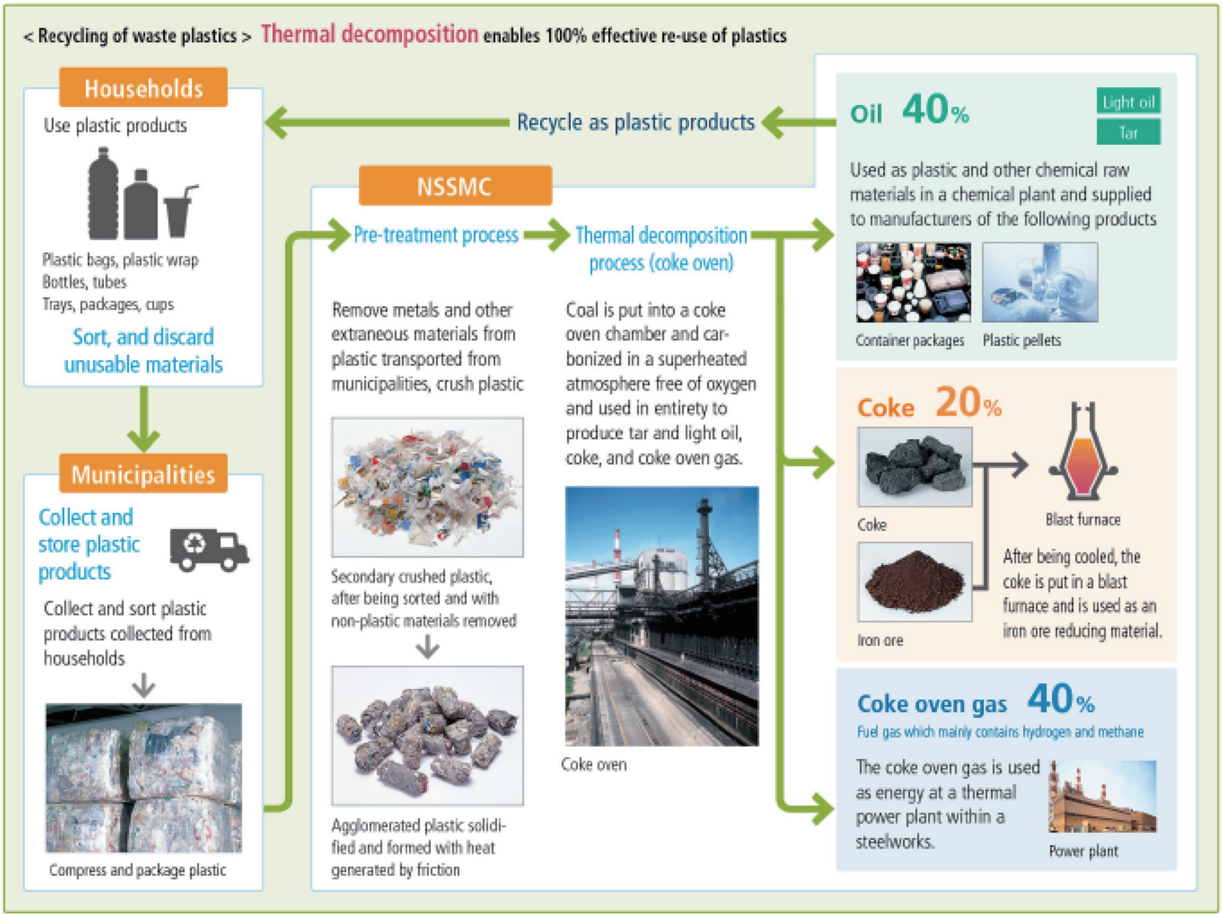

Fig. 5 Waste plastic recycling flow[7]

furnaces as a reducing agent.

Employing this chemical recycling method, Nippon Steel recycled a total of 3.28 million tons of waste plastics, mainly from containers and packaging, into chemical raw materials from FY 2000 to 2019: this is equivalent to a reduction of CO_2 emission of 10.5 million tons (Mt). Currently, it is responsible for recycling more than 0.2 Mt of plastic containers and packaging every year, which is roughly one-third of the total of this type of waste plastics arising annually from all over Japan (see **Fig. 6**[1]).

2.4 Expectations of more recycling of waste plastics and measures to realize it

Although Nippon Steel recycles more than 0.2 Mt of waste plastics every year, it is only a small part of the waste plastics arising from all of Japan. As shown in **Fig. 7**[8], as much as 8.5 Mt of plastics were discharged as waste in FY 2019, and although the recycling ratio has been increased so far, the majority is burned for thermal recycling, and Nippon Steel is expected to further increase the amount of chemical recycling of plastics using coke ovens.

In the meantime, the Japan Business Federation announced the start of the Challenge Net Zero Carbon Innovation (Challenge Zero in short) on June 8, 2020: it is a campaign to disseminate and support innovative actions of business enterprises and organizations aiming at realizing a carbon-free society in collaboration with the Government of Japan.[9] In response, as part of the initiative, Nippon Steel is currently taking on the challenge to raise the density of the pellets aiming at further increasing the recycling of waste plastics (20% increase in the recycling amount, additional effect of a CO_2 emission cut by 120000 t/y).[10–13] Since it is possible to increase the weight of the plastic agglomerates by increasing their density while keeping the surface area unchanged, a larger amount of waste plastics can be added to the coal without adversely affecting the coke strength.

[Specific approach policy]

- Evaluation and verification of the method for densification: FY 2020 to 2021
  - Design and manufacture of offline test equipment
  - Offline verification tests of densification principles, confirmation of operation conditions
- Online tests: FY 2021 to 2022
  - Modification design and manufacture of commercial equipment based on the findings of the offline tests
  - Remodeling of existing facilities, test runs and adjustments
  - Evaluation of the effects of high-density pellets in real coke ovens
- Verification using real coke ovens: from FY 2022
  - Expansion of the use of high-density pellets by modifying the forming facilities from one steelworks to another

By the recycling of waste plastics to which its steelmaking process is effectively applied, Nippon Steel has played a role as a constituent member of local material-recycling societies, and contributed to suppression of the discharge of greenhouse gases, both inside and outside the steelworks. The company will continue to make ef-

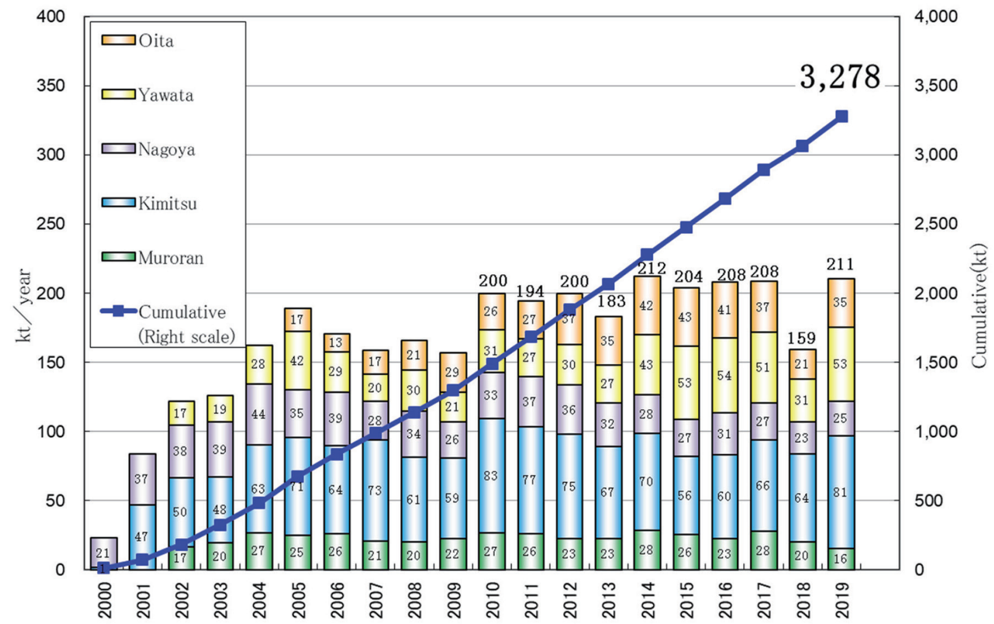

Fig. 6 Annual waste plastic recycled by works and cumulative company total of recycled amounts [1)]

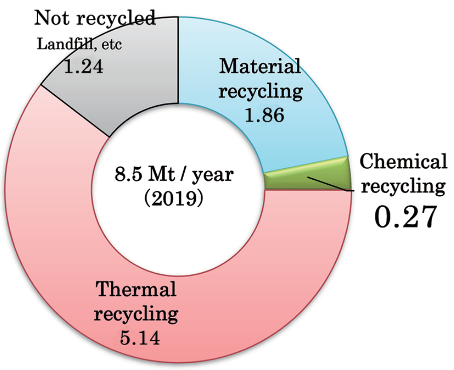

Fig. 7 Recycling of all waste plastics of Japan in 2019 [8)]

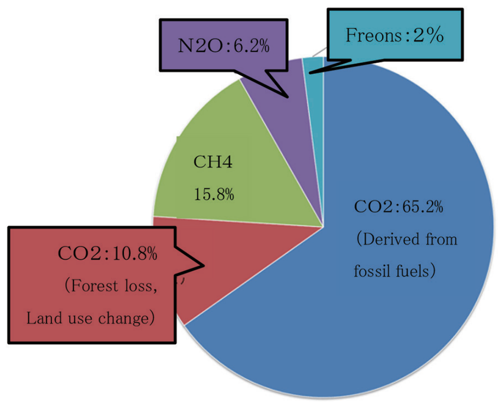

Fig. 8 Percentages of total anthropogenic greenhouse gas emissions by gas [15)]
※Numerical value in terms of carbon dioxide equivalent in 2010

forts to further increase plastic recycling as well as to have the waste plastic handling rules revised to include plastic goods that are not viewed at present as recycling objects.

3. Concept of Future Material-recycling Society: Effective Use of Overseas Landfill Waste—Possibility of Japanese Steel Industry Attaining SDGs

3.1 Impacts of waste landfill in the world

Besides CO_2, there are many greenhouse gases such as N_2O (dinitrogen monoxide) and CH_4 (methane), which is the main component of natural gas. The global warming effect per unit mass of N_2O is 298 times that of CO_2, and that of CH_4 25 times as much.[14)] Here the main focus of attention is methane. It is generated widely by the biodegradation of organic waste such as food, paper and animal carcasses, and as shown in **Fig. 8**[15)], the total of its impacts on global warming is significant, albeit smaller than that of CO_2.

While methane is generated also from the circulation of natural ecosystems, the problem here is that a good part of it is caused by the landfill of waste in huge amounts, especially organic waste, arising from human activities. Waste incinerators were constructed all over Japan up to the latter half of the 1990s, and the landfill of combustible waste has mostly been eliminated, but landfill and open dumping of waste are practiced widely in many countries around the world at present.[16)]

As a result, organic waste undergoes fermentation to generate methane, and then the area around a dumping site is rendered unpleasant for people to live in because of foul odors, waste scattered by wind, etc. In addition, rainwater becomes black water and pollutes ground water, rivers and the sea. Furthermore, in some of those countries, children get into landfill sites to collect metals and other valuable items to earn a living due to poverty.[17)]

We think that, in addition to the recycling of waste plastics, the steel industry can contribute also to the recycling and utilization of organic waste of many countries in the world. To this end, we propose specifically the following: organizations (companies) for waste reutilization are established in various countries where waste landfill is practiced; a carbonization process for burnable waste[18] that has been employed and proved effective in Japan is introduced to them; organic combustible waste is carbonized and refined by the process somewhere near the dumping site; and the carbonized product thus obtained is used at steelworks in Japan as a substitute for coal.

3.2 Significance of curbing greenhouse gas discharge by recycling landfill waste

Let us study the significance of the above scheme from the standpoint of curbing the discharge of greenhouse gases. To start with the conclusion, since the effect of suppressing methane generation is significant, the greenhouse gas reduction effect when coal is replaced by the carbonized product obtained from landfill waste is five times as much as that of ordinary biomass charcoal. In other words, in order for steelworks to achieve a state of virtual zero carbon (net zero carbon) by using common biomass charcoal, it is necessary to replace all the coal presently consumed with it, but by using the carbonized product made from landfill waste, it is enough to replace only a fifth of the coal.

The concept of this scheme is explained below using 1 t of coal or the mass of landfill waste required to replace 1 t of coal as a benchmark. **Figure 9** illustrates the material flow before and after the application of the proposed scheme and its effects, and **Fig. 10** shows the increase and decrease in the generation of greenhouse gases (converted to CO_2 equivalent) corresponding to 1 t of coal used at steelworks in Japan.

❶ Current greenhouse gas emissions from Japanese steelworks and overseas landfill sites

- Coal-derived carbon is used at steelworks in Japan. The amount of CO_2 generated per ton of coal is 2.6 t.
  (The carbon content of coal is assumed to be 70% based on the Standard Calorific Value and Carbon Emission Factors published by the Agency for Natural Resources and Energy of Japan.)
- Methane is generated by the bio-decomposition of landfilled organic waste. The mass of the waste required to obtain the amount of carbonized product that is equivalent to 1 t of coal in terms of calorific value is estimated at 12.8 t-wet (the details of the calculation are omitted here), and the amount of methane generated from this mass of organic waste is 0.75 t, which is equivalent to 18.6 t of CO_2 in terms of greenhouse effects.
  (The composition of waste and the calorific value of the carbonized product obtained through the waste processing were set according to the study results of Matsufuji et al.[19] For the calculation of methane generation, the manual[20] published by the Ministry of the Environment was referenced.)
  (Here, the amount of landfill waste required for replacing 1 t of coal was calculated supposing that the refining yield of the carbonized product was 100%, but when a more realistic yield is assumed, the required amount of waste will be far greater, and the amount of generated methane will increase in proportion.)
- In the total of Japan and the landfill site, greenhouse gases equivalent to 21.2 t of CO_2 are generated.

❷❸ Changes in greenhouse gas emissions in the country of waste discharge due to the introduction of the waste carbonization process

- Organic waste is carbonized and refined in the carbonization plants into carbonized product. As a result, methane generation is avoided, and greenhouse gas generation is reduced by an amount equivalent to 18.6 t of CO_2.
- On the other hand, 5.0 t of CO_2 is emitted to generate the heat required for the carbonization process.
  (It is assumed that this heat is obtained by burning the flammable gas generated from the carbonization process.)
  (The carbon contents of waste and the carbonized product were obtained based on the survey results of the Japan Society of Material Cycles and Waste Management[21] and the study results of Yamamoto et al.[22] The difference in carbon content between the two was attributed to the carbon contained in the combustible gas arising from the carbonization process.)

❹❺ Change in greenhouse gas emission from steelworks in Japan

- By importing the carbonized product obtained from waste and using it as a substitute for 1 t of coal, the generation of coal-origin greenhouse gases equivalent to 2.6 t of CO_2 is avoided.
- On the other hand, however, when the waste-derived carbonized product is used as a reducing agent for ironmaking, 2.8 t of CO_2 is emitted.
  (It is presumed that the difference in the amount of CO_2 generation despite the same amount of calorific value is due to the difference in the hydrogen contents between coal and the carbonized product.)

❻ Cancellation of the effects of biomass-origin greenhouse gases

- Organic waste contain carbon originating from biomass (animals and plants) and carbon originating from fossil fuels such as waste plastics.
- Of these, the biomass-origin carbon need not be counted as the cause of CO_2 emission, and for this reason, the emission of 3.8 t of biomass-origin CO_2 (1.3 t at dumping site + 2.5 t at steelworks in Japan) is cancelled out.
  (According to the present proposal, the carbon derived from biomass is burned, but if it is left as methane, it will not be decomposed for a long period exerting a huge greenhouse effect. When it is burned for the carbonization process, however, it is turned into CO_2, which can be decomposed by photosynthesis. This should also be counted as a benefit of the proposal.)
  (The proportions of biomass-derived and fossil fuel-derived carbons in waste were estimated based on the fixed carbon in the industrial analysis results[19] of waste of different compositions.)

❼ Total decrease in greenhouse gas emissions

- The outstanding greenhouse gas emissions after the cancellation according to ❻ above (originating from fossil fuels such as waste plastics) are 4.0 t-CO_2 (3.7 t at the dumping site + 0.3 t at steelworks in Japan).
- Presently, 2.6 t-CO_2 of greenhouse gases are emitted from 1 t of coal at steelworks in Japan (see a) in Fig. 10), but by replacing it with the carbonized product produced from landfill waste, the total emission of greenhouse gases at the two sites is decreased by 17.2 t (= 21.2 t − 4.0 t) in terms of CO_2 (see b) in Fig. 10), which means that the greenhouse gas emission reduction effect of the proposed scheme is more than fivefold (17.2 t ÷ 2.6 t = 6.6).

3.3 Further significance of effective recycling of landfill waste and SDGs

The significance of the emission reduction of greenhouse gases by the proposed scheme has been described above, but the benefits and value of this scheme are not limited to it. **Figure 11** shows conceivable benefits of the scheme, their interrelations and the 17 goals

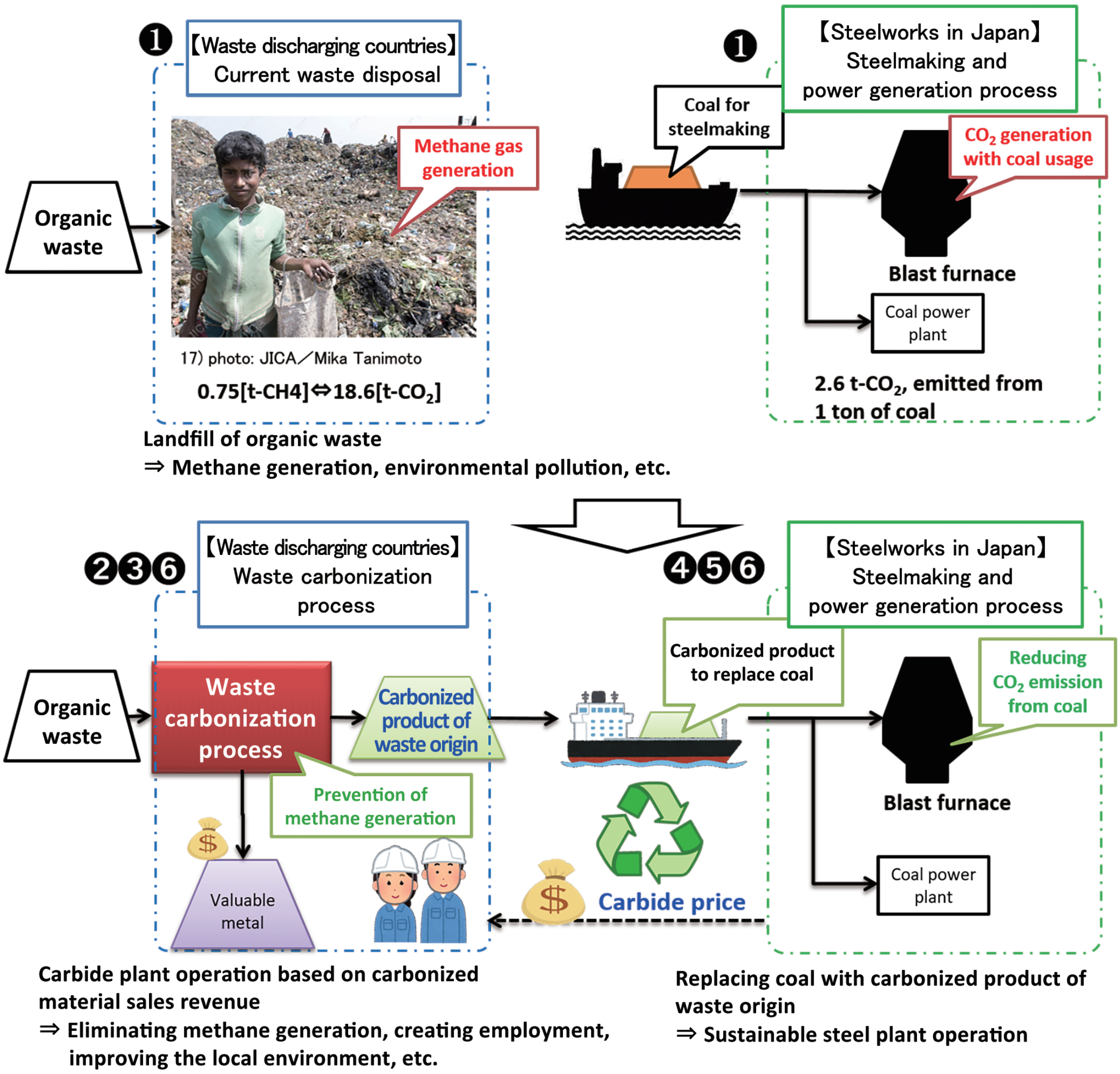

Fig. 9 Material flow before and after countermeasures and its impact

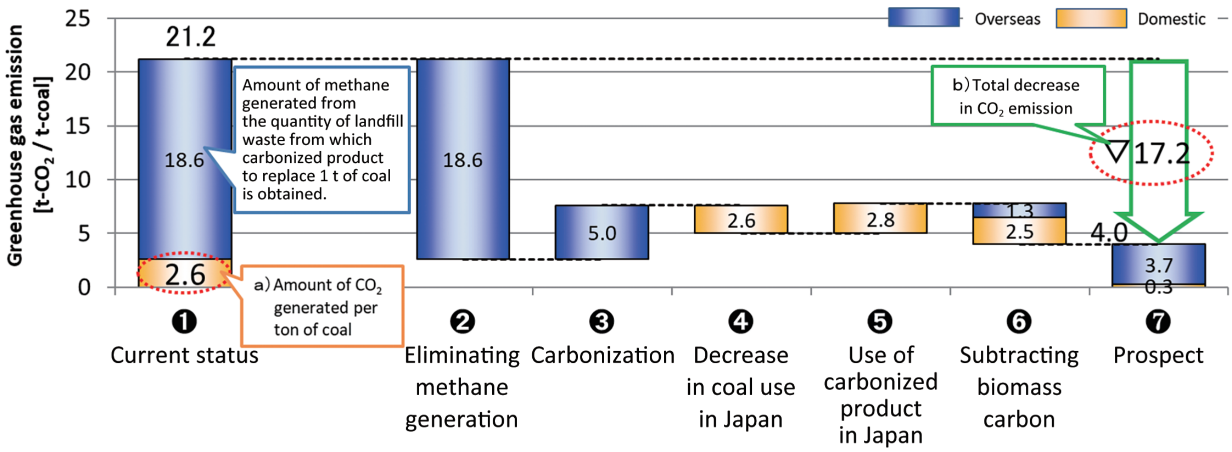

Fig. 10 Increase/decrease in greenhouse gas (CO_2 equivalent) corresponding to 1 ton of coal used in Japan

of the SDGs.

(A) With advanced plants for waste carbonization, people can be engaged in the worthy work of waste recycling regardless of gender.

(B) Thanks to the new jobs for nearby residents in (A) above, children are freed from the foul and awful business of collecting metals in garbage heaps, equal opportunity in education is promoted and the general level of education is improved. It will thus be easier for more people to get employment, which is one step closer to a safe society with less criminality.

(C) As a result of the waste treatment, the outflow of polluted water from waste heaps, foul odors and scattering of plastics and other waste will be eliminated, and ground water, rivers, the sea and the surrounding area will become clean, resulting in an environment more pleasant for human life.

(D) In addition to the above, the generation of methane is avoided at the waste dumping sites, and the use of coal at Japanese steelworks is decreased by replacing it with the carbonized product. As a consequence, the generation of greenhouse gases is cut on a global scale.

(E) The virtuous cycle of A → D → E → A →… will continue as long as it is supported by the partnership between Japanese steelmakers and overseas societies where the waste treatment plants are located based on the trade of the carbonized product.

The important point here is that the problem is not solved simply by constructing waste treatment plants at overseas waste dumping sites. The money for the construction, maintenance and operation of the plants is obtained only when the Japanese steelmakers buy the carbonized product that brings about the high greenhouse gas cutting effect at a reasonable price, and profit is earned. In other words, a sustainable system can be established only when a circular flow of economy is formed firmly between the Japanese steel industry and the waste discharging countries. (It has to be noted in this relation that one of the main reasons for waste landfill in overseas countries is that local governments and related organizations cannot afford to pay much for waste disposal.[16)])

4. Conclusion

In relation to the key phrase "material-recycling society (economy)," we reviewed Nippon Steel's past efforts for the recycling of waste plastics into valuable products, and considered the possibility of the Japanese steel industry playing a role in the recycling economy in the future, focusing on carbonization of landfill waste outside Japan.

- The blast furnace process of the Japanese steel industry using coke can exert an important function to support a recycling-oriented society.
- As stated in relation to the evaluation of waste plastic recycling, it is not important whether the efforts for decreasing the emission of greenhouse gases such as CO_2 are conducted inside steelworks premises or outside, but they have to be schemed on a global scale.
- In addition, attention has to be paid not only to the suppression of greenhouse gas emission, but also to achieving as many SDGs as possible. It is desirable that business entities be evaluated from the perspective of all such efforts and initiatives.

Making full use of the technologies that Nippon Steel has cultivated in the fields of iron- and steelmaking and environment control, we will endeavor to take part in the construction of a sustainable circulatory society, expanding the scope from the areas around steelworks to the entire world.

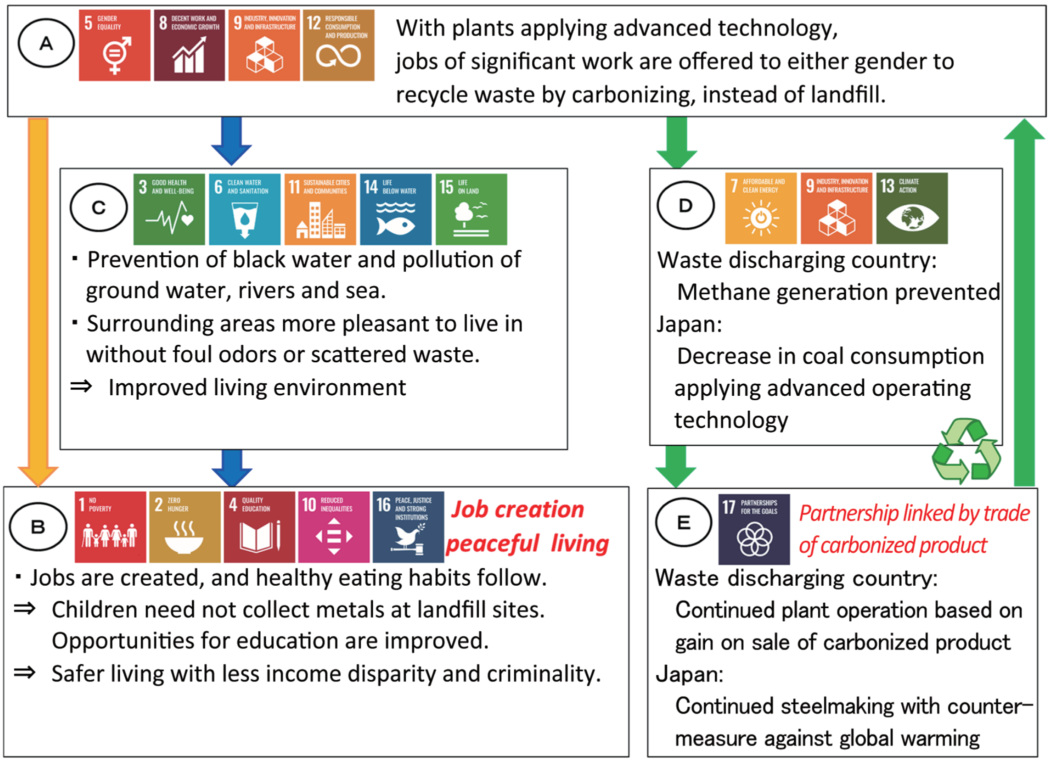

Fig. 11 Relationship between expected benefits of proposed scheme and SDGs

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