【Moonshot Goal 4】

The R&D concept of “Realization of sustainable resource circulation to recover the global environment by 2050”

February 2020
Ministry of Economy, Trade and Industry

1. Moonshot Goals

Within the Moonshot Goals (decided on January 23rd, 2020, by Plenary session of Council for Science, Technology and Innovation), the Ministry of Economy, Trade and Industry (“METI”) will, jointly with the New Energy and Industrial Technology Development Organization (“NEDO”) as a research promotion agency, undertake research and development activities for achieving the following Goal.

＜Moonshot Goal＞

“Realization of sustainable resource circulation to recover the global environment by 2050”

In order to recover the global environment, the Goal aims to solve the problem of global warming (the Cool Earth) and to solve the problem of environmental pollution (the Clean Earth) through realizing sustainable resource circulation, and aims to deploy commercial plants or products utilizing circulation technology globally by 2050.

○The Cool Earth

Development of circulation technology on a pilot scale for reducing greenhouse gases that is also effective in terms of life cycle assessment (LCA) by 2030.

○The Clean Earth

Development of technology on a pilot scale or in a form of prototype that converts environmentally harmful substances into valuable or harmless materials by 2030.

2. Related government policy

(1) Japan's Long-term Strategy under the Paris Agreement

① Based on the Japan's Long-term Strategy under the Paris Agreement (Cabinet decision, June 11, 2019, hereinafter the “Long-term Strategy”) and the Integrated Innovation Strategy 2019 (Cabinet decision, June 21, 2019), the Government of Japan aims to create disruptive innovation in energy and environmental areas which Japan has strength, and to make technologies affordable enough to be used globally in order to contribute to a drastic reduction of Green House Gas (GHG) emissions in Japan as well as worldwide.

② In order to solve urgent problems of climate change, the Long-term Strategy advocates business action toward a “Virtuous cycle of environment and growth”, rather than regulations. It also clearly states the contribution to the realization of the long-term goal of the Paris Agreement including the 1.5°C target. In order to realize the goal stated in the Long-term Strategy, various technology development and verification projects for practical use have been started in Japan for 2050. However, in order to realize the goal, it is important and necessary to not only achieve reduction of GHG emissions from product manufacturing process or energy supply, but also achieve innovation of technologies to capture and detoxify the GHG in the atmosphere.

③ The Moonshot Goal of the “Realization of sustainable resource circulation to recover the global environment by 2050” (hereinafter the “MS Goal”) and the goal of Long-term Strategy are facing in the same direction. Therefore, the Moonshot R & D Program shall aim to achieve the goal of the Long-term Strategy for contributing to the achievement of goal under the Paris Agreement. Carbon circulation by DAC (Direct Air Capture) and industrial nitrogen circulation could be examples of various approaches to achieve the MS Goal. In terms of how to reduce GHG emissions by these technologies as well as how to reduce cost of them, it is necessary not just for a capturing process but for an entire system level including utilization process after it to consider them from an early stage of R&D.

(2) Action plan for marine plastic litter

① Plastic is utilized widely as a material which brings convenience to human life due to it being light weight, tough and easy to process. As economic growth and production increases globally environmental pollution by marine plastic litter has also increased. Based on the background of increasing global concern regarding marine plastic litter on a global scale, the United Nations General Assembly for the Environment, held in March 2019, adopted a resolution on marine plastic litter and micro plastics. An international approach, such as accumulation of scientific knowledge and technical information to deal with marine plastic litter and micro plastics, reduction of one way (single use) plastic waste, and strengthening support for the innovation for development of alternative materials by utilizing industry-academia-government collaboration, are required.

② In such circumstances, Japan formulated the “Marine plastic litter countermeasure action plan”（cabinet decision dated May 31st, 2019, hereinafter the “Marine plastic action plan”）and the “Roadmap for Popularizing Development and Introduction of Marine Biodegradable Plastics” (formulated by METI dated May 7th, 2019, hereinafter the “Roadmap for Marine Biodegradable Plastics”).

③ The Marine plastic action plan aims to realize a world where effective use of plastic means no new plastic pollution is created. This is based on the idea of creating a virtuous cycle of environment and growth through innovation is the preferred approach rather than restricting economic activities. Promotion of innovation should serve as the base to proceed marine plastic countermeasure worldwide, including encouraging the development of materials which may not have adverse effects even if they flow into the sea (biodegradable plastic, paper, etc.) and enhancement of fact-finding for marine plastic litter and scientific knowledge. In addition, the Roadmap for Marine Biodegradable Plastics indicates three stages: social implementation of practical technologies, multi-use of material through technology development of composite materials, and research and development of innovative materials.

④ To deal with marine plastic litter, conventional recycle technologies such as collection and reuse of plastic and reinforcement of such activities by citizen is effective. However, it is important and necessary to have efforts beyond such conventional activities, specifically, to develop materials assuming the difficulty of its recovery.

3. Direction of research and development

Based on the discussion and proposal made in the Moonshot International Symposium (held in December 17, 18, 2019) [1], direction of research and development at present is shown as follows.

(1) Area and field to promote challenging R&D

The resource circulation technologies that contribute to the Cool Earth and the Clean Earth are mapped in a matrix in Fig. 1.

The horizontal axis shows the status of resources to be circulated, whether the concentration is high or low, or recovery is easy or difficult. Technologies are shown to the left of the matrix that are currently difficult to recover target substances because the substances spread widely or exist in low concentration. In order to solve such problems and realize sustainable resource circulation to recover the global environment, there are at least two methods to employ. One is the way to recover the target substances and convert them into beneficial substances, and the other is to decompose or detoxify the target substances.

The vertical axis shows where the degree of development of technology, from technologies that are already at the commercial stage to those that remain in the initial laboratory stage. Therefore, the lower left of the matrix is the area and field for challenging R&D to be promoted in Moonshot R & D Program, where recovery is difficult and development remains in the early stages.

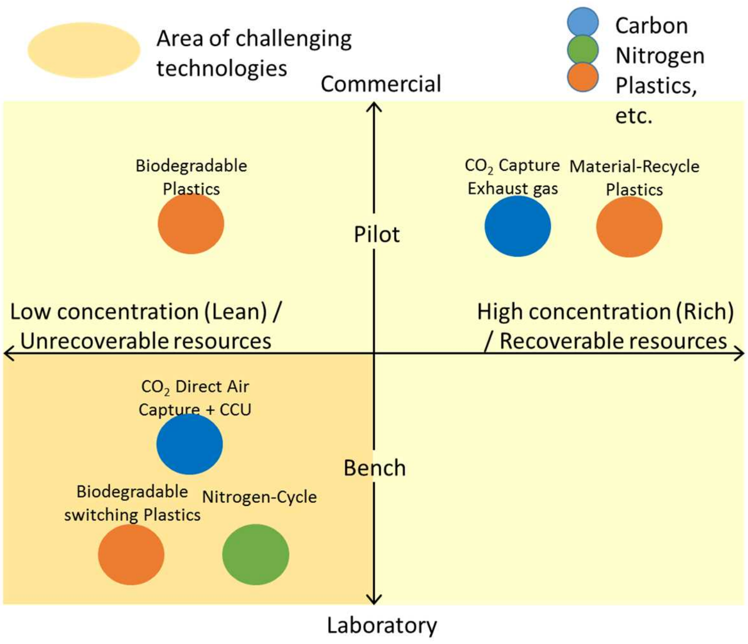

Fig. 1. Science and Technology Map for the Cool Earth and the Clean Earth

(2) Research subject for realization of the MS Goal

The lower left quadrant in Fig.1 is the area and field for challenging R&D to be promoted under the Moonshot R & D Program. R&D should proceed with keeping the following points in mind. In order to have the most effective and efficient countermeasure, the most cutting edge scientific trends shall be researched and used for R&D. In conducting R&D, various sources and types of knowledge and ideas will be adopted, stage gates will be established, and evaluation will be conducted to promote R&D to achieve the Goal.

In addition, from the viewpoint of smoothly implementing research results in society, a system that enables researchers in various fields to participate in ethical, legal, and social issues will be considered.

＜The Cool Earth＞

- R&D shall contribute to the recovery of the global environment, which is the MS Goal, and shall be challenging theme, except for ongoing national projects but including NEDO Feasibility Study Program.
- One example is DAC. In that case, R&D shall be evaluated as a total system including utilization of captured CO_2 and energy sources.

- From the viewpoint of GHG reduction, R&D for materials other than CO_2 for which the global warming potential ratio is high and its emission is large, such as N_2O and others, may be targeted.
- Assuming total system and considering cost and energy balance, target for the development theme shall be set.

＜The Clean Earth＞

- R&D shall contribute to the recovery of the global environment, which is the MS Goal, and shall be challenging theme, except for ongoing national projects but including the NEDO Feasibility Study Program.
- One example is marine biodegradable plastic. Based on the Roadmap for Marine Biodegradable Plastics, the development of new materials which provide marine biodegradability and have equal to or higher performance compared with the plastics currently used in various applications may be targeted. In that case, the new material shall provide a function which is not currently realized (such as the function to control the timing of degradability, the function of degradability works appropriately in various marine environments, and the biological safety of degradability including intermediate products generated by decomposition).

(3) Direction of research and development for realization of the MS Goal

○2030 (Output target)

<The Cool Earth>

Development of circulation technology on a pilot scale for reducing greenhouse gases, that is also effective in terms of life cycle assessment (LCA).

<The Clean Earth>

Development of technology on a pilot scale or in a form of prototype that converts environmentally harmful substances into valuable or harmless materials.

○2050 (Outcome target)

<The Cool Earth and The Clean Earth>

Realization of sustainable resource circulation to recover the global environment. Commercial plants or products utilizing circulation technology will be deployed globally.

For large-scale operations of resource circulation activities in 2050, the deployment period of large-scale facilities is to be ensured, assuming the establishment of demonstration facilities and pilot facilities necessary for the subsequent technological development in stages. Therefore, as of 2030, the goal is to establish several pilot plants and demonstration facilities with the establishment of the technology.

Fig. 2 shows the schematics timeline in 2030, 2040, 2050, and beyond, for achieving targets through the Moonshot projects.

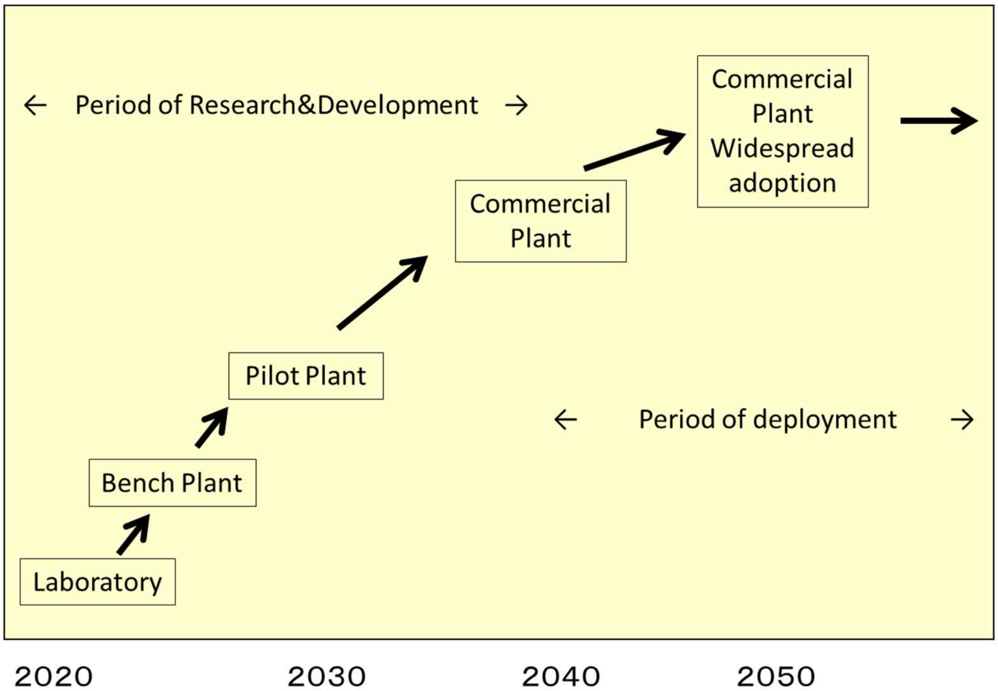

Fig. 2. Timeline for realization of the MS Goal

＜Reference：Analysis for realization of the MS Goal＞

Summary of content which is analyzed in the Initiative Report presented in Moonshot International Symposium is shown, as follows.

①The Cool Earth

a) Current status

Regarding global warming, there are many gases called greenhouse gases. Characteristics of 7 major greenhouse gases, which are subject to be reported, are described in Table 1.

As is well known, CO_2 has an overwhelming influence, but CH_4 and N_2O also have a certain influence.

Table 1. Characteristics of 7 major greenhouse gases

		Emission：V 100 million tons / year	Global Warming Potential：K (CO_2=1)	Impact on Global Warming ＝V×K
①CO_2		350	1	350
②CH_4		3	28	63
③N_2O		0.1	265	31
④Fluorine compounds	HFCs	0.1>	12,400>	-
	PFCs	0.1>	11,100>	-
	SF_6	0.1>	23,500	-
	NF_3	0.1>	16,100	-

Fig. 3, 4, and 5 show increase of annual greenhouse gas emissions and concentration, and increase of atmosphere temperature, respectively. The temperature continues to rise consistently, and its speed is about 0.1 °C per 10 years.

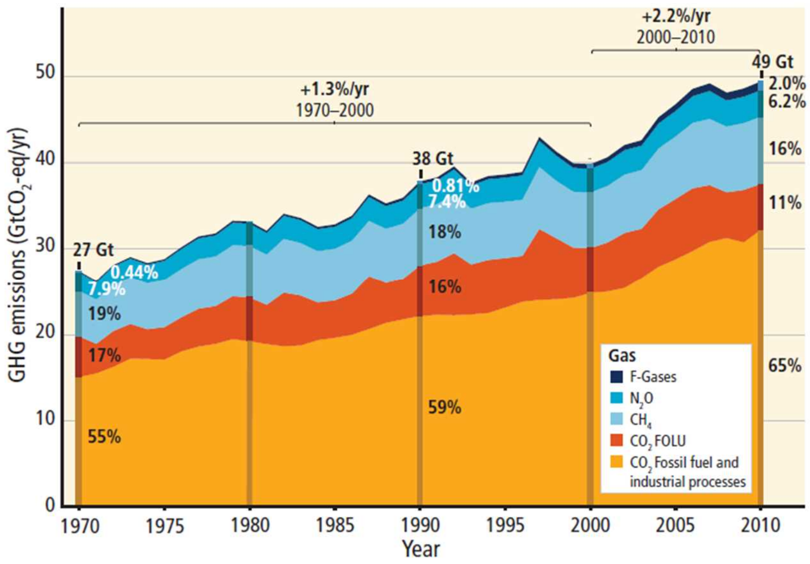

Fig. 3. Greenhouse gas emission trend [2]

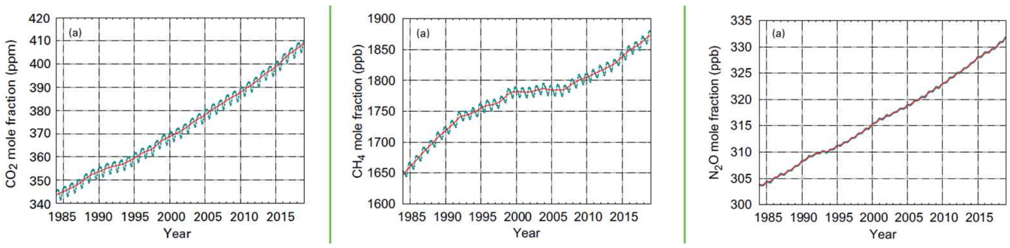

Fig. 4. Greenhouse gas atmospheric concentration trend [3]

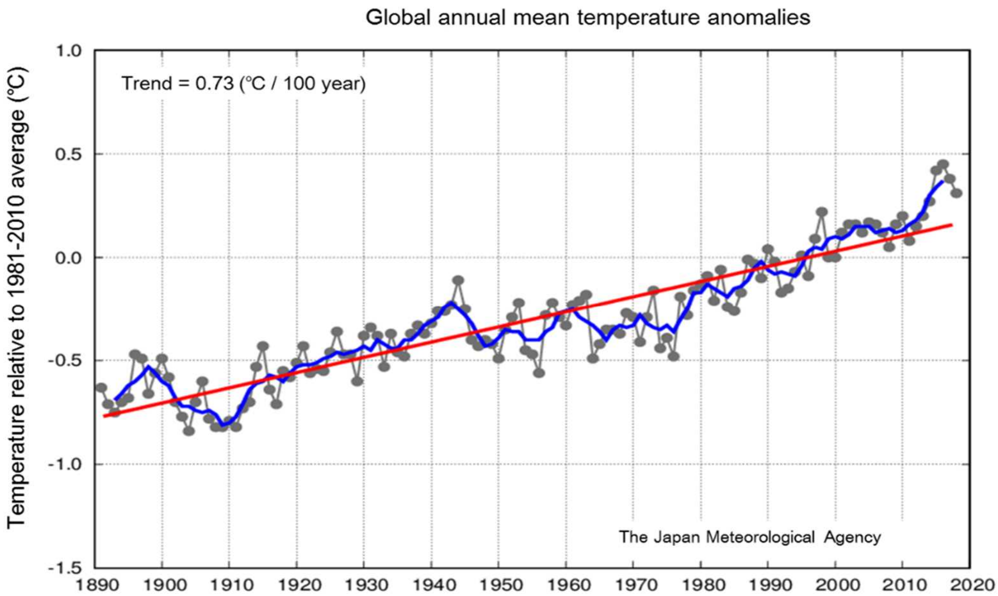

Fig. 5. Atmospheric temperature rise trend [4]

b) Approach

The countermeasures for each greenhouse gas are described below.

○CO_2

The CO_2 utilization flow chart concerning the biggest issues in global warming is shown in Fig. 6.

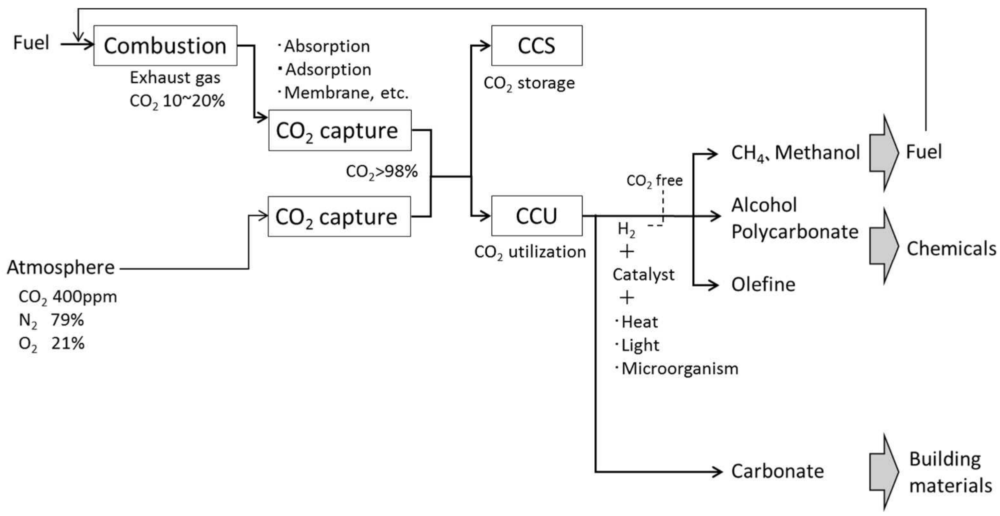

Fig. 6 CO2 capture and utilization flow chart

There are already some implementations of CO_2 recovery from exhaust gas combustion, which contains high concentration of CO_2, by absorption, adsorption and membrane.

On the other hand, few R&D regarding CO_2 recovery from the atmosphere has yet been carried out, because CO_2 concentration is as low as 400 ppm.

The recovered CO_2 can be stored underground and contained (Storage; CCS), or can be converted into fuel and/or various chemicals as a raw material (CCU). If CO_2 is converted to fuel and burned, fuel consumption can be reduced through circulation. If the various chemicals converted from CO_2 are distributed in the market, the consumption of conventional fossil resources can also be reduced. At present, although there is some commercial implementation, most of CCU activities are at the R&D stage and further development should be encouraged.

Regarding CO_2 removal from the atmosphere (negative emission technologies), there are some examples shown in Table 2. In these examples, DAC (Direct Air Capture) is the only purely-technological pathway which does not affect the natural environment. All the other pathways are likely to become unstable, or could cause unexpected results. Therefore, DAC is selected as a target subject of technological development.

Table 2. Summary table of pathways in the carbon dioxide removal portfolio, highlighting strengths, weaknesses and indicative technical potential [5]

		Cost	Energy Requirements	Land Use	Water Consumption	Risk of Reversal	Verifiability	Implement Readiness
NATURAL	Reforestation & Enhanced Forest Management	Generally Acceptable/ Available	Generally Acceptable/ Available	Potentially Unacceptable/ Unavailable	Exercise Caution	Exercise Caution	Generally Acceptable/ Available	Generally Acceptable/ Available
NATURAL	Wetland & Coastal Restoration	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Exercise Caution	Exercise Caution	Generally Acceptable/ Available
NATURAL	Soil Carbon Restoration	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Exercise Caution	Potentially Unacceptable/ Unavailable	Exercise Caution
TECHNOLOGICAL	DACS	Potentially Unacceptable/ Unavailable	Exercise Caution	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Exercise Caution
TECHNOLOGICAL	Terrestrial Enhanced Weathering	Exercise Caution	Exercise Caution	Generally Acceptable/ Available	Exercise Caution	Generally Acceptable/ Available	Generally Acceptable/ Available	Exercise Caution
TECHNOLOGICAL	Ocean Alkalinity Modification	Exercise Caution	Exercise Caution	Generally Acceptable/ Available	Generally Acceptable/ Available	Generally Acceptable/ Available	Exercise Caution	Potentially Unacceptable/ Unavailable
HYBRID	Hybrid Bioenergy with CCS (BECCS)	Exercise Caution	Generally Acceptable/ Available	Potentially Unacceptable/ Unavailable	Exercise Caution	Generally Acceptable/ Available	Exercise Caution	Generally Acceptable/ Available
HYBRID	Bioenergy with Biochar Sequestration (BEBCS)	Exercise Caution	Generally Acceptable/ Available	Potentially Unacceptable/ Unavailable	Exercise Caution	Exercise Caution	Potentially Unacceptable/ Unavailable	Generally Acceptable/ Available

LEGEND: Generally Acceptable/ Available; Exercise Caution; Potentially Unacceptable/ Unavailable

In 2050, CO_2 emissions must be reduced considerably, but not all the emissions can be stopped due to technology and cost constraints, and thus a certain amount of emissions is inevitable. In order to realize net zero emissions of greenhouse gases in the second half of this century as mentioned in the Intergovernmental Panel on Climate Change (IPCC) 2 °C scenario, negative emissions with the equivalent amount to the remaining emissions are necessary. Therefore, a considerable amount of capacity is expected for DAC.

DAC is now underway with some technologies and efforts as shown in Table 3 and 4. Various R&D initiatives have been carried out for conversion and utilization, and some are already implemented. [6] But these technologies have low efficiency and high energy consumption. By significantly improving these issues, DAC and CO_2 utilization should be realized with feasible cost for deployment, and should be effective also in terms of LCA.

Table 3. Examples of technology currently used in DAC [7][8][9]

Target	Current status	Examples of technology
DAC	Laboratory ～ Pilot plant	✓ Absorb CO_2 in alkaline solution → Immobilize in carbonate → Firing and release CO_2 ✓ Adsorb and desorb CO_2 with honeycomb ceramic adsorbent containing amine ✓ Adsorb and desorb CO_2 with activated carbon and K_2CO_3 adsorbent

Table 4. List of major characteristics on DAC pilot plant [5][8][10][11]

Company	Thermal energy/ tCO_2 (GJ)	Power/ tCO_2 (kWh)	Heat: Power ratio	Reference
Climeworks	9.0	450	5.6	Ishimoto 2017
Carbon Engineering	5.3	366	4.0	Keith 2018
Global Thermostat	4.4	160	7.6	Ishimoto 2017
APS 2011 NaOH case	6.1	194	8.7	APS 2011

Up to this point, this report has focused on CO_2. However, in order to achieve the IPCC 2 °C scenario, it is also necessary to take measures against greenhouse gases other than CO_2, which account for approximately 24% of the total.

○CH_4

CH_4 has negative impact following CO_2 on the environment. The main sources of CH_4 emissions are associated with fossil fuel production, livestock, landfills, waste and agriculture. [12] In fossil fuel production, some efforts have been made against the gas accompanying natural gas mining. In livestock, the gas discharged from cows accounts for a significant amount. There is a possibility of using biotechnology as a countermeasure against the emission from livestock. In landfills, waste, and agriculture, although there is also a possibility of using biotechnology, no effective solution has been found.

○N_2O

For N_2O, major artificial emissions originate from nitrogen chemical fertilizer used in agriculture (Fig. 7). In response to the global population increase, such fertilizer has been used for efficient food production and sprayed over farmland with excess amounts of the levels capable to be absorbed by plants. The excess fertilizer remaining in the farmland flows out, through rainwater and groundwater, into rivers and then into lakes and oceans. Thus, the target area against the N_2O emissions seems to be widespread. However, it is actually not a large area on a global scale as for the case in CH_4. Therefore, it is sufficiently possible to circulate N_2 from N_2O by controlling the behavior of N_2O emissions in the environment, such as lake bottoms, originating far from the fertilizer in the farmland. Although it has not been implemented yet, some R&D has been conducted as shown in Table 5.

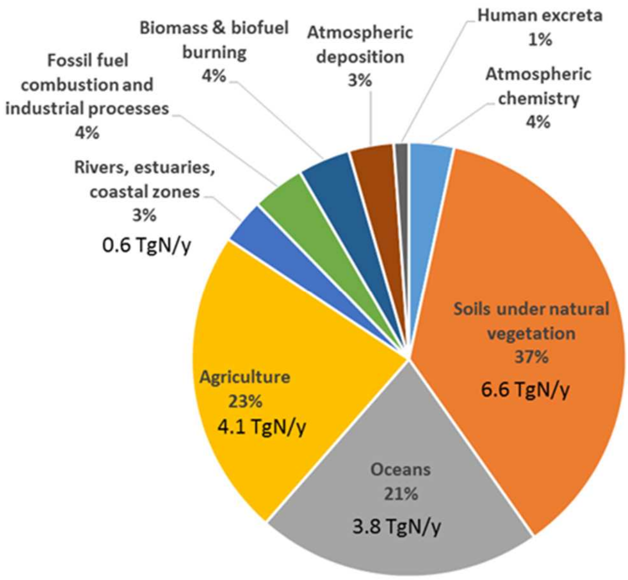

Fig. 7. Breakdown of N_2O sources [12]

Table 5. Examples of technology for the circulation of N_2O [13][14][15][16]

Target	Current status	Examples of technology
N_2O	Laboratory	✓ Reduce N_2O to N_2 with natural or artificially modified enzymes ✓ Reduce N_2O to N_2 by chemical reaction through a catalyst ✓ Reduce N_2O to N_2 using microorganisms ✓ Suppress the generation of N_2O by NH_3 and NO_3 adsorbent

○Fluorine compounds

Out of the 7 major greenhouse gases, four gases are fluorine compound gases.

These have a large global warming potential, but the impact on global warming is small (as its absolute amount is small). These fluorine compound gases are not naturally derived nor generated from a wide range, and the emission source is almost entirely limited to refrigerant gas or the like. Because of these characteristics, an appropriate recovery process before being released to the atmosphere is reasonable. Therefore, regulatory management is appropriate.

②The Clean Earth

a) Current status

Looking at the current status in Japan, harmful substances include various exhaust gases (NOx, SOx, PM2.5 and etc.), liquid drainage (oil, nitrogen, phosphorus, organic substances, etc.), and soil wastes (metals, organic pollutants, etc.) are regulated by law. However, nitrogen compounds are partially leaked to the environment even under regulations. This is one of the reasons why nitrogen has already exceeded the planetary boundary limits of high risk level. As shown in Fig. 8, the nitrogen compounds are leaked to the environment, including N_2O derived from chemical fertilizers, NOx in exhaust gas and nitrogen compounds contained in industrial wastewater.

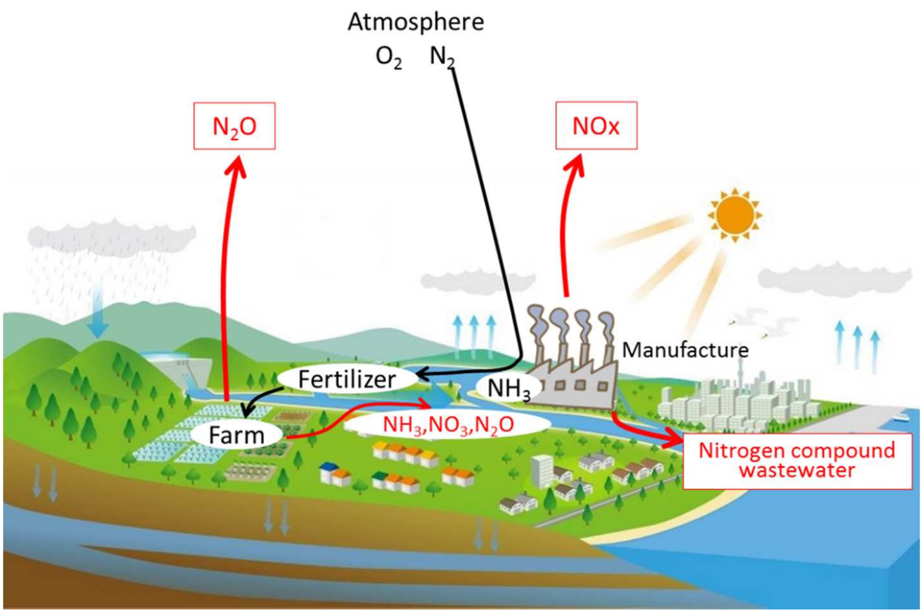

Fig. 8. Conceptual diagram of nitrogen circulation

Plastic garbage is one social problem that has leaked into the environment. Fig. 9 shows the amount of waste plastic and its treatment status in Japan.

Waste plastic which outflows from land to sea has become a global problem. The United Nations Environment Programme (UNEP) estimates that 9 million tons of plastic flow into the sea annually (Table 6). It is said that as many as 700 species in the sea, including endangered species, have been damaged by plastic tangles or accidental ingestion of plastic, so there are concerns about the adverse impacts on food chains and ecosystems. Protecting the richness of marine ecosystems is one of the targets of the Sustainable Development Goals (SDGs). So technology development for solving this problem should be addressed. For reducing marine plastic litter, waste management including recycling systems is necessary. In addition, it is effective to introduce biodegradable plastics.

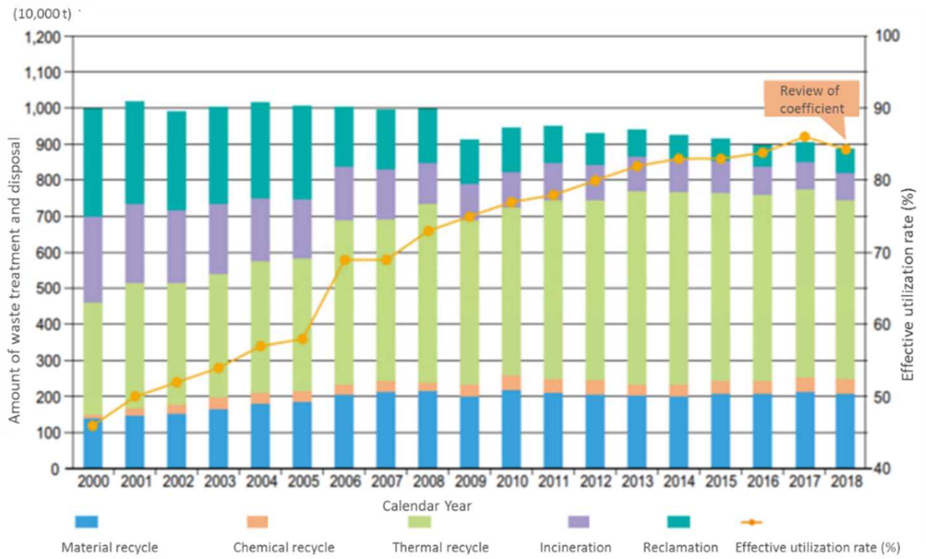

Fig. 9.Treatment status of waste plastic in Japan [17]

Table 6. Sources of plastic pollution reaching the marine ecosystem [18]

(thousand metric tones per annum)

Source	Tonnage plastics estimated to be entering the ecosystem
Rivers/land run off-land based	9,000
Direct dumping	1,500
Fishing gear	640
Lost cargo	600
Vehicle tire dust	270
Industrial pellet spills	230
Road and building paint	210
Textiles	190
Cosmetics	35
Marine paint	16

b) Approach

○Nitrogen compounds

Conventionally, NOx in exhaust gas is denitrated by ammonia. The remaining NOx has been released into the environment with its low concentration.

Nitrogen compounds in waste water from industry have also been released into the environment with their low concentration.

The circulation technology regarding NOx and nitrogen compounds, which is effective even for very low concentrations, is expected. Since it is still at the laboratory level, there is no example of social implementation. Examples of possible circulation technology are shown in Table 7.

Table 7. Examples of technology for the circulation of nitrogen compounds [19][20][21][22][23][24]

Target	Current status	Examples of technology
NOx	Laboratory	✓ Convert NOx in exhaust gas to ammonia by chemical reaction using a catalyst ✓ Convert NOx to nitric acid by chemical reaction
Nitrogen compounds in waste water	Laboratory	✓ Convert nitrogen-containing organic in wastewater to ammonia by catalytic reaction ✓ Convert nitrogen-containing organic in wastewater to ammonia using microorganisms

○Marine plastic litter

Regarding the actions for marine plastic litter, Fig. 10 shows the resource flow using biodegradable plastics. It is not necessary to replace all conventional hard-to-decompose plastics with biodegradable plastics. This is because even if it is difficult to decompose, it does not necessarily flow into the sea if properly managed and processed. On the other hand, it is necessary to introduce applications preferentially where biodegradability is suitable, such as applications that have a high possibility of spilling into the marine ecosystem or where use in river, lake, marsh, and marine takes place.

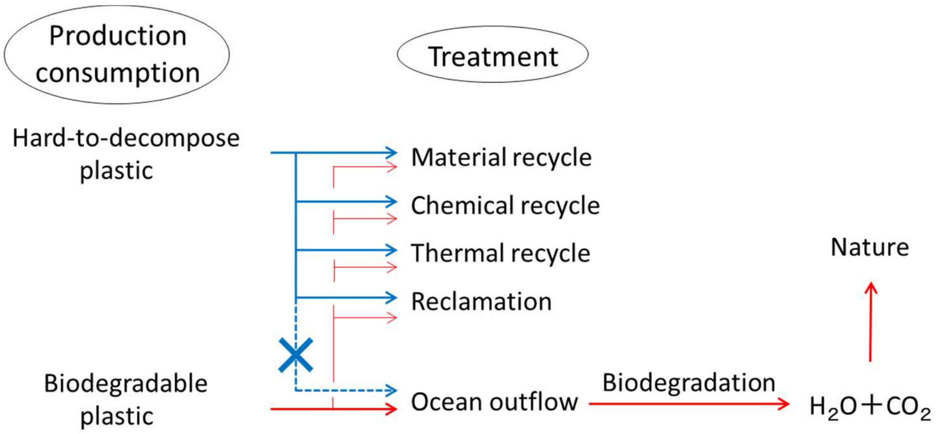

Fig. 10. Plastic resource flow with biodegradable plastics

Biodegradable plastics can be returned into the environment by becoming CO_2, nitrogen, and oxygen that lead to large ground, marine and air resource circulation.

Compared to the amount and type of microorganisms and enzymes in the soil, those in the sea are overwhelmingly less. Therefore, the development of plastics which decompose in the sea is more difficult than those that decompose in soil. Even under such circumstances, R&D on biodegradable and detoxifying plastics has already started, but the variety of such marine biodegradable plastics are limited. In general, plastic products fulfill its function by blending multi kind of plastic materials or by multi-layered plastics, rather than the single plastic material. If various functions are performed by increasing the kind of marine biodegradable plastics, it expands the usage and it contributes to the dissemination, therefore, development of plastics providing marine biodegradable capability is necessary. It is also noted that plastic products use not only plastic materials but also organic substances other than plastic material, such as, additives, surface treatment agent, pigment, paint and glue, and therefore, marine biodegradability of such substances shall be considered in designing the plastic products.

Examples of the products which have been commercialized and marketed are shown as below.

- Polylactic acid
- Fatty acid polyester
- Polyvinyl alcohol

In addition, state-of-the-art efforts to add a function (switch function) to control the start time and speed of biodegradation at the design stage have also recently started.

There is the application for which a biodegradable plastic having a so-called switch function capable of purposely biodegrading. For example, fishing gear is used mechanically, such as rewinding, so that it easily flows out into the sea when the net breaks. However, it is very beneficial for it to not decompose and maintain a predetermined performance while used as fishing gear. Thus, it has a function that starts to decompose when it flows into the sea but not when it is being used.

Since it is still at the laboratory stage, there are no examples of social implementation. Examples of possible biodegradable plastic technology to add a switch function are shown in Table 8.

Table 8. Examples of biodegradable plastic technology to add switch function [24][25][26][27]

Target	Current status	Examples of technology
Biodegradable plastic with switch function	Laboratory	✓ Technology to control the starting point of biodegradation • Biodegradation appears when the chemical structure changes in pH, salt concentration, etc. • Biodegradation appears when the enzyme in the material is activated by the physical stimulus due to outflow ✓ Technology to control the rate of biodegradation • Controlling biodegradation rate by changing crystallinity and crystal thickness • Controlling biodegradation rate by using microbiomes such as biofilm

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