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SPECIAL FEATURE: ORIGINAL ARTICLE

Material Cycles toward Carbon Neutral Society

Japan's greenhouse gas reduction scenarios toward net zero by 2050 in the material cycles and waste management sector

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Abstract

The first draft scenario toward net zero greenhouse gas (GHG) emissions by 2050 for the material cycles and waste management sector was presented by the Ministry of the Environment, Japan in August 2021. The details of the future GHG emission estimation used to create the draft scenario are described in this document. For multiple scenarios where more aggressive measures, such as carbon capture, utilization, and storage (CCUS), were included in addition to business-as-usual and the current policy continuity scenario, future GHG emissions were estimated as the sum of the products of activities and emission factors indicating changes in measures between scenarios. The estimation outcomes demonstrated that future GHG emissions from the solid waste management sector could be anticipated to be zero or even negative when material conversion to biomass, primarily for plastics, recycling to raw materials, and installation of CCUS at incineration facilities are assumed. Extensions of prior plans are not enough to reach the goal of net zero emissions, according to the measures necessary and the volume and pace of their implementation suggested in this study. Stakeholders should collaborate with great ambition.

Keywords GHG reduction · Material cycles · Waste management · 3R plus · Plastic management · CCUS

Introduction

Medium- and long-term efforts are being made around the world, including efforts to reach net zero greenhouse gas (GHG) emissions by 2050 and reduction processes by 2030 [1]. It is expected that all key sectors, including industry and households, will attempt to develop decarbonized supply chains toward net zero GHG emissions by 2050, and the material cycles and waste management sector is no exception. Planning at the national and local levels increasingly comes before such activities.

The United Kingdom declared a statutory policy goal of net zero GHG emissions by 2050 in 2019, making it the first Group of Seven (G7) nation to do so. The Climate Change Committee then created the Sixth Carbon Budget Report [2], which calls for a 78% reduction in GHG emissions from 1990 levels by 2035, and released five scenarios and summary reports of various sectors including this sector to achieve net zero GHG emissions by 2050. The Balanced Net Zero pathway, which is thought to be the most realistic of the five scenarios outlining ways to achieve net zero GHG emissions by 2050, calls for actions like waste reduction, encouraging reuse and recycling, carbon capture and storage (CCS) for incineration processes, landfill bans, and landfill methane recovery. The estimated GHG emissions in this sector by 2050 are around 7.8 million t-CO_2 eq, and although the waste sector alone will not achieve net zero GHG emissions, it is anticipated to achieve a 75% decrease from the baseline scenario. Effective actions in particular include landfill ban, waste reduction, recycling, and the use of CCS in waste facilities (starting in the early 2040s). In addition to the national government's actions,

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some stakeholders have created plans and goals to achieve net zero GHG emissions. One such example is the Environmental Services Association, which has established a goal to reach net zero GHG emissions in this sector by 2040, well in advance of the national target [3]. Additionally, the assessment report [4] issued by the National Infrastructure Commission for the infrastructure sector, which includes the waste sector, lists decarbonization and energy efficiency improvements in power generation and heat supply, as well as the development of new infrastructures, such as hydrogen supply networks and CCS, as concrete measures toward decarbonization, suggesting that the government, sectors, and industries are cooperating to speed up the transition to zero GHG emissions.

The United States has established a National Determined Contribution (NDC) aim to reduce GHG emissions by 50–52% (relative to 2005 levels) by 2030 and a long-term strategy to achieve net zero GHG emissions by 2050 following its readmission to the Paris Agreement in 2021 [5]. In order to achieve net zero GHG emissions by 2050, (1) the energy system must be transformed (decarbonizing electricity, shifting energy demand to electrification and clean fuels, improving energy efficiency) (totaling about 4.5 billion t-CO_2eq reduction); (2) non-CO_2 GHG emissions, such as CH_4, must be reduced (about 1 billion t-CO_2eq reduction); and (3) unavoidable GHG must be removed through atmospheric CO_2 removal (about 1 billion t-CO_2eq removed). The long-term strategy for the U.S. waste sector [5], which includes landfill avoidance, CH_4 recovery from a landfill or organic waste sources, CH_4 and N_2O reduction in wastewater treatment, and N_2O measures from livestock waste, emphasizes the significance of reducing CH_4 and other non-CO_2 GHG.

In France, a roadmap for implementing the Paris Agreement's climate change mitigation policies was created in March 2020, with two goals: carbon budgeting in the short/medium term and carbon neutrality by 2050, based on a strategy for a transition to a low-carbon economy across all sectors [6]. About 3% of all GHG emissions are produced by the waste sector, which has a reduction goal of 37 and 66% by 2030 and 2050, respectively (compared to 2015). Between 2015 and 2050, this decrease translate into a reduction of 300,000 t-CO_2 eq/year. The primary measures in the waste sector for the circular economy include control methods to reduce the intensity of waste generation, including food waste, by 20% by 2050, through the design stage of production, packaging restrictions, and product life extension. Additionally, it claims that better waste sorting and collecting will boost material recovery. By encouraging biogas recovery, the Energy Recovery Promotion Programme hopes to cut landfills by 90% by 2035 and stop GHG leakage. "The 2018 circular economy roadmap strategy" calls for changes to consuming habits, production procedures, and waste management in order to implement these measures. Additionally, "the antiwaste law for a circular economy" was formulated in February 2020. The regulation seeks to reduce waste in all of its manifestations by raising consumer awareness and enhancing manufacturing and distribution techniques.

In Canada, the Canadian Net-Zero Emissions Accountability Act was implemented in 2022, and it resulted in the creation of the first reduction strategy at the government level [7]. Reducing landfill methane emissions and using recovered products from biodegradable trash, which also contribute to such emissions, are the key areas of concentration in the waste sector. Due to methane production from landfills, the waste sector produced 28 million t-CO_2eq of GHG in 2019, which makes around 4% of all emissions in the nation. According to reports, landfill methane of 23 million t-CO_2eq accounts for 83% of the waste sector, with 11% coming from the waste wood disposal, 3.6% from wastewater treatment, 1.5% from composting, and 0.7% from incineration. Landfill methane accounts for 27% of total methane generation, reflecting the fact that more than 60% of waste disposal is landfilled. The 2030 ERP (Emission Reduction Plan) includes measures for waste reduction and circular economy strategies, such as composting and landfill gas recovery and usage.

Asian countries have also started to consider decarbonizing various sectors, and there are reports on GHG emission and mitigation measures from the waste sector in China [8]. According to the Intergovernmental Panel on Climate Change (IPCC) inventory model, GHG emissions from the waste sector in China increased from 55.38 million t-CO_2 eq in 2006 to 178 million t-CO_2 eq in 2019. This increment was due to a significant contribution from landfill methane, but it was also due to an increase in the contribution from incineration. In 2019, municipal solid waste incineration emitted 55.64 million t-CO_2 eq, an increase from 7.8% in 2006 to 22% of the total waste sector emissions. Based on this condition, mitigation measures in the waste sector include the promotion of waste separation and recycling, landfill management and landfill gas recovery and utilization, and the shift from landfill to incineration.

Meanwhile, in Japan, Prime Minister Yoshihide Suga declared in his diet policy speech on October 26, 2020, that Japan aims to be carbon neutral by 2050 [9]. The Japanese government adopted a global warming action plan at a cabinet meeting based on the Law on Promotion of Global Warming Countermeasures. The plan also stipulates measures to reduce GHG emissions from the waste sector; however, because the targets set out in the latest plan correspond to Japan's NDC under the Paris Agreement [10], the quantitative targets for sectors exist only for the year 2030. The long-term strategy, which was revised around the same time [11], sets out the basic approach and vision toward carbon neutrality by 2050. However, it does not seem to include future scenarios with relevant figures in the meaning of "a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships" [12]. Subsequently, the Ministry of Economy, Trade, and Industry, in collaboration with other relevant ministries and agencies, formulated the "Green Growth Strategy for Carbon Neutrality by 2050" in December 2020 [13], which set out an action plan for "resource recycling-related industries" to achieve net zero GHG emissions by 2050. Therefore, work needs to be done to organize the scope of GHG emissions to be covered and the basic approach to implementing GHG reduction measures, as well as to clarify the direction in which the government and other actors should work in the future to achieve the net zero target for this sector. This paper corresponds to the core work of the scenario-building study, and the results were used in the preparation of the "Draft Medium- and Long-term Scenarios for Net Zero Greenhouse Gas Emissions in the Material cycles and waste management sector by 2050," which was reported to the Sound Material-Cycle Society Committee of the Central Environmental Council by the Ministry of the Environment in August 2021. This study reports the results of setting scenarios for the first time, on the future measures in the material cycles and waste management sector targeting net zero GHG emissions by 2050, and their GHG emissions estimate for the Japanese material cycles and waste management sector.

The national GHG inventory of FY2019 submitted to the secretariat under the United Nations Framework Convention on Climate Change (UNFCCC) shows that Japan's total GHG emissions were 1.212 billion t-CO_2 eq. Of this amount, emissions from the waste sector, including those reported as energy- and non-energy-derived, totaled 39.67 million t-CO_2 eq, accounting for about 3.3% of the total emissions. Excluding energy use, GHG emissions from the waste sector amounted to 20.37 million t-CO_2 eq, which, like agriculture sector (31.68 million t-CO_2 eq) and cement production (25.33 million t-CO_2 eq), reflects that the sector is one of Japan's major sources of GHG emissions.

Materials and methods

Definition of GHG emissions in the material cycles and waste management sector

In this estimation, GHG emissions from the treatment and recycling of solid waste are defined as GHG emissions from the material cycles and waste management sector, and they are examined to achieve net zero emissions by 2050. Specifically, in addition to the GHG emissions from solid waste, which are recorded in the waste sector of the international guidelines for the preparation of GHG emissions and sink inventories (GHG inventories) to be submitted annually by Parties to Annex I to UNFCCC (developed countries and countries in transition to a market economy) under the Convention [14], the GHG emissions from waste incineration with energy recovery and waste utilization as raw materials or fuel, and CO_2 emissions from the use of energy required for waste treatment, which are accounted for in the energy sector of the same guidelines [14], were included in the calculation. Table 1 provides the details.

Equation for GHG emission estimation and future GHG estimation methods

Here, the GHG estimation methods used in the national GHG inventory are adopted. Namely, GHG emissions were calculated by multiplying activity data and GHG emission factors. The activity data and GHG emission factors from 1990 to 2019 were quoted from the national GHG inventory submitted by the Government of Japan to UNFCCC in April 2021 [15]. Original GHG estimation tools that were developed with Microsoft Excel were used for calculation. GHG emissions from the use of electricity and heat in the material

Table 1 Classification of GHG emissions in the material cycles and waste management sector

Sector	Categories	GHG emission sources
Waste	GHG emissions from solid waste	Solid waste disposal (CH_4), biological treatment of solid waste (CH_4, N_2O), incineration and open burning of waste (CO_2, CH_4, N_2O)
Energy	GHG emissions from waste incineration with energy recovery and waste utilization as raw material or fuel	Waste incineration with energy recovery (CO_2, CH_4, N_2O), direct use of waste for energy (CO_2, CH_4, N_2O), waste derived fuel (CO_2, CH_4, N_2O)
Energy	CO_2 emissions from the use of energy required for waste treatment	Electricity[a] and other energy consumption during waste collection, intermediate treatment, and final disposal of solid waste (CO_2)

[a] As CO_2 emissions from electricity consumption are not accounted for in the national GHG inventory, CO_2 emission factors for electricity use is separately set and used in the calculation

cycles and waste management sector were included in the scope of calculation. Based on the expectation of actions for net zero GHG emissions in the energy sector, the CO_2 emission factor for the use of electricity is expected to be zero by 2050. CO_2 emission factor for the use of electricity from 2019 to 2050, the transition stage to net zero, is expected to gradually reach zero by 2050.

The details of future GHG estimation methods for municipal waste and industrial waste are shown in Figs. ESM1 and ESM2 in the Online Resource 1, respectively.

GHG emissions in the business-as-usual (BAU) scenario in the material cycles and waste management sector, which represents GHG emissions without additional actions after 2019, were estimated until 2050 based on population and manufacturing trends in the materials industry and the amounts of future municipal and industrial waste with GHG emission factors for 2019. GHG emissions for each scenario shown in "Medium- to long-term scenario" were calculated by reflecting actions for GHG reduction to activity data or emission factors.

Municipal waste

The following procedure was used to estimate GHG emissions from municipal waste.

- Future municipal waste generation was calculated by multiplying the future population shown in the "National Institute of Population and Social Security Research, Estimated Future Population of Japan (2017 Estimates)" [16] by the unit municipal waste generation per person per day.
- Future municipal waste generation by waste composition was estimated by multiplying future municipal waste generation by future municipal waste composition.
- Future municipal waste generation by waste composition and treatment methods were estimated by multiplying the fractions of future waste treatment methods by waste composition and future municipal waste generation by waste composition.
- Future GHG emissions from municipal waste were estimated by multiplying future municipal waste generation by waste composition and treatment methods and future GHG emission factors.

The following procedure was used to estimate CO_2 emissions from energy use in municipal waste treatment.

- The amount of treated municipal waste and human waste [by waste treatment technologies, size of facilities, and facility installation (new/existing)] were estimated based on future municipal waste generation by waste composition and treatment methods, shown in the above procedure.
- Future CO_2 emissions from energy use in municipal waste treatment were estimated by multiplying the amount of treated municipal waste and human waste and future unit energy consumption by facility types with future CO_2 emission factor.

Industrial waste

The following procedure was used to estimate GHG emissions from industrial waste.

- Future industrial waste generation by waste type was estimated by multiplying future industrial waste generation by waste type in each industrial sector and future activity drivers (e.g., future material production) [17].
- Future industrial waste treatment by waste type and treatment methods were estimated by multiplying future industrial waste generation by waste types and fractions of future industrial waste treatment methods (landfill, composting, and incineration).
- Future GHG emissions from industrial waste were estimated by multiplying future industrial waste treatment by waste type and treatment methods and future GHG emission factors by waste type.

The following procedure was used to estimate CO_2 emissions from energy use in industrial waste treatment.

- Future energy consumption in industrial waste treatment (by waste type and treatment methods) was estimated on the basis of future industrial waste treatment by waste type and treatment methods and future unit energy consumption in industrial waste treatment.
- Future CO_2 emissions from energy use in industrial waste treatment was estimated by multiplying future energy consumption in industrial waste treatment (by waste type and treatment methods) and future CO_2 emission factors.

Methods of reducing GHG emission

Figure 1 shows the priority areas for GHG reduction in the material cycles and waste management sector. Since GHG emissions from waste, which are the primary GHG sources in the material cycles and waste management sector, are associated with the life cycle of materials, actions for materials that produce larger GHG emissions, namely, waste plastic, waste oil, and others (paper and textile waste), are classified as Priority Area 1. Particularly, for waste plastics, carbon neutralization by combining material and circular chemical recycling with substitution to biobased plastic are set to be the key actions, after the maximum introduction

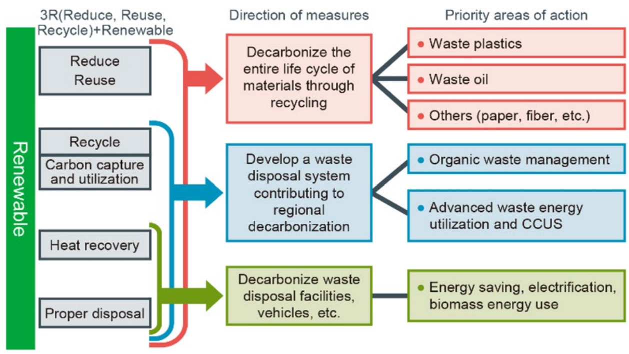

Fig. 1 Concept of priority areas of action

of reducing and reusing (2R) action. For waste oil, the substitution of waste oil from fuel use to material use for base oil of lubricant and solvent was set as a key action. Circular chemical recycling refers to the chemical feedstock recycling system through monomerization, gasification, and pyrolysis, which the Japan Chemical Industry Association has declared to promote in its agenda, "Chemical industry's future vision on the chemical recycling of plastic waste" [18], and waste plastics can be returned as new plastics after circular chemical recycling is achieved. In Priority Area 2, developing a waste disposal system that contributes to regional decarbonization and carbon capture, utilization, and storage (CCUS) and actions for organic waste includes actions associated with waste treatment systems that have large GHG reduction potentials in areas other than the material cycles and waste management sector. In Priority Area 3, actions for the decarbonizing operation of waste disposal facilities and vehicles are included since immediate and continuous decarbonization of waste treatment facilities is required to reduce accumulated GHG emissions and avoid lock-in of high GHG emitting facilities.

Medium- to long-term scenario

Four scenarios, namely, "Planning Scenario," "Expanded Planning Scenario," "Innovation Scenario," and "Advanced Innovation Scenario," differ in the strength of GHG-reducing actions, and two scenarios, namely "Net Zero Emission Scenario" and "Maximum Actions Scenario," which include CCUS for targeting net zero by 2050 are defined, as shown in Table 2.

Three assumptions were established for scenario-making and GHG estimation.

Firstly, this estimate conservatively considers the effects of 2R and focuses on how GHG-reducing technologies can contribute to establishing a net zero society. Of course, 2R must be an effective and important action for GHG reduction. However, since future progress and the impact of 2R are difficult to assess at this time, this estimate does not rely heavily on 2R. For example, the impact of 2R on waste plastics was set at only 25% by 2050.

Secondly, negative emission technology by CCS with biomass-oriented CO_2 is incorporated as CCUS technology for waste treatment facilities (incineration facilities, bio gasification facilities, etc.). However, in terms of CCS, CO_2 storage sites are not considered concretely. Also, CCUS needs further technology development, reduction of costs, and discussion for evaluation rules. Therefore, the assumptions

Table 2 Scenarios in the analysis

Name	Description
BAU (business-as-usual) Scenario	• Assumes current measures (as of around FY2019) will remain unchanged until 2050 • Estimated GHG emissions in the following scenarios are in comparison with the BAU scenario
Planning Scenario	• Assumes the implementation of existing government plans/regulatory frameworks and industry efforts for GHG emission reductions and material cycles (Japan's National Climate Action, Resource Circulation Strategy for Plastics, Roadmap for Bioplastics, Act on Promotion of Resource Circulation for Plastics, industry targets, etc.)
Expanded Planning Scenario	• Assumes that in addition to the Planning Scenario, additional measures are taken to reduce energy-related CO_2 emissions from waste treatment emissions from waste treatment facilities, waste collection/transport vehicles, etc.
Innovation Scenario	• Building upon the Expanded Planning Scenario, assumes further GHG emission reductions through technical innovations in each priority area, gauged realistically considering current innovation trends, etc.
Advanced Innovation Scenario	• Building upon the Innovation Scenario, assumes further progress, gauged more optimistically based on current innovation trends
Net Zero Emissions Scenario	• Building upon the Advanced Innovation Scenario, assumes waste treatment facilities will adopt CCUS (actually, CCS for this scenario)[a] to completely offset GHG emissions from the material cycles and waste management sector
Maximum Actions Scenario	• Building upon the Net Zero Emissions Scenario, assumes waste treatment facilities will use CCUS[a] to the maximum possible

[a] These scenarios assume that negative emission technologies by CCS will be used for biomass-derived CO_2 emissions

of CCUS in this estimate must be updated or revised as technology advances.

Thirdly, while this estimate proposes to promote power generation and heat recovery from waste incineration, GHG reduction by these actions is not considered in the estimation of GHG emissions. Because of the impact of decarbonization in future energy supply, GHG reduction by power generation and heat recovery from waste will be relatively decreased.

These scenarios have the following characteristics:

1. Japan is mountainous, and more than 100 million people live in a limited plane area. Therefore, Japan has a history of establishing waste incinerators in each area and reducing CH_4 from landfills by avoiding landfilling of biowaste without incineration. In contrast, the concept of "mottainai" [19] was widespread in Japan, and local community-based source separation action [20] evolved naturally from it. In 2000, "Fundamental Law for Establishing a Sound Material-Cycle Society" was introduced, and other subsequent individual recycling laws were developed. This historical progress of waste management in Japan and the underlying attitude of the Japanese toward waste are reflected in each scenario design.
2. Multiple future scenarios, including the BAU scenario, with various actions, are presented to demonstrate the degree of change and the extent to which reductions can be achieved. However, multiple scenarios that achieve net zero emissions are not presented. Furthermore, only a single future indicator was employed to estimate future waste generation.
3. The prospect of achieving net zero or negative emission was investigated by considering the dramatic expansion of recycling, the substitution of fossil for bio-based raw materials, and the development of CCS to waste incinerators. However, this estimation only considers solid waste, regulated under the Waste Disposal and Public Cleansing Act, and GHG emissions from wastewater treatment are not considered in the scope.

Since this study sets GHG emissions of the waste sector as the boundary of the analysis, contributions to GHG emission reductions in other sectors are not quantified (they are qualitatively discussed in "Potential reduction by more material cycles and resource efficiency" section). On the other hand, discussions continue for such contributions to GHG emission reductions in other sectors, for example, that appropriate LCA implementation is difficult for biomass plastics [21]. There are also issues regarding the feasibility of the measures set out in the scenarios, for example, that the psychosocial factors of citizens with regard to sorting household organic waste are also important [22].

Emission quantification parameters

In each scenario, the following parameters were set according to the measures to be introduced for each priority countermeasure area. Tables ESM 1–3 in the Online Resource 1 show the details. Additional data are given in the Online Resource 2.

Decarbonization of the entire life cycle of each material through material cycles

For waste plastics, based on the Reduce, Reuse and Recycle (3R) + Renewable basic principle in the Resource Circulation Strategy for Plastics established in May 2019 [23], the amount of waste plastics was expected to be significantly reduced by promoting 2R, maximal separation and collection of waste plastics and by performing material and circular chemical recycling. For newly introduced plastics in products, based on the roadmap established in January 2021 for the introduction of bioplastics [24], the substitution of fossil plastics with biobased plastics and an increase in biobased contents in recycled plastic (via material and circular chemical recycling) were expected. With the advancement of carbon recycling technology, the production of plastics from CO_2 and alcohol as raw materials may be realized by 2050. However, in this estimation, the circular use of plastics via material and circular chemical recycling and the substitution to biobased plastics were prioritized, whereas the production of plastics from CO_2 was not considered (Table 3).

For waste oil, the amount of waste oil in the future was estimated by considering a decrease in waste lubricants by the mid 2030s, which is expected to be caused by the shift from engine vehicles to electric vehicles (EVs). In the Advanced Innovation Scenario, waste lubricants were recycled to base oil and waste solvents were recycled to renewed solvents. Also, biobased lubricants and solvents have been introduced for waste oil activities since incineration with energy recovery or renewal to alternative fuel is common treatment methods at the moment.

For waste disposable diapers, it is difficult to consider a significant reduction due to future continuous demands for disposable diapers. Therefore, based on an interview with the Japan Hygiene Products Industry Association, the substitution of fossil super absorbent polymer (SAP) and other fossil raw materials to biobased raw materials in disposable diapers was included in the Advanced Innovation Scenario for targeting net zero waste disposable diapers.

For paper waste, the reduction of incineration supported by material recycling of paper waste was considered, as well

Table 3 Approach to waste plastic measures in this estimation

Type of measures	Specific measures to be taken
Promotion of reducing, reusing, and separate collection	Charging for plastic shopping bags under Cabinet Order on the Containers and Packaging Recycling Act Reduction of designated plastic products ((14 items such as forks and straws) under the Plastic Waste Recycling Promotion Act The generalization of these efforts for reducing plastics
Further promotion of material recycling	Promotion of environmentally friendly design of plastic products and promotion of separate collection of waste plastics in accordance with the Plastic Resource Circulation Act Upgrading of sorting technology and systems to promote the use of recycled products
Promotion of circular chemical recycling	Promotion of circular chemical recycling Improvement of yield ratio in the chemical recycling process The development of a system to increase the recycling value of plastic products, and efforts to increase waste plastics for circular chemical recycling
Further promotion of biobased plastics	The Innovation scenario assumes the introduction of approximately 2.5 million tonnes of biobased plastics in 2050 (assuming 2.5 million tonnes of biomass content) In the transitional period before full-scale introduction of biobased plastics, the use of polypropylene, polyethylene and other materials with the mass balance approach is expected

as the reduction of paper waste associated with future paperless society.

For synthetic textile waste, 2R (using used clothing, repairing, and appropriate production and stocking), recycling (recyclable design, using recycled PET (Polyethylene terephthalate) fibers, and chemical recycling of synthetic textile waste), and the introduction of biobased synthetic fibers were included.

For waste tires, reduction of waste tire generation by long-life design, reusing waste tires using retreading technology, circular chemical recycling of waste tires, and substitution of fossil materials, such as rubber or carbon black, with biobased raw materials were included.

Developing a waste management system that contributes to regional decarbonization

The landfilling of organic waste is not currently prohibited in Japan, but for the future scenario, our calculations assumed that it would stop in the medium term. In the Planning scenario and more ambitious scenarios, landfills for organic municipal solid waste are projected to be zero by 2035, and in the Innovation scenario and more ambitious scenarios, landfills for organic industrial waste are projected to be zero by 2035.

Besides the strengthening and enforcement of current national policy [25, 26] of expanding treatment areas and consolidating treatment facilities for municipal waste, which is under individual municipal responsibility, our estimations projected a shift from incineration to methane fermentation of biowaste, increased power generation efficiency (6 MPa, 450 °C), and the introduction of steam supply from incineration facilities to external uses. Demands of high-temperature heat in industries where electrification is difficult were considered promising destinations for the supplied steam.

When these scenarios were being developed, not determined timing for CCS introduction in Japan; thus, an assumption was made that CCUS would be introduced at incineration facilities during the 2040s, for the Net Zero Emissions Scenario and the Maximum Actions Scenario. The rate of CO_2 capture was assumed to be 90% [27].

Decarbonization of waste treatment facilities and vehicles

For waste treatment facilities and vehicles, assumptions were made on the introduction of various measures to improve energy recovery, reduce energy consumption, and realize an energy shift, depending on the level of ambition of each scenario. For electricity and fuel used for all types of facilities and vehicles, assumptions were made on reductions in CO_2 emission factors, depending on the level of ambition of each scenario. Here, the current energy consumption of waste treatment facilities referred to is the result of organizing the data collected in the “2016 General Waste Treatment Business Survey” by the Ministry of the Environment [28].

For waste treatment facilities, concrete measures were considered, with a focus on incineration and manure treatment facilities, which require substantial amount of energy.

For incineration facilities, assumptions included an end to incineration without energy recovery, a reduction in electricity consumption, and a reduction in the amount of auxiliary fuel consumed during start-up and shut-down.

In Japan, there are approximately 1000 municipal waste incineration facilities [29], of which approximately 100 are gasification facilities [30], and based on data on the amount of electricity used in each facility, it was determined that 100 kWh/t would be realistic for new facilities.

Auxiliary fuel consumption was projected to decline to two-thirds of current levels (approximately 79 MJ/t), considering the findings made by Tejima [31] that dioxin generation could be reduced by burning waste after increasing the combustion temperature to about 400 °C at start-up, which differs from the current practice of heating by auxiliary combustion burners up to 850 °C or more (maintained temperature above 900 °C is recommended) according to Guidelines for Preventing the Generation of Dioxins from Waste Treatment [32].

Many human waste treatment facilities that treat manure and septic tank (Johkasou) sludge use fossil fuels for drying or incinerating processed sludge. Sludge collected by truck from septic tanks (Johkasou), a decentralized sewage treatment equipment that treats manure and miscellaneous domestic wastewater, in individual buildings. In Japan, there are approximately 900 human waste treatment facilities [30], and fuel consumption data indicate that the fuel consumption rate of certain types of facilities described below is low, depending on the treatment method. In the case of the recycling method, average fuel consumption rate of recycling treated sludge into auxiliary fuel production is approximately 7 MJ/kL-treated, whereas the national average is 122 MJ/kL-treated. Therefore, in the Expanded Planning scenario, it is assumed that future facilities will not use fossil fuels.

Particularly, in the case of Oki Town [33] and Miyama City [34, 35] in Fukuoka Prefecture, the data obtained indicate that the amount of electricity purchased will be greatly reduced by integrated treatment of human waste and food waste into the methane fermentation process (reduction of energy-based CO_2 emissions by 70–95%), as assumed in the Innovation scenario.

For collection trucks, it was assumed that EVs would be introduced at rates described by Matsumoto [36] (2-ton compactor trucks transitioning from 2400 L diesel to 4500 kWh electric annually). For example, Kawasaki City [37] and Tokorozawa City [38] in Japan have introduced an EV waste collection truck with cassette-type batteries that can be exchanged in approximately 3 min.

Results and discussion

Estimated GHG emission by scenario by 2050

Figure 2 shows the GHG emission pathway to 2050 for each scenario, while Fig. 3 and Table ESM 4 in the Online Resource 1 show the breakdown of GHG emissions by source by 2050 for each scenario. Additional data are given in the Online Resource 2.

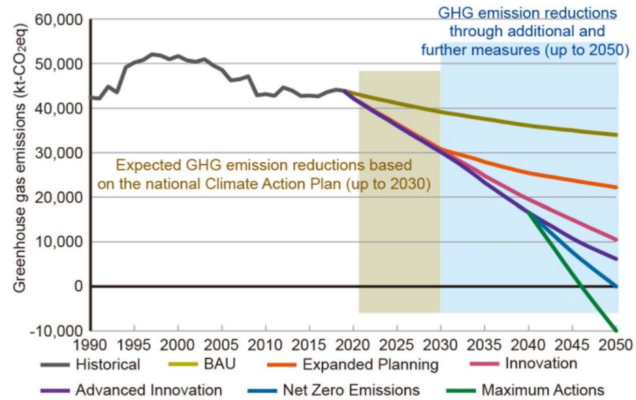

Fig. 2 Projected courses by scenario toward net zero emissions in the material cycles and waste management sector

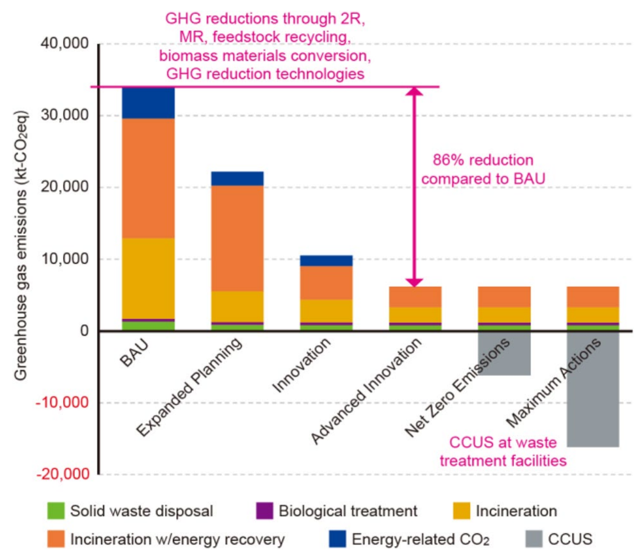

Fig. 3 Estimated GHG emissions by scenario in the material cycles and waste management sector by 2050

Compared to the BAU Scenario, the estimated GHG emissions by 2050 are approximately 35, 69, and 82% lower in the Planning Scenario and Expanded Planning Scenario, Innovation Scenario, and Advanced Innovation Scenario, respectively. In the Net Zero Emissions Scenario, energy-derived CO_2 emissions are zero based on the assumption that carbon emissions from electricity and fuel are zero, whereas the equivalent of nonenergy-derived GHG emissions (6.2 Mt-CO_2eq) are offset with CCUS. Furthermore, gross CO_2 emissions from incineration will be 17.9 MtCO_2 by 2050, of which 16.0 MtCO_2 is biomass and 1.9 MtCO_2 is nonbiomass. Note that CO_2 originated from biomass is not accounted for as GHG emissions elsewhere in this paper. As a result, net zero

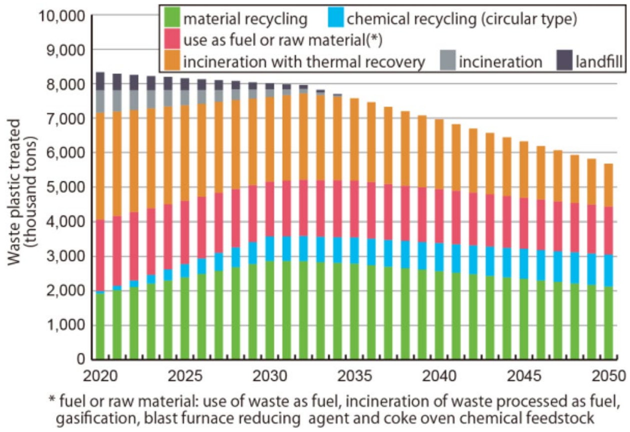

Fig. 4 Fraction of waste plastics using the treatment method (Advanced Innovation Scenario)

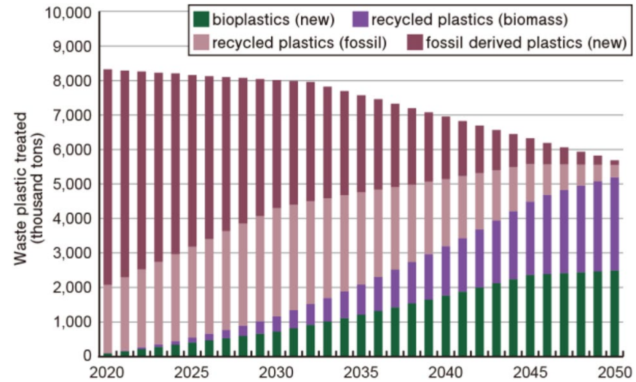

Fig. 5 Fraction of waste plastics by materials and origin

could be achieved by offsetting 34% emission using CCUS. The Maximum Action Scenario shows net GHG emissions at negative 10.0 Mt-CO_2eq by maximizing the use of CCUS.

Key measures for waste plastics and the projected decreasing courses by 2050

In each scenario in the material cycles and waste management sector, GHG emissions from waste plastics are reduced by reducing waste plastics generation, circular use of waste plastics through material and circular chemical recycling, and the introduction of carbon–neutral materials of biobased plastics. Particularly, compared to the BAU Scenario, waste plastics production is expected to be reduced by approximately 25% by 2050 in the Advanced Innovation Scenario due to the reduction of waste plastics generation and population reduction. Approximately 36% of the waste plastics are treated via material recycling, 16% via circular chemical recycling, 20% as alternative fuels, and 28% via incineration with energy recovery (Fig. 4). The use of waste plastic as an alternative fuel and incineration with energy recovery emit fossil CO_2. Therefore, the new introduction of about 2.5 million tons of biobased plastics, as well as the circular use of waste biobased plastics by material recycling and circular chemical recycling, are intended to offset most of the CO_2 emissions (Fig. 5). As a result, CO_2 emissions from waste plastics are expected to be significantly reduced from approximately 16.47 million tCO_2 in 2019 to approximately 1.09 million tCO_2 in 2050. This GHG reduction (13.69 million tCO_2 from the BAU Scenario) is approximately 50% of the total GHG reduction (27.8 million tCO_2) in the Advanced Innovation Scenario. Information on CO_2 emissions from incineration and energy use of waste plastics in 2019 are shown in Fig. ESM3.

Key measures for waste oil

In the BAU Scenario, CO_2 emissions from waste oil were estimated to decline to 7.95 million tCO_2 by 2050 due to a decrease in waste lubricant oil from engine cars caused by the shift to EVs. In the Advanced Innovation Scenario, GHG emissions from waste oil were significantly decreased (5.39 million tCO_2 in 2050 from the BAU Scenario). However, the material recycling ratio of waste lubricant oil in FY 2019 was almost zero, and waste solvents were only approximately 17%. To achieve significant GHG reduction from waste oil, innovative technology for recycling must be employed and strong policies must be implemented that prioritize material recycling of waste lubricant oil to base lubricant oil and waste solvents to renewed solvents, as in some European countries [39]. Information regarding the CO_2 emissions from incineration and energy use of waste oil in 2019 are shown in Fig. ESM4.

Key measures for municipal solid waste treatment and disposal

Figure 6 shows the annual trends of municipal solid waste (MSW) processing volume by processing method for each scenario. There are significant differences in future trends between the BAU, Planning and Expanded Planning, Innovation and Advanced Innovation scenarios and the two scenarios that include CCUS.

Compared to the BAU Scenario, incineration (Fig. 6a) decreases slightly to 7% by 2050 in the Planning and Expanded Planning scenarios. Process volumes in the resource recovery facility (Fig. 6b) remain at approximately current levels. Compared to current levels and the BAU scenario, methane fermentation (Fig. 6c) is considerably less than incineration in the Expanded Planning scenario, although the ratio increases significantly.

However, in more ambitious Innovation scenarios, annual incineration decreases from the current approximate value

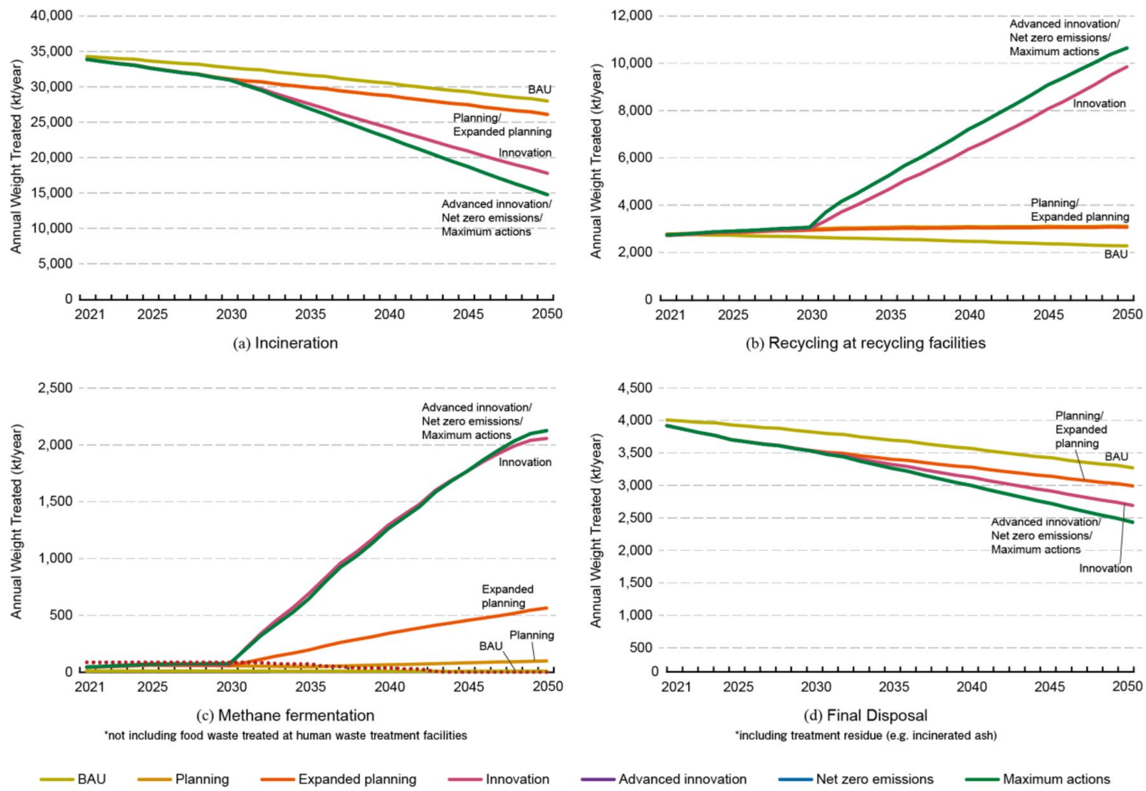

Fig. 6 Outlook of MSW throughput using the treatment method

of 34 million tons to approximately 18 million tons by 2050, and the annual volume of resource recovery facilities increases from the current approximate value of 3 million tons to about 10 million tons by 2050. Methane fermentation is also projected to increase by approximately 2 million tons by 2050. Compared to the number of methane fermentation facilities, which was 23 (10 by municipalities and 13 by private companies), and the weight of waste treated at the facilities, which was 0.095 Mt, in Japan in 2020 [30], the scale of methane fermentation introduced in the Innovation Scenario is much higher. In Europe, however, 17 Mt of bio-waste is anaerobically digested, with more than 50 kg/person-year of bio-waste either composted or anaerobically digested in many of the countries studied, including more than 100 kg/person-year in 10 countries [40]. The amount of food waste collected for treatment in methane fermentation facilities in our future scenarios is 50 kg/person-year, which is smaller than the amounts in many European countries, and therefore introduction and expansion of methane fermentation in Japan is not unrealistic. In the Advanced Innovation Scenario and its two derived scenarios with CCUS, there is an additional decrease in incineration volumes and an additional increase in resource recovery volumes.

For the final disposal volume (Fig. 6d), the calculations show no significant differences between the scenarios, because incineration is already widespread in Japan, although final disposal volumes decrease apace with the level of ambition in the scenarios.

Figure 7 shows the results of calculations based on expected incineration facility closures and new construction required based on future processing volume projections. Figure 7 presents the Planning and Innovation scenarios, indicating two groups with very different trends in processing volume forecasts.

The volumes treated at existing incineration facilities are projected to decrease, with only a small number remaining in 2050. The volumes treated at new facilities constructed by 2030 will be the same in both scenarios. Meanwhile, compared to the Planning scenario (Fig. 7a), the total amount of new facilities to be constructed between 2031 and 2040 is lower in the Innovation scenario (Fig. 7b), which has increased resource recovery and reduced incineration. Furthermore, after 2040, the number of new facilities constructed is projected to be insignificant in the Innovation scenario, while considerable capacity is introduced in the Planning scenario.

Figure 8 shows the trends in the energy balance of municipal waste treatment calculated based on facility decommissioning and introduction projections. Since we expected that incineration facilities without energy recovery would be closed by 2035, an improved energy balance is projected to be negative in 2035, meaning that the

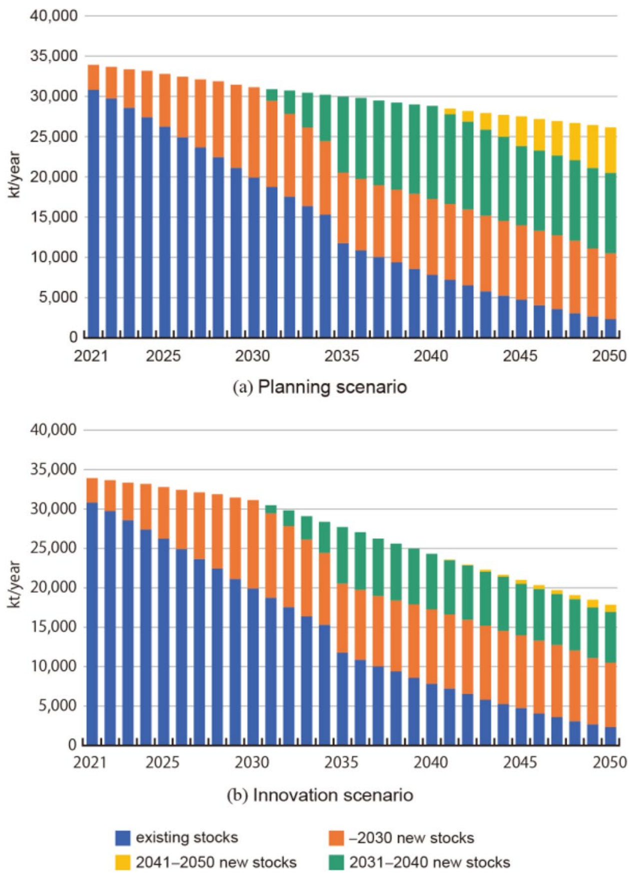

Fig. 7 Projected MSW incineration throughput by age of introduction

amount of energy supplied externally would exceed the amount of energy consumed by municipal waste treatment systems as a whole. In the Planning Scenario, the energy balance improves steadily through 2050. In the Innovation and Maximum Action scenarios, energy balances improve through energy conservation and increased energy recovery in treatment facilities through 2035. In 2035, the amount of energy supplied externally in the Innovation Scenario exceeds that in the Planning scenario. Although this study does not quantify CO_2 emission reduction contributions, power generation may be an effective CO_2 emission reduction measure during the transition period, until the electricity system is decarbonized. Furthermore, given that the industrial sector may still rely on fuels to meet its heat demand by 2050 [41], high-temperature heat supply is also promising during the transition period. The Innovation Scenario, which incorporates steam supply from incineration plants to industrial facilities, achieves a better energy balance than the Planning Scenario until mid-2040s. The Innovation Scenario would be a more attractive scenario if we take into account its contribution to the reduction of energy-derived CO_2 emissions during the transition period. However, in the Innovation

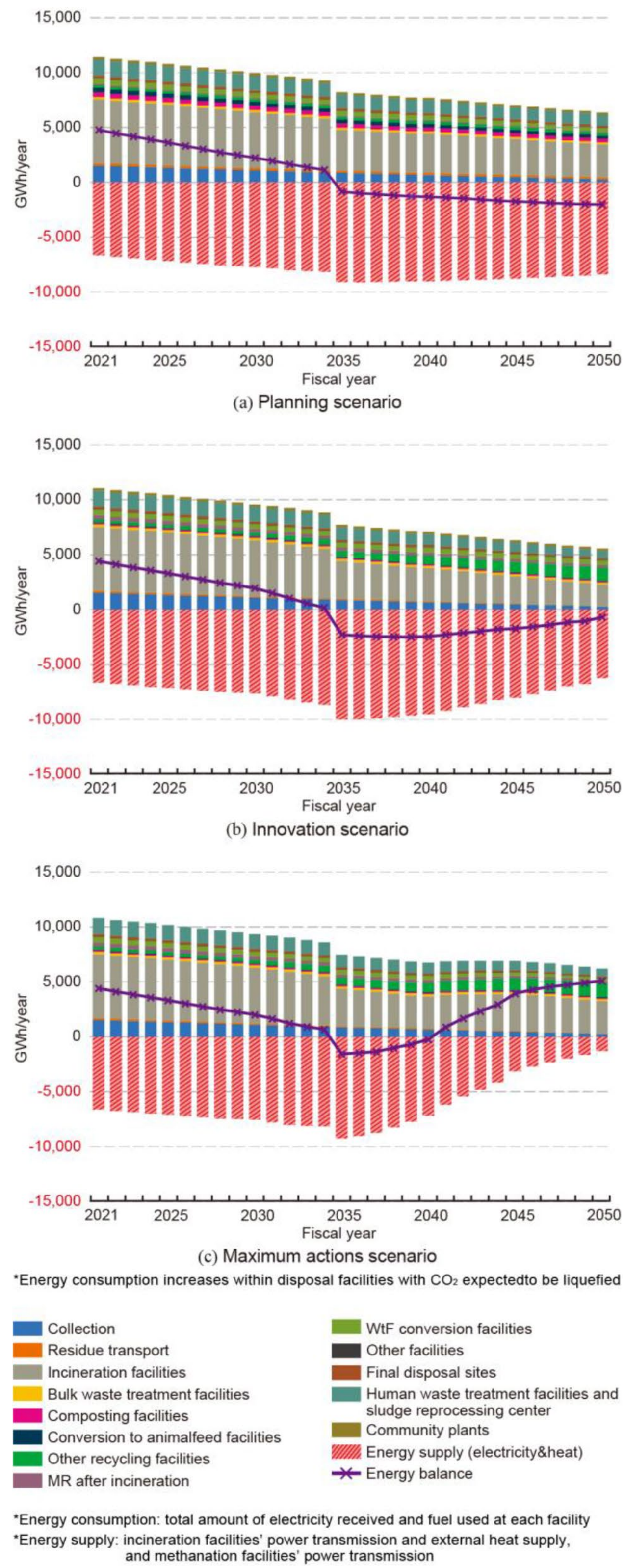

Fig. 8 Energy balance of municipal waste treatment systems

Scenario, energy balance improvements stagnate after 2035 due to lower municipal solid waste incineration and calorific value, and energy balances deteriorate further thereafter. In the Maximum Action scenario, the energy balance turns positive after 2040 due to the introduction of CCUS, resulting in net energy consumption, and it continues to deteriorate through 2050.

In scenarios that aim to significantly reduce GHG emissions from the material cycles and waste management sector since the unit calorific value of waste incinerated is expected to decrease due to significant progress with reducing waste plastics and other 3R initiatives, it will be necessary to improve the energy balance by introducing methane fermentation that includes integrated treatment with human waste treatment facilities, and simultaneously, to promote the consolidation of treatment facilities.

By ensuring that waste treatment facilities with long service lives are introduced and upgraded at an early stage, have excellent energy budgets, and use electricity instead of fuel, it will be possible to reduce the amount of energy consumed in waste treatment, and in particular, to avoid the combustion of fuel as much as possible. However, early improvements may reduce future facility upgrades, it would be preferable to move forward while keeping in mind the possibility of introducing CCUS in the future.

It is projected that the CO_2 emission factor of electricity used in waste treatment facilities and collection and hauling vehicles will be zero due to the introduction of renewable energy. In some scenarios, it is also projected that the CO_2 emission factor for fuels will be zero. These factors are external to waste treatment systems; however, since they are required for achieving net zero in this sector, waste management actors should pay close attention to evolving trends and actively work toward the introduction of such systems. In Japan, electrification is crucial because the availability of domestically procurable biomass fuels is probably limited.

Potential reduction by more material cycles and resource efficiency

Table 4 shows GHG reductions by measure in the medium- and long-term scenarios. It can be seen that the reduction by waste plastic measures has a significant impact. Of the total reduction of 27.8 million tCO_2 in the Advanced Innovation Scenario, approximately 50% (13.69 million tCO_2) is due to waste plastic measures. The basic idea behind this reduction through waste plastic measures, as discussed in the subsection "Decarbonization of the entire life cycle of each material through material cycles", is to reduce the amount of waste plastic incinerated by promoting the generation reduction, reuse, and sorted collection of waste plastic according to the Resource Circulation Strategy for Plastics and the Plastic Resource Circulation Act, and emphasizing recycling to plastic or its raw materials through material and circular chemical recycling of discharged waste plastics. The reduction rate of waste plastic generation is expected to be 25% by 2050 by introducing a charge for plastic shopping bags under the revised government ordinance of the Containers and Packaging Recycling Act, the designation of specific products using plastics (14 items, such as forks and straws) under the Plastic Resource Circulation Act, and the generalization through the adoption of such reduction efforts in other plastic products. For plastic recycling, both circular chemical recycling and conventional material recycling are being promoted, and the yield is expected to increase from 70 to 90% by 2050, according to the scenarios. The carbon neutrality measures for plastic-derived CO_2 include the promotion of biomass plastics, and the introduction of about 2.5

Table 4 Breakdown of GHG reductions under medium- and long-term scenarios in the material cycles and waste management sector

($ktCO_2$)	Scenarios					
	BAU	Expanded planning	Innovation	Advanced innovation	Net zero emissions	Maximum actions
GHG reduction actions						
Waste plastics	0	7983	12,406	13,690	13,690	13,690
Waste oil	0	408	4777	5838	5838	5838
Waste paper	0	0	638	865	865	865
Disposable diapers	0	0	820	820	820	820
Synthetic fiber scraps	0	0	458	601	601	601
Scrap tires	0	0	403	504	504	504
Other actions	0	941	1068	1119	1119	1119
Actions for energy-related CO_2	0	2456	2898	4367	4367	4367
CCUS	0	0	0	0	6164	16,138
Total	0	11,788	23,469	27,805	33,968	43,943

million tons of biomass plastics in 2050 is assumed in the Advanced Innovation Scenario or higher ones. According to European Bioplastics [42], the global production capacity of biomass plastics in 2021 is around 860 000 tons; therefore, setting a target of 2.5 million tons is currently ambitious; however, the document predicts that its production capacity will increase rapidly to 2.3 million tons by 2026 due to increased global demand. Simultaneously, the expansion of feedstock and the development of new feedstock are required to support the biomass plastic production.

For waste oil, the Innovation and Development Scenario reduces approximately 5.39 million tCO_2, following waste plastics. This is achieved by reorienting the previously dominant fuel use of waste lubricants and solvents toward material recycling. According to the U.S. Department of Energy [39], Italy has the highest percentage of recovered waste lubricating oil recycled into base oil at over 80%, followed by Brazil, Spain, and Saudi Arabia at over 60%. The study of measures to include material recycling in Japan has begun, regarding the leading recycling technologies, infrastructures, and support policies in these countries.

This study estimates GHG reductions in the material cycles and waste management sector in Japan. There has been no decisive method of such estimation for the realization of carbon neutrality at a national or regional level. In order to obtain more reliable results, it is effective to repeat benchmark studies, comparing results with published data of other regions, as well as reflecting data obtained in domestic regions to estimations. As seen in Table 4, the Advanced Innovation scenario shows 82% reduction of GHG emissions and the Innovation scenario succeeded in 71% reduction, and carbon neutrality was achieved with the introduction of CCUS technology. As seen in "Introduction", there are examples of decarbonization plans in the waste management sector in specific regions and countries. The United Kingdom anticipates a 75% decrease in GHG emissions[1)] and France estimates a 66% reduction[6)]. The reduction level of France without CCS technology is almost equal to the level calculated in Innovation Scenario. While on the other hand, the reduction level of UK with the use of CCS differs from Japan's calculation result, where carbon neutrality is achieved by the scenario that includes CCS. There is approximately 6 million tons of difference in CO_2 reductions between Net Zero Emissions Scenario and Advanced Innovation Scenario, and, therefore, Japan adopts CCUS as an effective measure for CO_2 reductions. Despite the difference, however, both UK and Japan place expectations on CCUS for achieving carbon neutral societies, and it is expected that CCUS technologies will be developed for practical use.

CCUS, which is regarded as the core technology for carbon neutrality in this study, will require further demonstration tests to improve its system. Bisinella et al. reported a detailed analysis result for Carbon Capture and Storage (CCS) system that captures CO_2 from exhaust gases after municipal solid waste incineration [43]. Results of Life Cycle Assessment (LCA) for multiple CCS systems using monoethanolamine (MEA) showed that about 800 kg of CO_2 can be captured per ton of waste, indicating that CCS can reduce climate change impacts. Based on this concept, this research group developed a conceptual design for the Amager Bakke incineration plant with a capacity of 600,000 tons/year in Copenhagen and published data of the remodeled plant [44]. While confirming GHG reduction of 850 kg CO_2-eq/ton, they also found a 50% reduction in power generation due to increase in the use of steam for CO_2 recovery. A similar trend was observed in the LCA study of a Waste-to-Energy plant with CCS in Norway [45]. It was shown that although energy recovery decreased in the CCS system, the existing 17 energy recovery plants with CCS using MEA achieved a contribution to climate change mitigation, but it should also be kept in mind and carefully examined that CCS could lead to more eutrophication potential and other environmental impacts. Since 2016, a CO_2 separation and recovery apparatus (CO_2 recovery of 10 tons/day) using MEA has been in operation in Saga City, Japan [46]. Demonstrations of the use of recovered CO_2 at plant factories and for algae cultivation in the surrounding area are being continued.

We must repeat demonstration tests to solve technical problems for practical use of innovative technologies. Sauve et al. suggest the importance of integrated early-stage assessment for the development of innovative technologies [47]. They recommend an approach, which includes scenario development, life cycle model establishment for the economy and the environment, and several scenario analyses. The CCUS system discussed here should follow such systematic approach of the innovative technologies assessment. Given the variety of recyclable resources, in addition to CCUS technology for exhaust gas from incineration, we must think of establishing a technology combined with CO_2 separation and recovery by methane fermentation, as well as gasification other than incineration.

In Japan's medium- and long-term scenario, which is a strategy focusing on the reduction of direct GHG emissions from the waste sector in the broad sense of the national GHG inventory (see Fig. 9A), a certain amount of reduction measures, such as plastic material conversion and recycling, and recycling of synthetic fibers are planned. However, their reduction effects are limited to the scope of the relevant direct emissions. However, the promotion of material cycles and circular economy can contribute to the reduction of GHGs over the entire life cycle by (1) optimizing the consumption of resources, such as raw materials, (2) improving efficiency in the production process, and (3) improving efficiency in the consumption process. Furthermore, recycling and heat recovery, which have already been achieved, should result in considerable reductions compared

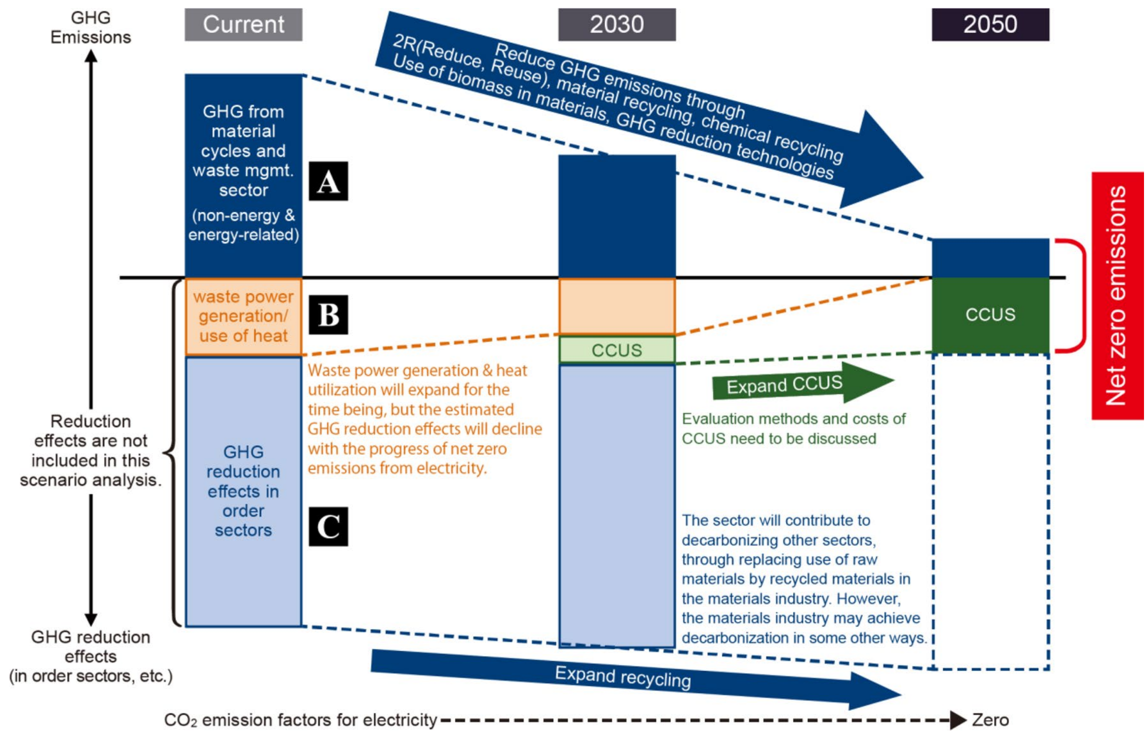

Fig. 9 Basic concept on material cycles and waste management sector toward carbon neutrality

to the case where they have not been performed (see Fig. 9B, C). Because the focus was primarily on substantial emission reductions, primarily in the waste management sector, the impacts of indirect reduction were excluded from the scope of GHG emissions aimed at net zero. However, it is insufficient to extensively disseminate among stakeholders the importance of material cycles and the circular economy in decarbonizing the social system as a whole.

Estimates from various quarters indicate that material cycles and the circular economy will make significant contributions to decarbonization. The Circularity Gap Report [48] estimates the effects of the circular economy based on the assumption that annual global GHG emissions will only be reduced to about 56 billion tCO_2 eq, even if the national reduction targets of the countries participating in the Paris Agreement are met. By applying the 21 circular economy promotion measures proposed by the organization (measures focusing on the material cycle in seven sectors: housing, nutrition, mobility, communications, consumption, healthcare, and services), it is estimated that the annual global GHG emissions could be reduced to about 33 billion tCO_2 eq. In other words, it is estimated that a reduction of approximately 23 billion tCO_2 eq (equivalent to 39% of 2019 GHG emissions) is possible, demonstrating the significant effect of the circular economy. At the city level, studies have reported potential reductions in GHG emissions through recycling and carbon storage as well as energy recovery from waste. Boston (U.S.), in the process of developing its Zero Waste plan in 2019 [49], has estimated its GHG reductions and discovered that, under the Zero Waste scenario for 2050, which promotes a shift from landfill and incineration to material recovery, a significant reduction of 1.32 million tons of CO_2 will be achieved by various material recovery conversions compared to the direct emissions of 82,000 tCO_2.

Based on a lifecycle evaluation that included the supply sector [50], Kua et al. (Singapore) examined climate change mitigation through food and plastic waste recovery and estimated a 37% reduction compared to the status quo scenario, which focuses on incineration. In a recent study in Japan, Watari et al. [51] quantitatively proposed a pathway to carbon neutrality in the Japanese cement and concrete sector based on both supply- and demand-side measures. One of the primary issues to be addressed in the future is the presentation of the GHG emission reduction effects of material cycle measures, including such demand-side behavioral changes, and their reflection in future scenarios.

Conclusion

By 2050, the majority of carbon emitted from waste treatment facilities such as incineration, gasification and methane fermentation will be of biomass origin, suggesting that if CCUS is implemented to the maximum extent at waste treatment facilities, there is a possibility of achieving net zero or even virtually negative emissions in the entire material cycles and waste management sector through those negative emission technologies.

Simultaneously, it has become evident that measures taken based on existing plans are insufficient. Not only technical and institutional measures be taken, but all parties concerned must also work together with considerable ambition. To achieve net zero emissions in this sector, it is also required to take measures in collaboration with the materials and manufacturing industries.

Based on the basic principle of reducing GHG emissions as much as possible in this sector, it is necessary to improve the 2R measures and promote the initiatives to reduce GHG emissions set as the three priority areas for action. Specific points to note are as follows:

1. Concerning measures against waste plastics, which account for the majority of GHG emissions in this sector, it is necessary to focus on the progress of material and circular chemical recycling, improved raw material yields and conversion to biomass plastics. For waste oil, new efforts should be made to implement material recycling of waste lubricants, solvents, and so on, following the lead of the leading countries. For disposable diapers and synthetic fiber waste, it is necessary to explore the possibility of material recycling while simultaneously promoting measures that focus on the biomass of materials. In both cases, ambitious innovations in GHG reduction technologies are required in addition to the current level of technology. Waste recovery and treatment systems must also be able to accommodate these new technologies.
2. For long-term waste treatment facilities, it is effective to develop decarbonized facilities at an early stage to reduce energy use by 2050, and in particular, to avoid fuel combustion as much as possible. In a scenario aimed at significantly reducing GHG emissions from the material cycles and waste management sector, it is expected that the need for methane fermentation, including integrated treatment with human waste treatment facilities, will increase, and the energy balance can be improved by promoting the consolidation of treatment facilities as the low calorific value of waste treated is expected to decline due to significant progress in the 3Rs of waste plastics.
3. For electricity used in waste treatment facilities and EVs for waste collection and transportation, it is predicted that the introduction of additional renewable energy sources will result in a CO_2 emission factor of zero, contributing significantly to GHG reduction in this sector. Thus, the situation toward achieving net zero emissions in power systems must be monitored closely. Additionally, the possibility of procuring carbon neutral fuels like biomass fuels should also be given significant consideration.

The draft medium- and long-term scenarios were reported on August 5, 2011, in the Sound Material-Cycle Society Committee of the Central Environmental Council, a permanent body established by the Ministry of the Environment to study and deliberate on important matters related to environmental protection by academic experts. In the Committee, the Ministry of the Environment presented the need for specific studies, deepening and elaborating measures, and the creation of mechanisms toward the realization of each measure to achieve carbon neutrality in this field, as well as the need to encourage relevant sectors to take a 3R + Renewable-based approach to improve resource productivity, to promote the research on the effects of the circular economy approach on the decarbonization of the entire socioeconomy, and to update the medium- and long-term scenarios. Future policy developments in this field are hoped to realize carbon neutrality.

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Data availability The datasets generated and/or analyzed during this study are openly available in the supplementary information files.

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