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Carbon reduction of plastic's circular strategies: tracking the effects along supply chains with waste input–output modeling

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Abstract

Plastic is a material associated with various Greenhouse Gas (GHG) emissions along the life cycles of different products. Many economies have adopted or planned for strategies to reduce, reuse, and recycle plastic goods and materials. The benefits of reductions in waste generation and GHG emissions need to be evaluated for setting the priority to select policy instruments for managing various plastic materials, products, and wastes. Several studies have made evaluations for the circulation of plastic using different models. However, many models for the circular economy focused on the effect on the macroeconomy rather than the detailed supply chain effects of an individual policy proposal. The reason could be the lack of an environmental assessment model with sufficient clear resolutions in the sectors, waste types, and waste treatments. In addition, the structure of the models limits many studies in modeling the scenarios diverting end-of-life products from waste treatments to recycling and reuse as secondary materials. To bridge this gap, this study adopted the waste input–output analysis methodology and compiled the models of baseline and four scenarios using the material flow and waste stream data of Taiwan with reference to a classification of four kinds of circular intervention from a review paper. We provide the details about the modeling results and settings for diverting plastic to the solid recovered fuel for power generation, closing the loops of plastic bags, extending the life of plastic cabinets and other plastic products, and improving the plastic products supply chain's resource efficiencies. In the illustration of the results of GHG reductions in the supply chains and waste treatment activities, we present Sankey diagrams, which make the analysis of supply chains more straightforward. The developed method to render the Sankey diagram from the modeling result of an input–output-based model is presented in this article.

Keywords Plastic, Circular economy, Greenhouse gas emissions, Waste input–output model, Sankey diagram, Supply chains

1 Introduction

Facing the need for significant Greenhouse Gas (GHG) mitigation, circular interventions in the economic systems have been recognized as a helpful instrument for approaching net-zero GHG emissions [1]. Resource circulation can potentially reduce GHG emissions from many economic activities along the supply chains and waste management of materials. For example, recycled materials and reused goods usually have lower carbon footprints than that made up of virgin material, which requires significant energy and material inputs. In addition, resource circulation can reduce the need for specific waste treatment that would transform the carbon in the wastes into CO_2 or CH_4. Many kinds of waste treatments are the sources of GHG emissions, including incineration, landfilling, composting, and wastewater treatment.

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Plastic is one material category associated with significant life-cycle GHG emissions because the majority of plastics in current use are sourced from fossil fuels, and the production is energy-intensive [2]. Meys et al. [3] suggest one of the import pathways toward net-zero emission, which combines the recycling of plastic wastes with the chemical reduction of carbon dioxide captured from incineration in their analysis. In a Material Economics [4] report, an EU scenario of making reuse and recycling the standard for end-of-life plastics can reduce the emissions from plastics supply chains by 50% (166 Mt CO_2) in 2050.

Several economies have made new policies for recycling more plastic, reducing consumption of plastic materials and products, or encouraging the use of recycled plastic in manufacturing. For example, the EU has adopted a Circular Economy Action Plan, which includes a plastic policy area to tackle plastic pollution and marine litter to accelerate the transition to a circular and resource-efficient plastics economy [5]. In the study area of this research, Taiwan EPA has set policy targets to reduce disposable plastic containers, improve recycling, and close the loop of plastic materials and goods. The industries are also developing new business models and processes to efficiently use materials for plastic products and services. One motivation is to reduce direct and indirect GHG emissions associated with the life cycle of plastic materials. The design of circular interventions in new policies requires methods or tools to evaluate the effectiveness of GHG mitigation.

Many studies have attempted to quantify various impacts of circular strategies by adopting applicable methodologies for different study scopes. Several studies focused on waste management systems have built models to characterize waste flows and the processes in the local or regional systems, such as the works of Hestin et al. [6] and Milios et al. [7]. This kind of studies is limited to exploring the indirect impacts of the system from a life cycle perspective. Several studies are coping with the impacts at large scopes, which need to consider economic or production systems at a global or multi-country level. The methods could be a global economic model or a regional energy model with an account of waste flows. For example, the PLAIA integrated assessment model used by Stegmann et al. [2] for future CO_2 mitigation pathways and the environmentally extended multi-regional input–output model used by Tisserant et al. [8] for global waste footprint are macroeconomic models. Large-scale models may fail to characterize the system's processes in detail enough to identify specific sectors or activities that matter to circular strategies' impacts. There are still others studies setting their systems between the very large and small areas mentioned above. To quantify the impacts of circular strategies, their models may benefit from more sufficient waste data than the large-scope studies and more comprehensive economy-wide systems than the small-scope studies. In the literature estimating the environmental impacts of an economy, the environmentally-extended input–output analysis (EEIOA) has been applied in several national or regional-level studies.

In a review of EEIOA studies, Aguilar-Hernandez et al. [9] found four major categories of circular intervention, including residual waste management (RWM), closing supply chains (CSC), product lifetime extension (PLE), and resource efficiency (RE). EEIOA is useful for tracking complex activities in supply chains. The impacts like GHG emissions can be estimated when the data or satellite account for all the sectors' coefficients is available. Towa et al. [10] reviewed 78 studies that used input–output models for waste management analysis before 2020. The four categories of models found in the review are waste extended IO, waste IO, Physical IO, and Hybrid IO. Among them, waste input–output (WIO) models have the most mature analytical framework and have been widely applied to various waste and resource management scenarios [10]. Although Hybrid IO (HIO) models are conceptually the most comprehensive in modeling monetary and physical flows, they are less widely applied than WIO models because collecting complete data and data structuring for the HIO-based waste management model is difficult.

However, EEIOA-based applications in circular economy research are relatively rare [11] and face a few limitations [9]. Many studies used an input–output table with relatively aggregate waste classification and waste treatment activities. The multi-regional input–output table EXIOBASE contains detailed economic sectors, 19 waste categories, and five waste management activities [12]. Donati et al. [13] modeled circular economy scenarios for PLE and RE strategies. They used EXIOBASE V3.3 for 2011. However, the circular interventions of RWM and CSC are hard to model using a monetary EEIO model. The framework of monetary EEIOA makes it hard to model the allocation of wastes to different waste management activities than the hybrid IO models, such as the waste input–output model [9].

Nakamura and Kondo [14, 15] developed the WIO analysis framework. WIO model's advantage over the mostly used Waste extended IO models is the specialized framework supporting the characterization of the physical flows of waste and the interactions between the industries producing goods and services and waste treatment activities. Using this harmonized model for monetary and physical flows, Kondo and Nakamura [16] assessed the GHG reduction of individual circular policy on the recycling of appliances and an advanced form of intensive recycling augmented by Design for Disassembly. Although there have been various applications and a number of WIO studies in Japan, WIO studies on specific circular interventions of plastics are still rare in Japan and other countries.

This paper aims to provide modeling examples that can demonstrate how to evaluate the GHG mitigation potential for circular intervention practices and the targets specific to certain products and sectors by changing the coefficients or values in corresponding components of the model. Since Aguilar-Hernandez et al. [9] have shown the model blueprints for using EEIOA for the four categories of circular intervention, and Donati et al. [13] have presented the modeling results for the PLE and RE. Still, there is no result of the RWM and CSC scenarios. This study presents our method with WIO models and the effects of policy proposals for all four circular interventions, which can capture the interactions between waste treatment and activities producing goods and providing services. Furthermore, this study presents a novel data visualization application for tracking the activities with GHG reduction along the supply chains. The Sankey diagrams may uncover more details on the hotspots of GHG reduction in the supply chains and waste treatment activities. These details could be hidden in the sum-up results of the literature using EEIOA for environmental impacts.

The following sections present the methods and datasets used to build a WIO model for the baseline GHG emissions. Next, we present the definition of the scenarios of the four policy proposals that correspond to the four categories of circular interventions. Then, the results section shows the GHG reduction potentials from the four scenarios. In addition, Sankey diagrams of the GHG mitigation are presented to identify the activities of higher reduction potentials and explain the interaction between upstream and downstream activities. Finally, in the discussion section, we examine the advantages and limitations of the methods.

2 Methods

2.1 Study area and the policy targets for plastic waste management

This study assessed Taiwan's potential to reduce GHGs via different management strategies for the plastic flows in the economy. The Taiwan EPA issued three plastic policy targets for 2025 in 2020 as follows:

1. Reduce the consumption of plastic packaging by 25%
2. Increase the recycling rate of plastic packaging to 50%
3. Push the plastic container producers to use more recycled plastics as raw materials (> 25% on average)

The first target could be achieved through several ongoing strategies, such as limiting single-use plastic packaging (including containers) and encouraging reusable ones. In this manner, the lifetime of plastic packaging can be extended. So, this target corresponds to the circular intervention of PLE indicated in the review paper by Aguilar-Hernandez et al. [9].

The second and third target corresponds to improving the collection of recyclable plastics and recirculating the plastics in the supply chain of plastic products. So, the third target corresponds to the circular intervention of CSC indicated in the paper by Aguilar-Hernandez et al. [9].

This study also evaluated the potential of GHG reduction of new RWM and RE practices. Regarding the RMW intervention, the rising waste treatment cost, new environmental policies, and alternative fuel standards have encouraged industries to transform combustible residuals to solid refuse fuel (SRF) for energy recovery with higher efficiency than incineration. Regarding resource efficiency, many industries in Taiwan keep improving processes and new business models to gain productivity by decreasing material inputs or wasted materials.

Looking at the plastic materials that need better circulation and resource efficiencies, we developed four scenarios and built WIO models for the four kinds of circular intervention.

2.2 WIO model

The model used for GHG reduction estimation in this study adopts the framework of the WIO model, which is a kind of EEIOA proposed by Nakamura and Kondo [14]. The data integration for building models and adopted of numerical schemes is illustrated in Fig. 1. First, we collected Taiwan's economic and environmental data to compile a WIO table with a framework, as illustrated in Table 1. The details about data sources are given in the following subsection.

Using the data from the WIO Table, we can model the future activities of general sectors X_I (producing goods and services) and waste management sectors X_{II}. The vector of the activities is a function (Eq. (1)) of many factors, including demands for goods and services $X_{I,F}$, demand for treating municipal solid waste (MSW) W_F, each sector's inputs from other sectors per unit output A, industries' waste generation intensities G, and allocation of waste streams to waste management sectors S [14].

$$\begin{pmatrix} X_I \\ X_{II} \end{pmatrix} = \left(I - \begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{.,I} & SG_{.,II} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{I,F} \\ SW_{.,F} \end{pmatrix} \quad (1)$$

GHG emissions of different scenarios can be estimated by multiplying the economic outputs of general

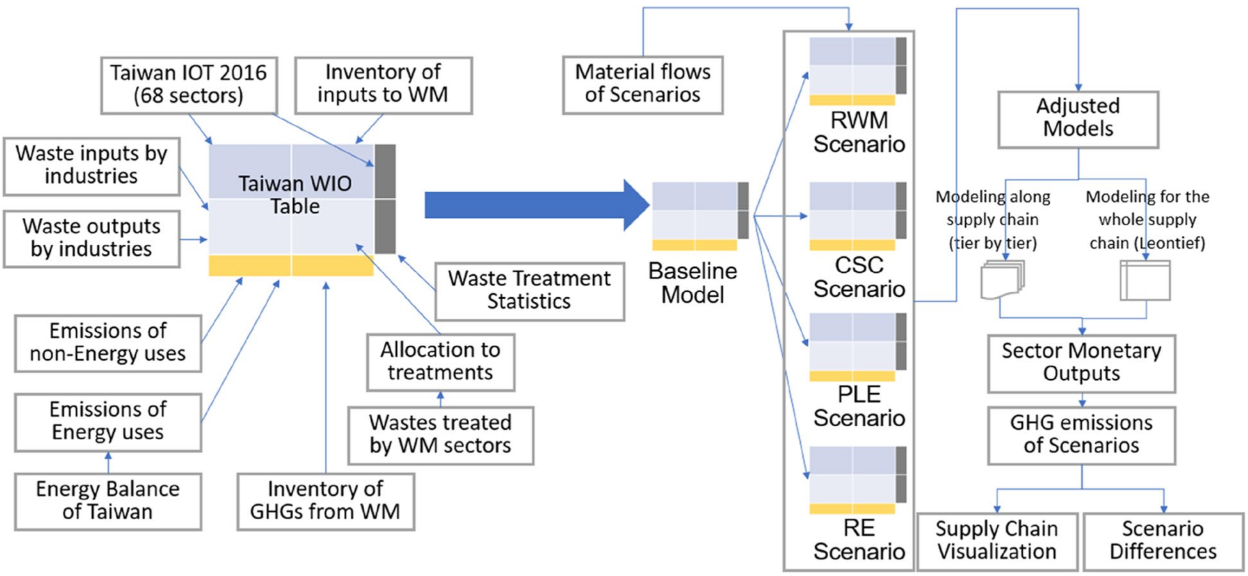

Fig. 1 Data integration and numerical scheme of WIO modeling for circular strategies in Taiwan. The words of two acronyms in the figures are Input–output table (IOT) and Waste management (WM)

Table 1 Schematic representation of the waste input–output table [14]

	Goods-producing sector	Waste treatment sectors	Final demand	Total
Goods input	$X_{I,I}$	$X_{I,II}$	$X_{I,F}$	X_I
Waste generation	$W^{\oplus}_{,I}$	$W^{\oplus}_{,II}$	$W^{\oplus}_{,F}$	$W^{\oplus}$
Waste input	$W^{\ominus}_{,I}$	$W^{\ominus}_{,II}$	$W^{\ominus}_{,F}$	$W^{\ominus}$

sectors and the wastes treated by each waste management sector with the corresponding GHG emission intensities ($R_{,I}$ and $R_{,II}$) [14], as shown in Eq. (2).

$$e = \begin{bmatrix} R_{,I} & R_{,II} \end{bmatrix} \left(I - \begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{,I} & SG_{,II} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{I,F} \\ SW_{,F} \end{pmatrix} + E_{,F} \quad (2)$$

The estimation with Eq. (2) would include indirect GHG emissions occurring in other countries because Taiwan's industries import many goods from global supply chains. To separate the domestic and foreign indirect GHG emissions, the model in this study also used Eq. (3), which is adapted from Eq. (2) by considering the import ratios of goods and services ($\widehat{M}$) to estimate the effects on domestic activities and associated emissions. Each diagonal element in the import ratio matrix is the ratio of imported goods of sector i to the sum of domestic supply and import of good i (Eq. (4)). The emission in the foreign supply chains was derived by subtracting the emissions from all supply chains (Eq. (2)) with the domestic emissions from Eq. (3).

$$\begin{pmatrix} X_I \\ X_{II} \end{pmatrix} = \left[\left(I - \left(I - \widehat{M} \right) \begin{pmatrix} A_{I,I} & A_{I,II} \\ SG_{,I} & SG_{,II} \end{pmatrix} \right) \right]^{-1} \left(I - \widehat{M} \right) \begin{pmatrix} X_{I,F} \\ X_{II,F} \end{pmatrix} \quad (3)$$

$$m_i = \frac{M_i}{X_i + M_i} \quad (4)$$

2.3 Data for WIO table and model coefficients

2.3.1 Monetary flows of WIO table

The monetary flows (upper part) of our WIO model adopted the 164 sectors' Input–output table of Taiwan in 2016, compiled by the Directorate-General of Budget, Accounting, and Statistics, Taiwan ROC [17]. The 164 × 164 sector Producers' Prices IO table was aggregated/merged into a 68-sector IO table in order to have consistent sector resolution with the data of GHG emissions. The name of the 68 sectors can be seen in the supplementary material (Table S1). The final demand was also organized from 164 to 68 sectors.

The monetary flows from the general sectors to the waste management sectors were collected from the operation report of the incineration plants [18] and a sewage treatment plants' operation manual in Taiwan [19]. From these reports, we collected water and electricity consumption of the sewage treatment plants and waste incinerators. To avoid double-counting, the value recorded in the area of the input from the industrial sector to the waste treatment sector will also be additionally deducted from the area of the corresponding input from the industry sector to other industry sectors.

2.3.2 Physical flows (Waste streams) of WIO table
The generation of waste input and output data is the statistics from Taiwan EPA's website of Circular Resource Analysis System [20]. This information system hosts the generation of 695 waste items from 524 sectors. The waste inputs of sectors are included in the datasets of this system.

The industrial classification of Taiwan EPA's system comprises 487 industrial sectors. So, the dataset was reclassified to 68 industries. This study collected data on demand for treating MSW from the environmental protection statistics of Taiwan [21]. This dataset describes the amount of treated MSW and domestic sewage, which are regarded as the $W_{,F}$ in Eq. (2).

2.3.3 GHG emissions of sectors
In this study, emission data is divided into two-part, general sectors and waste management sectors. Sixty-eight general sectors' GHG emission intensities of energy consumption were calculated by multiplying the energy flows from Taiwan's energy balance sheet [22] with corresponding energy carriers' GHG emission coefficients [23].

The energy balance sheet does not include information regarding non-energy used emissions. We collected other non-energy used emission data from the Greenhouse Gases Inventory [24], such as lime calcining and cement production. After calculating the total emissions of 68 sectors, GHG emissions intensities were calculated by dividing each sector's total emissions by the total output value. The vector $R_{,I}$ is the vector of 68 general sector's GHG emission intensities. The values of vector $R_{,I}$ are provided in Table S1 in the supplementary materials.

$R_{,II}$ is the vector of waste management sectors' GHG emission intensities. GHG emissions from waste treatments are included in the report of Taiwan's greenhouse gas emission inventory. Currently, the Taiwan EPA's industrial waste database contains 40 kinds of waste management activities. However, many waste management activities in Taiwan have no economy-wide GHG inventory data. So, only the waste treatment activities of significant contribution to direct GHG emissions have non-zero emission intensities in the $R_{,II}$ vector. These treatment activities are landfill, incineration, composting, sewage treatment, and industrial wastewater treatment. The values of vector $R_{,II}$ are provided in Table S2 in the supplementary materials.

2.4 Model validation and calibration for scenarios
We validated the model by comparing the baseline scenario's total GHG emissions from all sectors in Taiwan with the Greenhouse Gases Inventory for 2016 [24]. The difference is only 0.49%. The calibration of the models for scenarios adopted the percentages of changes in the demands, input coefficient, intensities of waste generation, and waste allocation coefficients.

2.5 Scenarios
This study set up four plastic management scenarios corresponding to the four circular interventions summarized by the review of Aguilar-Hernandez et al. [9]. The four scenarios are RWM, CSC, PLE, and RE. The model parameter adjustments for the four scenarios considered Taiwan's policy targets, material flows, technological conditions, and some assumptions. The following subsections provide the main differences in model settings for each scenario compared to the baseline model. Details about the model's parameter settings are provided in the supplementary material.

2.5.1 RWM
The RWM scenario models the changes in GHG emissions from waste treatment by changing the flow of wastes into different treatment methods, including various recycling, reuse, and energy recovery. Our model of this scenario explores GHG reduction by using plastic waste to produce SRF. The power generation efficiency from the plastic SRF is higher than the energy recovery from MSWIs (MSW Incinerators). Although the manufacturing and combustion of SRF would be associated with GHG emissions, the emissions from waste treatment and power generation using fossil fuels can be decreased.

The setting of this scenario is that 10% of the plastic materials in MSW sent to the incinerator will be separated for manufacturing pure plastic SRF. The WIO model of this scenario compared the GHG emission effect between the baseline situation and the SRF scenario. The energy consumption of the SRF manufacturing process and power generation data of SRF refers to the data from South Korea [25].

Adjustment of coefficients in the WIO model of this scenario is illustrated in Fig. 2, which consists of four submatrices, a final demand vector, and an emission vector. There are two primary adjustments. First, part of the waste plastic is diverted to reuse as fuel from incineration. So, in the submatrix S-WT, the allocation coefficients of plastic waste to incineration and reuse as fuel were adjusted. In the submatrix PS-WT, we set a negative value in the input coefficient of reuse waste as fuel's input for power generation. Thus, the model can simulate the effect of replacing electricity from traditional power plants with that from SRF power plants. There is still one secondary adjustment in the W-FD vector, in which plastic waste from households for incineration reduces, and the reuse of plastic as fuel increases.

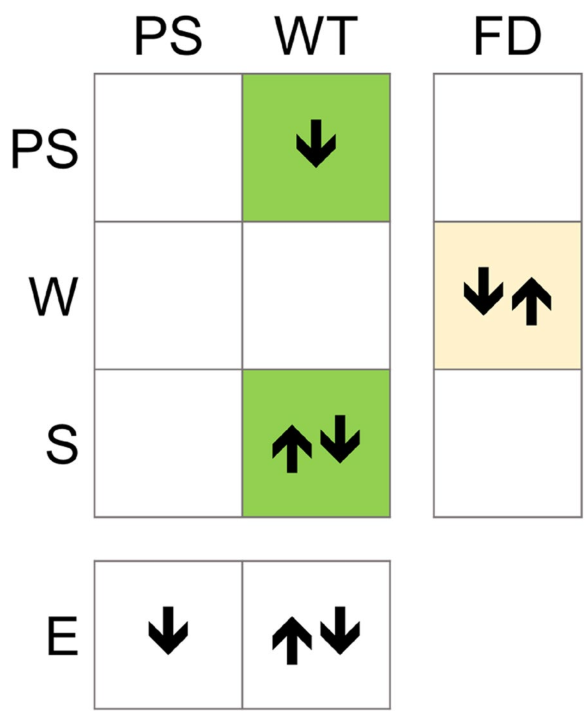

Fig. 2 Adjustments in the WIO table for RMW Scenario using plastic as SRF. The labels PS, WT, W, FD, S, and E, indicate the sectors producing Products and Services, activities of waste treatment, different wastes, final demand, allocation of wastes to treatment activities, and emissions, respectively. The downward and upward arrows indicate that some values were increased or decreased in comparison to the baseline scenario

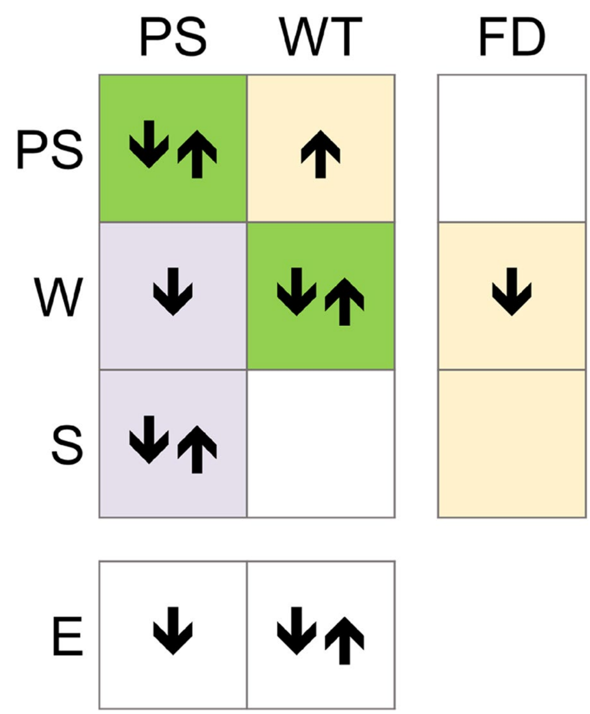

Fig. 3 Adjustments in the WIO table for the CSC Scenario with a higher recycling rate and using more recycled material for plastic products

2.5.2 CSC

In the CSC scenario, we examined the effect of closing the life cycle loop of plastic bags by using a higher recycling rate of plastic. Taiwan's domestic sales of plastic packaging in 2016 were about 163.24 kt, and the recycling amount was 8.59 kt [26]. So, the baseline model set the recycling rate as 5.26%. This scenario explores the GHG reduction potential when the plastic bag recycling rate reaches 10%.

Several adjustments are made to the WIO model for this scenario, as shown in Fig. 3. Because of the higher recycling rate, the submatrix W-WT for this scenario has less waste treated and more plastic being recycled than the baseline model. This is the first major adjustment. We made a second major adjustment in the CSC scenario model, in which the sector of plastic products in the submatrix PS-PS has less input from virgin material and more from recycled plastic. The other minor adjustments include:

W-FD vector: less plastic waste from households.

PS-WT submatrix: more recovery of plastic bags and associated power and water inputs.

W-PS submatrix: less waste from the supply chains of plastic bags.

S submatrix: the allocation coefficient for recycling increases while the allocation coefficients to other treatments decrease.

2.5.3 PLE

In the PLE scenario, we built a model to estimate the influence of the lifetime extension of products from the "plastic cabinet and parts" sector. According to Taiwan's industrial classification in 2016, plastic parts include the parts used for machinery equipment, automobiles, and motorcycles. We assumed the improved durability of plastic cabinets and the products containing plastic parts could extend the products' lifetime by 3%. Extended lifetime would lead to less frequent replacement of products. So, the final and intermediate demand for plastic cabinets and parts will decrease. The decreasing production will contribute to GHG reduction along the supply chains.

Several adjustments are made to the WIO model for this scenario, as shown in Fig. 4. The primary changes are on the final demand vector and intermediate demands in the PS-PS submatrix for plastic cabinets and other products made up of plastic parts. The secondary changes include:

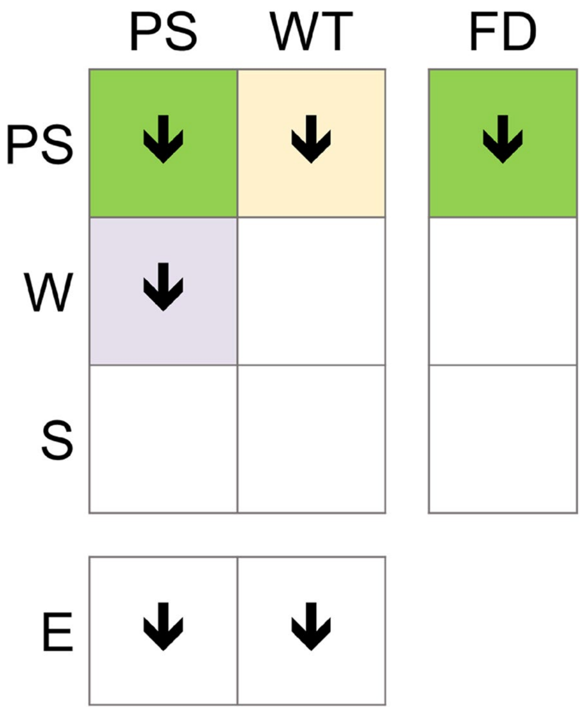

Fig. 4 Adjustments areas in the WIO table for the PLE Scenario with an extended lifetime of plastic products

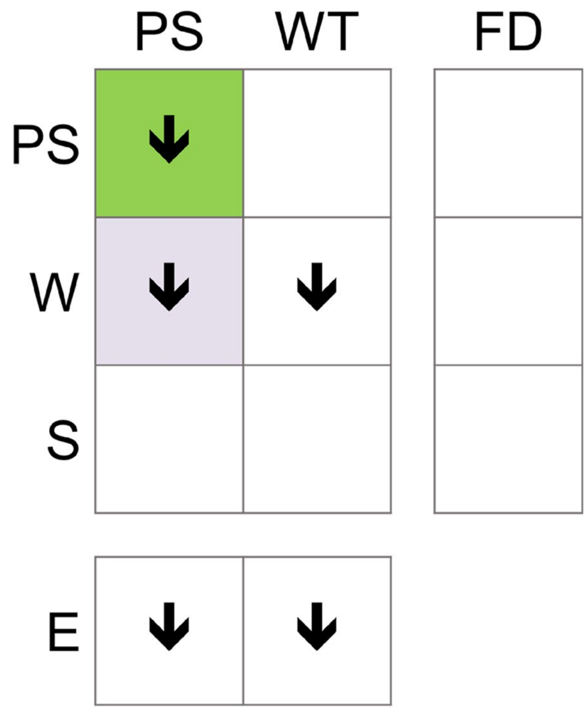

Fig. 5 Adjustments in the WIO table for the RE Scenario with higher resource efficiency in plastic production

PS-WT submatrix: less plastic products reach end-of-life each year leads to less need for plastic product waste treatments.

W-PS submatrix: less waste from the supply chains as a result of less production of plastic cabinet and parts.

2.5.4 RE

In the RE scenario, we built a model to simulate the situation of higher RE of plastic product manufacturing that can use less raw material to produce the same amount of products. In this manner, we assumed that the "plastic products" sector could reduce the plastic waste generated during the manufacturing process by 10%.

Several adjustments are made to the WIO model for this scenario, as shown in Fig. 5. The primary adjustments are at the input coefficients of the plastic supply chain in the PS-PS submatrix. The secondary change is the reduction of wasted material from the manufacturing plastic product in the W-PS submatrix.

2.6 Data visualization

This study developed a program to render Sankey diagrams that show GHG emissions differences between the baseline scenario and the four circular intervention scenarios throughout the supply chains. The code with R programming language is available upon request. The reason for using R language is that one package called networkD3 can be used to create Sankey diagrams by using a data table containing the fields of the source, destination, and value of all the flows.

To get the data ready for a Sankey diagram, we need to extract emission data from the calculated result and format the data as many links from each downstream sector to its upstream sectors with GHG emissions as the values for the thickness in the Sankey diagram's flows. The steps of data manipulation for generating a Sankey diagram of GHG reductions along the supply chain are as follows:

1. Calculate GHG emissions by tracking the four tiers of upstream activities that supply directly (Tier 1) and indirectly (Tier 2–4) to the final demands from all sectors and the needs for treating MSW.
2. The method to calculate the direct supply Tier 1 output matrix of general and waste treatment sectors is given by Eq. (5). Having these outputs, a matrix of GHG emissions can be derived from Eq. (6), in which e^{1}_{ij} denotes the emission from sector i attributable to the demand of downstream sector *j*.

$$\begin{bmatrix} X^1_{I,I} & X^1_{I,II} \\ X^1_{II,I} & X^1_{II,II} \end{bmatrix} = \begin{bmatrix} A'_{I,I} & A'_{I,II} \\ S'G'_{.,I} & S'G'_{.,II} \end{bmatrix} \times \begin{bmatrix} \widehat{X'_{I,F}} \\ SW'_{.F} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} E^1_{I,I} & E^1_{I,II} \\ E^1_{II,I} & E^1_{II,II} \end{bmatrix} = \begin{bmatrix} \widehat{R_{.,I}} \\ R_{.,II} \end{bmatrix} \times \begin{bmatrix} X^1_{I,I} & X^1_{I,II} \\ X^1_{II,I} & X^1_{II,II} \end{bmatrix} \quad (6)$$

3. Among the 108×108 values in the emission matrix, each non-zero $e^1{}_{ij}$ value is transformed into a record of the link that goes from downstream attributional sector I to emitting sector j. The values amount emission links of tier 1 would be the amount of non-zero e_{ij}.
4. To calculate the Tier 2 indirect emissions, the output matrix from Eq. (5) was summed up by each row to get the column of outputs (Eq. (7)). Then, the Tier 2 output matrix can be derived from Eq. (8). Similarly, the Tier 2 matrix of GHG emissions can be calculated by multiplying the diagonal emission intensities with Tier 2 output matrix (Eq. (9)).

$$\begin{bmatrix} X^2_I \\ X^2_{II} \end{bmatrix} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \times \begin{bmatrix} X^1_{I,I} & X^1_{I,II} \\ X^1_{II,I} & X^1_{II,II} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} X^n_{I,I} & X^n_{I,II} \\ X^n_{II,I} & X^n_{II,II} \end{bmatrix} = \begin{bmatrix} A'_{I,I} & A'_{I,II} \\ S'G'_{.,I} & S'G'_{.,II} \end{bmatrix} \begin{bmatrix} X^{n-1}_I \\ X^{n-1}_{II} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} E^n_{I,I} & E^n_{I,II} \\ E^n_{II,I} & E^n_{II,II} \end{bmatrix} = \begin{bmatrix} \widehat{R_{.,I}} \\ R_{.,II} \end{bmatrix} \times \begin{bmatrix} X^n_{I,I} & X^n_{I,II} \\ X^n_{II,I} & X^n_{II,II} \end{bmatrix} \quad (9)$$

5. Following steps 3 and 4, we can calculate Tier 3–4 indirect emissions.
6. Also, the emissions matrices of Tier 2–4 were transformed into records of links that go from downstream attributional sectors to emitting sectors. Then, the Tier 1 emission links are concatenated to form a data table of all the emission links along supply chains.
7. Prefixes of 1, 2, 3, or 4 were added to each sector name in the combined data tables according to the sector's upstream level in the supply chains.
8. We calculated and built the data tables of GHG emission links for a baseline and four plastic circular intervention scenarios. Then, differences in all links between the baseline and each circular intervention scenario were calculated.

Using the data table of differences in GHG emissions, we used the networkD3 library in R to draw two Sankey diagrams, including one diagram for the

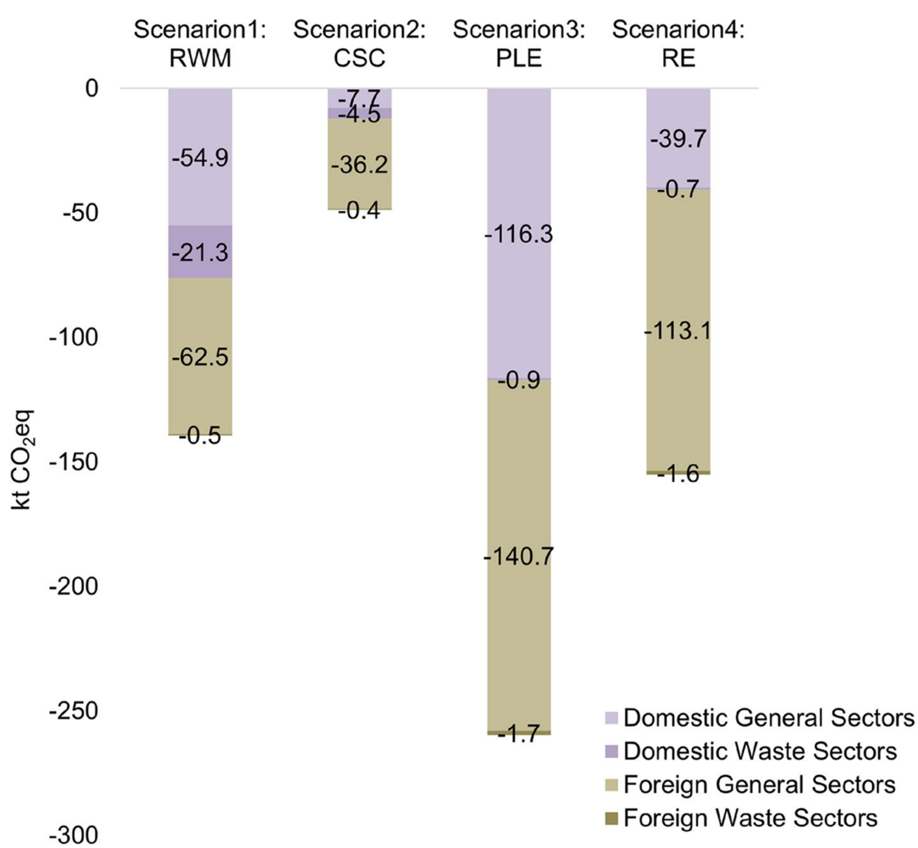

Fig. 6 GHG emission differences after applying four scenarios' interventions in Taiwan in comparison to the baseline scenario

sectors with reductions in GHG emissions and one for the increases.

3 Results

3.1 Comparison of four scenarios

Four scenarios have been set up for the intervention on the flows of specific products, waste, or materials. We can see the estimated potential of these scenarios to reduce GHG emissions in Fig. 6. The result of the PLE in plastic cabinets and parts shows the largest potential, equivalent to 260 kt CO_2eq reduction. In contrast, the scenario of CSC of plastic bags has the least potential, equivalent to 49 kt CO_2eq reduction. The reduction potentials of RWM and RE scenarios are 139 and 155 kt CO_2eq, respectively.

Three main factors determine the overall mitigation potentials of the plastics management scenarios. The first factor is the changed volume of flows. For example, plastic bags' material flow is minor compared to plastic containers and other materials. The second factor is how the supply chain relationship that the demand changes

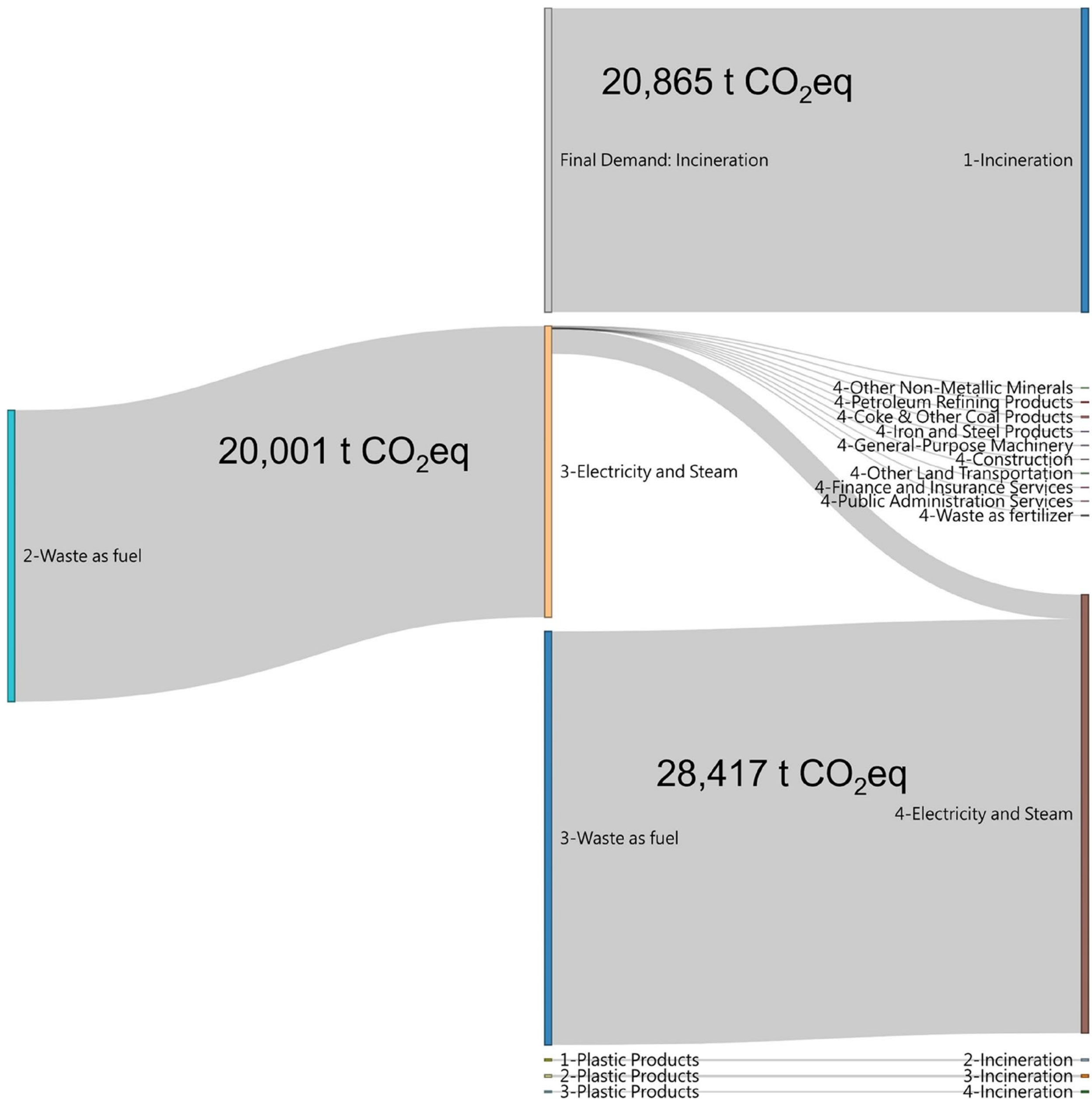

Fig. 7 Significant GHG reductions in the RWM scenario. Each prefix number of one GHG-emitting activity indicates its upstream position in the supply chains' production and waste management activities

can affect industries' upstream activities to produce more or less. For example, the PLE scenario lowers the final demands for plastic cabinets and parts; the RE scenario lowers the material required for making plastic products. As a result, the CSC, PLE, and RE scenarios have numerous indirect reductions on the upstream supplying sectors. The third factor is the direct GHG reduction in waste treatment and the indirect reduction due to the increased power from waste-to-energy activities. The Sankey diagrams in the following sub-sections can uncover many indirect GHG reductions.

We can look at the main material flow changes in the four scenarios for an explanation of the scenarios' differences.

The RWM scenario diverts 72.2 kt of plastic waste from the incinerators for more efficient energy recovery.
The CSC scenario increases the circulation of plastic bags by 5.2kt.
The PLE scenario's extension of product lifetime reduced the annual consumption of plastic material by 24.2 kt.
The RE scenario's higher efficiency in the plastic product manufacturing sector reduces both the generation of plastic waste and raw materials demand by 1.1 kt.

Although the change of plastic flow in the RWM scenario is the largest among the four scenarios, it does not contribute to most GHG reduction. The reason could be that most of the plastic waste in Taiwan is treated by incinerators. This diversion of plastic waste only increases the efficiency of energy recovery by SRF power plants. The result shows that The PLE and RE scenarios have higher GHG reduction than the RWM scenario. The major reduction comes from the general sectors rather than the waste management sectors. The significant reduction is attributable to the lower demand for the materials and energies from plastic products' supply chain. A more detailed breakdown of the GHG reduction hotspots can be seen in the following sections.

3.2 Residual Waste Management by diverting to efficient energy recovery

The modeling for the RMW scenario shows both decrements and increments of GHG emissions in various economic and waste treatment activities.

Figure 7 shows three obvious GHG reductions in supply chain activities. The reduction link on the top is a result of diverting waste plastic from waste incinerators. Reduction in incinerated waste will contribute to reduced emissions. The other two reduction links stand for the reduced emissions from power generation. One emission

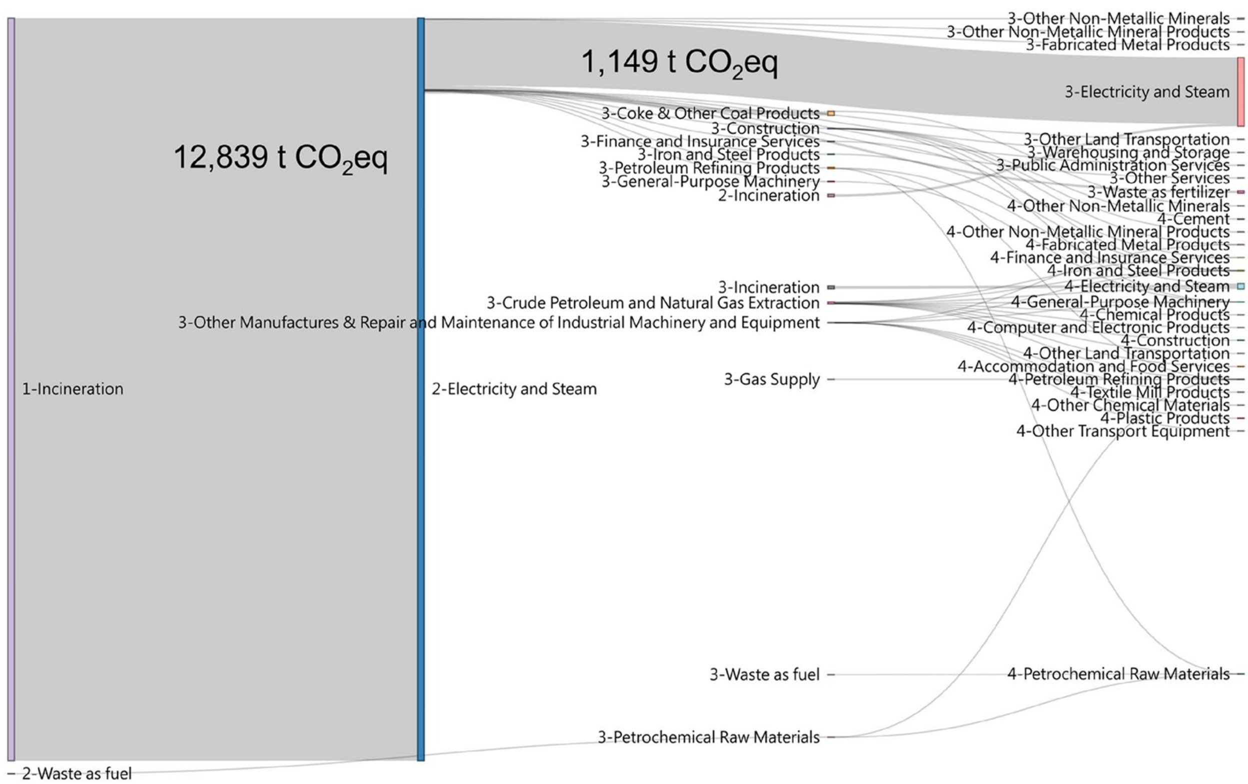

Fig. 8 Significant GHG additions in the RWM scenario

reduction in the middle is attributable to the plastic SRF derived from MSW. Another one at the bottom is attributable to the SRF derived from industrial wastes. The power from SRF power plants can substitute part of the electricity and steam for the power station using fossil fuels. Therefore, the GHG emissions from the Electricity and Steam sector can be reduced.

We also found several activities having emissions added to that of the baseline. As the links displayed in Fig. 8, the most significant one is the increase in the emission from the increased power from the Electricity and Steam sector that can compensate for the reduction of power from MSWIs. When MSWIs receive less plastic input, they cannot generate the same amount of power to the grid.

3.3 Closing Supply Chains by using more secondary material from plastic bag recycling

The illustration of GHG reductions of the CSC scenario setting shows that emissions from many activities in different supply chains would decrease. For example, on top of the Sankey diagram in Fig. 9, one significant reduction in waste treatment is attributable to reduced waste incineration due to better recycling of plastic bags. In addition, numerous reductions in the production chains of plastic can be seen in the Sankey diagram. Using material from recovered plastic decreases the demand for fossil-based supply activities for manufacturing plastic products. The activities include the sectors of Other Chemical Materials, Petrochemical Raw Materials, and the Electricity and

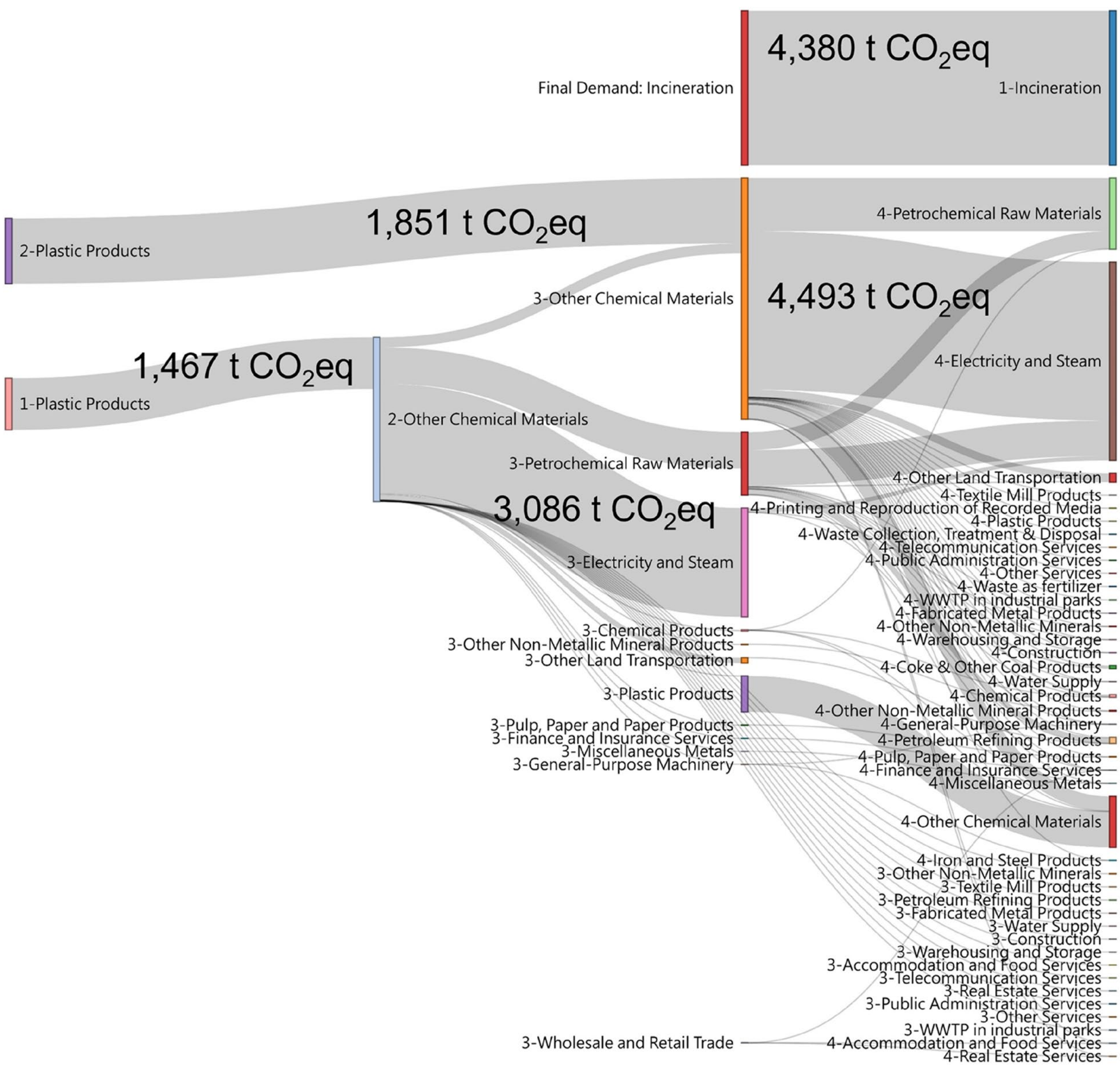

Fig. 9 Significant GHG reductions in the CSC scenario

Steam that supply the energy. The most considerable 4.49 kt CO_2eq GHG reduction in the supply chains is in the emissions from the Electricity and Steam sector that supply the power demand for the Other Chemical Materials.

We also found several activities having additional emissions than the baseline scenario. Figure 10 illustrates the emissions associated with using plastic waste as raw material that needs energy and water to separate and recover. One emission addition is associated with the recovery of plastic from households (1.51 kt CO_2eq). The other one is associated with recovering plastic from industrial waste (1.68 kt CO_2eq). We also see an increase of 2.70 kt CO_2eq in the emission from the Electricity and Steam sector that is attributable to compensation for the less power from waste incineration.

3.4 PLE of plastic products

Life extension of plastic cabinets and parts will reduce the demand in the long run. Figure 11 shows the emission reductions along the supply chains resulting from demand reduction. The sectors with significant reductions in GHG emissions are Plastic Products (7.35 kt CO_2eq), Other Chemical Materials (10.43 kt CO_2eq), Petrochemical Raw Materials (4.40 + 2.93 kt CO_2eq), and Electricity and Steam sectors. There are numerous sectors showing minor reductions, including those not producing plastic-related materials.

Also, we can observe detailed linkages between the sectors influenced by the reduced demand for plastic cabinets and parts. For example, most sectors producing plastic products or the materials for plastic products have significant energy input from the Electricity and Steam sectors. The most considerable reduction belongs to the emissions from the Electricity and Steam sector that supply the demand for the Plastic Product sector. The amount of this reduction equals 42.84 kt of CO_2.

3.5 RE in plastic production

When the REs of the plastic production chain rise, less material is required for producing the same amount of plastic product. Thus, the material inputs and energy input from the upstream sectors fall, and so do the GHG emissions associated with the inputs.

The Sankey diagram in Fig. 12 reveals the emission reductions along with the supply chains resulting from the reduced material inputs. The sectors having significant reductions include the Other Chemical Materials (2.76 + 3.80 kt CO_2eq), Petrochemical Raw Materials (1.94 + 0.73 kt CO_2eq), Petroleum Refining Products (3.10 + 1.47 kt CO_2eq), and Chemical Materials sectors (0.85 + 2.36 kt CO_2eq). Similar to the result of the PLE scenario, the Electricity and Steam sector also shows GHG reductions in different supplies to the plastic supply chains' sectors. The most considerable 9.24 kt GHG reduction in the supply chains is in the Electricity

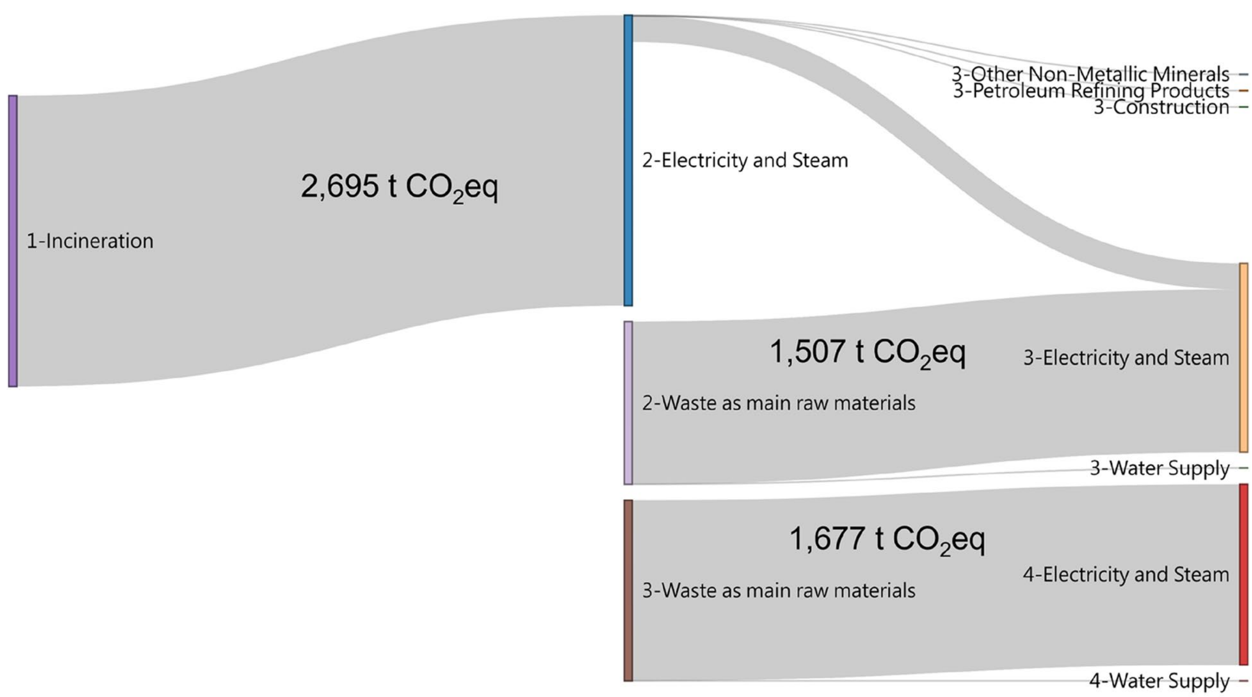

Fig. 10 Significant GHG additions in the CSC scenario

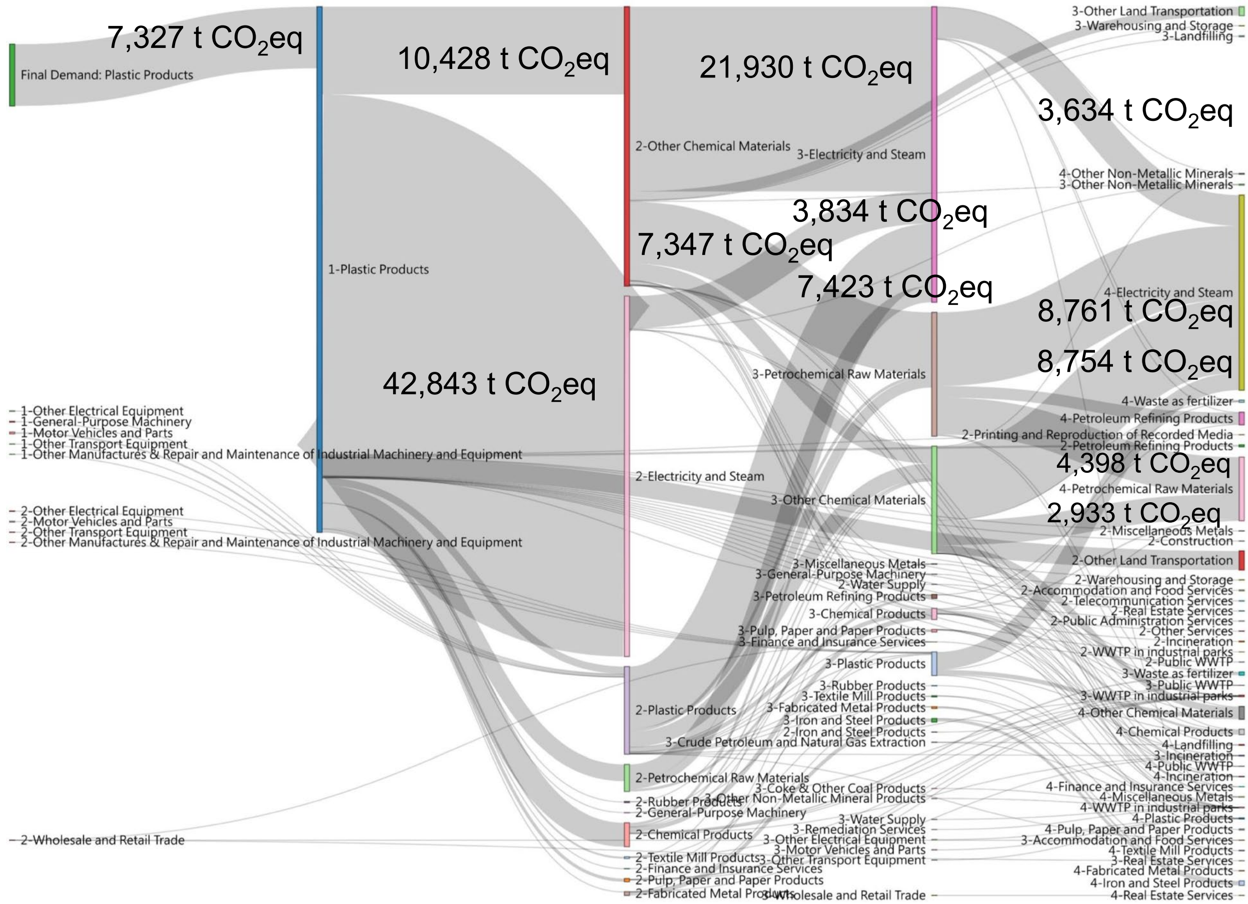

Fig. 11 Significant GHG reductions in the PLE scenario

and Steam sector that supplies the demand for the Other Chemical Material sector.

4 Discussion

This study presents new applications of WIO models for different circular interventions. The results above demonstrate how the GHG reduction potentials of individual plastic management proposals focusing on specific products, waste, and processes can be evaluated using WIO models. We fill a gap in the previous research that most models for a circular economy of plastic did not assess the RWM and CSC type interventions because the model cannot capture a change of waste flows like the WIO model. Therefore, these models may underestimate CO_2 mitigation of transition to a more circular economy. Furthermore, the methodological information of this study paves the way for future studies that will look at the GHG reduction potentials of circular interventions for different materials. Like Kondo and Nakamura's paper [16] on recycling appliances, this study details the settings in allocating plastic wastes and increasing plastic waste inputs of the sectors that can close material loops.

A new data visualization method has been introduced in this study to display the supply chain relationship of the economic activities and highlight activities having significant emission differences compared to the baseline situation. The complex supply chain impacts are not easy to illustrate in previous studies. A few studies use a grid with different darkness to highlight the flows between sectors in an IO model. To uncover the supply chain GHG emissions in the backbox of the Leontief inverse of EEIO models, we developed the code to render Sankey diagrams that can present the significant flows in the supply chains. The method described and the code (provided upon request) used in this paper can be used in many EEIOA future studies to better describe the impacts caused by downstream and upstream activities in the supply chains with the Sankey diagram.

This study has a few limitations due to the modeling methodology and data availability. The WIO model in

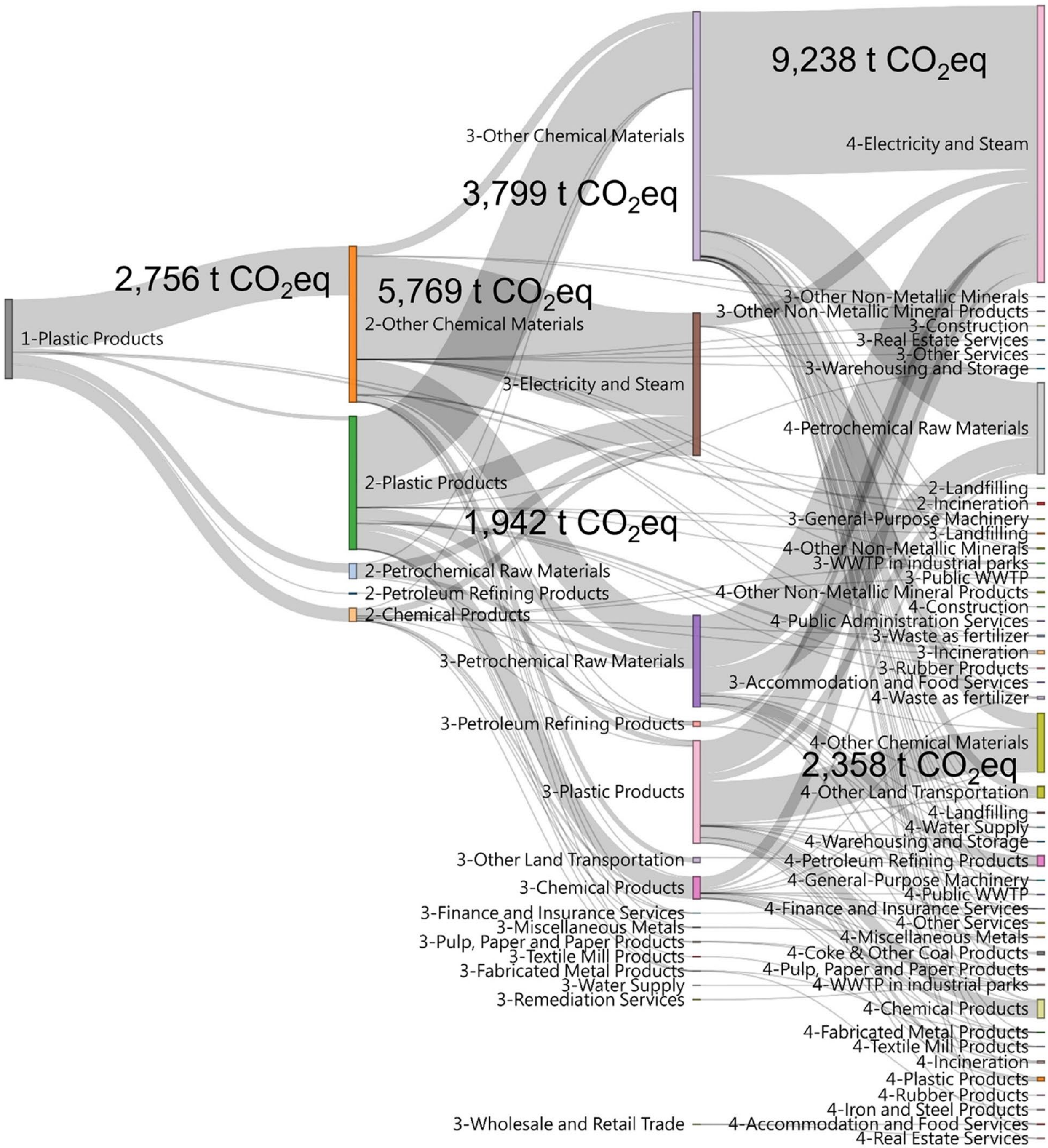

Fig. 12 Significant GHG reductions in the RE scenario

this study cannot predict the dynamic changes in the future like Computable General Equilibrium (CGE) models. However, the low sectoral resolutions of most CGE models have been a challenge in defining detail settings in specific circular interventions. One future work could be adopting the dynamic waste input–output model developed by Nakamura and Kondo [27].

We encountered challenges in building a more precise model. First, a 164-sector IO table was considered to build a WIO model with high sectoral resolution. However, current publicly available data (mainly from the energy balance) for compiling GHG emissions cannot break down the energy use and other GHG emissions into 164 sectors. So, a 68-sector IO table was incorporated into the WIO model. The second challenge is that the available datasets on the waste treatment sectors' inputs from the 68 good and service sectors are not comprehensive. As mentioned in the method section, we only collected the water and energy inputs for the several waste treatments of the largest treatment volumes and the inputs for plastic recycling and recovery. A more comprehensive life cycle inventory of other waste treatments will be conducted in the future.

There would be potential to use the results and methods of this study in the waste and resource management policies of Taiwan and other countries. For Taiwan, the model can access the different strategies for making more efficient use of plastic from the raw material, components, products, and waste streams on their potential for GHG mitigation. We have created models in spreadsheets that allow the policy planner to adjust the different policies' objectives to see the different mitigation potential, such as further improving the recycling rate of plastic bags that are not well reused and recycled in Taiwan. For the application in international society, only a few countries have compiled their WIO tables in the literature, such as Japan [14], Australia [28], and the UK [29]. Many countries are short of detailed classified waste data from the industries. This data shortage may limit these countries in building a WIO model complete enough to assess their resource and environmental management policies. However, many economies are enhancing their waste data collection. For example, several European countries have been using European Waste Catalogue Code to effectively classify and monitor waste flows. As a result, more countries will have sufficient industrial waste data for compiling WIO tables and models. Integrating waste data with the IO table can adopt one type of EEIO model, such as WIO, Waste Extended IO, Physical IO, or HIO, depending on the applications and data sufficiency [10].

5 Conclusions

This paper presents the GHG mitigation potential modeling for the circular interventions on specific plastic waste, treatment, product, and sector. So, the practitioners evaluating the impacts of individual policy proposals can refer to the method used in this study to set up waste input–output models for the scenarios of residual waste management, closing the supply chains, product life extension, and higher resource efficiency. The GHG reduction potentials are 139 kt CO_2 for diverting plastic to the SRF for power generation, 49 kt for closing the loops of plastic bags, 260 kt for extending the life of plastic cabinets and other plastic products, and 155 kt for improving plastic products supply chain's resource efficiencies.

The WIO model of Taiwan can capture the interactions between economic sectors with waste treatment activities. Thus, we can see and compare the significant contributions of GHG emissions. In the scenarios we have modeled, we found the reduction of emissions from general sectors is greater than that from waste treatment. In addition, the modeling considering import ratios of goods can distinguish the reductions in domestic and foreign supply chains. This study also innovates in developing a data visualization method for detailed impacts along supply chains. Using the modeling results of sectors' emissions and their downstream sectors, the R language program can render Sankey diagrams for tracking and highlighting emissions along upstream sectors.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-023-00178-7.

Additional file1. DAQetailed model settings and parameters of four scenarios. Table S1. GHG emission intensities of 68 sectors of goods and services in the waste input-output model for the circular interventions. Table S2. GHG emission intensities of 40 waste treatment methods in the waste input-output model for the circular interventions.

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Authors' contributions

Prof. Pi-Cheng Chen supervised the research. Jui-Hao Chang Chien collected data and built the models. Prof. Pi-Cheng Chen verified the model, developed a data visualization method, and designed the program. The manuscript was written by Jui-Hao Chang Chien and Prof. Pi-Cheng Chen. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are available upon request.

Declarations

Competing interests

The authors declare they have no competing interests.

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