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A Study on the Optimal Method of Eco-Friendly Recycling through the Comparative Analysis of the Quantitative Calculation and Scope of Recycling

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Abstract

Purpose: The purpose of this study is to present an efficient emission reduction ratio of plastic to reduce carbon dioxide, the main cause of greenhouse gases. **Research design, data and methodology:** This study calculated the absolute value of carbon dioxide by setting an equation through the emission coefficient using the US EPA's WARM model. **Results:** In the recycling ratio of 70%, it was found that the energy recovery ratio was 15.6%, which was the energy recovery ratio without generating carbon dioxide. When carbon dioxide is generated by changing plastic waste emissions, optimal efficiency is achieved by reducing emissions by 10% to 30% of energy recovery ratio, 20% to 50% of energy recovery ratio, and 30% to 80% or more of energy recovery ratio. **Conclusions:** The recycling rate should be set at a minimum of 70%, so that a carbon dioxide-free energy recovery rate could be obtained during the recycling process, supporting an eco-friendly basis for environmental policies aimed at this rate. In addition, it was possible to suggest that it is essential to reduce emissions by at least 30% for eco-friendly recycling measures that can achieve both economic and environmental feasibility in the energy recovery process through incineration during recycling in Korea.

Keywords : Climate change problem, Recycling, Carbon dioxide

JEL Classification Code: C20, Q26, Q53, Q56

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1. Introduction

1.1. Background of the Study

Today, a phenomenon that is attracting attention as a serious global environmental problem is an abnormal climate phenomenon caused by global warming. Global average temperatures continue to rise due to global warming. In the Paris Agreement adopted at the 2015 United Nations Climate Change Conference, international agreements were made to ensure that the global average temperature increase did not exceed 1.5°C. As a comprehensive international law that has been applied since November 4, 2016, the world is making great efforts to solve the abnormal climate phenomenon caused by global warming.

The 1989 Basel Convention shares the status of waste plastic migration and pollution into the ocean. The OECD Secretariat and member states are paying attention to several areas, including the suppression of the use of single-use plastic waste and the prevention of marine plastic waste, for environmental conservation purposes.

The EU aims to recycle at least 70% of packaging waste and 55% of plastic by 2030. The US EPA is trying to strengthen the secondary recycling market and build measurement and infrastructure data for material management to improve recycling systems.

There are two representative policies in Korea: the waste pay-as-you-go system and the Extended Producer Responsibility (EPR). First, the garbage volume-rate system is a policy aimed at suppressing the generation of garbage and promoting the separation and discharge of recycled products by allowing them to bear the cost as much as they are thrown away. Second, the producer responsibility recycling system is a system that imposes a certain amount of recycling obligations on product producers and levies on producers if they do not implement it.

As such, we are trying to protect the earth by choosing recycling as the main way to reduce waste such as waste plastic worldwide. Since Korea is also showing an increasing trend of waste generation, we want to increase the recycling rate.

However, despite these efforts, the global average temperature reached 17 degrees in July 2023. So far, the above policies have not produced satisfactory results. Therefore, in order to solve the abnormal climate phenomenon caused by global warming, international efforts to protect the environment, such as reducing greenhouse gases and recycling plastic, are needed.

1.2. The Purpose of the Study

According to the 6th National Waste Statistical Survey conducted from 2021 to 2022, the unit of household waste generation was 950.6g/day/person, an increase of 2.2% compared to the unit of generation in the 5th survey. The amount of household waste generated seems to have increased due to the influence of COVID-19.

In addition, it is difficult to recycle due to colors and labels, single-person households, online shopping, and the generation of disposable products and packaging waste surged.

As a result, the Ministry of Environment established a comprehensive recycling waste measure in 2018 and sought to strengthen the role of each subject, including the government, local governments, producers, and consumers. It also aims to establish a production and consumption structure to curb the generation of household waste such as plastic, and promote recycling. As a result, the Ministry of Environment proposed a 50% reduction in plastic waste generation and 70% recycling by 2030.

Therefore, based on this, a scenario of recyclable plastic waste recycling ratio can be created using the EPA WARM method, and the amount of carbon dioxide generated during recycling and carbon dioxide generated during incineration can be quantified to calculate the amount of carbon dioxide converted into consideration of emissions. Through this, we intend to study the optimal recycling activation plan that proves the effectiveness of recycling and minimizes the environment from a policy perspective, focusing on its ratio and figures.

2. Theoretical Background

2.1. Designation of Representative Gas of Greenhouse Gas

Greenhouse gases are gaseous substances that stay in the atmosphere for a long time and are important in maintaining the average temperature of the earth, but when excessive, they trap heat emitted from the earth and cause a greenhouse effect that causes an increase in the average global temperature. Sources

Representative greenhouse gases include six types of direct greenhouse gases caused by human activities adopted in Kyoto, Japan in 1997. According to the Kyoto Protocol, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFCs), perfluorocarbon (PFCs), and sulfur hexafluoride (SF_6) are present, respectively.

Table 1: Comparison of Global Warming Potential (GWP) and Emissions Ratio

Types of greenhouse gases	Global Warming Potential figures	Proportion of emissions (%)
CO_2	1	91.9
CH_4	21	3.7
N_2O	310	2.1
HFCs	140 - 11,700	1.1
PFCs	6,500 - 9,200	0.2
SF_6	23,900	1.0

Among them, carbon dioxide has the lowest global warming index (GWP) among the six major greenhouse gases, but the proportion of emissions by greenhouse gas is the highest at 91.9% as of 2016.

Therefore, since carbon dioxide accounts for the largest proportion of greenhouse gases that affect climate change, it can be seen as a representative gas of greenhouse gases, and the study was conducted with carbon dioxide as a calculation factor.

2.2. Waste Disposal Status and Recycling Rate

2.2.1. Household Waste

Household waste excluding recyclable materials, briquettes, food waste, and large-scale waste is collected and transported to a landfill in the metropolitan area or directly transported to a landfill by a compressed vehicle for disposal.

In the case of separate emission of recyclable resources, 52.3% in the household sector and 47.7% in the non-family sector, compared to the 5th survey, showed an increasing trend in the household sector and a decreasing trend in the non-family sector. This seems to have been affected by the impact of COVID-19 and the increase in single-person households.

According to the 6th National Waste Statistical Survey, the proportion of household waste to be treated compared to the amount generated in 2020 was 45.6% recycled, 31.5% incinerated, 7.0% non-incineration intermediate disposal, and 16.0% direct landfilling.

Table 2: Status of household waste disposal, (unit: ton/year, %)

Waste type	Recycling	Interim disposition		Reclamation
		Incineration	etc	
Volume-based mixed discharge	904,519	4,530,217	93,760	2,513,469
	11.25	56.33	1.174	31.25
Separation and discharge of food and logistics	3,452,501	60,847	1,072,427	84,604
	73.92	1.30	22.96	1.81
Separate discharge of recyclable resources	3,341,468	726,585	12,336	104,369
	79.85	17.36	0.29	2.49
	7,698,489	5,317,648	1,178,524	2,702,441
Total	**45.56**	**31.47**	**6.97**	**15.99**

2.2.2. Incineration Rate during Recycling

Article 2, Paragraph 7 of the Waste Management Act in Korea is as follows.

7. The term "recycling" means any of the following activities.

A. Activities to make waste reused, recycled, or reusable

I. Activities prescribed by Ordinance of the Ministry of Environment as activities to recover or recover energy under subparagraph 1 of Article 2 of the Energy Act from waste or to use waste as fuel.

A closer look at paragraph 7 here indicates that activities prescribed by Ordinance of the Ministry of Environment are recognized as recycling when energy is recovered or made recoverable.

For this reason, there is an incineration process, but if energy is recovered as a result of the process, Korea will be included in the recycling category.

Therefore, the recycling rate in Korea is about 45%, accounting for nearly half of the recycling items excluding incineration and landfill. Compared to overseas, the high level of recycling accounts for most of Korea's plastic waste treatment by energy recovery from heat generated during incineration. The biggest reason can be that energy recovery companies are registered as recycling companies, and if the incineration process is included in the energy recovery process included in the recycling figures, air pollutants and greenhouse gas emissions are also generated, so the perception of energy recovery facilities and resource recovery facilities is not very good.

However, incineration in actual waste treatment and incineration in energy recovery through incineration, which is treated as recycling in Korea, do not form a separate line, and since it is the same process of incineration with an incinerator, it can be seen as a classification based on the presence or absence of energy recovery using heat generated by incineration.

Table 3: The 6th National Waste Statistical Survey on Household Waste Disposal in 2021, (unit:t/year, %)

Processing type	Total amount	Ratio (%)
Recycling	7,698,489	45.56
Incineration	6,496,172	38.44
Reclamation	2,702,441	15.99
Total	**16,897,102**	**100**

2.3. US EPA – WARM Program

The EPA WARM Method was developed to provide a high-level estimate of the economic impact of potentially occurring greenhouse gas emissions reduction, energy conservation, and various waste management.

The basic information required to implement the EPA WARM Method requires data on waste throughput by material type, related waste management methods currently used, and alternative methods. Furthermore, basic data such as landfill gas recovery rate, average landfill gas collection efficiency, and transport distance, "National Average," are available. However, more accurate results can be obtained if users can input data directly, such as landfill characteristics, anaerobic digestion characteristics, material characteristics, and waste transport distance.

perspective of Life Cycle in EPA WARM begins at the time of waste generation, and only considers greenhouse gas emissions related to material acquisition and manufacturing among the four end-of-life material management. In addition, EPA WARM includes emission factors for combustion, along with emission reductions for plastics, recycling, landfilling, and energy recovery. At this time, recycling can only be applied to HDPE and PET resins.

Reducing emissions means reducing greenhouse gas emissions associated with plastic manufacturing when plastic production is reduced. Recycling in EPA WARM presents a recycling model for HDPE and PET as described previously.

Recovering and recycling such plastic means manufacturing again with the same product. Incineration is considered to result in carbon emissions from plastic combustion because plastic is made from fossil fuels. In addition, the amount of plastic CO_2 emissions burned in EPA WARM depends on the carbon content of the plastic and the amount of carbon converted to CO_2 during combustion.

Therefore, the method of obtaining the amount of carbon dioxide using the EPA WARM model is as follows.

WARM sets the scope of recycling until the same product is produced through secondary raw materials produced by recycling products from primary raw materials, and calculates the amount of greenhouse gases through recycling in three stages.

Step 1: Calculate the amount of greenhouse gases generated in the production of products from primary raw materials

Step 2: Calculate the amount of greenhouse gases generated to produce the same product from secondary raw materials that are recycled from waste products

Step 3: The difference between the amount of greenhouse gases generated in Steps 1 and 2 is expressed as a reduction amount (-).

It also uses $MTCO_2eq$/ton units that convert the amount of greenhouse gases into carbon dioxide.

Therefore, it can be seen that the amount of carbon dioxide reduction available from recycling in the EPA WARM model is only limited to the production of new products through pure recycling.

Finally, emissions associated with plastic landfills at EPA WARM only take into account what happens as plastic waste moves to landfills.

3. Research methods

In the case of energy recovery due to incineration, energy is obtained by recycling waste resources, so there is an advantage of economic feasibility and resource utilization.

However, since this is still in the process of incineration, we should consider emitting greenhouse gases from incineration.

Therefore, it is important to set an eco-friendly recycling rate that can minimize the environmental impact or increase the amount of energy recovery while maintaining it within its limits if the resulting greenhouse gas generation exceeds the amount reduced through recycling.

It is also possible to reduce carbon dioxide conversion by reducing plastic emissions, so it is also important to set the ratio in consideration of eco-friendliness to how much recycling to obtain the desired energy recovery ratio and how much plastic generation should be reduced.

However, in WARM, landfills are calculated by calculating only the amount generated when transporting waste to landfills, so this study excluded the ratio of landfills in recycling.

Therefore, this study used the WARM tool of the US EPA to calculate the amount of carbon dioxide reduction from recycling.

3.1. Target Material Selection

3.1.1. Plastic

The types of plastic covered by EPA WARM Method are as follows.

High-density polyethylene(HDPE), Low-density polyethylene(LDPE), Polyethylene (PET), Linear Low-density polyethylene(LLDPE), Polypropylene(PP), General purpose polystyrene(PS), Polyvinyl chloride(PVC), Mixed Plastics

Among them, PET, which EPA's WARM model opposes, is most often used in synthetic fibers, followed by beverage bottles.

Currently, recyclable plastic waste investigated in Korea is classified into vinyl, foamed resin, PET bottles, and others.

In this study, we intend to use the EPA WARM method using the amount of PET disease that is known to have the highest emission.7)

In order to determine the quantity of plastic, data on the collection status of each recycled product item posted on the Seoul Metropolitan Government Resource Recovery Facility website were selected and utilized.

The relevant data corresponds to household wastes collected through separate discharge and door-to-door collection methods, such as multi-family housing areas and detached housing areas.

Table 4: Collection status by item of Seoul Resource Recovery Facility (2021)

Collection status by item (2021) (ton/day)		
Waste type	**collection volume**	**Ratio (%)**
Paper	667	27.0
Waste synthetic resin	851	34.5

In addition, waste synthetic resin refers to the disposal of plastics and plastic products made using resin obtained from the chemical process of the petroleum industry, and includes waste plastics and waste plastics. According to the nationwide waste generation and disposal status in 2019, plastic waste is statistically managed under the name of waste synthetic resin or waste synthetic resin.

Therefore, in this study, waste synthetic resin was regarded as the largest proportion of plastics, and the sum of 142,013.8 t/year of vinyl, 15,494.8 t/year of foam resin, 39,452.2 t/year of PET bottles, and 113,616.5 t/year of other waste synthetic resin was converted into t/day, and the amount of plastic was calculated as 851t/day, assuming that it was the amount of PET with the highest emission.

3.2. Emission Coefficient and Incineration Ratio Setting

The emission coefficient calculation principle described in EPA WARM is the calculation of greenhouse gas emissions related to the acquisition and manufacture of raw materials. First, the greenhouse gas emissions of energy used in the process of acquiring and manufacturing raw materials consist of carbon dioxide emissions from the combustion of fuel used in acquiring and manufacturing raw materials. At this time, carbon dioxide emissions from biomass combustion are not calculated as greenhouse gas emissions. It also includes indirect carbon dioxide emissions because fuel is required for direct combustion of fuel or transportation of fuel. Here, the greenhouse gas emissions of the energy used to transport the fuel consist of carbon dioxide emissions from fossil fuel combustion used in transportation at the manufacturing stage and distribution at manufacturing facilities.

EPA WARM models up to five options depending on the material: recycling, composting, combustion, anaerobic digestion, and landfill.

Among them, recycling is based on the assumption that the demand for new materials, products, and the demand for recycled materials remain constant. At this time, the greenhouse gas emission from recycling is calculated as the difference between the greenhouse gas emission from 100% recycling material and the emission from 100% new material production.

In incineration, when certain substances are burned, greenhouse gases in the form of CO_2 and N_2O are emitted. The abiotic CO_2 emitted during combustion is calculated as the greenhouse gas emissions associated with combustion, but the biological CO_2 is not. In addition, WARM assumes that it only includes waste energy facilities that generate electricity.

Therefore, the greenhouse gas emission coefficient of PET presented in the EPA WARM Method is 3.48 MT CO_2E/ton. Greenhouse gases can be reduced by 1.04 MT CO_2E/ton when recycling per ton of PET, and greenhouse gases are emitted by 0.02 MT CO_2E/ton and 1.24 MT CO_2E/ton, respectively, when landfilling and incineration.

As previously described, household waste is currently treated at a rate of 45.6% recycled, 31.5% incineration, 7.0% non-incineration intermediate disposal, and 16.0% direct landfilling. Based on this, we intend to compare the amount of carbon dioxide emission reduction by preparing a basic scenario for each recycling ratio and an alternative scenario based on the 70% recycling target suggested by the Ministry of Environment. In addition, we will use plastic emission reduction to create an alternative scenario to consider emission reduction, prove that recycling and plastic generation reduction are effective in reducing greenhouse gas emissions through two scenarios, and compare the figures.

However, in this study, as described above, since emissions related to plastic landfilling only consider emissions from transportation, we do not consider emissions in the case of landfilling, but only emissions from recycling and incineration. For the waste material flow data to be used at this time, the 6th National Waste Statistical Survey and the National Statistical Portal (KOSIS), a statistical service provided by the National Statistical Office, were referred to the environmental statistics information of the National Waste Generation and Treatment and Resource Circulation Maru.

3.3. Calculation of CO_2 Generation in Incineration

3.3.1. Calculation of PET Recycling Rate Consideration

Looking at the emission coefficient of PET, PET emits greenhouse gases as much as 3.48 MT CO_2E per ton. It emits greenhouse gases as much as -1.04 MT CO_2E per ton of recycling, 0.02 MT CO_2E per ton of landfill, and 1.24 MT CO_2E per ton of incineration. At this time, (-) means reducing greenhouse gases.

Therefore, the following factors are needed to calculate the appropriate ratio of recycling and incineration.

1. Current waste volume T (ton/day)

2. Current household waste recycling rate 46 (%) Recycling category in South Korea

A) Pure recycling A

B) Recycling B by energy recovery (incineration included in WARM calculation)

3. Pure incineration without energy recovery process 54 (%), C

The emission coefficient is summarized using the EPA WARM tool as follows.

1. Reduction of emission factor by 1.04 (ton/ton) during recycling, -k

2. Incineration emission factor of 1.24 (ton/ton) / Simple y

The absolute value of carbon dioxide generation after recycling is calculated through these factors as follows.

$$CO_2(\text{ton/day}) = (-kA + yB) \cdot T + yCT = -kAT + y(B+C) \cdot T \quad (1)$$

3.3.2. Calculation of PET Emission Rate Consideration

Considering only the recycling rate, there is a limit to offsetting the amount of carbon dioxide generated by energy recovery. Due to the nature of Korea, it is important to offset the high amount of carbon dioxide generated during the process because the rate of energy recovery through incineration is high among the recycling rates. Therefore, it is necessary to reduce the amount of plastic generated in the plastic production process to further reduce the amount of carbon dioxide converted.

EPA's WARM Method states that carbon dioxide reductions can be calculated when reducing plastic production.

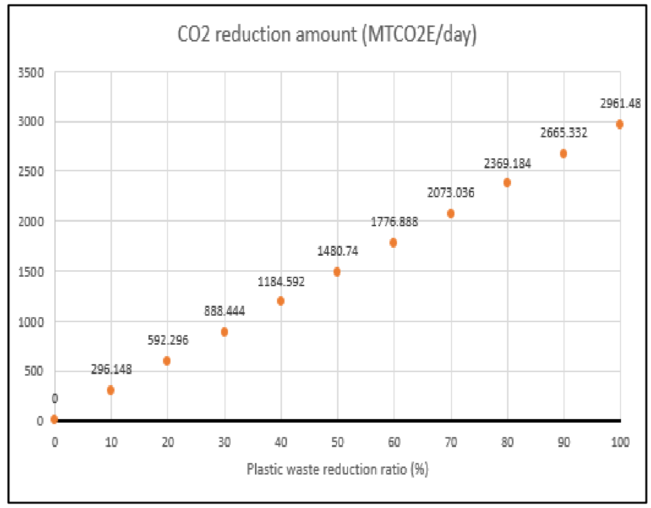

Figure 1: Changes in CO_2 Reduction by Plastic Generation

If the amount generated is reduced during the production stage rather than the recycling stage, the amount of carbon dioxide generated will also be reduced because the fundamental carbon dioxide emission factors will be reduced.

Based on the previous data, the amount of carbon dioxide generated per actual waste generation according to the reduction ratio can be obtained by changing the generation ratio from 100% to 0% in units of 10%.

It is shown as a reduction factor of 3.48 MT CO_2E/ton in carbon dioxide conversion according to plastic reduction obtained through EPA's WARM method. Since this is the same as the generation coefficient, it is considered that no carbon dioxide that should be generated as much as the actual waste is reduced, and the difference can be viewed as the reduction amount.

Therefore, when the amount of plastic generated in the rightmost yellow column of the figure is reduced, the amount of carbon dioxide that can be reduced can be obtained, and if the absolute value becomes negative in addition to the amount of carbon dioxide generated when the energy recovery ratio is increased, the energy recovery ratio can be increased to the ratio where the value becomes zero.

4. Research Results and Review

$$CO_2(\text{ton/day}) = (-kA + yB) \cdot T + yCT = -kAT + y(B+C) \cdot T \quad (1)$$

Using the above equation, as of 2018, a graph of carbon dioxide conversion generation can be obtained according to the energy recovery ratio by calculating the amount of carbon dioxide conversion with a household waste recycling ratio of 46%, incineration ratio of 54%, emission amount of 851 tons/day, and energy recovery ratio of 0% to 100%.

Thus, if we find the x-intercept where y of the corresponding expression in the graph becomes 0, then x = -0.1879

Regardless of the energy recovery rate, carbon dioxide is generated in the recycling process, so the current recycling rate needs to be improved for eco-friendly measures.

Therefore, it is important to set the recycling target at what percentage to determine whether the final CO_2 generation becomes negative when considering the heat recovery by incineration during the recycling process.

Since the current recycling rate is 46%, the recycling rate at which the final carbon dioxide generation becomes negative for the first time is calculated by increasing 5% from 45%, regardless of the energy recovery rate.

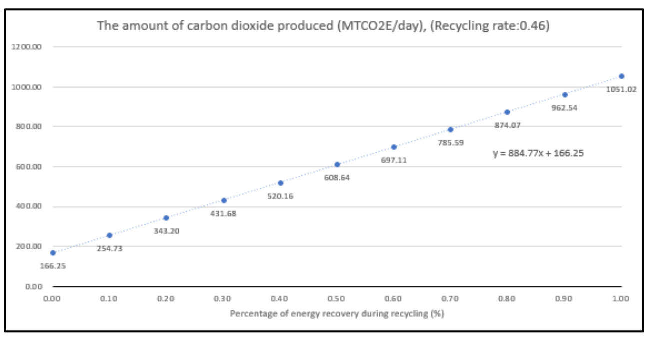

Figure 2: Graph of CO_2 conversion according to energy recovery ratio

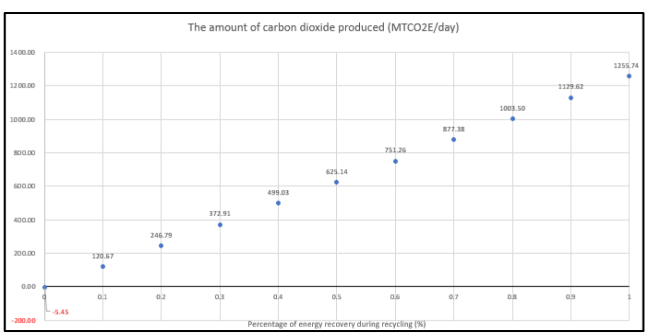

Figure 3: CO_2 conversion at 65% recycling rate

For the first time, the recycling rate of negative numbers in the amount generated is 65%. However, only when the energy recovery ratio is zero, the amount generated is negative, so it cannot be a significant value.

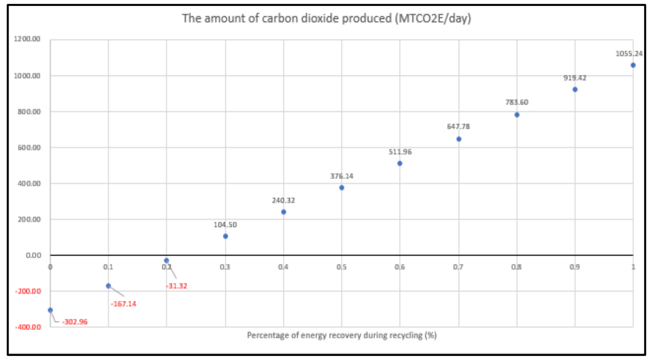

Figure 4: CO_2 conversion at 70% recycling rate

Next, the recycling rate at which negative numbers are generated is 70%. Since the higher the recycling rate, the higher the recycling rate, the negative number appears at the higher energy recovery rate, so when setting the recycling rate, the minimum recycling rate that can find eco-friendliness that can reduce carbon dioxide during the recycling process can be viewed as 70%.

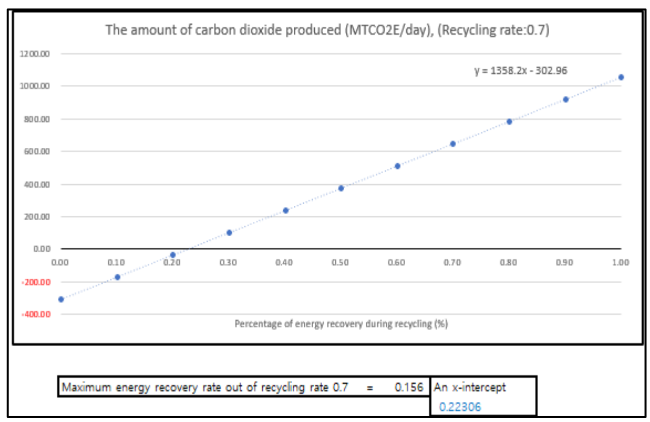

Figure 5: Graph of CO_2 conversion at 70% recycling rate

At this time, the X-intercept in which the amount of carbon dioxide generated due to the increase or decrease in the incineration ratio changes from reduction to emission is 0.22306. This is 0.22306 ratio of 70% recycling ratio, so it appears as 0.156 and 15.6%. 15.6% of the recycling rate is the maximum rate at which energy recovery is possible through incineration without generating carbon dioxide during the recycling process, and even if the recycling rate is increased by 80% and 90%, the minimum energy recovery rate tends to rise.

However, since most of the recycling rates in Korea account for energy recovery through incineration, the low energy recovery rate of about 15% does not fit the reality of Korea, so additional carbon dioxide reduction measures are needed to compensate for this.

Therefore, when the energy recovery ratio is increased from 0% to 10% with emissions up to 100% to 0%, the sum of the carbon dioxide conversion generated during recycling and the carbon dioxide conversion reduced when plastic emissions are reduced must be negative to be the acceptable ratio of energy recovery that does not generate greenhouse gases in consideration of eco-friendliness.

In addition, if a positive value is obtained for the first time, how much waste emissions must be reduced to become negative again to determine the emission reduction rate.

The following is the result of showing the absolute value of carbon dioxide conversion according to the energy recovery ratio considering emissions based on the recycling ratio of 70%.

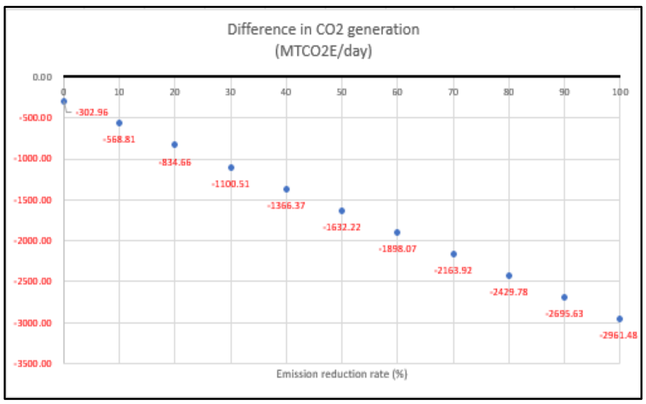

Figure 6: The absolute value of the final CO_2 conversion when the energy recovery ratio is 0%

There is no need to reduce emissions because the energy recovery ratio of 0% results in negative numbers regardless of emissions.

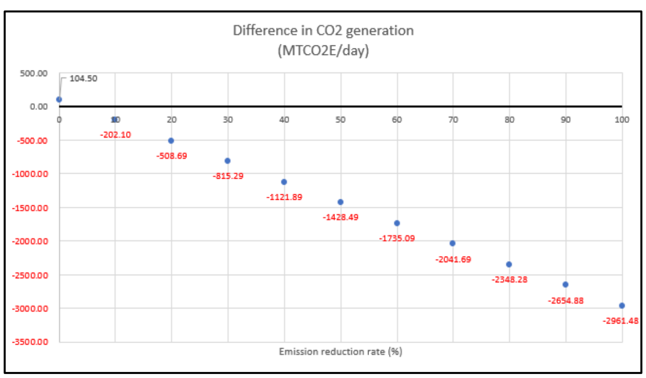

Figure 7: The absolute value of the final CO_2 conversion when the energy recovery ratio is 30%

The energy recovery rate at which positive water is produced for the first time is 30%. At this time, a 10% reduction in emissions results in a negative number, so when the energy recovery ratio is set at 30%, emissions should be reduced by 10% to consider eco-friendliness.

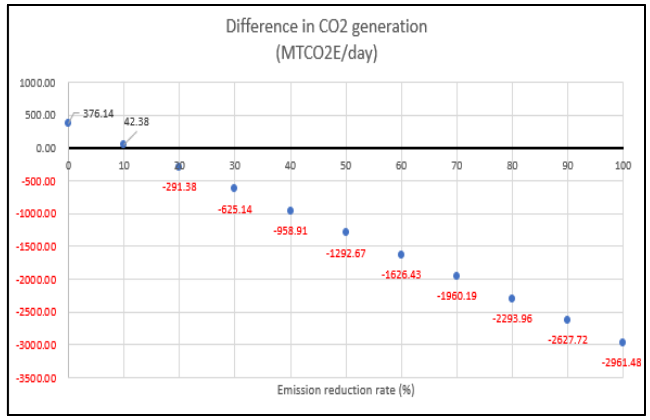

Figure 8: The absolute value of the final CO_2 conversion when the energy recovery ratio is 50%

Similarly, when the energy recovery ratio is set at 50%, emissions must be reduced by 20% in order to become negative again.

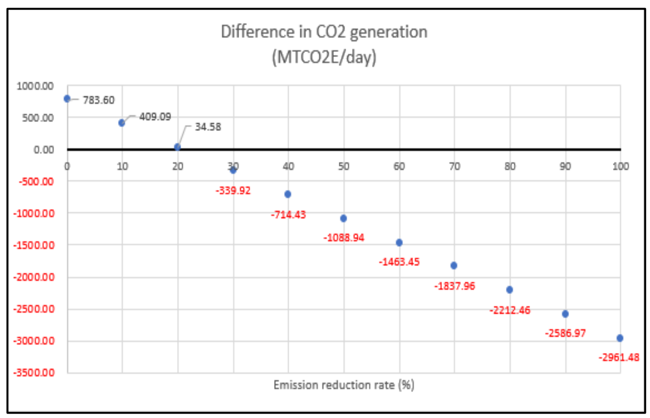

Figure 9: The absolute value of the final CO_2 conversion when the energy recovery ratio is 80%

When the energy recovery rate is 80%, emissions must be reduced by 30% to become negative.

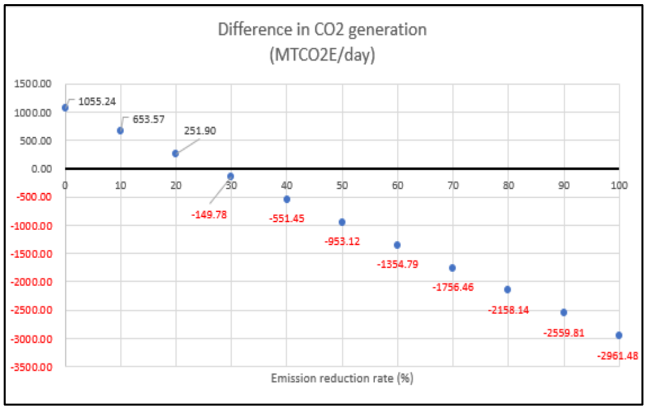

Figure 10: The absolute value of the final CO_2 conversion when the energy recovery ratio is 100%

When the energy recovery rate is 100%, that is, when the entire recycling rate is 70% energy recovery through incineration, emissions must be reduced by 30% to become negative.

Therefore, regardless of the energy recovery rate, the ratio of emission reduction in which the sum of carbon dioxide conversion and waste emission reduced during recycling becomes negative is 30%, indicating that plastic waste emissions must be reduced by at least 30% to allow both energy recovery rates.

5. Conclusion

The results of the study are summarized as follows. First, the highest critical recycling rate at which the amount of carbon dioxide generated during the recycling process becomes negative from positive to negative according to the recycling rate is 65%. However, as described above, when the recycling ratio is 65%, the amount of carbon dioxide generated is negative (reduced) only when the energy recovery ratio is zero, so it is not a significant result. Therefore, it can be seen that the recycling rate must be set at least 70%, so that reduction rather than emission can be considered when carbon dioxide conversion is recycled.

Therefore, figures can support the evidence that implementing the minimum energy recovery ratio by raising the recycling rate to a minimum of 70% from the current 46% recycling rate, and then increasing the minimum energy recovery rate by increasing the recycling rate sequentially by 80% and 90%.

Table 6: Changes in CO_2 conversion according to recycling rate

Recycling rate	Incineration rate	Amount of generation	Result
0%	100%	Positive	Emission
5%	95%	Positive	Emission
10%	90%	Positive	Emission
15%	85%	Positive	Emission
20%	80%	Positive	Emission
25%	75%	Positive	Emission
30%	70%	Positive	Emission
35%	65%	Positive	Emission
40%	60%	Positive	Emission
45%	55%	Positive	Emission
50%	50%	Positive	Emission
55%	45%	Positive	Emission
60%	40%	Positive	Emission
65%	35%	Negative	Reduction
70%	**30%**	Negative	Reduction
75%	25%	Negative	Reduction
80%	20%	Negative	Reduction
85%	15%	Negative	Reduction
90%	10%	Negative	Reduction
95%	5%	Negative	Reduction
100%	0%	Negative	Reduction

Second, due to Korea's high energy recovery rate through incineration during recycling, a high energy recovery rate must be secured, so the higher the energy ratio, the more carbon dioxide generated by incineration, the less plastic emissions themselves, so carbon dioxide must be reduced.

Therefore, the study shows that if plastic emissions are not reduced, the energy recovery ratio of about 20% based on the recycling ratio will be the maximum, and if carbon dioxide is reduced by 10%, the energy recovery ratio should be up to 40% and up to 20% considering eco-friendliness that does not exceed the reduction in carbon dioxide during the recycling process, and finally, the minimum plastic emission reduction rate at which the difference between the two figures becomes negative by offsetting both carbon dioxide emissions through plastic reduction regardless of the energy recovery rate should be 30%.

Table 7: Changes in the percentage of possible energy recovery according to the emission reduction rate

Emission reduction rate	Maximum possible energy recovery rate
0%	20%
10%	40%
20%	70%
30%	100%
40%	100%
50%	**100%**
60%	100%
70%	100%
80%	100%
90%	100%
100%	100%

Therefore, it is desirable to sequentially increase the emission reduction rate by 10% to reach the city's plastic emission reduction target of 50% as of 2018, but this study suggests that at least 30% reduction in emissions is essential due to the nature of Korea, where most energy recovery rates are based on 70% recycling rates to obtain both economic and environmental performance in the energy recovery process through incineration.

As a result, in order to obtain a high energy recovery rate, the figure can be presented to reduce plastic generation by at least 30%, and the energy recovery rate can be increased to a high rate, thereby securing economic feasibility and minimizing carbon dioxide generation in the recycling process.

Finally, the limitation of this study is that the landfill ratio was calculated as 0. In the EPA's WARM method, the range of landfills was calculated as the amount of carbon dioxide converted upon movement to the landfill, so this was excluded from the calculation. However, since there is also a landfill item in the waste treatment part of Korea, it is considered necessary to consider the landfill part in order to apply the significance of this study in reality.

And in this study, waste synthetic resin was considered waste plastic, and the type of waste plastic was limited to PET for calculation using EPA's WARM model. However, since there are various types of plastic such as PET, PP, PS, and HDPE, it is necessary to consider other types of plastic when calculating actual waste plastics.

In addition, the expected point of this study is that if new and renewable energy technology develops in the future, the amount of greenhouse gas generated from incineration will decrease, so the slope of the graph will be lowered to obtain a higher energy recovery ratio from incineration.

Therefore, if follow-up research is conducted in response to the upcoming climate change crisis, it is expected that measures that can consider both economic and eco-friendly in ways that have less environmental impact, such as high-efficiency incineration methods and bioplastic, will be studied in a more accurate numerical direction.

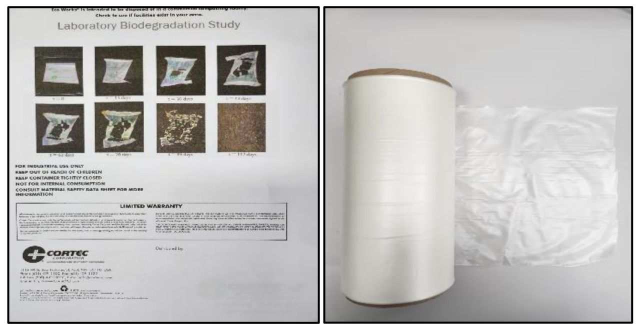

Figure 11: Biodegradable vinyl Eco Works under development at CORTEC

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