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Optimal Greenhouse Gas Reduction Technology for Waste Incineration Facilities during the 4th ETS Plan Period

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Abstract

In the fourth compliance period (2026–2030) of the Korea Emissions Trading Scheme (K-ETS), greenhouse gas reduction targets have been strengthened and the proportion of auctioned allowances has increased compared to the previous period. As a result, a significant rise in allowance prices is widely anticipated, increasing the reduction burden on industrial combustion facilities, including waste incineration plants. This study aims to identify technically feasible and economically practical greenhouse gas reduction technologies applicable to waste incineration facilities and to determine optimal solutions considering capital investment requirements. The study analyzes the institutional framework of K-ETS, emission characteristics of waste incineration processes, waste composition effects, and energy recovery structures. Major mitigation options evaluated include low-pressure steam turbine power generation, carbon capture utilization and storage (CCUS), flue gas recirculation (FGR), and industrial heat pump technologies. The results indicate that emission intensity is strongly influenced by fossil-based waste fractions such as plastics, and that efficiency improvement and energy recovery technologies provide more practical short-term mitigation pathways than large-scale capture systems under current economic conditions. The findings suggest that technology selection for incineration facilities should consider regulatory structure, energy cost, and facility configuration rather than relying solely on theoretical reduction potential.

Keywords : Waste incineration facilities, greenhouse gas emissions, carbon credits, and carbon reduction technologies

JEL Classification Code : Q58, Q54, Q48

1. Introduction

1.1. Study Background

According to data released by the Korea Meteorological Administration, the average annual temperature in 2024 will be the highest since meteorological observations began in 1973. Furthermore, 2025 and 2023 will be the second and third highest-ever years, respectively. Measured to be approximately 1.2 to 2 degrees Celsius higher than average, these figures are effectively higher than the global average annual temperature increase. This recent rise in average annual temperature demonstrates that the climate crisis is no longer a problem for future generations, but rather an ongoing issue.

While each country's attitude toward and regulatory intensity in response to the climate crisis may differ, it is expected that over time, citizens' voices calling for the government to proactively address the climate crisis will grow louder, and ultimately, depending on the will of voters, stronger regulations and systems than those currently in place will be established.

In Korea, the reduction targets for the fourth phase of the greenhouse gas emissions trading system have been strengthened compared to the third phase, and the proportion of paid allocations has also increased. Consequently, the prevailing expectation is that the price of greenhouse gas emissions permits will also increase significantly. Manufacturing is the backbone of South Korea's economy and generates more greenhouse gases than the transition sector, including power generation. In addition to coal- and LNG-fired power plants and waste incinerators, greenhouse gases are also emitted from a wide variety of combustion facilities in the industrial sector. In particular, most of the heat required in many industrial fields, such as primary steel manufacturing, cement manufacturing, petroleum refining manufacturing, non-ferrous metal manufacturing, and pulp and paper manufacturing, is directly or indirectly generated from combustion facilities.

This study aims to identify technologies that reduce greenhouse gases generated when burning waste in waste incineration facilities among technologies that can economically reduce greenhouse gases during the 4th plan period of the greenhouse gas emissions trading system, and to study the effects considering facility investment costs to identify the optimal technology that can be realistically installed.

1.2. Trends and limitations of existing research

Incinerators operating in Korea use different fuels and combustion methods across various industries. Many are licensed as waste treatment facilities under the Waste Management Act, operating as incineration heat recovery facilities within recycling facilities or as incineration facilities within intermediate treatment facilities. For this reason, expansion and new plant construction are strictly restricted, making new construction and expansion virtually impossible. South Korea is a developed industrial nation, operating a diverse range of incineration facilities across various industries. Each facility burns a variety of fuels. This study identified ways to secure steam, a domestic heat source, while simultaneously reducing greenhouse gas emissions by 2030, the fourth phase of the Greenhouse Gas Emissions Trading System. By identifying realistic, long-term and short-term technologies, the study identified the technology's potential and its specific characteristics.

1.3. Research method and scope

The only way to reduce carbon emissions from waste incineration facilities, aside from reducing the amount of waste burned or switching to fuels like biomass, is to capture the carbon emissions. Most other technologies will be limited to reducing steam or electricity production or improving efficiency. For example, there may be technologies such as process or operation optimization of heat sources or electricity produced from incinerator boilers, advancement of heat recovery facilities, and change or pretreatment of waste properties.

This study aims to compare technologies that can reduce carbon emissions at waste incineration facilities, excluding methods that increase the utilization of heat or steam generated during their operation. Therefore, the study aims to apply the marginal reduction costs of carbon reduction technologies feasible in the short term (2026-2030) to each technology to determine whether they meet optimal conditions.

2. Korea's emissions trading system

2.1. Korea's emissions trading system structure

The Korea Emissions Trading Scheme (K-ETS) is a market-based greenhouse gas reduction system that allows emitters to allocate and trade emission rights within the total allowable emissions set by the government. Based on the Framework Act on Low Carbon, Green Growth, the ETS was implemented in 2015 and is managed by the Greenhouse Gas Information Center, overseen by the Ministry of Climate, Energy and Environment. Korea's ETS (Emissions Trading System) operates on a five-year planning period, with the Third Planning Period running from 2021 to 2025 and the Fourth Planning Period running from 2026 to 2030. This system regulates total greenhouse gas emissions over a five-year planning period, while gradually increasing the intensity of reductions. The government allocates a set number of emissions permits to emitters and allows them to trade any surplus or insufficient permits to address the regulations. If emissions are not reduced under the ETS, greenhouse gas emitters are required to continue to fulfill their existing obligations, including legal action such as fines and surcharges, and must either emit within the allocated emissions or purchase emission rights through the ETS.

2.2. Major changes during the 4th plan period

Waste incineration facilities in Korea are divided into facilities that operate waste treatment and waste combustion and incineration facilities in manufacturing industries.

Waste treatment facilities can be divided into those operated by local governments and those operated by private companies. This distinction clarifies the distinction between free and paid allocation of greenhouse gas emission rights. During the 4th Plan period, waste incineration facilities will be allocated 100% free of charge, depending on whether they are classified as public or as a carbon leakage-prone industry. For waste combustion and incineration facilities within the manufacturing sector, the BM (Benchmark) allocation has been expanded depending on the industry.

The 4th Emissions Trading Basic Plan, announced by the Ministry of Strategy and Finance and the Ministry of Environment in December 2024, included an improved proposal imposing a 20.1% reduction obligation on all sectors (industry, waste management, transportation, buildings, public works, etc.) other than power generation. Accordingly, all sectors and industries other than conversion are expected to be subject to greenhouse gas reduction obligations ranging from a minimum of 11.4% to a maximum of 20.1% by 2030.

2.3. Institutional position of waste incineration facilities

Under Korea's ETS system, waste incineration facilities are not categorized as a single industry, but rather are subject to different standards depending on their sector.

For facilities classified as part of the transition sector (waste treatment), the free allocation rate is designed to be relatively high due to their public nature and infrastructure nature. However, those in the manufacturing sector that operate their own incineration and combustion facilities will face relatively strong regulations within the Fourth Plan period, although this may vary depending on the industry's efficiency. While there are year-to-year variations within the Fourth Plan period, the allocation coefficient for the conversion portion is expected to be slightly below 1, with the manufacturing sector's incineration facilities projected to be below 0.9.

3. Greenhouse gas emission characteristics of waste incineration facilities

3.1. Incineration plant process and heat recovery structure

3.1.1. Basic process

Waste incineration facilities are comprised of a continuous process of "input-combustion-heat recovery-exhaust gas treatment" to achieve both stable waste treatment and energy recovery. Waste is first temporarily stored in a waste pit, where it undergoes homogenization before being fed into an incinerator. Incinerators typically use stoker furnaces or fluidized beds, and the waste is completely combusted at high temperatures (typically around 900-1,100°C).

The heat generated during the combustion process is released through the oxidation of organic matter within the waste, generating a large amount of high-temperature combustion gas. The residual waste is discharged as bottom ash, which undergoes metal recovery and stabilization processes before being recycled or landfilled. Meanwhile, the combustion gas is transferred to a downstream process where it undergoes heat recovery and air pollutant removal before being released into the atmosphere.

3.1.2. Role and location of heat recovery processes

In waste incineration facilities, heat recovery processes are installed and operated immediately after the combustion process, before the exhaust gas enters the air pollution control system. This process maximizes the thermal energy of the high-temperature combustion gas while lowering the gas temperature to ensure the stability of downstream equipment. The equipment typically performing this function is a waste heat boiler or heat recovery boiler.

In a waste heat boiler, high-temperature combustion gas passes through a boiler tube cluster, exchanging heat with water to generate steam. This steam can be used for various purposes, including power generation, processing heat supply, and district heating, depending on the incinerator's installation purpose and location. Heat recovery is a key element in transforming an incinerator from a simple waste treatment facility to an energy recovery facility.

3.2. Greenhouse gas emissions sources

Greenhouse gas emissions from waste incineration facilities are primarily divided into direct emissions from the combustion process and indirect emissions resulting from facility operation. Of these, carbon dioxide (CO_2), generated during the combustion process, accounts for the largest proportion. Nitrous oxide (N_2O) and methane (CH_4), while relatively small, are considered greenhouse gases.

3.2.1. Direct emissions (Scope 1)

The greenhouse gas that accounts for the largest proportion of emissions from waste incineration facilities is carbon dioxide (CO_2). CO_2 is produced when organic matter and combustible components in waste are oxidized at high temperatures, and accounts for most total greenhouse gas emissions. In particular, CO_2 generated from the combustion of fossil fuel-based materials such as plastics, synthetic resins, and rubber is explicitly recorded as direct emissions in the ETS and national greenhouse gas inventories.

On the other hand, CO_2 generated from biomass waste, such as food waste and paper, is classified as non-petroleum from a carbon cycle perspective. However, incinerators still emit CO_2 during the combustion process. Therefore, the higher the proportion of waste derived from petroleum or coal, the higher the total CO_2 emissions from the incinerator. If an incinerator uses non-petroleum fuels, such as food waste or bio-SRF, it is excluded from CO_2 emissions under the ETS system.

Nitrous oxide (N_2O) is a representative non-CO_2 greenhouse gas emitted during waste incineration. While its emissions are significantly lower than CO_2, its greenhouse effect per unit mass is so significant that it contributes significantly to greenhouse gas emissions (CO_2eq).

Methane (CH_4) is classified as a major greenhouse gas in waste incineration facilities, but its emissions are very low in large-scale, modern incinerators.

3.2.2. Indirect emissions (Scope 3)

In addition to direct emissions from combustion, incinerators generate indirect CO_2 emissions using electricity and auxiliary fuels for facility operation. Examples include the electricity required to operate waste heat boilers, blowers, dust collectors, and exhaust gas treatment equipment, or the consumption of auxiliary fuels used to start the incinerator. Although these indirect emissions are not the main source of emissions from incinerators, they are calculated as a certain level of greenhouse gas emissions depending on the facility size and operating conditions and are managed as separate indirect emissions items in the ETS and greenhouse gas management system.

3.3. Discharge characteristics according to waste properties

Greenhouse gas emissions and their characteristics from waste incineration facilities are fundamentally determined not only by the incinerator's type and operating conditions, but also by the nature and type of waste being burned. Waste combustion characteristics vary depending on factors such as composition, calorific value, moisture content, and carbon origin (fossil or biogenic), which in turn leads to differences in carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions.

3.3.1. Petroleum waste and biowaste

The most important criterion determining greenhouse gas emissions of waste is its carbon origin. Plastics, synthetic resins, rubber, and synthetic fibers are classified as petroleum-based fossil wastes, and when these are burned, all CO_2 emissions are considered fossil fuel-derived CO_2. Therefore, incineration of waste with a high proportion of plastics tends to significantly increase CO_2 emissions per unit mass.

On the other hand, food waste, paper, and wood are considered biogenic waste, and the CO_2 generated from them is classified as non-fossil from a carbon cycle perspective. However, since the same CO_2 is emitted during actual combustion, the total emissions from the facility increase. However, the method of calculating emissions under the ETS or national inventories may differ.

3.3.2. Discharge characteristics by waste type

Plastic waste has a very high calorific value (higher calorific value) and a high fossil carbon content, making it the waste with the highest CO_2 emissions per ton when incinerated. While combustion itself is relatively stable, CO_2 emissions are concentrated when high-temperature combustion conditions are created. Therefore, an increase in the proportion of plastics can dramatically increase the greenhouse gas emissions intensity of incinerators. Food waste often requires the use of auxiliary fuel during incineration due to its high moisture content and low calorific value. This can increase CO_2 emissions not only from direct combustion but also indirect CO_2 emissions from auxiliary fuel combustion. Furthermore, due to its high content of organic matter, including nitrogen, the potential for N_2O emissions can be relatively high depending on combustion conditions.

Paper and wood are typical bio-wastes. While they produce significant CO_2 emissions when burned, their fossil emissions are considered limited. Their calorific value is relatively stable, resulting in good combustion efficiency. However, fluctuations in combustion temperature due to changes in waste composition can impact N_2O emission characteristics.

Industrial waste is highly diverse in composition, resulting in significant variability in greenhouse gas emissions. The inclusion of plastics, sludge, rubber, textiles, and chemical residues increases the proportion of fossil CO_2 emissions. Furthermore, waste with high nitrogen content or sludge components can result in relatively high N_2O emissions. Consequently, industrial waste incineration facilities tend to be conservatively assessed when applying emission factors.

Table 1. presents data on carbon emissions by waste type.

Table 1: Carbon emissions by waste type

Waste Types	Emissions [tCO_2eq/ton]
Household Waste	App. 0.736
Plastics	App. 2.7
Food Waste	App. 0.31–35
Industrial Waste	App. 1–1.5

3.4. Electricity Cost Outlook

The Korea Energy Economics Institute (Yeonje Jeong, Why Normalizing Electricity Rates Is Necessary) predicted that electric energy will gain momentum in all regions of the world, rapidly increasing from the current 21% of final energy consumption to over 50% globally by 2050. In fact, Korea's industrial electricity costs are increasing rapidly, increasing by approximately 10% (16.1 kWh) in 2024. The rate of increase may vary depending on various domestic conditions, but it is increasing at a rate similar to the long-term forecast data.

If the Basic Plan for Electricity Supply and Demand and the 11th Transmission and Distribution Plan are maintained, there is a possibility that electricity rates will increase to 44.5 won per kWh by 2030 and by 2038. The domestic RPS(Renewable Portfolio Standard: A system that requires power generation companies with power generation facilities of a certain scale 500 MW or more to supply a certain percentage or more of their total power generation using new and renewable energy) mandatory supply ratio is projected to increase by 25% by 2030. Furthermore, the allocation of greenhouse gas emission rights in the power generation sector is projected to be reduced by 50% by 2030 compared to 2018 levels, and with the long-term transition to fully paid allocation, regulations are certain to be strengthened. Therefore, an increase in electricity rates seems certain. However, as shown in Table 2, Korea Electric Power Corporation's financial status is projected to return to surplus by 2025, compared to 2024, suggesting a gradual increase rather than a sharp one in the short term.

Table 2: Summary of Korea Electric Power Corporation's financial information [Unit: trillion won]

Year	2021	2022	2023	2024	2025.6
Take	59.7	69.0	85.8	91.6	46.2
Operating profit	-7.4	-33.9	-6.5	3.2	5.9
Net profit	-5.6	-25.3	-3.2	0.8	3.5
Evaluation method	Cost method	Cost method	Cost method	Cost method	Cost method

3.5. Greenhouse Gas Emissions Price Forecast

Forecasting greenhouse gas emission allowance prices during the 4th Plan period is extremely challenging. According to the National Emissions Allocation Plan (Draft) for the 4th Plan period (2026-2030) of the Greenhouse Gas Emissions Trading System, announced by the Ministry of Climate, Energy and Environment in October 2025, the Climate Response Fund (paid allocation revenue) was established based on the assumption that the price of emissions allowances during the 3rd Plan period would be 20,000 won per ton.

Table 3: Status of emission permits imported during the 3rd plan period [Unit: 100 million won]

Year	2023	2024	2025
Planned	4,009	2,897	3,487
Actual	852	1,877	458
Actual/Planned	21.3%	64.8%	13.1%

However, as shown in Table 3, the income status of the Climate Response Fund in July 2025, the last year of the 3rd plan period, shows that the income was 45.8 billion won, which is 13.1% of the target amount of 348.7 billion won, resulting in a fund shortage. This lack of funding has made it difficult to support small-scale reduction projects by small and medium-sized enterprises, increased the risk of domestic carbon neutrality investments, and led to a deterioration in the profitability of leading investment companies. In a situation where reductions and delays in carbon neutrality investment continue, it is predicted that the increase in GDP due to economic recovery will lead to the carryover of carbon surplus and excess emissions, and the total domestic greenhouse gas emissions in 2025 are expected to be approximately 650 million tons, and the difference between the emission allowance allocation and actual emissions will be 100 to 150 million tons of surplus, making it difficult to achieve the national NDC(Nationally Determined Contribution : refers to a 'national greenhouse gas reduction target.' It is a target established by each country every five years to reduce greenhouse gases by 2030. Many countries are responding by establishing NDCs tailored to their own circumstances) by 2030. During the 4th Plan period, various measures are planned to achieve the 2030 NDC by using up the excessively low emission allowance price during the 3rd Plan period and the large amount of surplus emission allowances that will be released to the market and securing a climate response fund. Measures such as reducing free allocations, increasing paid allocations, and expanding the BM allocation method will result in increasing the price of greenhouse gas emission allowances.

Although the government's planned greenhouse gas emission price cannot be confirmed, the IMF recommends setting a target of at least $50 per ton by 2030 as an appropriate greenhouse gas emission price for achieving Korea's NDC by 2030, as viewed from abroad. In addition, in the ‘Carbon Emissions Mid- to Long-Term Price Outlook Report’ published in October 2025 by NAMU EnR, a domestic energy and environmental consulting firm, it was predicted that the price of greenhouse gas emissions would steadily rise to KRW 28,680 at the end of 2026, KRW 34,211 in 2027, KRW 41,152 in 2028, KRW 47,642 in 2029, and KRW 53,699 in 2030.

3.6. REC Price Outlook

As carbon reduction strategies have been identified by paper product manufacturers, power generation using biomass or bio-SRF is considered as a potential method. To consider biomass or bio-SRF power generation facilities, it's important to review global development trends, examine recent developments in Korea, and consider the potential benefits of installing power generation facilities in Korea, such as the potential acquisition of RECs(Renewable Energy Certificate: The Renewable Energy Supply Certificate is a system designed to encourage and promote renewable energy power generation projects. It is a type of certificate that proves that electricity was generated through renewable energy. REC is a certificate that certifies that 1 MWh of electricity was produced from a renewable energy power generation facility supplied to the power grid. It can be sold and is an important factor in reviewing the economic feasibility of a project when installing a power generation facility). When operating power generation facilities using a domestic REC weighting system, sales profits are calculated as "SMP + (REC x Weighting)." For wood pellet/chip-based power generation, the weighting is 0.5 times the power generated, while for power generation using Bio-SRF (waste wood/plant residue) fuel, the weighting is 0.25 times the power generated. Since most of the wood pellets/chips distributed domestically have already been used for a certain purpose among the total amount generated, it is difficult to secure raw materials for the expansion of power generation facilities using additional wood pellets/chips. However, according to a study on efficient resource utilization of agricultural and livestock waste resources by the Korea Rural Economic Institute, Bio-SRF has sufficient economic feasibility when considering not only direct benefit balance considering only sales cost and production cost but also indirect benefits such as REC and carbon emission rights price, and local governments are expanding the distribution of facilities that produce livestock waste as Bio-SRF due to problems such as odor when processing livestock waste. Therefore, at this point in time, if a corrugated board manufacturer is considering installing a power generation facility that takes REC into account, it may consider a facility that uses Bio-SRF as fuel, if not a solar power generation facility.

According to the Korea Institute of Energy Technology, the share of renewable energy power generation facilities in Europe will be 44% in 2023 and is projected to reach 66% by 2030. However, the growth rate of renewable energy power generation capacity is much faster than this projection, reaching approximately 74% in the first half of 2024 alone. Unlike oil and gas, most renewable energy sources are largely unaffected by issues in oil-producing countries, such as war, affecting their supply prices. Furthermore, whenever conflicts arise between oil-producing countries, such as the Russia-Ukraine War, their share is expected to increase. In particular, the proportion of offshore wind and solar power generation facilities is rapidly increasing, and it is expected that Grid Parity(Grid Parity: From the perspective of the final energy consumer, this refers to the point at which the cost of producing electricity using renewable energy sources is balanced with the price of purchasing electricity from the existing power grid. After Grid Parity, the cost of producing electricity using renewable energy sources became cheaper than the cost of producing electricity using existing coal, leading to an increase in the construction of new renewable energy power generation facilities) will be achieved in Korea after 2028. Therefore, Bloomberg New Energy Finance predicted that new and renewable energy generation facilities such as offshore wind and solar power generation facilities will rapidly expand after 2030.

The rapid increase in new power generation facilities in Europe, China, and India, including solar power plants and offshore wind power, is largely due to the proactive policy guidance of each government, but it is also the result of policy decisions that have lowered the installation and maintenance costs of new and renewable energy power generation facilities compared to those using existing fossil fuel power generation facilities.

According to the Electricity Statistics Information System, domestic power generation by energy source in 2023 will be generated at similar rates by nuclear, coal, and gas-fired power plants. With the expansion of renewable energy power generation facilities still expected, global nuclear power generation in 2025 is projected to surpass the previous peak in 2021, reaching a record high. This is also the result of the growing recognition that it would be difficult to secure stable power consumption in the future solely through renewable energy generation, following the large-scale blackouts experienced in Europe during the Russo-Ukrainian War while relying on renewable energy generation. With new nuclear power plants recently starting commercial operation in several countries and the restart of reactors in France and Japan, global nuclear power generation is expected to increase by approximately 10% in 2026 compared to 2023. Furthermore, at COP28 in 2023, more than 20 countries signed a joint declaration committing to more than tripling nuclear power by 2050.

Table 4: Annual average REC spot price

Year	Average Annual REC Price [KRW/REC]
2020	42,309
2021	33,677
2022	56,904
2023	72,738
2024	76,179

Ultimately, the cost of renewable energy generation will decline over time, but to ensure a stable power supply, renewable energy and nuclear power generation facilities are expected to increase in complementary ways. The Korean government's 11th Basic Plan for Electricity Supply and Demand projects that renewable energy generation will quadruple and nuclear power, including SMRs, will increase by approximately 42% by 2038 compared to 2023. REC prices are likely to continue their upward trend in the short term, as shown in Table 4, but they are expected to gradually decline and trading volumes to decline.

4. Greenhouse Gas Reduction Technologies and Case Studies

4.1. Incineration boiler turbine installation

Incineration facilities of a certain scale or larger typically utilize the waste heat generated by the waste incinerator to produce steam. Furthermore, some industrial facilities utilize the waste heat generated before the incinerator is installed, installing power generation facilities alongside the incinerator or adding power generation facilities to an operating incinerator. As in the study on “Analysis of the Effect of Improving Power Generation Efficiency by Strengthening Heat Recovery Capability in Waste Incineration Facilities,” the practice of installing generators in incineration facilities is already a common trend in leading regions around the world, and sufficient examples can be found in domestic research data. There are many studies on energy conversion from waste resources, such as “Study on Efficient Waste Heat Utilization through Waste Incineration,” which have studied methods necessary for optimal design to reduce operating costs and improve energy recovery rates of domestic incineration facilities.

Company A modified its incinerator boiler, which previously produced 10 bar of steam, by installing a superheated steam generator to produce superheated steam of over 60 bar. Similar to a combined heat and power plant, this system produces superheated steam, which is then used to drive a generator to generate electricity. The reason Company A was able to install the power generation facility during a construction period of several months is believed to be that it was able to proceed with the construction without shutting down the factory during the construction period because it had an SRF incinerator and LNG boiler available on site. Installing these carbon-reduction devices is difficult for most factories operating only a single incinerator. If the plant were to shut down for several months, it would be difficult to sustain the enormous fuel costs, either by halting production or by operating an LNG boiler. In addition, Company A operates a waste incineration facility for the purpose of using it as a heat source for manufacturing, so its direction will be somewhat different from this study, which aims to identify the optimal technology for reducing greenhouse gas emissions from incineration facilities in the waste disposal industry.

Another approach involves installing turbines in waste incinerators to generate electricity and reduce greenhouse gas emissions. Company H operates a Micro Steam Turbine (MST) system, which installs a generator in its incinerator. In the case of a secondary condenser turbine, a generator of 40 bar or higher must be installed in most cases, but if the difference between the pressure of the steam produced and the pressure of the steam used is 5 bar or more, such as when an operating incinerator produces steam of 10 bar or higher and a steam of 5 bar or lower is used in the papermaking process, a low-pressure turbine can be installed to produce and use electricity. Although it may take more than 10 years to recover the installation cost compared to combined heat and power generation facilities, if the facility can be installed with government subsidies, the investment can be recovered within 5 years, and in this case, the period of incinerator shutdown is short and the installation cost is relatively low, so it can be a sufficient advantage. However, in cases where the boiler design pressure of an existing incinerator is less than 10 bar or the facility has been installed for a long time and the boiler needs to be reinstalled, the period for recovering the investment may still take at least 10 years or more.

If the investment payback period of a low-pressure power plant in a 4-ton/hr waste incinerator is calculated using Chat-GPT under the following assumptions

a) 5 tons of steam produced when 1 ton of waste is incinerated

b) Turbine: Back pressure, discharge 5 bar

c) Turbine isentropic efficiency 70%

d) Case A: Boiler pressure 12 bar

e) Case B: Boiler pressure 9 bar

f) Electricity cost: 200 won/kWh

g) Generator efficiency: 0.97

h) Payback period = Investment cost/Annual savings

i) Produced steam is saturated steam

j) Annual operating hours: 8,000 hours/year

The calculation results are as shown in Table 5 below.

Table 5: Low-pressure turbine investment payback period

Investment cost [100 million won]	Production Pressure is 12bar	Discharge pressure is 9 bar
30	3.4 Year	5.2 Year
50	5.7 Year	8.6 Year
80	9.1 Year	13.8 Year
100	11.1 Year	17.3 Year

Table 6: Low-pressure turbine electricity savings

Division	Production Pressure is 12bar	Discharge pressure is 9 bar
Power generation	App. 550kW	App. 110,000 won/hr
Electricity savings	App. 362kW	App. 72,4000 won/hr

In the case of technology that produces electricity using low-pressure turbines, it is expected that the efficiency of reducing greenhouse gases will be limited to reducing operating costs rather than greenhouse gas emissions, as shown in Table 6, as it produces electricity necessary for the operation of waste treatment and management facilities rather than directly reducing greenhouse gases.

4.2. CCUS

Airane, a domestic CCUS (Carbon Capture Utilization and Storage) specialist, has signed business agreements with Lotte, POSCO, Hyundai Steel, and Hansol Paper and is currently installing and testing pilot facilities to separate and capture carbon dioxide from incinerator exhaust gas. This method is a technology that separates and captures only carbon dioxide from the combustion gas of an incinerator and stores it. Looking at domestic research, pilot tests, and installation cases, it can be divided into wet capture technology, dry capture technology, and membrane capture technology. The technology that Hansol Paper is conducting a pilot test for is a membrane capture technology.

Current achievements include capturing carbon dioxide with a purity of over 98%, exceeding the industrial carbon dioxide utilization standard. Demonstration projects are currently underway or have been completed by several companies.

Currently, the significant installation costs of gas separation membrane facilities and future issues surrounding the disposal of liquid carbon dioxide remain. If the incinerator capacity is 4 tons/hr (96 tons/day), the installation cost of the gas separation membrane facility is estimated to be approximately 25 to 30 billion won (replacement cycle of 5 to 10 years), and it is known that the membrane installation space will require 25 m x 30 m. Considering the problem of installing a pretreatment system to lower the exhaust gas temperature to below 40℃ and the fact that the carbon dioxide produced in the form of liquid or dry ice is sold and the domestic annual consumption is approximately 1.5 million tons, and the long-term trend toward mineral carbonation and underground and deep-sea storage methods, the cost of installing and operating a gas separation membrane is estimated to be at least KRW 5 billion per year. It is known that most of the carbon dioxide captured through CCUS in Korea is disposed of in the form of dry ice, and some power plants are selling it in the form of sodium bicarbonate or sodium carbonate. The study on "Production of Carbon-Neutral High-Value-Added Compounds Using Carbon Dioxide" and "Current Status of Carbon Dioxide Conversion Technology" introduces a method of producing high-value-added aromatic chemicals by using carbon dioxide to convert it into carbon monoxide and then into methanol. These technologies are part of a long-term research project aimed at achieving Net Zero by 2050. However, if we consider conversion to sodium bicarbonate or sodium carbonate as a method of converting carbon dioxide, focusing on available technologies within the 4th plan period until 2030, and considering the limited domestic distribution cost of sodium bicarbonate and sodium carbonate and the consumption of dry ice, when CCUS is expanded, we will inevitably have to store the excess captured carbon dioxide through mineral carbonation, underground storage, and deep-sea storage.

As there are currently no cases of carbon dioxide disposal in Korea through mineral carbonation or underground or deep-sea storage, it is difficult to predict the exact cost, but the costs of transportation, storage, and preservation are expected to be quite high. For this reason, if we assume that the captured carbon dioxide can be disposed of domestically only in the form of dry ice, the conclusion is that the cost of purchasing carbon emission rights for an incinerator with a daily waste incineration capacity of 96 tons (4 ton/hr) will be at least 1 billion won per year, or if the tangible and intangible corporate value through CCUS increases to at least 1 billion won per year, then the installation of the facility can be considered.

Even excluding the cost of replacing the membrane and the cost of processing the captured carbon, it will be difficult to select a carbon emission reduction technology based on economic logic.

4.3. FGR

FGR targeted the high-temperature FGR method, as in the 'Study on the Impact of High-Temperature FGR Equipment on Carbon Emission Reduction in the Corrugated Board Manufacturing Industry'. In the existing low-temperature FGR facility, after controlling pollutants such as acid gas and fly ash to a low concentration, the exhaust gas is recycled to the incinerator, which is highly effective in reducing nitrogen oxides, but the heat contained in the exhaust gas cannot be recovered. In the case of high-temperature FGR, however, the heat contained in the exhaust gas at approximately 220-250℃ when discharged from the boiler can be recovered to the incinerator.

Assuming that the weight composition of waste incinerated in a waste incineration facility is 48% carbon, 20% moisture, 1.5% nitrogen, and 14.5% non-combustible matter, and calculating the excess air coefficient as 1.3, the specific heat of the exhaust gas at 1,100℃ and 220℃ is calculated using Chat GPT as shown in Table 7, 8 below.

In the case of high-temperature FGR, if the exhaust gas recirculation rate is assumed to be 50% and the efficiency improvement in the heat balance is calculated by comparing only the difference in heat capacity compared to when FGR is not installed, it can be estimated that the improvement will be up to approximately 16.6%, as shown in Table 8.

Table 7: Exhaust gas specific heat

Waste Compo.	Gas Compo. (Mole Fraction)	Temp [℃]	Speci. Heat [kcal/kg·℃]
C 48 wt% H 6 wt% O 30wt% N 1.5wt % Ash 14.5wt%	N_2 68% CO_2 20% H_2O 10% O_2 2%	220	0.269
		1100	0.324

Table 8: The amount of heat received by the incinerator

Division	1100℃	220℃
FGR Not installed	1100℃ ×0.324kcal/kg·℃ =356.4kcal	0
High temperature FGR	1100℃ ×0.324kcal/kg·℃ ×0.5 (outside air ratio) =356.4kcal	220℃ ×0.269kcal/kg·℃ ×0.5(circulation rate) =59.18kcal

In incinerators without high-temperature FGR equipment, the only way to control the combustion rate when the combustion reaction occurs in the combustion chamber is to control fuel input and oxygen supply. In an incinerator equipped with an FGR facility, the amount of air, oxygen, and wind speed supplied to each section of the combustion chamber (drying section, semi-drying section, combustion section, and post-combustion section) by FGR recirculated gas and outside air (FD: Forced Draft) can be controlled, making combustion chamber temperature control relatively easy, greatly expanding the range of automatic operation. By utilizing these advantages of FGR, operation has become much easier than by operating only by controlling the combustion amount or outside air input.

Most foreign incinerator autonomous operation technologies are designed for power generation using fuels with consistent composition and calorific value. This differs from domestic waste incineration facilities, which simply incinerate waste or recover waste heat after combustion to supply steam to end users. SK-Ecoplant, a domestic waste treatment specialist, also possesses its own autonomous incinerator operation technology and has achieved approximately 5% thermal efficiency improvement through AI guidance and semi-automated operation.

Not only incinerators, but most plant equipment and systems are rapidly becoming automated and AI-enabled. Even if an FGR system is installed purely for carbon reduction purposes, without any intention of automating the incinerator operation system, the minimum cost is estimated to be approximately 1 to 1.5 billion won. If an incinerator with an incineration capacity of 96 tons (4 tons/hour) achieves 8% operational efficiency, the resulting reduction in incineration volume will also result in an 8% reduction in carbon emissions.

4.4. Heat pump

Among technologies to reduce greenhouse gas emissions from waste incineration facilities, some industries requiring steam in the manufacturing sector can convert some incinerators to non-incinerators. This can be applied when the capacity of existing incinerators is insufficient or when production facilities are planned to be expanded.

Consider the paper manufacturing industry. During the paper drying process, the dried moisture is released into the atmosphere as white vapor, without any heat recovery. If a cooling process were added to remove the white vapor or recover the moisture, more energy would be required, ultimately resulting in the waste of heat energy.

Company J applied heat pump technology, as shown in Fig. 1, to its process, capturing and recycling heat emitted into the atmosphere during the drying process. Furthermore, research is currently underway on combining mechanical vapor recompression (MVR) technology with heat pumps to produce high-temperature steam that can be reused on-site.

The study on the industrialization of large-capacity industrial heat pumps to replace incinerators is a project being conducted as a demonstration research project by a corrugated board support manufacturer with the same contents as the study on “Development of Core Technology for Large-Capacity Large Temperature Difference Heat Pumps.” Company J was selected as a national project by the Korea Energy Technology Evaluation and Planning Institute under the Ministry of Trade, Industry and Energy in 2023, and plans to complete installation of the equipment and begin demonstration operation in 2025. Heat pumps are a technology that can recover heat from the heat pump to produce necessary steam even when incinerator capacity is limited or the amount of incineration is reduced. However, their operating principle generates significant electricity demand. Given that industrial electricity costs in Korea are on the rise annually and are expected to continue to increase in the long term, installation of these facilities is expected to be cautious without government support or incentives. However, if high-temperature, large-capacity compressors and refrigerants used in industrial heat pumps are developed and installed at a cost that can be commercialized, the greenhouse gas reduction effect through reduced incineration is expected to be certain.

5. Consideration

The results of this study suggest that greenhouse gas reduction strategies for waste incineration facilities are not a matter of selecting a single technology, but rather a decision-making process complexly influenced by institutional environments, emissions permit prices, electricity costs, waste properties, and facility conditions. In particular, with the anticipated reduction in allocation coefficients and increase in the paid allocation ratio during the Fourth Plan period, incineration facilities in the manufacturing sector are likely to face relatively stronger reduction pressure than those in the conversion sector. This means that even with the same technology, its economic feasibility can vary depending on the industry and institutional context. While the reduction potential itself is limited, low-pressure turbine power generation technology offers a clear cost-saving benefit relative to the investment. Combined with government subsidies or financial support, it also offers a short-term payback period, making it a valuable transitional reduction tool.

On the other hand, while CCUS's technological sophistication is rapidly improving, its current structure makes it difficult to apply solely based on economic feasibility due to installation and operating costs, as well as the final disposal of CO_2. This technology is expected to face rapid changes in the future depending on rising carbon prices, the development of storage infrastructure, and government subsidies. Furthermore, the economic feasibility assessment used in this study was conducted based on a simple payback period, and thus has limitations in that it fails to adequately reflect factors such as discount rates, financing costs, tax benefits, electricity rate volatility, and emissions price volatility. In particular, emissions price and REC price are market variables highly sensitive to policy changes. Therefore, scenario-based analysis should be incorporated in actual investment decisions.

Future research requires the following expansions. First, a precise emissions model that reflects changes in waste composition and emission factors is required. Second, a dynamic economic analysis that reflects long-term cost reduction scenarios for CCUS and heat pump technologies is needed. Third, a composite revenue structure analysis that integrates the ETS, electricity market, and REC market will provide more realistic investment decision criteria.

6. Conclusion

This study was conducted to compare applicable greenhouse gas reduction technologies for waste incineration facilities during the 4th plan period of the Greenhouse Gas Emissions Trading System (2026-2030) from technical, institutional, and economic perspectives, and to derive the optimal alternative that can be realistically applied. To this end, the structure of the Korean ETS system and the direction of regulatory strengthening during the 4th plan period were reviewed, and the process characteristics of waste incineration facilities, discharge characteristics by waste type, and energy recovery structure were analyzed. Then, low-pressure turbine power generation, CCUS, FGR, and heat pump technologies were compared and evaluated as major applicable reduction technologies.

Greenhouse gas emissions from waste incineration facilities are largely influenced by the nature of the waste, and in particular, the mixing ratio of waste with a high proportion of fossil carbon, such as plastics, was confirmed to be a key variable that governs total emissions. Additionally, even with the same amount of incineration, there was a significant difference in the indirect emission reduction effect depending on the heat recovery and energy utilization method. Although the power generation method using low-pressure turbines is not a direct CO_2 capture technology, it has been evaluated as a practical means of reducing indirect emissions and operating costs by producing the electricity necessary for operating the incineration facility.

This approach offers significant short-term applicability, particularly in cases where the existing boiler pressure is 10 bar or higher and the process operating pressure is lower, as it can be applied without requiring additional large-scale equipment changes. However, in cases where the boiler design pressure is low or the equipment is significantly older, the investment payback period may be extended. CCUS technology is theoretically the most direct means of reducing greenhouse gases, but considering the current level of technology, equipment costs, massive installation space, membrane replacement costs, and CO_2 treatment and storage costs, it has been confirmed that its economic feasibility is very limited for widespread application to general incineration facilities within the 4th plan period. Especially for small and medium-sized incinerators, reducing emissions costs alone is not realistically enough to recover the investment.

High-temperature FGR technology can simultaneously improve combustion stability and thermal efficiency, and can be implemented with relatively low investment costs. When combined with automated operation and AI control technologies, further efficiency gains of approximately 8% are expected. An 8% increase in combustion efficiency can reduce waste incineration by 8%, making it one of the optimal technologies for short-term greenhouse gas reduction.

Heat pump technology has the potential to replace incineration heat in the long term, but its current application scope is limited given the rising electricity prices and the commercialization level of large-capacity, high-temperature heat pumps.

The most realistic and optimal reduction strategy for waste incineration facilities within the 4th Plan period is a phased approach that prioritizes efficiency improvements and partial power recovery technologies based on existing facilities over large-scale facility replacement technologies and examines CCUS as a mid- to long-term option.

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