

Review

An Overview of Waste-to-Energy Incineration Integrated with Carbon Capture Utilization or Storage Retrofit Application

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Abstract: This paper provides an overview of the integration of Carbon Capture, Utilization, or Storage (CCUS) technologies with Waste-to-Energy (WtE) incineration plants in retrofit applications. It explains the operational principles of WtE incineration, including the generation of both biogenic and fossil CO₂ emissions and the potential for CCUS technologies to mitigate these emissions. In addition, the paper covers the regulatory framework influencing the adoption of such technologies and highlights the recent Directive 2023/959 for the inclusion of WtE incinerators in the European Union Emissions Trading System (EU ETS) by 2028. This measure could provide a significant impulse for the integration of CCUS in WtE incineration plants. Moreover, it discusses the use of CO₂ captured, which could be used in Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU), and offers a comparison of the CCUS projects that have already been implemented worldwide, with a focus on the Netherlands and Italy. It illustrates the Netherlands' advantageous position due to its developed CO₂ market and early CCUS adoption, compared to Italy's emerging market and initial storage solutions.

Keywords: environmental sustainability of WtE plants; waste-to-energy plant retrofit with carbon capture; carbon capture utilization or storage



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1. Introduction

Waste-to-energy (WtE) incineration is an essential component of modern waste management and represents the major treatment technology in Europe, where approximately 500 WtE incineration plants treat 100 million tons of municipal, commercial, and industrial waste each year [1]. WtE incineration involves processing non-recyclable waste to provide essential sanitary services to communities while generating electrical and thermal energy [2]. WtE incineration also plays a significant role in reducing greenhouse gas emissions by preventing the dumping of waste in landfills, thus preventing methane release, a greenhouse gas more potent than CO₂ over both short (86 times more potent over 20 years) and long terms (28 times more potent over 100 years) [3]. Additionally, the energy generated through WtE incineration provides a sustainable alternative to energy produced using fossil fuels, further reducing their environmental footprint [4,5].

Despite these environmental benefits, the combustion process in WtE incineration plants produces the unavoidable emission of CO₂, particularly from the combustion of fossil carbon in waste, which contributes to climate change [6]. This poses a challenge in moving toward a sustainable and low-carbon energy system, especially in light of Europe's plan to integrate WtE incineration plants into the European Union Emissions Trading System (EU ETS) by 2028 as defined by Directive 2023/959 [7]. This measure would require the WtE incinerator plants to financially account for their fossil CO₂ emissions, thereby underlining the need for greenhouse gas emission reduction. In this context, Carbon

Capture, Utilization, or Storage (CCUS) technologies become particularly significant, as they can be integrated with WtE incineration to mitigate CO₂ emissions [8,9].

CCUS technologies are increasingly recognized as essential in the fight against climate change, recognized for their potential to significantly reduce atmospheric emissions of CO₂ [10–12]. The International Energy Agency underscores the indispensability of CCUS in realizing the goals of the Paris Agreement, aiming to limit global temperature increases to below 2 °C [13]. CCUS technologies are categorized into Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU). CCS involves the process of capturing CO₂, transporting it, and storing it permanently [14], whereas CCU focuses on the conversion of the captured CO₂, integrating it into the carbon cycle to achieve a long-term sustainable pathway and generate economic benefits that help reduce the overall cost of capture [15].

Research in the field of CCUS technologies in the context of WtE plants has predominantly focused on the technical potential and environmental impacts of these systems. Bringezu [16] highlights the potential of CCU in WtE incineration, demonstrating how CO₂ can be utilized as a raw material for polymer production. Christensen and Bisinella [8] investigate the potential of CCU in utilizing CO₂ captured from a WtE plant, demonstrating the energy and environmental benefits of integration. Haaf et al. [17] conducted a techno-economic analysis on the use of calcium looping cycles to remove CO₂ from WtE incineration plants for large-scale application. Lv et al. [18] investigated the gasification of municipal solid waste (MSW) to produce syngas, followed by a chemical looping cycle for CO₂ capture. Roussanaly et al. [19] compared three post-combustion solutions (MEA absorption, advanced amine absorption, and membrane separation) to determine their design and cost implications in full-scale CCS solutions in WtE incineration plants. While these studies provide valuable insights into the potential and implementation of CCUS technologies, they often overlook how normative frameworks and market conditions can either facilitate or limit the practical implementation of these technologies in WtE plants. This suggests a need for further investigation into the factors that facilitate or block the practical application of CCUS technologies.

Given the large number of plants in Europe, exploring the integration of CCUS technologies with WtE incineration in retrofit applications becomes particularly interesting. However, integrating CCUS technologies into WtE incineration plants is a complex issue involving technical, regulatory, and economic considerations. To be successful, it requires an understanding of the regulatory frameworks, applicable incentives, and CO₂ market (especially in terms of tons) within the host country. Some countries have already implemented this technology, such as the Netherlands, whereas in most other countries worldwide, e.g., Italy, there are no examples of this implementation.

This paper provides an overview of the integration of CCUS technologies in WtE incineration plants in retrofit applications. It explains the operational principles of WtE incineration plants, the types of emissions generated (biogenic and fossil CO₂), the regulatory frameworks governing the adoption of CCUS technologies, and some cases of the integration of CCUS technologies with existing WtE incineration plants in retrofit applications. Additionally, it explores and presents the configurations for carbon capture, the CO₂ separation methods, and the prospects for carbon utilization and carbon storage. Through an examination of the current state and potential of the integration of CCUS technologies in WtE incineration plants, this paper provides an overview of the potential for integration.

2. Waste-to-Energy Incineration

WtE incineration is a sustainable alternative to traditional waste management methods such as landfilling, composting, and recycling. According to the Confederation of European Waste-to-Energy Plants (CEWEP) data of 2021 [20], waste treatment in Europe consists of 49% recycling and composting and 26% landfill disposal, with the remaining portion directed to WtE incineration. Based on these statistics, around 100 million tons of waste are treated annually by 500 WtE incineration plants in Europe, highlighting the importance of this technology for waste management [1].

Compared to conventional waste management methods, WtE incineration provides a more sustainable and efficient solution for waste disposal. Despite the environmental impact associated with landfilling, including the uncontrolled release of methane, it remains widely utilized, especially in developing countries due to the low investment cost [21]. On the other hand, WtE incineration plants require a relatively high investment cost, which is why most WtE plants are placed in high-income countries [22]. Nevertheless, once the investment costs have been made back, waste can be a low-cost source of energy and can even be considered a source of revenue since municipalities have to pay other parties to manage their waste. Consequently, the global WtE market is expected to expand, driven by increasing waste generation, economic benefits, and the need for sustainable waste management practices [23].

WtE incineration is the most mature and prevalently employed technology within WtE [24]. However, there are other methods such as thermal conversion (pyrolysis and gasification), biological conversion (anaerobic digestion), and landfill with energy recovery [25]. In particular, pyrolysis decomposes organic waste materials at high temperatures in the absence of oxygen, producing a mixture of gas, liquids (such as bio-oil), and solid residue (char) [26], whereas gasification involves the conversion of waste into a combustible gas (CO_2 , H_2 , CO , and CH_4) by heating waste in an oxygen-reduced environment using an Air Separation Unit [22]. However, both pyrolysis and gasification techniques are not economically feasible compared to traditional incineration and need further research [27].

A waste-to-energy incineration plant includes several stages: a combustion chamber, an energy recovery section, and a flue gas treatment section [28]. Figure 1 provides an overview of a WtE incineration plant.

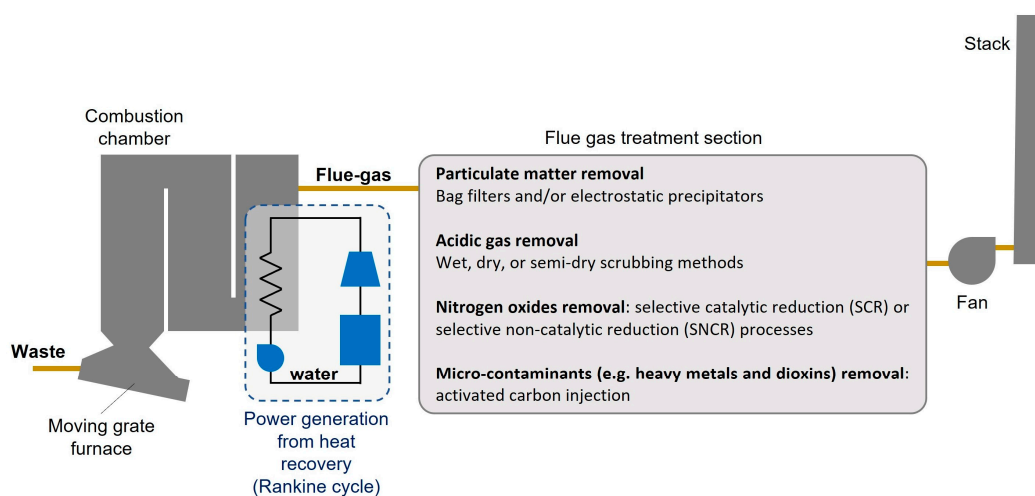


Figure 1. Process diagram for a WtE incineration plant, highlighting the combustion chamber, energy recovery section, and flue gas treatment section.

In the combustion chamber, waste is incinerated at temperatures exceeding $850\text{ }^{\circ}\text{C}$ to prevent the formation of dioxin precursors, according to Directive 2010/75/EU [29]. The combustion chamber employs technologies such as moving grates or fluidized bed furnaces, which ensure efficient air and waste mixing for consistent and complete combustion. In the energy recovery section, the heat produced by burning waste is transferred to water, which is then converted into steam. This steam can be utilized in various ways: it can be used in a turbine to generate electricity supplied to the electricity grid or in Combined Heat and Power (CHP) configurations, where it is directly supplied to industrial or civilian users, thus improving the efficiency of energy recovery from waste [30]. In the flue gas treatment section, several advanced systems work together to neutralize pollutants [31,32]. Bag filters and electrostatic precipitators are primarily used to capture particulate matter, such as fly ash. Wet, dry, or semi-dry scrubbing methods remove acidic gases, in particular

hydrogen chloride (HCl), sulfur dioxide (SO₂), and hydrogen fluoride (HF). Nitrogen oxides (NO_x) are controlled through selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) processes. SCR utilizes catalysts and ammonia gas (NH₃) to react with NO_x at temperatures ranging from 300–400 °C. SNCR, on the other hand, does not require catalysts and can remove NO_x at temperatures ranging from 950–1000 °C. Additionally, the injection of activated carbon treats micro-contaminants such as heavy metals and dioxins.

Beyond pollutant removal, the process facilitates the recovery of valuable materials such as aluminum, iron, steel, copper, and zinc from the collected bottom ash [33]. To ensure compliance with the high environmental standards set by the European Union, WtE incineration plants are planned and designed following the “Best Available Techniques (BAT) for Waste Incineration” guidelines, which include advanced strategies for managing combustion by-products, such as fly ashes, heavy metals, carbon compounds, and acid gases [34].

3. WtE Incineration Emission of Biogenic and Fossil CO₂

The CO₂ emissions from WtE incineration plants are significantly influenced by the composition of the waste they process. The composition of the waste can lead to two types of emissions: biogenic CO₂ and fossil CO₂. Biogenic CO₂ is produced by the biodegradable part of waste such as paper, cardboard, wood, and green residues. Fossil CO₂ mostly comes from fossil-based waste such as plastics and fossil-based textiles. According to the guidelines provided by the Intergovernmental Panel on Climate Change [35], biogenic CO₂ is considered carbon neutral and is not counted as contributing to climate change; as a result, its climate impact is zero [2]. This principle is also applied in the EU ETS [7] and in the Monitoring and Reporting Regulation (MRR) [36] to exclude biogenic CO₂ emissions from the overall emissions calculation of a generic industrial plant.

The ratio of fossil to biogenic CO₂ in WtE incineration emissions varies with the waste’s composition. Studies show that, on average, WtE incineration plants in the EU report about 60% biogenic and 40% fossil CO₂ emissions [1,37–39]. Moreover, in a typical WtE incineration plant, almost 99% of the carbon contained in residual waste is converted into CO₂ [37], leading to an emission of approximately 1 ton of CO₂ per ton of waste treated. Considering that 60% of the CO₂ generated is biogenic and 40% is fossil, the average emission factor for WtE would be approximately 400 kg of fossil CO₂ per ton of waste treated.

In the future, the amount of biogenic material in residual waste is expected to increase due to better separation of plastics from the waste and an increase in the use of bio-based products such as packaging paper and bioplastics [1]. This could lead to an increase in the amount of biogenic CO₂ in the flue gas, thus naturally reducing the environmental impact of the WtE incineration sector.

4. Regulatory Framework

The integration of WtE incineration with CCUS technologies can be a significant step toward achieving sustainable waste management and carbon neutrality. This effort is highly influenced by the changing regulatory framework, which aims to align the industrial field with international and European climate targets. The Paris Agreement [13] has set the global goal to limit temperature increases to less than 2 °C above pre-industrial levels, which requires a significant reduction in greenhouse gas emissions. In line with this, the European Parliament launched the European Green Deal [40], which aims to achieve net-zero greenhouse gas emissions across Europe by 2050 and a 55% reduction by 2030 relative to 1990 levels.

Within this context, the European Union has decided to include WtE incineration plants into the EU ETS by 2028, as defined in Directive 2023/959 [7]: “By July 2026, the Commission should also assess and report to the European Parliament and to the Council on the feasibility of including municipal waste incineration installations in the EU ETS, including with a

view to their inclusion from 2028, and provide an assessment of the potential need for an option for a Member State to opt out until the end of 2030, taking into account the importance of all sectors contributing to emission reductions". This is a critical step towards incentivizing the reduction of fossil CO₂ emissions from these facilities.

Regarding the CCUS technologies, they are becoming increasingly important in meeting ambitious decarbonization goals [10,11,41,42], particularly in sectors where reducing emissions poses significant challenges, such as generating energy from non-renewable (fossil fuel) sources [11,12]. The International Energy Agency has highlighted the role of CCUS in achieving the Paris Agreement's goal and emphasizes CCUS as a key technology for significantly reducing emissions from large-scale energy systems [11].

The European strategy mandates that CCUS be developed and tested during the 2020–2030 decade, enabling their utilization in the next twenty years for true decarbonization post-2030 [43]. To promote and develop CCUS technologies, Europe has established the Innovation Fund, which supports demonstration and commercialization projects for innovative technologies, including CCU and CCS. The Innovation Fund is financially supported by the credit obtained by EU ETS.

In the European regulatory framework, the EU ETS [7] plays a crucial role in the reduction of greenhouse gas emissions. It works by using a "cap-and-trade" mechanism that was launched in 2005. The mechanism sets a "cap" on the amount of greenhouse gases that power plants, industrial factories, and the aviation sector covered by the EU ETS can emit. Within the "cap", companies receive or buy emission allowances, which they can trade as needed. The cap is reduced every year, ensuring that total emissions decrease. This mechanism encourages the industries included in the EU ETS to use new technologies and methods to reduce their greenhouse gas emissions, especially in light of the increasing cost of emitting greenhouse gases under the EU ETS, which has consistently risen in recent years [44] and has now reached EUR 82, while it was around EUR 20 in 2018 [45].

Until the new EU ETS Directive was published in May 2023, WtE was not a part of the EU ETS [7]. However, the possible inclusion of WtE incineration plants in the EU ETS by 2028 could encourage the implementation of CCUS, especially CCS. This is because the CO₂ captured, transported, and permanently stored will be exempt from fees and considered as non-emitted by the EU ETS. On the other hand, plants using CCU technologies are not yet included under the EU ETS. They must pay for captured CO₂ used in chemicals or fuels as it is counted as emitted CO₂.

By including WtE in the EU ETS, WtE incineration plants have to monitor their fossil CO₂ emission based on the MRR [36]. The MRR offers two methods for estimating emissions: calculation-based (standard method and mass balance method) and measured-based. However, estimating emissions from WtE incineration plants is challenging due to the heterogeneous composition of waste. Since waste combustion produces both biogenic and fossil CO₂, accurately estimating fossil CO₂ emissions from incinerators becomes difficult [46–48].

Regarding permanent storage, the European Union approved Directive 2009/31/EC [49] on the geological storage of carbon dioxide in 2009, which covers all phases of the storage cycle, from exploration to closure of sites, and regulates inspection and control activities by the competent Authority and the management of significant CO₂ leakages.

Table 1 provides a clear summary of the regulatory measures mentioned in this paragraph.

Table 1. Summary of major environmental policies and mechanisms in Europe against climate change and promoting sustainability.

Name	Code	Scope
Paris Agreement	Not applicable; this is a global treaty.	To strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels.
European Green Deal	Not applicable; this is a set of policy initiatives.	A set of policy initiatives by the European Commission with the overarching aim of making Europe climate-neutral by 2050, boosting the economy through green technology, creating sustainable industry, and cutting pollution.
European Union Emission Trading System (EU ETS)	Directive 2023/959	To promote the reduction of greenhouse gas emissions cost-effectively and economically by setting a cap on total emissions and allowing for trading of emission allowances.
Innovation Fund	Financed by the EU ETS	To finance innovative low-carbon technologies, aiming to bring to the market industrial solutions to decarbonize Europe and support the transition to a clean energy system.
Monitoring Reporting Regulation (MRR)	Regulation 2018/2066	To establish rules for monitoring and reporting greenhouse gas emissions to ensure accuracy, consistency, and transparency under the EU ETS.
Geological storage of carbon dioxide in Europe	Directive 2009/31/EC	To provide a legal framework for the environmentally safe geological storage of CO ₂ , to contribute to the fight against climate change.

5. Carbon Capture, Utilization, or Storage (CCUS)

This section focuses on Carbon Capture, Utilization, or Storage (CCUS). Various configurations for capturing CO₂ are presented, with a particular focus on the post-combustion configuration suitable for retrofitting WtE incineration plants. Chemical absorption technology is also discussed, which is effective in separating CO₂ in low-CO₂ partial pressure applications, such as WtE flue gases. Additionally, the potential uses of captured CO₂ are presented, including CCU and CCS systems.

5.1. Carbon Capture Configurations and Capture Technologies

CO₂ capture technologies enable the capture of carbon dioxide from flue gases, reducing the amount of CO₂ released into the atmosphere. There are several configurations to capture CO₂, including pre-combustion, oxy-fuel combustion, and post-combustion [50], as shown in Figure 2. In pre-combustion configuration, the fuel is pre-treated to generate syngas, from which CO₂ is separated before the syngas is combusted [51]. In oxy-fuel combustion, a mixture of oxygen and CO₂ is used instead of air as the oxidizing agent, resulting in a flue gas mainly composed of CO₂ and water, which can be easily separated through condensation from the stream [52]. In the post-combustion configuration, CO₂ is removed from the flue gases after combustion; the flue gases, exiting the boiler and headed towards the chimney, are intercepted and sent to a capture unit to separate CO₂ from the flue gases.

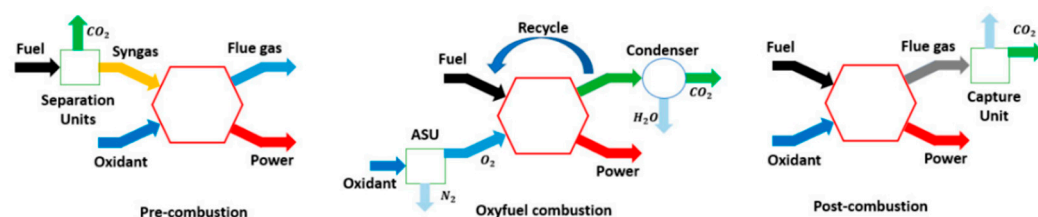


Figure 2. Flow diagram of carbon dioxide capture configurations: Pre-combustion; Oxy-fuel; Post-combustion (adapted from [50]).

The post-combustion configuration is the most suitable option for retrofitting an existing plant without making excessive modifications to the plant [12,53]. It involves intercepting the flue gases that exit the boiler and head towards the chimney with a capture unit. This system allows working with the entire flow of flue gases emitted by the plant or just a portion of it.

In the post-combustion configuration, various methods can be used to separate CO₂ from flue gases. These methods are divided into physical and chemical methods [54], as shown in Figure 3. Physical methods include membrane separation, cryogenic condensation, and physical absorption. Chemical methods, on the other hand, involve chemical absorption and chemical adsorption.

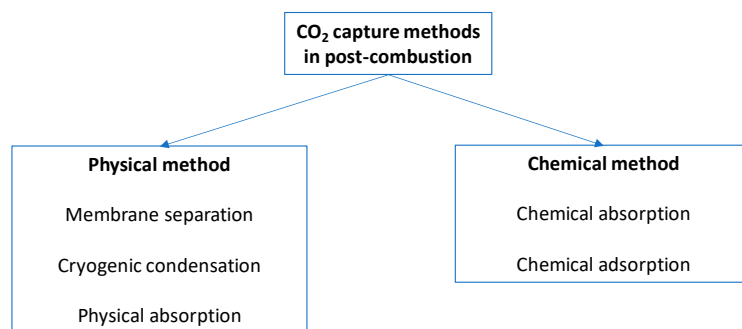


Figure 3. CO₂ capture methods from post-combustion application (adapted from [54]).

The membrane separates the CO₂ from the flue gases by applying a pressure difference across the membrane that drives the permeation of the gas; in contrast with the other methods, they do not require a separation agent. However, applying membrane technology is challenging for post-combustion CO₂ capture due to the very low pressure of the flue gas stream, the high selectivity required, the large membrane surface needed, and the particulate matter that needs to be removed before membrane purification [12].

Cryogenic condensation uses different points of condensation or solidification to separate CO₂ from the gas stream. However, the application limit of this method for post-combustion purification is the high energy required [53].

Physical and chemical adsorption use solid sorbent beds with an affinity for CO₂. Both require a cyclical process of CO₂ removal and release with the regeneration of the adsorbent bed. The materials are not as expensive as membranes and do not require a large amount of heat compared with the chemical absorption processes [53]. However, these approaches present a capture cost that is still considered too high [55].

Chemical adsorption is the most effective method, particularly the use of amine-based solutions, which have proven their effectiveness [56–59]. These systems are commercialized and are especially effective for low-CO₂ partial pressure applications such as WtE flue gases [56]. The next section will provide a detailed description of this method.

Incorporating post-combustion configuration with absorption technology into a WtE incineration plant requires integrating various sections, as shown in Figure 4. The composition of these sections changes depending on whether the captured CO₂ is used for CCU or CCS. This discrepancy is due to the specific properties required of the captured CO₂, such

as the required state (gaseous or liquid) and purity level. However, the first two sections, which are for cooling and capture, remain the same in both cases, while the subsequent sections differ based on CCU or CCS.

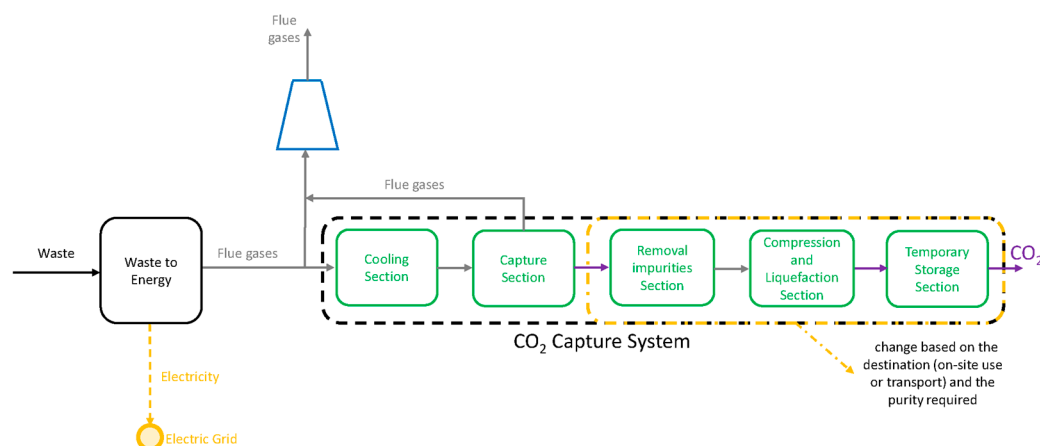


Figure 4. Flow diagram of a CO₂ Capture system that is integrated with a WtE incineration plant. The system contains several sections, including the cooling section, capture section, removal impurities section, compression and liquefaction section, and temporary storage section. The last three sections depend on the destination where the captured CO₂ will be utilized.

5.2. Carbon Capture (Chemical Absorption)

Figure 5 shows in detail the components present in each section of the Carbon Capture process, in line with the literature [14,60–65]. The process is divided into two main sections: the Cooling section and the Capture section.

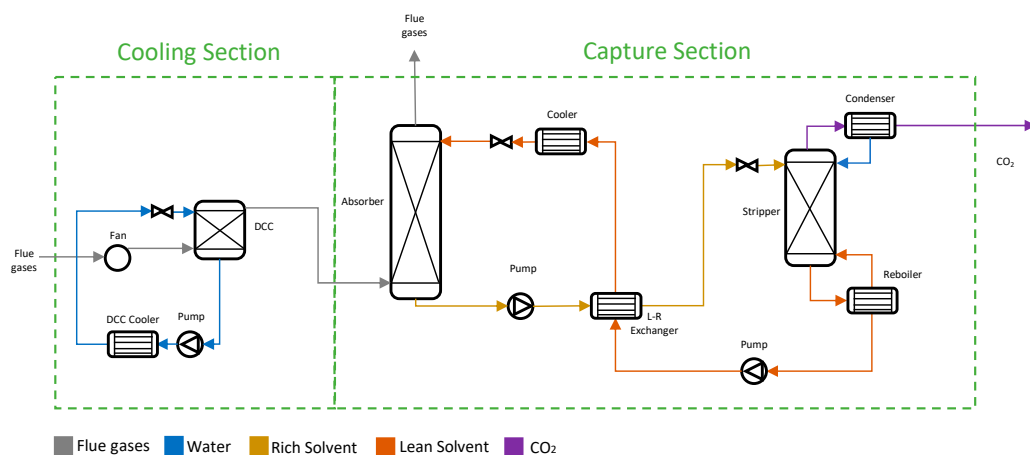


Figure 5. Flow sheet of the chemical absorption process for CO₂ capture with the cooling and capture sections (adapted from [14,60–65]).

The Cooling section includes two circuits: a primary one dedicated to cooling the flue gases (in grey) and a secondary one used for the cold water (in blue). The main component is the Direct Contact Cooler (DCC), in which the water from the secondary circuit is used to lower the temperature of the flue gas (directed towards the absorber). After exiting the DCC, the water is cooled via a local cooling circuit.

In the Capture section, the system includes two main components: the absorber and the stripper. In the absorber, the CO₂ is transferred from the vapor/gas phase to the liquid by the reaction between the CO₂ and the solvent. Specifically, when considering a monoethanolamine (MEA) solvent, the CO₂ is absorbed by MEA at approximately 1 bar and 40–60 °C with an efficiency of 85–95% in an exothermic reaction [66,67]. In the

stripper, a reverse reaction regenerates the solvent and CO₂ is transferred back to the gaseous phase. For an MEA solvent, the CO₂-rich solution is heated to 100–140 °C at a pressure close to 1 bar to recover the solvent [68]. The CO₂ is then condensed from the gas stream, allowing the CO₂ to move to the next section. A crucial element in this capture section is the cross-heat exchanger (L-R exchanger), which interconnects the absorber and the stripper, optimizing the energy efficiency of the capture process. The recovered solvent, post desorption, is recycled back to the absorber [51].

The main energy penalty induced on the plant by the CO₂ capture process is linked to the steam required to recover the solvent [37,69]. There are several solvents available from different manufacturers, and the main difference among them is the amount of heat required for regeneration. Table 2 lists the amine-based solvents available on the market, along with the heat required for their regeneration.

Table 2. List of the amine-based solvents available on the market along with the heat required for their regeneration.

Technology	Producer	Heat Duty (GJ/tCO ₂)
MEA	Commercially available	4 [70]
TS-1	Toshiba	2.6 [71]
H3-1	Hitachi	2.4 [72]
S21	Aker	2.8 [73]
DC	Shell	2.6 [74]

5.3. Carbon Capture and Utilization (CCU)

In CCU systems, the captured CO₂ can be used directly without conversion in the food and beverage sector or, with conversion, in the production of fuels and chemicals. Figure 6 provides an overview of the destinations present in the literature. The use of CO₂ can be divided into two categories: applications that require a conversion process and those that directly use CO₂. Conversion applications could integrate with the CO₂ capture system, eliminating the need for additional steps such as compression and liquefaction.

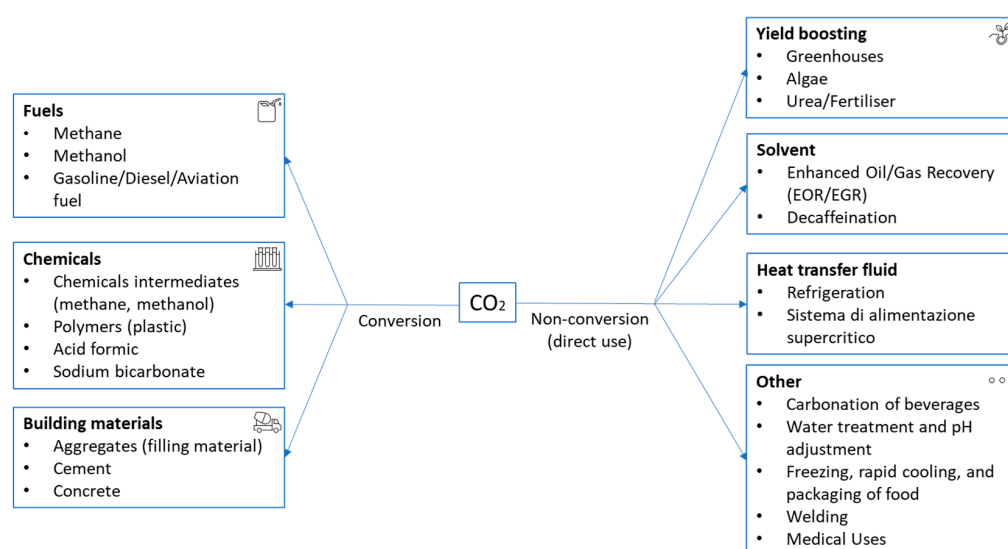


Figure 6. CO₂ destination is divided into conversion or non-conversion (direct use) (adapted from [15,75]). In conversion applications, CO₂ is transformed into a new product, such as methane or methanol. In non-conversion applications, CO₂ is used directly.

5.3.1. Non-Conversion (Direct Use)

CO₂ can be used directly in various processes, as shown on the right side of Figure 6. CO₂ can be used to optimize the yield of biological processes in greenhouse horticulture,

which can increase productivity by up to 30% [76]. This technique is commonly used to cultivate tomatoes, cucumbers, peppers, and eggplants. The amount of carbon dioxide that can be used per hectare is 300 t CO₂/ha/year [77]. The CO₂ is also used in algae farming to produce biomass for the feed, food, or biochemical industries [78].

CO₂ is used in food conservation by substituting air with CO₂ to reduce the degradation of food. In the carbonation of beverages, CO₂ is added to soft drinks and water [79]. In freezing, CO₂ is used as a refrigerant in refrigerators and cooling facilities or as dry ice for specific purposes. In the food and beverage industry, CO₂ is classified as a food additive and is identified by code E290, as per European regulation 231/2012 [80]. This regulation defines the specifications for food additives and affirms that CO₂ used as a food additive must have a purity of 99%. The European Industrial Gases Association [81] provides a guideline for the pollutants that need to be controlled in CO₂ used in food and beverages, based on the source.

5.3.2. Conversion

CO₂ can be used directly in various processes, as shown on the left side of Figure 6. In the construction sector, there are new technologies that can incorporate CO₂ into building materials. The CO₂-curing process is one of the most promising techniques, in which CO₂ is used in the hardening process of concrete [82]. Carbonation of residual materials from other industrial processes is another technique. In EOR/EGR, the CO₂ captured is injected into oil or gas sites to increase the pressure and enhance the extraction of the oil or gas [83]. In the chemical sector, CO₂ can be used in the production of a variety of compounds such as polymers, fibers, and synthetic rubbers. These processes typically start with the production of methanol, which is then converted. In the fuel sector, CO₂ is used to produce fuels such as methane and methanol through CO₂ synthesis and hydrogenation [84].

5.4. Carbon Capture and Storage (CCS)

CCS systems involve capturing CO₂ emissions from flue gases and storing them in a permanent and secure way [14]. These systems could be an effective way for WtE incineration plants to achieve a negative balance in greenhouse emissions, as CCS allows the capture and storage of biogenic CO₂ [6,51,85–87]. This CO₂ is derived from waste biomass combustion and is considered carbon-neutral and not counted as contributing to climate change, as explained in Section 3.

According to the study by the Center for Economic Studies [88], if the price of the carbon tax (due to EU ETS) continues to rise, it could lead to the establishment of a carbon storage market. The study identifies specific threshold values for the carbon tax that would create favorable conditions for the development of a market for the geological storage of CO₂. Indeed, the cost incurred for capture, transport, and storage would be lower than the carbon tax, leading companies to save money.

In CCS, after capturing CO₂ from the flue gas, there are three important sections: conditioning, transport, and permanent storage [14].

5.4.1. CO₂ Conditioning

The process of CO₂ conditioning includes the removal of impurities, compression and liquefaction, and temporary storage. In the design of a conditioning system, it is crucial to take into account the composition of CO₂ mixtures and process constraints, including the working conditions and impurity limits [89]. In general and following the work of Aspelund and Jordal [89], CO₂ conditioning includes compression and cooling of the gas coming from the CO₂ capture unit, water extraction through separator drums and adsorption techniques, and eliminating unwanted chemical components through specific treatment methods. Subsequently, CO₂ is condensed using external cooling systems or expansion through Joule–Thomson valves. Further purification steps involve the removal of volatile gases using flash tanks or distillation columns. In CO₂-conditioning operations, compressors and pumps, along with heat exchangers used for CO₂ condensation and

liquefaction, represent the most significant components in terms of energy consumption and financial investment [90].

5.4.2. CO₂ Transport

The transportation of CO₂ to permanent storage locations varies depending on the distance and involves pipelines, ships, or tanker trucks [91]. Pipelines are the principal method utilized for CO₂ transport, recognized as a mature market technology [14]. In pipeline systems, the CO₂ stream is typically compressed to pressures exceeding 8 MPa. This compression increases the density of the CO₂, facilitating and reducing the cost of transportation by avoiding two-phase flow conditions. However, for longer distances, ship transport may be more economical due to its flexibility [12]. The ship transport infrastructure includes an intermediate storage tank, loading and unloading facilities, a transport ship, and CO₂ carrier tanks.

5.4.3. CO₂ Permanent Storage

For permanent storage, there are two ways: geological and ocean storage. Geological storage can be achieved by injecting CO₂ into deep saline aquifers, exhausted oil or gas wells, or unexploitable coal layers [12]. These geological storage options can further be categorized into onshore and offshore storage. To ensure the safety and efficacy of this method, dispersion models are utilized. These models help in analyzing the dispersion of the CO₂ plume under various atmospheric conditions and assessing its environmental impacts [92]. On the other hand, ocean storage involves the injection of captured CO₂ into the ocean at significant depths, ensuring that most of the CO₂ remains isolated from the atmosphere for centuries [12]. However, this method requires rigorous monitoring to prevent potential leakages and to manage adverse effects such as ocean acidification, necessitating precise and careful measurement strategies [93].

6. WtE Incineration Plants with CCUS

Currently, five companies have implemented a CCUS system in a WtE incineration plant, as summarized in Table 3. These companies are in The Netherlands (AVR, HVC, and Twence), Norway (Klemetsrud), and Japan (Saga City). AVR, Twence, HVC, and Saga City are examples of CCU systems, while Klemetsrud is an example of a CCS system.

AVR is the first company to implement a large-scale CO₂ capture system in their WtE in Duiven (The Netherlands), which has the capacity to capture 60 kt of CO₂ per year. The captured CO₂ is then liquefied and transported for use in the greenhouse agriculture industry. Twence has implemented a CCU system at their WtE facility in Hengelo (The Netherlands) which can capture up to 2 kt of CO₂ per year [94]. The CCU system works by capturing CO₂ from the flue gas stream, purifying it, and combining it with sodium carbonate to create sodium bicarbonate slurry (SBC). The SBC slurry is then injected into the flue gas to remove acidic components such as HF, HCl, and SO₂ [95]. The CCU system produces 8 kt of SBC annually, capturing approximately 2–3% of the total CO₂ in the flue gas [95]. This approach helps reduce the operating costs associated with Carbon Capture and contributes to a lower carbon footprint. Currently, Twence is developing a system that can capture 100 kt CO₂ annually. Klemetsrud has implemented a CO₂ capture pilot plant in their WtE plant in Oslo (Norway). The main objective of this project was to test the efficiency of CO₂ capture and collect data on solvent degradation during actual WtE flue gas operations. In addition, Klemetsrud's WtE plant in Oslo has been identified as a potential recipient of government funding for large-scale CO₂ capture, with the aim of capturing over 400 kt of CO₂ annually [96]. Saga City (Japan) has implemented a CCU system that uses an aqueous amine solvent to capture 2.5 kt of carbon dioxide each year. The captured CO₂ is then utilized for local crop cultivation and algae culture. The goal behind this initiative is to develop a capture system that can capture up to 10 t of CO₂ from the plant's flue gases [97].

Table 3. Global overview of CO₂ Capture projects in WtE incineration plants.

Country	Company	WtE and Waste Processed (t/Year)	Project Status	Type	Captured CO ₂ (kt/Year)	Configuration and Capture Technology	Destination
The Netherlands	AVR (Rotterdam-Botlek, The Netherlands)	Duiven 360.635	Operational	Large scale	60	Post Combustion, Absorption	Greenhouse horticulture
		Rozenburg -	Feasibility Study	Large scale	-	Post Combustion, Absorption	Ongoing study based on the pilot
	HVC (Alkmaar The Netherlands)	Alkmaar -	Operational	Pilot	4	Post Combustion, Absorption	Greenhouse horticulture
			Feasibility Study	Large scale	75	Post Combustion, Absorption	Ongoing study based on the pilot
	Twence (Hengelo, The Netherlands)	Hengelo 608.000	Operational	Pilot	2	Post Combustion, Absorption	Sodium bicarbonate
			Under construction	Large scale	100	Post Combustion, Absorption	Study on greenhouse horticulture, formic acid production, and construction material carbonation
Norway	Fortum (Oslo, Norway)	Klemetsrud -	Operational	Pilot	-	Post Combustion, Absorption	Geological storage in the North Sea
			Feasibility Study	Large scale	400	Post Combustion, Absorption	Ongoing study based on the pilot
Japan	Saga City (Saga City, Japan)	Saga City 74.010	Operational	Pilot	2.5	Post Combustion, Absorption	Algae cultivation

Table 3 shows that WtE plants use only post-combustion configurations to capture CO₂ for retrofitting applications. This is because post-combustion is a mature and simple technology, making it a suitable choice for retrofitting existing plants [12,53]. As shown in Table 3, most carbon capture projects in the WtE sector are still in the pilot phase, with feasibility studies focused on scaling up. However, it is important to note that these studies only consider a fraction of the CO₂ present in flue gases.

The Netherlands is leading in active carbon capture projects in the WtE sector, with greenhouse horticulture being the primary destination for the captured CO₂. This is probably due to the country's CO₂ market in greenhouse horticulture, which accounts for 1.2 million tons of CO₂ annually [77]. Additionally, the Dutch government is committed to innovative and sustainable CO₂ management strategies and private companies are actively involved in developing the CO₂ sector. In 2006, as part of the Dutch government's initiative, the OCAP project was launched to repurpose an existing oil pipeline from Pernis near Rotterdam to the port of Amsterdam, connecting Noord-Holland and Zuid-Holland [98]. Although none of the mentioned WtE currently use the pipeline, the OCAP project is an excellent example of the Netherlands' commitment to innovative and sustainable CO₂ management strategies. The Phortos project has been initiated along with the OCAP project [99]. The aim of this project is to establish the Port of Rotterdam CO₂ Transport Hub and Offshore Storage facility. The primary objective of this collaboration is to capture, utilize, and store CO₂. The CO₂ extracted from the plants associated with the OCAP will be the primary source of CO₂. A portion of the captured CO₂ will be utilized for greenhouse farming to enhance plant growth, while the remaining CO₂ will be compressed and stored in a depleted gas site located in the North Sea.

7. Italian Case

Italy has 37 waste-to-energy (WtE) incineration plants, which collectively process 6.4 million tons of waste annually. Most of these plants are located in the northern regions of the country (26 facilities), while the remaining 11 are in the central and southern parts. The annual amount of waste treated by these plants is 6.4 million tons, with an average plant capacity of 173 kt per year, resulting in the emission of 171 kt of CO₂ per year, using the conversion coefficient of Bisinella et al. [37]. However, this calculation does not differentiate between biogenic and fossil CO₂. Although Italy's waste management strategy has a robust commitment to environmental sustainability, it still relies heavily on landfilling, with a disposal rate of 23%, which is an area for improvement. In comparison, countries such as Belgium, Sweden, Finland, and Denmark have near-zero landfill rates [20]. Therefore, there is potential for Italy to implement WtE incineration more aggressively to reduce its landfill dependency.

To lower greenhouse gas emissions and transition towards a circular economy, Italy has aligned with the European Green Deal and outlined a strategic plan that aims to achieve climate neutrality by 2050. The long-term Italian strategy suggests using CO₂ capture with permanent storage (CCS) and reusing captured CO₂ (CCU) to balance any remaining greenhouse gases by 2050 [100]. CCUS technologies offer a way to capture CO₂ from centralized emission sources and reuse it in creating carbon-neutral alternative fuels, such as synthetic methane (Power-to-gas) or synthetic methanol (Power-to-liquid).

For CCU, the Italian market for CO₂, which is used in food and industrial applications, is estimated to be around 285 kt, according to Table 4 of Italian production data. Production usually meets the market demand, except during specific periods such as the summer months when demand exceeds supply (Nippon Gases). The table also shows that CO₂ production capacity is classified into two categories: CO₂ from chemical plants, which represents 66% of the total production (about 188 kt per year), and CO₂ extracted from geothermal sources, which constitutes 34% (about 97 kt per year). Less than two WtE plants could cover the entire Italian market, given that each plant emits an average of 171 kt of CO₂ per year, as mentioned above.

Table 4. Annual CO₂ Capture capacities by Company and Location. This table lists various companies across Italy, highlighting their locations, sources of CO₂ (geothermal or chemical plant), and their CO₂ capture capacities.

Company/Group	Location	Source of CO ₂	Capacity (kt _{CO2} /Year)
AIR LIQUID (Milan, Italy)	S. Albino (SI)	Geothermal	27
	Rapolano (SI)	Geothermal	14
NIPPON GASES (Milan, Italy)	Castelnuovo Berardenga (SI)	Geothermal	46
	Ferrara	Chemical plant	82
S.I.A.D. (Osio Sopra, BG, Italy)	Montefiascone (VT)	Geothermal	10
	Osio Sopra (BG)	Chemical plant	5
SAMAC (Vobarno, BS, Italy)	Ferrara	Chemical plant	25
	Scarlino (GR)	Chemical plant	25
SAPIO (Monza, MB, Italy)	Mantova	Chemical plant	4
	Novara	Chemical plant	12
SOL (Monza, MB, Italy)	Falconara (AN)	Chemical plant	35

Regarding CO₂ permanent storage, Italy produced the SEA (Strategic Environmental Assessment) in 2012 in response to Directive 2009/31/EC [49], which identified areas of the national territory and the exclusive economic zone suitable for geological CO₂ storage sites. However, sites for the geological storage of CO₂ have not yet been identified and implemented, except for a recent project in the Adriatic Sea by Eni and Snam with a 500 Mton CO₂ storage capacity [101]. Therefore, currently, the geological storage of carbon dioxide is not a feasible option in Italy, but this may change in the future due to the project announced by Eni and Snam.

To summarize, national policies and strategies incentivizing the development of markets for CO₂ and the implementation of storage infrastructure are needed in view of building up the sustainable management of CO₂ emissions. Nevertheless, according to

historical data from the European Environmental Agency's annual greenhouse gas (GHG) inventories [102], the total fossil CO₂ emissions from WtE plants represent only 1% of all GHG sources in Europe. Despite an increase in the amount of waste treated at WtE plants, this number has essentially remained constant over the last decade, indicating that the WtE sector's actual carbon footprint is not significant compared to the total CO₂ emitted by all the sectors in Europe.

8. Conclusions

This paper provides an overview of the integration of CCUS technologies with WtE incineration plants in retrofit applications. The exploration of technology, current regulations, and case studies highlights the importance of adopting CCUS systems in WtE contexts to mitigate CO₂ emissions. This step aligns with the ambitious goals of achieving carbon neutrality in European waste management. EU ETS Directive 2023/959 provides a plan to include WtE incinerators in the EU ETS by 2028. This measure could provide a significant impulse for the integration of CCUS in WtE incineration plants since the inclusion requires WtE to financially account for their fossil CO₂ emissions.

Despite the promising prospects offered by CCUS integration within WtE incineration plants, challenges persist related to the availability of markets for captured CO₂ and the maturity of permanent storage solutions. Although the technology for capturing CO₂ exists, the lack of a destination (in terms of tons) for the captured CO₂ makes it difficult to implement, especially if CCUS is to be adopted by different industries to meet European goals (not only WtE). Governments need to develop incentives, regulatory frameworks, and CO₂ markets that support the adoption of CCUS technologies.

The international panorama shows a marked difference between countries such as the Netherlands, which benefit from an already developed CO₂ market (for the greenhouse) and an early commitment towards the adoption of CCUS technologies (OCAP and Phortos project), and other countries such as Italy, where the CO₂ market is smaller and permanent storage solutions are only beginning to emerge, as illustrated by Snam and Eni's projects. This disparity highlights the importance of national policies and strategies that incentivize the development of markets for CO₂ and the implementation of storage infrastructure.

Integrating CCUS technologies into WtE incinerators is a critical strategy for sustainable energy transition. The implementation of the EU ETS directive could serve as a catalyst for accelerating this integration, supporting European efforts to reduce greenhouse gas emissions and promote long-term environmental sustainability. The contrast between countries such as the Netherlands, benefiting from a developed CO₂ market and an early commitment to CCUS technologies, and Italy, where the CO₂ market is still emerging and permanent storage solutions are just beginning to be explored, underscores the need for suited strategies to address these disparities.

In this paper, the integration of CCUS within WtE frameworks, primarily examining the regulatory, technical, and infrastructural challenges involved, was analyzed, whereas no details from an economic perspective were provided. Future studies should be focused on the economic criticalities, in order to provide an overall evaluation of the issue of integrating CCUS within WtE.

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