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CORSO DI DOTTORATO IN METODI, MODELLI E TECNOLOGIE PER L'INGEGNERIA

DIPARTIMENTO DI INGEGNERIA CIVILE E MECCANICA



Integration of Carbon Capture Utilization and Storage system with Waste-to-Energy incineration plant

by

Michele Bertone

Dissertation for the purpose of obtaining the degree of Doctor of Philosophiae in Mechanical Engineering

Supervisors
Prof. Giorgio Buonanno
Ing. Michelangelo Petea

Coordinator
Prof. Fabrizio Marignetti

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Author: **Michele Bertone**

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Glossary

AEC	Alkaline Electrolyser Cell
BAT	Best Available Techniques
BF	biomass fraction of the total carbon content
CC	Carbon Capture
CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization or Storage
CEWEP	Confederation of European Waste-to-Energy Plants
CHP	Combined Heat and Power
DCC	Direct Contact Cooler
EEA	European Environmental Agency
EIC	Equipment Installed Cost
EF_{PRE}	Preliminary Emission Factor
EU ETS	European Union Emissions Trading System
EWC	European Waste Catalogue
GHG	Greenhouse gas
H	Humidity
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MEA	monoethanolamine
MRR	Monitoring Reporting Regulation
NCV	Net Calorific Value
NOK	Norwegian Kroner
OF	oxidation factor
PtG	Power-to-Gas
PtL	Power-to-Liquid

SRF	Solid Refuse Fuel
SNCR	Selective Non-Catalytic Reduction
TIC	Total Installed Cost
WtE	Waste-to-Energy

1 Introduction

Waste-to-Energy (WtE) incineration plants are crucial in modern waste management, processing non-recyclable waste and thus providing sanitary services to communities while generating electrical and thermal energy (Astrup et al., 2009). With approximately 500 plants across Europe treating nearly 100 million tons of municipal, commercial, and industrial residual waste annually (Poretti and Stengler, 2022), their impact on sustainable waste management is significant. They contribute to reducing greenhouse gas emissions by limiting landfill use and thus reducing the associated methane emissions (Cucchiella et al., 2014; D. Wang et al., 2020). By preventing the dumping of waste in landfills, WtE incineration plants prevent methane release, a greenhouse gas more potent than CO_2 over both short (86 times more potent over a 20-year) and long terms (28 times more potent than over a 100-year) (Y. Wang et al., 2020). Additionally, the energy generated through WtE incineration provides a sustainable alternative to energy produced using fossil fuels, further reducing their environmental footprint (Cucchiella et al., 2014; D. Wang et al., 2020).

Despite these environmental benefits, the combustion process in WtE incineration plants produces the unavoidable emission of CO_2, particularly from the combustion of fossil carbon in waste, which contributes to climate change (Christensen et al., 2009). 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 the Directive 2023/959 (European Parliament, 2023). This measure would require the WtE incinerator plants to financially account for their fossil CO_2 emissions, thereby underlining the need for 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 CO_2 emissions (Christensen and Bisinella, 2021; Wienchol et al., 2020).

From a broader perspective, CCUS technologies are increasingly recognized as essential in mitigating climate change (C2ES, 2016; IEA, 2020; Metz et al., 2005). The International Energy Agency underlines the role of CCUS in achieving the Paris Agreement's goal to limit global temperature increases to below 2°C (Paris Agreement, 2016) and highlights CCUS as a key technology for significantly reducing emissions from large-scale energy systems (IEA, 2020). The application of Carbon Capture technology requires combining with Storage (CCS) or Utilization (CCU). CCS involves removing CO_2 from carbon sources and compressing it for storage underground (Golombek et al., 2021a), while CCU utilizes captured CO_2 for conversion, focusing on incorporating CO_2 into the carbon cycle, seeking a long-term sustainable path and generating economic benefits by using CO_2, thereby reducing the overall cost of Capture (IEA, 2019).

1.1 Motivation and Scope

The integration of carbon CCUS technologies in WtE incineration plants is an innovative approach toward sustainable waste management. This doctoral thesis aims to enhance the environmental sustainability of WtE incineration plants by exploring effective strategies for reducing their carbon emissions through the adoption of CCUS systems.

The thesis focuses on analyzing the technical feasibility, economic implications, and potential environmental benefits of integrating CCUS technologies into WtE incineration plants. It examines the current status of CCUS technologies within WtE incineration plants, identifies the challenges and opportunities in their adoption, and explores the technological and economic aspects that can facilitate their effective implementation.

The ultimate goal of this research is to provide a comprehensive insight into how WtE plants can evolve to meet the demands of a changing environmental paradigm. The research will offer a valuable contribution to the ongoing discussion on sustainable waste management and carbon emission reduction.

1.2 Dissertation outline

This doctoral thesis consists of six chapters, each addressing a critical aspect of integrating CCUS technologies within WtE incineration plants. Below is a brief description of each chapter to outline the scope and focus of the investigation. The final chapter, Chapter 7, offers a comprehensive summary of the findings and conclusions.

1.2.1 Content of Chapter 2

This chapter introduces Waste-to-Energy (WtE) incineration, emphasizing its significance in sustainable waste management and renewable energy generation. It explores the categorization and growth of waste, particularly municipal solid waste as a biomass source, thereby making it a renewable energy resource. It also discusses Europe's dependence on WtE incineration and the implications of incineration versus landfilling. Detailed descriptions of WtE plant components - combustion chamber, energy recovery, and flue gas treatment - outline the process's technical aspects. The chapter also addresses the treatment and recovery of incineration residues. Focusing on Italy, it shows the country's WtE infrastructure and the potential for improved sustainability through reduced landfill dependence.

1.2.2 Content of Chapter 3

This chapter provides an overview of integrating CCUS technologies with the WtE incineration plants in retrofit applications. It explains the generation of both biogenic and fossil CO_2 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 integrating CCUS in WtE incineration plants. Moreover, it discusses the use of CO_2 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 CO_2 market and early CCUS adoption, compared to Italy's emerging market and initial storage solutions.

1.2.3 Content of Chapter 4

This chapter presents the results of the estimation of both fossil and biogenic CO_2 emissions from a WtE incineration plant, following the Standard Method set by the Monitoring and Reporting Regulation 2018/2066. Utilizing data collected in 2022, it explores the complexities involved in estimating CO_2 emissions from WtE incineration plants. The chapter outlines the methodology used to calculate the fossil CO_2 emitted by the WtE incineration plant and the ratio between biogenic and fossil CO_2 resulting from the combustion of industrial waste, specifically mechanically separated rejects from the pulping of waste paper and cardboard (Solid Refuse Fuel (SRF)). The heterogeneous composition of waste poses significant challenges, resulting in the emission of both biogenic and fossil CO_2 and complicating the accurate estimation of fossil CO_2 emissions. The results indicate that most emissions from the WtE plant are biogenic, thus not contributing to the overall atmospheric CO_2 emissions. This chapter underscores the importance of an accurate methodological approach in estimating emissions from WtE facilities.

1.2.4 Content of Chapter 5

This chapter offers a detailed techno-economic assessment of Carbon Capture (CC) integration in an existing WtE incineration plant, focusing on retrofit application. Post-combustion carbon capture using monoethanolamine (MEA) was modeled for various low-scale plant sizes (3000, 6000, and 12000 t of CO_2 per year), using a process simulator, highlighting the feasibility and implications of retrofitting a WtE incineration plant with CC technology. The comprehensive analysis covers the design of the CC plant and a detailed cost evaluation. Capture costs range from 156 €/t to 90 €/t of CO_2. Additionally, integrating the CO_2 capture system reduces the overall plant absolute efficiency from 22.7% (without carbon capture) to 22.4%, 22.1%, and 21.5% for the different capture capacities. The research fills a gap in studying small-scale CC applications for the WtE incineration plants, providing critical insights for similar retrofit projects.

1.2.5 Content of Chapter 6

This chapter offers an economic assessment of converting CO_2 into methane through the Power-to-Gas (PtG) process and into methanol via the Power-to-Liquid (PtL) process. These processes

offer the possibility of utilizing the captured CO_2 and producing renewable and sustainable fuels. Methane, resulting from the PtG process, can be used for energy generation or heating, while methanol, derived from the PtL process, represents a viable green alternative for the transport sector and the chemical industry, as well as a solution for storing excess electrical energy. The amount of CO_2 required to power a 1 MW PtG or PtL system (electrolyzer) is minimal compared to the annual emissions of a WtE incineration plant. Specifically, a 1 MW electrolyzer uses only 873 t of CO_2 to produce methane and 1163 t of CO_2 to produce methanol. These values are minimal when compared with the annual emissions of a WtE plant, such as 171 kt of CO_2 per year for the Italian WtE. Moreover, the chapter shows that the current cost of electricity used for electrolysis is prohibitive; in fact, it is more economically advantageous to sell the energy to the grid rather than use it in hydrogen production.

2 Waste-to-Energy incineration

This chapter aims to introduce WtE incineration plants by covering the fundamental principles of their operation and the various configurations they may have. It will provide a comprehensive overview of their use by analyzing the current state of WtE incineration plants. Additionally, it offers information on the waste, and at the end, it provides details on the current situation in Italy.

2.1 Waste

Waste refers to any substance or object that the holder discards, intends to discard, or is required to discard in the field of waste management. Municipal solid waste represents waste generated in households and other types of waste that share similar characteristics. All other forms of waste are classified as special waste. Hazardous and non-hazardous categories classify waste based on specific hazard characteristics, such as the presence of particular substances and the potential for releasing certain chemicals. The European Waste Catalogue (EWC) provides a system of codes essential in determining the waste's origin and primary attributes, including its classification as hazardous or non-hazardous, for a more comprehensive analysis.

The amount of waste is expected to increase significantly, from 2.01 billion tons to 3.4 billion tons by 2050 (Kaza et al., 2018). This increase underscores the importance for the waste management sector to develop sustainable practices that prevent waste from becoming a dangerous threat to both the environment and human health.

Municipal solid waste is a mixture of materials such as paper, cardboard, wood, cloth, green waste, and food, making it a renewable source of energy. These materials are biodegradable and fall under the category of biomass as defined by the European Directive 2009/28/ec (European Parliament, 2009a). Because these components are biomass, municipal solid waste qualifies as a renewable energy resource, important from both legal and economic perspectives. Indeed, renewable energy resources often receive financial and political support, which can help in the developming systems that recover energy from waste (Wienchol et al., 2020).

2.2 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 (Cewap, 2021), waste treatment in Europe consists of 49%

recycling and composting, 26% landfill disposal, and the remaining portion directed to WtE incineration, as shown in Figure 1. 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 (Poretti and Stengler, 2022).

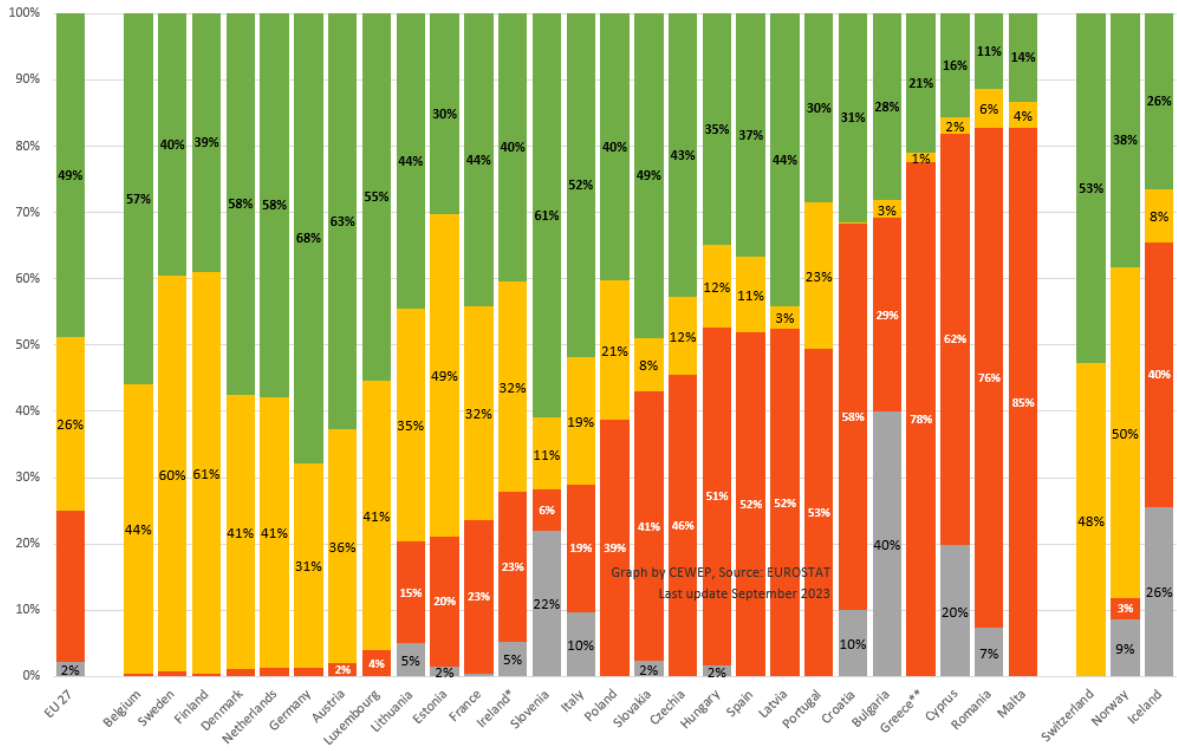


Figure 1 – Municipal waste treatment in 2021 in Europe (Cewap, 2021)

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 (Jouhara et al., 2017). 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 (Kumar and Samadder, 2017). Nevertheless, once the investment costs have been made, 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 (Makarichi et al., 2018).

WtE incineration is the most mature and prevalently employed technology within WtE (Dastjerdi et al., 2019), but there are other methods, such as thermal conversion (pyrolysis and gasification), biological conversion (anaerobic digestion) and landfill with energy recovery (Moya et al., 2017). In particular, pyrolysis decomposes organic waste materials at high temperatures in the absence of oxygen, producing a mixture of gas, liquids (like bio-oil), and solid residue (char) (Tan et al., 2023), whereas gasification involves the conversion of waste into a combustible gas (CO_2, H_2, CO, CH_4)

by heating waste in an oxygen-reduced environment using an Air Separation Unit (Kumar and Samadder, 2017). However, both pyrolysis and gasification techniques are not economically feasible compared to traditional incineration and need further research (Mamad Gandidi et al., 2017). Figure 2 shows the main thermal conversion processes.

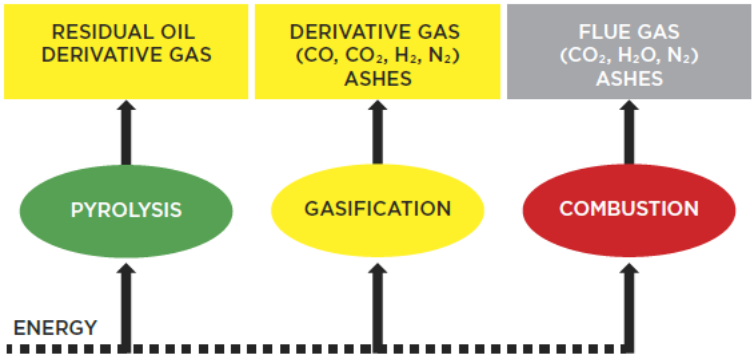


Figure 2 – Schematic representation of thermal conversion processes: pyrolysis, gasification, and combustion (incineration).

The incineration of waste is a process of thermal oxidation of the waste, in which the elements constituting the organic substances contained are oxidized, giving rise to simple molecules and to the gaseous state (flue gas). During this process, organic carbon is oxidized into carbon dioxide (CO_2), hydrogen into water (H_2O), and sulfur into sulfur dioxide (SO_2), etc.; whereas the inorganic part of the waste is also oxidized and results in a solid residue that can be disposed of or recovered as heavy ash (Neuwahl et al., 2019). Since the process is an oxidative one, the presence of oxygen is necessary for the reactions. Air is normally used, supplied in excess of the stoichiometric quantity to facilitate the chemical reactions.

2.3 Waste-to-energy incineration plant

A waste-to-energy incineration plant includes several stages: a combustion chamber, an energy recovery section, and a flue gas treatment section (Clift et al., 2004).

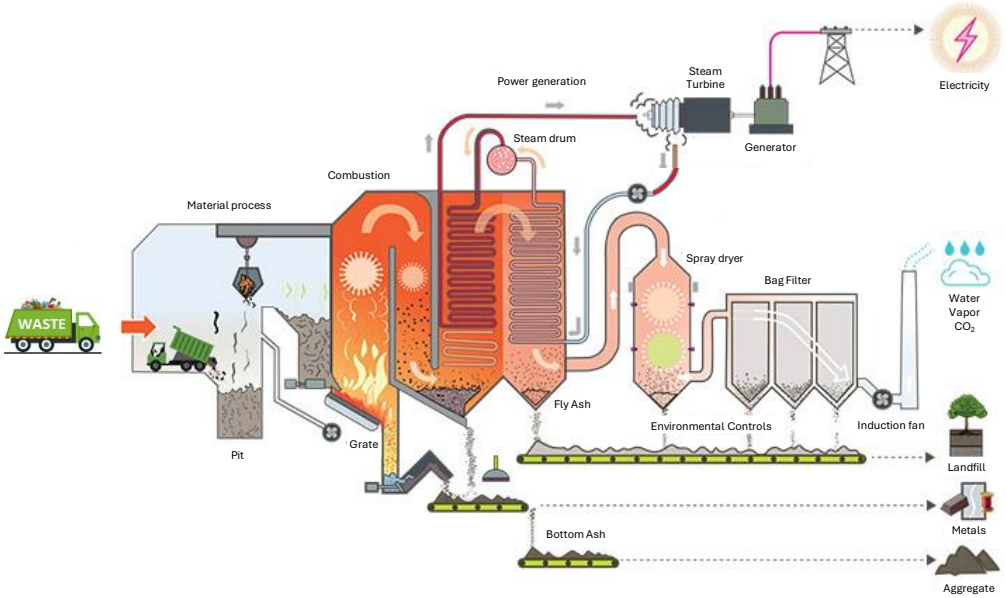


Figure 3 provides an overview of the process flow for a typical WtE incineration plant. Additionally, it is crucial to consider the solid residual fractions that need to be eliminated. In the following paragraphs, each stage will be explained, along with how to treat the solid fraction.

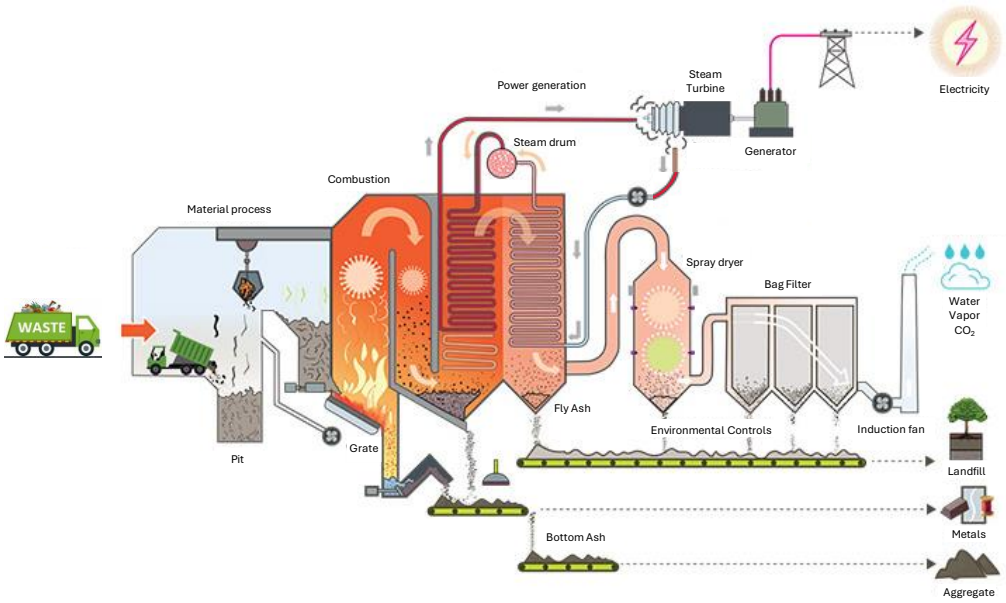


Figure 3 - Typical process flow diagram for WtE incineration plant (adapted from the national energy education development program).

2.3.1 Combustion chamber

The most common technologies for combusting waste are the moving grate furnace and the fluidized bed furnace. Grate furnaces are widely used for their operational flexibility and reliability, as they have numerous applications. These furnaces consist of a grille, which can be horizontal or inclined, on which a bed of waste, several dozen centimeters thick, is placed. The grille is made up of a set of elements called "fire bars," arranged in a way that allows the passage of combustion air and its distribution throughout the waste bed. Combustion air is injected both under the grille and directly inside the combustion chamber.
The fluid-bed furnace has a combustion chamber in which a certain amount of inert material (the "bed") is kept, usually consisting of sand held in suspension ("fluid") by an upward current of air (which also acts as a comburent). The movement of the grit bed ensures good comburent-fuel contact and considerable uniformity of temperature and mixing, which helps to ensure constant and complete combustion.
Incineration operates by burning waste at temperatures exceeding 850°C to prevent the formation of dioxin precursors within the combustion chamber, as required by Directive 2010/75/EU (European Parliament, 2010). Also, it guarantees the almost complete oxidation of the organic components in the combustion processes, thus minimizing the emissions of unburnt products.

2.3.2 Energy recovery section

Energy recovery takes place in the form of the production of electricity and/or thermal energy, obtained through the use of steam generated in a special boiler conceptually constituted by a heat exchanger.
The plant layout is very similar to the typical one of thermoelectric power plants, even if the operating conditions (pressure and temperature) are much less severe. This is due to the presence of corrosive compounds and entrained ash in the flue gas, which can give rise to corrosion and erosion phenomena, as well as to the formation of material deposits on the heat exchange walls.
The steam produced by combustion of the waste may be used in one of the following ways:

- direct supply of steam to industrial thermal users or of hot/superheated water to civil users by means of a heat exchanger (heat only);
- production of electricity by means of steam expansion in a turbine with a condensation cycle (electricity only);
- combined heat and power (CHP) configurations, the incinerators supply thermal energy to district heating systems, which improves the efficiency of energy recovery from waste (Themelis, 2012).

2.3.3 Flue gas treatment section

An incineration plant generates gaseous, liquid, and solid emissions (Šyc et al., 2020). Before being released into the atmosphere, the flue gas undergoes treatment with the target of substantially reducing the concentrations of contaminants. The flue gas treatment section is complex due to strict regulations and technological advancements. To comply with EU standards, incineration plants follow 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 (Neuwahl et al., 2019). The advanced flue gas treatment system includes:

- bag filters and electrostatic filters (or electric filters) are the most widely used devices for the abatement of particulate matter such as fly ash;
- wet, dry, or semi-dry washing method that removes gases with acidic behavior, in particular hydrogen chloride (HCl), sulfur dioxide (SO_2), and hydrogen fluoride (HF);
- emissions of nitrogen oxides are controlled by means of two different systems: the first includes measures to reduce their formation during the process so that the concentration is lower than the legal limit; the second involves the removal of NOx through a chemical reaction with ammonia gas (NH_3), which transforms them into elementary nitrogen. The removal can be carried out in two different ways: at low temperature (300 - 400 °C) in the presence of catalysts (SCR, Selective Catalytic Reduction) or at high temperature (950 - 1000 °C) in the absence of catalysts (SNCR, Selective Non-Catalytic Reduction);
- activated carbon injection is commonly used to treat micro-contaminants (heavy metals and dioxins). It should also be noted that organic micro-contaminants (dioxins and furans, in particular) can also be abated within the SCR systems used to reduce nitrogen oxides.

During the incineration process, organic pollutants are destroyed through combustion, while inorganic pollutants are removed using an advanced flue gas cleaning system (Dal Pozzo et al., 2023; Vehlow, 2015). This process ensures that waste-related pollutants are neutralized, reducing their concentrations and protecting the environment and public health. It also facilitates the recovery of valuable materials such as aluminum, iron, steel, copper, and zinc from bottom ash collected.

2.3.4 Residual fractions

There are two types of solid residues that come from the incineration process of waste: bottom ash and fly ash. The characteristics and quantities of bottom ash are closely related to the treatment process and the type of waste input. From the bottom ash, valuable raw materials such as ferrous and non-ferrous metals can be recovered. This includes metals and alloys like steel, aluminum, copper, and zinc, which are recycled from the bottom ash as secondary raw material, resulting in a lower environmental cost than the production of new metals (Šyc et al., 2020). On the other hand,

fly ash is removed through the flue gas treatment system and is typically disposed of in hazardous waste landfills. Moreover, there are salts from flue gas treatments that depend on the type of reagent used. For example, RSP (Residual Sodium Products) is used when sodium bicarbonate is used. These salts are generally hazardous wastes that can be disposed of in special landfills or even sent to recovery processes. The possibility of reusing or recycling solid residues is determined by their characteristics in terms of organic matter content and leachability of metals and salts.

2.4 Italian Case

Italy has 37 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 CO_2 per year, using the conversion coefficient of Bisinella et al. (2021). 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 (Cewap, 2021), as shown in Figure 1. Therefore, there is potential for Italy to implement WtE incineration more aggressively to reduce its landfill dependency.

2.5 Conclusion

This chapter emphasizes the importance of WtE incineration in addressing the global waste problem and its potential to contribute to sustainable energy production. WtE incineration not only offers a promising solution for managing municipal solid waste, but also aligns with renewable energy goals due to the biomass fraction of waste. Additionally, the main components of a incineration plant are presented, explaining each stage (combustion chamber, an energy recovery section, and a flue gas treatment section), including how to treat the solid fraction.
The Italian context illustrates the potential and challenges of adopting WtE incineration as a critical component of national waste management strategies. It highlights the need for a shift towards more sustainable practices to reduce dependence on landfilling.

3 Overview of WtE incineration integrated with CCUS retrofit application.

This chapter provides an overview of the integration of CCUS technologies with WtE incineration plants in retrofit applications. It explains the types of emissions generated (biogenic and fossil CO_2), 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. It also explores and presents the configurations for carbon capture, the CO_2 separation methods, and the prospects for carbon utilization and storage. Through an examination of the current state and potential of the integration of CCUS technologies in WtE incineration plants, this chapter provides an overview of the potential integration.

3.1 WtE incineration emission of biogenic and fossil CO_2

The CO_2 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 CO_2 and fossil CO_2. Biogenic CO_2 is produced by the biodegradable part of waste such as paper, cardboard, wood, and green residues. Fossil CO_2 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 (Eggleston, 2006), biogenic CO_2 is considered carbon neutral and is not counted as contributing to climate change; as a result, its climate impact is zero (Astrup et al., 2009). This principle is also applied in the EU ETS (European Parliament, 2023) and in the Monitoring and Reporting Regulation (MRR) (European Parliament, 2018) to exclude biogenic CO_2 emissions from the overall emissions calculation of a generic industrial plant.

The ratio of fossil to biogenic CO_2 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 CO_2 emissions (Bisinella et al., 2021; Fuglsang et al., 2014; Larsen et al., 2013; Poretti and Stengler, 2022). Moreover, in a typical WtE incineration plant, almost 99% of the carbon contained in residual waste is converted into CO_2 (Bisinella et al., 2021), leading to an emission of approximately 1 ton of CO_2 per ton of waste treated. Considering a 60% of the CO_2

generated is biogenic and 40% is fossil, the average emission factor for WtE would be approximately 400 kg fossil CO_2 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 like packaging paper and bioplastics (Poretti and Stengler, 2022). This could lead to an increase in the amount of biogenic CO_2 in the flue gas, thus naturally reducing the environmental impact of the WtE incineration sector.

3.2 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 (2016) has set the global goal to limit temperature increase 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 (European Parliament, 2019), 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 (European Parliament, 2023), as reported: "*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 CO_2 emissions from these facilities.
Regarding the CCUS technologies, they are becoming increasingly important in meeting ambitious decarbonization goals (C2ES, 2016; Gambhir et al., 2019; Gasser et al., 2015; IEA, 2020), particularly in sectors where reducing emissions poses significant challenges, such as generating energy from non-renewable (fossil fuel) sources (IEA, 2020; Metz et al., 2005). 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 (IEA, 2020).
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 (European Parliament, 2020). 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 (European Parliament, 2023) 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 (Nikolić and Filipović, 2020) and has now reached 82€, while it was around 20€ in 2018 (Emer, 2024).

Until the new EU ETS Directive was published in May 2023, WtE was not a part of the EU ETS (European Parliament, 2023). 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 CO_2 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 CO_2 used in chemicals or fuels as it is counted as emitted CO_2.

Including the WtE in EU ETS, the WtE incineration plants have to monitor their fossil CO_2 emission based on the MRR (European Parliament, 2018). 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 CO_2, accurately estimating fossil CO_2 emissions from incinerators becomes difficult (Lee et al., 2018, 2021; Mohn et al., 2008).

Regarding the permanent storage, the European Union approved a Directive 2009/31/EC (European Parliament, 2009b) 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 CO_2 leakages

3.3 Carbon Capture, Utilization or Storage (CCUS)

This section focuses on Carbon Capture, Utilization or Storage (CCUS). Various configurations for capturing CO_2 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 CO_2 in low CO_2 partial pressure applications, such as the WtE flue gases. Additionally, the potential uses of captured CO_2 are presented, including CCU and CCS systems.

3.3.1 Carbon Capture configurations

CO_2 capture technologies enable the capture of carbon dioxide from flue gases, reducing the amount of CO_2 released into the atmosphere. There are several configurations to capture CO_2, including pre-combustion, oxy-fuel combustion and post-combustion (Thomas Adams II et al., 2017), as shown in Figure 4. In pre-combustion configuration, the fuel is pre-treated to generate syngas, from which CO_2 is separated before the syngas is combusted (Pour et al., 2018). In oxy-fuel combustion, a mixture of oxygen and CO_2 is used instead of air as the oxidizing agent, resulting in a flue gas mainly composed of CO_2 and water, which can be easily separated through condensation from the stream (Toftegaard et al., 2010). In the post-combustion configuration, CO_2 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 CO_2 from the flue gases.

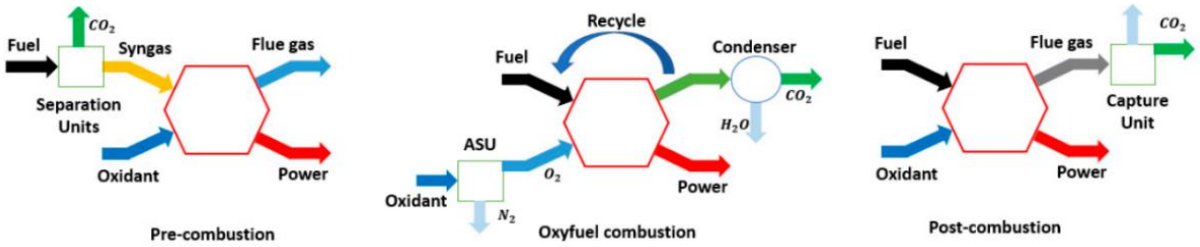


Figure 4 - Flow sheet of carbon dioxide capture configurations: Pre-combustion, left; Oxy-fuel, middle; Post-combustion, right (Thomas Adams II et al., 2017).

The post-combustion configuration is the most suitable option for retrofitting an existing plant without making excessive modifications to the plant (Leung et al., 2014; Metz et al., 2005), since 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 CO_2 from flue gases. Among these methods, chemical absorption is the most effective method, particularly the use of amine-based solutions, which have proven their effectiveness (Bui et al., 2014; Plaza et al., 2009; Tan et al., 2012; Wang et al., 2011). These systems are commercialized and are especially effective for low CO_2 partial pressure applications like the WtE flue gases (Bui et al., 2014).

Incorporating post-combustion configuration with absorption technology into a WTE incineration plant requires integrating various sections as shown in Figure 5. The composition of these sections changes depending on whether the captured CO_2 is used for CCU or CCS. This discrepancy is due to the specific properties required of the captured CO_2, 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.

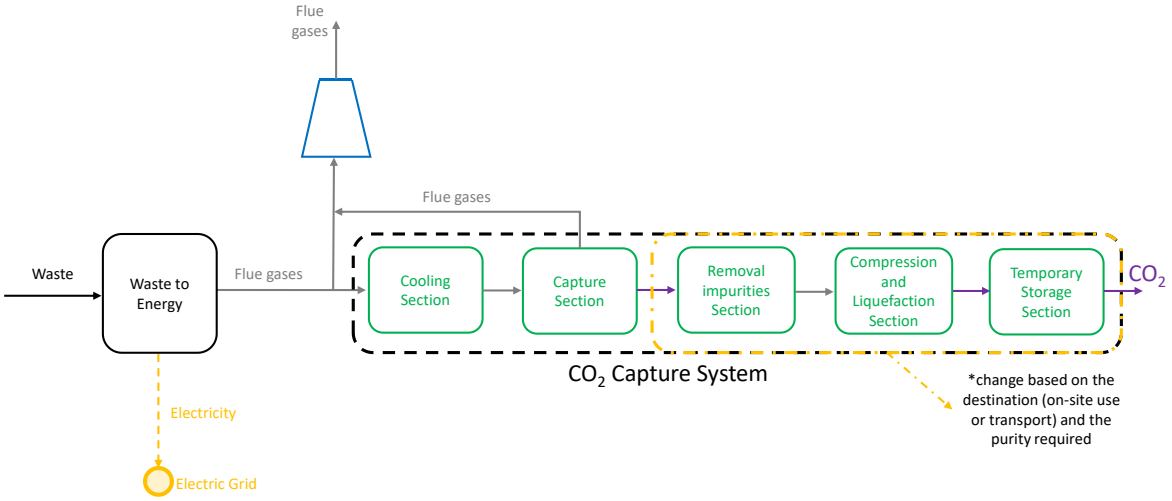


Figure 5 - Flow diagram of a CO_2 Capture system that is integrated with a WtE incineration plant. The system contains several sections, including the cooling section, capture section, removal impurities section, compression and liquefaction section, and temporary storage section. The last three sections depend on the destination where the captured CO_2 will be utilized.

3.3.2 Carbon Capture

Figure 6 shows in detail the components present in each section of the Carbon Capture process, in line with the literature (Alie et al., 2005; De Miguel Mercader et al., 2012; Nittaya et al., 2014; Seader et al., 2011; Singh et al., 2003; Sinnott, 2005; Tan et al., 2016). The process is divided into two main sections: the Cooling section and the Capture section.

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 CO_2 is transferred from the vapor/gas phase to the liquid by the reaction between the CO_2 and the solvent. Specifically, when considering a monoethanolamine (MEA) solvent, the CO_2 is absorbed by MEA at approximately 1 bar and 40-60 °C with an efficiency of 85-95%, in an exothermic reaction (Reiter and Lindorfer, 2015; Tang and You, 2018). In the stripper, a reverse reaction regenerates the solvent and CO_2 is transferred back to the gaseous phase. For MEA solvent, the CO_2-rich solution is heated to 100-140°C at a pressure close to 1 bar to recover the solvent (Madeddu et al., 2019). The CO_2 is then condensed from the gas stream, allowing the CO_2 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 recover solvent, post desorption, is recycled back to the absorber (Pour et al., 2018).

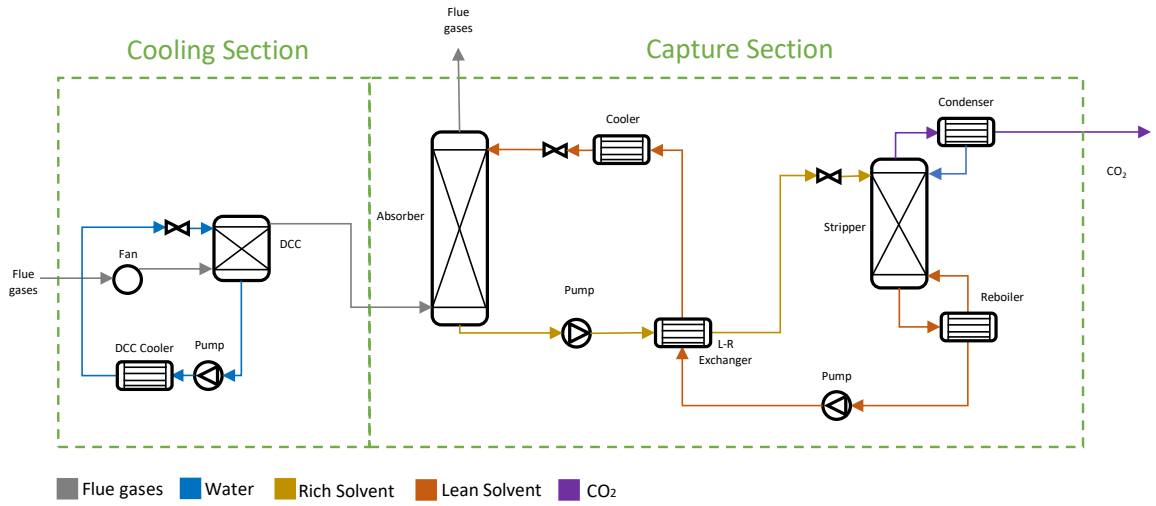


Figure 6 - Flow sheet of the chemical absorption process for CO_2 capture with the cooling and capture section.

The main energy penalty induced on the plant by the CO_2 capture process is linked to the steam required to recover the solvent (Bisinella et al., 2021; Husebye et al., 2012). There are several solvents available from different manufacturers, and the main difference among them is the amount of heat required for regeneration. Table 1 lists the amine-based solvents available in the market, along with the heat required for their regeneration.

Table 1 - List of the amine-based solvents available in the market along with the heat required for their regeneration.

Technology	Producer	Heat duty (GJ /tCO_2)
MEA	Commercially available	4 (Markewitz et al., 2012)
TS-1	Toshiba	2.6 (Saito et al., 2014)
H3-1	Hitachi	2.4 (Honoki et al., 2013)
S21	Aker	2.8 (Gorset et al., 2014)
DC	Shell	2.6 (Singh and Stéphenne, 2014)

3.3.3 Carbon Capture and Utilization (CCU)

In CCU systems, the captured CO_2 can be used directly without conversion in the food and beverage sector or, with conversion, in the production of fuels and chemicals. Figure 7 provides an overview of the destinations present in the literature. The use of CO_2 can be divided into two categories: applications that require a conversion process and those that directly use CO_2. Conversion applications could integrate with the CO_2 capture system, eliminating the need for additional steps like compression and liquefaction.

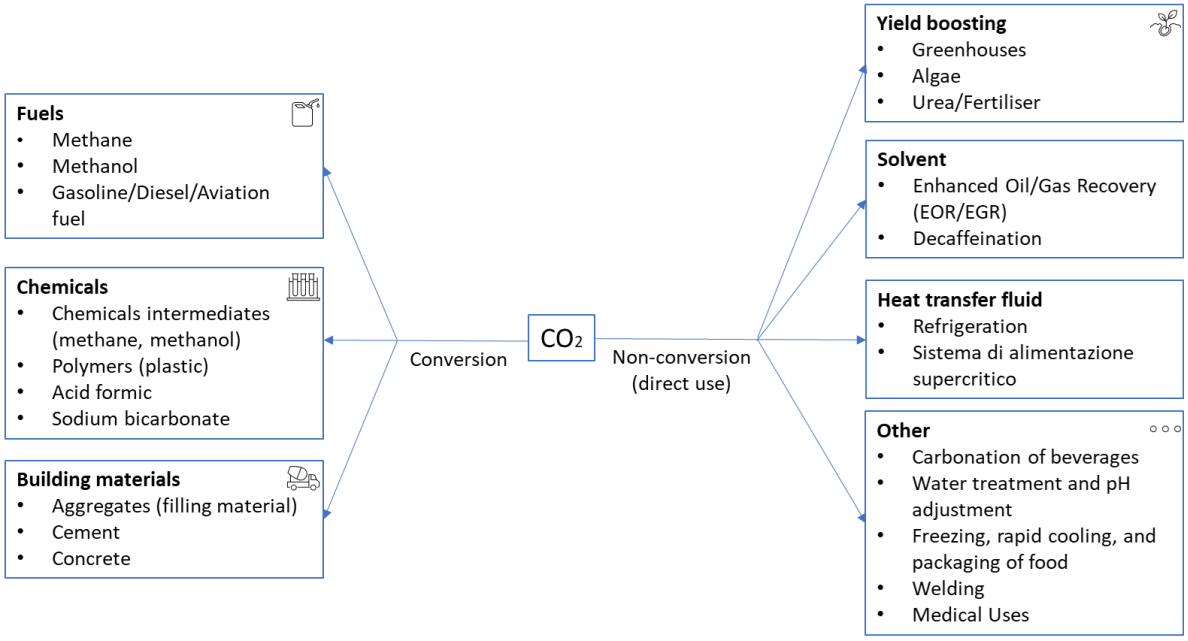


Figure 7 - CO_2 destination dived by conversion or non-conversion (direct use) (ECOFYS, 2017; IEA, 2019). In conversion applications, CO_2 is transformed into a new product, such as methane or methanol. While in non-conversion applications, CO_2 is used directly.

CO_2 can be used to optimize the yield of biological processes in greenhouse horticulture, which can increase productivity up to 30% (Incrocci et al., 2008). This technique is commonly used in the cultivation of tomatoes, cucumbers, peppers and aubergines. The amount of carbon dioxide that can be used per hectare is 300 tCO_2/ha/year (TNO, 2015). The CO_2 is also used in algae farming to produce biomass for feed, food or biochemical industries (Saravanan et al., 2022).

CO_2 is used in the conservation of food by substituting air with CO_2 to reduce degradation. In the carbonation of beverages, CO_2 is added to soft drinks and water (Descoins et al., 2006). In freezing, CO_2 is used as a coolant in refrigerators and cooling facilities or as dry ice for specific purposes. In the food and beverage industry, CO_2 is classified as a food additive and is identified by code E290, as per European regulation 231/2012 (European Parliament, 2012). This regulation defines the specifications for food additives and affirms that CO_2 used as a food additive must have a purity of 99%. Whereas the European industrial gases association (2017) provide a guideline for the pollutants that need to be controlled in CO_2 used in food and beverages, based on the CO_2 source.

In the construction sector, there are new technologies that can incorporate CO_2 into building materials. The CO_2-curing process is one of the most promising techniques, in which CO_2 is used in the hardening process of concrete (Zhan et al., 2018). Carbonation of residual materials from other industrial processes is another technique. In EOR/EGR, the CO_2 is used to enhance the extraction of the oil or gas from oil or gas sites (Kumar et al., 2024). In the chemical sector, CO_2 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, the CO_2 is used to produce fuels like methane and methanol through CO_2 synthesis and hydrogenation (Agora Energiewende, 2018).

3.3.4 Carbon Capture and Storage (CCS)

CCS systems involve capturing CO_2 emissions from flue gases and storing them in a permanent and secure way (Tan et al., 2016). These systems could be an effective way to achieve a negative balance in emissions for WtE incineration plants, as it captures and stores the biogenic CO_2 (Christensen et al., 2009; Creutzig et al., 2015; Gough and Upham, 2011; Materazzi et al., 2024; Pour et al., 2018). CCS includes a conditioning section, where impurities are removed and the captured CO_2 is compressed, liquefied, and temporarily stored. The design of a conditioning system must carefully consider the composition of CO_2 mixtures and process constraints, including the working condition and impurity limits (Aspelund and Jordal, 2007). The transport step to the storage location must also be considered and CO_2 can be transported to storage sites by pipeline, ships or tanker trucks, depending on the distance (Luo et al., 2014). For the permanent storage, there are two ways: geological and ocean storage. Geological storage can be done by injecting CO_2 into deep saline aquifers, exhausted oil or gas wells or unexploitable coal layers (Metz et al., 2005).
According to the study by the Center for Economic Studies (Golombek et al., 2021b) 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 CO_2. Indeed, the cost incurred for capture, transport, and storage would be lower than the carbon tax, leading companies to save money.

3.4 WtE incineration plant with CCUS

Currently, five companies have implemented a CCUS system in a WtE incineration plant, as summarized in Table 2. These company 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 CO_2 capture system in their WtE in Duiven (The Netherlands) which has the capacity to capture 60 kt of CO_2 per year. The captured CO_2 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 CO_2 per year (de Vries et al., 2020). The CCU system works by capturing CO_2 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 SO_2 (Huttenhuis et al., 2016). The CCU system produces 8 kt of SBC annually, capturing approximately 2-3% of the total CO_2 in the flue gas (Huttenhuis et al., 2016). 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 CO_2 annually. Klemetsrud has implemented a CO_2 capture pilot plant in their WtE plant in Oslo (Norway). The main objective of this project was to test the efficiency of CO_2 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 CO_2 capture, with the aim of capturing over 400 kt of CO_2 annually (Fagerlund et al., 2021). Saga City (Japan) has implemented a CCU system that uses the aqueous amine solvent to capture 2.5 kt of carbon dioxide each year. The captured CO_2 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 CO_2 from the plant's flue gases (CCS Institute, 2018).

Table 2 - Global overview of CO_2 Capture projects in WtE incineration plants.

Country	Company	(WtE) Waste processed (t/year)	Project status	Type	Captured CO_2 (kt/year)	Configuration	Capture Technology	Destination
The Netherlands	AVR	Duiven 360.635	Operational	Large scale	60	Post combustion	Absorption	Greenhouse horticulture
		Rozenburg -	Feasibility Study	Large scale	-	"	"	Ongoing study based on the pilot
	HVC	Alkmaar -	Operational	Pilot	4	"	"	Greenhouse horticulture
			Feasibility Study	Large scale	75	"	"	Ongoing study based on the pilot
	Twence	Hengelo 608.000	Operational	Pilot	2	"	"	Sodium bicarbonate
			Under construction	Large scale	100	"	"	Study on greenhouse horticulture, formic acid production, and construction material carbonation
Norway	Fortum	Klemetsrud -	Operational	Pilot	-	"	"	Geological storage in the North Sea
			Feasibility Study	Large scale	400	"	"	Ongoing study based on the pilot
Japan	Saga City	Saga City 74.010	Operational	Pilot	2.5	"	"	Algae cultivation

Table 2 shows that WtE plants use only post-combustion configuration to capture CO_2 for retrofitting applications. This is because post-combustion is a mature and simple technology, making it a suitable choice for retrofitting existing plants (Leung et al., 2014; Metz et al., 2005). As shown in Table 2, 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 CO_2 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 CO_2. This is probably due to the country's CO_2 market in greenhouse horticulture, which accounts for 1.2 million tons of CO_2 annually (TNO, 2015). Additionally, the Dutch government is committed to innovative and sustainable CO_2 management strategies and private companies are actively involved in developing the CO_2 sector. In 2006, as part of Dutch government 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 (Ros et al., 2014). 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 CO_2 management strategies. The Phortos project has been initiated along with the OCAP project (Porthos, 2024). The aim of this project is to establish the Port of Rotterdam CO_2 Transport Hub and Offshore Storage facility. The primary objective of this collaboration is to capture, utilize, and store CO_2. The CO_2 extracted from the plants associated with the OCAP will be the primary source of CO_2. A portion of the captured CO_2 will be utilized for greenhouse farming to enhance plant growth, while the remaining CO_2 will be compressed and stored in a depleted gas site located in the North Sea.

3.5 Italian Case

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 CO_2 capture with permanent storage (CCS) and the reuse of captured CO_2 (CCU) to balance any remaining greenhouse gases by 2050 (Governo Italiano, 2021). CCUS technologies offer a way to capture CO_2 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 CO_2, which is used in food and industrial applications, is estimated to be around 285 kt, according to Table 3 of Italian production data. Production usually meets the market demand, except during specific periods like summer months when demand exceeds supply (Nippon Gases). The table also shows that CO_2 production capacity is classified into two categories: CO_2 from chemical plants, which represents 66% of the total production (about 188 kt per year), and CO_2 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 CO_2 per year, as mentioned above.

Table 3 - Annual CO_2 Capture capacities by Company and Location. This table lists various companies across Italy, highlighting their locations, sources of CO_2 (geothermal or chemical plant), and their CO_2 capture capacities.

Company/Group	Location	Source of CO_2	Capacity (kt_{CO2} /year)
AIR LIQUID	S. Albino (SI)	Geothermal	27
	Rapolano (SI)	Geothermal	14
NIPPON GASES	Castelnuovo Berardenga (SI)	Geothermal	46
	Ferrara	Chemical plant	82
S.I.A.D.	Montefiascone (VT)	Geothermal	10
	Osio Sopra (BG)	Chemical plant	5
SAMAC	Ferrara	Chemical plant	25
	Scarlino (GR)	Chemical plant	25

SAPIO	Mantova	Chemical plant	4
SOL	Novara	Chemical plant	12
	Falconara (AN)	Chemical plant	35

Regarding CO_2 permanent storage, Italy produced the SEA (Strategic Environmental Assessment) in 2012 in response to the Directive 2009/31/EC (European Parliament, 2009b), which identified areas of the national territory and the exclusive economic zone suitable for geological CO_2 storage sites. However, sites for geological storage of CO_2 have not yet been identified and implemented, except for a recent project in the Adriatic Sea by Eni and Snam, with 500 Mton CO_2 storage capacity (Eni and Snam, 2024). 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.
Summarizing, national policies and strategies incentivizing the development of markets for CO_2 and the implementation of storage infrastructure are needed in view of building up a sustainable management of CO_2 emissions. Nevertheless, according to historical data from the European Environmental Agency's annual greenhouse gas (GHG) inventories (EEA, 2022), the total fossil CO_2 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 CO_2 emitted by all the sectors in Europe.

3.6 Conclusion

This chapter provides an overview of the integration of CCUS technologies with the 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 CO_2 emissions. This step aligns with the ambitious goals of achieving carbon neutrality in European waste management. The EU ETS Directive 2023/959 provides a plan to include the 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 CO_2 emissions.
Despite the promising prospects offered by CCUS integration within WtE incineration plants, challenges persist related to the availability of markets for captured CO_2 and the maturity of permanent storage solutions. Although the technology for capturing CO_2 exists, the lack of a destination (in terms of tons) for the captured CO_2 makes it difficult to implement, especially if CCUS is to be adopted by different industries to meet European goals (not only WtEs). Governments need to develop incentives, regulatory frameworks, and CO_2 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 CO_2 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 market for CO_2 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 CO_2 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 like the Netherlands, benefiting from a developed CO_2 market and an early commitment to CCUS technologies, and Italy, where the CO_2 market is still emerging and permanent storage solutions are just beginning to be explored, underscores the need for suited strategies to address these disparities.

4 Estimation of fossil and biogenic CO_2 emissions from a WtE incineration plant according to the Standard Method set by Monitoring and Reporting Regulation 2018/2066.

This chapter shows how to estimate the CO_2 emissions from a WtE incineration plant, following the standard method proposed by the MRR, using data gathered in 2022. By examining the complexity of CO_2 emission estimation from WtE incineration plants, this chapter contributes to the broader discussion on sustainable waste management. The chapter shows the calculation of the share of biogenic CO_2 emitted by the WtE incineration plant and the ratio between biogenic and fossil CO_2 due to the combustion of industrial waste, specifically mechanically separated rejects from pulping of waste paper and cardboard (Solid Refuse Fuel (SRF)).

4.1 Monitoring and Reporting Regulation (MRR) 2018/2066

The Monitoring and Reporting Regulation (MRR) 2018/2066 (European Parliament, 2018) presents two approaches for emission estimation: calculation-based, including the standard and mass balance methods, and measurement-based. The challenges in estimating emissions from WtE incineration plants lie in the heterogeneous composition of waste, which results, after waste combustion, in the emission of both biogenic and fossil CO_2, complicating the accurate estimation of fossil CO_2 emissions (Lee et al., 2018, 2021; Mohn et al., 2008). Biogenic CO_2, produced by the biodegradable part of waste such as paper, cardboard, wood, and green residues, is considered carbon neutral (Astrup et al., 2009) and is not counted as contributing to climate change, in line with the Intergovernmental Panel on Climate Change (Eggleston, 2006), EU ETS (European Parliament, 2023) and MRR (European Parliament, 2018).

The calculation-based method involves using activity data collected through measurement systems along with additional parameters obtained from laboratory analyses or standard values. On the other hand, the measurement-based method is based on direct measurements. In the case of biomass combustion, the MRR specifies the use of analysis and sampling techniques described by

EN ISO 13833 (International Standard, 2013) or ISO 18466 (International Standard, 2016). The EN ISO 13833 specifies sampling methods and analysis methods for the determination of the ratio of biomass- and fossil-derived CO_2 in the CO_2 from exhaust gases of stationary sources, based on the radiocarbon (^{14}C isotope) method (International Standard, 2013). On the other hand, ISO 18466 enables the determination of the biogenic fraction in CO_2 in stack gas using the balance method. The balance method uses a mathematical model that is based on different operating data of the WtE plant (including stack gas composition) and information about the elementary composition of biogenic and fossil matter present in the fuel used (International Standard, 2016). The choice between these methods depends on several factors, such as the required accuracy, costs, and system complexity.

4.2 Methodology

This section presents the methodology used to estimate the amount of fossil and biogenic CO_2 emitted by an existing WtE incineration plant, following the standard method proposed by the MRR. As per Chapter III, Section 1, Article 19 of the MRR, the WtE owner classifies the plant based on the total fossil CO_2 emitted and then identifies the source streams and emission sources. Depending on this classification, a specific procedure is followed, which is explained in detail in the following paragraphs. It's important to note that only the combustion of the waste biomass contributes to the emission of biogenic CO_2, which is not considered for EU ETS.

4.2.1 Waste-to-Energy incineration plant

The WtE incineration plant selected in this study is located in Italy and produces electricity through mechanically separated rejects from pulping of waste paper and cardboard (Solid Refuse Fuel (SRF)) combustion. The characteristics of the facility of a typical year are presented in Table 4.

Table 4 - Characteristics of WtE incineration plant. The values presented refer to a typical year.

Parameter	Unit	Value
SRF (Solid Refuse Fuel)	t/h	13.9
Net electrical power	MW	10.8
Flue gas flow rate	Nm^3/h	93080

Based on Chapter III, Section 1, Article 19 of the MRR, the owner has to categorize the plant's stationary installations according to the total fossil CO_2 emitted and identifies the source streams and emission sources. *Category*: The WtE incineration plant falls under category B due to its average annual emissions, which is more than 50 kt of CO_2 but less than 500 kt of CO_2. The count excludes CO_2 that comes from biomass but includes the transferred CO_2. *Source streams*: The plant has three emission sources: the boiler, which represents a major source, the gaseous effluent washing tower,

which is a *de minimis* source and the auxiliaries, which is always a *de minimis* source. *Emission sources*: (i) The boiler is the primary source of emissions, and the fuels used include Solid Refuse Fuel, made up of a percentage of biomass that does not produce emissions, and methane. (ii) The gaseous effluent washing tower uses sodium bicarbonate, which are responsible for producing the remaining CO_2 emitted, as also classified as process emissions. (iii) The auxiliaries include diesel fuel for the electric generator set and diesel fuel for the fire pumps. Table 5 shows the classification of the WtE incineration plant, and the source streams and emission sources identified.

Table 5 - Classification of the WtE incineration plant and the source streams and emission sources identified.

Category	Source streams	Emission sources	Characteristics
B	Boiler	Solid Refuse Fuel (SRF) combustion	major source
		Methane combustion	*de minimis*
	Gaseous effluent washing tower	Sodium bicarbonate	*de minimis*
	Auxiliary	Diesel for electric generator	*de minimis*
		Diesel for fire pumps	*de minimis*

4.2.2 Applicable tiers

Once the plant is categorized and its source streams and emission sources are identified, the tiers must be identified. The tiers are defined by Chapter III, Section 2, Article 26 of the MRR. For category B plants and major source streams, the highest level defined in Annex II should be used. For de minimis source streams, the owner can use conservative estimates based on activity data and calculation factors.

MRR allows three tiers. Tier 1 requires standard factors for estimating CO_2 emissions, while Tier 2 requires country-specific factors based on fuel type. Tier 3 requires fuel analysis data to estimate CO_2 emissions and requires that the analysis be performed at a specific frequency. Chapter III, Section 3, Article 35 establishes frequencies for analyzing fuels and other materials. Solid fuel must be analyzed every 10 kt of waste treated.

For our case study, each source stream required a specific tier, which will be shown in the following paragraphs.

4.2.3 Estimation of emissions resulting from SRF combustion

In this section, it is discussed the method and calculation factors used to estimate the amount of CO_2 emitted from the combustion of SRF. The fossil CO_2 (FCO_2E) emission is calculated using Equation 1, while the biogenic CO_2 (BCO_2E) emission is calculated using Equation 2. Finally, the total CO_2 emission (FCO_2E) is determined using Equation 3.

$$FCO_2E(t) = FQ(t) * NCV\left(\frac{TJ}{t}\right) * EF_{PRE}\left(\frac{tCO_2}{TJ}\right) * (1 - BF(\%)) * OF \quad (1)$$

$$BCO_2E(t) = FQ(t) * NCV\left(\frac{TJ}{t}\right) * EF_{PRE}\left(\frac{tCO_2}{TJ}\right) * BF(\%) * OF \quad (2)$$

$$TCO_2E(t) = FQ(t) * NCV\left(\frac{TJ}{t}\right) * EF_{PRE}\left(\frac{tCO_2}{TJ}\right) * OF \quad (3)$$

where FQ is quantity of SRF processed, NCV is the net calorific value, EF_{PRE} is the preliminary emission factor, calculated as written in Equation 4, BF is the biomass fraction of the total carbon content and OF is the oxidation factor.

$$EF_{PRE}\left(\frac{tCO_2}{TJ}\right) = (1 - H(\%)) * CC\left(\frac{ton\ C}{t\ ds}\right) * \frac{1}{NCV\left(\frac{TJ}{t}\right)} * 3.664\ \frac{t\ CO_2}{t\ C} \quad (4)$$

where H is humidity, CC is the carbon content express as dry solid and the factor 3.664 derived from the ratio between molar mass of CO_2 (44.01 g/mol) and molar mass of C (12.01 g/mol).

Each parameter in the Equation 1, 2, 3 and 4 are estimated using the tiers presented in Figure 9.

Table 6 - Tiers applicable for each factor.

Parameter	FQ	NCV	EF_{PRE}	BF	OF
Tiers	4	3	3	3	3

For the quantity of SRF processed (FQ), to comply with MRR 2018/2066 for solid fuels and Category B, tire 4 is necessary. This means measuring devices with a maximum uncertainty of less than 1.5% are required. At the plant entrance, there are two scales to measure the SRF. For the Net Calorific Value (NCV), Preliminary Emission Factor (EF_{PRE}), biomass fraction (BF) and oxidation factor (OF) tier 3 is adopted. This means that for all these factors the values resulting from the laboratory analysis are used. The parameters and method used for analysis are shown in the Table 7.

Table 7 - Method used for the analysis on the SRF.

Symbols	Parameters	Method	U.M.
H	Humidity	UNI EN 15414-3:2011	%
NCV	Net Calorific Value	ISO 21654: 2021	TJ/t
CC	Carbon Content	UNI EN 15407:2011	% ds
BF	Biomass fraction of the total carbon content	UNI EN 21644:2021 Annex B	%

The chosen analysis frequency is weekly, around 2.5 kt of waste treated.

4.2.4 Estimation of emissions resulting from methane combustion

The combustion chamber operates at a temperature exceeding 850°C. This is required to prevent the formation of dioxin precursors during the incineration process, as required by Directive 2010/75/EU (European Parliament, 2010). To assist the incineration process, two methane burners are used. These burners are activated if the temperature inside the combustion chamber falls below 850°C and during the starting phase.

The fossil CO_2 emission (FCO_2E) is determined using Equation 5:

$$FCO_2E(t) = FQ(Nm^3) * NCV\left(\frac{TJ}{Nm^3}\right) * EF\left(\frac{tCO_2}{TJ}\right) * OF \quad (5)$$

The applicable levels for activity data and calculation factors are shown in Table 8.

Table 8 - Tiers applicable for each factor.

Parameters	FQ	NCV	EF	OF
Tiers	4	2a	2a	1

For compliance with MRR requirements for liquid and gaseous fuels, Tier 4 mandates the use of measuring devices with a maximum uncertainty of less than 5% for measuring the quantity of processed methane (FQ). In our case, the consumption of methane is taken from the consumption reported on the bills provided by the supplier. Net Calorific Value (NCV) and Emission Factor (EF) required tier 2a. According to this, the owner should utilize country-specific factors for each fuel type, following the guidelines in Article 31(1)(b) and (c). Alternatively, the values determined in accordance with Article 31(1)(d) can also be used. The Net Calorific Value and Emission Factor used in our case are adopted from the national emissions inventory and are equal to 0.000037 TJ/Nm^3 and 56.2 tCO_2/TJ, respectively. Furthermore, for the Oxidation Factor (OF), tier 1 is used, and therefore, the Oxidation Factor used is 1.

4.2.5 Estimation of process emissions

In the process of cleaning flue gases to remove acidic pollutants, sodium bicarbonate is used. This results in the neutralization of acids present in the flue gases and the production of carbon dioxide. The fossil CO_2 emission (FCO_2E) is determined using Equation 6:

$$FCO_2E(t) = FQ(t) * EF\left(\frac{tCO_2}{t}\right) * CF \quad (6)$$

The applicable levels for activity data and calculation factors are shown in Table 6.

Table 9 - Tiers applicable for each factor

Parameters	FQ	*EF*	CF
Tiers	Estimation	Estimation	Estimation

The amount of sodium bicarbonate (FQ) used in the flue gases cleaning system is determined from the supplier invoice. The Emission Factor (EF) is calculated using the standard factor listed in Annex VI, section 2, table 2, which is 0.52 tCO_2/t. Finally, the conversion factor (CF) is set to 1.

4.2.6 Estimation of emissions for auxiliaries

Diesel fuel is used to power the electric generator and fire pumps, and its combustion causes the emission of CO_2 into the atmosphere. The carbon dioxide emitted is estimated according to equation 7:

$$FCO_2E(t) = FQ(t) * NCV\left(\frac{TJ}{t}\right) * EF\left(\frac{tCO_2}{TJ}\right) * OF \quad (7)$$

The applicable levels for activity data and calculation factors are shown in Table 10.

Table 10 - Tiers applicable for each factor.

	Parameters	FQ	NCV	*EF*	OF
Diesel for electric generator	Tiers	Estimation	Estimation	Estimation	1
Diesel for fire pumps	Tiers	Estimation	Estimation	Estimation	1

The quantity of diesel (FQ) used for the electric generator and fire pumps is estimated based on the data provided in the supplier's invoice. An estimated value is used for the Net Calorific Value (NCV) and Emission Factor (EF). For the Oxidation Factor (OF), tier 1 is used, which means that the Oxidation Factor used is 1.

4.3 Results and discussions

This section presents the findings of the CO_2 emission estimation using the Standard Method set by MRR. The emission estimation results indicate that the WtE incineration plant has emitted 92663 t of fossil CO_2 and 53903 t of biogenic CO_2.

The total CO_2 emitted is 146566 t, with SRF combustion accounting for 98.5% of the total. Figure 8 shows the CO_2 emission due to the combustion of SRF during the 52 weeks of 2022. Biogenic CO_2 is equal to 63%, while Fossil CO_2 is equal to 37%.

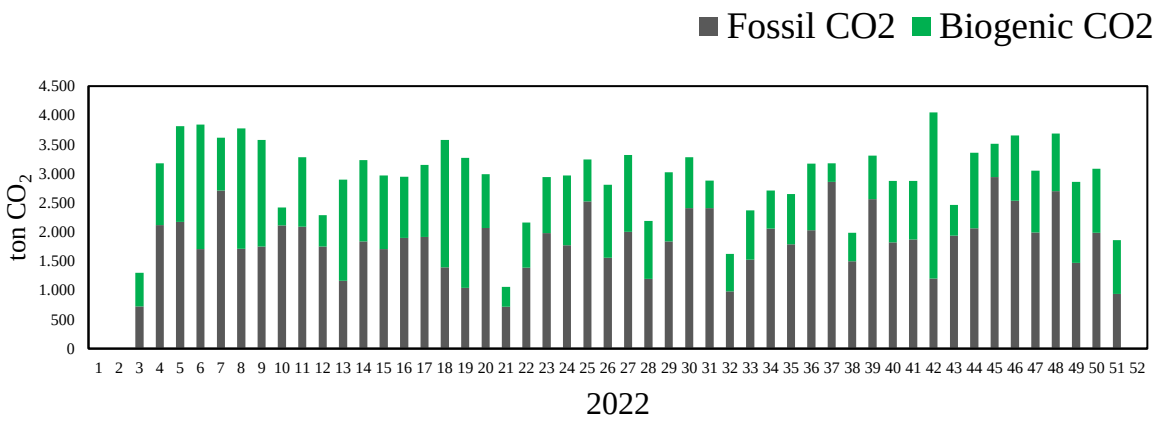


Figure 8 - Fossil and Biogenic CO_2 emitted by WtE incineration plant under analysis.

4.4 Conclusion

This chapter shows how to estimate the CO_2 emissions from a WtE incineration plant using data gathered in 2022, following the standard method proposed by the Monitoring and Reporting Regulation 2018/2066. It explains the complexity of CO_2 emission estimation from WtE incineration plants and shows that most of the emissions from a WtE plant are biogenic and, thus, do not contribute to the overall CO_2 emissions in the atmosphere.

5 Techno-economic assessment of amine-based carbon capture in WtE incineration plant retrofit.

This chapter presents the results of an assessment of the integration of post-combustion absorption technology using MEA in a real WtE incineration plant. The assessment is based on real operating data, which includes net power production, operating hours, flue gas flow rate, and flue gas compositions. The study aims to determine the technical and economic feasibility of a small-scale Carbon Capture system for various sizes (3000, 6000, and 12000 t of CO_2 per year) and provides valuable insights for similar implementations. This chapter deals with the design and cost estimation of CC and provides a perspective on their integration of WtE incineration plants, whereas the potential end-uses of the captured CO_2 are behind the scope of the chapter.

5.1 Methodology

This section presents the methodology adopted for the design of the Carbon Capture system (scheme and simulation) and the cost estimation approach focusing on the existing WtE incineration plant.

5.1.1 Waste-to-Energy incineration plant

The WtE incineration plant selected in this study is located in Italy and produces electricity through the combustion of Solid Refuse Fuel (SRF). The facility has three incineration lines, with the Carbon Capture system hypothetically integrated into one of these lines. High-pressure steam is generated at conditions of 42 bar and 415°C from the energy recovery system and is subsequently directed to a turbine for electricity production. The plant's annual operational time is assumed to be 8000 hours to account for any scheduled or unscheduled maintenance. The cooling system offers an average water temperature of 40°C. Detailed characteristics of the facility, and average values of a typical year of flue gases produced and macro-composition of the flue gases are presented in Table 11.

Table 11 - Characteristics of Waste-to-Energy incineration plant and macro-composition of the flue gases. The values presented refer to the average of a typical year.

Parameter	Unit	Value
Operative time	h/y	8000
CO_2 emission	t/y	119747
Flue gas temperature	°C	131.5
Flue gas pressure	bar	1.006
Biomass-derived	%	58
SRF (Solid Refuse Fuel)	t/h	12.5
Net electrical power	MW	10.8
Flow rate	Nm^3/h	86027
CO_2	vol.%	8.9
O_2	vol.%	10.3
H_2O	vol.%	14.0
N_2	vol.%	66.8

After having passed thermal recovery, the flue gases generated by combustion move through an advanced flue gas treatment system, crucial to minimize the environmental impact (Dal Pozzo et al., 2023; Vehlow, 2015). The system includes the following components: (i) an electrostatic precipitator, which serves as the first stage in dust removal from the boiler flue gases; (ii) a dry reactor that employs sodium bicarbonate to eliminate acidic pollutants; (iii) a bag filter, acting as the second stage of flue gas filtration post-reactor in dust removal; (iv) a DeNOX unit that utilizes Selective Catalytic Reduction (SCR) technology to reduce NOx emissions by injecting an ammoniacal solution counter-current to the flue gases. Continuous monitoring and analysis of the cleaned flue gases are performed to ensure agreement with regulatory emission standards. Contaminants and pollutants such as CO, NH3, NOx, and SOx were neglected.

5.1.2 Carbon Capture system scheme

Figure 9 provides a detailed overview of the Carbon Capture system integrated into the WtE plant. The process is divided into distinct phases, each with a specific role. Firstly, the flue gases produced in the WtE are cooled in the 'Cooling Section' to ensure an optimal temperature for the subsequent capture stage. Then, in the 'Capture Section', the CO_2 from the cooled gases is effectively captured with the amine-based solvents. The electrical and thermal energy required for the capture process is directly sourced from the WtE plant.

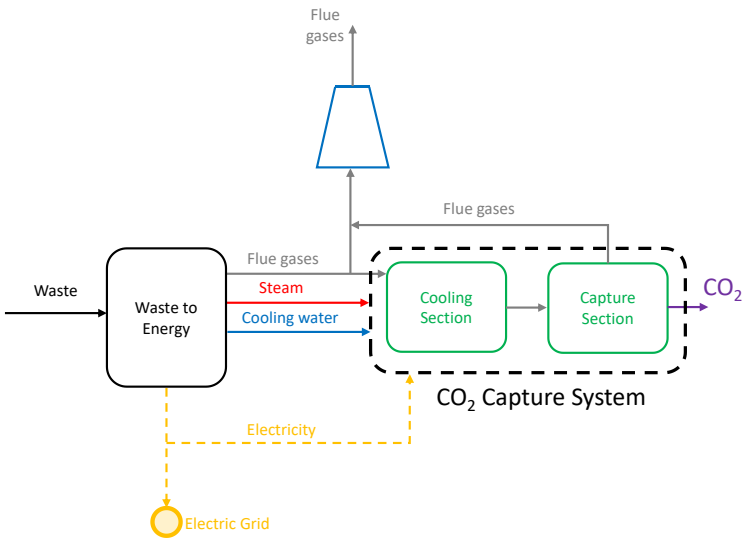


Figure 9 - Flow diagram of CO_2 Capture system integrated with a WtE incineration plant.

Figure 10 shows in detail the components present in each section. 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, C-101), in which the water from the secondary circuit is used to lower the temperature of the flue gas (directed towards the absorber). The water that exits the DCC is then cooled via a local cooling circuit. In the Capture Section, the system includes two main components: the absorber (C-201) and the stripper (C-202). In the absorber (C-201), the carbon dioxide is transferred from the vapor/gas phase to the liquid by the reaction between the CO_2 and the solvent. In the stripper (C-202), on the other hand, a reverse reaction regenerates the solvent and CO_2 is transferred back to the gaseous phase. A cross heat-exchanger (E-201) interconnects the two main components. This configuration differs from the classic absorption-regeneration process used in literature (Alie et al., 2005; De Miguel Mercader et al., 2012; Nittaya et al., 2014; Seader et al., 2011; Singh et al., 2003; Sinnott, 2005), since the water from the condenser (E-203) is not recycled back to the top of the stripper as reflux but it is instead direct to the Water-Wash (C-203). This choice is motivated by energy-saving reasons, in line with Madeddu et al. (2019) and Oexmann and Kather (2009). Then, the CO_2 captured is directed to the following section.

Typical values for the absorption efficiency range from 75% to 95% (Metz et al., 2005; Notz et al., 2012). Considering the amount of CO_2 needed and the fact that deep decarbonization of the process is not the goal of this work, a CO_2 capture efficiency of 85% was chosen. We simulated low-scale CC system of different sizes: 3000, 6000, and 12000 t of CO_2 per year. The choice of the CC system sizes here considered was based on the following considerations: the lowest size (3000 t CO_2/y) was considered equal to those adopted in the above-mentioned pilot projects (Fagerlund et al., 2021; Huttenhuis et al., 2016), whereas the highest size was limited to 12000 t CO_2/y in order to avoid extreme WtE efficiency reduction (please consider that the power required for CC system is obtained from the extraction of turbine steam as described in section 4.2.3). Considering the objective of efficiency and the size of the CC system, the flow was partialized as follow: 2.95% (i.e.

2538 Nm3/h), 5.90% (i.e. 5076 Nm3/h), and 11.80% (i.e. 10151 Nm3/h) for 3000, 6000, and 12000 t CO_2/year plant size, respectively.

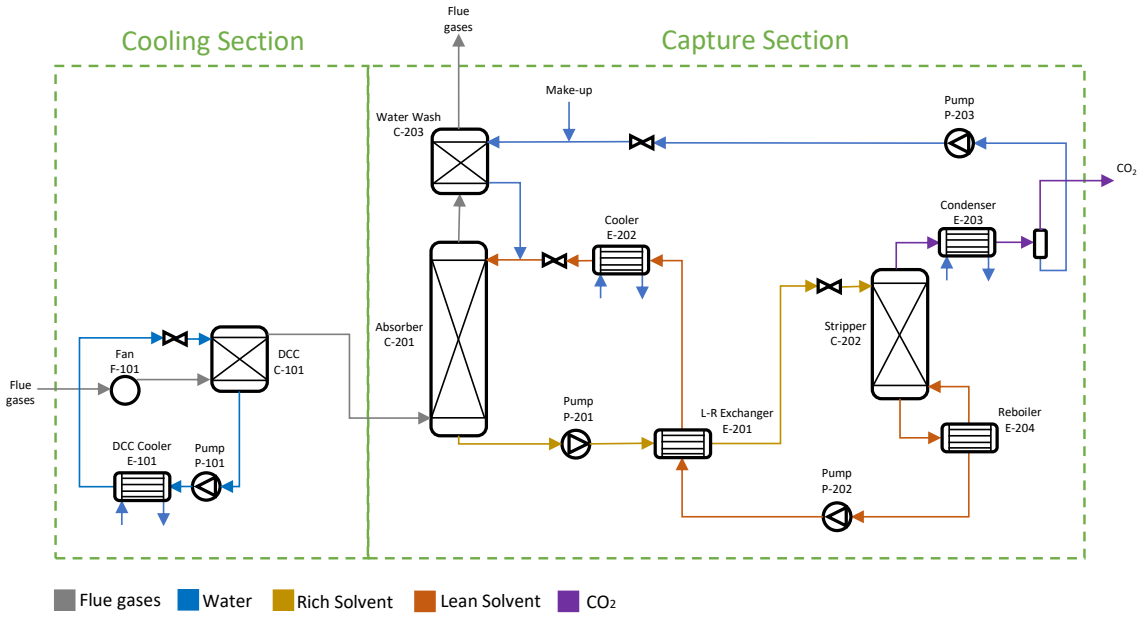


Figure 10 - Absorption and desorption process for CO_2 removal with MEA technology.

5.1.3 Carbon Capture system simulation

The Carbon Capture system was modelled using Aspen Plus. The equipment size is crucial for the equipment cost (Smith, 2005), highlighting the importance of this factor in the design and economic feasibility. The design of the Cooling and Capture sections follows the approach delineated in the work of Madeddu et al. (2019). This involves designing a post-combustion CO_2 capture facility utilizing MEA for reactive absorption and stripping, with a RedFrac model to determine the appropriate dimensions for both the absorption and stripping columns.

For the evaluation of thermodynamic properties in the liquid phase, the Electrolyte-Non-Random-Two-Liquid (Electrolyte-NRTL) model was employed, given its suitability for describing the electrolytic interactions inherent to the CO_2-MEA-H_2O system (Austgen et al., 1989; Biliyok et al., 2012; Errico et al., 2016; Kvamsdal and Rochelle, 2008; Lawal et al., 2009; Liu et al., 1999; Moioli et al., 2012; Plaza et al., 2009; Posch and Haider, 2013; Razi et al., 2013). In contrast, for the calculation of non-ideal behaviour in the vapour/gas phase, the Redlich-Kwong Equation of State was implemented, consistent with findings in existing literature (Austgen et al., 1989; Errico et al., 2016; Lawal et al., 2010).

Concerning chemical reactions, the model incorporates both kinetic and equilibrium reactions in line with the literature (Aboudheir et al., 2003; Errico et al., 2016; Meldon and Morales-Cabrera, 2011; Moioli et al., 2012; Razi et al., 2013; Tobiesen et al., 2007). Specifically, the model considers a set of three equilibrium reactions (Eq. 8, 9 and 10) and two kinetic reactions (Eq. 11 and 12):

$$2H_20 \leftrightarrow H_3O^+ + OH^- \quad (8)$$

$$CO_2 + 2H_20 \leftrightarrow HCO_3^- + H_3O^+ \quad (9)$$

$$MEA + HCO_3^- \leftrightarrow MEACOO^- + H_20 \quad (10)$$

$$MEA + H_3O^+ \leftrightarrow MEA^+ + H_20 \quad (11)$$

$$HCO_3^- + H_20 \leftrightarrow CO_3^{--} + H_3O^+ \quad (12)$$

For what concerns the equilibrium reactions, for the determination of the equilibrium constants were determined according to Standard Gibbs free-energy change (Eq. 13):

$$K_{eq} = exp\left(-\frac{\Delta G^0}{RT^L}\right) \quad (13)$$

where the values of the ΔG^0 are retrieved from the software database.
On the other hand, for kinetic reactions, the default expression in the software is the classic power law, where the kinetic constants are expressed utilizing the Arrhenius law (Eq. 14):

$$k = k^0\left(-\frac{E_a}{RT^L}\right) \quad (14)$$

The models adopted for each component illustrated in Figure 10 are described below.

- Fan (F-101): The pressure is set to overcome flue gas pressure drops passing through the DCC (C-101), Absorber (C-201) and Water-Wash (C-203), with a required total pressure of 1.18 bar. The isentropic efficiency is set to $\eta_{is} = 0.75$.
- DCC (C-101): The DCC is modelled using a RedFrac model. A packed column is selected. The cooling water temperature is set at 50°C due to the availability of a heat exchanger for water cooling, which operates at 40°C per the plant's available temperature.
- Absorber (C-201): The operational pressure within the absorber is set to 1.1 bar, and the lean solvent loading is fixed at 0.3 mol CO_2/mol MEA, reflecting an average of values reported in the literature (Abu-Zahra et al., 2007; Cau et al., 2014; De Miguel Mercader et al., 2012; Lawal et al., 2012; Nittaya et al., 2014). In line with the methodology defined by Madeddu et al. (2019), the design of the absorber proceeds by first determining the minimum solvent flow rate $\left(L_0^{min}\right)$ and the column diameter, assuming an infinite packing height. Subsequent steps include assessing the effective packing height, which considers a range of solvent flow rates using the equation $L_0^{eff} = (1 \div 2) \cdot L_0^{min}$. This is followed by analysing the temperature profile of the liquid and the CO2 vapor composition to verify the absence of isothermal zones within the column, in line with Kvamsdal and Rochelle (2008) and Seader et al. (2011). For our Absorber, the effective packing height is chosen based on a liquid flow rate of $1.2 \cdot L_0^{min}$ across all size. A packed column is selected for the absorber due to its higher contact area and less pressure drop compared to plate columns, as suggested by Madeddu et al. (2019).

- Stripper (C-202): The stripper operates in combination with the Reboiler (E-202) and the Condenser (E-203). In the stripper, high temperatures help dissociate CO2 from the MEA (Freguia and Rochelle, 2003), but temperatures must not exceed 110°C to prevent solvent degradation (Davis and Rochelle, 2009). Therefore, pressure is adjusted to keep the boiling point below this threshold, resulting in an operating pressure of 1.8 bar. The criterion for determining the minimum packing height is based on the analysis of liquid temperature profiles and temperature gradients (always maintained above 0.5°C/m), following the methodology of Madeddu et al. (2018). Regarding the condenser temperature (E-203), given the availability of cooling water at 40°C, it is set to 50°C.
- Water-Wash (C-203): The Water-Wash column is designed to recapture a portion of the vaporized solvent (MEA) from the flue gases leaving the absorber. In this configuration, MEA is physically reabsorbed by the condensed and make-up water, which together determine the solvent flow rate within this column. The maximum allowable concentration of MEA is set at 3 ppm, in line with the material safety data sheet from Dow Chemical Company (2023). The diameter of the column is equal to the absorber diameter since both the water-wash section and the absorber are inside the same vessel.
- Exchangers: DCC Cooler (E-101), L-R exchange (E-201), Cooler (E-202), Condenser (E-203) and Reboiler (E-204): For the L-R exchange (E-201), the temperature is fixed to the boiling point since it is typical for the stripper to send the feed as a saturated liquid (Seader et al., 2011; Sinnott, 2005). The heat transfer areas of the heat exchanger are calculated based on the duties obtained from the simulation and a temperature approach $\Delta t = 10°C$. Overall, the heat transfer coefficients are assumed to be: for DCC cooler, 800 W/(m²K); for lean-rich exchange, 500 W/(m²K); for lean amine cooler, 800 W/(m²K); for the reboiler, 800 W/(m²K); for the condenser, 1000 W/(m²K) (Øi, 2012). Shell and tube heat exchangers are considered in this study, particularly the BEM type for E-101, E-201, E-202 and E-203 and the BKE type for E-204.
- Pump (P-101, P-201, P-202 and P-203): P-101 is configured with an output pressure of 4 bar, essential for water circulation within the cooling system. P-201 is configured with an output pressure of 7 bar to prevent CO_2 flashing in the heat exchanger. P-202 and P-203 are set to operate at an output pressure of 6 bar. All these pumps are centrifugal types. Their isentropic efficiency is set to $\eta_{is} = 0.75$.
- Valve (V-101, V-201, V-202 and V-203): They are needed to equalize the stream pressure to the operating column to which they are fed.

Table 12 presents the main simulation parameters for the CO_2 capture plant, which are valid for various system sizes.

Table 12 - Simulation parameters for a CO_2 capture plant, valid for various system sizes.

Simulation parameter	Unit	Value
Flue gas temperature from the process	°C	131.5

Absorber: inlet flue gases temperature	°C	52
Absorber: inlet flue gases pressure	bar	1.13
Lean solvent: temperature	°C	50
Lean solvent: pressure	bar	1.1
Lean Solvent: MEA Content	Mass-%	30
Lean Solvent: CO2 Content	Mass-%	6.5
Stripper: inlet rich temperature	°C	98
Stripper: pressure	bar	1.8
Reboiler: temperature	°C	120
Exchanger: ΔT	°C	10

5.2 Cost estimation

This section presents the cost estimation approach for our amine-based carbon capture system, following the methodology presented by Ali et al. (2019). The estimation process is divided into capital cost (Capex) and operational cost (Opex) estimation, with each category requiring specific calculations and consideration.

5.2.1 Capital cost (Capex) estimation

It is essential to specify that in the Capex assessment, the initial focus is on the equipment purchase cost, followed by the installed equipment cost. The Aspen Process Economic Analyzer was utilized to estimate the purchase cost, whereas the Enhanced Detailed Factor method was used to estimate the installed cost. For the Capex estimation, we employ the Aspen Process Economic Analyzer, based on process simulation outcomes, to determine equipment costs. This tool provided cost data based on 2018 price levels within the European market. Meanwhile, the Enhanced Detailed Factor method, developed by Nils Henrick Eldrup at USN and Sintef Tel-Tek, is applied to estimate the installed costs in Norwegian Kroner (NOK). This method includes a comprehensive range of expenses, such as direct (f_{direct}), engineering (f_{engg}), administrative ($f_{edministration}$), commissioning ($f_{commissioning}$), and contingency costs ($f_{contingency}$). A summary table of the applied factors is presented in Appendix A.

In line with (Ali et al., 2019), the price obtained from Aspen in euros is converted to NOK, using the 2018 exchange rate, equal to 9.6 (CEIC, 2023), as the Aspen database and coefficients are valid for that year. Furthermore, it is essential to consider the material; all components are made of stainless steel, whereas the method is valid for carbon steel. Therefore, as suggested by Ali et al. (2019), we divide the price by corrective factors (f_{mat}) to account for the material: 1.3 for machined equipment (pumps, blowers and compressor) and 1.75 for welded equipment (columns and heat exchangers), as per Husebye et al. (2012). The method accounts for this by readjusting the coefficient (f_{mat}) in the price calculation. Then, the Equipment Installed Cost (EIC) for each piece of equipment is calculated:

$$EIC_{SS}(NOK) = Equipment\ Cost_{CS}(NOK) \cdot F_{Total,SS} \quad (15)$$

where $F_{Total,SS}$ is calculated by:

$$F_{Total,SS} = \left(f_{Total,CS} + \left((f_{mat} - 1) \cdot (1 + f_{piping})\right)\right) \quad (16)$$

where $F_{Total,CS}$ is calculated by:

$$f_{Total,CS} = f_{direct} + f_{engg} + f_{edministration} + f_{commissioning} + f_{contingency} \quad (17)$$

The Total Installed Cost (TIC) in NOK is the sum of all EICs, subsequently converted to euros using the 2018 exchange rate. Costs are updated to 2023 levels to reflect current economic conditions, considering European consumer price inflation, equal to 1.6% for 2019, 0.5% for 2020, 2.6% for 2021 and 8.8% for 2022 (Macrotrends Inflation, 2023). Additionally, the labor costs between Norway and Italy are adjusted, considering the ratio between Norway's GDP per capita (Macrotrends GDP Norway, 2023) and Italy's GDP per capita (Macrotrends GDP Italy, 2023). This coefficient effectively reduces the costs by approximately 33%.
It is essential for plant cost evaluation to calculate the Annualized Capex cost using the equation proposed by Ali et al. (2018), dependent on the interest rate (p) and plant operational lifetime (n):

$$Annualized\ factor = \sum_{n=1}^{20} \left[\frac{1}{(1+p)^n}\right] \quad (18)$$

We consider an interest rate of 7.5% and a plant's useful life of 20 years (2-year construction time and 18 years for operational lifetime). Using these values, we can calculate the Annualized Capex cost for the plant.
Then, the annualized installed cost (€/yr) is calculated by dividing the installed cost by the annualized factor:

$$Annualized\ Capex\left(\frac{€}{yr}\right) = \frac{Total\ Installed\ Cost}{Annualized\ factor} \quad (19)$$

5.2.2 Operational cost (Opex) estimation

Opex includes both fixed and variable components. Fixed operating costs primarily involve maintenance, considered at 4% of Equipment Installed Cost (EIC) (Ali et al., 2019), and labor expenses, which are essential for the consistent functionality of the system. The cost associated with labor expenses is considered null as it is integrated with the system already present in the plant. On the other hand, variable operating costs, being a function of the amount of CO_2 captured, cover consumption of utilities, such as electricity (GME, 2023), steam, cooling water and make-up of demineralized water and MEA (Ali et al., 2019). These costs are estimated based on utility

consumption rates obtained from process simulations and the corresponding utility costs listed in Table 13. A key consideration is that the cost of electricity is equal to the revenue lost from not supplying it to the grid, and the cost associated with steam usage is linked to the lost opportunity for electricity production, reflecting the inherent trade-offs in utility utilization within the plan.

Table 13 - Assumptions and Opex costs adopted to estimate the cost of the proposed CC system.

Parameter	Unit	Value
Plant life	year	20
Interest rate	%	7.5
Currency conversion	NOK/€	9.6
Operating hours per year	h	8000
CO2 removal efficiency	%	85
Maintenance	% of EIC	4
Electricity	€/MWh	128
Steam	€/t	12.1
Cooling water	€/m3	0.038
Demineralized water	€/m3	2
MEA	€/m3	1866

In our system, the steam required for releasing CO_2 from the solvent is sourced from medium-pressure turbine steam. The cost of this steam is directly linked to energy commodity prices, such as loss of production. Consequently, the steam cost is estimated based on the electricity production lost due to this extraction.
All operating costs are calculated using the general expression:

$$Yearly\ Utility\ Cost\left(\frac{€}{yr}\right) = Annual\ consumption\left(\frac{unit}{hr}\right) \cdot \frac{Opereting\ hours}{year} \cdot Utility\ price\left(\frac{€}{unit}\right) \quad (20)$$

where the unit can be in m^3, kg or kWh.

5.2.3 Key Performance Indicators

In assessing the effectiveness of CO_2 capture systems in WtE incineration plant, our study focuses on two fundamental parameters as key performance indicators: global energy efficiency and CO_2 capture cost. These key performance indicators are crucial for understanding such systems' economic sustainability and energy impact. It's important to note that our calculation of efficiency does not reference the Best Available Techniques (BAT) (Neuwahl et al., 2019) as BAT considerations are limited to thermal cycle efficiency and overlook the energy auto-consumption on the plant, making them unsuitable for an accurate efficiency estimation in our context. This distinction ensures a more accurate assessment of the real impact of CC technologies when integrated into WtE plants.

The global energy efficiency is calculated both excluding and including the integration of the CO_2 capture system. Initially, efficiency is determined as the ratio of the net electric power (electricity generated from the WtE process and supplied to the grid) to the thermal input to the boiler. This thermal input is calculated based on the quantity of SRF burned and its lower heating value, as demonstrated in the following formula:

$$\eta_{\,without\ CO_2\ captured} = \frac{W_e}{Q_{th}} \tag{21}$$

where We represent the net electric power in MWe, Q_{th} is the thermal input to the boiler, calculated based on SRF combusted and its lower heating value, in MWth. Subsequently, the efficiency is recalculated to include the presence of the CO_2 capture system, along with all associated losses or energy consumption.

$$\eta_{\,with\ CO_2\ captured} = \frac{W_e - Power\ required\ by\ Carbon\ Capture}{Q_{th}} \tag{22}$$

where the Power required for Carbon Capture is related to the extraction of steam from the turbine, the electrical energy consumed to operate the auxiliary equipment, and the energy used for cooling water systems. The cooling water system needs approximately 12 kWh of electrical energy to remove 465.5 kWh of thermal energy.
The CO_2 capture cost is calculated by dividing the combination of annualized Capex and yearly Opex by the amount of CO_2 captured, as shown in:

$$CO_2\ capture\ cost\left(\frac{€}{t\ CO_2}\right) = \frac{Annualized\ CAPEX\left(\frac{€}{yr}\right) + Yearly\ OPEX\left(\frac{€}{yr}\right)}{Amount\ of\ CO_2\ captured\left(\frac{t}{yr}\right)} \tag{23}$$

These key performance indicators offer a view of the system's performance, enabling a balanced cost and energy efficiency assessment in integrating CO_2 Capture. It is important to note that achieving a low CO_2 capture cost does not always imply high energy efficiency. Hence, assessing both aspects is essential for developing long-term sustainable solutions.

5.3 Results and discussions

This section presents the findings of our study on CO_2 capture system, focusing on the key performance indicators of global energy efficiency and CO_2 capture cost. The results are structured to first address the energy efficiency, examining how integrating CO_2 Capture impacts the overall energy balance of WtE incineration processes, and then reporting the economic feasibility of CO_2 Capture, delineating the interaction between capital and operational cost.

5.3.1 Global energy efficiency results

The integration of the CO_2 capture system into the operations of the WtE incineration plant has been quantitatively assessed for its impact on the plant's efficiency. Indeed, extra energy is consumed by the capture process, which includes steam for the solvent, electricity for the auxiliary, and electricity for the cooling systems, as detailed in Table 14.

Table 14 - Power required from CO_2 Capture system as a function of the CC system size.

Size	Auxiliary [MW]	Steam [MW]	Cooling water [MW]
3000 t CO_2 captured	0.03	0.08	0.01
6000 t CO_2 captured	0.05	0.15	0.02
12000 t CO_2 captured	0.10	0.31	0.05

The extra energy consumed by the capture process leads to reduction of the energy efficiency of the WtE plant as a function of the CO_2 capture scales: without CO_2 capture, the plant has an efficiency of 22.7%, which is within the typical WtE incineration efficiency range of 10-30% (Neuwahl et al., 2019). However, introducing the CO_2 capture system results in a decline in efficiency as the size of CO_2 capture increases: the plant efficiency decreases to 22.4%, 22.1%, and 21.5%, respectively, at the capture levels of 3000, 6000, and 12000 t of CO_2/y.

5.3.2 Cost evaluation results

The costs involved in installing a CO_2 capture system at the WtE incineration plant are estimated to be 2.5 M€, 3.0 M€, and 4.2 M€ for capturing 3000, 6000, and 12000 t of CO_2, respectively. Figure 11a indicates, as expected, that the cost per ton of CO_2 captured decreases as the capacity of the system increases, from 156 €/t to 90 €/t, demonstrating the efficiency achieved by scaling up the system. For capacities of 6000 and 12000 t, the capital costs (Capex) are observed to be lower than the operational costs (Opex), with Capex at 49 €/t and 35 €/ton and Opex at 41 €/t (considering both Fixed and Variable Opex). This trend confirms the strategic benefit of large-scale CO_2 Capture.
In comparison to Ali et al. (2019) study, which used the same approach to estimate the cost of carbon capture with MEA, our study found a higher cost per ton of CO_2 captured. They reported a capture cost of 62.5 €/t CO_2, significantly lower due to the economies of scale realized in their larger system. Their system captured approximately 945 kt of CO_2 annually, which highlights the influence of scale on the total cost. On the other hand, our study used a small-scale system and thus had a higher cost per ton of CO_2 captured.

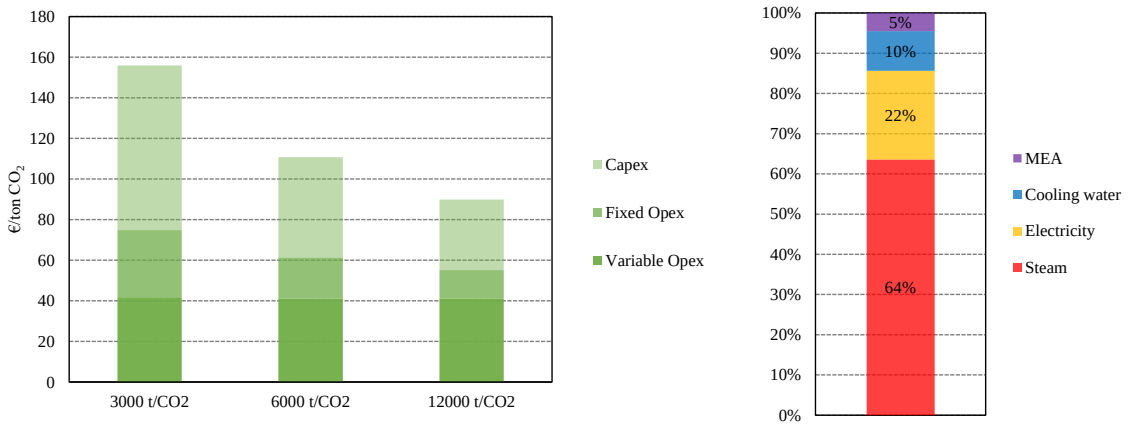


Figure 11 - (a) Cost of CO_2 captured: capital cost (Capex) alongside operational costs (Opex), both Fixed and Variable, at different capture capacities. (b) Variable Opex costs: percentages indicating the cost contributions of MEA, cooling water, electricity, and steam to the overall variable Opex for CO_2 capture.

In light of the captured cost observed in Figure 11a, categorized by Capex, Fixed and Variable Opex, Figure 11b illustrates the composition of variable costs. Steam and electricity emerge as the predominant costs, accounting for 86% of the Variable Opex, highlighting their crucial role in the operational cost, in line with findings in the existing literature (Husebye et al., 2012; Roussanaly et al., 2020). Indeed, extracting steam from the medium-pressure turbine to regenerate solvent in the stripper represents a significant energy cost. The remaining 15% is distributed among cooling water and MEA. This cost distribution underlines the importance of optimizing thermal and electric utilities, which could result in substantial cost reductions. The focus on Variable Opex is particularly relevant since operational costs exceed Capex at the medium and highest capacity analysed, further highlighting the significance of managing operational costs in the goal of cost-effective CO_2 capture solutions.

Figure 12 presents the allocation of Capex for the different equipment within the CO_2 Capture System at three sizes. The analysis shows a distinct trend in Capex distribution as capacity increases. The proportion of Capex for columns (C-101, C-201, and C-202) increases significantly, indicating a more substantial capital investment at larger scales, increasing from 63.35% to 68.19%. Exchangers (E-101, E-201, E-202, E-203, and E-204) and pumps and blowers (F-101, P-101, P-201, P-202, P-203) demonstrate a relatively stable Capex share, with slight decreases from 20.11% to 18.17%, and 16.31% to 13.11%, respectively. The costs for MEA and the water used to fill the circuit are so negligible that they do not markedly affect the overall Capex distribution. The distribution of Capex, as depicted in , indicates the varying cost implications of scaling up components in CO_2 capture systems, providing essential guidance for capital allocation decisions in the design and expansion of such facilities, aligning with literature that highlights the absorber and stripper as the most costly components (Husebye et al., 2012).

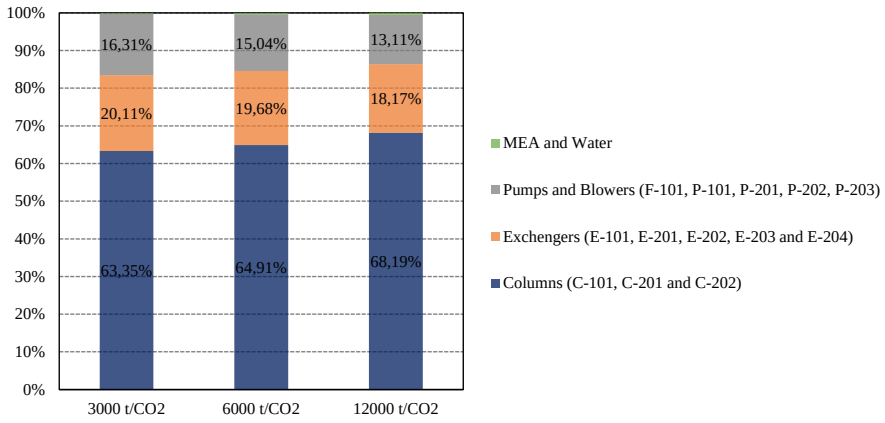


Figure 12 - Impact of different equipment on the total cost (Capex): MEA and Water, Pumps and Blowers, Exchangers, and Columns, at different capture capacities.

5.3.3 Limitations of the study and research needs

The findings of the paper are of great interest as they attempt to fill a gap in studying small-scale CC applications for the WtEs, providing critical insights for similar retrofit projects. For the very first time a detailed cost analysis for retrofitting WtEs with carbon capture systems is proposed. Nonetheless, a main limitation has to be pointed out: indeed, our analysis is confined solely to the CO_2 capture section, without accounting for the post-hoc utilization (CCU) or storage (CCS) of the CO_2 captured. Integrating these additional stages would result in increased costs and a comprehensive and detailed cost assessment including CCU or CCS solutions could represent a research need to be addressed in future studies. As for an example, a rough estimate of including compression in the CO_2 capture process could raise expenses, as suggested by Deng et al. (2019), by approximately 15 €/t of CO_2 captured, excluding transportation costs. On the other hand, converting CO_2 into products like methane or methanol would necessitate extra equipment such as an electrolyzer for hydrogen production and a methanation section, significantly elevating the overall costs.

Furthermore, if WtE plants will be incorporated into the Emissions Trading System as stipulated by the EU ETS Directive 2023/959 (European Parliament, 2023), they would be obligated to pay for their fossil CO_2 emissions. In this scenario, the economic benefit of capturing and geologically storing CO_2 (only fossil CO_2 would qualify for exemption) should be considered, potentially offsetting some costs. Nonetheless, the current trading price of 80 €/t (Sandbag, 2024) would be not adequate to cover the expenses incurred for the CO_2 capture section.

5.4 Conclusion

The chapter provides a detailed techno-economic analysis of integrating an amine-based Carbon Capture system into WtE incineration plants, focusing on three different small-scale plant sizes (3000, 6000, and 12000 t of CO_2 per year).

The analysis shows that the viability of carbon capture in WtE plants heavily depends on the scale of implementation. The Capex costs for the capacities analyzed are 2.5 M€, 3.0 M€, and 4.2 M€, respectively. As the capacity increases, the costs per ton of CO_2 captured decrease, indicating economies of scale, with the capture costs ranging from 156 €/t to 90 €/t of CO2. However, the cost per t of CO2 captured in WtE plants is consistently higher than the potential financial returns from CO_2 emission exemptions in the Emission Trading System (ETS). This highlights a significant challenge to the financial sustainability of carbon capture technologies. Therefore, policy support and financial incentives could be necessary to bridge the economic gap in implementing carbon capture.

The operational costs, mainly attributed to steam and electricity, were found to be significant, accounting for a major portion of the variable Opex. This emphasizes the importance of optimizing thermal and electric utilities to achieve cost-effective CO_2 capture solutions. Additionally, integrating the CO_2 capture system reduces the overall plant absolute efficiency from 22.7% (without carbon capture) to 22.4%, 22.1%, and 21.5% for the different capture capacities.

The study's findings are essential in comprehending the techno-economic viability of implementing carbon capture technologies in WtE incineration plants. It could serve as a crucial resource for similar implementations.

6 CCU: Utilization of CO_2 in Power-to-Gas (PtG) and Power-to-Liquid (PtL).

This chapter explores the process of converting CO_2 and hydrogen into methane and methanol, using a case study that focuses on economic analysis and the amount of CO_2 that can be used with a specific electrolyzer size (1 MW). This analysis aims to clarify the potential use of CO_2 in the production of methane and methanol and to investigate the CO_2 can be used in this conversion process and related investment (Capex) and operational (Opex) costs. Furthermore, it provides some insights into this technology's advantages and critical issues when used alongside WtE incineration plants.

6.1 Methodology

This section presents the methodology adopted for designing the system for producing methane and methanol (scheme and assumption) and the cost estimation approach focusing on the existing WtE incineration plant.

6.1.1 Methane Production (Power-to-Gas)

The PtG process for the synthesis of methane (CH_4) is based on the Sabatier reaction, in which hydrogen (H_2) and carbon dioxide (CO_2) react to form methane (CH_4) and water (H_2O):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (24)$$

This exothermic reaction (Bahari et al., 2019) requires the use of specific catalysts, mainly nickel-based (Reiter and Lindorfer, 2015), and takes place under controlled conditions of pressure (6-7 bar) and temperature (180-350°C) (Reiter and Lindorfer, 2015).
Figure 13 shows the block diagram of the PtG process, outlining the steps from renewable energy generation to water electrolysis, and finally to methanization.

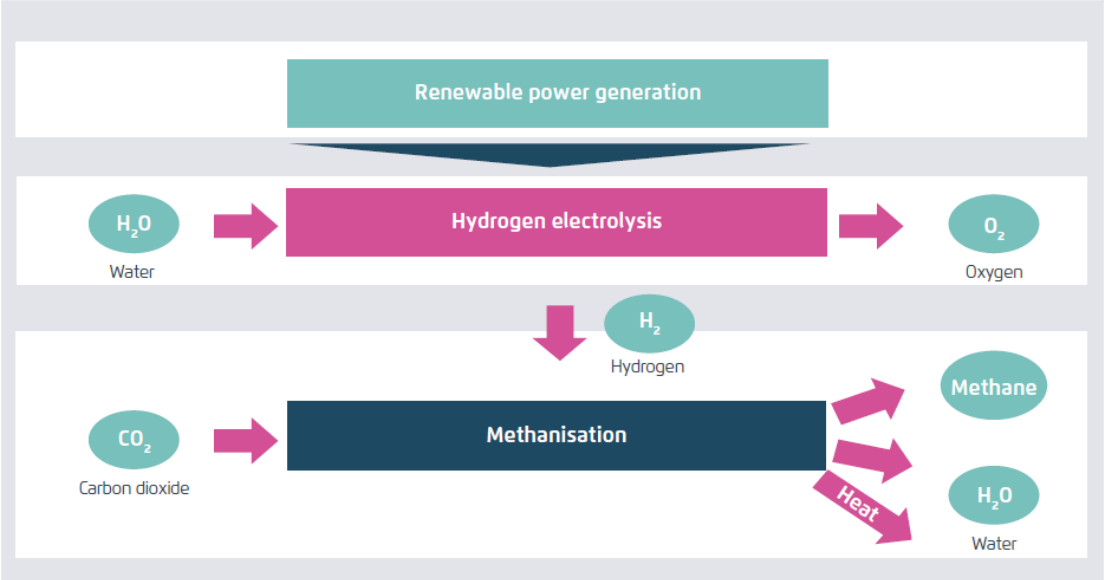


Figure 13 – Process diagram for Power-to-Gas (Agora Energiewende, 2018).

The methane obtained can be injected into the gas distribution grid, used as a fuel for energy generation, or as a raw material in the chemical industry. Specifically, in a WtE incineration plant, methane can compensate for the methane taken from the grid, which is necessary for the starting phases or to maintain the temperature in the combustion chamber above 850°C. This use helps prevent the formation of dioxin precursors in the combustion chamber, as required by Directive 2010/75/EU (European Parliament, 2010).

A crucial aspect of the PtG process is the need for "green" hydrogen, which must be produced using renewable energy sources. However, integrating this practice into systems such as WtE incineration plants presents significant criticism, as only a fraction of the electricity generated in such plants is considered renewable. As a result, it is not always possible to ensure that the hydrogen produced meets the criteria to be defined as "green".

6.1.2 Methanol Production (Power-to-Liquid)

The PtL process for the synthesis of methanol (CH_3OH) is obtained via the direct reaction between CO2 and H2, according to the chemical reaction:

$$3H_2 + CO_2 \rightarrow CH_3OH + H_2O \quad (25)$$

This reaction takes place in the presence of specific catalysts, such as copper (Cu), zinc oxide (ZnO), and alumina (Al_2O_3), at temperatures of approximately 235°C and pressures between 40-80 bar, inside reactors that use multiple reaction cycles to ensure high CO_2 conversion.

Figure 14 shows the process diagram of the PtL process, showing the steps from the generation of renewable energy to the electrolysis of water and finally to the production of not only methane but also fuels such as gasoline, kerosene, and diesel. The chapter did not include this final step, which can occur via methanol refining or the Fischer-Tropsch synthesis.

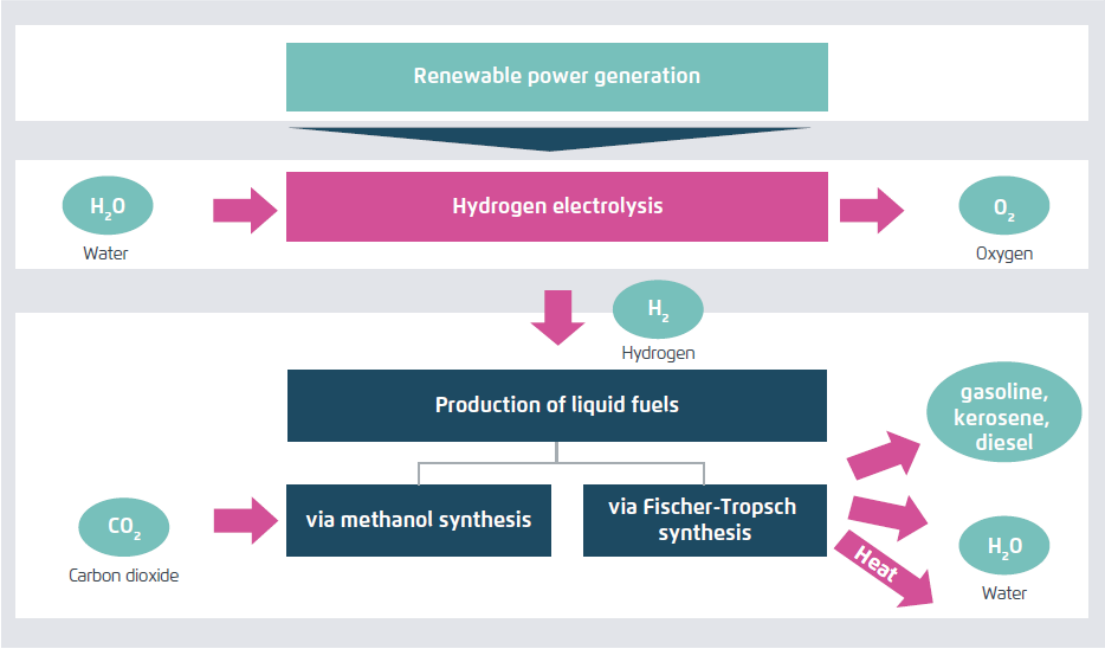


Figure 14 - Process diagram for Power-to-Liquid (Agora Energiewende, 2018).

6.1.3 Case study

The production of methane and methanol involves the development of a dedicated plant, where carbon dioxide, previously captured, reacts with hydrogen, obtained from electrolysis. The energy needed for electrolysis comes from the waste-to-energy plant. Figure 3 shows the process diagram of the system.

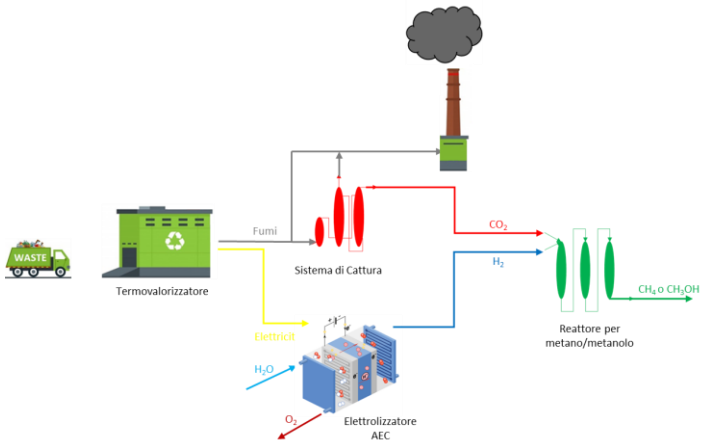


Figure 15 – Process diagram and its integration with the WtE incineration plant.

The project's economic analysis focuses on Capex, Opex, the amount of CO_2 used, and the revenues associated with the methane and methanol produced. The cost of electricity is a crucial element in the analysis, which is crucial for the project's economic feasibility. Currently, the high energy cost

can make the production of hydrogen, and consequently methane and methanol, less convenient than selling electricity to the grid.

For this case study, the use of a 1 MW AEC (Alkaline Electrolyser Cell) type electrolyzer and 8000 hours of operation for the entire system was considered.

Electrolysis:

- Capex: €1150/kWe, including purchase, installation, grid connection, compression, purification, and storage operations (Buttler and Spliethoff, 2018).
- Opex: 3% of Capex (Buttler and Spliethoff, 2018).
- Electricity cost: €84/MWhe.

Methane Production

- Capex: €748/kW of capacity for methane production (Agora Energiewende, 2018).
- Opex: 3% of Capex (Buttler and Spliethoff, 2018).
- Price of methane: The price of methane is currently set at 0.4 €/scm CH_4 based on data updated to 2023.

Methanol production

- Capex: €788/kW of capacity for methanol production (Agora Energiewende, 2018).
- Opex: 3% of Capex (Buttler and Spliethoff, 2018).
- Methanol price: The price of methanol is estimated at €400/t CH3OH, according to the most recent data from 2023.

6.2 Results and discussions

The estimation results are Capex and Opex are shown in Figure 16.

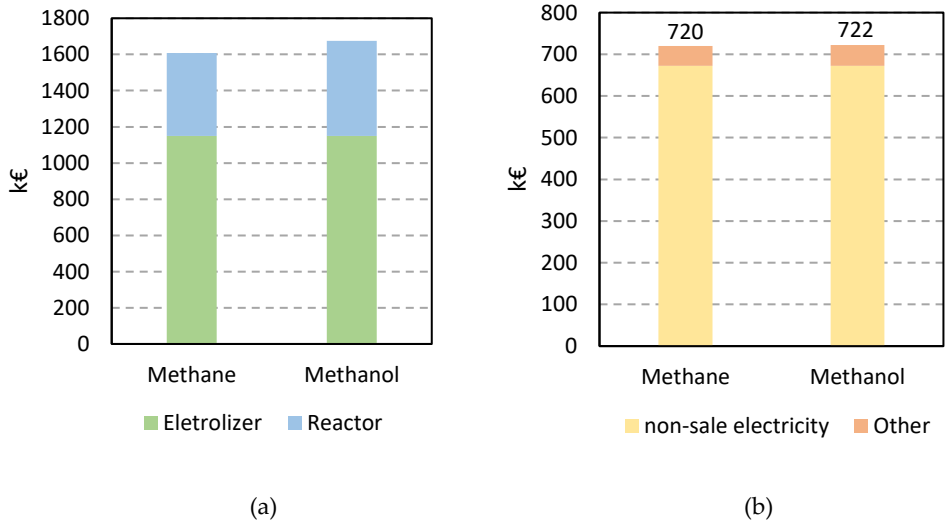


Figure 16 - Results of economic analysis of methane/methanol production plant: (a) Capital cost (Capex), (b) Operational cost (Opex).

Figure 16a shows a slight difference in Capex between methane and methanol production, with the latter requiring a slightly higher investment. In both cases, the electrolyser is the predominant cost component. Figure 16b shows that the Opex for the two processes is almost equivalent. It is interesting to note that the failure to sell electricity constitutes the most significant part of Opex, underlining the importance of carefully evaluating the opportunity to sell energy to the grid versus internal use for hydrogen production.
Figure 17 shows the amount of CO_2 used, the methane and methanol produced.

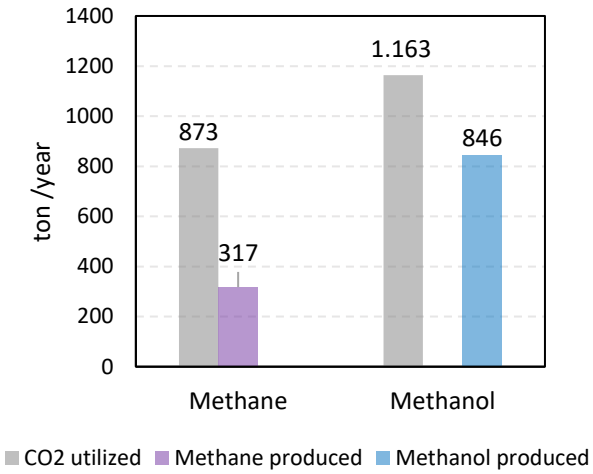


Figure 17 - Results of CO_2 utilized, methane and methanol produced.

Figure 17 highlights that, using a 1 MW electrolyzer, 317 t of methane can be produced annually, consuming 873 t of CO_2, while methanol production reaches 846 t, consuming 1163 t of CO_2. This difference reflects the greater efficiency of the methanol synthesis reaction in fixing CO_2, a relevant aspect when large quantities of CO_2 are available.
Considering the potential gross revenues deriving from the sale of methane and methanol. The methanol has the potential to generate an annual gross revenue of 33 k€, almost double that of methane, whose revenue is estimated at 178 k€. This significant difference is attributable to the greater quantity of methanol that can be produced and to its higher market price than methane, as indicated in the data in the previous paragraph.
However, it is important to underline that in both cases, the revenues from the sale do not compensate for the loss of earnings due to the non-sale of the electricity produced, which instead would have been possible if the energy had been fed directly into the electricity grid rather than used for hydrogen production through the electrolyzer.

6.3 Conclusion

The chapter highlights various aspects related to the production of methane and methanol:

- Although methanol requires a slightly higher initial investment (Capex), it offers a higher economic return than methane, thanks to its higher energy density and higher market price.
- The current cost of electricity used for electrolysis is prohibitive; in fact, it is more economically advantageous to sell the energy to the grid rather than use it in the production of hydrogen.
- Despite the recognition of PtG and PtL processes in Italian long-term strategies, an incentive system that actively supports these production paths is currently lacking.
- Costs associated with CO_2 capture, not included in the current economic analysis, would negatively impact economic estimates if they were considered.
- The amount of CO_2 required to power a 1 MW PtG or PtL system (electrolyzer) is minimal compared to the annual emissions of a waste-to-energy plant. To be more specific, a 1 MW electrolyzer uses only 873 t of CO_2 to produce methane and 1163 t of CO_2 to produce methanol. These values are minimal when compared with the annual emissions of a WtE plant, such as 171 kt of CO_2 per year for the Italian WtE, as seen in paragraph 2.6.

7 Summary and conclusions

This doctoral thesis investigates the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies within Waste-to-Energy (WtE) incineration plants, focusing on retrofit applications. It emphasizes the critical role of these technologies in the larger context of sustainable energy transition and waste management sector. The investigation reveals the challenges, opportunities, and economic aspects of retrofitting WtE facilities with CCUS systems.

Chapter 2 introduces WtE incineration, highlighting its importance in sustainable waste management and renewable energy generation. It explores into the classification and increase of waste, particularly municipal solid waste, which has a fraction of biomass, making it a renewable energy resource. Additionally, it discusses Europe's dependence on WtE incineration and implications of incineration versus landfilling. Technical aspects of the process such as the combustion chamber, energy recovery, and flue gas treatment are outlined through comprehensive descriptions. The chapter also addresses the treatment and recovery of incineration residues. Looking at Italy, it reveals the country's WtE infrastructure and the possibility of improved sustainability through reduced landfill dependence.

Chapter 3 provides an overview of the integration of CCUS technologies with WtE incineration plants to mitigate CO_2 emissions and achieve carbon neutrality in the European waste management sector. The EU Emissions Trading System (EU ETS) will include WtE incinerators by 2028, requiring them to financially account for their fossil CO_2 emissions. However, the lack of CO2 markets and permanent storage solutions creates challenges for CCUS integration. Governments need to develop incentives, regulatory frameworks, and CO_2 markets to support the adoption of CCUS technologies. The contrast between countries like the Netherlands, with a developed CO_2 market, and Italy, where the CO_2 market is still emerging, underscores the need for national policies that incentivize the development of markets for CO_2 and the implementation of storage infrastructure.

Chapter 4 shows an analysis of CO_2 emissions estimation from a real WtE incineration plant, using data gathered in 2022 and following the standard method set by Monitoring and Reporting Regulation 2018/2066. It explains the complexity of CO_2 emission estimation from WtE incineration plants and shows that part of the emissions from a WtE plant are biogenic and, thus, do not contribute to the overall CO_2 emissions in the atmosphere.

In Chapter 5, it is analyzed the integration of an amine-based Carbon Capture system into WtE incineration plants of three different small-scale plant sizes. The feasibility of carbon capture in WtE plants heavily depends on the scale of implementation. The operational costs are significant, emphasizing the importance of thermal and electric utilities. Integrating the CO_2 capture system reduces the overall plant efficiency. The findings are crucial in understanding the techno-economic viability of implementing carbon capture technologies in WtE incineration plants.

Chapter 6 shows an economic assessment of converting captured CO_2 into valuable products like methane and methanol through Power-to-Gas (PtG) and Power-to-Liquid (PtL) processes. It shows the potential for these technologies to use the CO_2 captured. However, the chapter critically assesses the current economic barriers, including the high cost of electricity for electrolysis and the lack of active incentive systems to support these pathways.

Based on the insights from these chapters, it becomes evident that integrating CCUS technologies in WtE plants is not just a technical challenge but a complex contribution of technological and economic feasibility, regulatory support, CO_2 market, and permanent storage solutions. The path forward requires an approach that includes developing policy frameworks, promoting better market conditions supporting CCUS adoption, and advancing technological innovations to reduce costs.

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Appendix

Appendix A

Enhanced Detailed Installation Factor Sheet for 2016-2018 (Ali et al., 2019).

kNOK	0–20	20–100	100–500	500–1000	1000–2000	2000–5000	5000–15000	>15000
Equipment	1	1	1	1	1	1	1	1
Erection/Installation	0.89	0.47	0.25	0.18	0.14	0.11	0.10	0.08
Piping	3.56	1.92	1.12	0.83	0.65	0.48	0.41	0.29
Electric	1.03	0.71	0.48	0.41	0.34	0.28	0.25	0.18
Instrument	3.56	1.92	1.12	0.83	0.65	0.48	0.41	0.29
Civil	0.55	0.36	0.25	0.20	0.17	0.14	0.13	0.09
Steel & Concrete	1.79	1.17	0.79	0.64	0.55	0.43	0.39	0.28
Insulation	0.67	0.34	0.18	0.14	0.11	0.09	0.05	0.04
Direct Cost	13.05	7.89	5.19	4.23	3.61	3.01	2.74	2.25
Engineering Process	1.23	0.43	0.24	0.18	0.15	0.13	0.11	0.09
Engineering Mechanical	0.98	0.24	0.10	0.05	0.04	0.03	0.01	0.01
Engineering Piping	1.08	0.58	0.34	0.25	0.18	0.14	0.13	0.09
Engineering Electric	1.04	0.30	0.15	0.11	0.10	0.09	0.05	0.04
Engineering Instrument	1.85	0.72	0.36	0.25	0.20	0.14	0.13	0.09
Engineering Civil	0.39	0.11	0.04	0.03	0.03	0.01	0.01	0.01
Engineering Steel & Concrete	0.58	0.24	0.13	0.10	0.09	0.05	0.05	0.04
Engineering Insulation	0.27	0.09	0.03	0.01	0.01	0.01	0.01	0.01
Engineering Cost	7.42	2.71	1.39	0.98	0.80	0.60	0.50	0.38
Procurement	1.55	0.52	0.20	0.13	0.09	0.04	0.03	0.03
Project Control	0.37	0.14	0.05	0.04	0.04	0.03	0.03	0.03
Site Management	0.66	0.42	0.28	0.24	0.20	0.17	0.15	0.11
Project Management	0.89	0.46	0.29	0.24	0.20	0.17	0.15	0.11
Administration Cost	3.47	1.54	0.82	0.65	0.53	0.41	0.36	0.28
Commissioning	0.72	0.33	0.17	0.10	0.10	0.05	0.05	0.04
Contingency	4.99	2.55	1.57	1.24	1.06	0.87	0.78	0.64
Total Plant Cost, $F_{Total, CS}$	29.65	15.02	9.14	7.20	6.10	4.94	4.43	3.59

Appendix B

Equipment Sheet with Installed Cost

			3000 t CO_2 Captured			6000 t CO_2 Captured			12000 t CO_2 Captured		
	Equipment	**Material**	**Peculiarity**	**Equipment cost in Aspen [€]**	**EIC for Italy [k€]**	**Peculiarity**	**Equipment cost in Aspen [€]**	**EIC for Italy [k€]**	**Peculiarity**	**Equipment cost in Aspen [€]**	**EIC for Italy [k€]**
F-101	**Fan**	SS316 m	Duty: 30 kW	10	95	Duty: 55 kW	17	99	Duty: 75 kW	22	130
P-101	**Pump**	SS316 m	Duty: 1.5 kW	8	77	Duty: 3 kW	10	90	Duty: 7.5 kW	12	115
E-101	**Exchanger**	SS316 w	Surface: 14.6 m^2	20	94	Surface: 29.3 m^2	22	103	Surface: 60.3 m^2	38	178
C-101	**DCC**	SS316 w	Diameter: 0.71 m TT Height: 9.7 m	88	418	Diameter: 0.94 m TT height: 10.4 m	169	638	Diameter: 1.4 m TT height: 10.8 m	272	881
C-201	**Absorber**	SS316 w	Diameter: 0.71 m TT Height: 23.1 m	263	854	Diameter: 0.94 m TT Height: 23.6 m	365	975	Diameter: 1.4 m TT Height: 27.7 m	609	1.626
C-202	**Stripper**	SS316 w	Diameter: 0.44 m TT Height: 8.8 m	64	303	Diameter: 0.6 m TT Height: 9.3 m	76	358	Diameter: 0.84 m TT Height: 9.75 m	106	402
P-201	**Pump**	SS316 m	Duty: 3 kW	9	83	Duty: 7.5 kW	11	101	Duty: 11 kW	13	122
P-202	**Pump**	SS316 m	Duty: 2.2 kW	8	78	Duty: 4 kW	10	94	Duty: 7.5 kW	13	119
P-203	**Pump**	SS316 m	Duty: 0.75 kW	8	73	Duty: 0.75 kW	8	73	Duty: 0.75 kW	8	73
E-201	**Exchanger**	SS316 w	Surface: 9.3 m^2	19	89	Surface: 18.6 m^2	22	103	Surface: 37 m^2	30	140
E-202	**Exchanger**	SS316 w	Surface: 16.9 m^2	22	103	Surface: 33.9 m^2	30	140	Surface: 67.6 m^2	43	202
E-203	**Exchanger**	SS316 w	Surface: 3.9 m^2	15	116	Surface: 7.6 m^2	16	123	Surface: 15.4 m^2	20	94
E-204	**Exchanger**	SS316 w	Surface: 10.2 m^2	21	98	Surface: 20.9 m^2	27	128	Surface: 40 m^2	34	160