# Carbon capture for Energy-from-Waste plants: comparison of three appliable technologies

L. Cretarola[1], G. Mazzolari[2], E. De Lena[2], M. Spinelli[2], M. Gatti[1,2], F. Viganò[1,2]

[1]Department of Energy, Politecnico di Milano, Milan, 20153, Italy
[2]LEAP Scarl, Piacenza, 29121, Italy
Keywords: Carbon Capture, Energy, Waste, Amines, Calcium looping, Molten Carbonate Fuel Cell (MCFC).
Presenting author email: letizia.cretarola@polimi.it

## Introduction

Energy recovery from non-recyclable waste is an essential process to warrant the sustainability of waste management (Consonni *et al.*, 2011). $CO_2$ emissions from Energy-from-Waste (EfW) plants that burns mainly Municipal Solid Waste (MSW) are partly biogenic (therefore climate neutral) and partly fossil (therefore GreenHouse Gas – GHG – emissions, see *i.a.* Mohn *et al.*, 2008). In 2020, EU-27 sent to EfW plants more than 81 million tons of non-recyclable MSW (CEWEP, 2023), emitting roughly 40 million tons of fossil $CO_2$ (IEAGHG, 2020), about 1.3% of the 2020 overall EU-27 GHG emissions (EEA, 2021).

Capturing the $CO_2$ emissions from EfW plants not only mitigates the environmental impact of this practice, but also opens the door to the opportunity of making BioEnergy with Carbon Capture and Storage (BECCS), thanks to the possibility of capturing biogenic emissions. BECCS is an enabling element for the roadmap toward climate neutrality by 2050 proposed by the "EU Green Deal" (EU, 2019).

Currently the only CCS technology that is claimed as "commercial ready" for EfW is flue gas scrubbing with aqueous solutions of amines (mainly MEA – MonoEthanolAmine). However, other possibilities have been studied, and two among the most promising ones are based on Calcium Looping (CaL) and Molten Carbonate Fuel Cells (MCFCs). This work presents a coherent comparison of the three technologies (MEA, CaL and MCFC) applied to the same reference EfW plant, highlighting the main pros and cons from a performance perspective.

## Material and Methods

A real 70 $MW_{LHV}$ power-input, two-lines, grate-based, state-of-the-art EfW plant is considered. An Aspen Plus® model of the plant was developed and calibrated to reproduce actual operating performances. The plant is currently fired with about 160 kt/y of lightly pre-treated (bags opening and trommel screening) Unsorted Residual Waste (URW), featuring a Lower Heating Value (LHV) around 11 MJ/kg. Each combustion line is equipped with dual-stage dry Air Pollution Control (APC), including final, low-T Selective Catalytic Reduction (SCR) system for $NO_X$ abatement. The exploitation of the energy recovered from waste incineration relies on a Combined Heat and Power (CHP) steam cycle, based on an air-condensed steam turbine (rated power output of 17.8 $MW_e$).

The MEA system (Chiesa, 2020; Su *et al.*, 2023) is applied downstream of the APC of the two combustion lines, after flue gas cooling down to 40 °C by means of a Direct Contact Cooler (DCC). The absorption-desorption model is taken from Zhang and Chen (2013). The captured $CO_2$ is delivered in supercritical state at 111 bar and 40 °C for all the considered cases. All the possible heat recovery from the MEA system and $CO_2$ compression is carried out to maximise the plant performances. However, no heat recovery from flue gas condensation is considered in this case, neither in the other cases.

CaL (Mazzolari, 2022; Mazzolari *et al.*, 2022) is integrated with the EfW plant by means of several modifications. One combustion line is replaced by the CaL system, comprising carbonation and calcination reactors. Flue gas is extracted from the APC line and fed to the carbonator, a circulating fluidised-bed reactor operating at 650°C, where calcium oxide (CaO) reacts with $CO_2$ to form calcium carbonate ($CaCO_3$); then, $CO_2$-depleted flue gas is cooled down (with energy recovery) and sent back to the APC line. The solid $CaCO_3$ is transferred to the calciner, a second circulating fluidised-bed reactor where, thanks to oxy-combustion, temperature is raised to 920 °C allowing for the calcination of $CaCO_3$ back to CaO and the release of the captured $CO_2$, which is evacuated together with the flue gas produced by oxy-combustion. This mixture of high temperature gases mainly composed of $CO_2$ and $H_2O$, after cooling (with energy recovery) undergoes compression and low temperature distillation, to meet the same specifications for the captured $CO_2$ as of the MEA case. Oxy-combustion is fired with Solid Recovered Fuel (SRF), produced with Mechanical Biological Treatment (MBT) of the URW inside the plant. The same amount of URW annually treated by the reference plant is received. Then it undergoes a light shredding (bags opening), biodrying (Viganò *et al.*, 2011), and trommel screening. The oversize fraction, after being demetallized, undergoes secondary shredding, a further demetallization step and a fine screening. The final oversize fraction is the SRF, whereas the undersize fractions from the two screening stages end up into the residual waste that is fed to the grate-based combustion line. The split between SRF and residual waste can be controlled to match the requirements of the two combustors (grate-based and calciner) by tuning the operating

parameters of the primary trommel screen. Oxygen for oxy-combustion is produced on-site, thanks to an Air Separation Unit (ASU).

MCFC (Cretarola, 2022; Viganò *et al.*, 2022) is conceptually coupled to the existing plant layout by cooling flue gas down to 40 °C through a DCC, to limit humidity level so to increase $CO_2$ and $O_2$ concentrations, by adding some ambient air to further increase $O_2$ concentration and by heating up to 570 °C. Such heating is carried out with significant internal heat recovery and with a final combustion step that exploits tail fuel gas from the MCFC. The hot flue gas is fed to the cathode of the MCFC, where it provides $CO_3^{--}$ ions to allow the functioning of the device. The cathode exhaust is $CO_2$-depleted flue gas that is released to atmosphere after heat recovery. The anode stream of the MCFC is desulfurized, preheated, and humidified Natural Gas (NG) mixed with some tail fuel gas. Such fuel gets steam reformed and oxidised by the $CO_3^{--}$ ions inside the MCFC anode side, providing the electrons, and is discharged as spent fuel, enriched in $CO_2$ and $H_2O$, from which further heat is recovered. By means of a low temperature phase change system, $CO_2$ is separated, purified, and compressed, whereas combustible species are recycled back to provide part of the energy required by the capture section. The MCFC system features tight heat integration and, as a side effect of NG consumption, it produces additional power output, as well as some thermal power to integrate the production of the EfW plant for District Heating (DH).

The performance estimates of the four cases are carried out for the same thermal power supplied to the DH network, so that differences can be appreciated solely on the electric power output. The Specific Primary Energy per Carbon Capture Avoidance (SPECCA - Chiesa, 2011) index is evaluated by considering two different reference systems to quantify avoided/additional $CO_2$ emissions for balancing electric production.

**Results and Discussion**

Table 1 reports the estimates of the achievable performances of the three carbon capture options compared against those of the reference plant. In all cases, the same 160 kt/y of URW is considered. This causes the adoption of a slightly different average load level for the grate-based combustor in the CaL case.

Table 1. Main performance indexes for the three capture options compared against those of the reference case. All figures are expressed as percentage of the overall energy input in terms of LHV (URW + NG).

| Case: | Reference | MEA | CaL | MCFC |
|---|---|---|---|---|
| URW overall input, $\%_{LHV}$ | 100 | 100 | 100 | 63.3 |
| NG input (to MCFC), $\%_{LHV}$ | 0.0 | 0.0 | 0.0 | 36.7 |
| Grate combustor(s) input, $\%_{LHV}$ | 100 | 100 | 49.4 | 63.3 |
| SRF / Calciner input, $\%_{LHV}$ | 0.0 | 0.0 | 48 | 0.0 |
| Load of grate combustor(s), % of rated value | 76.5 | 76.5 | 76.4 | 76.5 |
| Steam cycle electric power output, $\%_{LHV}$ | 20.1 | 10.9 | 20.9 | 12.9 |
| MCFC electric power output, $\%_{LHV}$ | 0.0 | 0.0 | 0.0 | 22.1 |
| EfW section electric auxiliaries, $\%_{LHV}$ | 3.5 | 3.5 | 2.0 | 2.2 |
| $CO_2$ capture section electric auxiliaries, $\%_{LHV}$ | 0.0 | 2.2 | 9.9 | 2.0 |
| Net electric power output, $\%_{LHV}$ | 16.6 | 5.2 | 9.0 | 30.8 |
| Thermal power to DH, $\%_{LHV}$ | 20.0 | 20.0 | 20.0 | 12.7 |
| $CO_2$ capture section heat requirements, $\%_{LHV}$ | 0.0 | 31.6 | 0.0 | 0.0 |
| $CO_2$ cap. sec. heat recovery (for DH), $\%_{LHV}$ | 0.0 | 1.0 | 1.1 | 1.3 |
| SPECCA[(a)], $MJ/kg_{CO2}$ | - | 2.547 | 1.535 | 0.254 |
| SPECCA[(b)], $MJ/kg_{CO2}$ | - | 2.633 | 1.663 | -0.684 |

*References for power production (EBTF, 2011):*

*(a) A NG-fired combined cycle featuring 58.3 $\%_{LHV}$ net electric efficiency and 351.8 kg/MWh $CO_2$ emission.*

*(b) The same combined cycle with 90% $CO_2$ capture through MEA (resulting in 49.9 $\%_{LHV}$ net electric efficiency and 36.2 kg/MWh $CO_2$ emission).*

Results show that both CaL system and MCFC can achieve much better performances than MEA, as highlighted by the SPECCA values, which can go even negative for the MCFC case. The MCFC-based system pays a very limited energy penalty, since MCFCs convert NG to electricity with almost the same efficiency of the cutting-edge NG-fired combined cycle adopted as reference for power production, and with no additional $CO_2$ emissions than those residual from the EfW plant (*i.e.*, electricity from NG is 100% decarbonised).

The main pitfall of the MEA configuration is the relevant heat requirement for amine regeneration, which subtracts a significant flowrate of steam from the final stages of the steam turbine. CaL configuration is very effecting in capturing $CO_2$ (it achieves 95% capture rate) with very limited penalisation of the steam cycle. However, the oxygen production impacts appreciably on the electric auxiliary consumptions. Finally, the MCFC-based system exploits the very high efficiency of MCFC to mitigate the impact of the required NG consumption.

**Conclusions**

The three technologies considered for $CO_2$ post-combustion capture in EfW plants show different potential performances when analysed on a coherent basis. Both CaL-based and MCFC-based options achieve appreciably better performances than the "conventional", "commercial ready" MEA option. The estimated SPECCA index is about 2.5 for the MEA case, 1.5 for the CaL case and ranges between 0.2 and -0.7 for the MCFC case depending on the reference system considered to account for the conventional power production.

All considered systems may be applied as retrofit of existing plants, even if this work considers for the CaL configuration heavy modifications, to keep the reference to the same waste amount. In the case of CaL as pure retrofitting solution, the amount of waste to be treated must double circa (see Mazzolari *et al.*, 2022).

**References**


CEWEP, 2023. Waste-to-Energy in Europe in 2020. Available at https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2020/, last accessed on 11/04/2023.

Chiesa, A., 2020. Carbon capture and sequestration applied to an energy from waste plants. Master of Science Thesis in Energy Engineering. Politecnico di Milano.

Chiesa, P., Campanari, S., Manzolini, G., 2011. $CO_2$ cryogenic separation from combined cycles integrated with molten carbonate fuel cells. International Journal of Hydrogen Energy 36, 10355-10365.

Consonni, S., Giugliano, M., Massarutto, A., Ragazzi, M., Saccani, C., 2011. Material and energy recovery in integrated waste management systems: Project overview and main results. Waste Management 31, 2057-2065.

Cretarola, L., 2022. Carbon Capture and Storage in Energy from Waste plant using Molten Carbonate Fuel Cells. Master of Science Thesis in Energy Engineering. Politecnico di Milano.

EEA (European Environmental Agency), 2021. EEA greenhouse gases — data viewer, Product id: DAS-270-en.
Available at https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, last accessed on 11/04/2023.

EBTF (European Benchmarking Task Force), 2011. European best practice guidelines for assessment of CO2 capture technologies. Report D 4.9, CAESAR Project, FP7 – ENERGY.2007.5.1.1, Project no. 213206.

EU, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal, COM/2019/640 final. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640.

IEAGHG, 2020. IEAGHG Technological report 2020-06 – CCS on Waste to Energy. IEA Environmental Projects Ltd., December 2020.

Mazzolari, G., 2022. $CO_2$ capture by Calcium Looping in Waste to Energy plants: case studies for medium scale applications. Master of Science Thesis in Mechanical Engineering. Politecnico di Milano.

Mazzolari, G., De Lena, E., Spinelli, M., Gatti, M., Fantini, M., Viganò, F., Consonni, S., 2022. The potential of Calcium Looping technology as BECCS system in Waste-to-Energy plants. In Proceedings of the 2022 WTERT Biennial Conference, New York, USA, 13-14 October 2022. ASME Publisher.

Mohn, J., Szidatb, S., Fellner, J., Rechberger, H., Quartier, R., Buchmann, D., Emmenegger, L., 2008. Determination of biogenic and fossil $CO_2$ emitted by waste incineration based on $^{14}CO_2$ and mass balances. Bioresource Technology 99, 6471-6479.

Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., Chalmers, H., 2023. Thermal integration of waste to energy plants with Post-combustion $CO_2$ capture. Fuel 332, 126004.

Viganò, F., Consonni, S., Ragazzi, M., Rada, M.C., 2011. A model for mass and energy balances of bio-drying. Paper 5457 in Proceedings of NAWTEC19: 19th Annual North American Waste-to-Energy Conference, Lancaster (PA), USA, 16-18 May 2011. ASME Publisher.

Viganò, F., Cretarola, L., Spinelli, M., 2022. Molten Carbonate Fuel Cells (MCFC) for the carbon capture in Energy-from-Waste (EfW) plants. Paper no. C06.1 in Proceedings of the 9th International Symposium on Energy from Biomass and Waste, Venice, Italy, 21-23 November 2022. CISA Publisher.

Zhang, Y., and Chen, C-C, 2013. Modeling CO2 absorption and desorption by aqueous monoethanolamine solution with Aspen rate-based model. Energy Procedia 37, 1584-1596.