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

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Introduction
Energy recovery from non-recyclable waste is an essential process to warrant the sustainability of waste management (Consonni et al., 2011). CO₂ 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 CO₂ (IEAGHG, 2020), about 1.3% of the 2020 overall EU-27 GHG emissions (EEA, 2021).

Capturing the CO₂ 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 – MonoE thanolAmine). 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_iHV 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 NOx 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 MWₑ).

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 CO₂ 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 CO₂ 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 CO₂ to form calcium carbonate (CaCO₃); then, CO₂-depleted flue gas is cooled down (with energy recovery) and sent back to the APC line. The solid CaCO₃ 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 CaCO₃ back to CaO and the release of the captured CO₂, which is evacuated together with the flue gas produced by oxy-combustion. This mixture of high temperature gases mainly composed of CO₂ and H₂O, after cooling (with energy recovery) undergoes compression and low temperature distillation, to meet the same specifications for the captured CO₂ 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 demetalized, undergoes secondary shredding, a further demetalization 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 CO₂ and O₂ concentrations, by adding some ambient air to further increase O₂ 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 CO₃⁻ ions to allow the functioning of the device. The cathode exhaust is CO₂-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 CO₃⁻ ions inside the MCFC anode side, providing the electrons, and is discharged as spent fuel, enriched in CO₂ and H₂O₂ from which further heat is recovered. By means of a low temperature phase change system, CO₂ 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 CO₂ 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).

<table>
<thead>
<tr>
<th>Case:</th>
<th>Reference</th>
<th>MEA</th>
<th>CaL</th>
<th>MCFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>URW overall input, % LHV</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>63.3</td>
</tr>
<tr>
<td>NG input (to MCFC), % LHV</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>36.7</td>
</tr>
<tr>
<td>Grate combustor(s) input, %LHV</td>
<td>100</td>
<td>100</td>
<td>49.4</td>
<td>63.3</td>
</tr>
<tr>
<td>SRF / Calciner input, %LHV</td>
<td>0.0</td>
<td>0.0</td>
<td>48</td>
<td>0.0</td>
</tr>
<tr>
<td>Load of grate combustor(s), % of rated value</td>
<td>76.5</td>
<td>76.5</td>
<td>76.4</td>
<td>76.5</td>
</tr>
<tr>
<td>Steam cycle electric power output, %LHV</td>
<td>20.1</td>
<td>10.9</td>
<td>20.9</td>
<td>12.9</td>
</tr>
<tr>
<td>MCFC electric power output, %LHV</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>22.1</td>
</tr>
<tr>
<td>EfW section electric auxiliaries, %, %LHV</td>
<td>3.5</td>
<td>3.5</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>CO₂ capture section electric auxiliaries, %, %LHV</td>
<td>0.0</td>
<td>2.2</td>
<td>9.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Net electric power output, %LHV</td>
<td>16.6</td>
<td>5.2</td>
<td>9.0</td>
<td>30.8</td>
</tr>
<tr>
<td>Thermal power to DH, %LHV</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>12.7</td>
</tr>
<tr>
<td>CO₂ capture section heat requirements, %LHV</td>
<td>0.0</td>
<td>31.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>CO₂ cap. sec. heat recovery (for DH), %LHV</td>
<td>0.0</td>
<td>1.0</td>
<td>1.1</td>
<td>1.3</td>
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<td>SPECCA(a), MJ/kgCO₂</td>
<td>-</td>
<td>2.547</td>
<td>1.535</td>
<td>0.254</td>
</tr>
<tr>
<td>SPECCA(b), MJ/kgCO₂</td>
<td>-</td>
<td>2.633</td>
<td>1.663</td>
<td>-0.684</td>
</tr>
</tbody>
</table>

References for power production (EBTF, 2011):

(a) A NG-fired combined cycle featuring 58.3 %LHV net electric efficiency and 351.8 kg/MWh CO₂ emission.

(b) The same combined cycle with 90% CO₂ capture through MEA (resulting in 49.9 %LHV net electric efficiency and 36.2 kg/MWh CO₂ 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 CO₂ 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 effective in capturing CO₂ (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 CO₂ 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