Decarbonized Energy from Waste via Ca-Looping

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Introduction

Achieving net zero CO_2 emissions by 2050 is crucial to limit global warming to 1.5°C (Net Zero 2050 Horizon, IEA [1]). To that end, Carbon Capture and Storage (CCS) offers the possibility to accelerate the reduction of CO_2 emissions by decoupling them from the use of carbon based materials. The concept can be conveniently applied to Waste-to-Energy plants to move toward the sustainability of waste management, another challenge faced by our society for which European directives prioritize the reduction of landfilling and favour energy recovery [2].

Calcium-Looping (CaL) is a promising CCS technology where CO_2 is captured using calcium oxide (CaO) to form calcium carbonate ($CaCO_3$) at high temperature (650°C). As the reaction is exothermic, the reactor (carbonator) is cooled. The captured CO_2 is then released through calcination (endothermic), in a second reactor (calciner) which works at about 920°C. The heat needed for the reaction is provided by burning some fuel in the reactor through oxycombustion, in order not to dilute the CO_2-rich stream. The high reactors operating temperatures make available heat that is recovered and used for electricity generation through a steam cycle.

This study, developed in the framework of Horizon Project *Calby2030* [3], focuses on a state-of the-art WtE plant with a waste-treating capacity of 1200 kt/year equipped with an RDF-fired CaL system, analyzing plant scheme, energy and environmental performances.

Integrating CaL into WtE plants offers benefits like high CO_2 capture efficiency, negative net CO_2 emissions due to the biogenic fraction of carbon in the waste and possible increase in power output. Furthermore, by feeding the calciner combustion with RDF (Refuse Derived Fuel), it becomes possible to utilize the waste itself to provide the additional energy input required for capture, thereby transforming the waste into a resource for decarbonization and enhancing the plant's waste treatment capacity.

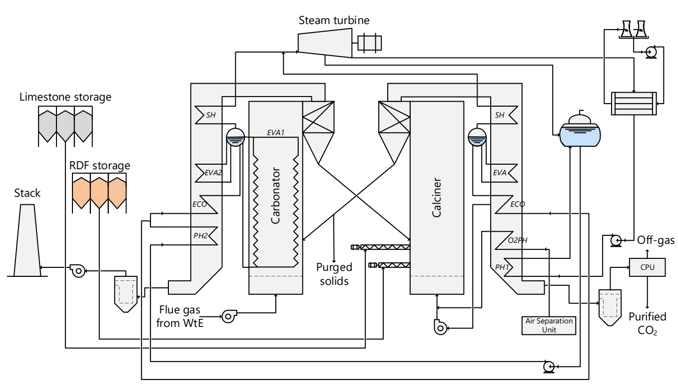

Figure 1 - Process flow diagram of the CaL process

Reference WtE plant

For this analyses, a large-scale state-of-the-art plant compliant with the "Best Available Techniques (BAT) Reference Document for Waste Incineration" [4] is considered. The plant comprises two grate-based combustion lines, capable of processing a total of 700 kt/year of municipal solid waste (MSW) along with 500 t/year of clinical-non-hazardous waste. Based on an average LHV of the waste of 10 MJ/kg, each boiler has a thermal power input of 121.5 MWth, operating for 8000 equivalent hours per year. The released thermal energy is utilized to generate 291.1 t/h of superheated steam at 424°C and 50 bar, which is then fed to a steam turbine with a gross electric power output of 78 MWe. The steam cycle features an air-cooled condenser with condensing pressure of 0.085 bar (42.7°C). Furthermore, up to 60 MWth of heat can be supplied to the district heating network bleeding LP steam from the turbine.

The flue gas treatment (FGT) system integrated into the plant, also compliant with BAT, comprises Hydrated lime and activated carbon injection for pollutant abatement, separation of injected solids and fly ashes in a bag filter, working at 145°C, and abatement of nitrogen oxides in a Selective Catalytic Reduction (SCR). Lastly the flue gases are treated in a wet scrubber that ensures compliance with emission limits for SO_2 and acid gases.

Integration of CaL system into the WtE plant

The Calcium-Looping system, shown in Figure 1, is integrated into the WtE plant in a tail-end configuration, being positioned before the wet scrubber, where the flue gases have a temperature of 120°C. The stream entering in the Cal section has a flowrate of around 450’000 Nm3/h, and a CO_2 content of 9.5%. The CO_2 mass flow-rate at the carbonator inlet is 83.3 t/h. The CO_2-lean flue gases from the Cal section are then routed to the stack at 120°C after the heat recovery section. The heat recovered from gas streams leaving the reactors and from the cooling of the carbonator is utilized for superheated steam generation and oxygen preheating, contributing to the overall energy efficiency of the system. Air infiltrations of 1% on mass basis in the boiler and 3% in the bag filters have been assumed, given that the plant is operated at negative pressure. The calciner is fed with Refuse Derived Fuel (RDF), with an assumed biogenic carbon content of 40% (with respect to the total carbon content) and a LHV of 16’600 kJ/kg. The CO_2-rich stream leaving the calciner is partly recirculated and mixed with oxygen -produced by the Air Separation Unit (ASU)- to regulate the combustion in the reactor, and then sent the Compression and Purification Section (CPU) where it is further purified and compressed up to 110 bar in supercritical state for pipeline transportation and storage.

The CaL make-up ratio (F_0/F_{CO2}) and recirculation ratio (F_R/F_{CO2}) are chosen to achieve a carbonator CO_2 capture efficiency close to 90% while minimising material and energy consumptions. The CaL superheated steam is generated at 60 bar and 500°C, and expanded in an independent steam turbine for electricity generation with a resulting nominal power output of 76.5 MW_e, almost doubling the gross electric power output of the plant.

Energy and environmental key performance indicators

Table 1 shows the main energy and environmental Key performance indicators of the WtE-Cal integrated plant, compared with those of the reference WtE plant. The yearly waste processing capacity increases, due to the use of RDF in the calciner. The gross electric power duplicates, while the net one increases only of 40%, because of the electric consumption of the CaL section, mainly due to the ASU and to the CPU. The carbonator CO_2 capture efficiency is 89,6%. Considering also the CO_2 produced the RDF combustion and the loss of CO_2 in the CPU vent gases, the CCR (CO_2 Capture Rate) of the system is 85%, and the percentage of avoided CO_2 is 70,5%. The resulting SPECCA index (Specific Primary Energy Consumption for CO_2 avoided), is 5.32 MJ_{LHV}/kg_{CO2}

Table 1 – Energy and environmental Key Performance Indicators

		WtE	WtE+CaL
Overall Fuel consumption	$t/y – TJ_{LHV}/y$	700’000-7’000	1’092’000 – 13’500
Gross electric power	$MW_e – MWh_e/y$	77.0 – 616’000	153.6 – 1’229’000
Gross electric efficiency	%	31.68%	32.76%
Net electric power output	$MW_e – MWh_e/y$	70.0 – 560’000	98.12 – 785’000
Net electric efficiency	%	28.80%	20.93%
Carbonator CO_2 capture efficiency	%		89.62%
Direct CO_2 emissions at stack	$t/y – kg/t_{fuel}$	673'000 – 961.90	197’000 – 281.4
Indirect CO_2 emissions[i)]	$t/y – kg/t_{fuel}$		-271’900 – -388.4
Equivalent CO_2 emissions	$t/y – kg/t_{fuel}$		-74’900 – -107.0
Net CO_2 emissions	$t/y – kg/t_{fuel}$		-658’600 – -940.9
CO_2 avoided from flue gas	%		70.5%
CCR (CO_2 Capture Rate)	%		85.5%
SPECCA	MJ_{LHV}/kg_{CO2}		5.32

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