Integration of Carbon Capture and Storage in Waste-to-Energy plants: comparison of MEA, CaL and MCFC technologies

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Agenda

01 **Introduction**

02 **Carbon Capture technologies for WtE plants**

03 **Methodology for CC implementation**

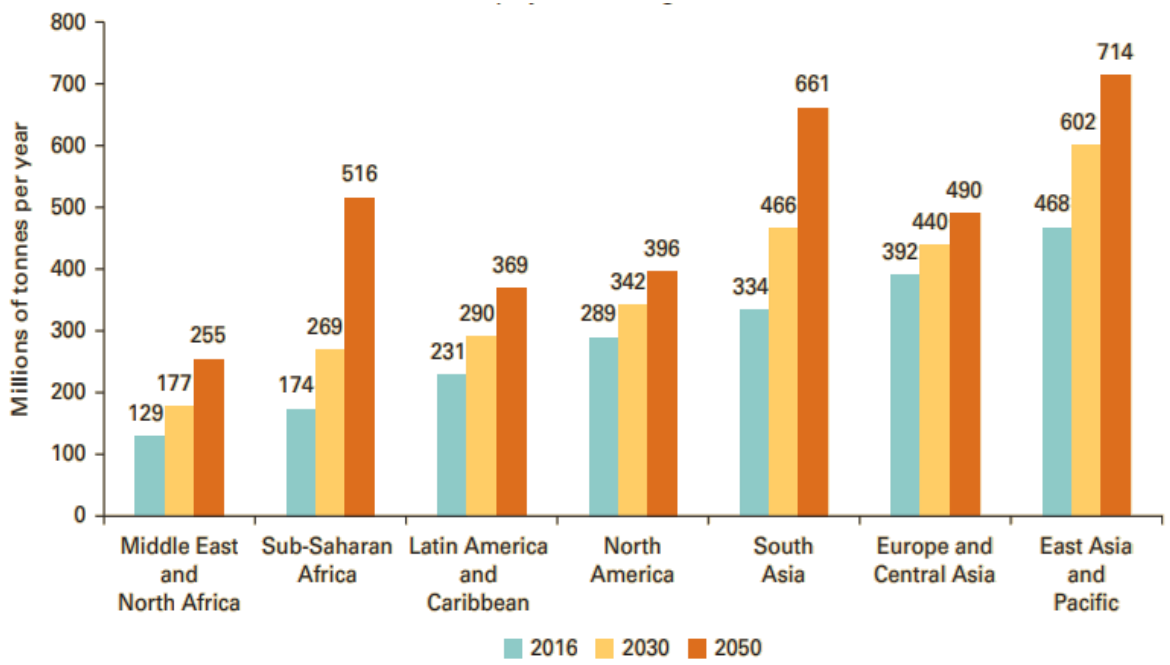
04 **Results**

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Municipal solid waste potential

3.88 billion tonnes of waste will be generated in 2050 due to rapid population growth.

Each tonne of municipal solid waste burnt typically releases between **0.7 and 1.7 tonnes** of CO_2, considering both the fossil and biogenic parts.

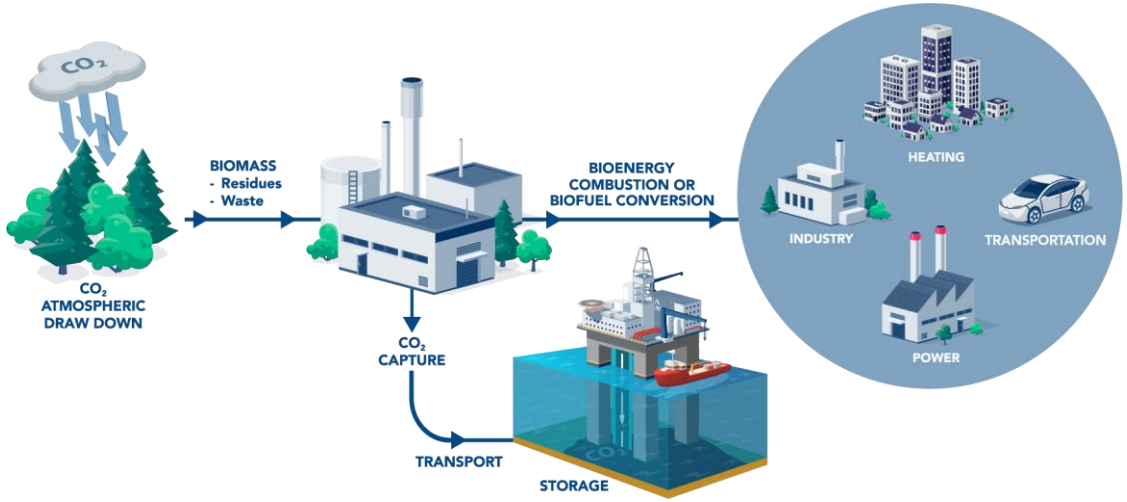


https://openknowledge.worldbank.org/handle/10986/30317

Energy-from-Waste potential

In existing European WtE plants there is a capture of **60-70 million tons** of CO_2 per year.

WtE plants coupled with CCS are part of "**BECCS systems**", considered one of the most important negative-emission technologies, since energy is produced while reducing carbon dioxide in the atmosphere.



https://www.babcock.com/home/renewable/biomass-to-energy/bioenergy-with-carbon-capture-and-sequestration/

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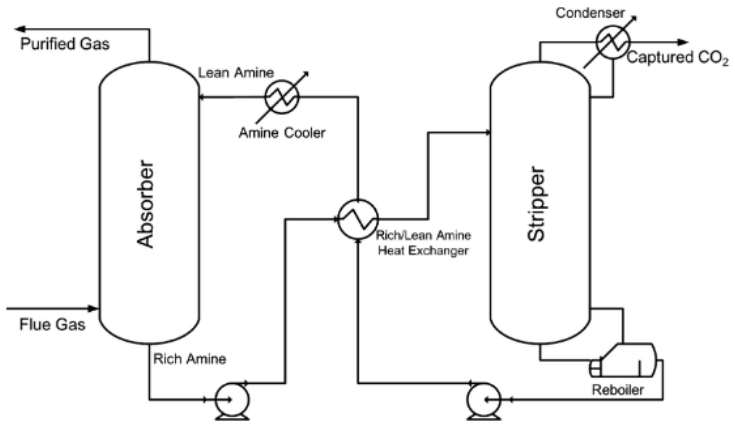
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MonoEthanolAmine



⊕ **TRL**: 9 (commercial full scale)

⊕ **Retrofittability**: end-of-pipe

⊖ **High heat requirement** for regeneration (~ 3 GJ/ tonCO_2)

⊖ **Solvent degradation**

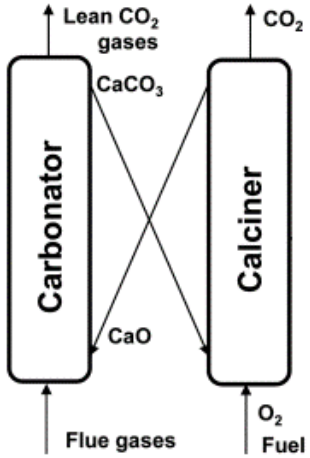


- Since August 2019 **AVR's facility in Duiven** (Netherlands) has included a unique CO_2 capture plant with a capacity of **60 ktons per year**.
- The captured CO_2 can be put to good use by the greenhouse **horticulture** and industry sectors.

- Norway's largest WtE plant **Hafslund Celsio** started a project to capture **400 kt of CO_2 per year**, which is the world's first full-scale CCS facility on WtE.
- The successful 9-month pilot project ended in December 2019, and has captured **3.5 tons of CO_2 per day** using **Shell's Cansolv** technology.



Calcium Looping



⊕ Possibility of **thermal recovery**

⊕ **Lower energy penalty**

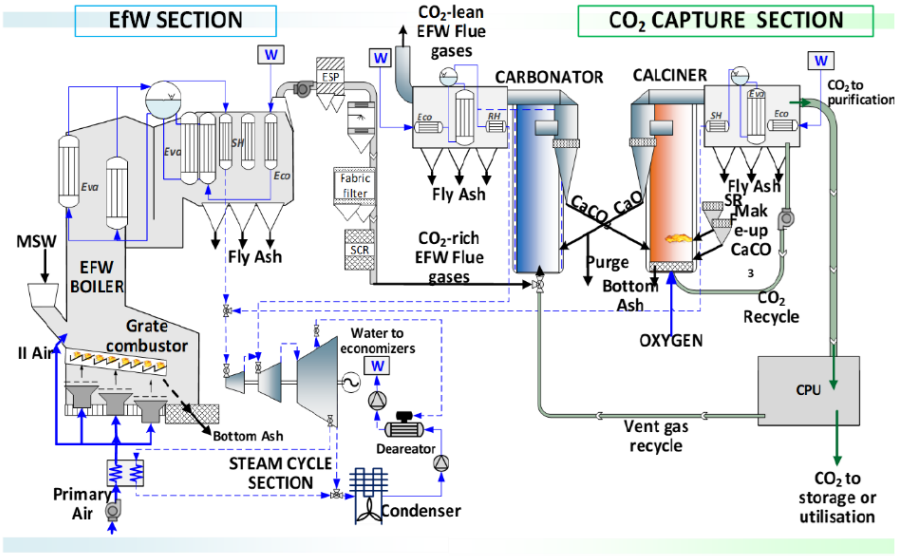
⊖ **Loss of CO_2 carrying capacity** due to unwanted reactions

⊖ Only **pilot plant** demonstration

HERCCULES project

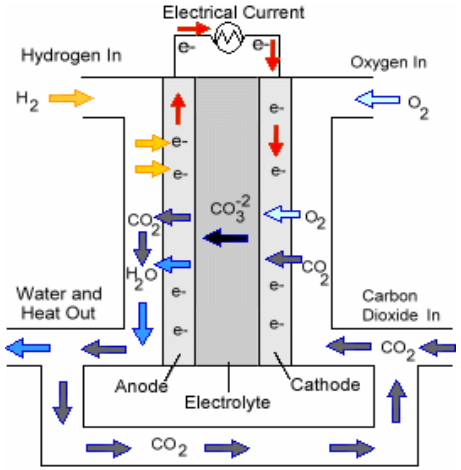
- Demonstration of the full CCUS chain for the **decarbonization of hard-to-abate industries** in southern Europe, focusing on cement and waste to energy sectors in northern Italy and Greek clusters.
- The consortium is **coordinated by LEAP** and includes **23 partners** and **4 affiliates**.





- First time demonstration at **TRL 7-8** for the CaL process coupled with CPU.
- The demo plant will be installed and operated at the **WtE Silla 2** plant owned by **A2A Ambiente.**

Molten Carbonate Fuel Cell



⊕ **Additional** energy production

⊕ **Retrofittability**: end-of-pipe

⊖ Additional **natural gas** consumption

⊖ High **uncertainty** on cost and degradation



- **First** application of MCFCs for CO_2 capture in an industrial environment.
- Project developed by **Esso Nederland BV** (subsidiary of ExxonMobil) to set up a pilot plant at its Rotterdam Manufacturing Complex, in cooperation with **FuelCell Energy**.

- The Rotterdam Manufacturing Complex is a **petrochemical and refining site**.
- The captured CO_2 will be transported and stored under the North Sea through the **Porthos project**.



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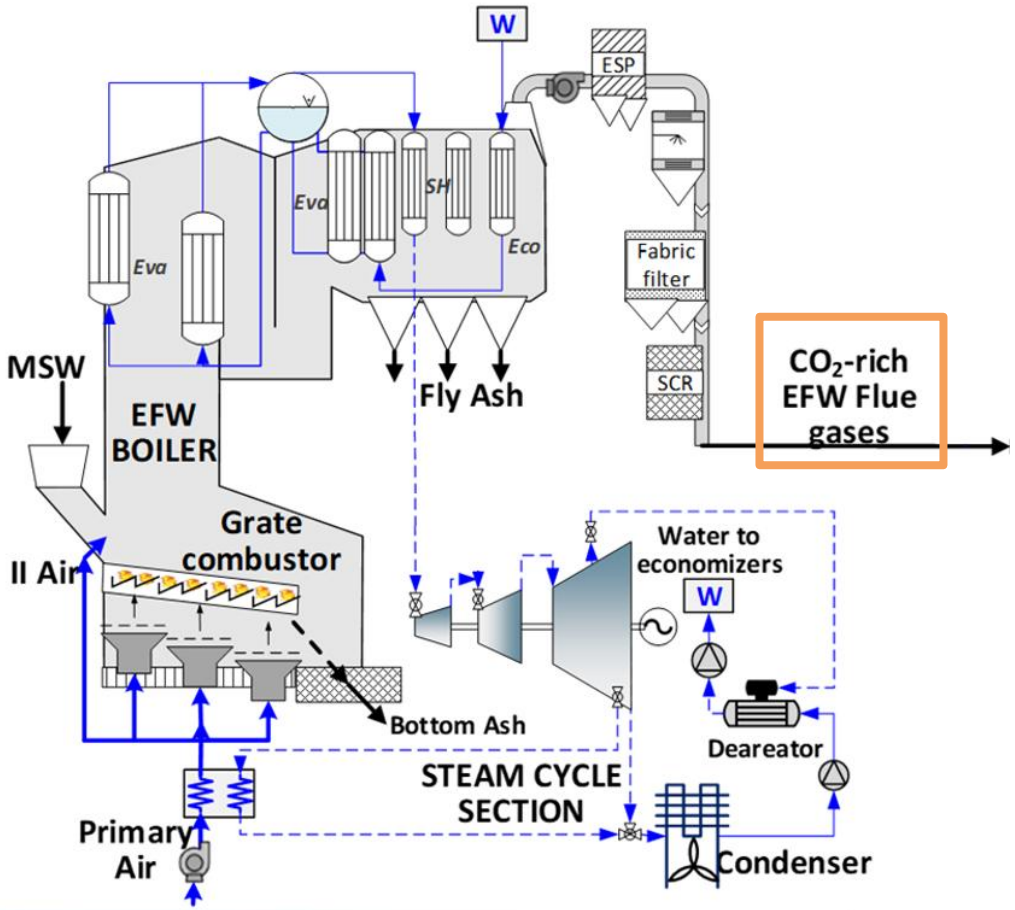
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Reference WtE plant



The WtE plant is inspired by a **medium-size** plant located in northern Italy which consists of **2** identical grate-based **lines**, and can treat **160'000 tons of waste per year**.

Ultimate waste composition, %	
C	27.85
Cl	0.27
F	0.004
H	4.26
N	0.62
O	15.74
S	0.03
Ash	14.50
Moisture	36.72

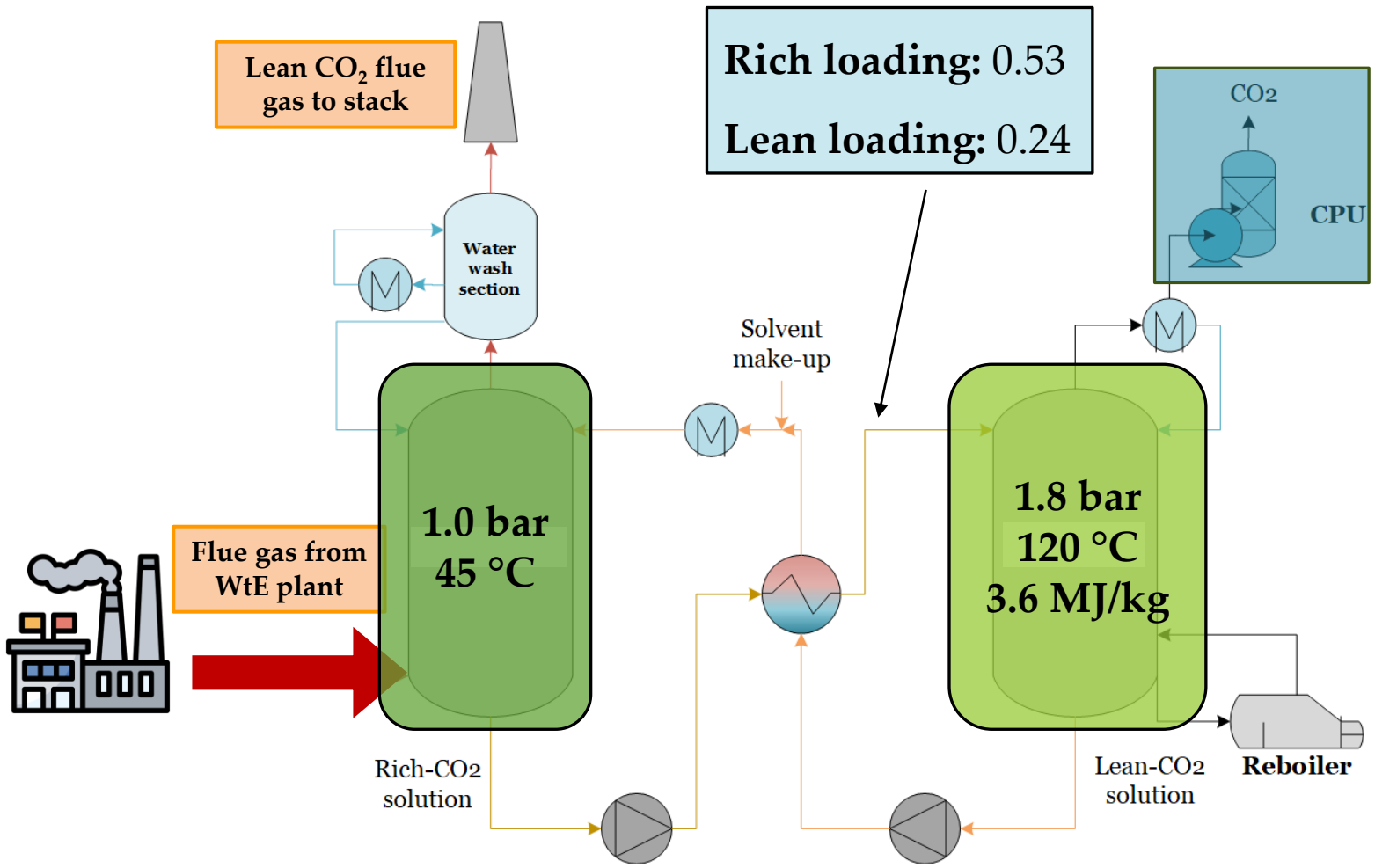
CO_2 emission factors

- Overall CO_2: 97.69 kg/GJ_{LHV}
- Biogenic CO_2: 49.63 kg/GJ_{LHV} (share: 50.8%)
- Fossil CO_2: 48.06 kg/GJ_{LHV}

LHV, GJ/ton	10.45

MEA-based CC section

- The solvent is a **30 $\%_{w/w}$** aqueous solution of **MEA**, with a CO_2 removal rate of **90%**.
- Two main reactors: the **absorber** and the **stripper**, equipped with the reboiler for the regeneration of the solvent.
- **Compression and Purification Unit**: a series of inter-refrigerated compressors to bring the CO_2 flow to 110 bar.

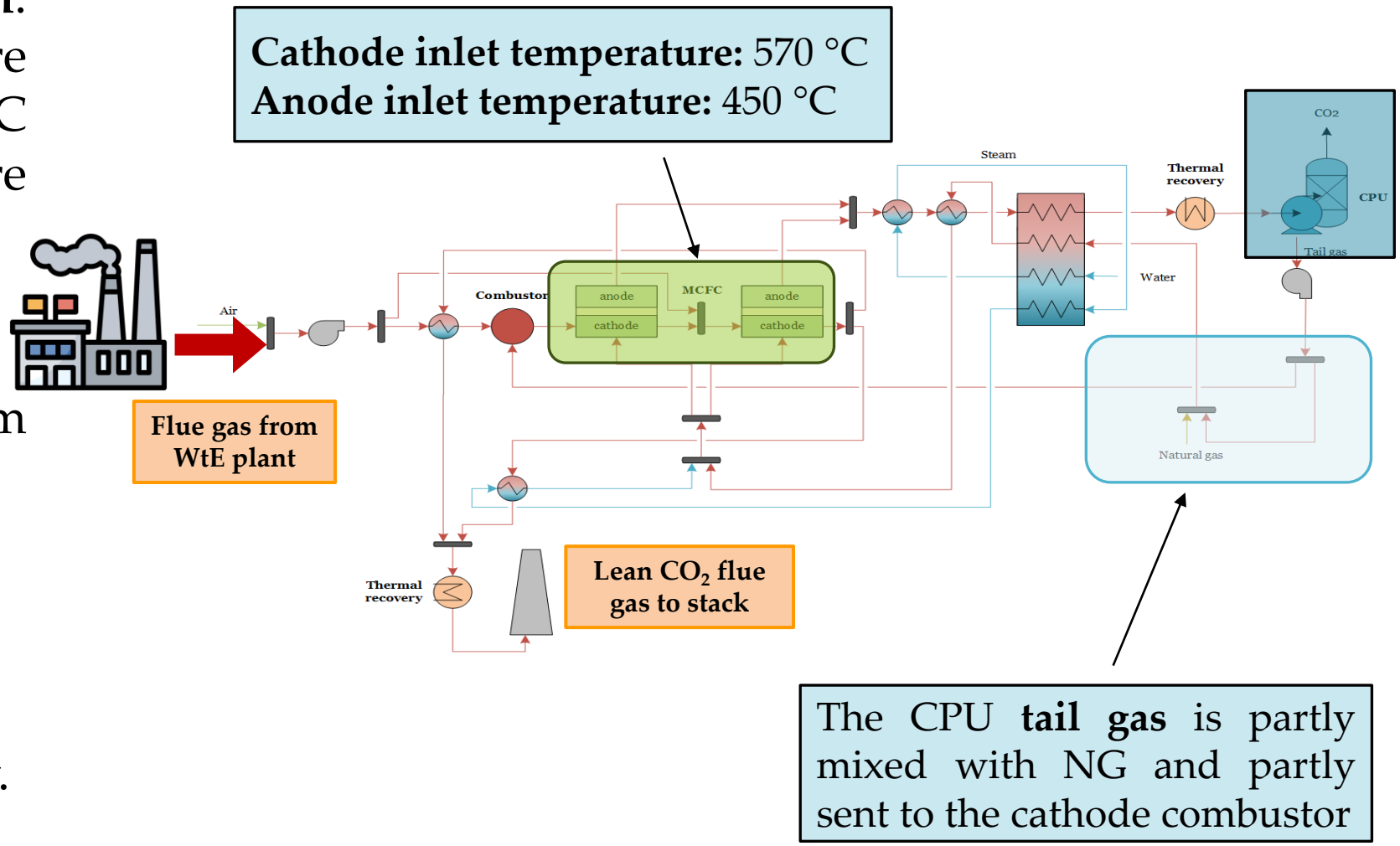


MCFC-based CC section

- **Cathode side connection**: series/parallel mixed, to ensure the inlet temperature of 570 °C and the maximum temperature difference across the cell.

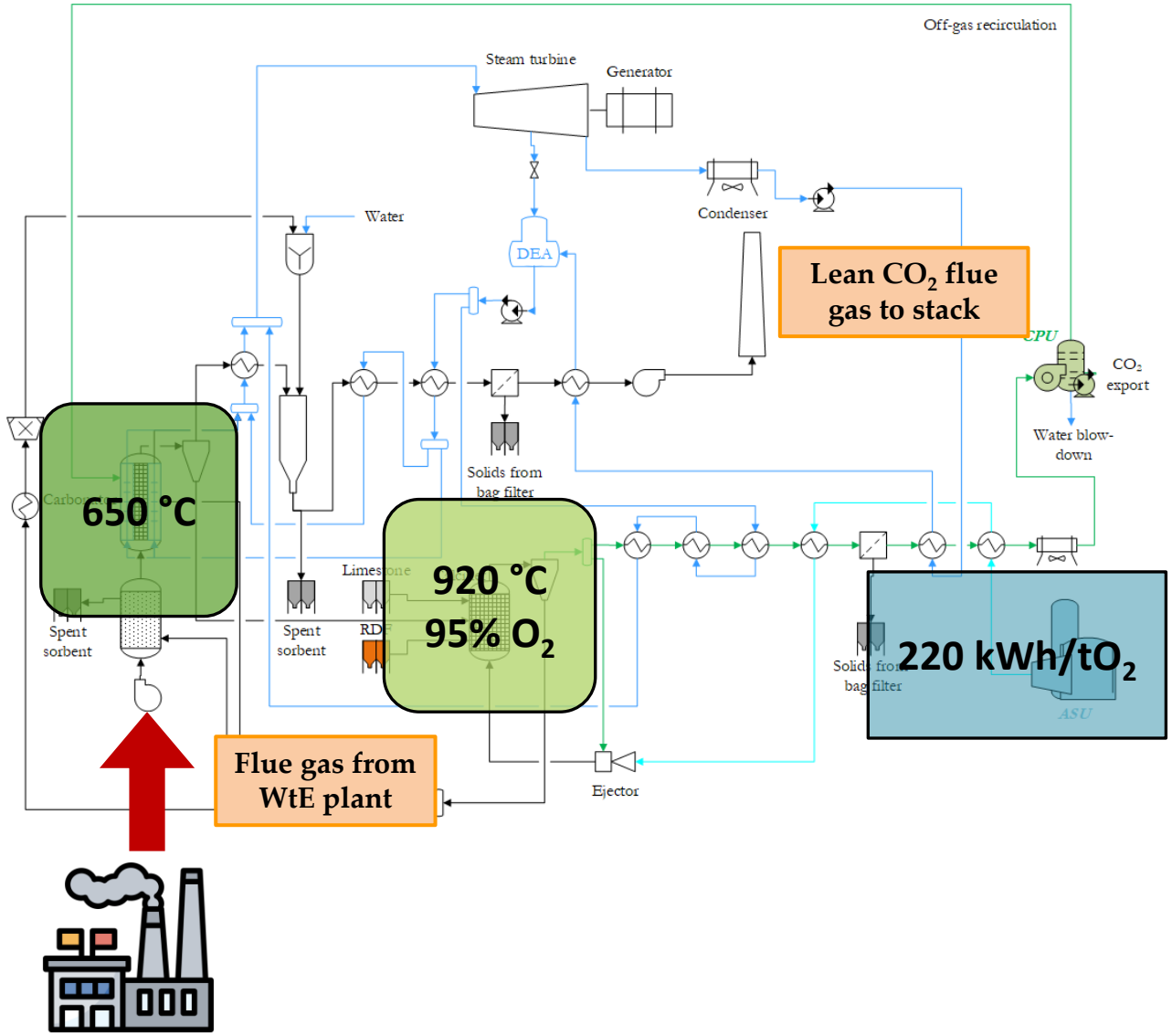
- CO_2 removal rate of **90%** from WtE flue gas.

- **Compression and Purification Unit**: necessary to separate the tail gas from the pure CO_2-flow.



CaL-based CC section

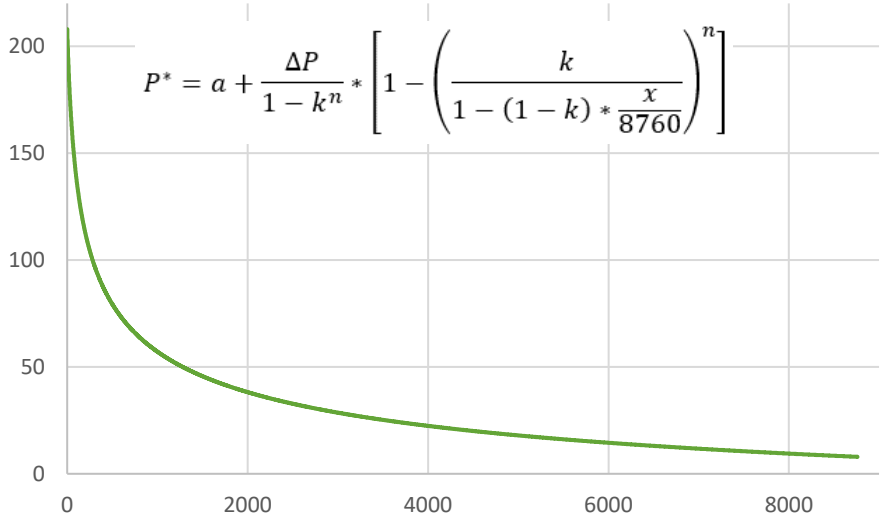
- **Line 2 is dismissed**: only Line 1 continues working at nominal point.
- Two main reactors: the **carbonator** and the **calciner**, equipped with SRF combustion (produced with Mechanical Biological Treatment of the same MSW of the reference plant).
- The amount of treated MSW remains constant.
- Oxygen for oxy-combustion is produced on-site, thanks to the **Air Separation Unit**.



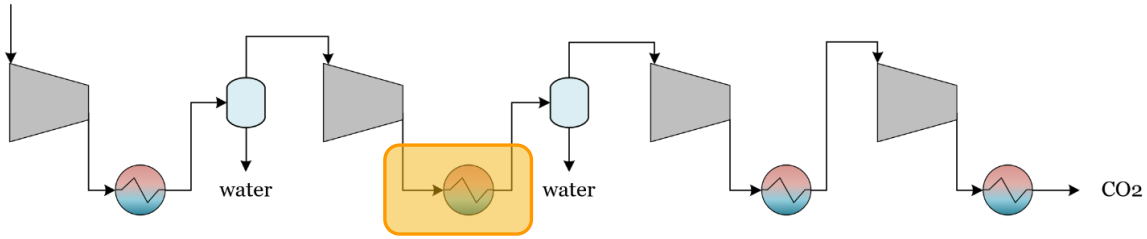
DH network

- The coupling with the District Heating network is analysed analytically.
- DH network receives heat from steam turbine bleedings and CPU thermal recovery, when reasonable power are involved (> 0.5 MWth).

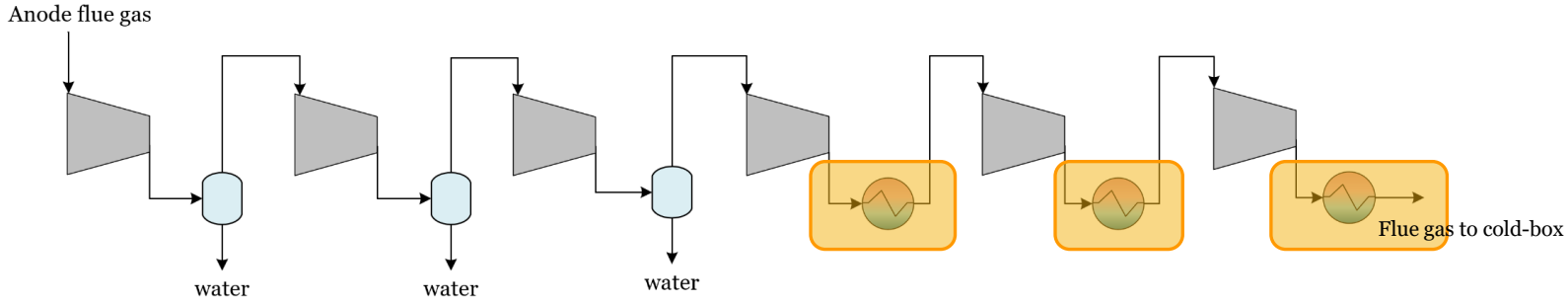
DH load duration curve



Compression section MEA-based CC



Compression section MCFC-based CC



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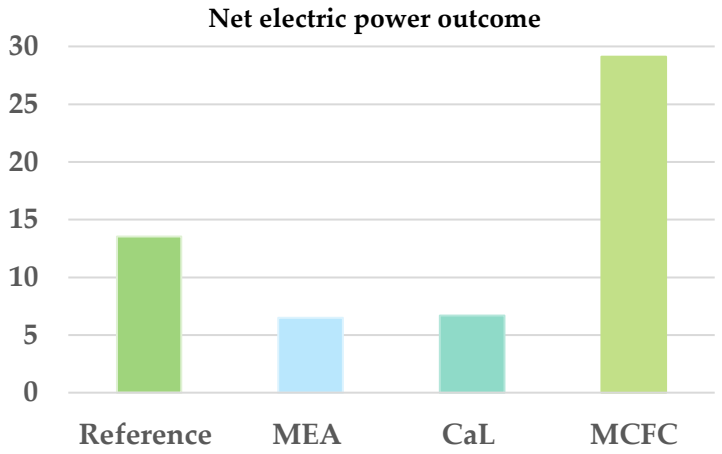
Energy balance results

	UoM	Reference	MEA	MCFC	CaL
Energy potential of treated waste	MW_{LHV}	71.32	71.32	71.32	64.97
Amount of managed waste	t/y	160 000			
NG input to MCFCs	MW_{LHV}	-	-	32.88	-
Steam cycle electric power output	MW_{EL}	16.49	12.29	16.49	16.13
MCFCs electric power output	MW_{EL}	-	-	20.17	-
Auxiliaries of CC section	MW_{EL}	-	2.58	4.38	6.23
Net electric power outcome	MW_{EL}	13.53	6.48	29.12	6.67
Thermal power required by CC section	MW_{TH}	-	23.11	-	-
Thermal power recovery from CC section	MW_{TH}	-	0.55	0.85	0.00
Overall net electric efficiency	$\%_{LHV}$	18.97	9.41	27.94	10.31

- The analysis has been done considering the **same amount of managed waste** for all the configurations.
- The results presented are for the **minimum cogeneration configuration**: the cogenerated power is only the one recoverable from the CCS section.
- The electric power output of the **steam turbine** remains unchanged for the MCFC-based case while it is slightly reduced in the CaL-based case due to the lower steam flow from the CaL system compared to the WtE line it replaces.

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- In terms of energy performances, the most promising configuration is the **MCFC-based one**, considering the **extra electricity** production.
- In the **MEA-based** case, the efficiency reduction is mainly due to the **heat duty for the regeneration**.
- In the **CaL-based** case the **CCS auxiliaries** (46%) and the **ASU** (35%) penalize the system.

SPECCA index

- **ΔPE** and **ΔCO_2**: primary energy and carbon dioxide emissions difference between CCS and reference plant
- E_{NG}: potential natural gas consumption for CCS plant
- ΔE_{el} and ΔE_{th}: electric and heat production difference between CCS and reference plant
- $\eta_{STD,el}$, $\eta_{STD,th}$, $e_{el,STD}$ and $e_{th,STD}$: reference electrical and thermal efficiencies/emissions

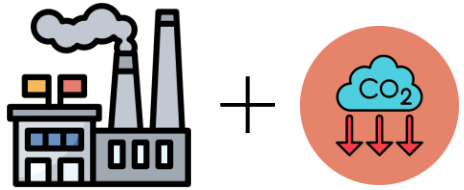
	NGCC with CC
Standard electric efficiency, %	49.9
Standard specific CO_2 emissions, kg/kWh	36.2

$$SPECCA = -\frac{\Delta EP}{\Delta CO_2} = -\frac{E_{NG} - \left(\frac{\Delta E_{el}}{\eta_{STD,el}} + \frac{\Delta E_{th}}{\eta_{STD,th}}\right)}{CO_{2,CCS} - CO_{2,ref} - \left(\Delta E_{el} * e_{el,STD} + \Delta E_{th} * e_{th,STD}\right)}$$

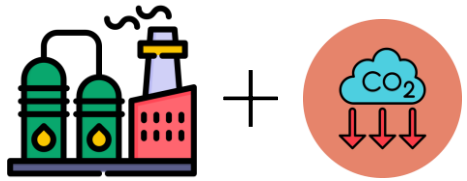
Compared power plants



Reference plant: WtE without CCS



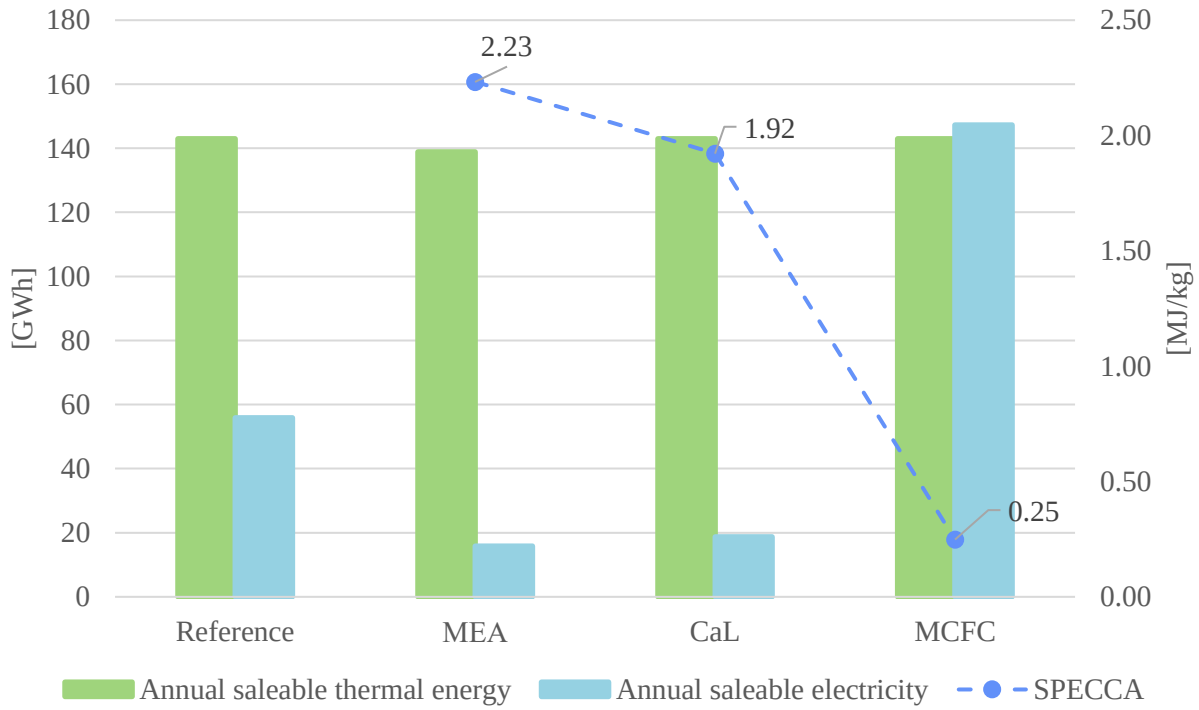
CCS plant: WtE with CCS



Benchmark plant: NGCC with CCS

SPECCA index results

$$SPECCA = -\frac{\Delta EP}{\Delta CO_2} = -\frac{E_{NG} - \left(\frac{\Delta E_{el}}{\eta_{STD,el}} + \frac{\Delta E_{th}}{\eta_{STD,th}}\right)}{CO_{2,CCS} - CO_{2,ref} - \left(\Delta E_{el} * e_{el,STD} + \Delta E_{th} * e_{th,STD}\right)}$$



- The SPECCA analysis has been done on **annual basis**, considering the coupling with the DH network and the actual operating hours of the plants.
- **MCFC-based system** has the lowest SPECCA index, despite the additional natural gas input, due to the higher energy efficiency.
- **MEA-based and CaL-based system** highly penalize electric production, which also affects the SPECCA index.

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MEA-based carbon capture has the highest TRL at the moment. However, **MCFC-based** and **CaL-based** carbon capture systems prove to be much more competitive from the electrical and thermal performance point of view.



A properly defined **SPECCA index** can be a suitable KPI to quantify the energy performance of different carbon capture options.



Future developments include conducting an **economic analysis** to compare the various technologies from a profitability perspective.

Thank you for your attention!

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References

- Consonni, S., and Viganò, F., 2011, "Material and energy recovery in integrated waste management systems: The potential for energy recovery", Waste Management 31, 2074-2084.
- Viganò F., Consonni S., Ragazzi M., Rada E. 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, May 16-18, 2011.
- Viganò, F., Cretarola, L., Spinelli, M., 2022, "Molten Carbonate Fuel Cells (MCFC) for the carbon capture in Energy-from-Waste (EfW) plants", Proceedings of Venice 2022: 9th International Symposium on Energy from Biomass and Waste, Venice, Italy, November 21-23, 2022.
- G. Mazzolari, S. Consonni, M. Spinelli, and E. De Lena, "CO 2 capture by Calcium Looping in Waste to Energy plants: case studies for medium scale applications TESI DI LAUREA MAGISTRALE IN MECHANICAL ENGINEERING-INGEGNERIA MECCANICA," 2021.