full CCUS chain demonstration

Bologna, 24-25/06/2025

ZEP Projects Network

II meeting

The HERCCULES project: CO_2 capture and purification requirements in different industrial sectors

Maurizio Spinelli
LEAP s.c.a r.l.

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Summary

The HERCCULES project: CO_2 capture and purification requirements in different industrial sectors

- CO_2 emissions sources and carbon capture technologies portfolio
- Role of impurities in the CCUS chain
- CO_2 capture and purification integration: examples
  - Solvent-based systems – role of contaminants
  - MCFCs + CPU - role of contaminants

- **HERCCULES** Horizon Europe project
  - Project overview
  - HERCCULES CO_2 capture and purification systems and demonstration sites
  - Next steps

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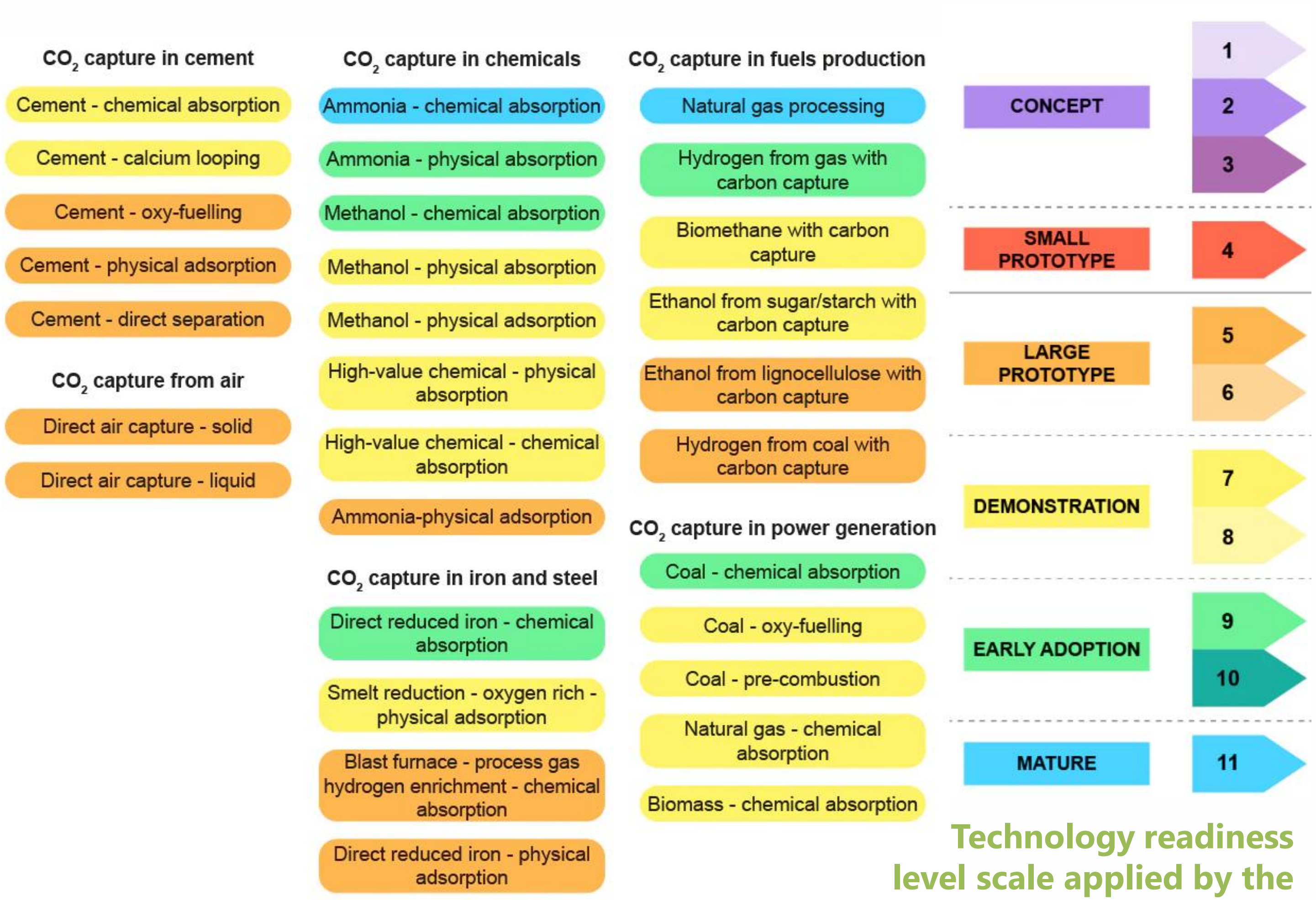
CCS technologies

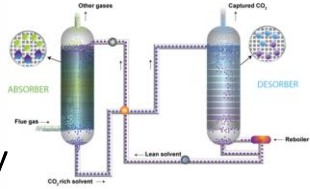


Technology readiness level scale applied by the IEA

from IEA – Energy technology perspectives 2020 -Special Report on Carbon Capture Utilisation and Storage - CCUS in clean energy transitions

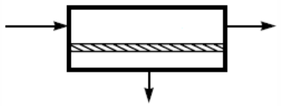
Post combustion

Chemical absorption (amine & solvents)

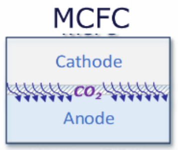


Physical separation (adsorption/MOF/cry

Membranes/Hybrid systems

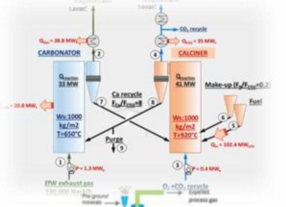


Electrochemical (i.e. MCFCs)



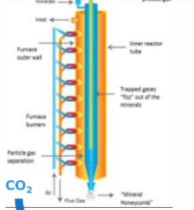
Oxy-fuel combustion (+ CPU)

Precombustion/Other

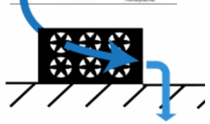


Chemical looping, Calcium looping

Direct separation (LEILAC)



Supercritical CO_2 power cycles



Direct Air Capture systems

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CC technologies – selection

- Flue gas properties (CO_2 concentration, impurities)
- Emission Source process (cement industry, steel, power, oil and gas, glass, etc.)
- Efficiency
  - Primary energy consumption for CO2 avoided
  - Process integration with the hosting plant
- TRL & Scalability
- Costs
  - CAPEX & OPEX
  - Cost of CO_2 avoided
- Footprint and logistic/operational aspects

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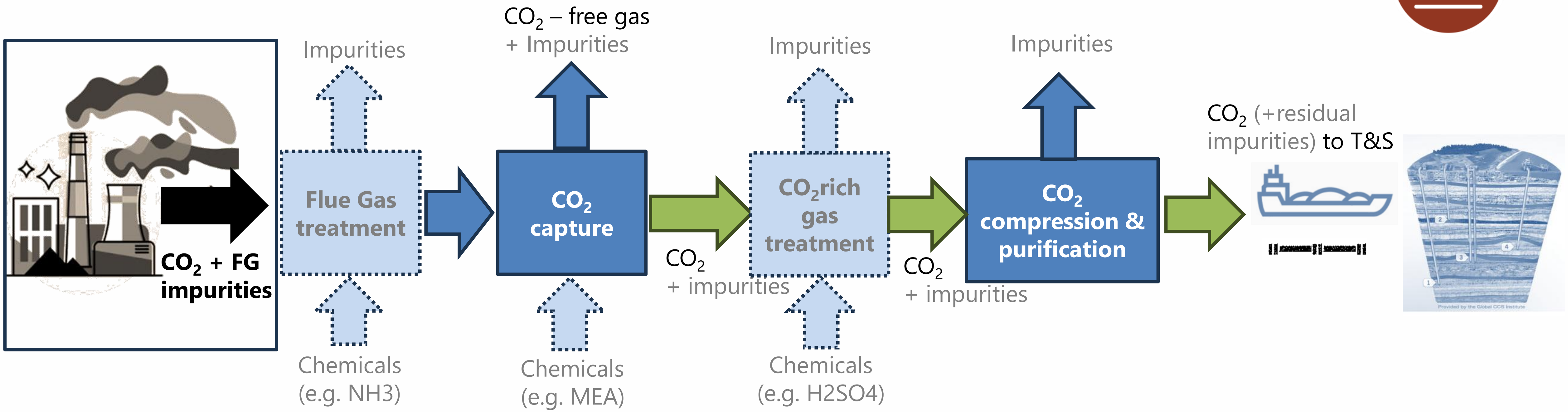
CO_2 emission sources - impurities



- Power: 3–15% CO_2, NO_x, SO_x, particulates
- Cement: 15–20% CO_2, dust, CO, NO_x, So_x, HCl,..
- WTE: 7–12% CO_2, HCl, NO_x, CO, SO_x, VOCs, Hg, metals, dust, dioxines..
- Steel: 10–25% CO_2, Dust, NO_x, SO_x, CO, H_2
- Glass: 12–20% CO_2, Alkali vapors, SO_x, particulates

+ non-condensable (N_2, O_2, Ar..)

HERCCULES full CCUS chain demonstration
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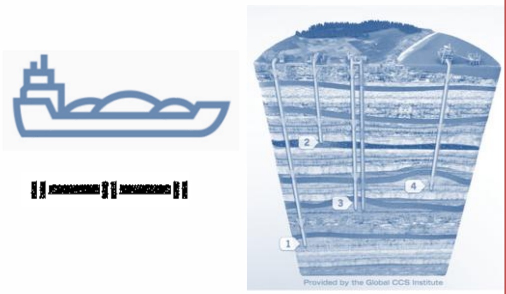
The impact of impurities - CO_2 T&S specifications

Project	(a) Northern Lights (Liquid CO_2)	(b) Aramis	(c) Cemcap	(d) DYNAMIS	(e) Ecofys	(f) Kinder Morgan	(g) GRTgaz	(h) Fluxys (Lower)	(i) Fluxys (Upper)	(j) DNV	(k) IPCC	(l) NETL
Reference	(Northern Lights, 2024)	(CCS-Aramis Project, 2023)	(Monteiro et al., 2018)	(de Visser et al., 2008)	(Race et al., 2012)	(de Visser et al., 2006)	(GRTgaz, 2024)	(Fluxys, 2021)	(Fluxys, 2021)	(Teberikler et al., 2022)	(IPCC, 2005)	(U.S DOE, 2019)
CO_2 (%)	≥ 99.81	≥ 95	≥ 99	> 95.5	> 95	> 95	> 95	> 95	> 99	Balance	> 95	> 95
H_2O (ppm)	≤ 30	≤ 70	≤ 40[i]	< 500	< 500	< 630	< 40	< 40	< 40	50-100	< 0.48[ii]	< 500
O_2	≤ 10 ppm	≤ 40 ppm	-	-	-	≤ 10[i]	< 40 ppm	< 40 ppm	< 40 ppm	< 10 ppm	< 10[i]	<0.001 %
N_2	≤ 50 ppm	≤ 2.4%	-	-	-	-	< 2%	< 2%	< 0.5%	-	< 4%	< 4%
H_2	50 ppm	≤ 7,500 ppm	-	-	-	-	< 0.75%	< 0.75%	< 0.2%	-	-	< 4%
Ar (%)	≤ 0.01	≤ 0.4	-	-	-	-	< 0.4	< 1	< 0.2	-	-	< 4
CH_4	≤ 100 ppm	≤ 1%	-	Aquifer: <4% EOR: < 2%	-	-	< 1%	< 1%	< 0.1%	0.5-2%	-	< 4%
CO (ppm)	≤ 100	≤ 750	≤ 1.1	< 2,000	< 2,000	-	< 750	< 100	< 100	< 400	-	< 35
$O_2+N_2+H_2+Ar+CH_4+CO$	-	≤ 40,000 ppm	-	< 4%	< 4%	< 5%	< 4%	< 4%	< 0.8%	-	-	< 4%
SO_x (ppm)	≤ 10	-	-	< 100	-	-	< 10	< 10	< 10	< 100	-	-
SO_2 (ppm)	-	-	-	-	-	-	-	-	-	-	-	< 100
SO_3 (ppm)	-	-	-	-	-	-	< 0.1	-	-	-	-	-
NO_x (ppm)	≤ 1.5	≤ 2.5	-	< 100	-	≤ 10	< 10	-	-	< 100	-	< 100
NO (ppm)	-	-	≤ 2.5	-	-	-	-	< 2.5	< 2.5	-	-	-
NO_2 (ppm)	-	-	≤ 2.5	-	-	-	-	< 2.5	< 2.5	-	-	-
$H_2S+COS+SO_x+DMS$ + mercaptans (ppm)	-	≤ 20	≤ 5	-	-	-	< 20	-	-	-	-	-
H_2S	≤ 9 ppm	≤ 5 ppm	-	< 200 ppm	< 200 ppm	10-200 ppm	< 9 ppm	< 5 ppm	< 5 ppm	< 100 ppm	< 1,500 ppm[i]	<0.01%
COS (ppm)	-	-	-	-	-	-	-	< 0.1	< 0.1	-	-	trace
DMS (ppm)	-	-	-	-	-	-	-	< 1.1	< 1.1	-	-	-
Amine (ppm)	≤ 10	≤ 1	-	-	-	-	< 10	< 10	< 10	< 100	-	-
NH_3 (ppm)	≤ 10	≤ 3	-	-	-	-	< 10	< 10	< 10	-	-	<50
Formaldehyde (ppm)	≤ 20	-	-	-	-	-	< 20	-	-	-	-	-
Acetaldehyde (ppm)	≤ 20	-	-	-	-	-	< 20	-	-	-	-	-
Aldehydes (ppm)	-	≤ 10	-	-	-	-	-	-	-	-	-	-
Carboxylic acids & amides (ppm)	-	≤ 1	-	-	-	-	< 1	-	-	-	-	-
Phosphorus-containing compounds (ppm)	-	≤ 1	-	-	-	-	< 1	-	-	-	-	-
Hg (ppm)	≤ 0.0003	-	-	-	-	-	< 0.03	-	-	-	-	-
Cadmium + Thalium (ppm)	≤ 0.03	-	-	-	-	-	< 0.03	-	-	-	-	-
VOC (ppm)	≤ 10[iii]	≤ 10[iv]	≤ 1.2	-	-	-	< 10[v]	< 350	< 350	-	-	-
Methanol (ppm)	≤ 30	≤ 620	-	-	-	-	< 620	-	-	-	-	-
Ethanol (ppm)	≤ 1	≤ 20	-	-	-	-	< 20	-	-	-	-	-
Glycol (ppb)	-	-	-	-	-	-	-	-	-	-	-	< 46
MEG (ppm)	≤ 0.005	-	-	-	-	-	-	-	-	-	-	-
TEG	Not allowed	Dew-point specs.	-	-	-	-	-	-	-	-	-	-
BTEX (ppm)	≤ 0.5	-	-	-	-	-	-	-	-	-	-	-
Ethylene (ppm)	≤ 0.5	-	≤ 1	-	-	-	-	< 1	< 1	-	-	-
HCN (ppm)	≤ 100	≤ 2	≤ 20	-	-	-	< 2	< 15	< 15	-	-	trace
Aliphatic hydrocarbons (ppm)	≤ 1,100 (C_1^+)	≤ 1,200 (C_2^+)	-	-	-	-	< 1,200 (C_2-C_{10})	-	-	-	-	-
Aromatic hydrocarbons (ppm)	-	≤ 0.1	≤ 0.1	-	-	-	< 0.1 (C_6-C_{10})	< 0.1[vi]	< 0.1[vi]	-	-	-
Hydrocarbons	-	-	1,200 ppm	-	-	< 5%	-	< 1,200 ppm (C_2-C_6)	< 1,200 ppm (C_2-C_6)	-	< 5%	< 1% (C_1^+)
Ethane	75 ppm	-	-	-	-	-	-	-	-	-	-	< 1%
Solids, particles, dust	≤ 1 µm	≤ 1 µm	-	-	-	-	-	-	-	-	-	1 ppm

E.G. Nikolaidou et al, "The role of impurities in CCS from pilot capture plants to sequestration sites—A review", International Journal of Greenhouse Gas Control

Major concerns related to H_2O, SO_x, NO_x, O_2 , H_2S, (**Chemical effects**, **corrosion**) and non-condensable N_2, Ar, O_2 (**Physical effects**)

CO_2 (+residual impurities) to T&S



Many differences among specifications, that are periodically updated (ongoing process):

→ Need for standardization to connect different CCUS networks, ensuring **safety and storage integrity**;

→ **Balance** between purification and transport costs;

→ Some projects still reserve the right to conduct **additional risk assessments** for any species not included in the specifications

HERCCULES full CCUS chain demonstration
DECARBONISING WITH CCUS
LEAP
zep ZERO EMISSIONS PLATFORM
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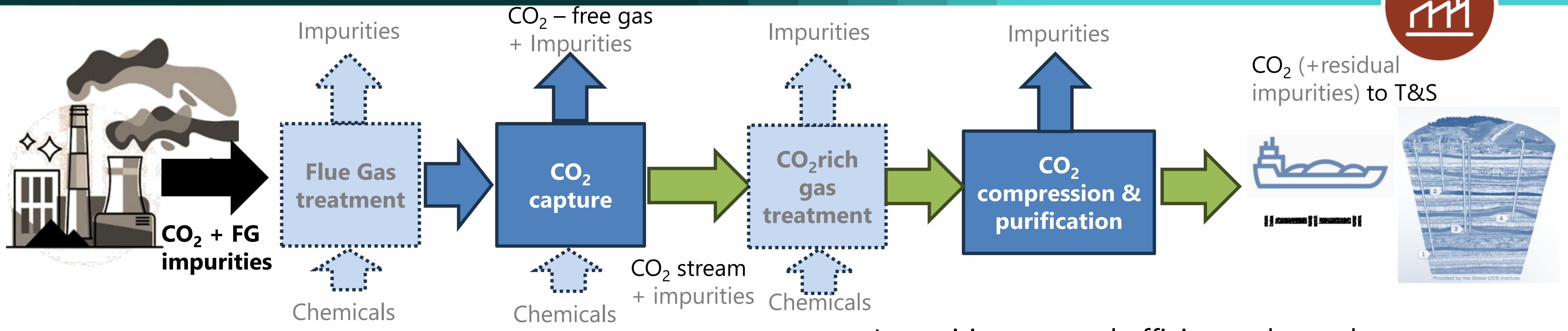
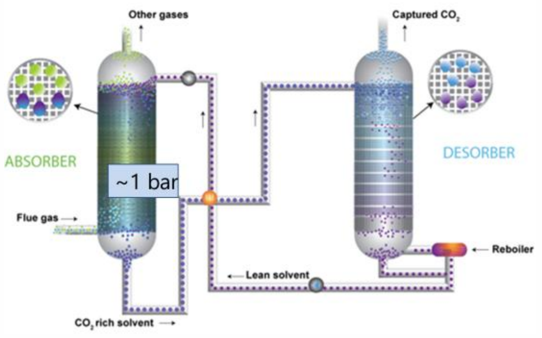
An example - Solvents



Solvent-based systems



Impurity*	Flue Gas to Capture	CO_2 from the Stripper
NOx	3-250 mg/Nm^3	0.5–10 mg/Nm^3
SOx	0.5–250 mg/Nm^3	0.1 – 10 ppm
NH_3	1–100 mg/Nm^3	1–20 mg/Nm^3
O_2	4-16%	10-1200 ppm
H_2O	2.5-23% vol	0.1–4.5% vol
Aldheydes	-	4–200 mg/Nm^3
VOCs	-	0.5–20 mg/Nm

Values extracted from E.G. Nikolaidou et al, "The role of impurities in CCS from pilot capture plants to sequestration sites—A review", International Journal of Greenhouse Gas Control

- Impurities removal efficiency depends on configuration, use of auxiliary treatments (e.g., water/acid washes, filters), solvent type and operational conditions.
- Solvent systems are generally effective for many contaminants, but less for some volatile compounds (NH_3, aldehydes, degradation products)
- process improvements and post-treatment upgrades are essential to meet CO_2 purity standards in all the operating conditions.

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LEAP zep
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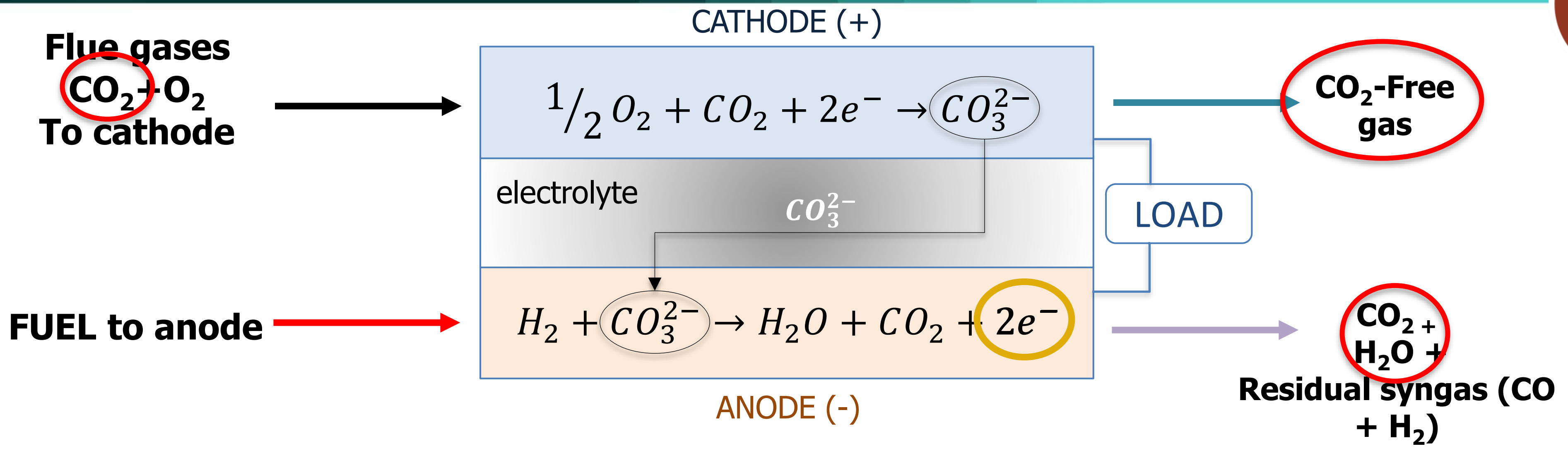
An example - MCFC – operating principle



- **High electrical efficiency** (up to 50% LHV)
- **Ready for CCS applications** in the power and industrial sectors (cement, steel, petrochemical)
- Commercially **available**: in the market there are modules ranging from 1.4 MWe to 4 MWe
- **Internal reforming**: The high operating temperature (650°C) and the presence of catalytic materials allow for internal fuel conversion (direct and indirect reforming) on various hydrocarbon fuels (e.g., biogas)
- MCFCs can operate as an **active NO_x separation**, owing to secondary electrochemical reactions
- Capability to produce **blue hydrogen** in addition to low-carbon electricity
- Main drawbacks include **corrosion/degradation** of materials and **low tolerance to contaminants**
- Investment **costs are high**, mainly due to the need for periodic stack replacement

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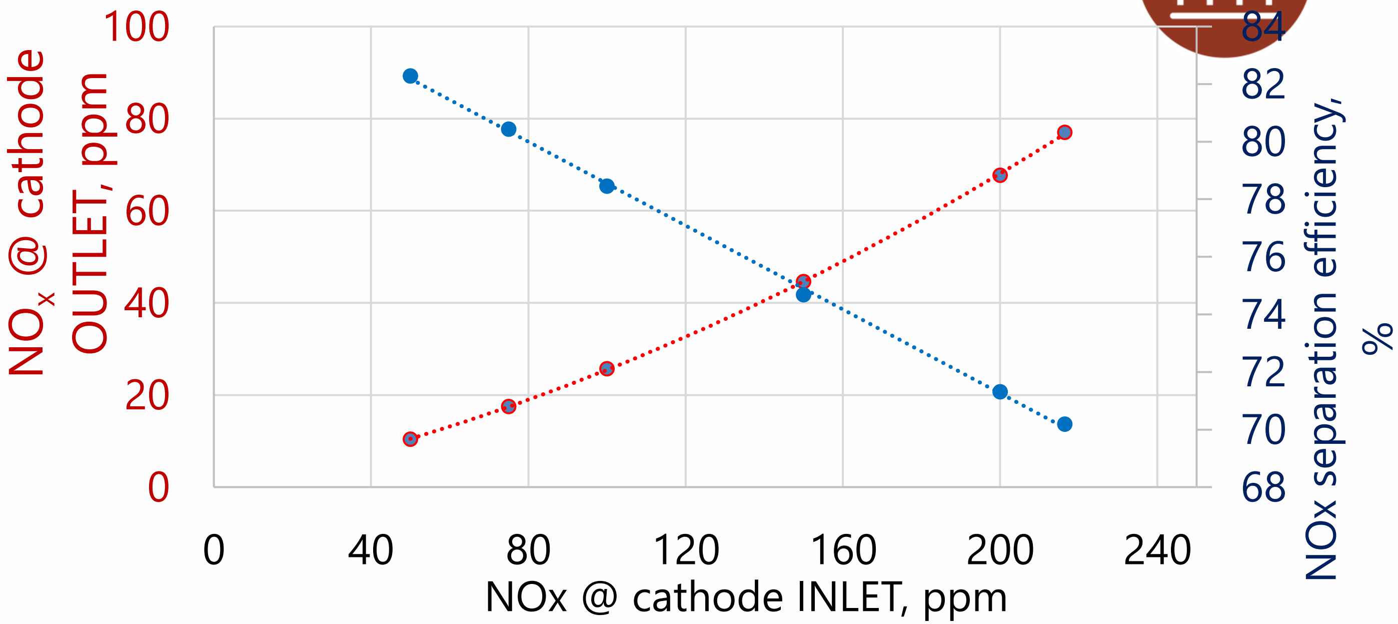
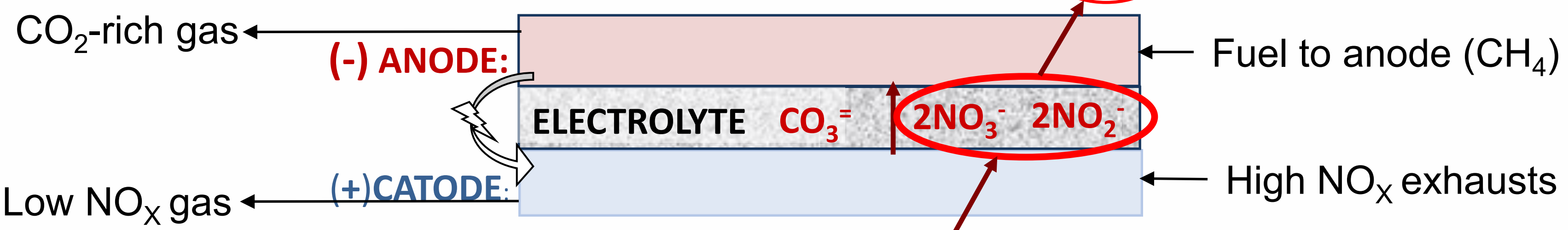
An example - MCFCs as active NOx separator

The MCFC separates NO_x fed to the cathode: the catalytic materials in the cell actively promote the NOx separation via side electrochemical reactions, followed by the transfer of NO_2^- and NO_3^- ions through the electrolyte (from cathode to anode). Experimental tests have shown promising NO_x removal efficiencies (70%), achieved with inlet concentrations > 200 ppm



MCFC separates NO_X

$$CO_2 + 5H_2 + 2NO_3^- \Rightarrow CO_3^= + 5H_2O + N_2 \quad ; \qquad CO_2 + 3H_2 + 2NO_2^- \Rightarrow CO_3^= + 3H_2O + N_2$$



$$\frac{1}{2}O_2 + 2NO_2 + CO_3^= \Rightarrow 2NO_3^- + CO_2 \quad ; \qquad \frac{1}{2}O_2 + 2NO + CO_3^= \Rightarrow 2NO_2^- + CO_2 \quad ; \qquad \frac{3}{2}O_2 + 2NO + CO_3^= \Rightarrow 2NO_3^- + CO_2$$

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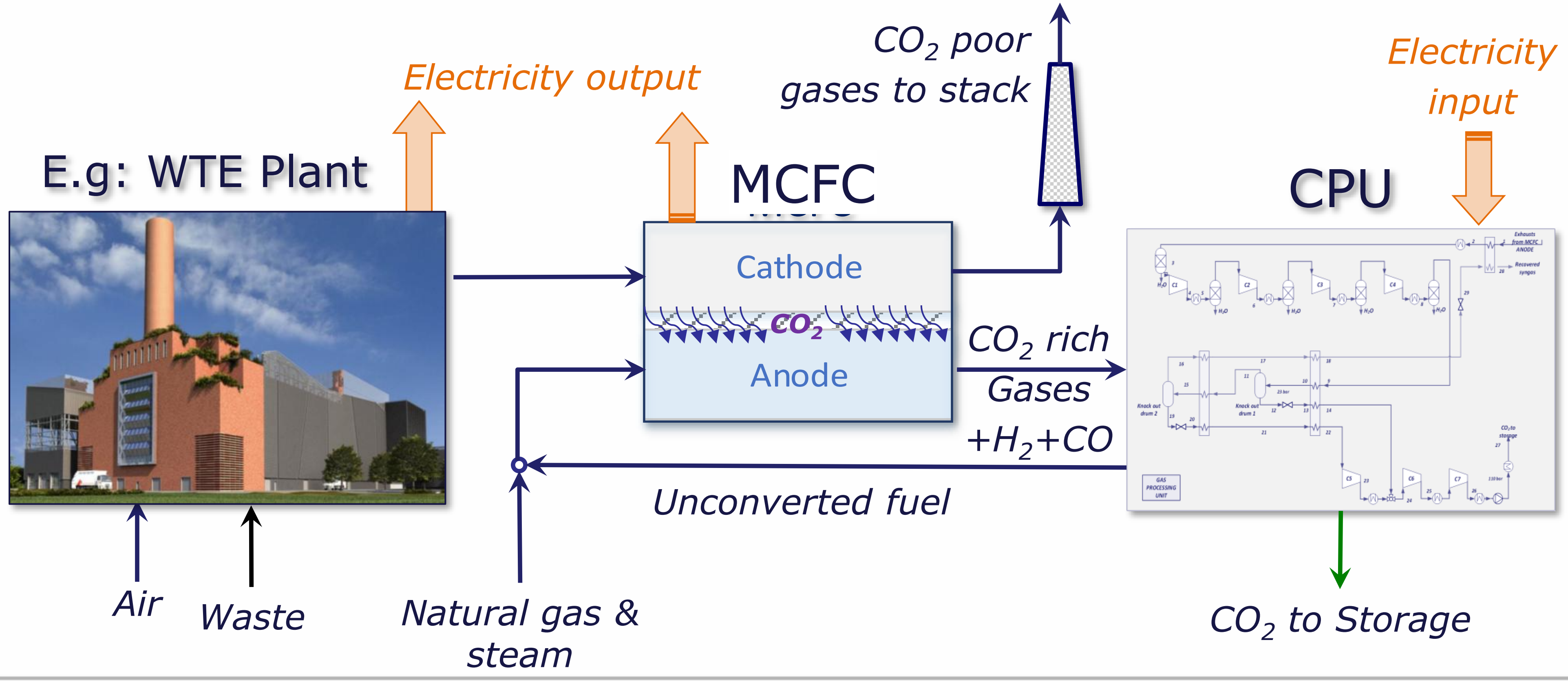
CO_2 cryogenic compression & purification process: sinergy

The MCFC must be integrated with a CO_2-rich stream purification system to meet the required **specifications** for downstream storage or utilization, and to **recover unconverted fuel** (residual syngas from the anode).



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full CCUS chain demonstration

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II meeting

HERCCULES

HERCCULES Project Concept

HERCCULES: HEROES IN SOUTHERN EUROPE TO DECARBONIZE INDUSTRY WITH CCUS

56 Deliverables,**18** Milestones

- **Coordinator:** LEAP
- **Partnership:** 25 partners + 5 affiliated
- **Topic:** HORIZON-CL5-2022-D3-01
- **Duration:** 1 Jan, 2023 - 31 Dec, 2027
- **Budget total:** € 39.627.208,00
- **UE Contribution:** € 29.632.076,48

HERCCULES NUMBERS

- 3 CO_2 capture pilot plants
- 3 CO_2 use pilot plants
- 2 Storage sites
- >10.000 test hours
- >3500 ton CO_2 captured
- >1000 ton CO_2 stored
- >8000 ton of low-carbon concrete
- 7 Pre-feed and Hazop studies

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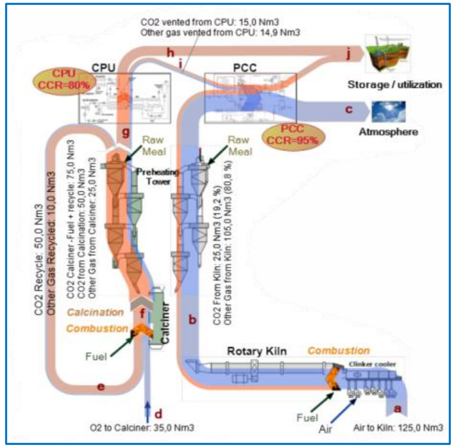
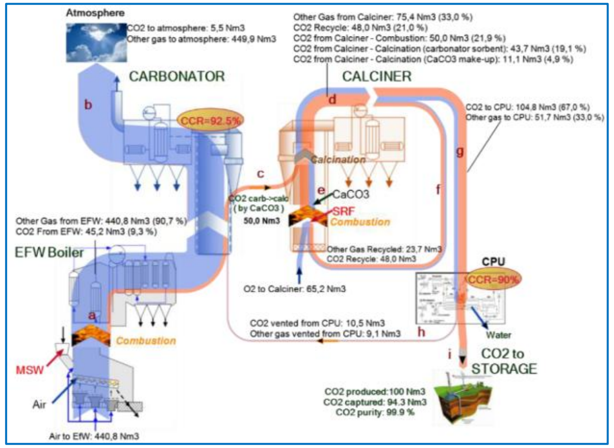
HERCCULES - CO_2 capture in cement & EfW





Process modeling, design and construction *of the pilot units*

2023 → 2024 → 2025 → 2026 → 2027

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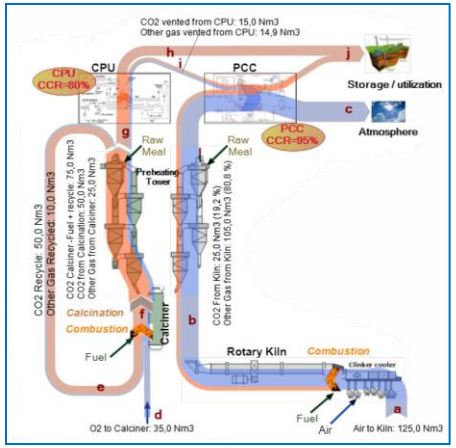
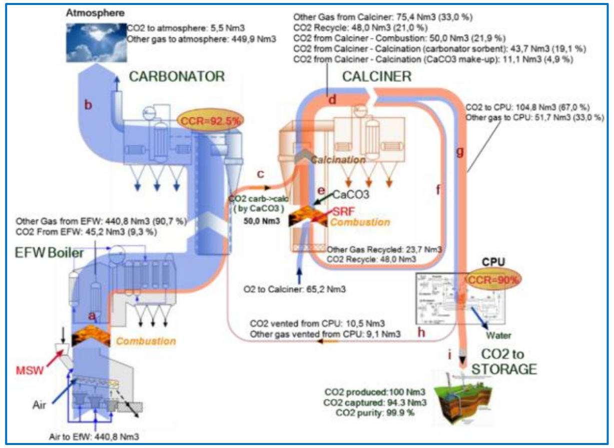
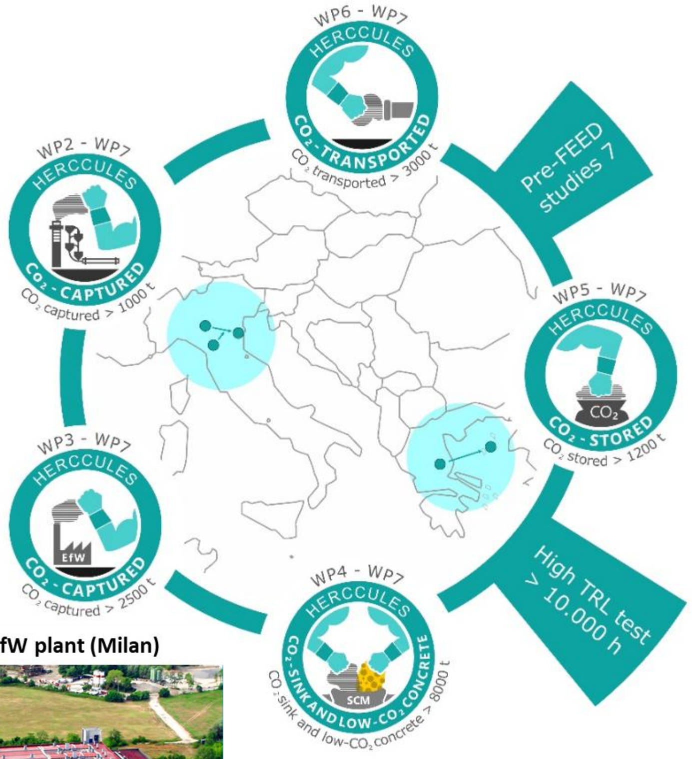
HERCCULES - CO_2 capture in cement & EfW - status



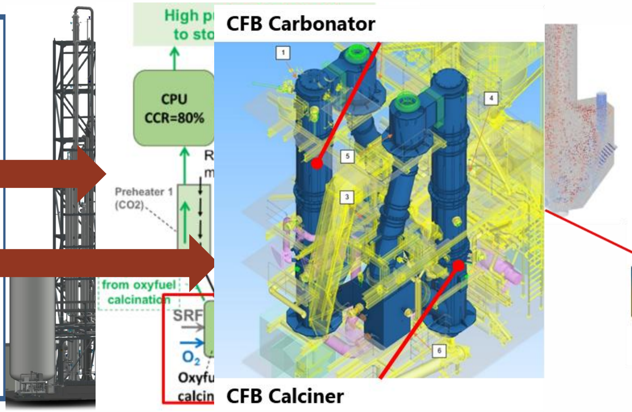


Process modeling, design and construction *of the pilot units*



2023 → 2024 → 2025 → 2026 → 2027

- PCC (post combustion unit) pilot plant has been designed and built (→ commissioning ongoing)
- The design of the oxyfuel calciner is completed (→*Hybrid* configuration for cement, in Greece)
- Design and procurement of the CaL demonstrator to be integrated in EfW plant in Milan is ongoing
- The design and procurement of the CPUs (CO_2 purification units for hybrid and CaL systems) is ongoing



Silla 2 EfW plant (Milan)

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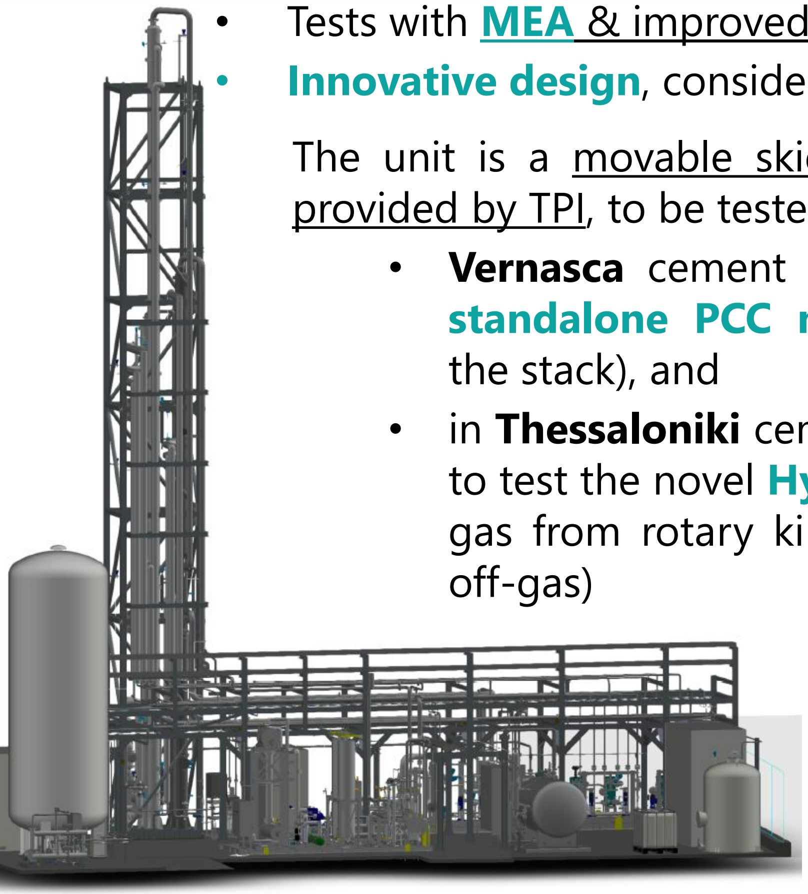
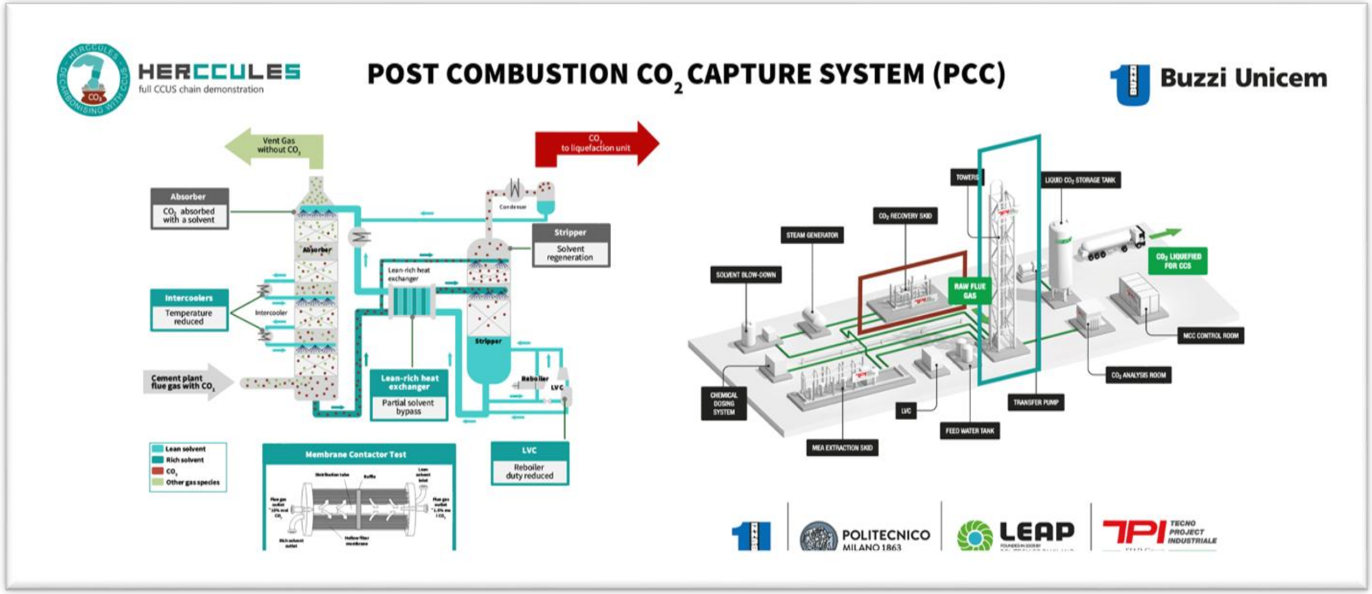
CO_2 capture in cement – PCC unit, oxyfuel and hybrid

- **PCC pilot plant has been designed (→ Under commissioning)**
  - Treats 250-300 Nm^3/h of cement flue gases (2.5-3 ton_{CO2}/day)
  - **Capture rate >95%**
  - Tests with **MEA** & improved **solvent**
  - **Innovative design**, considering:

The unit is a movable skid-mounted system provided by TPI, to be tested in

- **Vernasca** cement plant (Italy) in the **standalone PCC mode** (flue gas at the stack), and
- in **Thessaloniki** cement plant (Greece) to test the novel **Hybrid concept** (flue gas from rotary kiln mixed with CPU off-gas)





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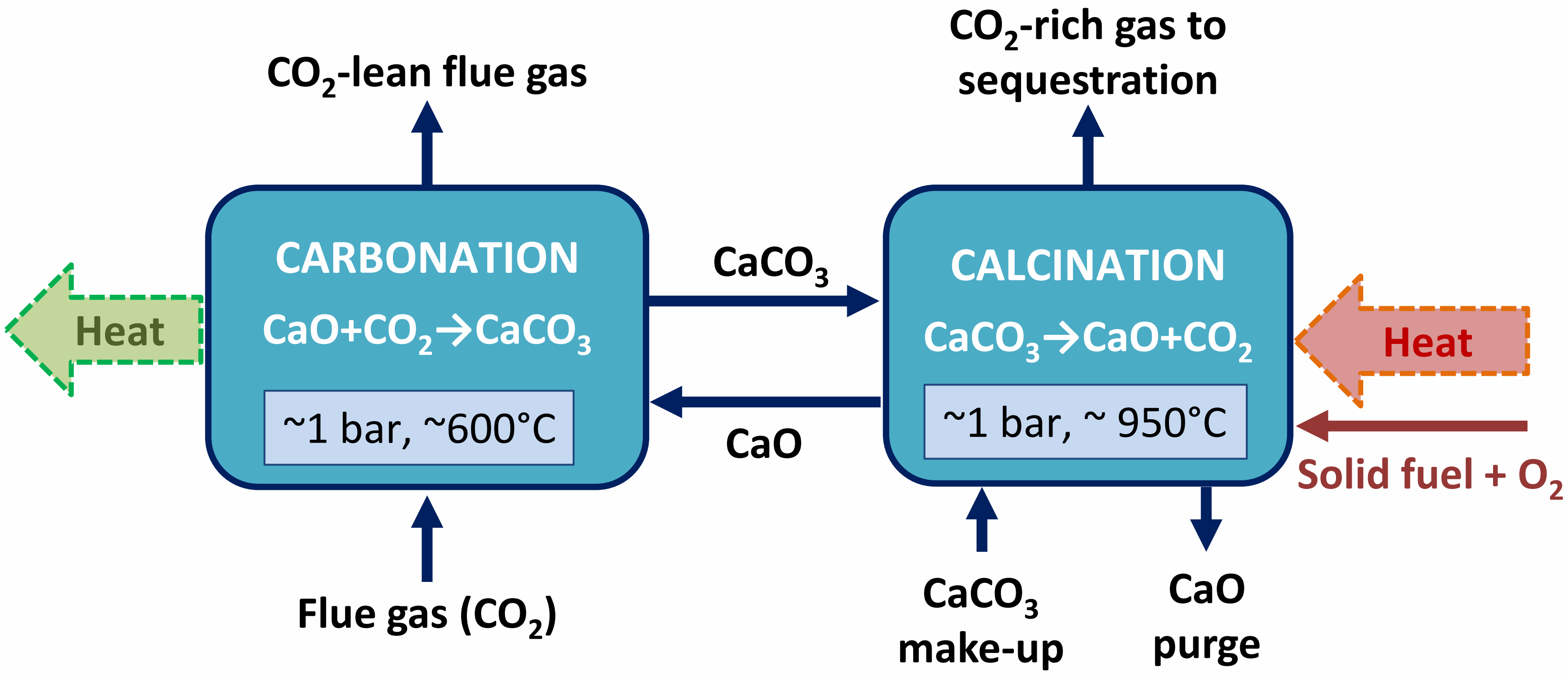
Ca-Looping in Herccules – CaL operating principle

High temperature CO_2 sorption with CaO as sorbent
Sorbent regeneration by high temperature heat supply (coal/biomass/waste oxycombustion)



HERCCULES full CCUS chain demonstration
LEAP
zep
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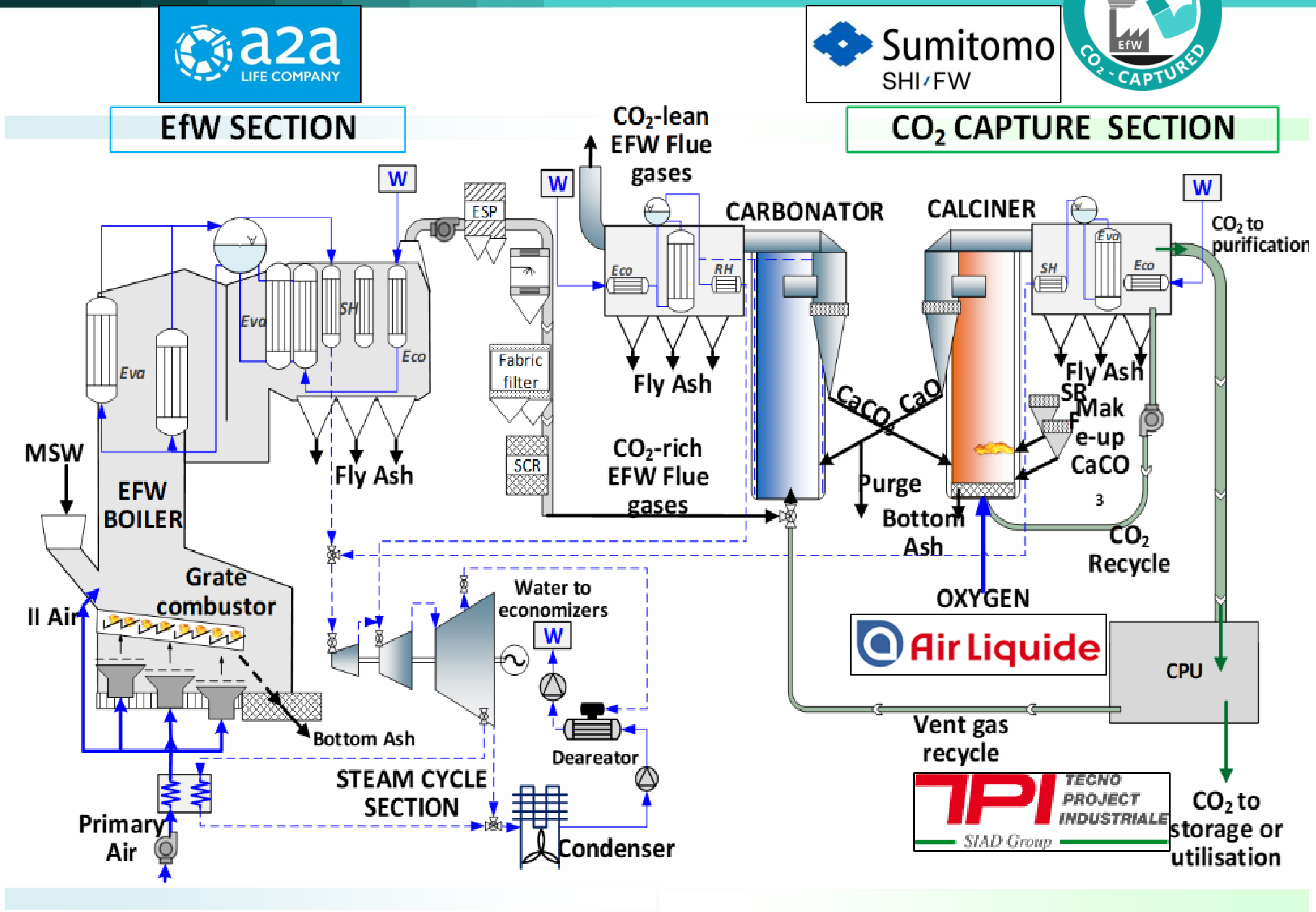
Ca-Looping in Herccules – CaL+CPU application in EfW

- HERCCULES will demonstrate at **TRL 7-8** for the first time the **CaL process coupled with CPU,** with CPU **vent gas recirculation** → the integration allows to achieve both:
  - High Carbon Capture Rate (CCR) (>95%)
  - High purity of liquid CO2 (>99.9%vol)
- About 4000 cumulative hours of test
- Preliminary lab experiments will characterize the **Ca-based sorbent** exposed to EfW flue gases
- The CFB (Circulating Fluidized Bed) CaL pilot will be operated with **solid recovered fuel (SRF)**, burnt in the calciner with oxycombustion
- Possibility to achieve negative CO_2 emissions **(<-400 kg$_{CO2}$/t$_{waste}$)** thanks to capture of biogenic CO_2



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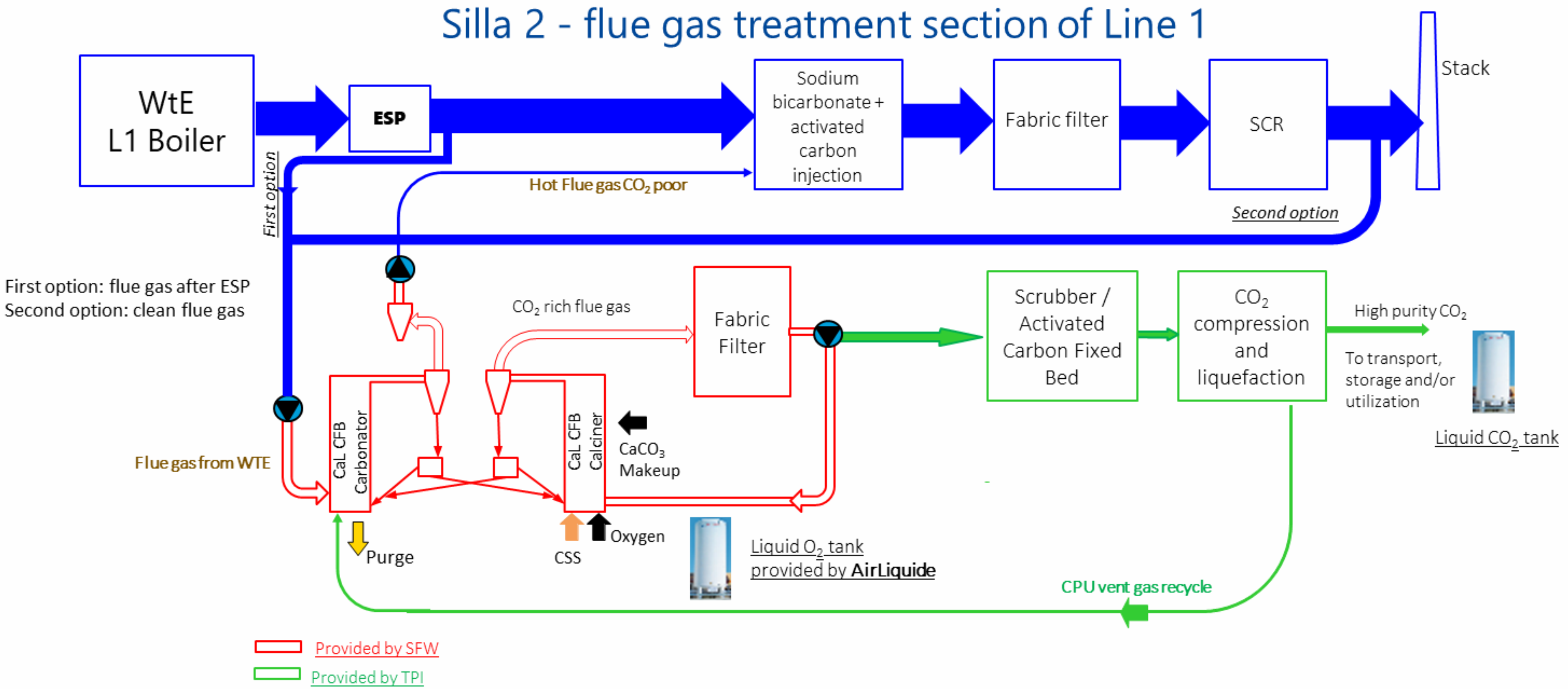
Ca-Looping and EfW impurities



Test site: Silla 2

A2A WtE plant in Milan

- Test with **clean and dirty flue gases** will be executed to evaluate the CaL capability of capturing **SO_2** (->$CaSO_4$) but also **HCl** and HF will be verified, as well as the effects of those contaminants on the sorbent reactivity.
- CSIC will carry out complementary lab experiments to evaluate the **impact of such contaminants on the sorbent** performance along multiple carbonation/calcination cycles.

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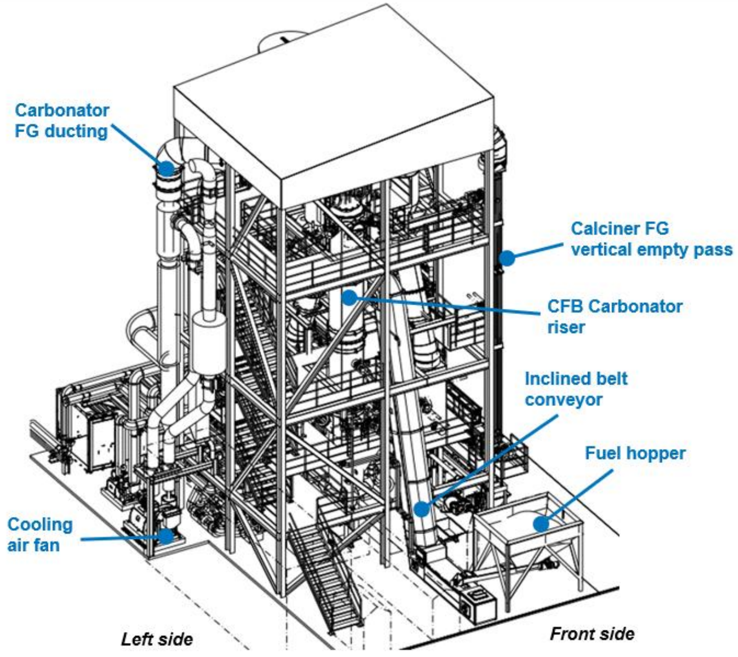
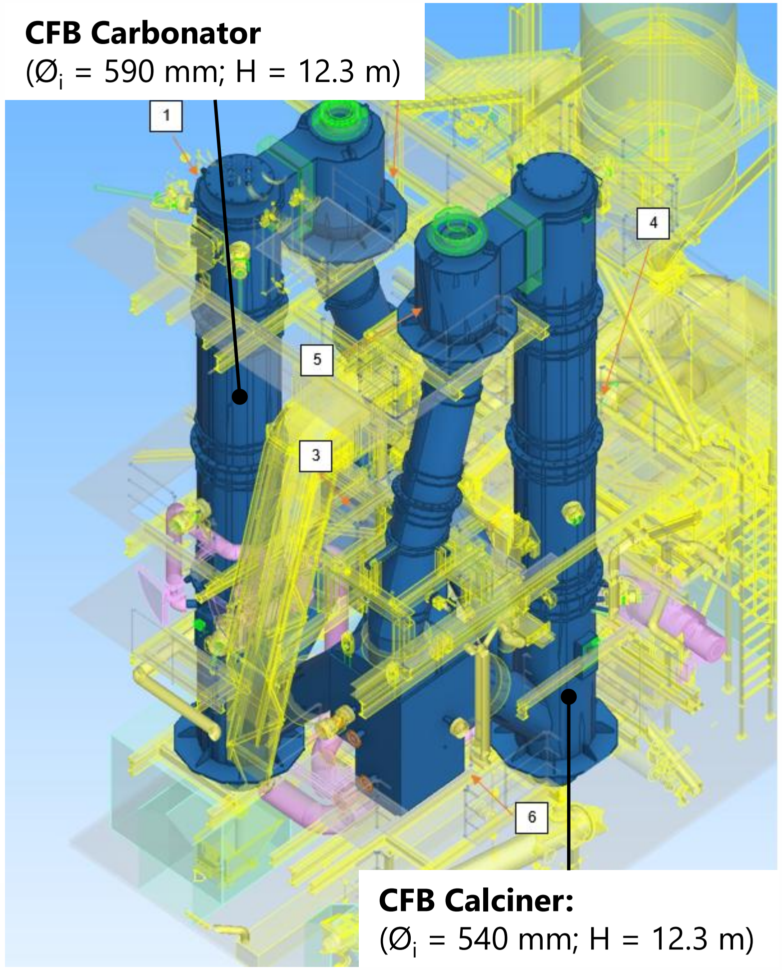
CO_2 capture in EfW – CaL engineering (SFW)



CaL unit axonometric view (left to front side view)



CFB carbonator and calciner system 3D layout view

- Basis of design conditions and parameters
- Conceptual design
  - Dual-CFB hot loop
  - Auxiliary systems
- Basic engineering and detail design
  - Performance engineering
    - Heat and material balance calculations
    - Component dimensioning
  - Mechanical design area and layout
  - Automation, Electrification, Instrumentation engineering
  - Civil and steel structure
  - System and equipment engineering
    - 25 PIDs
    - 10 System descriptions
    - Operational strategy
  - Risk Assessment

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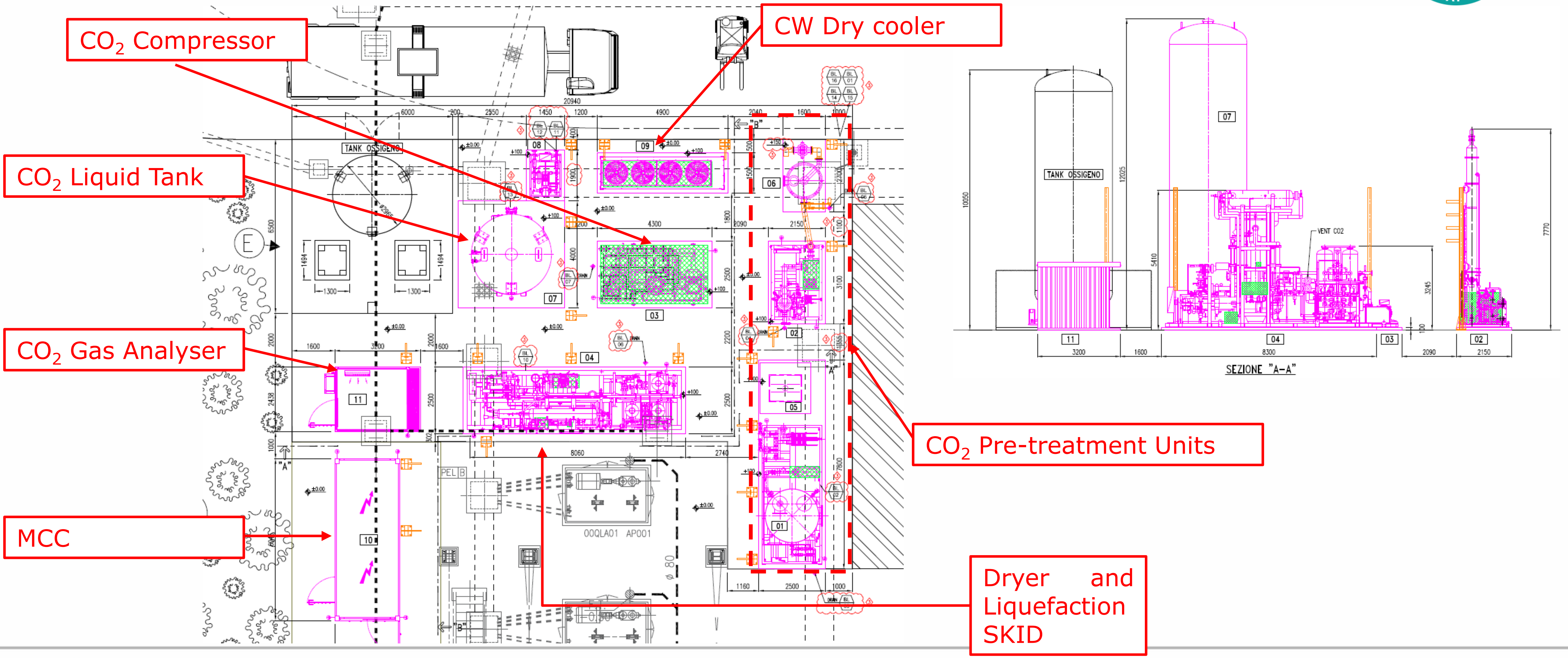
Task 3.1 CPU Section TPI: Layout



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HERCCULES – Other activities

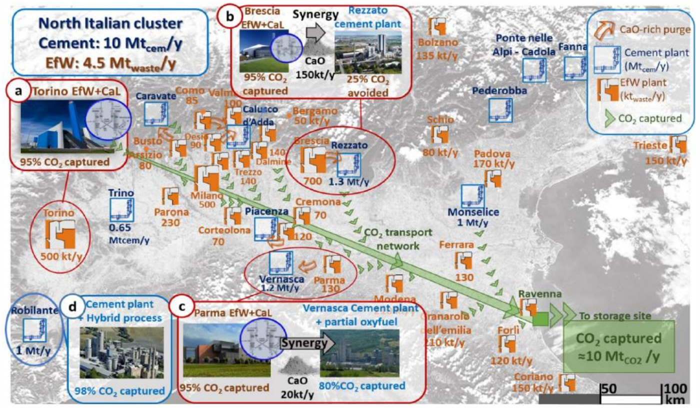
	A	1)	2)	3)	4)
	Reference concrete	TITAN and BUZZI - HERCCULES concrete with CCUS (5.000 m^3)	CELITEMENT - HERCCULES Concrete (5-10 m^3)	TITAN - HERCCULES Concrete (4000 m^3)	BUZZI - Zeolite HERCCULES Concrete (50 m^3)
Cement type	CEM II A-LL 42.5 R	CEM II A LL 42.5 CO_2 capture and geological storage (****)	HERCCULES CELITEMENT	CEM II A LL 42.5 CO_2 capture and geological storage (****)	
Cement content:	320 kg/m^3	320 kg/m^3	340 kg/m^3 *	280 kg/m^3	280 kg/m^3
Technology		CO_2 capture technology in cement making (WP2)	CELITEMENT production from carbon neutral CaO rich CaL purge (WP4)	CO_2 use by demolished concrete mineral carbonation (WP4)	CO_2 use by Natural zeolite (clinoptilolite) CO_2 uptake (WP4)
Additions				40 kg/m^3 CO_2 treated C&D waste	40 kg/m^3 CO_2 treated Zeolite
CO_2 emission	240 kg/m^3	50 kg/m^3 (negative with biomass firing)	100 kg/m^3	negative emission	negative CO_2 emission
OPEX	80 €/m^3***	125 €/m^3	70 €/m^3 (**)	110 €/m^3	110 €/m^3
Approach	ETS	CO_2 storage	Innovation cement relat	CO_2 storage and SCMs	CO_2 storage and SCMs
Scale factor:	Mass production	Mass Production		Mass production	Mass production

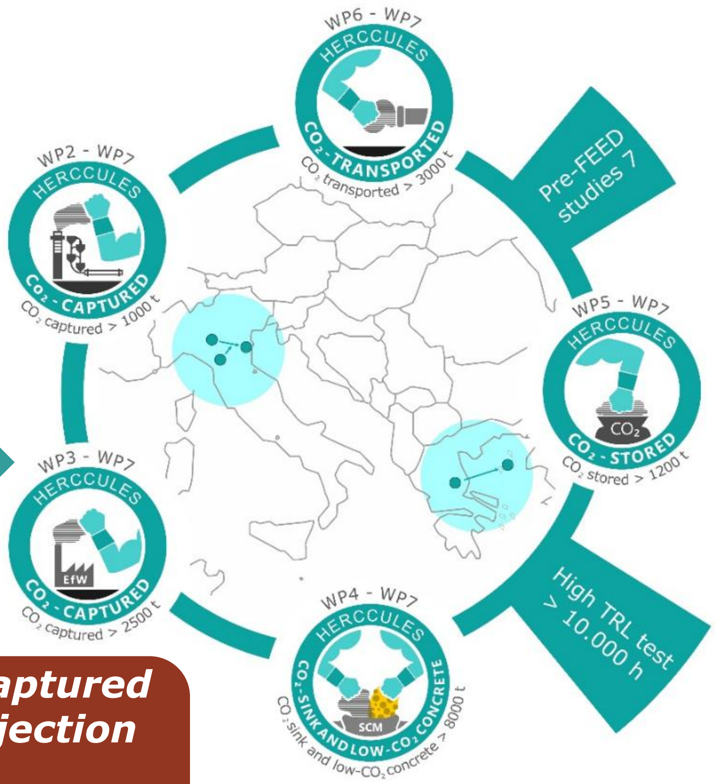
Testing and demonstration of ***demolished-concrete CO_2 mineralization*** *and production of* ***low carbon concrete***

2023 – 2024 – 2025 – 2026 – 2027

Design and optimization *study of* ***CO_2 transportation*** *in Northern Italy*

Demonstration of ***captured CO_2 transport, injection and permanent storage*** *in Ravenna and Prinos sites*





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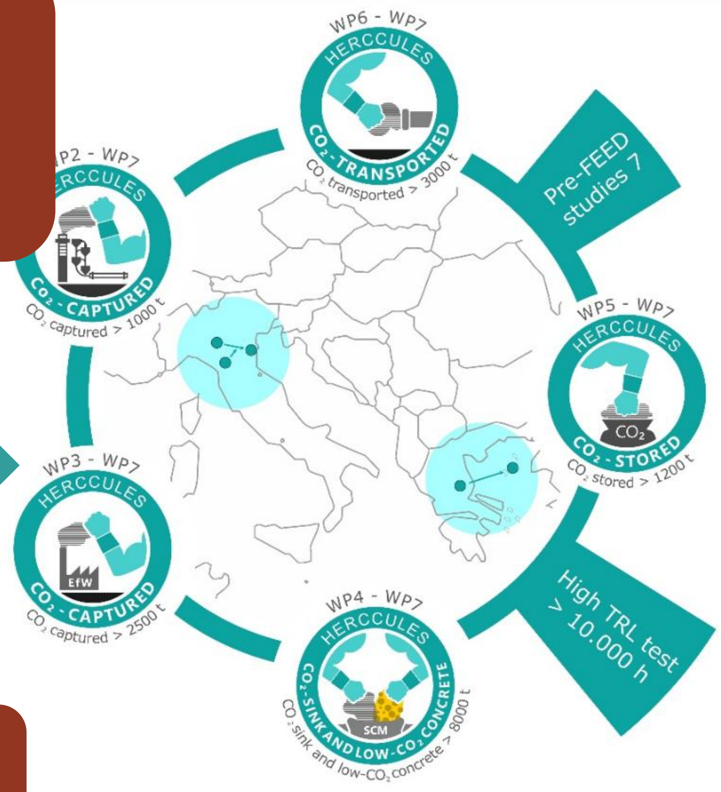
HERCCULES – Other activities

- ***Exploitation & Business plan***
- ***Guidelines for citizen engagement***
- ***Definition of high-level economics***
- ***LCA and CBA of CCUS chain***

2023 › 2024 › 2025 › 2026 › 2027



WP10: Communication, dissemination and knowledge sharing
WP8: Social perception and community engagement

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Dissemination event on CO_2 Capture, Transport, Use and Storage (CCUS), 13th June 2024, Tallinn

- **Dissemination Event on CO_2 Capture, Transport, Use and Storage (CCUS**) took place in on 13th June 2024, the Tallinn University of Technology in Estonia.
- It was organised by HERCCULES partner **SHOGenergy** company and the **TalTech Department of Geology** (CCUS ZEN project partner)

Time*	Topic	Speaker
09:00 – 09:30	**Registration of the participants and coffee**	
09:30 – 11:00	*Session 1. Introduction of Horizon Europe projects and CCUS technology* *Convener: Martina Fantini (EUCORE–HERCCULES)*	
09:30 – 10:00	Introduction to Horizon Europe HERCCULES project	Maurizio Spinelli, Projec Coordinator (LEAP)
10:00 – 10:30	Introduction to Horizon Europe CCUS ZEN project	Romain Viguier (SCCS - CCUS ZEN)
10:30 – 11:00	CO_2 Capture in Waste to Energy plants	Adriano Carrara (A2A SpA-HERCCULES)
11:00 – 11:30	**Coffee break**	
11:30 – 13:00	*Session 2. CCUS projects and future scenarios* *Convener: Pierre Cerasi (SINTEF - CCUS ZEN)*	
11:30 – 12:00	Infrastructures for the transport and storage Examples of Projects sites in Europe	Roberto Ferrario (ENI - HERCCULES)
12:00 – 12:30	Techno-economic modelling of the Baltic CCUS Scenario (Denmark, Sweden & Germany)	Leandro-Henrique Sousa (Rambol-CCUS ZEN)
12.30 – 13.00	Analysis of the value chain scenarios in the Baltic and Mediterranean Regions	Alla Shogenova (TalTech-CCUS ZEN)
13.00 – 14.00	**Lunch**	
14.00 – 16:30	*Session 3. Regulations, public acceptance and policies* *Convener: Alla Shogenova (TalTech–CCUS ZEN, SHOGenergy–HERCCULES)*	
14:00 – 14:30	Regulatory aspects: Obstacles/barriers to overcome	Lena Wammer Ostgaard (IOM LAW- CCUS ZEN)
14:30 – 15:00	Public acceptance and the role and the potential contribution of the policy makers	Anne Kantel (Fraunhofer ISI - HERCCULES)
15:00 – 16:00	**Panel discussion involving CCUS ZEN networking partners, HERCCULES and local stakeholders**	Anne Kantel (Fraunhofer ISI - HERCCULES)
16.00 – 16.30	Wrap-up session	Alla Shogenova (TalTech-CCUS ZEN) Martina Fantini (EUCORE–HERCCULES)

Event highlights

- More than **50 participants** in presence and **40 connected online,** including consortium members, relevant stakeholders and the general public from **HERCCULES** and **CCUS ZEN** projects
- **3 main sessions** and the **Panel Discussion** including **Global CCS Institute**, **Bellona Europe** and **industrial experts** from the projects.
- The takeaway messages, public slides, flyer, agenda and video of the event are available in HERCCULES Zenodo community: link: https://zenodo.org/records/12570378

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Second Dissemination event on CCUS in Italy – 22/10/2025

- **Dissemination Event on CO_2 Capture, Transport, Use and Storage (CCUS)** took place in on 13th June 2024, the Tallinn University of Technology in Estonia.
- It was organised by HERCCULES partner **SHOGenergy** company and the **TalTech Department of Geology** (CCUS ZEN project partner)

HERCCULES

Event highlights

2nd Dissemination Event

- More than 50 participants in presence and 40 connected **online**, including consortium members, relevant stakeholders and the general public from **HERCCULES** and **CCUS ZEN** projects
- **3 main sessions** and the **Panel Discussion** including **Global CCS Institute**, **Bellona Europe** and **industrial experts** from the projects.
- The takeaway messages, public slides, flyer, agenda and video of the event are available in HERCCULES Zenodo community: link: https://zenodo.org/records/12570378

Time*
09:00 – 09:30
09:30 – 11:00
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16.00 – 16.30

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HERCCULES

full CCUS chain demonstration

Thanks for Your Attention

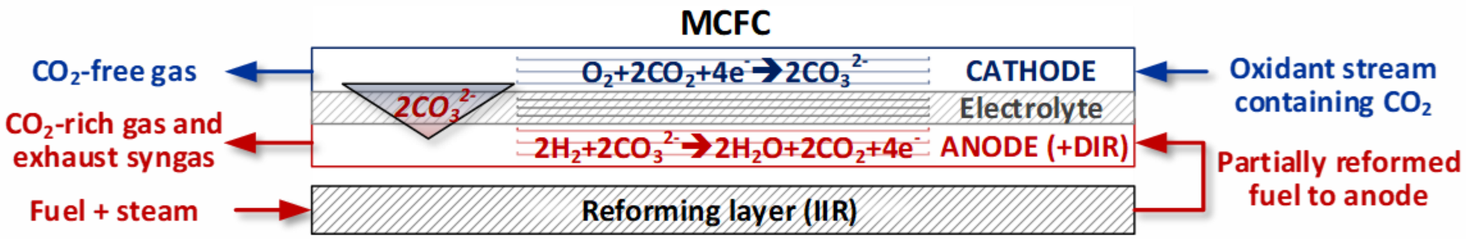
Contacts

Maurizio.Spinelli@polimi.it (LEAP)

Manuele.Gatti@polimi.it (Politecnico di Milano)

Matteo.Romano@polimi.it (Politecnico di Milano)

An example - MCFCs – effect of SO_2/H_2S



$$SO_2 + \frac{1}{2}O_2 + CO_3^{=} \Rightarrow CO_2 + SO_4^{=}$$

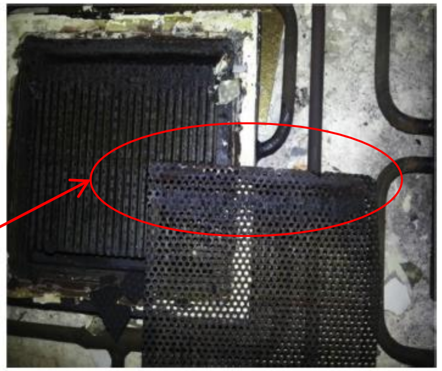
$$H_2S + CO_3^{=} \Rightarrow CO_2 + S^{=} + H_2O$$

$$5CO_2 + SO_4^{=} + H_2O + 8e^- \Rightarrow H_2S + 5CO_3^{=}$$

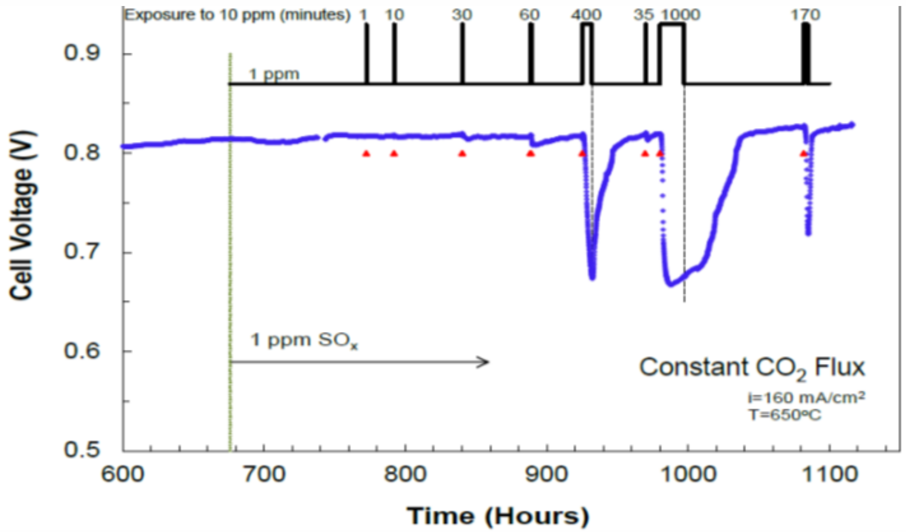
$$\frac{3}{2}Ni + S^{=} \Rightarrow \frac{1}{2}Ni_3S_2 + 2e^-$$

- SO_2 – Double effect

- Loss of electrolyte
- Loss of catalyst



Corrosion effect due to sulfur compounds, Bosio et al.



MCFC continuos operation with 1 ppm SO_2 gas and 10 ppm (short transients): voltage drop f(t)
Provided by Fuel Cell Energy Inc.

Similar irreversible effects observed for H2S

Other limits for MCFC operation (examples): HCl<200 ppbv, Hg<250 ppbv.

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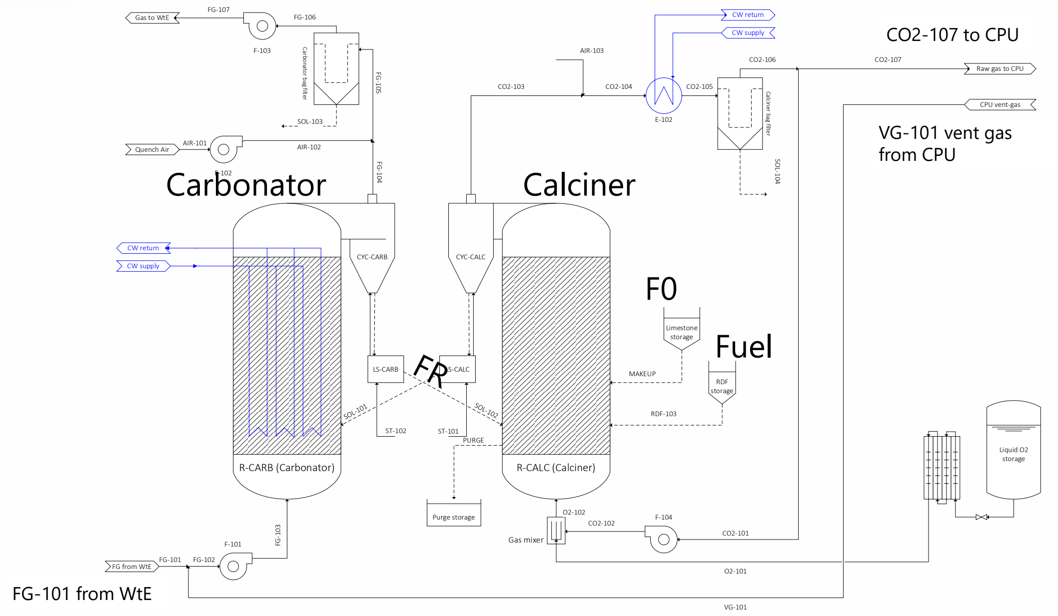
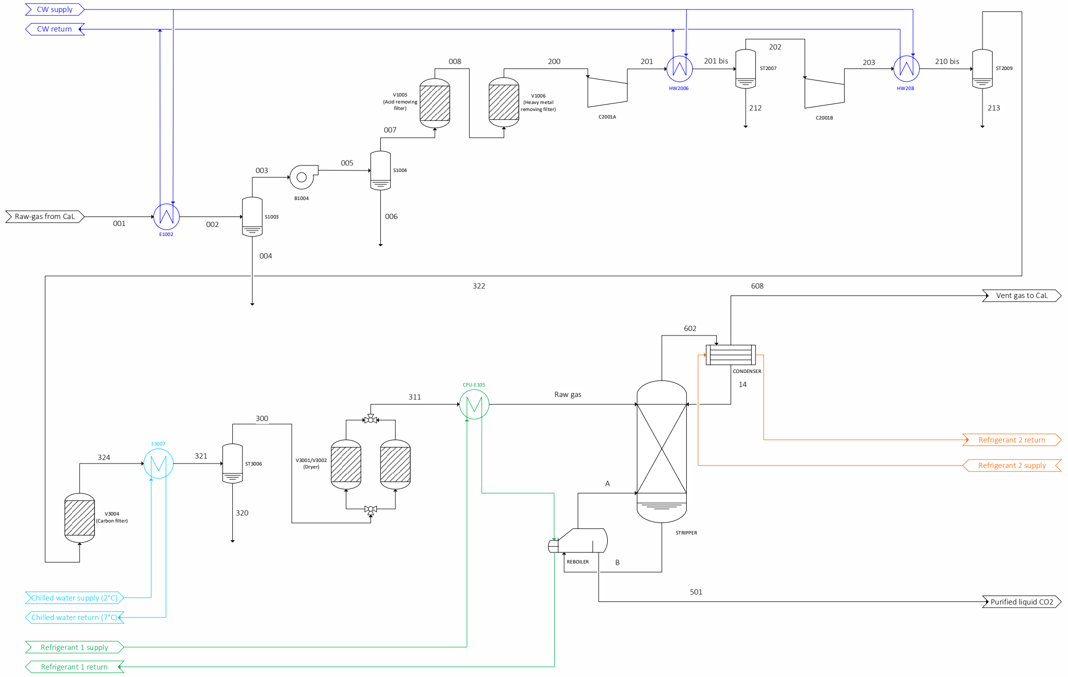
CO_2 capture in EfW – CaL + CPU process design (WP3)



- **CaL model validation** by SFW
- **Main assumption:**
  - Carbonator temperature 650°C
  - F_0/F_{CO2} = 0.2
  - F_R/F_{CO2} = 12
  - Calciner temperature 900°C
  - Calciner duty 1 MW_{th}
  - O_2 in the oxidant flow 40%$_{vol}$
  - 3.2%$_{vol}$ excess of oxygen
  - 3% of air leakage

- **CPU model validation** by TPI
- **Main assumption:**
  - CPU top condenser temperature -37°C
  - CPU stripper at 20 bar
  - O_2 in liquid CO_2 < 9.5 ppm_{vol}
  - Self-refrigeration system decreasing the minimum temperature of the system to -46°C and the vent gas



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CPU (self-refrigerated, 2-steps)

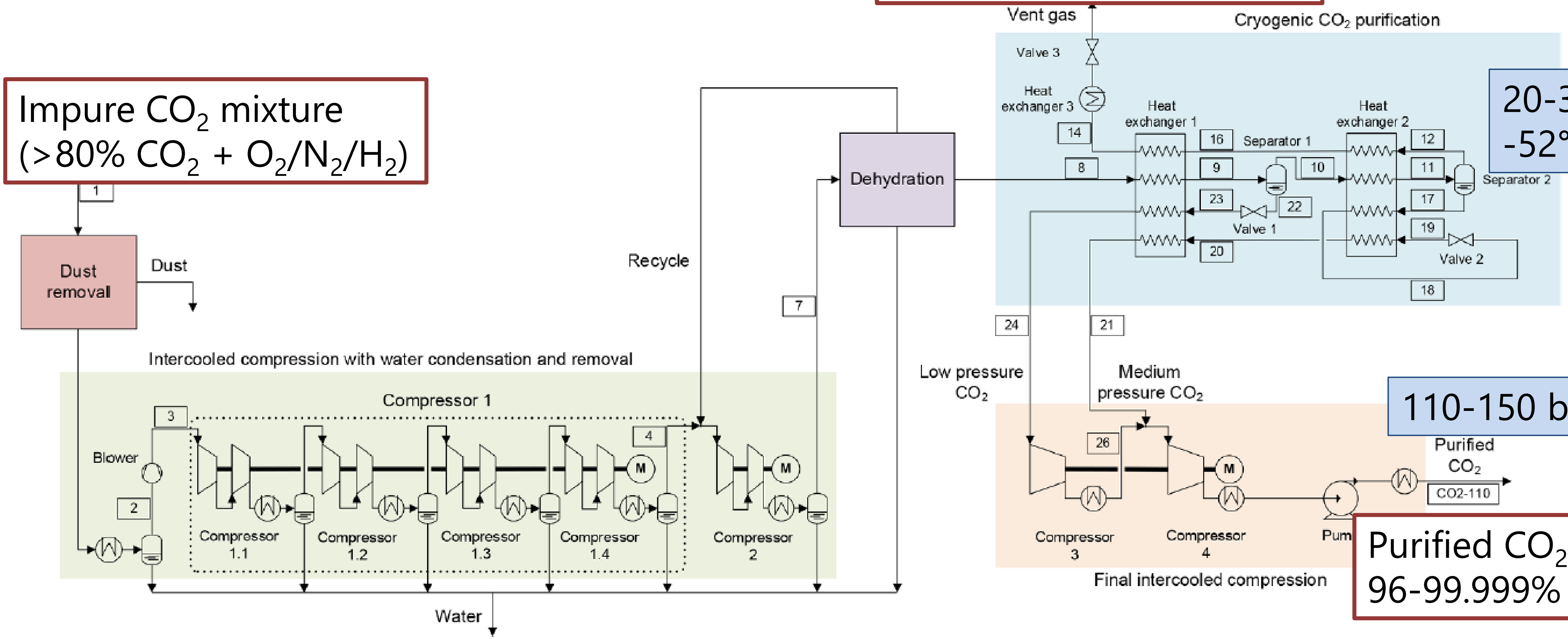
Vent gas: 2-10% CO_2 loss

Impure CO_2 mixture (>80% CO_2 + $O_2/N_2/H_2$)

20-30 bar
-52°C

110-150 bar

Purified CO_2: 96-99.999% purity



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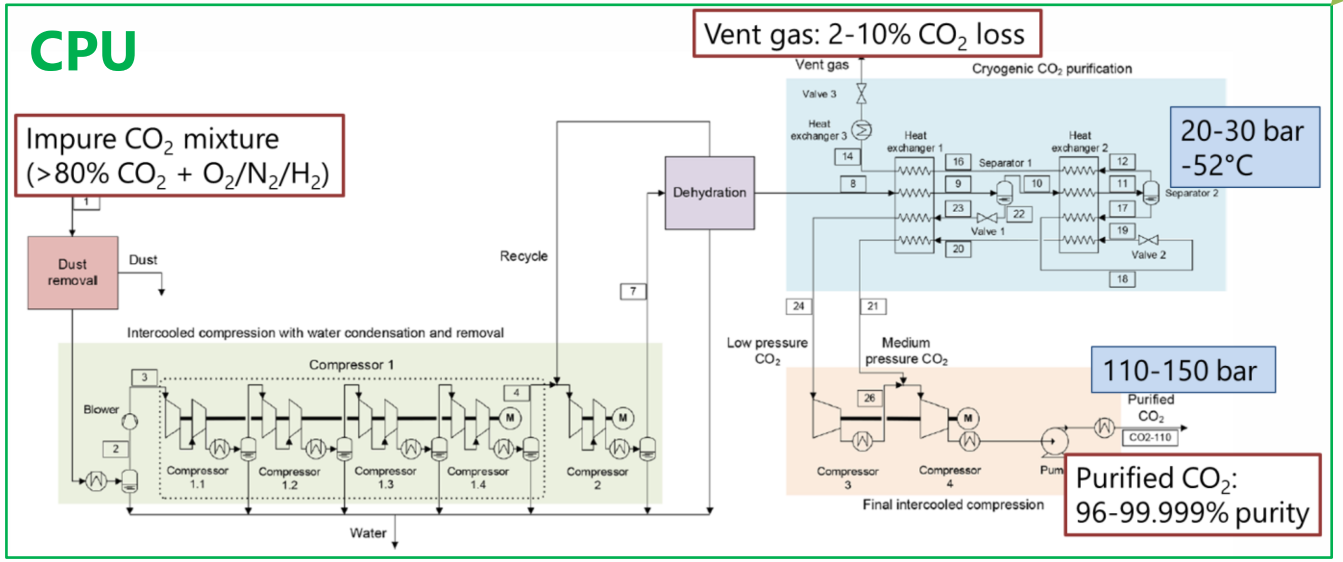
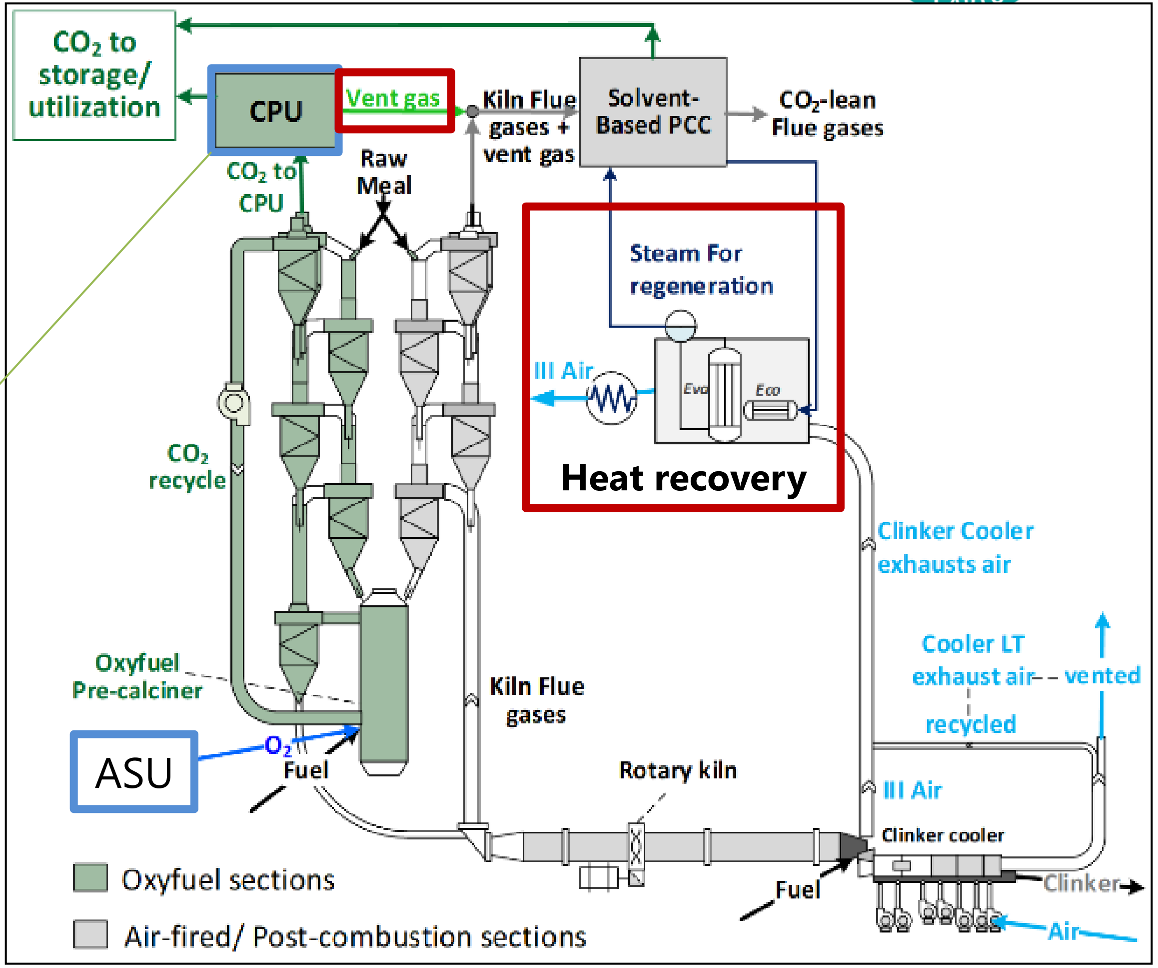
CO_2 capture in cement – Hybrid (full scale)

- Heat recovery for PCC
- CO_2 recovery from CPU vent

→ **>99.9% CO_2 purity**
→ **>98% CO_2 capture**





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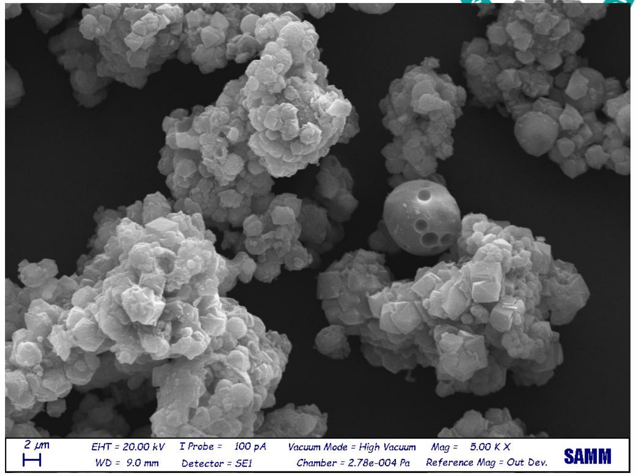
CO_2 utilization – mineralization (WP4)

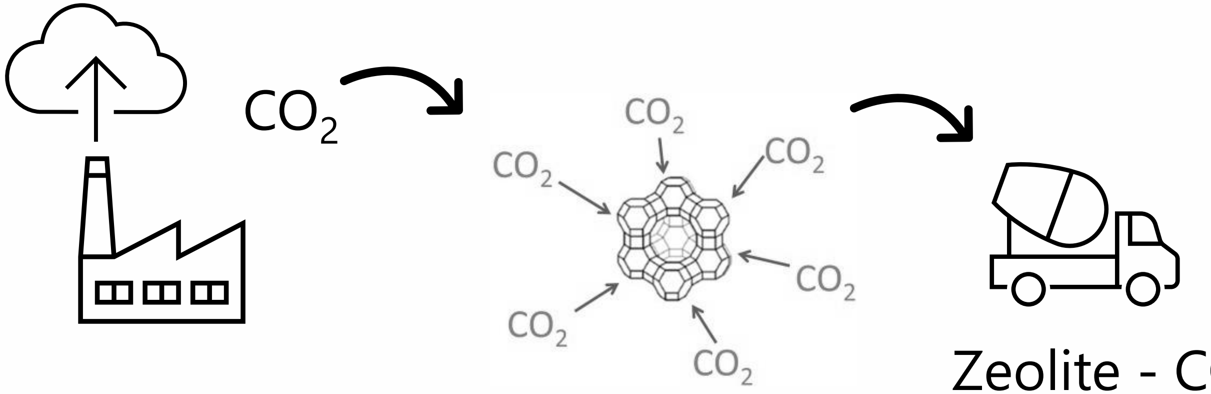
3

Construction and demonstration of a TRL7-scale, **zeolite-based CO_2 (natural and syntetic) mineralization plant**

Integrated with cement plant of Vernasca (Buzzi)

2 tons of CO_2 enriched Zeolite as SCMs for casting 50m^3 of **HERCCULES – Zeolite concrete** with low carbonfootprint





Zeolite - CO_2
Green binder

No-regenerative technology patent, that will be installed in the Vernasca cement plant will exploit natural zeolites

BUZZI
POLITECNICO MILANO 1863
ARTIDEK

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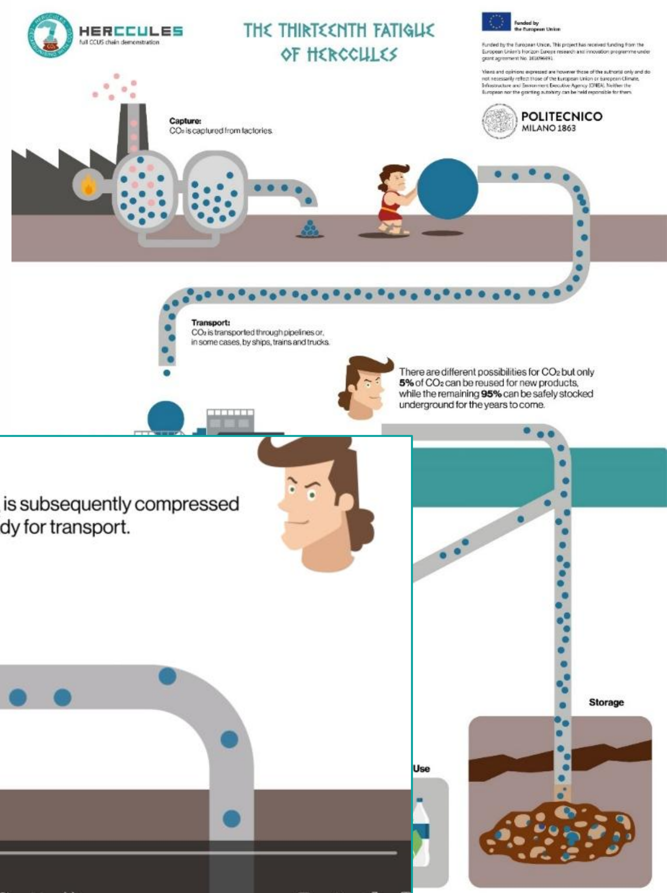
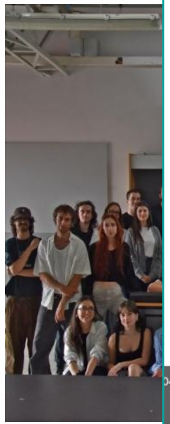
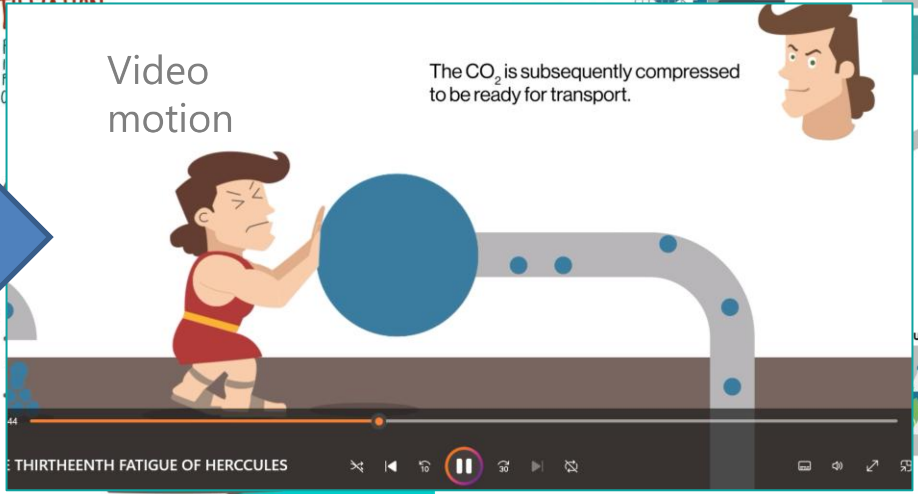
HERCCULES at POLIMI - DENG and School of Design (WP10)

Manuele Gatti, Lia Tagliavini, Matteo Romano and Riccardo Cremona from POLIMI organized a didactic workshop with Sabrina Scuri and team from POLIMI School of Design and with Martina Fantini (EUCORE).

The aim was to provide knowledge on CCUS to the students of the School of Design for them to develop and create in 5 working days **multimedial CCUS content** within the framework of an academic course.







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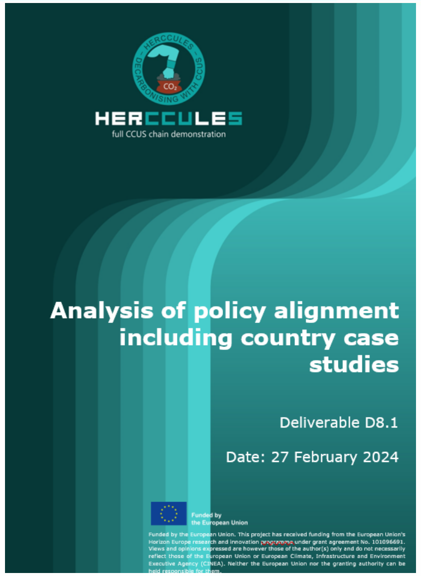
Questionnaire on CCUS for National Policy Makers (WP8)

In the HERCCULES project, the Italian and Greek questionnaires were developed specifically for national and regional policymakers, including 12 questions in 6 described areas and options to explain the answers.

The **target**:

- ➢ to investigate the policymakers' approach concerning the international and national CCUS regulations influencing the implementation of CCUS clusters and hubs in the targeted regions (Climate Strategies, London Protocol, EU CCS Directive, EU ETS Directive, national CO_2 tax, infrastructure, CCUS permits)
- ➢ the regulatory situation and the political strategies for implementing integrated-chain CCUS at European, national (Italy and Greece) and regional levels.

The collected answers are included and analysed in the Report **D8.1 Analysis of policy alignment including country case studies**
Public - Deliverables - Herccules - Europe)


HERCCULES
full CCUS chain demonstration
Analysis of policy alignment including country case studies
Deliverable D8.1
Date: 27 February 2024
Funded by the European Union

- Six Italian and two Greek policymakers answered the questions.
- Italian policymakers were better informed regarding regulatory issues and national plans than Greek policymakers.
- A higher percentage of Italian politicians gave positive answers about possibly to implement industrial-scale CCUS, and CCS-related regulations compared to negative or uncertain answers.
- Some policymakers from both countries mentioned that CCUS was not yet a priority in their country.

Example

1) Do you expect that CCUS will be implemented in Italy on a wider industrial scale by 2050?

2) Does your government actively work on supporting CCUS cluster and hub projects in Italy?

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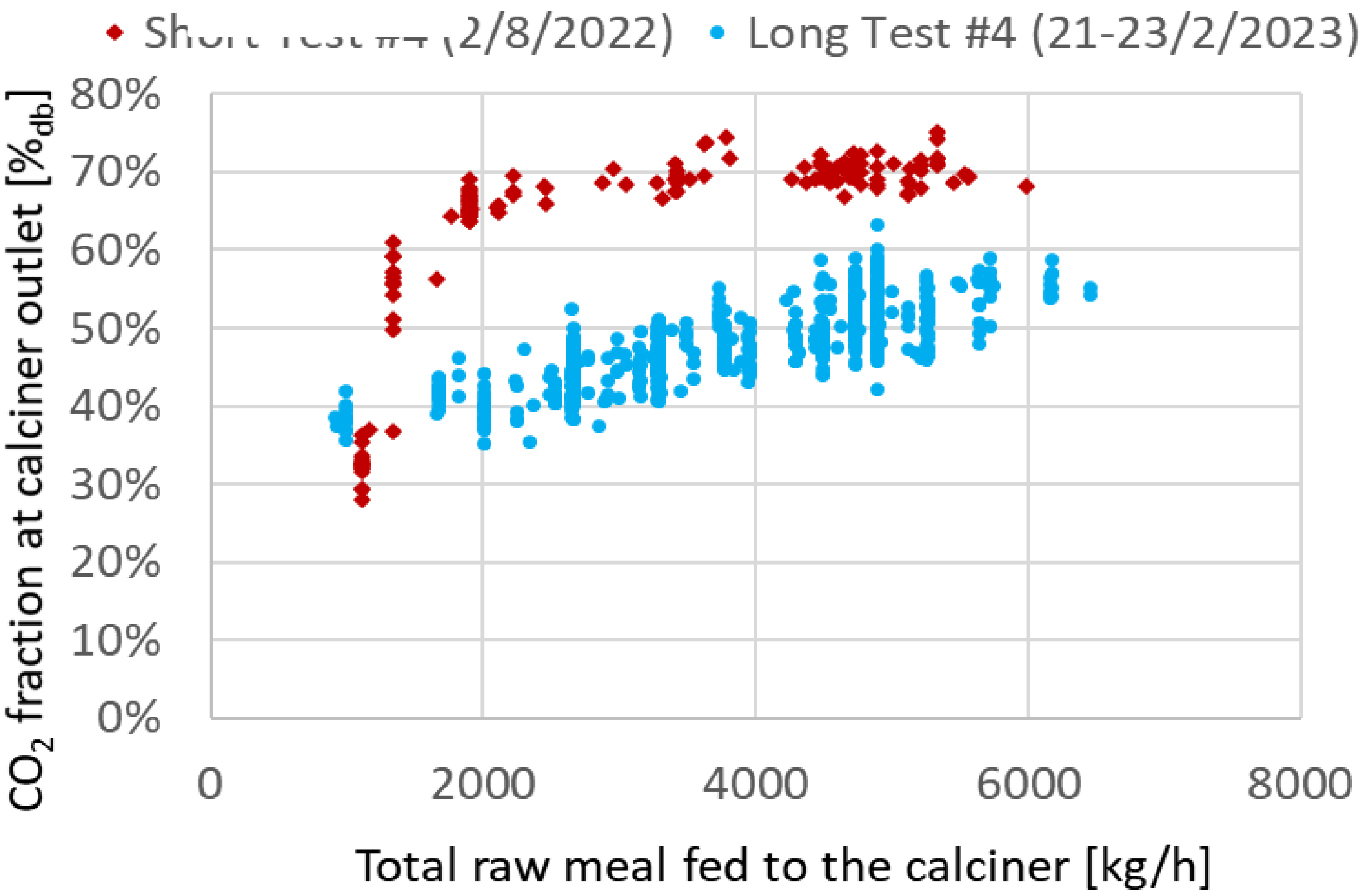
CO_2 capture in cement – Oxyfuel calciner (WP2)

➢ **Design of the oxyfuel calciner (→ Hybrid)**
- Fed by NG/biomass (thermal Input > 1.5 MWth)
- Raw meal feed >2.5 t/h
- CO_2 purity to CPU - 85% (*after* CPU purity>99.9%, >7 tpd of liquid CO_2 in hybrid mode)
- **O_2 concentration 21-50%**

Challenge: to build and operate an **entrained flow calciner** capable of working with different **O_2 concentrations** in the oxidant stream, while **minimizing air in-leakages**:

➢ High O_2 concentration reduces the CO_2 recycle flow rate (->lower energy penalty)

➢ Low air in leakages reduce the downstream CPU consumption



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Impurities – non condensable gases physical effect

Table 2 Effect of impurities on CO_2 storage capacity

Cases	Depth (m)	P (MPa)	T (°C)	T grad (°C/m)	Ea (-)	Storage Capacity		Fb (-)
						Pure	Impure	
Shallow-Low Temp	895	9.2	33	0.020	0.07	647.68	253.96	0.392
Shallow-Mid Temp	895	9.2	38	0.025	0.10	540.97	231.20	0.427
Shallow-High Temp	895	9.2	45	0.033	0.09	364.48	208.72	0.573
Median-Low Temp	2338	24	62	0.020	0.12	750.04	550.35	0.734
Median-Mid Temp	2338	24	75	0.025	0.13	675.00	493.67	0.731
Median-High Temp	2338	24	92	0.033	0.13	584.92	432.23	0.739
Deep-Low Temp	3802	38.8	92	0.020	0.15	777.66	611.13	0.786
Deep-Mid Temp	3802	38.8	113	0.025	0.16	700.29	551.25	0.787
Deep-High Temp	3802	38.8	141	0.033	0.17	611.35	485.19	0.794

[a] Storage coefficient.
[b] Capacity factor given as the ratio of the CO_2 storage capacity in the presence of impurities to that in the absence of impurities.

This shows the greatest effect from a high impurity stream of 15% non-condensables could potentially be a reduced capacity of around 40% at pressures and temperatures found in relatively shallow, low temperature CO_2 storage reservoirs. As the depth of the formations increase, the effect of impurities on CO_2 storage capacity decreases; at a depth of 3800 m, the capacity approaches 80% of that for pure CO_2.

report IEA – «effect of impurities…»

Impurities influence the CO_2 thermodynamic properties, such as density, the viscosity and the critical point;
Non-condensable impurities (N2, O2, Ar, CH4, H2, CO and H2S) significantly decrease the stream density.
Studies reported by IEA evaluated the density of a CO_2 stream with 10-15 % vol. impurities (N2, O2, Ar) and found that it can be reduced by 35-60 % compared to pure CO2.

- extra compression work (especially H2)
- **reduced storage capacity of the reservoir from 20% to 60% depending on the depth (higher impacy in the shallow, decreasing with depth**

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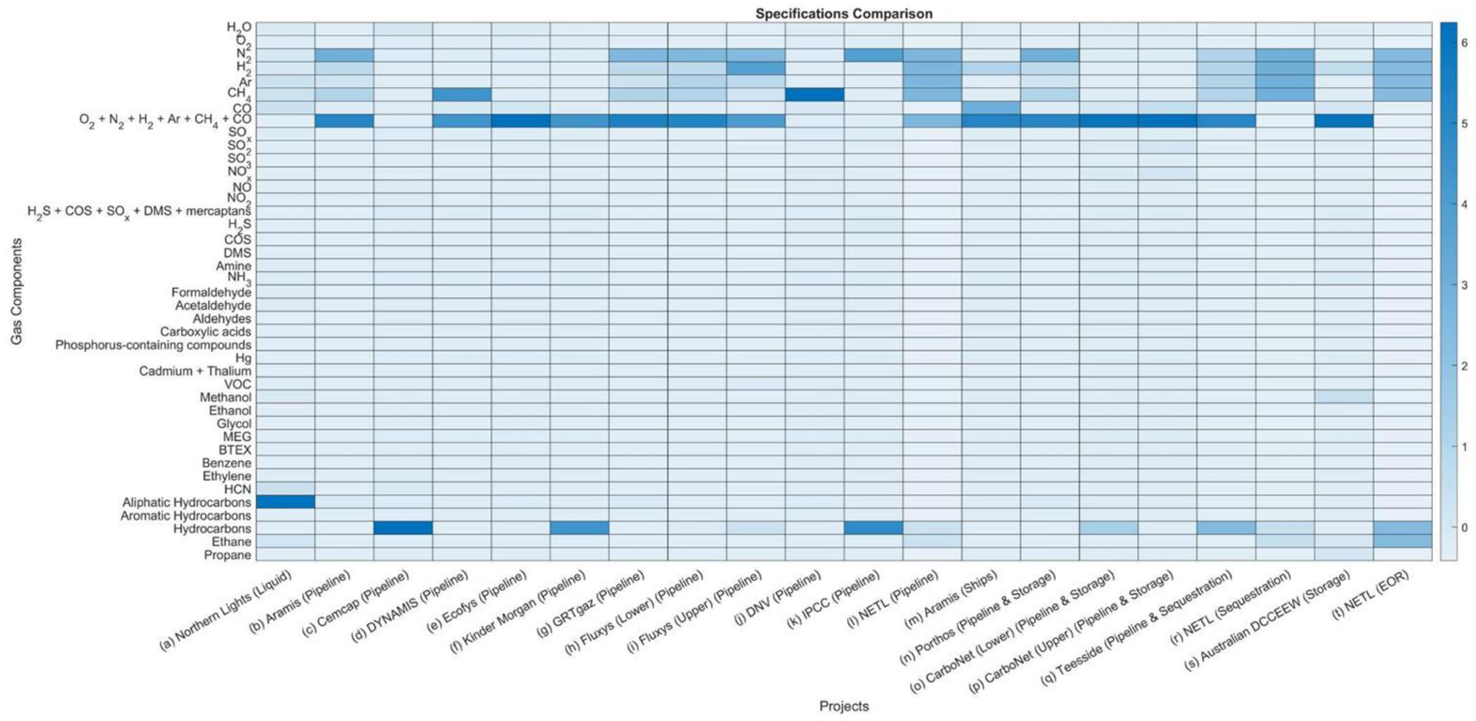
Selection criteria and CO_2 purity constraints (3/3)

CO_2 specifications (T&S)

Qualitativo – differenze tra le specifiche



ISBT specifications

Product quality according EIGA (70/17 Annex A) and Coca Cola standard (WER-SU 100 -August 2019 and BP-SP11 O - 07.01.2018)

Parameter	Specification	Methods
Purity	99,9% v/v min.	CGA/EIGA/ISBT
Moisture	20 ppm v/v max.	CGA/EIGA/ISBT
Oxygen	30 ppm v/v max.	CGA/EIGA/ISBT
Carbon Monoxide	10 ppm v/v max.	CGA/EIGA/ISBT
Ammonia	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Monoxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Dioxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Non-volatile residue	10 ppm w/w max.	CGA/EIGA/ISBT
Non-volatile Organic Residue	5 ppm w/w max.	CGA/EIGA/ISBT
Methanol	10 ppm v/v max.	CGA/EIGA/ISBT
Acetaldehyde	0,05 ppm w/w max.	CGA/EIGA/ISBT
Ethil Acetate	0,05 ppm w/w max.	CGA/EIGA/ISBT
Total Volatile Hydrocarbons (as Methane)	50 ppm v/v max. (including 20 ppm v/v max as total non-methane hydrocarbons)	CGA/EIGA/ISBT
Acetaldehyde	0,2 ppm v/v max.	CGA/EIGA/ISBT
Aromatic Hydrocarbon	20 ppb v/v max.	CGA/EIGA/ISBT
Total Sulfur Content (as S): (Total sulfur-containing impurities excluding sulfur dioxide)	0,1 ppm v/v max.	CGA/EIGA/ISBT
Sulfur Dioxide	1 ppm v/v max.	CGA/EIGA/ISBT
Odor of Solid CO2 (Snow)	No foreign odor	CGA/EIGA/ISBT
Appearance of Solid CO2 (Snow)	No foreign appearance	CGA/EIGA/ISBT
Odor & Taste in Water	No foreign odor or taste	CGA/EIGA/ISBT
Appearance in Water	No color or turbidity	CGA/EIGA/ISBT

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CO_2 Impurities – HERCCULES Pilot Plants - ISBT

HERCCULES-> ISBT specifications

Product quality according EIGA (70/17 Annex A) and Coca Cola standard (WER-SU 100 -August 2019 and BP-SP11 O - 07.01.2018)

Parameter	Specification	Methods
Purity	99,9% v/v min.	CGA/EIGA/ISBT
Moisture	20 ppm v/v max.	CGA/EIGA/ISBT
Oxygen	30 ppm v/v max.	CGA/EIGA/ISBT
Carbon Monoxide	10 ppm v/v max.	CGA/EIGA/ISBT
Ammonia	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Monoxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Dioxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Non-volatile residue	10 ppm w/w max.	CGA/EIGA/ISBT
Non-volatile Organic Residue	5 ppm w/w max.	CGA/EIGA/ISBT
Methanol	10 ppm v/v max.	CGA/EIGA/ISBT
Acetaldehyde	0,05 ppm w/w max.	CGA/EIGA/ISBT
Ethil Acetate	0,05 ppm w/w max.	CGA/EIGA/ISBT
Total Volatile Hydrocarbons (as Methane)	50 ppm v/v max. (including 20 ppm v/v max as total non-methane hydrocarbons)	CGA/EIGA/ISBT
Acetaldehyde	0,2 ppm v/v max.	CGA/EIGA/ISBT
Aromatic Hydrocarbon	20 ppb v/v max.	CGA/EIGA/ISBT
Total Sulfur Content (as S): (Total sulfur-containing impurities excluding sulfur dioxide)	0,1 ppm v/v max.	CGA/EIGA/ISBT
Sulfur Dioxide	1 ppm v/v max.	CGA/EIGA/ISBT
Odor of Solid CO2 (Snow)	No foreign odor	CGA/EIGA/ISBT
Appearance of Solid CO2 (Snow)	No foreign appearance	CGA/EIGA/ISBT
Odor & Taste in Water	No foreign odor or taste	CGA/EIGA/ISBT
Appearance in Water	No color or turbidity	CGA/EIGA/ISBT

Pilot plants design

Symbol	Description
XX	Found and abated/vented back
-	Pilot plant not designed to abate it (design based on the FG received)
-X	Not found (or data not available), but able to abate/vent back
-/X	Not found (or data not available), but able to partially abate

COMPONENT (->ISBT)	Reference - ISBT target (in principle) ppm unless otherwise not specified	CaL+CPU in WTE	MEA/CPU in CEMENT	
		At tank inlet	After MEA extraction	At tank inlet
Carbon dioxide (CO2)	99,9%			
Water (H2O)	20	XX	XX	XX
Oxygen (O2) + Ar	30	XX	XX	XX
Carbon monoxide (CO)	10	XX	XX	-
Ammonia (NH3)	2,5	-	-	-
Nitrogen monoxide (NO)	2,5	-	-	-
Nitrogen dioxide (NO2)	2,5	-	-	-
Non-volatile residue	10	-	-	-
Non-volatile organic residue	5	-	-	-
Methanol (CH3OH)	10	-	-	-
Acetaldehyde (CH3CHO)	0,2	-	-	-
Ethil Acetate	0,05	-	-	-
total volatile Hydrocarbon (as CH4)	50	-/X	-	-
total volatile Hydrocarbon (not as CH4)	20	-/X	-	-
Aromatic Hydrocarbon (BTEX)	20 ppb	-/X	-/X	-X
Total Sulfur content (as S no SO2)	0,1	-	-/X	-
Sulfur dioxide (SO2)	1	XX	XX	-

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CO_2 Impurities – HERCCULES Pilot Plants – Other species

HERCCULES-> ISBT specifications

Product quality according EIGA (70/17 Annex A) and Coca Cola standard (WER-SU 100 -August 2019 and BP-SP11 O - 07.01.2018)

Parameter	Specification	Methods
Purity	99,9% v/v min.	CGA/EIGA/ISBT
Moisture	20 ppm v/v max.	CGA/EIGA/ISBT
Oxygen	30 ppm v/v max.	CGA/EIGA/ISBT
Carbon Monoxide	10 ppm v/v max.	CGA/EIGA/ISBT
Ammonia	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Monoxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Nitrogen Dioxide	2,5 ppm v/v max.	CGA/EIGA/ISBT
Non-volatile residue	10 ppm w/w max.	CGA/EIGA/ISBT
Non-volatile Organic Residue	5 ppm w/w max.	CGA/EIGA/ISBT
Methanol	10 ppm v/v max.	CGA/EIGA/ISBT
Acetaldehyde	0,05 ppm w/w max.	CGA/EIGA/ISBT
Ethil Acetate	0,05 ppm w/w max.	CGA/EIGA/ISBT
Total Volatile Hydrocarbons (as Methane)	50 ppm v/v max. (including 20 ppm v/v max as total non-methane hydrocarbons)	CGA/EIGA/ISBT
Acetaldehyde	0,2 ppm v/v max.	CGA/EIGA/ISBT
Aromatic Hydrocarbon	20 ppb v/v max.	CGA/EIGA/ISBT
Total Sulfur Content (as S): (Total sulfur-containing impurities excluding sulfur dioxide)	0,1 ppm v/v max.	CGA/EIGA/ISBT
Sulfur Dioxide	1 ppm v/v max.	CGA/EIGA/ISBT
Odor of Solid CO2 (Snow)	No foreign odor	CGA/EIGA/ISBT
Appearance of Solid CO2 (Snow)	No foreign appearance	CGA/EIGA/ISBT
Odor & Taste in Water	No foreign odor or taste	CGA/EIGA/ISBT
Appearance in Water	No color or turbidity	CGA/EIGA/ISBT

OTHER COMPONENTS (EU table)	Reference - ISBT target (in principle) ppm unless otherwise not specified	CaL+CPU in WTE	MEA/CPU in CEMENT	
		At tank inlet	After MEA extraction	At tank inlet
Hydrogen (H2)		-X	XX	XX
Sulphur trioxide (SO3)		XX	XX	-
Sulphur oxides (SOx)		XX	-/X	-
Nitrogen oxides (NOx)		-	-	-
Hydrogen sulphides (H2S)		-/X	XX	-
Carbonyl sulphide (COS)		-	-	-
Dimethyl sulphide (OMS)		-	-	-
Total sulphur-contained comp.		-	-	-
Total aldehyde compounds		-	-	-
Total carboxylic acids, amide c.		-	-	-
Total phosphorus-contained c.		-	-	-
H2 + N2 + Ar + CH4 + CO + O2		XX	XX	XX
Amine/ total amine compounds		-	-	XX
Formaldehyde (CH20)		-	-	-
Mercury (Hg)		XX	-	-
Cadmium (Cd) + Thallium (Tl)		XX	-	-
Methane (CH4)		-X	XX	XX
Nitrogen(N2)		-X	XX	XX
Argon (Ar)		-X	XX	XX
Ethanol (C2H5OH)		-	-	-
Total volatile organic comp. (VOC)		-/X	-	XX
Mono-ethylene glycol (MEG)		-	-	-
Tri-ethylene glycol (TEG)		-	-	-
Aromatics (incl. BTEX)		-/X	-	-/X
Ethylene		-	-	-
Hydrogen cyanide (HCN)		-	-	-
Heavy metals		XX	-	-
Solids / full removal cut-off diam.		XX	-	-

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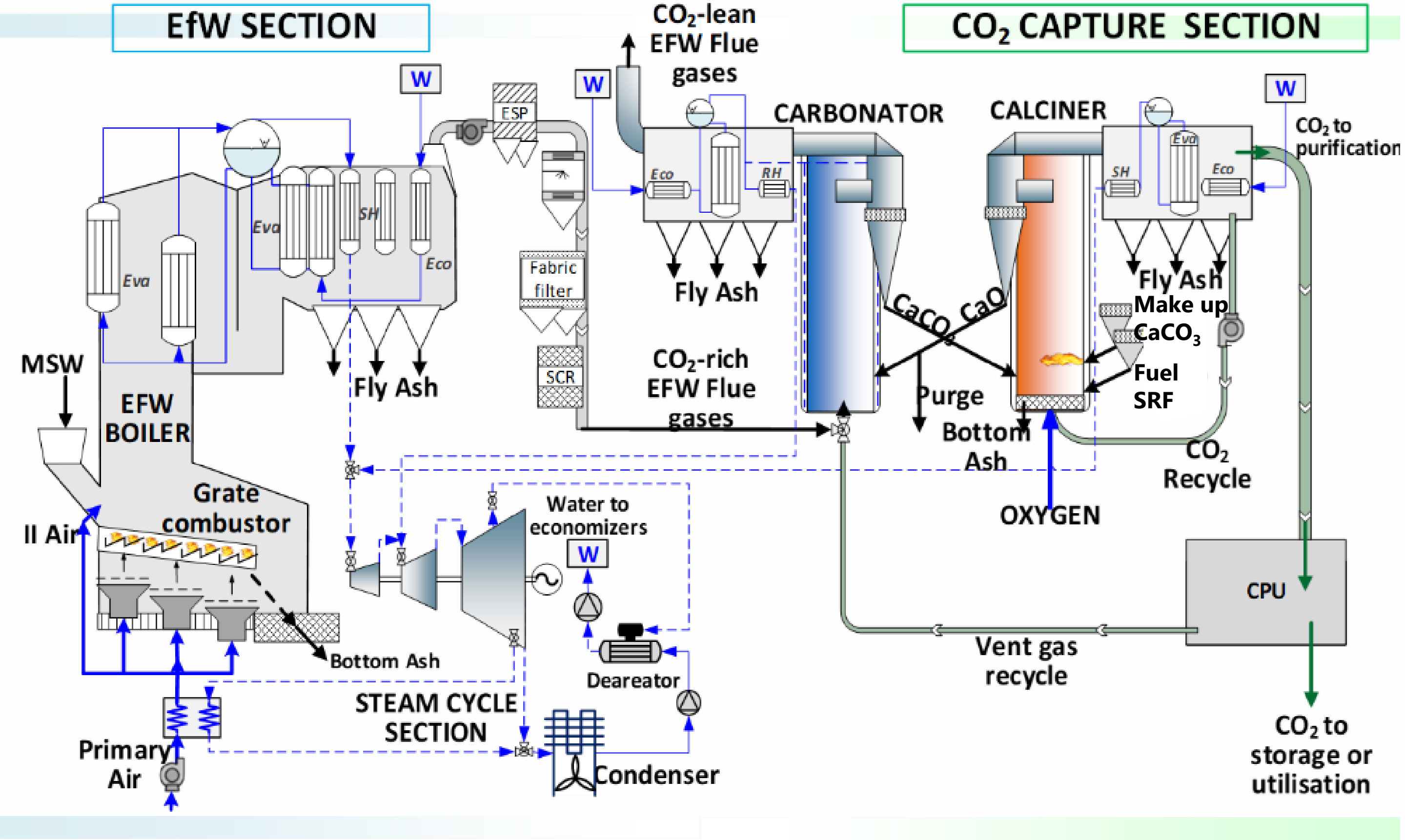
CO_2 capture in EfW – Ca-Looping (CaL) + CPU (WP3)

- Focus on the **influence of critical parameters** on the overall performances
- Demonstrate that the **integration of CaL and CPU** allows to achieve both **high CCR levels and high purity of liquid CO_2 (>99.9%$_{vol}$)**
- **Air infiltration** in CaL pilot and **minimum CPU temperature** significantly affect the CPU performance in terms of **CO_2 recovery**

- **Without the vent gas recirculation**:
  - Flue gases treated in the carbonator ~1350 Nm^3/h
  - Overall CCR ~75%
  - Gross liquid CO_2 produced ~640kg/h
- **With the vent gas recirculation**:
  - Flue gases treated in the carbonator ~690 Nm^3/h
  - Overall CCR ~94%
  - Gross liquid CO_2 produced ~650kg/h



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