From Clean Combustion to CCU: intriguing topics for process engineering and materials scientists

O.Senneca[1,2*], P. Ammendola[1], M. Alfè[1], S. Cimino[1], R. Chirone[1], A. Coppola[1], R, Kneer[3], G.L. Landi[1], L. Lisi[1], F. Montagnaro[4], F. Raganati[1], M. E. Russo[1], P. Salatino[4], F. Scala[4], R. Solimene[1], M. Urciuolo[1]

[1]CNR-STEMS, P.le V. Tecchio 80, 80125, Napoli, Italy
[2]RUB University, Universitätsstr. 150, 44780, Bochum, Germany
[3]RWTH Aachen University, Augustinerbach 6, 52062, Aachen,Germany
[4]Università degli Studi di Napoli Federico II, P.le V. Tecchio 80, 80125, Napoli, Italy

**+39 081 7682969, +39 3395709346,*
osvalda.senneca@stems.cnr.it

Numbers
Napoli, Torino, Ferrara
98 Tenured researcher 58 Administrative and technical staff

Consiglio Nazionale delle Ricerche
STEMS
Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

Outline

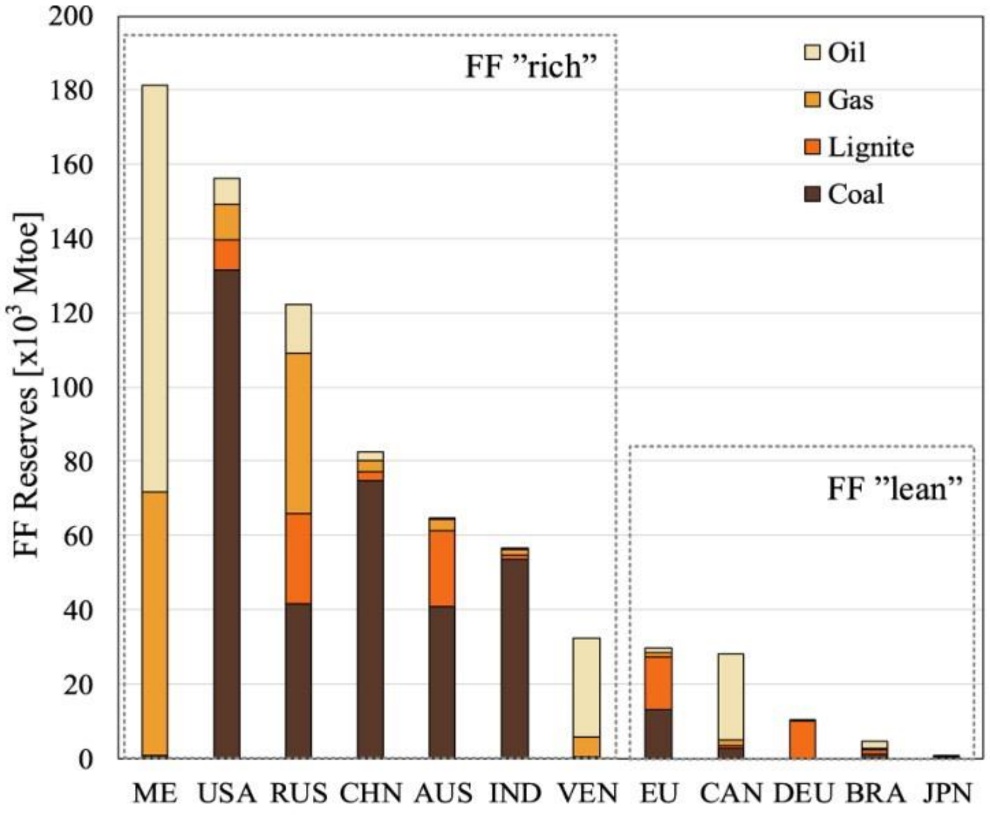
- Intro: the fossil fuel lean and fuel fuel rich scenarios
- Capture ready combustion: Oxycombustion and CLC
- CO_2 capture: CaL, Capture with fine powders
- CCU: methanation; Met-OH production; enzymatic CCU
- CCU and solar energy: Solar aided *CaL; Thermochemical splitting of CO_2*

CCUS is one of the pillars of global energy transitions, together with renewables-based electrification, bioenergy and hydrogen

Why?

Energy Agency (IEA) *Energy Technology Perspectives 2020*

Two trends:
The fossil fuel rich vs the fossil lean countries



The threat to climate change mitigation posed by the abundance of fossil fuels,
[Filip Johnsson](#) http://orcid.org/0000-0003-3106-5379

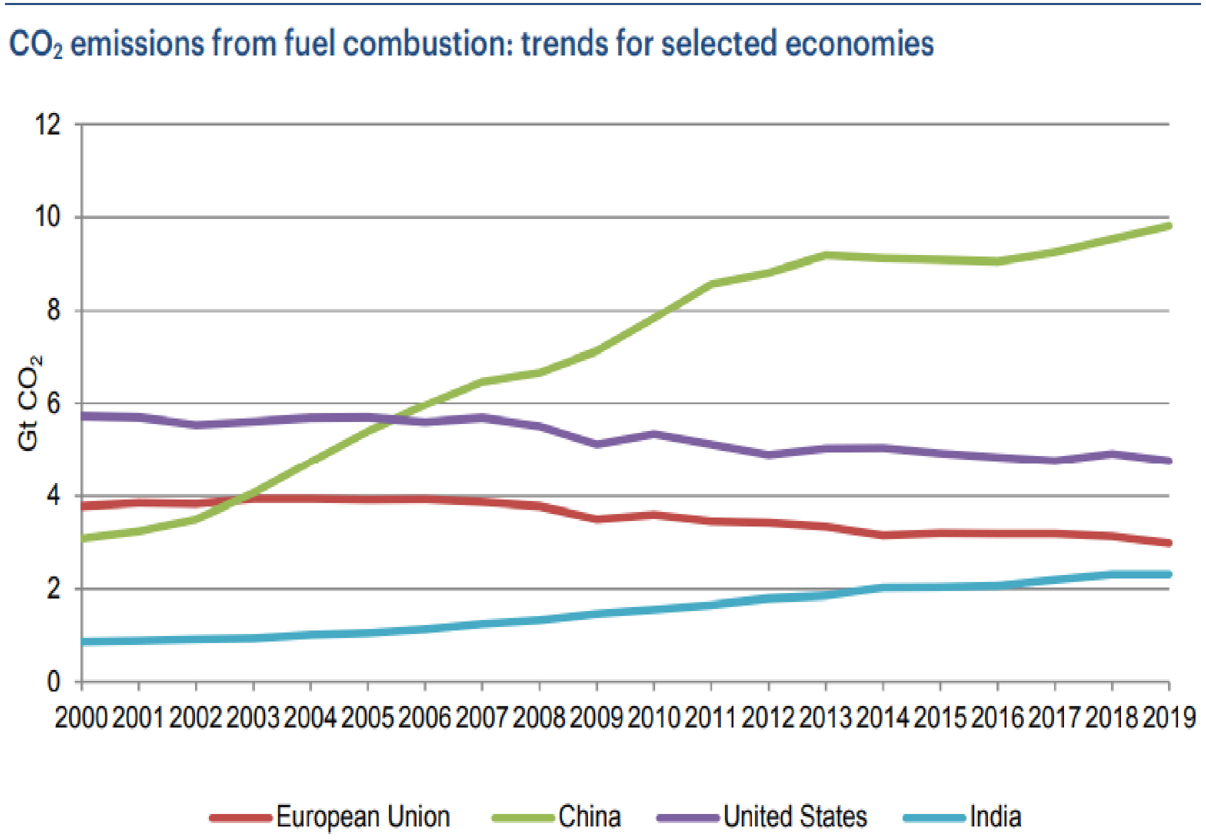
Fossil fuel lean countries

…are facing a remarkable increase of renwable energy but---

- Moreover fossil power will still be needed to some extent to balance the fluctuations in Solar/wind power
- Carbon removal technologies are still required in certain sectors: steel, chemicals and cement, aviation, road freight and maritime shipping
- BECCS technologies can provide a means of removing CO_2 from the atmosphere, i.e. "negative emissions (eg. power station fueled with biomass and equipped with CCUS)
- The use of the CO_2 for an industrial purpose can provide a potential revenue stream (not only enhanced oil recovery, but also as feedstock for synthetic fuels, chemicals and building materials.

Fossil fuel rich countries…

…will not stop producing energy from fossil fuels neither easily nor shortly



Example: China

- Chinese coal-based power generation capacity doubled in less than 10 years
- Chinese coal-fired power plants are relatively new: 70% of installed capacity less than 10 years of age (power plant life time=40 years)
- CO_2 capture technology can be retrofitted to existing plants

China has stated, in its nationally determined contribution to the Paris Agreement, that it aims to peak GHG emissions in 2030

- Share of CCS in electricity generation of only 3% in 2030 for the USA, China, Japan and the European Union.
- Currentyly 37 projects of CCS

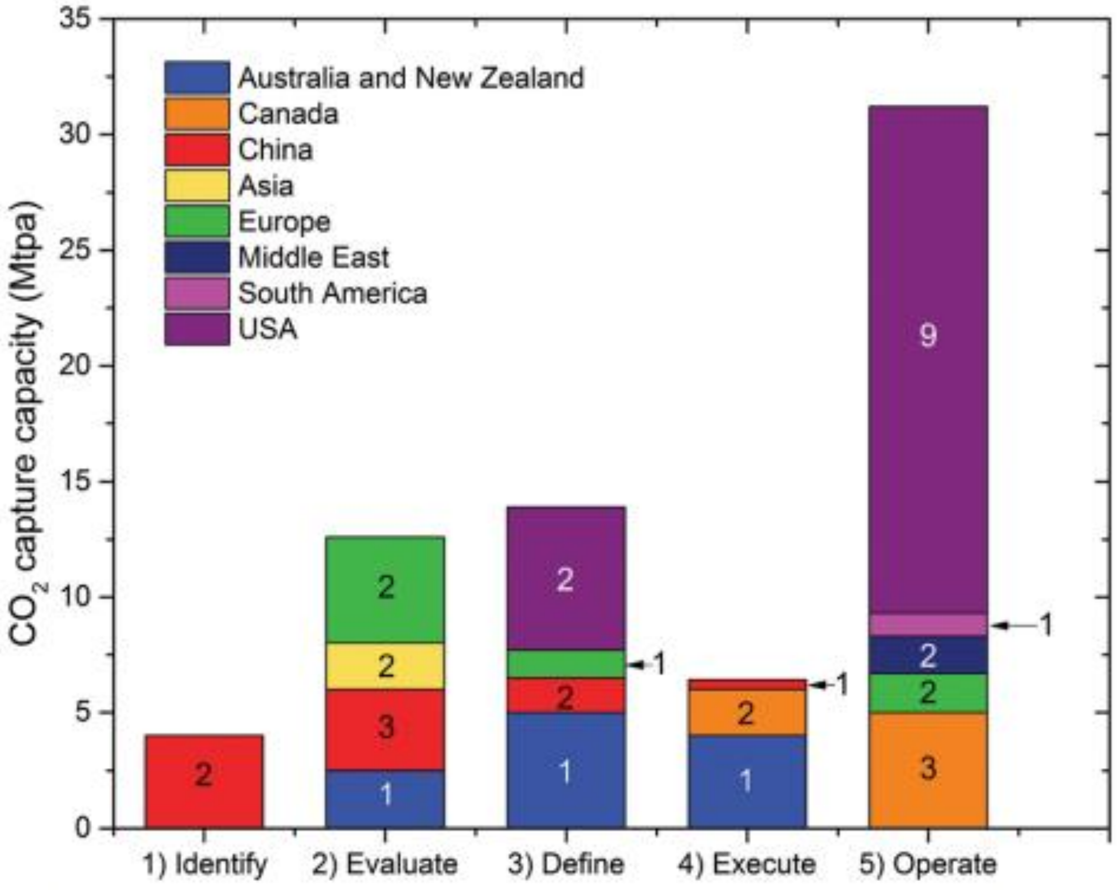
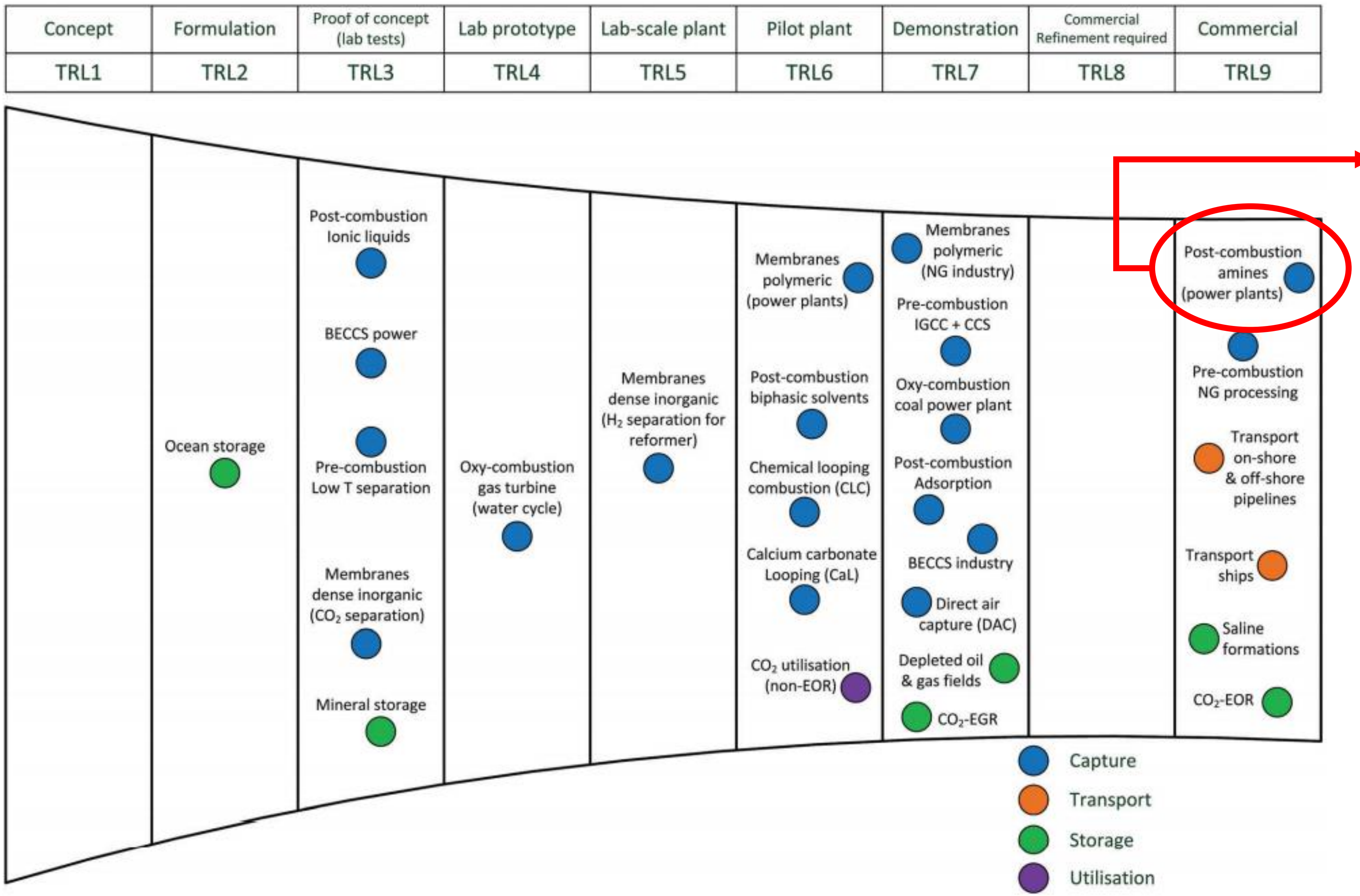


Fig. 2 The CO_2 capture capacity of commercial-scale CCS projects worldwide. The number labelled on each proportion of capture capacity corresponds to the number of projects. Data from the Global CCS Institute.[4]

Adapted From Energy Environ. Sci., 2018, 11,1062



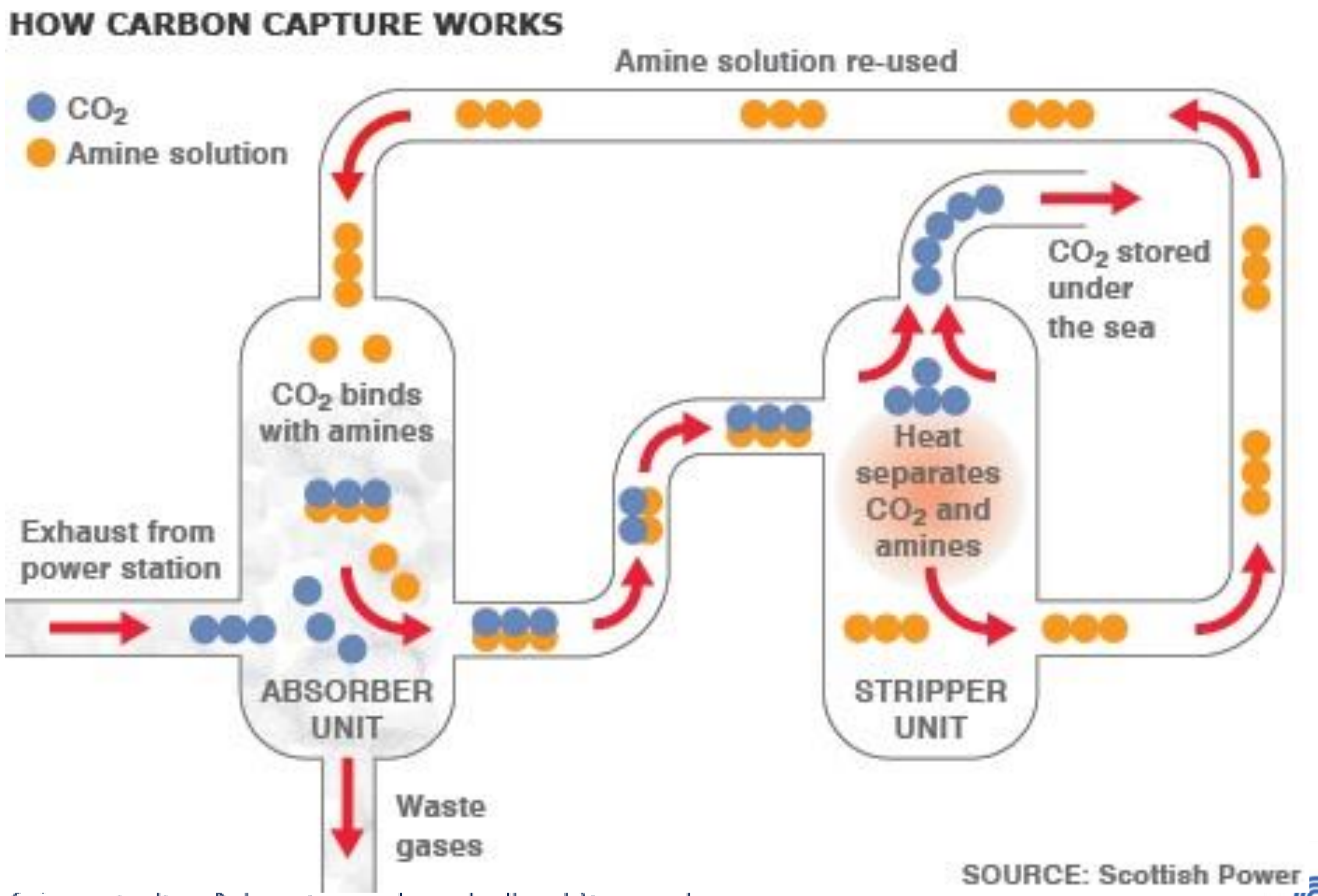
energy intensive CO_2 desorption step: high cost

CO_2 capture cost ≈40 €/ton

Consig

Fig. 1 Current development progress of carbon capture, storage and utilisation technologies in terms of technology readiness level (TRL). BECCS = bioenergy with CCS, IGCC = integrated gasification combined cycle, EGR = enhanced gas recovery, EOR = enhanced oil recovery, NG = natural gas. Note: CO_2 utilisation (non-EOR) reflects a wide range of technologies, most of which have been demonstrated conceptually at the lab scale. The list of

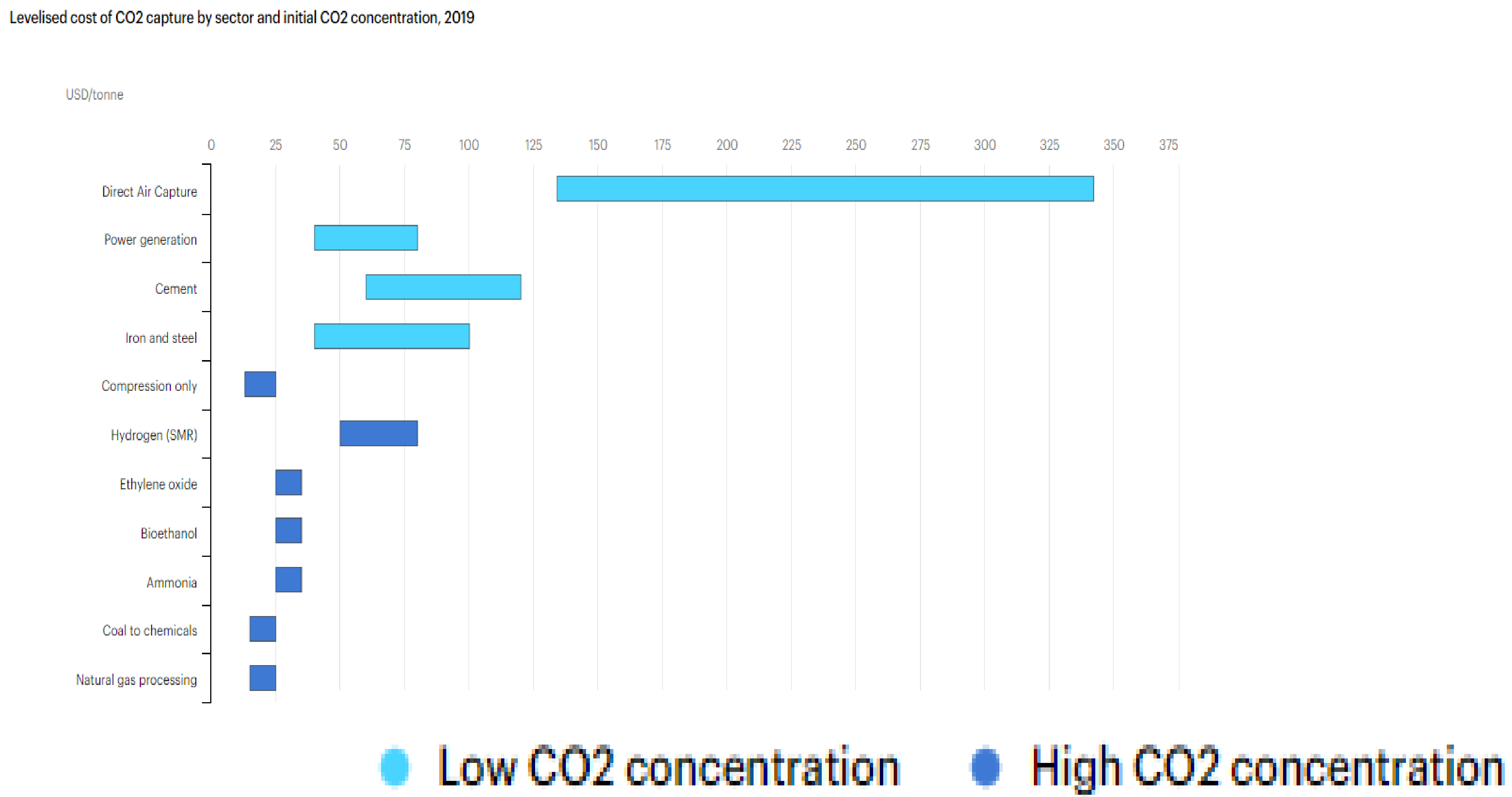
The current benchmark is chemical absorption with aqueous amine solutions (30 wt% MEA which was originally proposed in 1930).



Energy intensive CO_2 desorption step: high cost

- CO_2 capture cost ≈40 €/ton
- Up to 40% energy penalty

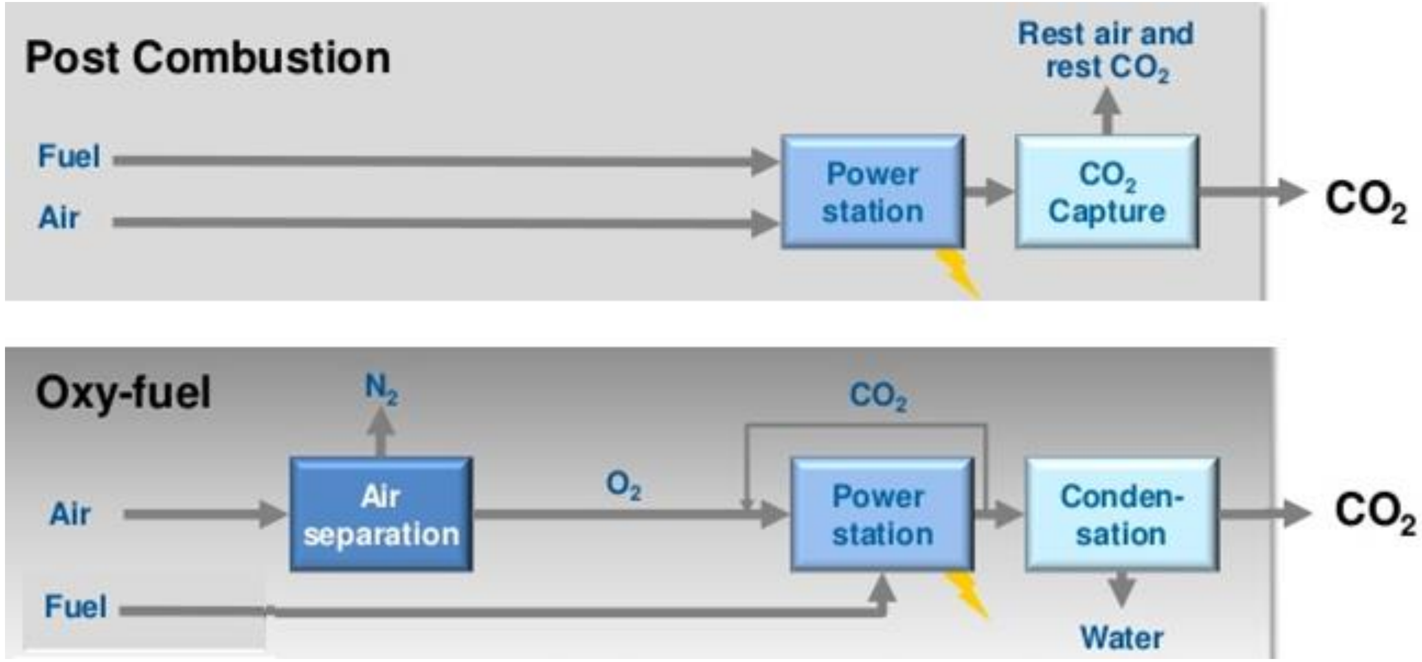
The cost of CO_2 removal is high if CO_2 is diluted



Consiglio Nazionale delle Ricerche

STEMS Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

Capture ready combustion: **oxycombustion**



-Efficient and scalable
-Well suited for retrofit
-Well suited for BECCS

- Oxycombustion is a combustion process using **oxygen and recirculated flue gas**
- exhaust gas consists almost exclusively of CO_2

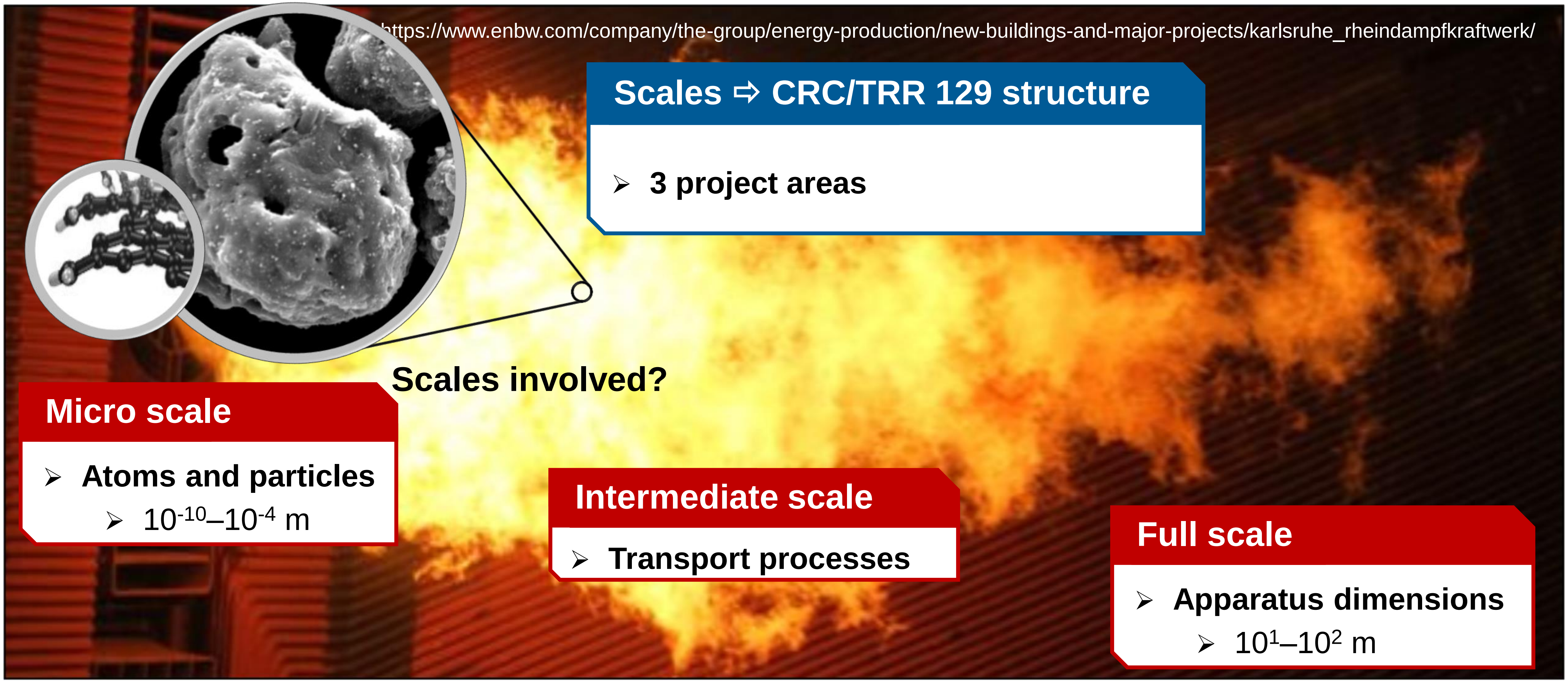
Oxyflame project

RWTH AACHEN UNIVERSITY | RUHR UNIVERSITÄT BOCHUM RUB | TECHNISCHE UNIVERSITÄT DARMSTADT

OXYFLAME

Challenges – Scales involved

RWTH AACHEN UNIVERSITY | RUHR UNIVERSITÄT BOCHUM | RUB | TECHNISCHE UNIVERSITÄT DARMSTADT



Scales ⇨ CRC/TRR 129 structure

- 3 project areas

Scales involved?

Micro scale

- Atoms and particles
  - 10^{-10}–10^{-4} m

Intermediate scale

- Transport processes

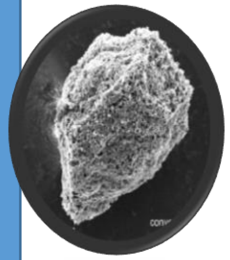
Full scale

- Apparatus dimensions
  - 10^{1}–10^{2} m

[ENBW]

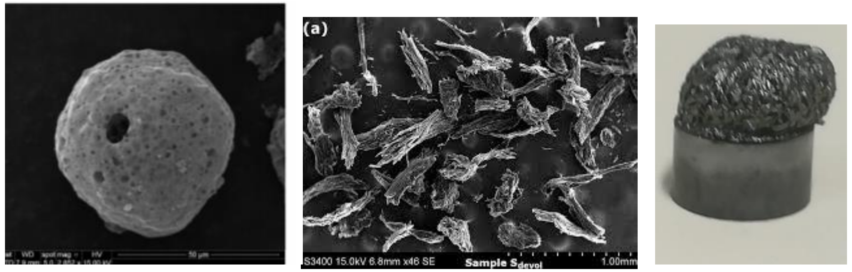
Materials in Oxycombustion

Model of fragmentation for thermal stress and internal pressure

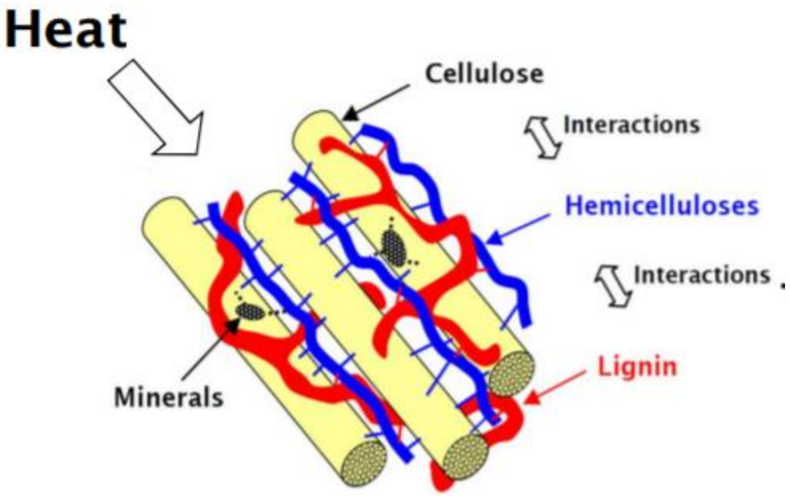


Fragmented or unfragmented char particle ?

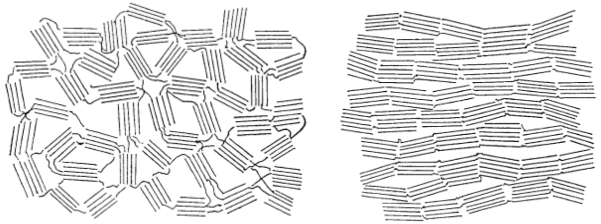
Spherical or elongated char; swollen or non swollen, porous or not ?



in a boiler

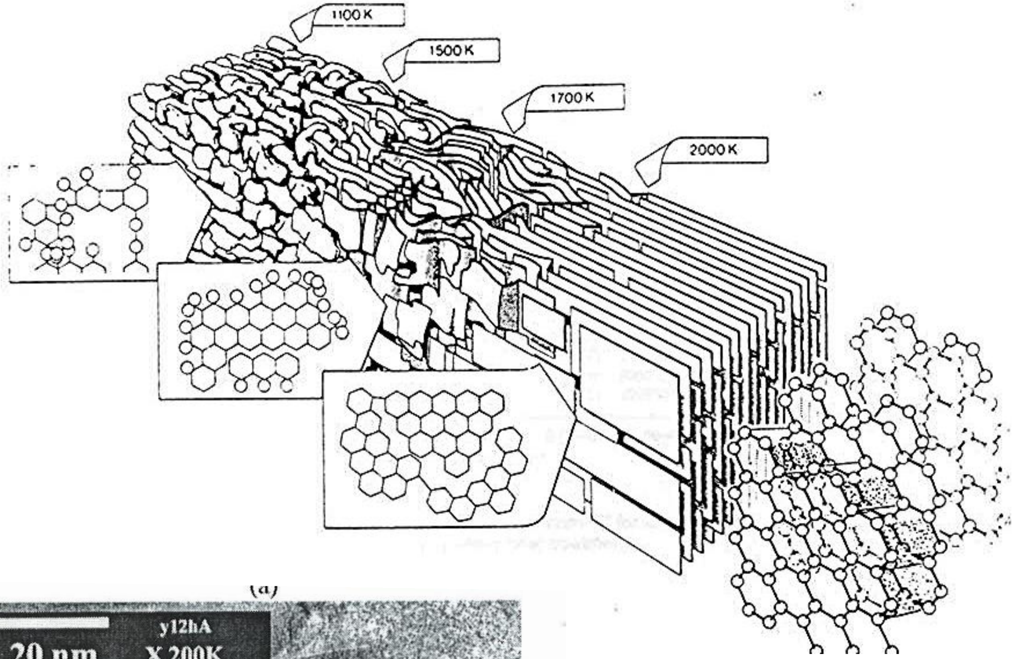


Graphitized or disordered char ?

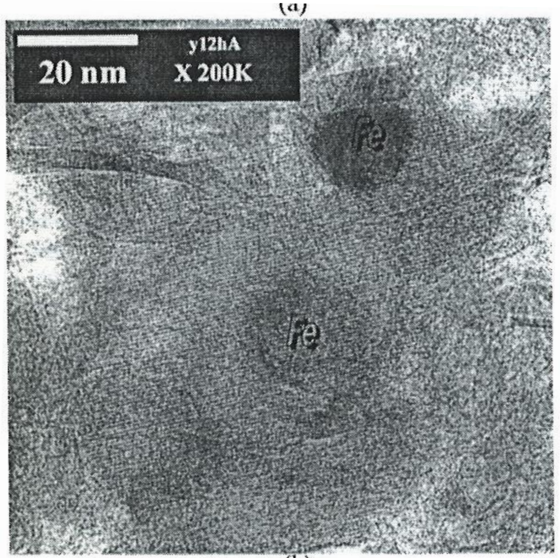


Model of thermal annealing

erche

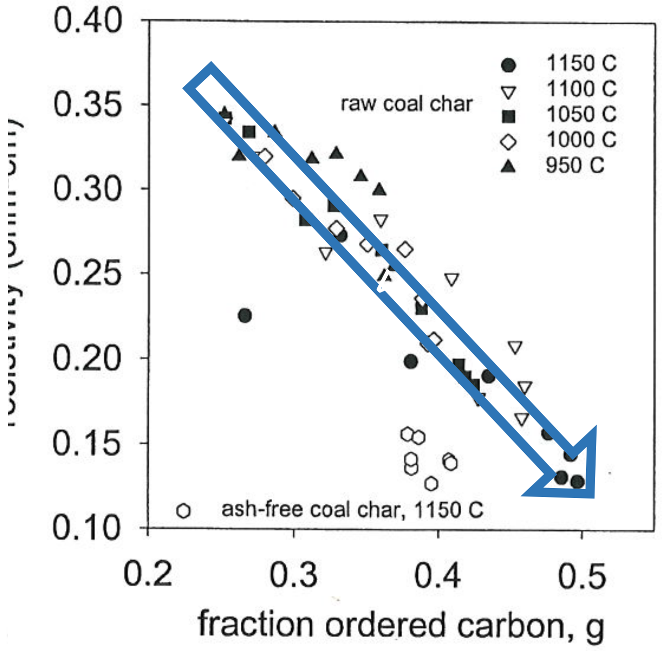


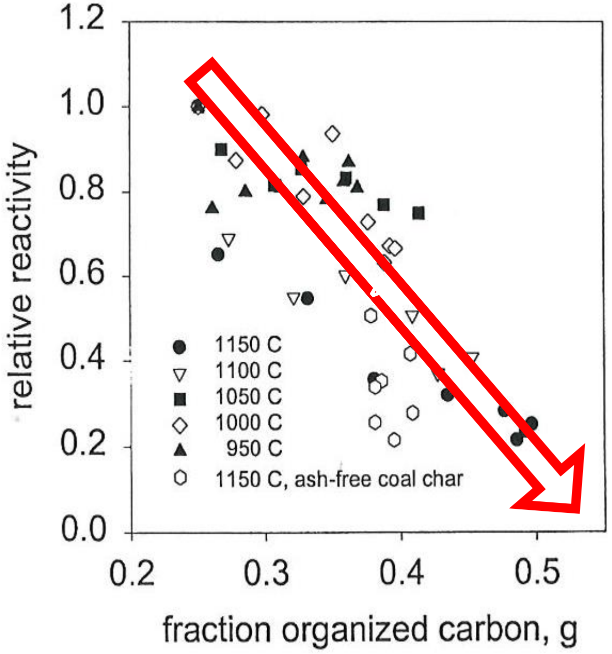
(a)



(b)

Fig. 4. High resolution transmission electron micrographs of the carbon structure around the iron particles for y12hA. (a) Micrograph showing many randomly oriented crystallites, (b) near-perfect crystallite structure around the iron particles.

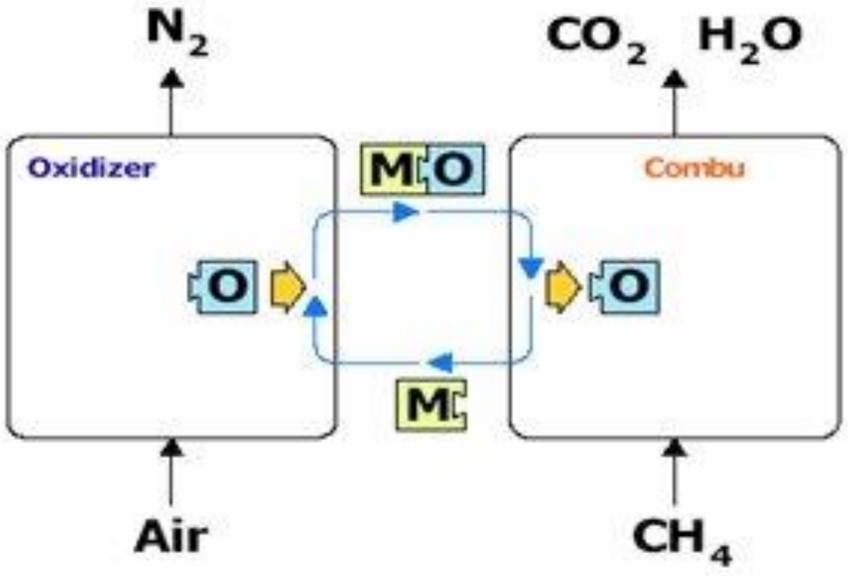




Graphitization:
- reduces reactivity in boilers
-decreasese resisitivity of the material

Capture ready combustion

Chemical Looping Combustion (CLC) of <u>liquid and gaseous</u> fuels



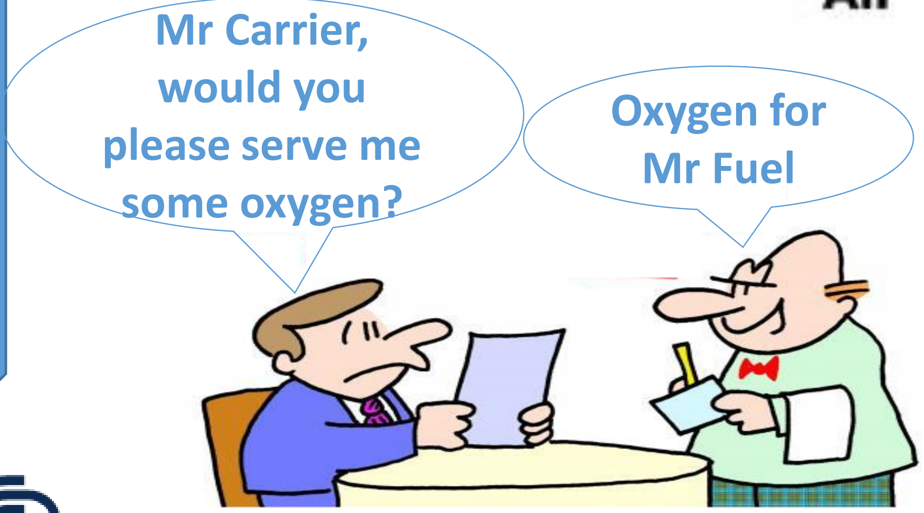
- **Oxidation : exothermic**

$$M + \frac{1}{2}O_2 \rightarrow MO$$

- **Reduction : endothermic**

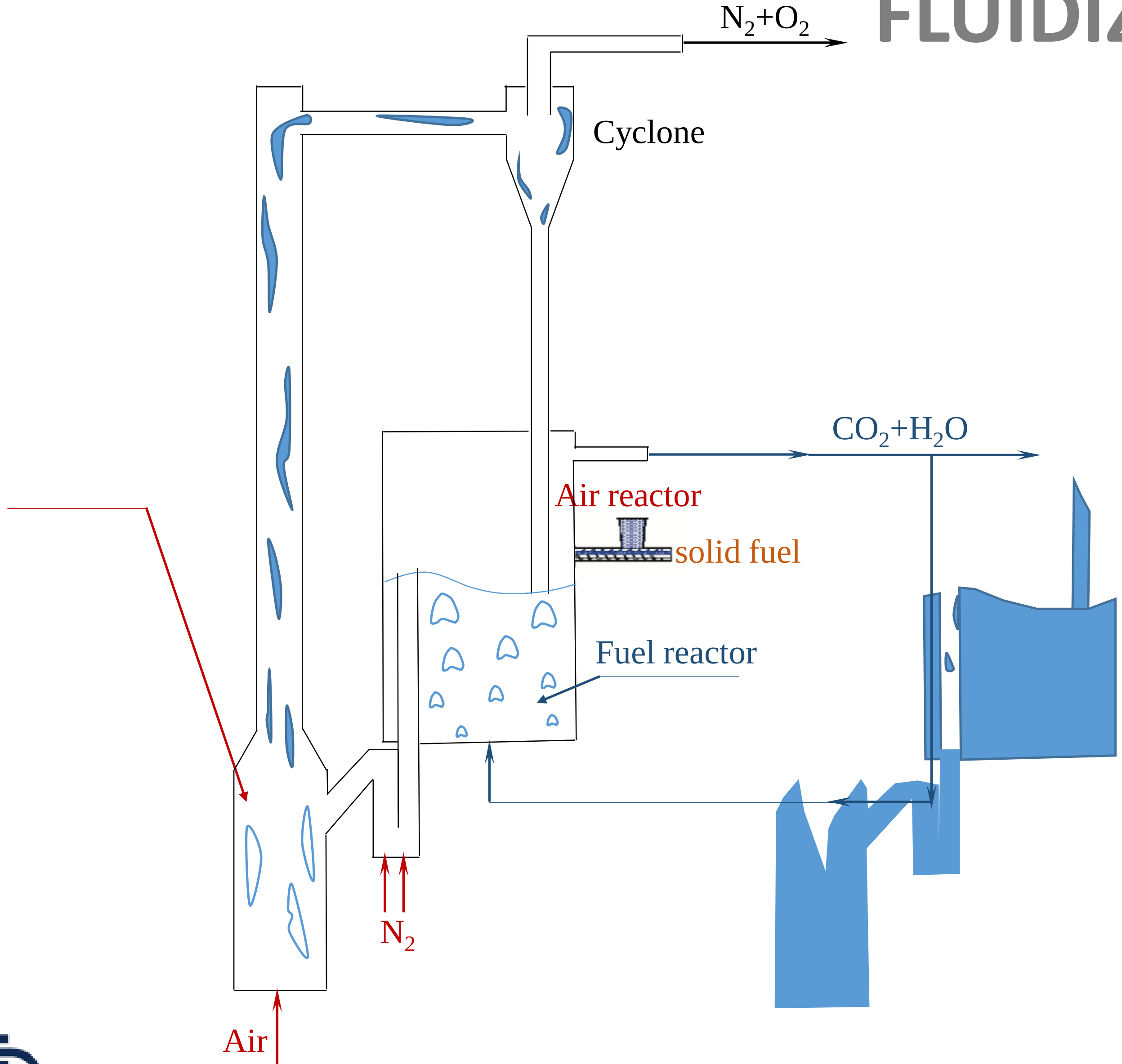
$$CH_4 + 4MO \rightarrow CO_2 + 2H_2O + 4M$$

M : metal, MO : metal oxide

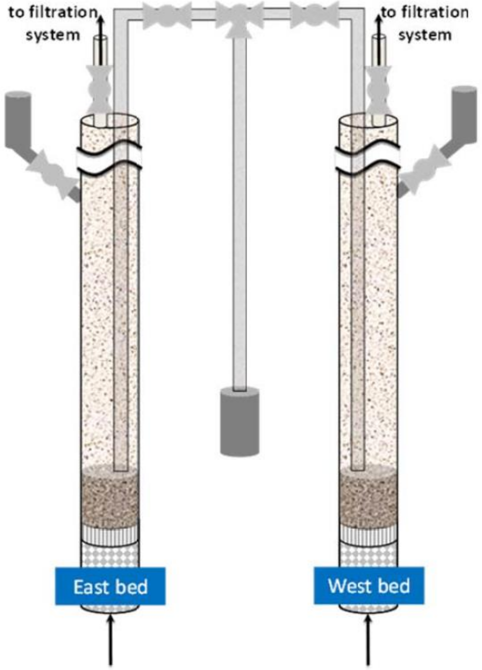


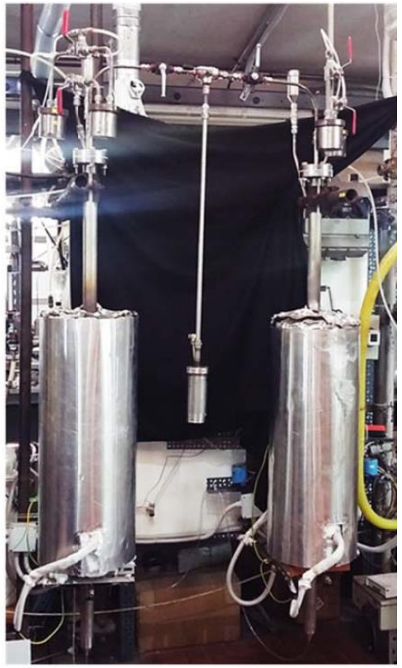
THE "GOOD" WAITER

DUAL INTERCONNECTED FLUIDIZED BEDS FOR CLC



Ping pong reactor
for lab scale testing





Materials in CLC

Oxygen carriers

✓High reactivity
✓Good selectivity
✓High oxygen storage capability
✓No carbon deposition
✓Environmental friendly
✓No attrition
✓No agglomeration
✓Long lifetime over high temperature redox cycles

In anatural gas-fired CLC system, operating at 10 bar with an oxygen carrier consisting of NiO on alumina ($15.3 per kg) to break even with a NGCC system fitted with an amine scrubber, the particles would have to last 500-700 hours.

Ni-based oxygen-carriers

✓very high reactivity with almost complete CH_4 conversion
×prone to carbon deposition .

Cu-based oxygen-carriers

✓high reaction rates and oxygen transfer capacity
×high tendency to agglomeration

Fe-based oxygen-carriers

✓low cost and environmental compatibility
×low CH_4 conversion and low oxygen transport capacity

Consiglio Nazionale delle Ricerche

STEMS Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

Lisi et al. *Int. J. Hydrogen Energy* **2015**, 40, 204.
Cimino et al. *Catalysts* **2019**, 9, 147

Novel oxygen carriers for Chemical Looping Combustion at STEMS

Lanthanum oxysulphates doped with trantion metals (Co, Mn, Cu)

5% CH_4/air cycles @800°C over Co-doped lanthanum oxysulphate

$La_2O_2SO_4 + 4\ H_2 \rightarrow La_2O_2S + 4\ H_2O$ (*reduction*)

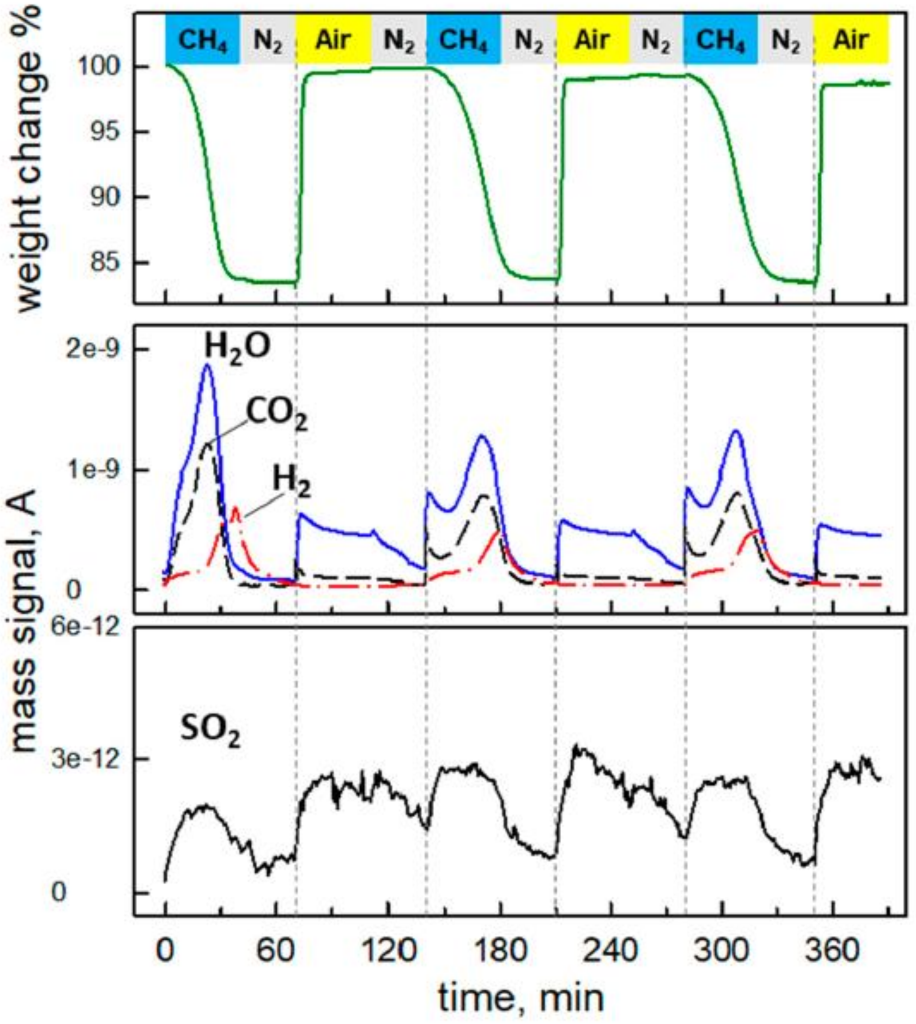
$La_2O_2S + 2\ O_2 \rightarrow La_2O_2SO_4$ (*oxidation*)

Doping with transition metals increases both performances and thermal stability of $La_2O_2SO_4$

Repeatable cycles
Stoichiometric reduction/oxidation

High selectivity to H_2O and CO_2

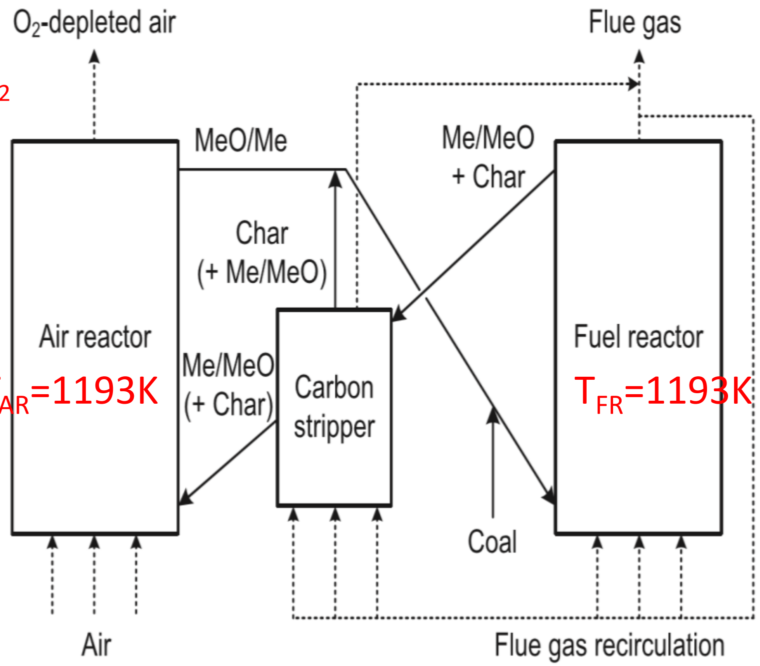
Negligible degradation of carrier by sulphate decomposition



Chemical Looping Combustion (CLC) of solid fuels

Is difficult because we cannot realize the contact between the solid carrier and the solid fuel

CuO (50%) on TiO_2



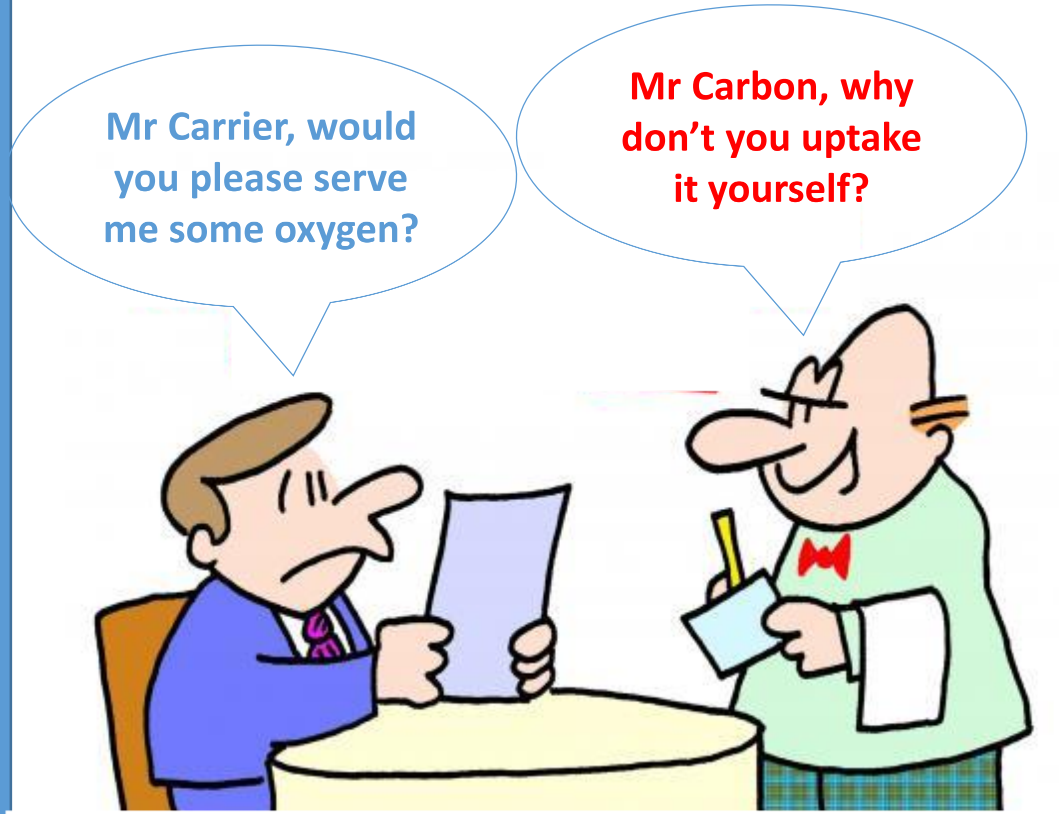
T_{AR}=1193K

T_{FR}=1193K

CLOU concept

1. Coal is firstly gasified and then, CLC for gases is applied
2. Gaseous oxygen is released from the metal carrier to burn coal (Chemical looping with oxygen uncoupling, CLOU)

Chemical Looping Combustion (CLC) of solid fuels



THE "LAZY" WAITER

$$2C_{(s)} + O_{2(g)} \rightarrow 2C(O)_{(s)}$$

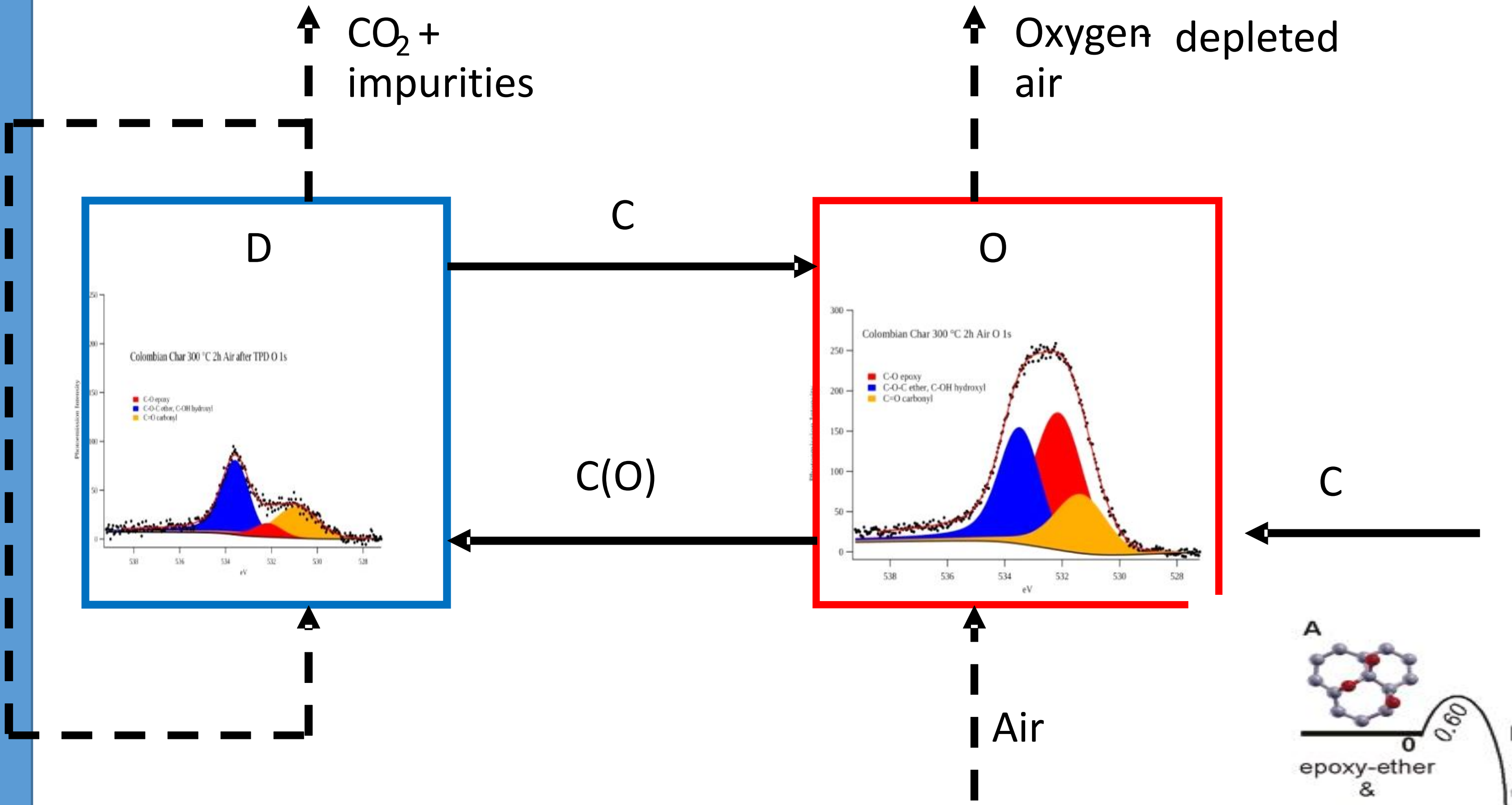
OXIDIZER
low-to-moderate temperature

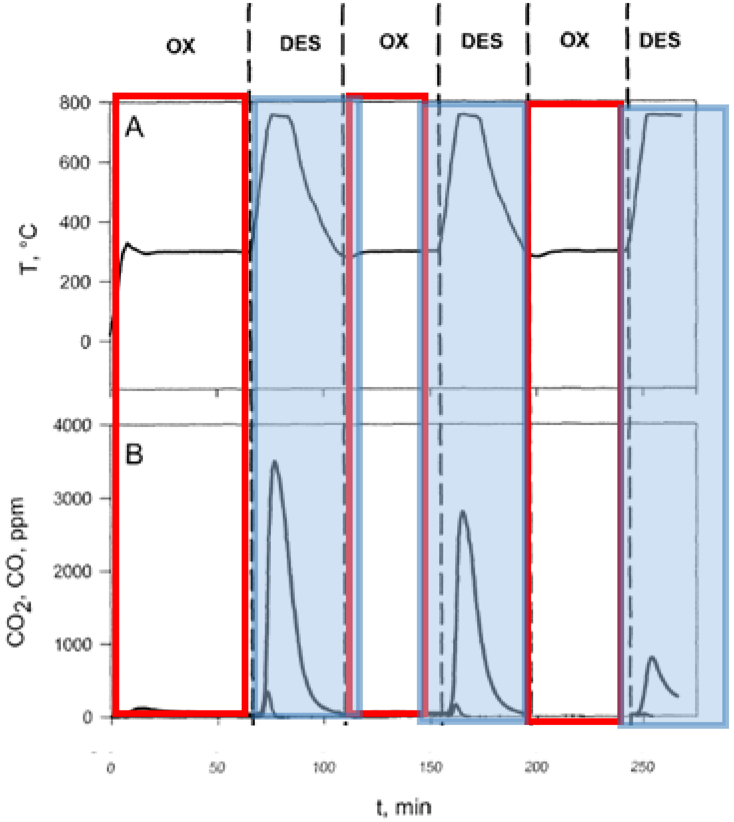
$$2C(O)_{(s)} \rightarrow CO_{2(g)} + C_{(s)}$$

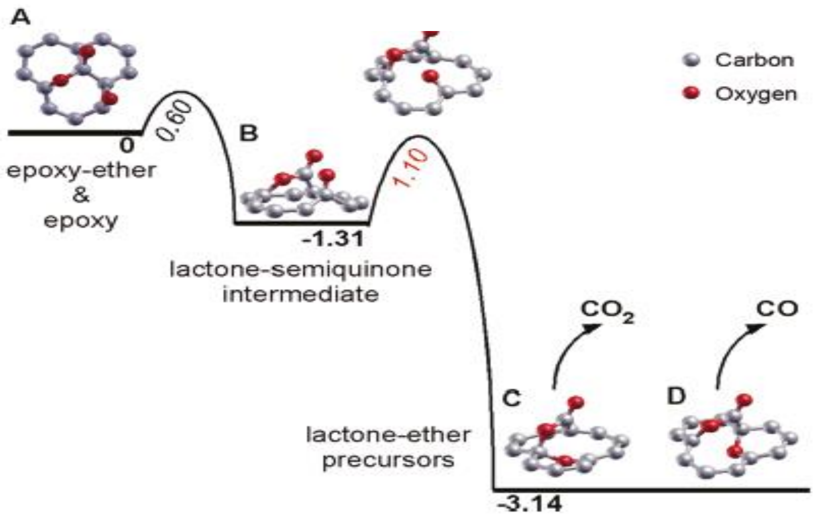
DESORBER
moderate-to-high temperature

Carboloop concept

For materials scientists







CarboLoop versus metal based CLC for solids

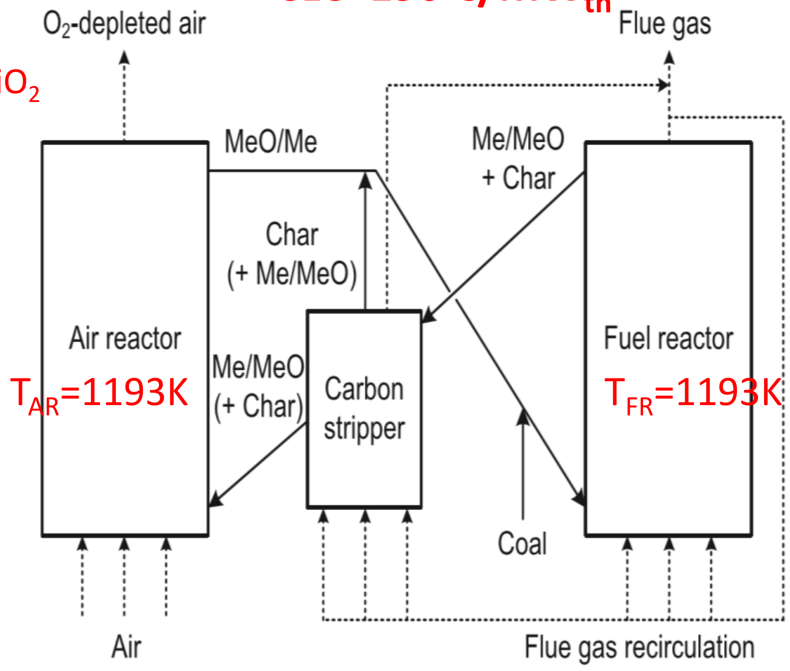
Less complex (no stripper needed)

Lower temperature (600-1000K vs 1193s)

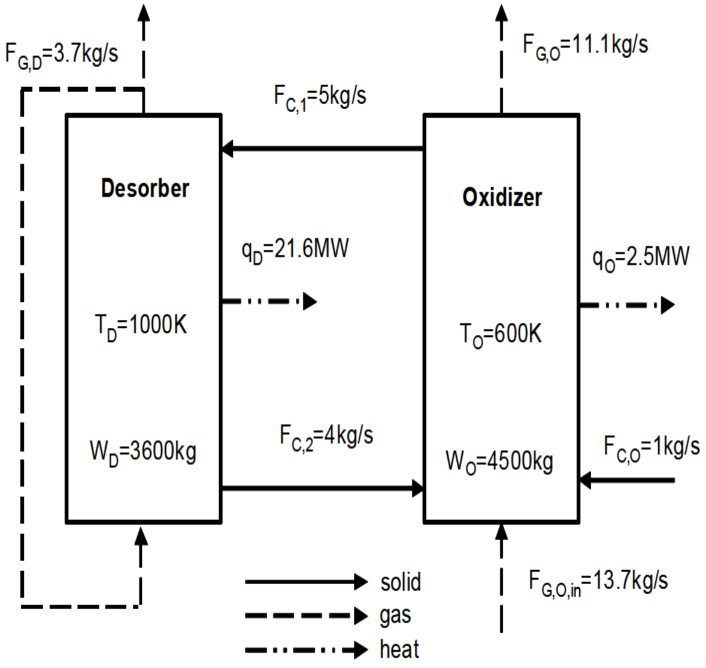
40 % Lower capital investment cost

CLC=190 €/MW$_{th}$

CuO (50%) on TiO_2



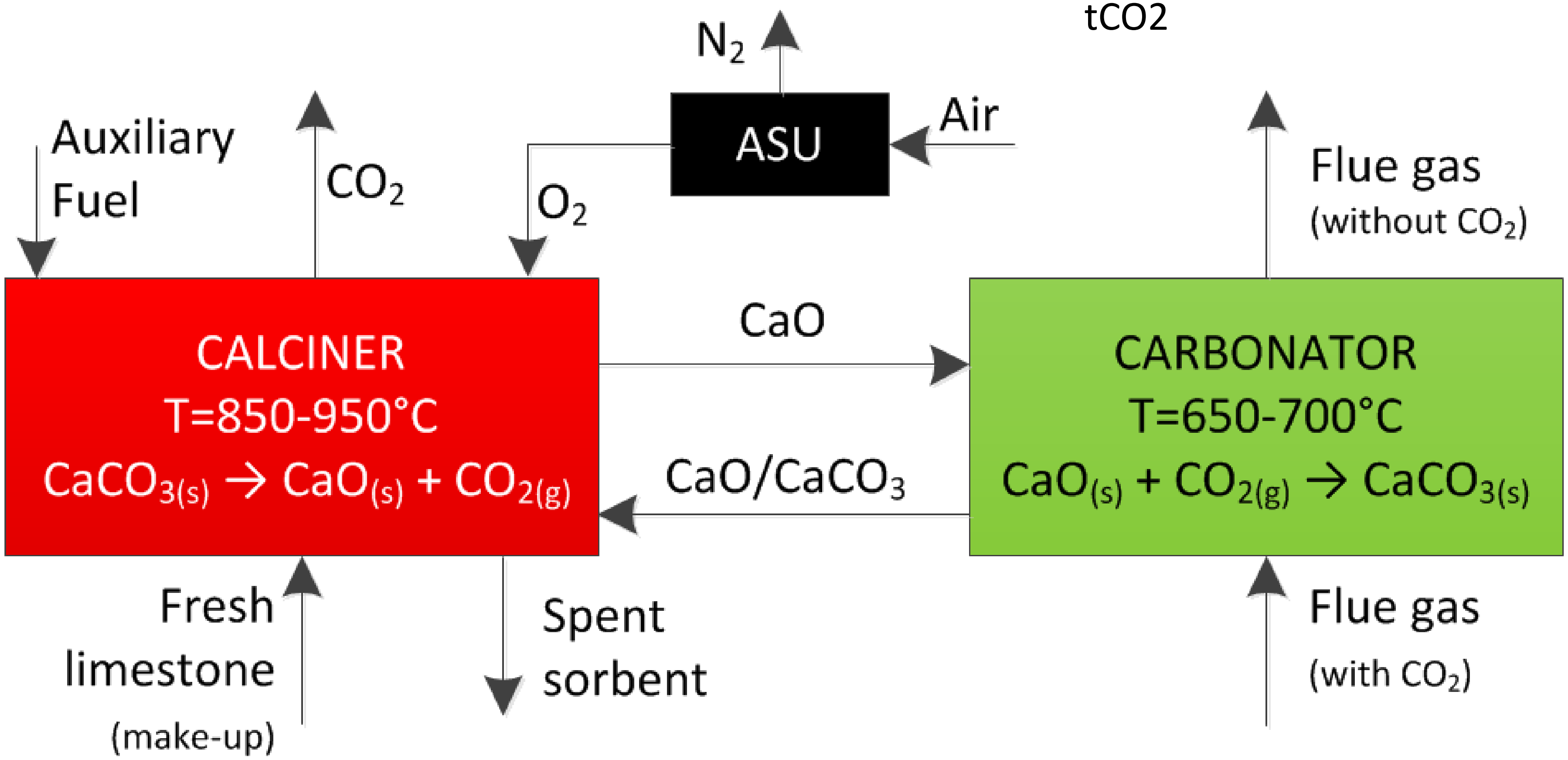
CarboLoop= 107 €/MW$_{th}$



From M. Spinelli et al. / Energy 103 (2016) 646e659

CO_2 capture: Calcium Looping

- TRL 6-7
- Calcium looping can be combined with cement industry
- Costs are in the order of \$30 per tCO2 (lile MEA)
- Integrated CaL process would offer a carbon capture cost of less than \$30 per tCO2

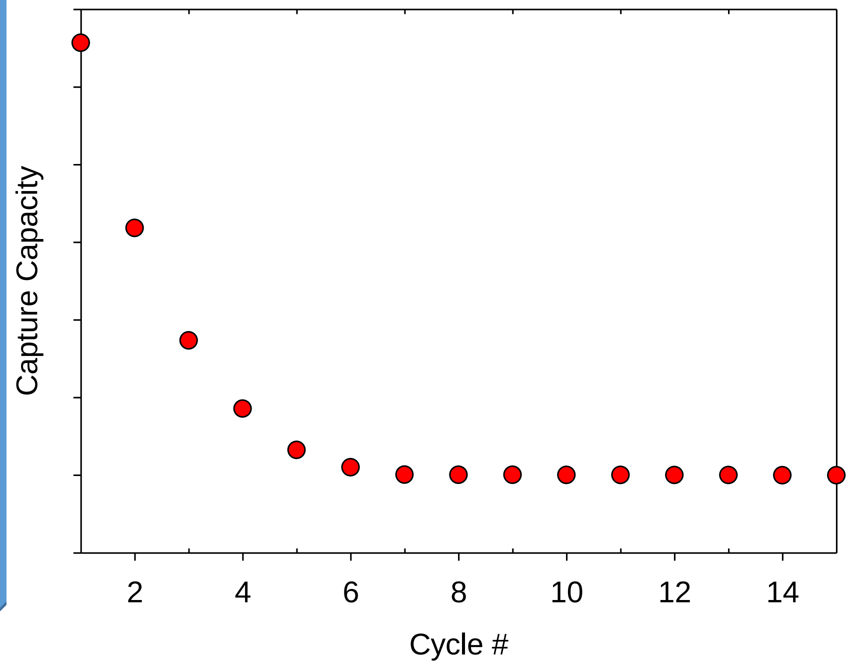


Ca-L for materials scientists

Decay of CO_2 Capture Capacity of the sorbent

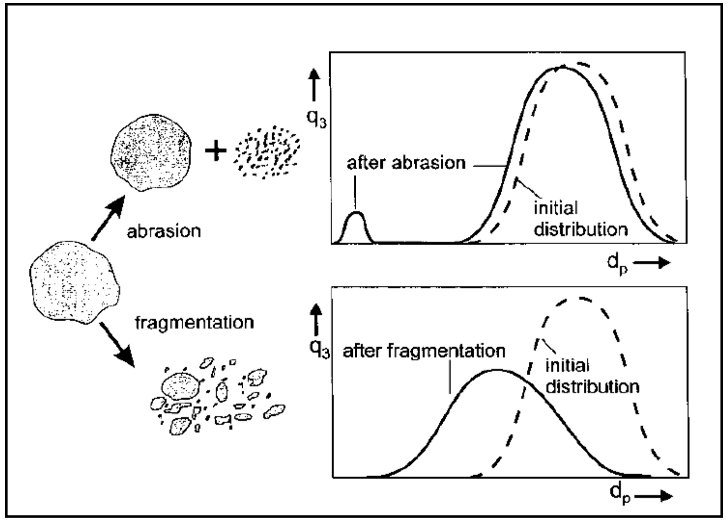
- *Sintering*
- *Presence of SO_2*

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4$$



Attrition/Fragmentation Phenomena ⇒

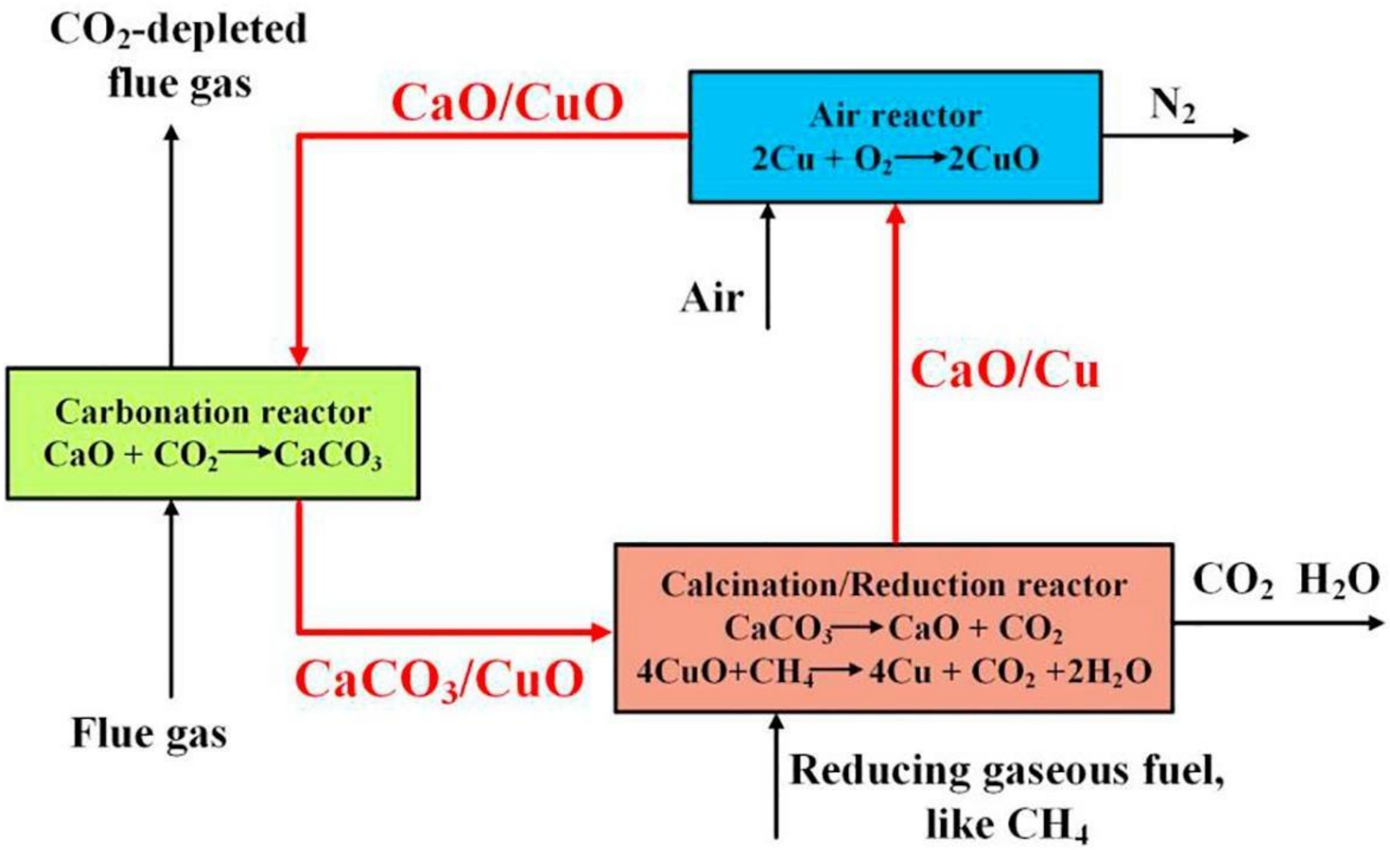
- *Primary Fragmentation*
- *Secondary Fragmentation*
- *Attrition by Abrasion*



Modified sorbents:

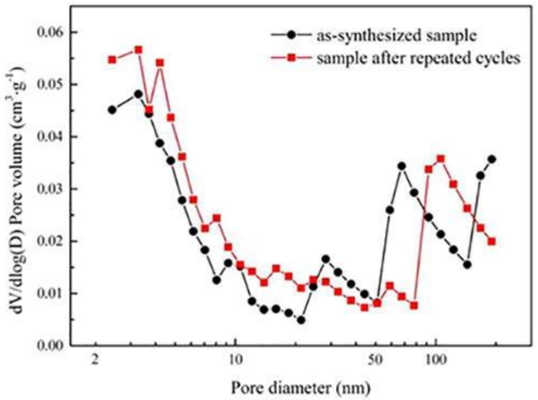
- hydration, re-carbonation, doping with various reagents, pellettization, thermal pre-treatment, sol–gel or precipitation of calcium carbonate, preparation of nano-materials
- Some additives may actually weaken the resulting sorbent which fragment under FB conditions

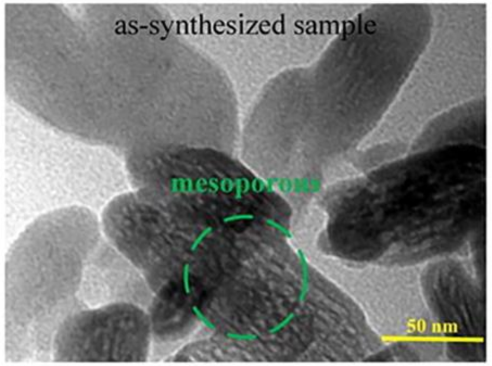
CO_2 capture: Calcium Looping +CLC

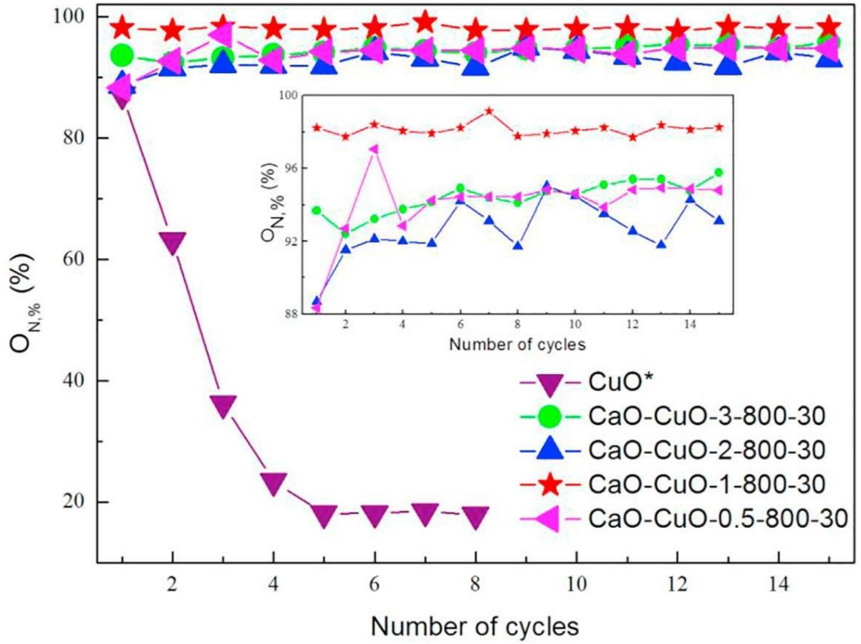


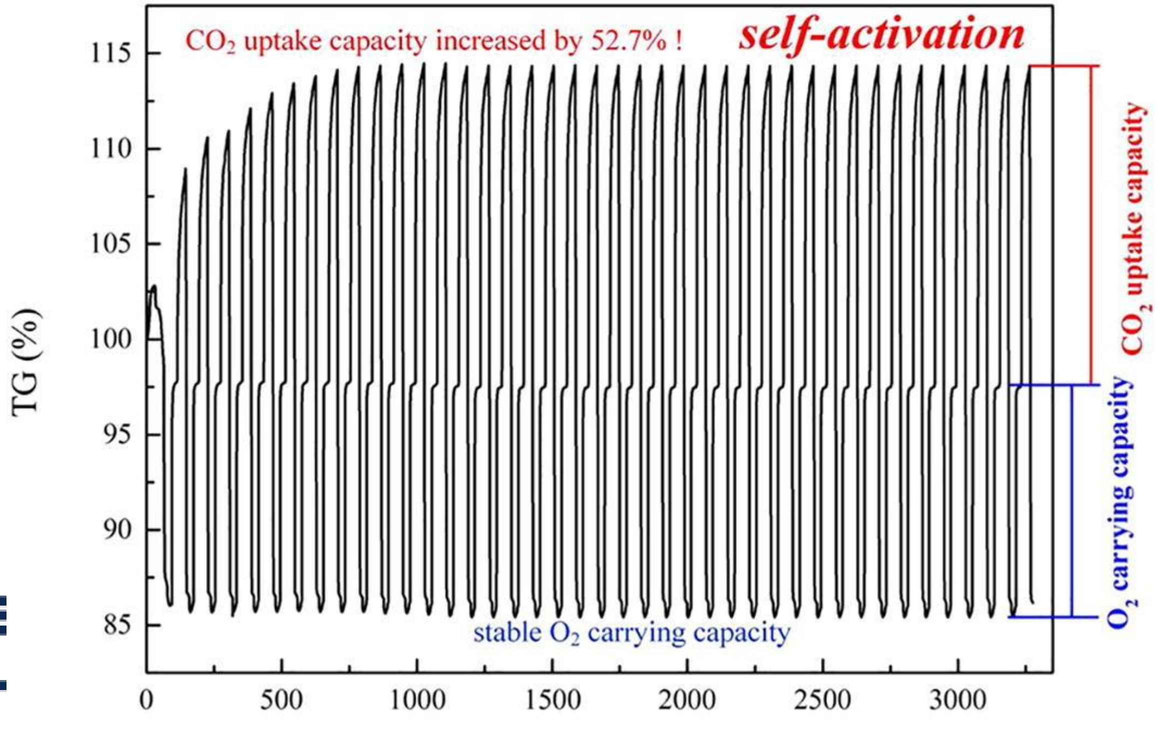
Self-activated, nanostructured composite for improved CaL-CLC technology, Edward J.Anthony, Chem Eng. Journal 2018

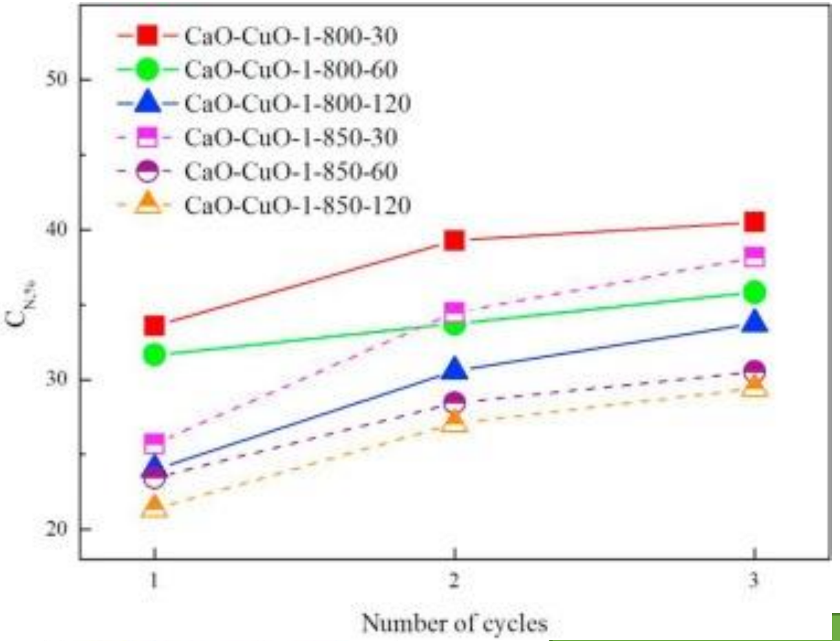
Materials in CaL+CLC





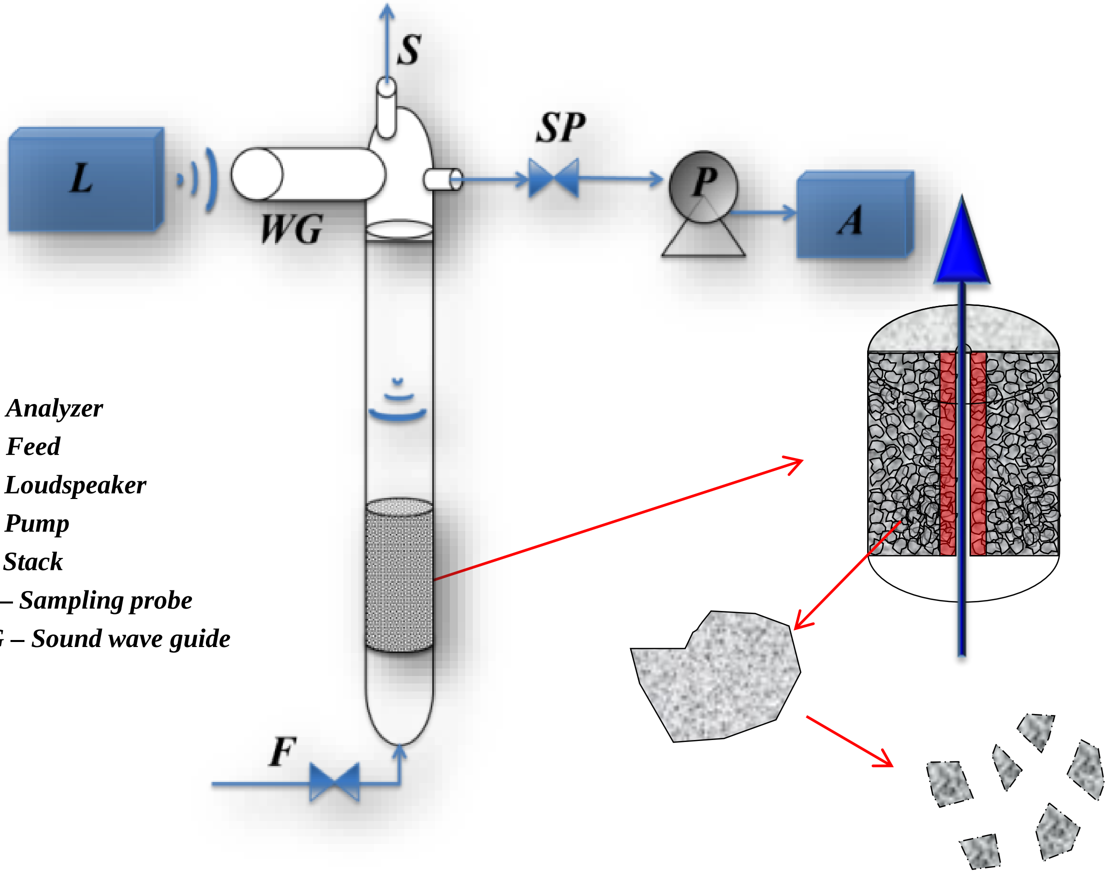






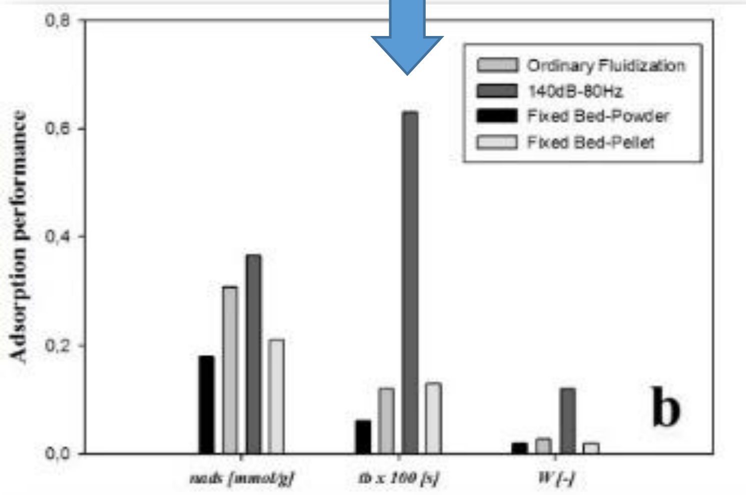
CO_2 capture: fine powders in a sound assisted fluidized bed

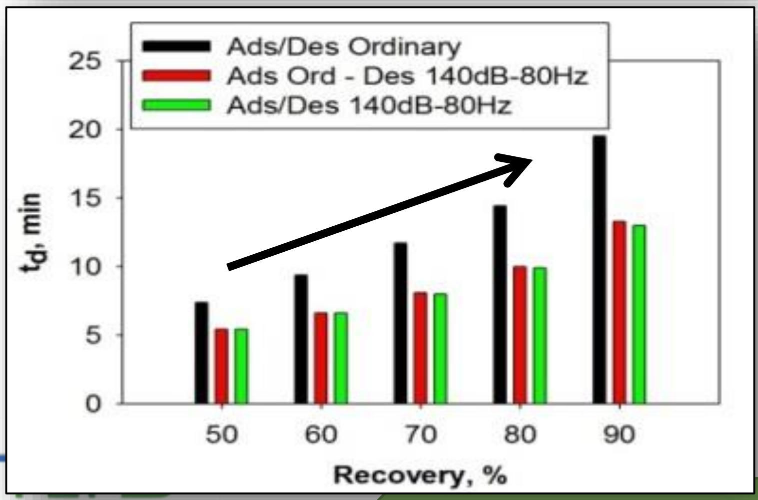
- 1.78 MJ/kgCO2 (against 3.6-4 in case of MEA)
- Tested with low percent of CO2



- *A – Analyzer*
- *F – Feed*
- *L – Loudspeaker*
- *P – Pump*
- *S – Stack*
- *SP – Sampling probe*
- *WG – Sound wave guide*

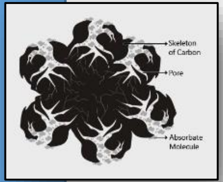
Effect of sound





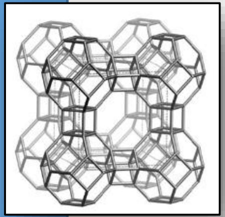
Link between adsorption performances and porosity

Adsorption performances



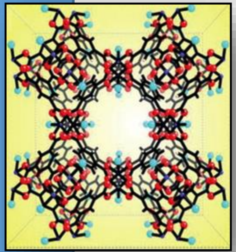
HKUST-1

CB-FM



AC Sigma

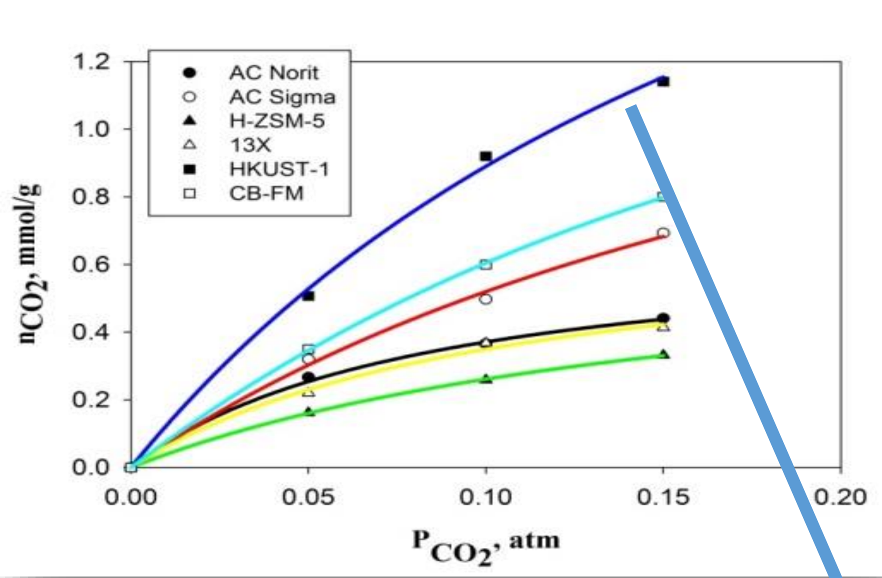
AC Norit



13X

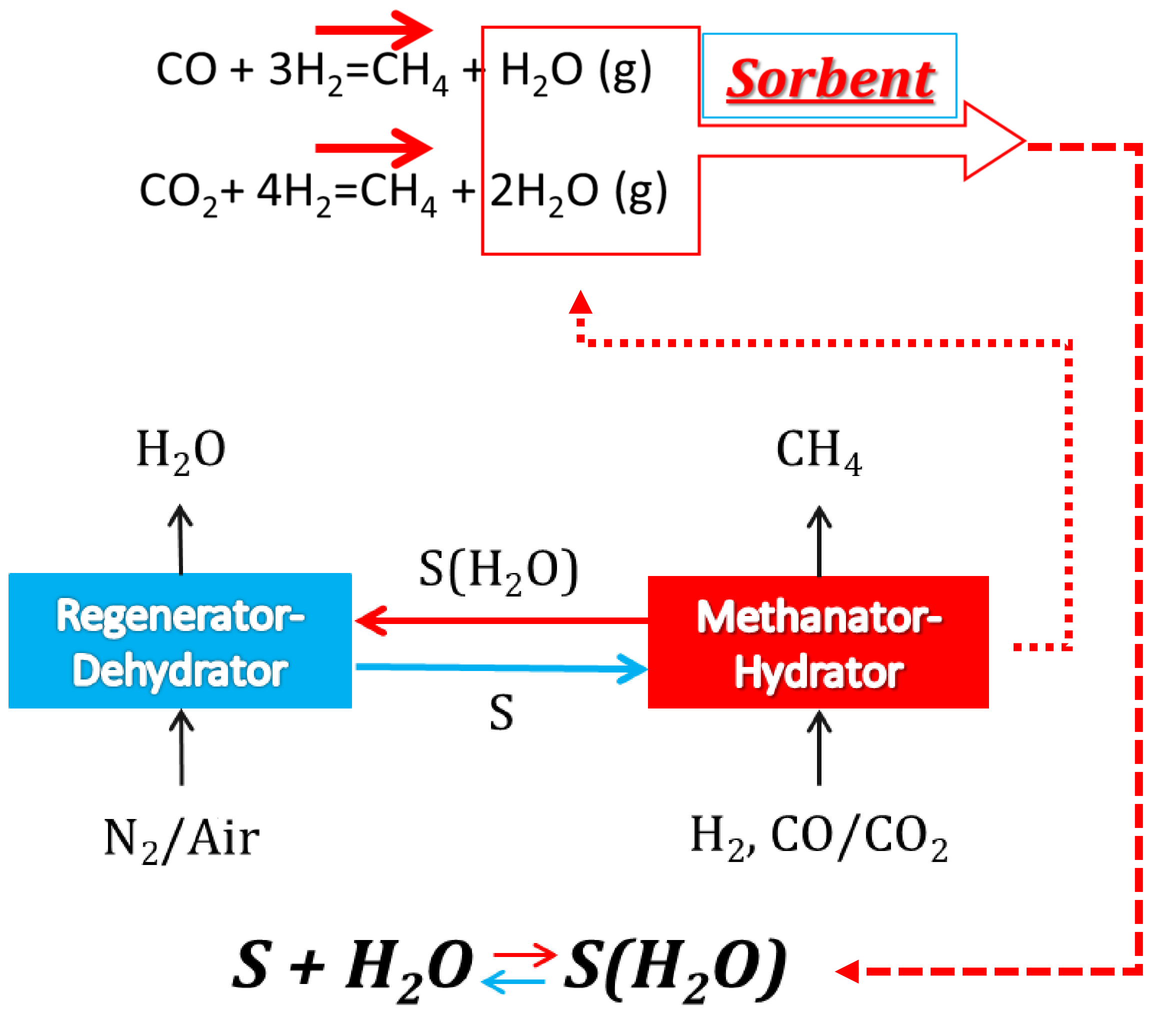
H-ZSM-5

Wednesday at 10.00, Michela Alfé



Materials	BET, m^2/g	Pore volume, cm^3/g
AC Norit	1060	1.34
AC Sigma	1038	1.14
H-ZSM5	400	0.41
13X	960	0.41
H-KUST-1	680	0.66
CB-FM	157	1.05

CCU: Chemical Looping Sorption Enhanced Methanation (CL-SEM)



Methanation: T> 300°C
Regeneration: T> 400°C

Advantage: lower pressures compared to commercial methanation (fixed bed-adiabatic stages).

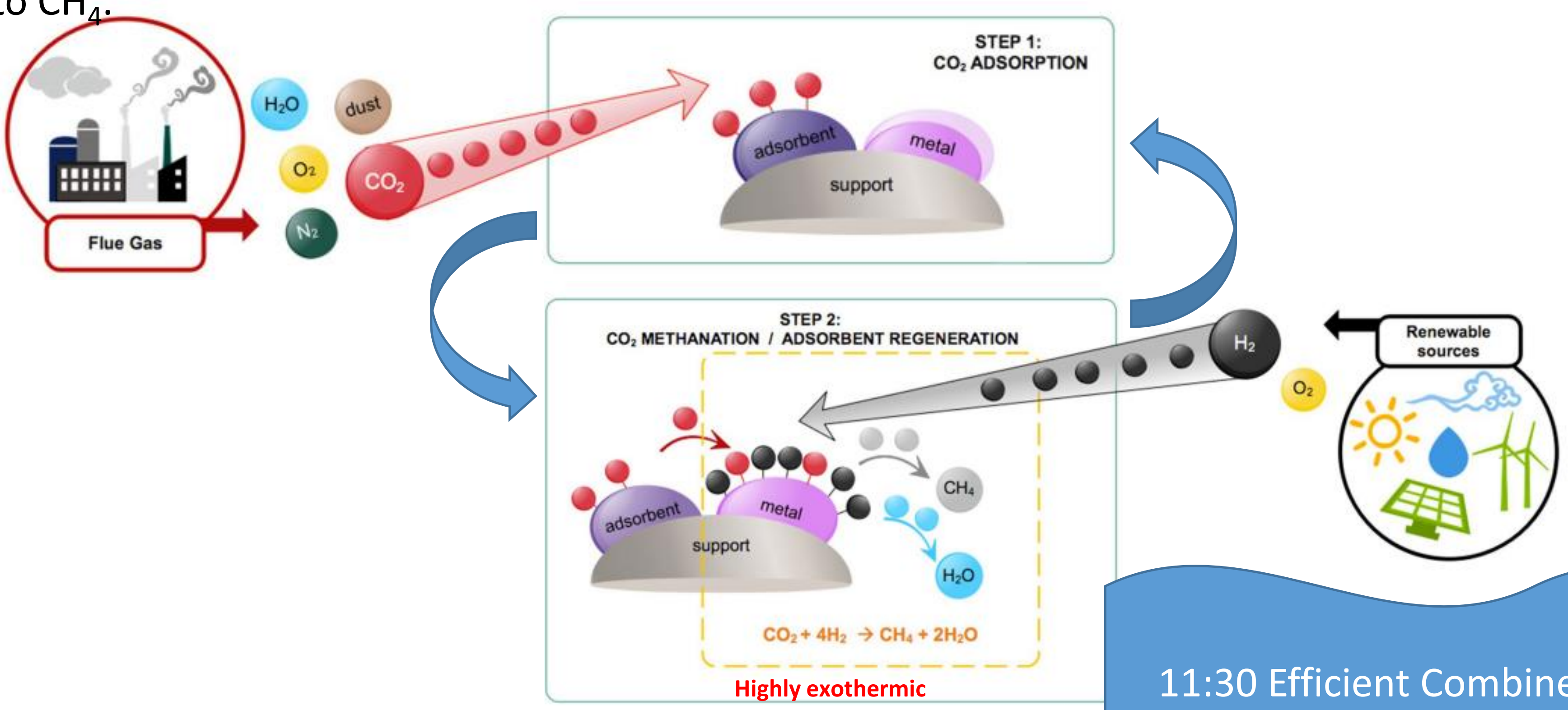
-**Need for tailored sorbents**
So far CaO and a 3A zeolite have been tested
-3A zeolites (low adsorption capacity) CaO fragile and active towards CO_2

Massa et al., Journal of CO2 Utilization, 2020
Coppola et al., Biomass Conversion and Biorefinery, 2020

CCU: Combined CO_2 Capture & Methanation

<u>Dual Function Materials</u> capture CO_2 from industrial flue gases (or even air) and release it as concentrated synthetic natural gas (SNG)

Two key capabilities: 1) large & fast CO_2 adsorption 2) high catalytic activity for the hydrogenation of CO_2 with high selectivity to CH_4.



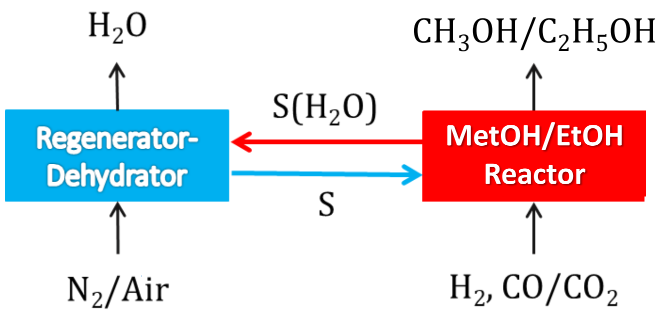
Highly exothermic process

11:30 Efficient Combined CO2 Capture and Methanation S. Cimino

CCU: CO_2 Capture & Met-OH production

PtL-MetOH/EtOH

Sorption Enhanced Processes



$$S + H_2O \rightleftarrows S(H_2O)$$

$CO_2 + 3H_2 = CH_3OH + H_2O$

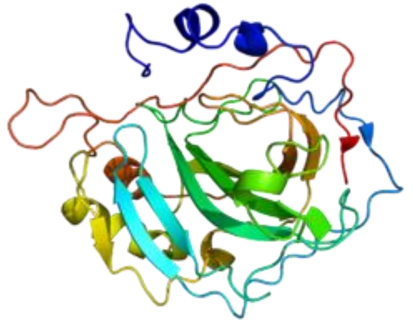
Cu-based Catalyst
220-300°C
50-100 bar

$2CO_2 + 6H_2 = C_2H_5OH + 3H_2O$

Co-based Catalyst
200-300°C
>50 bar

CCU: enzymatic CO_2 capture and utilization

human Carbonic anhydrase II



Who? **Carbonic anhydrase (CA)** **(EC number 4.2.1.1)**:
enzyme expressed in different forms in most of the living organisms and microorganisms

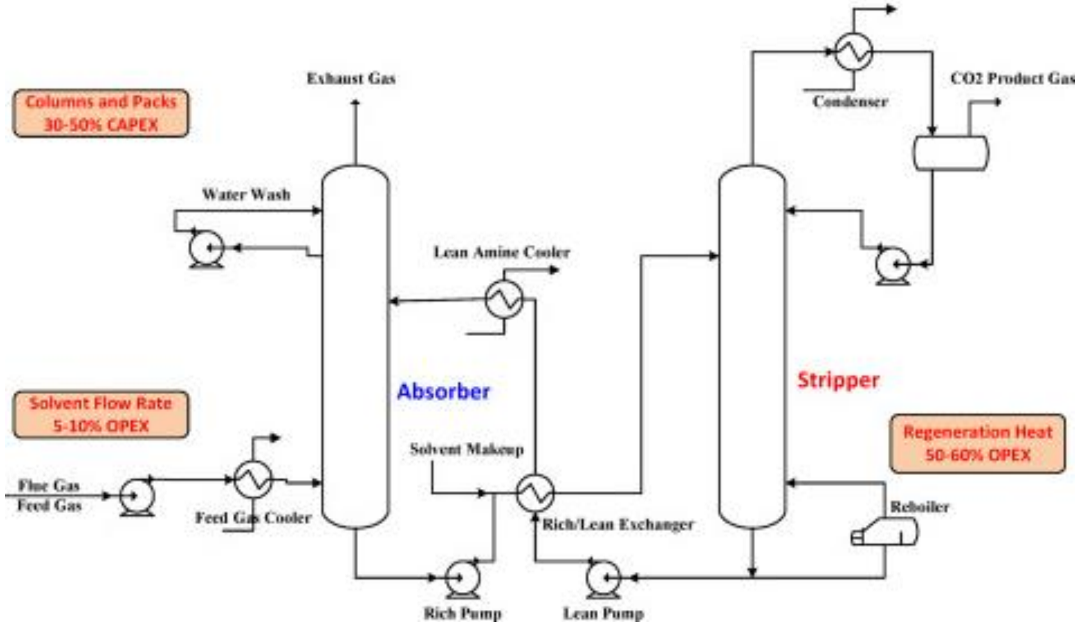
What? Catalyzes **CO_2 hydration reaction**

$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$

Reactive CO_2 absorption in aq solvents (KCO_3, $NaCO_3$, …)

Where? Post combustion in power plants, industrial plants

Why? **Alternative to amines as absorption rate promoter:** advantages in use of CA in case of CO_2 conversion in aq phase → construction materials through mineralization, microalgae cultivation, biochemical CO_2 fixation (enzyme cascade)



Liang et al. International Journal of Greenhouse Gas Control 40, 2015, 26-54

Materials enzymatic CO_2 capture and utilization

Enzyme immobilization: enabling the use of CA in continuous CO_2 absorption units (e.g. packed columns, bubble columns, G-L membrane, …)

CA immobilization:

Confines CA into CO_2 capture units: **biocatalyst morphology** ⟺ **reactor design**

Stabilizes CA up to **70-80°C**

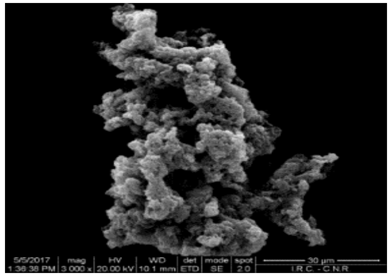
CA covalent attachment on solid supports

- Paramagnetic nanoparticles
- Polymeric resins
- Siliceous supports
- Tube wall (membrane)
- Monolith

Peirce et al., Biochemical Engineering Journal 138 (2018) 1–11

CA Cross Linked Enzyme Aggregates (CLEA)

Carrier free biocatalyst



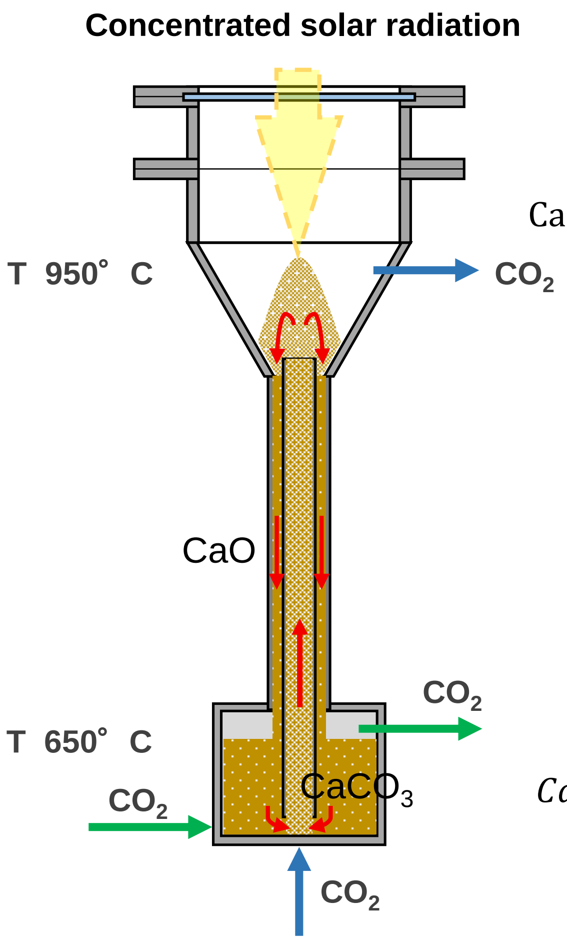
Peirce et al., Biochemical Engineering Journal 127 (2017) 188–195

***In vivo* immobilization**

CA as cell membrane protein: biocatalyst → cell membrane debris dispersed in liquid solvent

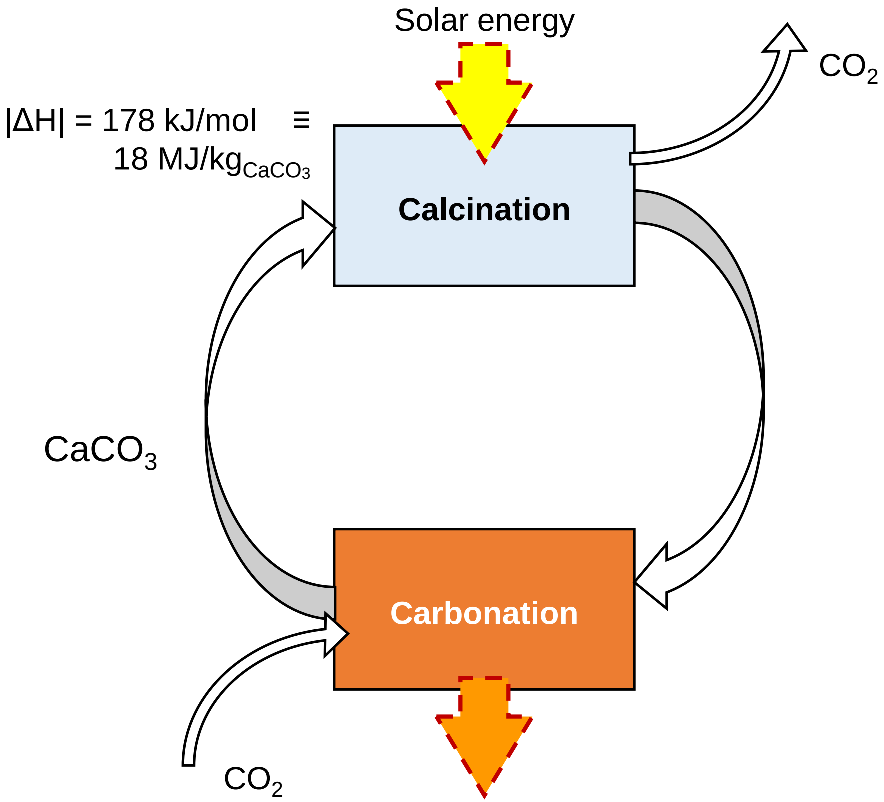
Fabbricino et al., Journal of Biotechnology, submitted Jan 2021

CCU and solar energy: **CaL with solar energy**

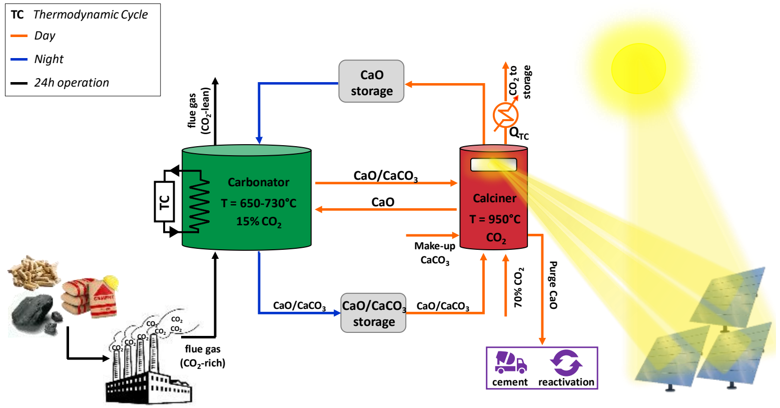


$$CaCO_3 \xrightarrow{calc} CaO + CO_2$$

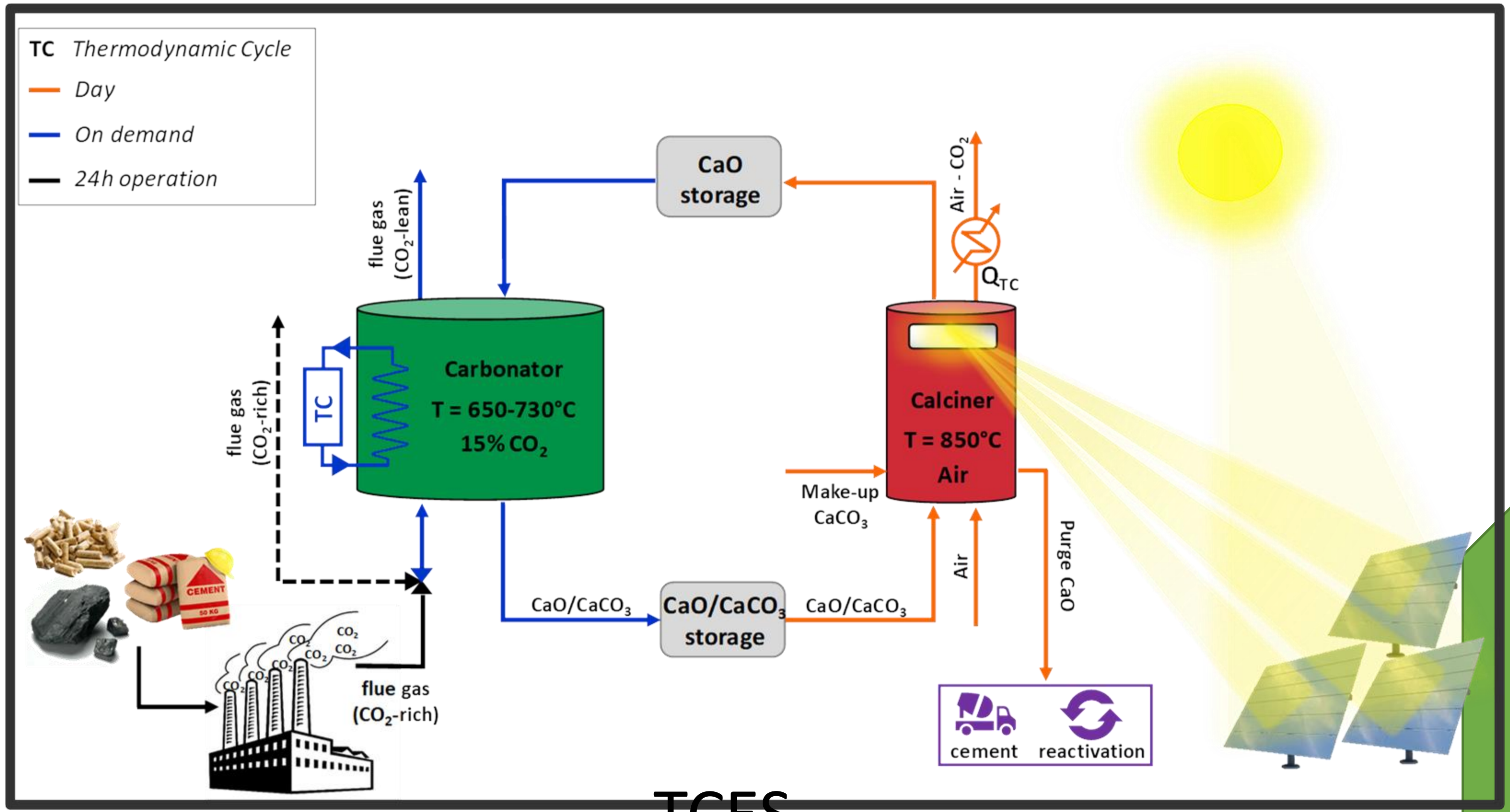
$$CaO + CO_2 \xrightarrow{carb} CaCO_3$$



SOLAR CALCIUM LOOPING: Thermochemical energy storage (TECS)



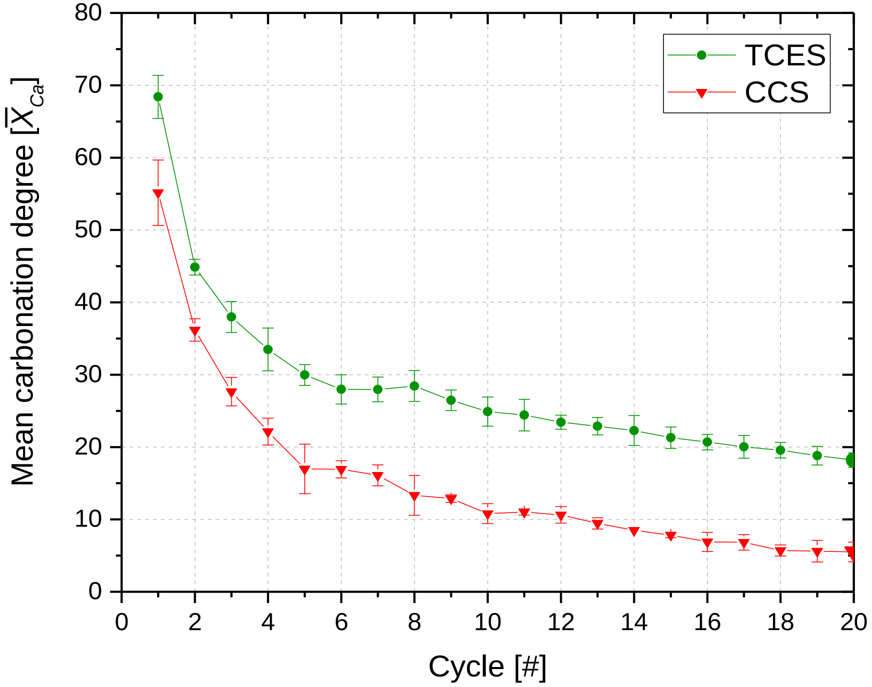
CCS

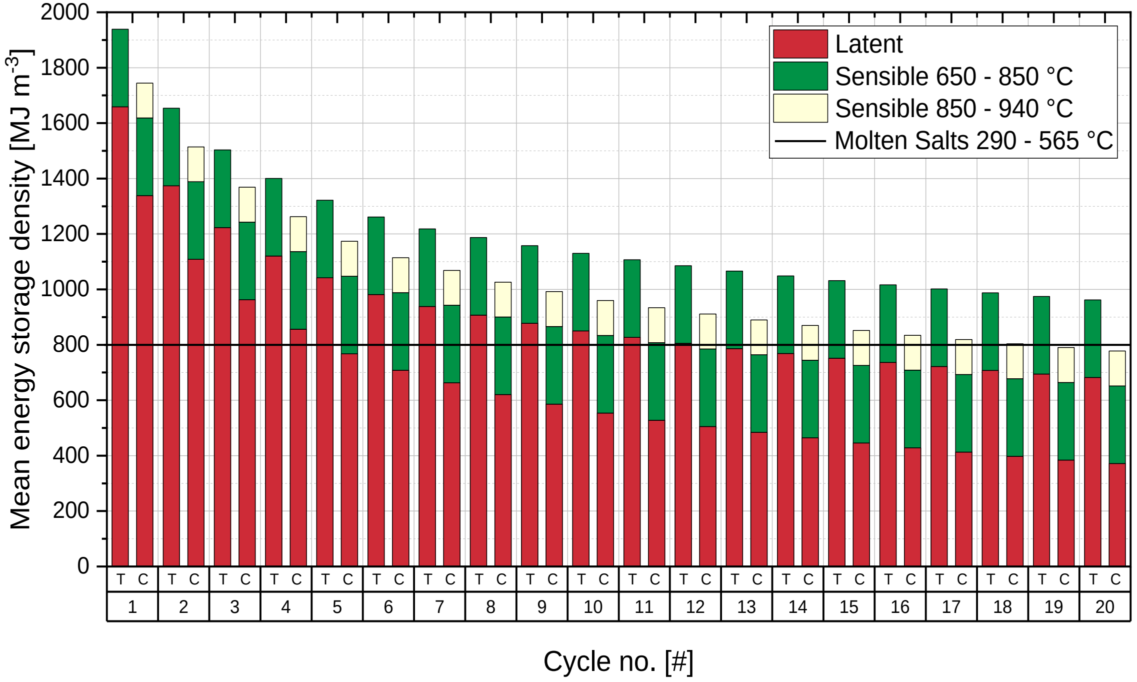


TCES

Tregambi et al., I&ECR (2019)

Solar calcium looping: CCS vs TCES



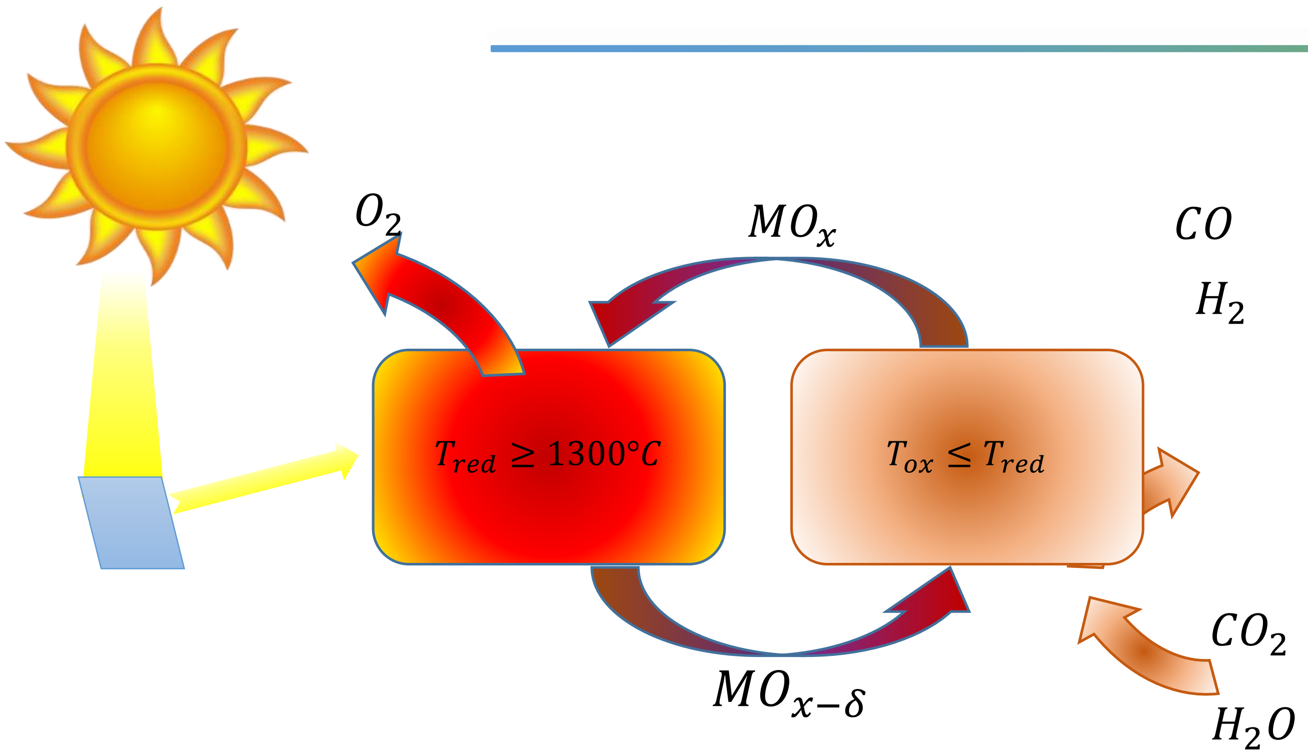


Tregambi et al., I&ECR (2019)

Consiglio Nazionale delle Ricerche

STEMS
Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

Solar Thermochemical Splitting



Generates concentrated H_2 (CO)

11:45 Thermochemical cycles for CO2 capture/utilization, R. Solimene/ G. Landi

Cycle	Red. T, °C	Ox. T, °C
Iron oxide	2000-2300	400
Zinc oxide	1600-1800	400
Cerium oxide	1300-1600	1000-1300
Perovskite	1200-1600	800-1000

- Very high temperature (>1300°C)
- Stability of materials

Conclusions

- I tried to provide a very quick overview of research topics in the field of CCSU. I picked some «research topics» that we are currently investigating at STEMS-CNR, but there is much more going on worldwide.
- There is a lot to do for materials scientists in all the fields: CaL, CLC, Capture with solid sorbents, Splitting of CO_2/H_2O, methanation…
- The rate at which new materials progress from the lab- or bench-scale to the pilot-scale is too slow.
- Laboratory-scale work should investigate materials under conditions representative of the real world.
- The take home message is: «process engineers and materials scientists need to work together». Any collaboration is welcome

name.surname@stems.cnr.it

Sound assisted capture in Fuidized beds
Riccardo Chirone,
Paola Ammendola,
Federica Raganati



Materials for CO2 capture
Michela Alfè

Biotech processes
Maria Elena Russo

Materials for CLC, methanation
Luciana Lisi
Stefano Cimino
G.L. Landi

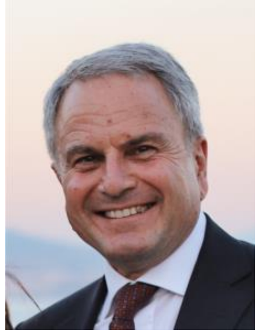

Oxyflame
Reinhold Kneer
(RWTH)

CO2 and H2O splitting
Gianluca Landi (Matrials)
Roberto Solimene
(reactors)

Loops, CaL, CLC
Antonio Coppola
Massimo Urciuolo
Fabio Montagnaro
(UNINA)
Piero Salatino (UNINA)







Solid fuels (CLC of solids, oxicombustion, annealing, fragmentation)
Osvalda Senneca

Solar aided processes
Roberto Solimene

Consiglio Nazionale delle Ricerche

STEMS
Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

References

1. Coppola A, Senneca O, Scala F, Montagnaro F, Salatino P. Looping cycles for low carbon technologies: A survey of recent research activities in Naples. Fuel [Internet]. 2020;268(February):117371. Available from: https://doi.org/10.1016/j.fuel.2020.117371
2. Coppola A, Massa F, Salatino P, Scala F. Evaluation of two sorbents for the sorption-enhanced methanation in a dual fluidized bed system. Biomass Convers Biorefinery. 2020;11(1):111–9.
3. Coppola A, Scala F, Gargiulo L, Salatino P. A twin-bed test reactor for characterization of calcium looping sorbents. Powder Technol [Internet]. 2017;316:585–91. Available from: http://dx.doi.org/10.1016/j.powtec.2016.11.067
4. Cerciello F, Coppola A, Lacovig P, Senneca O, Salatino P. Characterization of surface-oxides on char under periodically changing oxidation/desorption conditions. Renew Sustain Energy Rev [Internet]. 2020;137(March 2020):110453. Available from: https://doi.org/10.1016/j.rser.2020.110453
5. Coppola A, Esposito A, Montagnaro F, Iuliano M, Scala F, Salatino P. The combined effect of H2O and SO2 on CO2 uptake and sorbent attrition during fluidised bed calcium looping. Proc Combust Inst. 2019;37(4).
6. A. Coppola, R. Solimene, P. Bareschino, P. Salatino, *Mathematical modeling of a two-stage fuel reactor for chemical looping combustion with oxygen uncoupling of solid fuels*, Appl Energy **2015**, 157, 449.
7. C. Tregambi, F. Montagnaro, P. Salatino, R. Solimene, (2015) “A model of integrated calcium looping for CO2 capture and concentrated solar power”, Solar Energy, 120, 208-220
8. C. Tregambi, P. Salatino, R. Solimene, F. Montagnaro, (2018) “An experimental characterization of Calcium Looping integrated with concentrated solar power”, Chemical Engineering Journal, 120, 208-220
9. C. Tregambi, F. Di Lauro, F. Montagnaro, P. Salatino, R. Solimene, (2019) “110th anniversary: Calcium looping coupled with concentrated solar power for carbon capture and thermochemical energy storage”, Industrial and Engineering Chemistry Research 58(47), 21262-21272
10. C. Tregambi, S. Padula, M. Galbusieri, G. Coppola, F. Montagnaro, P. Salatino, M. Troiano, R. Solimene, *Directly irradiated fluidized bed reactor for thermochemical energy storage and solar fuels production*, Powder Technology**2020**, 366, 460
11. C. Tregambi, C. Bevilacqua, M. Troiano, R. Solimene, P. Salatino, *A novel autothermal fluidized bed reactor for concentrated solar thermal applications*, Chem Eng J **2020**, 398, 125702
12. Bareschino, P., Mancusi, E., Urciuolo, M., Paulillo, A., Chirone, R., Pepe, F., Life cycle assessment and feasibility analysis of a combined chemical looping combustion and power-to-methane system for CO2 capture and utilization (2020) 130, DOI: 10.1016/j.rser.2020.109962
13. Bareschino, P., Mancusi, E., Urciuolo, M., Coppola, A., Solimene, R., Pepe, F., Chirone, R., Salatino, P., Modelling of a combined biomass CLC combustion and renewable-energy-based methane production system for CO2 utilization, (2020) 373, pp. 421-432, DOI: 10.1016/j.powtec.2020.06.059
14. Bareschino, P., Mancusi, E., Pepe, F., Urciuolo, M., Coppola, A., Feasibility analysis of a combined chemical looping combustion and renewable-energy-based methane production system for co2 capture and utilization, (2020) 24 (6 part a), pp. 3613-3624, doi: 10.2298/tsci200328281b
15. G. Luciani, G. Landi, A. Aronne, A. Di Benedetto, *Partial substitution of B cation in* $La_{0.6}Sr_{0.4}MnO_3$ *perovskites: A promising strategy to improve the redox properties useful for solar thermochemical water and carbon dioxide splitting,* Sol Energy **2018,** 171, 1.
16. G. Luciani, G. Landi, C. Imparato, G. Vitiello, F.A. Deorsola, A. Di Benedetto, A. Aronne, *Improvement of splitting performance of* $Ce_{0.75}Zr_{0.25}O_2$ *material: Tuning bulk and surface properties by hydrothermal synthesis*, Int J Hydrogen Energy **2019**, 44, 17565
17. Peirce S., Russo M. E., Perfetto R., Capasso C., Rossi M., Fernandez-Lafuente R., Salatino P., Marzocchella A. (2018) ‘Kinetic characterization of carbonic anhydrase immobilized on magnetic nanoparticles as biocatalyst for CO2 capture’, *Biochemical Engineering Journal*. Elsevier B.V., 138, pp. 1–11. doi: 10.1016/j.bej.2018.06.017.
18. Peirce S., Russo M.E., Isticato R., Fernández-Lafuente R., Salatino P., Marzocchella A. (2017) ‘Structure and activity of magnetic cross-linked enzyme aggregates of bovine carbonic anhydrase as promoters of enzymatic CO2 capture’, *Biochemical Engineering Journal*. Elsevier B.V., 127, pp. 188–195. doi: 10.1016/j.bej.2017.08.014.
19. Bareschino, P. ; Urciuolo, M. ; Scherer, V …More, Effect of O-2/CO2 atmospheres on coal fragmentation, FUEL 267 (2020)
20. Senneca, Osvalda ; Ontyd, Christian ; Cerciello, Francesca …Extension of the Thermal Annealing Concepts Developed for Coal Combustion to Conversion of Lignocellulosic Biomass, ENERGY & FUELS 34 3661-3670 (2020)
21. Erans, M; .. ; Senneca, O.; Scala, F.; Anthony, EJ, Fragmentation of biomass-templated CaO-based pellets, FUEL 187 388-397 (2017) DOI: 10.1016/j.fuel.2016.09.061
22. P. Ammendola, F. Raganati, R. Chirone, Effect of operating conditions on the CO2 recovery from a fine activated carbon by means of TSA in a fluidized bed assisted by acoustic fields, Fuel Process. Technol. 134 (2015) 494–501. doi:10.1016/j.fuproc.2015.03.010.
23. P. Ammendola, F. Raganati, R. Chirone, CO2 adsorption on a fine activated carbon in a sound assisted fluidized bed: Thermodynamics and kinetics, Chem. Eng. J. 322 (2017) 302–313. doi:10.1016/j.cej.2017.04.037
24. F. Raganati, P. Ammendola, R. Chirone, CO2 adsorption on fine activated carbon in a sound assisted fluidized bed: Effect of sound intensity and frequency, CO2 partial pressure and fluidization velocity, Appl. Energy. 113 (2014) 1269–1282. doi:10.1016/j.apenergy.2013.08.073.
25. F. Raganati, P. Ammendola, R. Chirone, CO2 capture performances of fine solid sorbents in a sound-assisted fluidized bed, Powder Technol. 268 (2014) 347–356. doi:10.1016/j.powtec.2014.08.062.
26. F. Raganati, P. Ammendola, R. Chirone, On improving the CO2 recovery efficiency of a conventional TSA process in a sound assisted fluidized bed by separating heating and purging, Sep. Purif. Technol. 167 (2016) 24–31. doi:10.1016/j.seppur.2016.05.001.
27. F. Raganati, R. Chirone, P. Ammendola, CO 2 Capture by Temperature Swing Adsorption: Working Capacity As Affected by Temperature and CO 2 Partial Pressure, Ind. Eng. Chem. Res. 59 (2020) 3593–3605. doi:10.1021/acs.iecr.9b04901.
28. Raganati F.; Gargiulo V.; Ammendola P.; Alfe M.; Chirone R. CO2 capture performance of HKUST-1 in a sound assisted fluidized bed, Chemical Engineering Journal, 2014, Volume 239, pp:75-86 DOI: 10.1016/j.cej.2013.11.005
29. Gargiulo V.; Gomis-Berenguer A.; Giudicianni P.; Ania Conchi O.; Ragucci R.; Alfe M.Assessing the Potential of Biochars Prepared by Steam-Assisted Slow Pyrolysis for CO2 Adsorption and Separation, Energy & Fuels, 2018, Volume 32(10), pp:10218-10227DOI: 10.1021/acs.energyfuels.8b01058
30. Gargiulo V; Alfe M.; Raganati F.; Lisi L.; Chirone R.; Ammendola P. BTC-based metal-organic frameworks: Correlation between relevant structural features and CO2 adsorption performances, Fuel, 2018, Volume 222, pp:319-326 DOI: 10.1016/j.fuel.2018.02.093
31. Gargiulo V.; Alfe M.; Ammendola P.; Raganati F.; Chirone, R.CO2 sorption on surface-modified carbonaceous support: Probing the influence of the carbon black microporosity and surface polarity, Applied Surface Science, 2015, Volume 360, pp:329-337DOI: 10.1016/j.apsusc.2015.11.026
32. Alfe, M., Policicchio, A., Lisi, L., Gargiulo, V. Solid sorbents for CO2 and CH4 adsorption: The effect of metal organic framework hybridization with graphene-like layers on the gas sorption capacities at high pressure, Renewable and Sustainable Energy Reviews, 2021, 141,110816
33. Alfe M.; Ammendola P.; Gargiulo V.; Raganati F.; Chirone R. Magnetite loaded carbon fine particles as low-cost CO2 adsorbent in a sound assisted fluidized bed, Proceedings of The Combustion Institute, 2015, Volume 35, pp:2801-2809DOI: 10.1016/j.proci.2014.06.0
34. Lucio, B., Bayon, A., Olivares, R., (...), Vidal, J., González-Aguilar, J.Round robin test on enthalpies of redox materials for thermochemical heat storage: Perovskites2019 AIP Conference Proceedings 2126, 210001
35. Holland, T., Fletcher, T.H., Senneca, O. , Review of Carbonaceous Annealing Effects on O2 and CO2 Coal Reactivity, Energy & Fuels 2019, 33, 11, 10415-10434
36. O.Senneca, C.Ontyd, F.Cerciello, M.Schiemann, and V.Scherer Extension of the Thermal Annealing Concepts Developed for Coal Combustion to Conversion of Lignocellulosic Biomass. Energy Fuels 2020, 34, 3, 3661–3670, DOI: 10.1021/acs.energyfuels.9b03172