Carbon capture and re-use: technological and other challenges

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Science and technology Faculty of Settat, Morocco

CHEMICAL ENGINEERING

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University of Liège - ULiège

- Liège: 3rd urban area in Belgium
  - ~750 000 inh.
- ULiège, a pluralist university
  - 11 faculties, 23 000+ students, 122 Nationalities
  - 38 bachelor study lines, more than 200 master study lines

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Outline

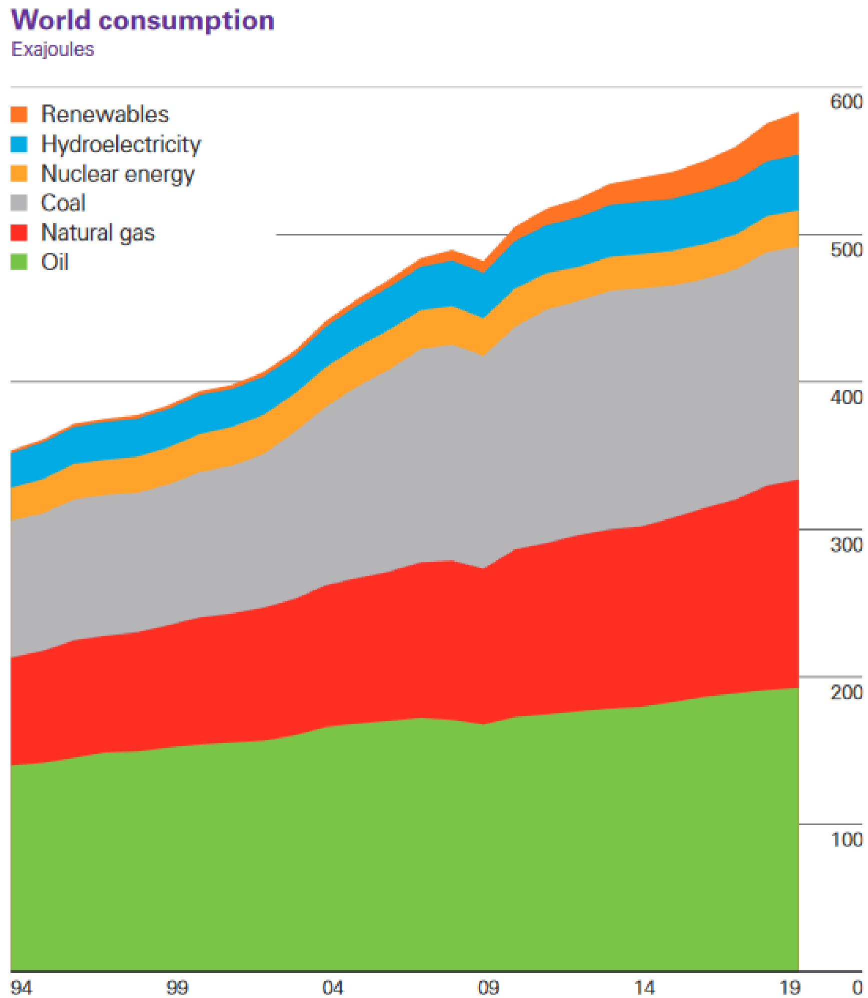
1. How big is the CO_2 challenge?
2. Carbon Capture
3. Storage and/or re-use?
4. Perspectives

The energy ~~transition~~ revolution is on-going…

It has to address 2 objectives in contradiction:

- Limit GHG emissions
- Meet the worldwide increasing energy demand!

Meeting the increasing demand is already a challenge in itself!



5%

6.5%

4.3%

27%

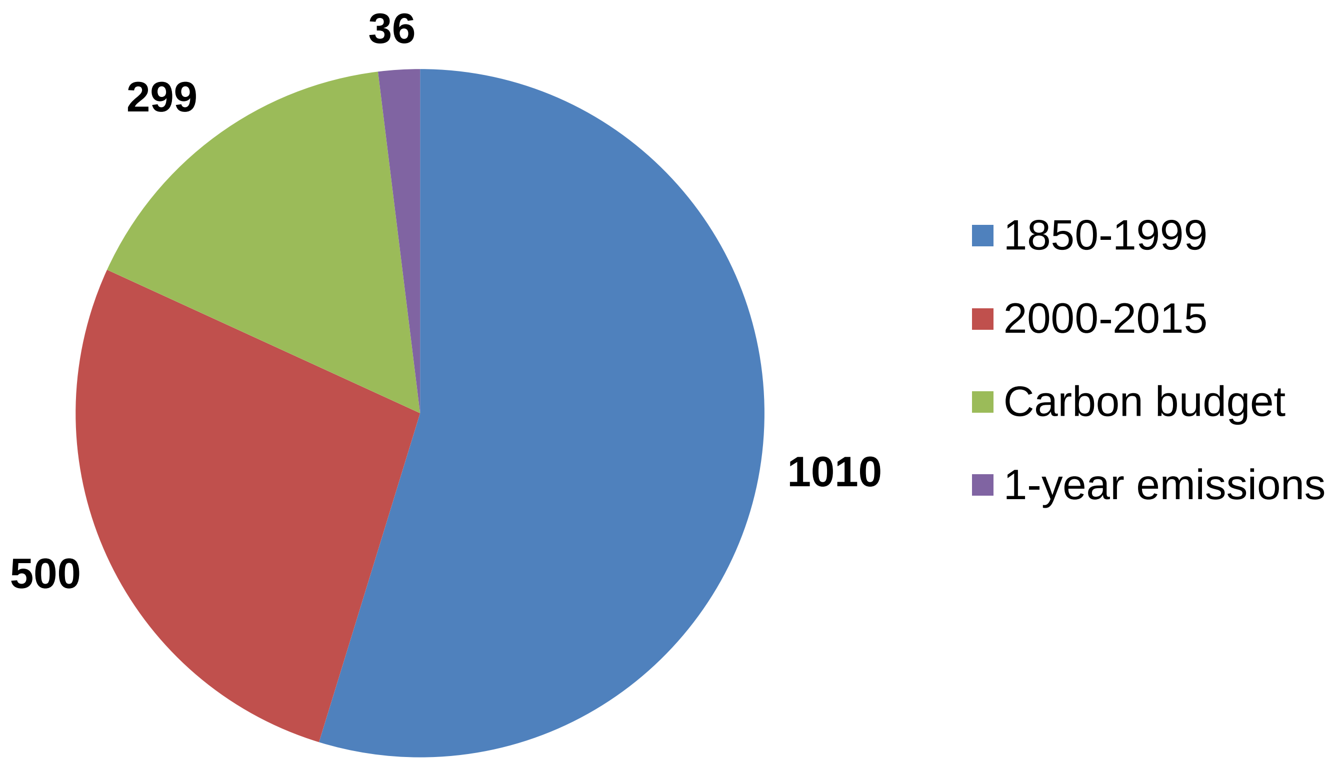
24.2%

33%

BP Statistical Review of World Energy 2020.

CO_2 Budget

Budget by 2050 for having 80% chances to stay below 2°C



Note: Values in Gt CO_2 eq

IPCC, SR15 (2018).

At european level…

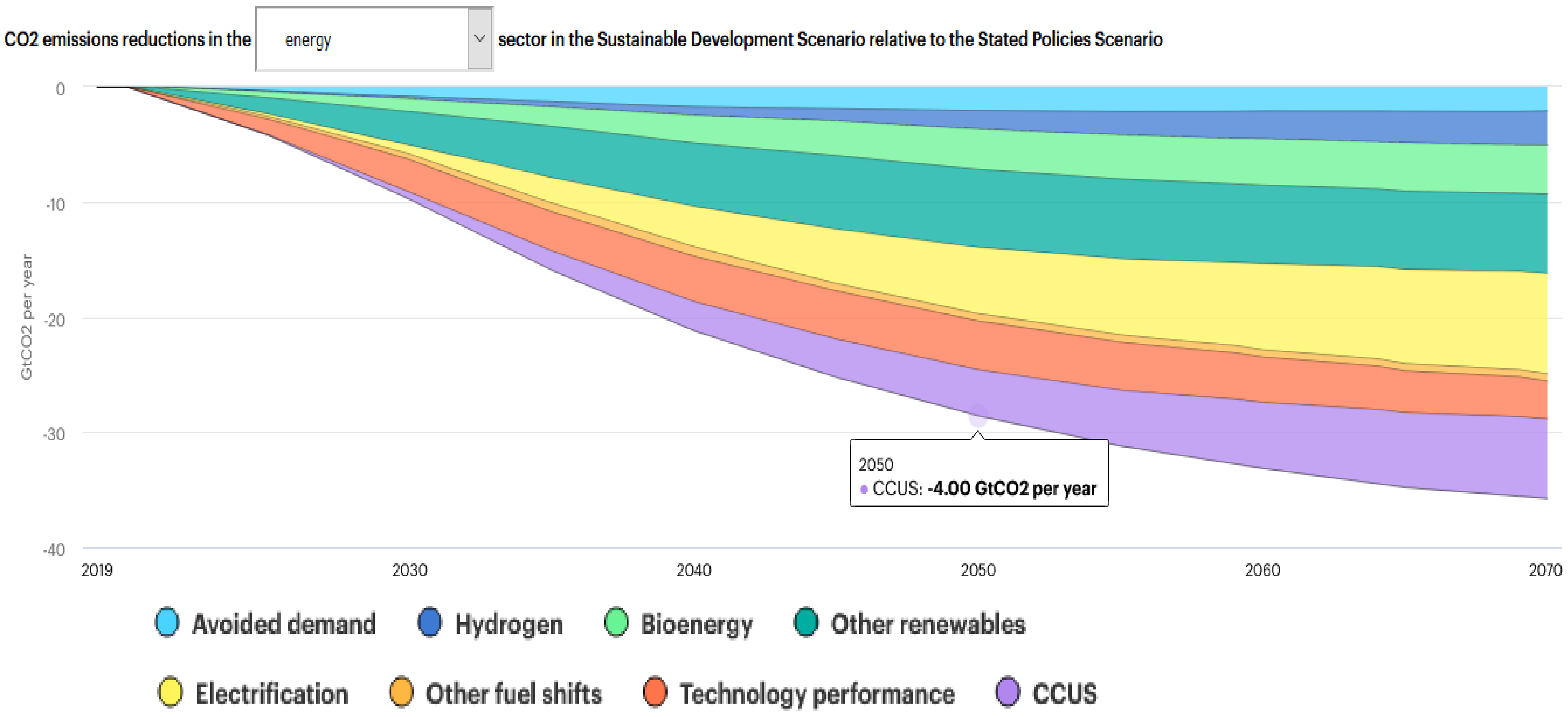
The EU Green Deal

- Carbon neutrality by 2050
- - 55% CO_2 by 2030

The Economist

CCUS forecasts

- CCUS = Carbon Capture, Utilization and Storage



IEA, 2020. https://www.iea.org/reports/energy-technology-perspectives-2020

2. CO_2 Capture

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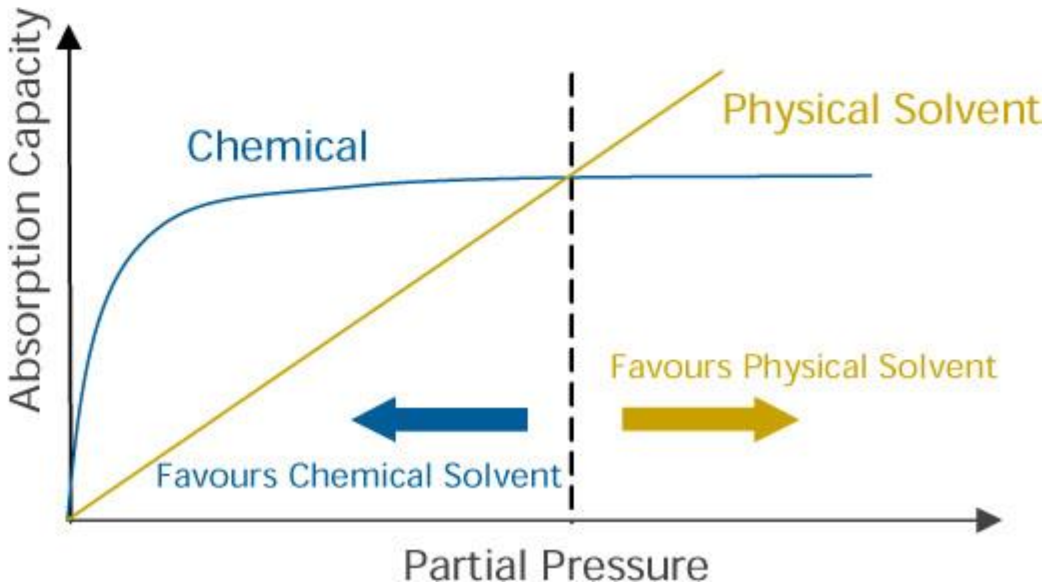
CO_2 capture

- It's a question of fluid separation!
  - Sources usually contain CO_2, N_2, H_2O, H_2, CH_4, O_2 …
  - CO_2 concentration varies between 0.04% and almost 100%
  - Mature (exist for >50 years) & flexible, but costly!

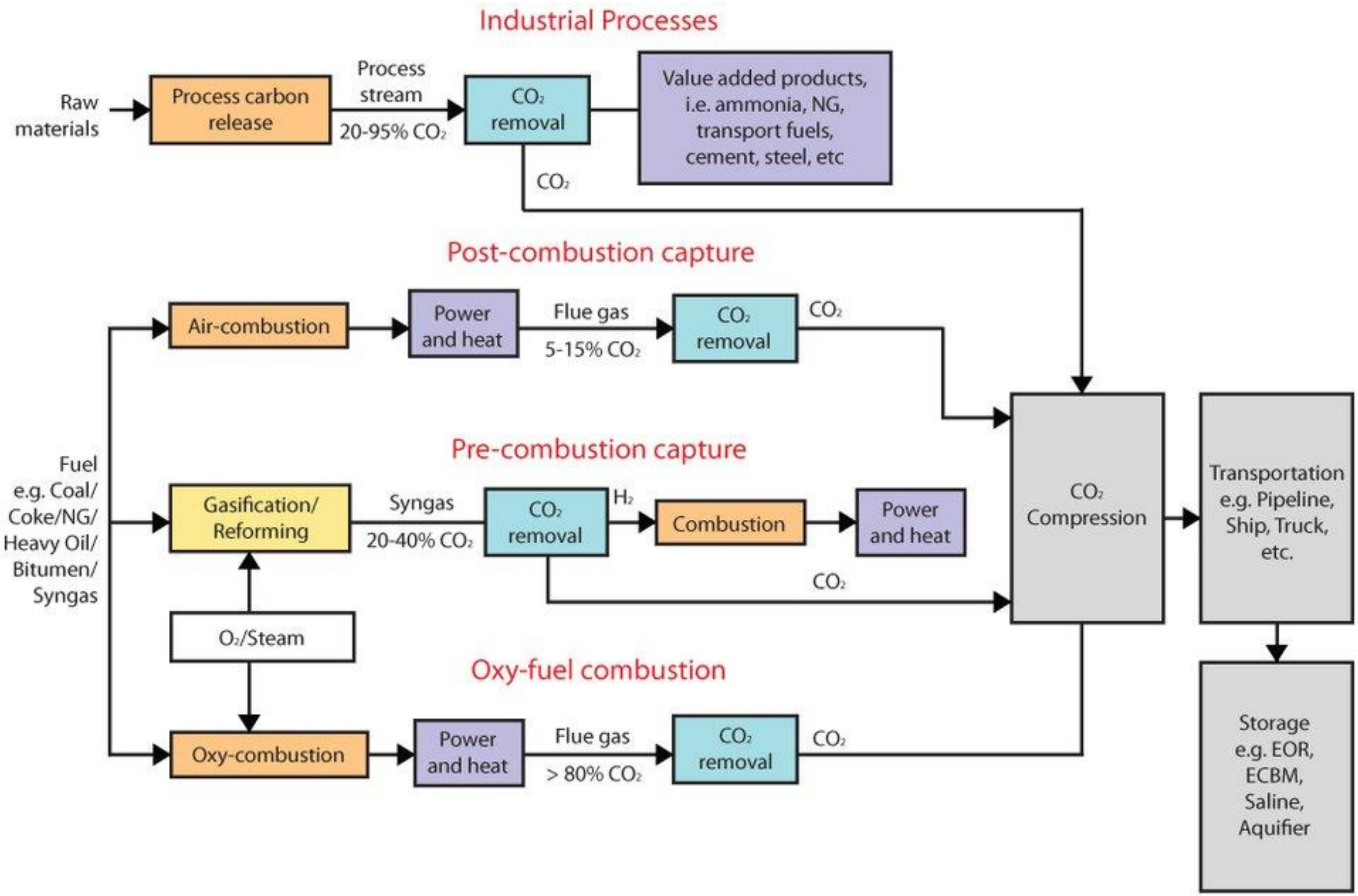
CO_2 separation technologies

- Avoid fluid mixtures
- Absorption
  - Physical
  - Chemical
- Adsorption
- Membranes
- Cryogenic separation
- Others…



Threshold value ~15 vol-% in flue gas,
or 4 bar of P_CO2

CO_2 capture configurations



CO_2 capture benchmark – Power sector

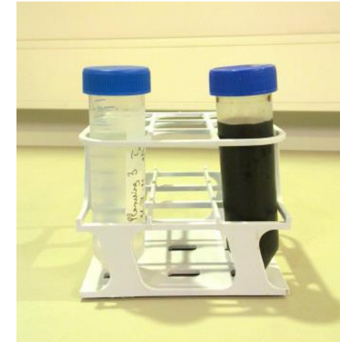
	Ultra-supercritical coal-fired power plant			Natural-gas combined-cycle power plant		
	W/O PCC	MEA	PZ/AMP	W/O PCC	MEA	PZ/AMP
Technical performance						
Gross power output (MW)	900	900	900	890	890	890
Auxiliary power (MW)	83	266.1	215.6	12	161.8	128.2
Net power output (MW)	817	633.9	684.4	878	728.2	761.9
Net plant higher heating value efficiency (%)	42.5	32.97	35.59	52.66	43.91	45.94
Net plant lower heating value efficiency (%)	44.4	34.48	37.23	58.25	48.57	50.82
CO_2 generation (t/h)	604	604	603.3	310	310	310
CO_2 emission (t/h)	604	61	59.1	310	31	31
CO_2 emission (t/MWh)	0.739	0.095	0.084	0.353	0.042	0.040
CO_2 capture (t/h)	0	543	544	0	279	279
Equivalent energy consumption (MWh/tCO_2)	–	0.337	0.244	–	0.506	0.423
Economic performance						
Total capital requirement (million €)	1342.8	1681.1	1659.5	835.7	1172.8	1166.3
Specific capital requirement (€/kW)	1647	2654	2424	939	1611	1531
Fixed operations & maintenance (O&M) (million €)	37.7	46.3	45.9	29.2	39.7	39.5
Variable O&M (million €)	7.54	20.1	17.8	3.41	11.9	9.1
LCOE (€/MWh)	51.6	87.0	79.5	52.9	77.6	73.8
CO_2 avoided cost (€/tCO_2)	–	55.0	42.8	–	79.3	67.1

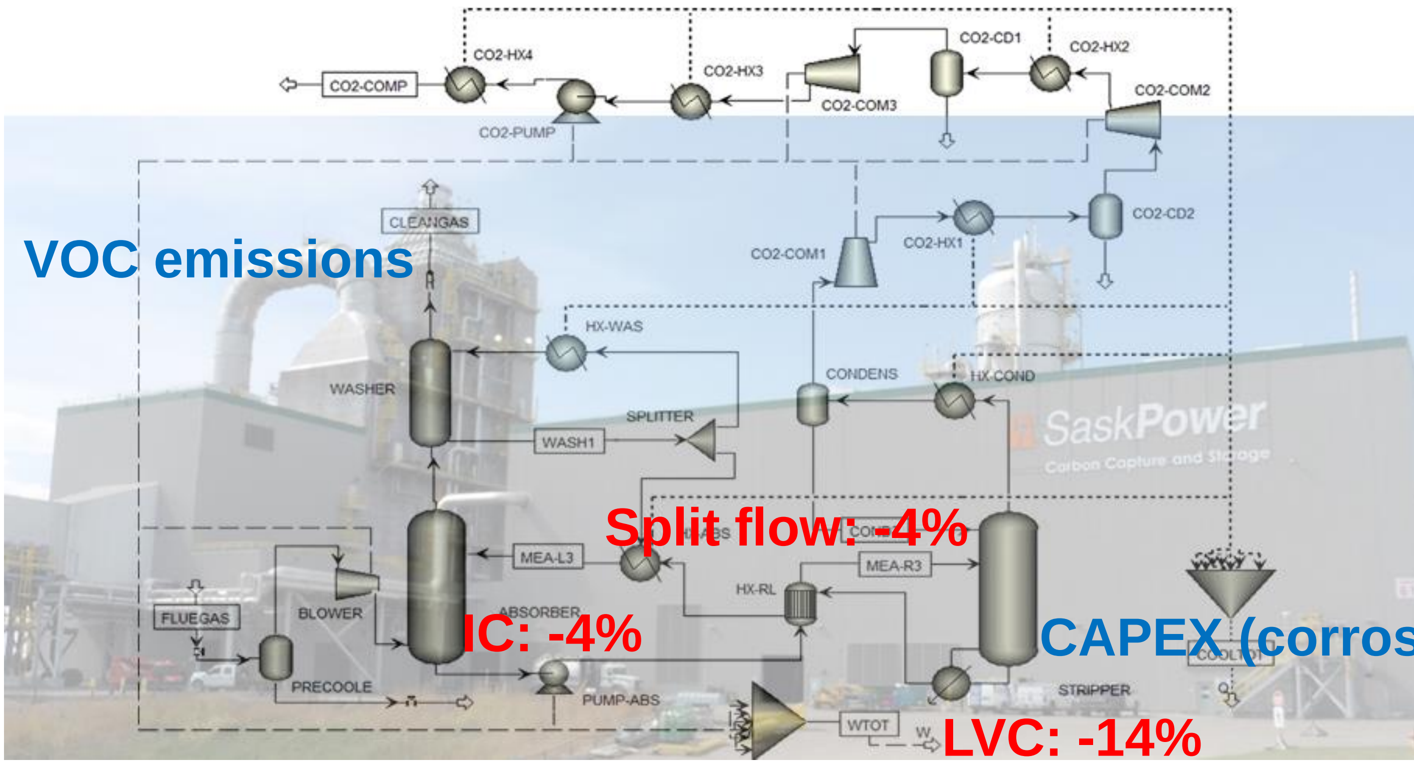
W/O PCC = without post-combustion capture

IEAGHG, 2019. Further assessment of emerging CO_2 capture technologies for the power sector and their potential to reduce costs

Post-combustion CO_2 capture

- Modeling and optimization of processes
- Stability of chemical solvents





OPEX: viscosity, altered properties…

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Léonard et al., 2014&2015. DOI:10.1021/ie5036572, DOI: 10.1016/j.compchemeng.2015.05.003

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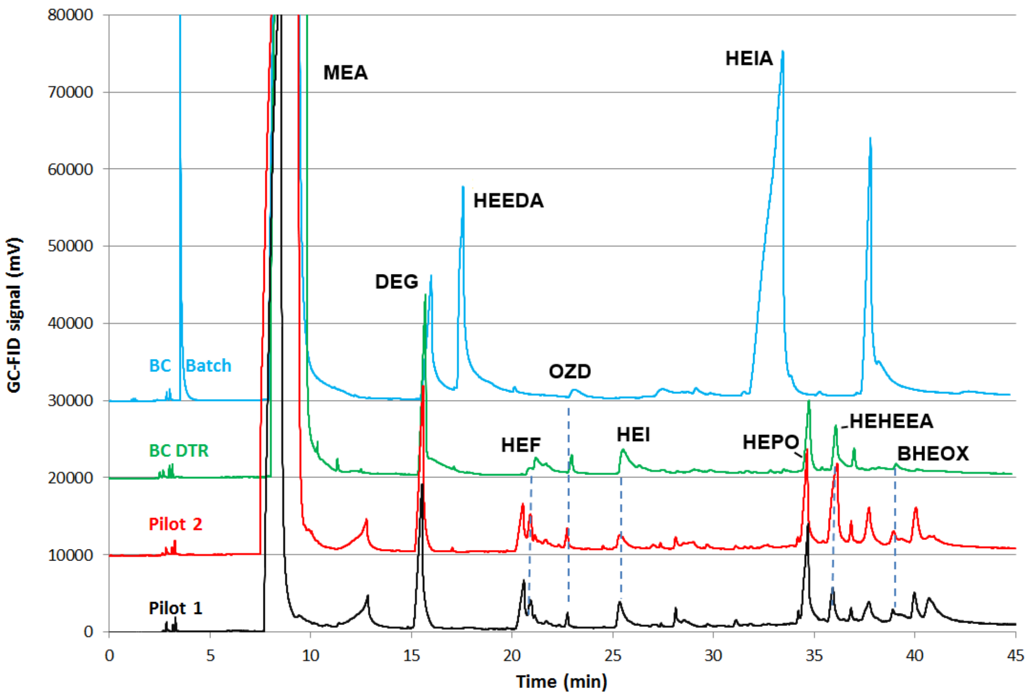
Post-combustion CO_2 capture

Objective: Representativity of accelerated degradation versus industrial degradation



=> 21% MEA loss after 7 days vs. 4% loss in 45 days

Léonard et al., 2014. Int. J. Greenhouse Gas Control 30, 171.
DOI: 10.1016/j.ijggc.2014.09.014

Post-combustion CO_2 capture

Leads to a kinetic model of solvent degradation:

=> 2 main degradation mechanisms

=> Equations balanced based on the observed proportion of degradation products

Oxidative degradation

$$r = 5.35\ 10^5 . e^{-\frac{41\ 730}{8.314\ T}} . [O_2]^{1.46}$$

$$MEA + 1,3\ O_2$$
$$\downarrow$$
$$0,6\ NH_3 + 0,1\ HEI + 0,1\ HEPO + 0,1\ HCOOH + 0,8\ CO_2 + 1,5\ H_2O$$

Thermal degradation with CO_2

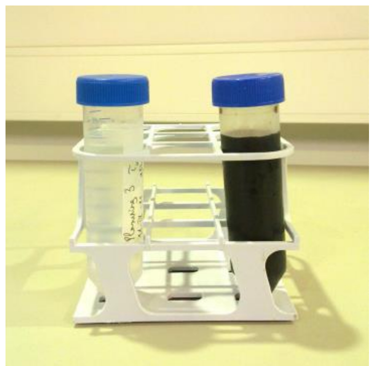
$$MEA + 0,5\ CO_2 \rightarrow 0,5\ HEIA + H_2O$$

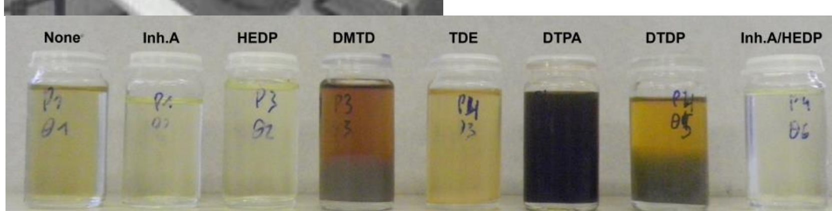
$$r = 6.27 . 10^{11} . e^{-\frac{143\ 106}{8.314\ T}} . [CO_2]^{0.9}$$

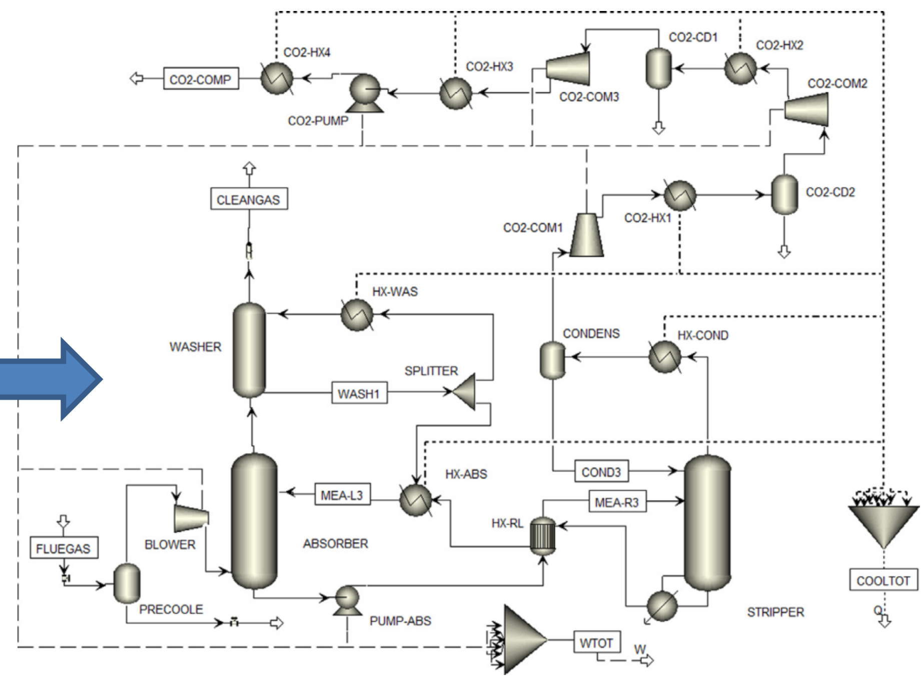
Post-combustion CO_2 capture

- Include degradation model included into process model
  - Steady-state simulation, closed solvent loop
  - Additional equations in the column rate-based models

=> predicts degradation in the capture process (80 vs 300 g MEA/tCO_2)





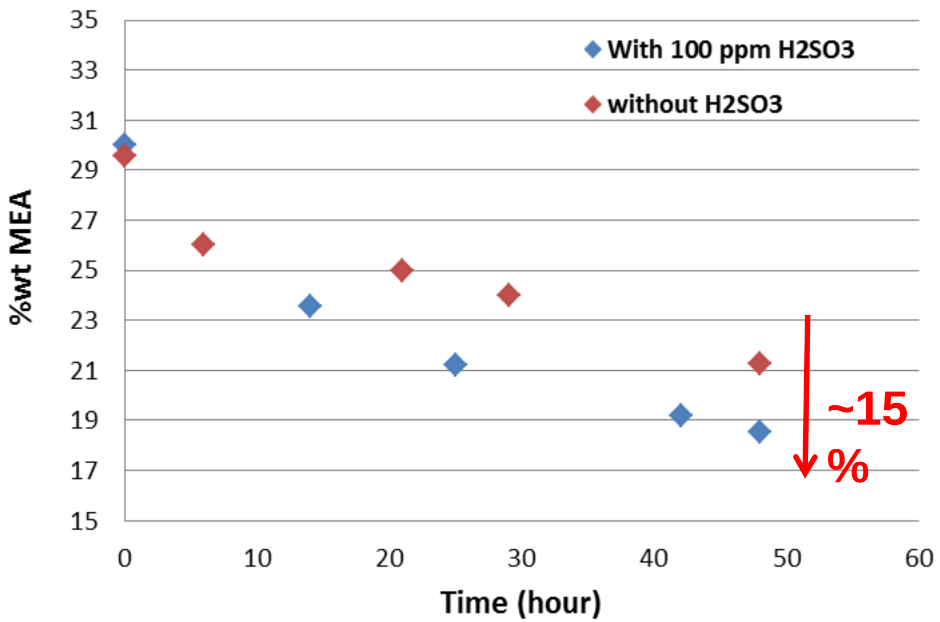


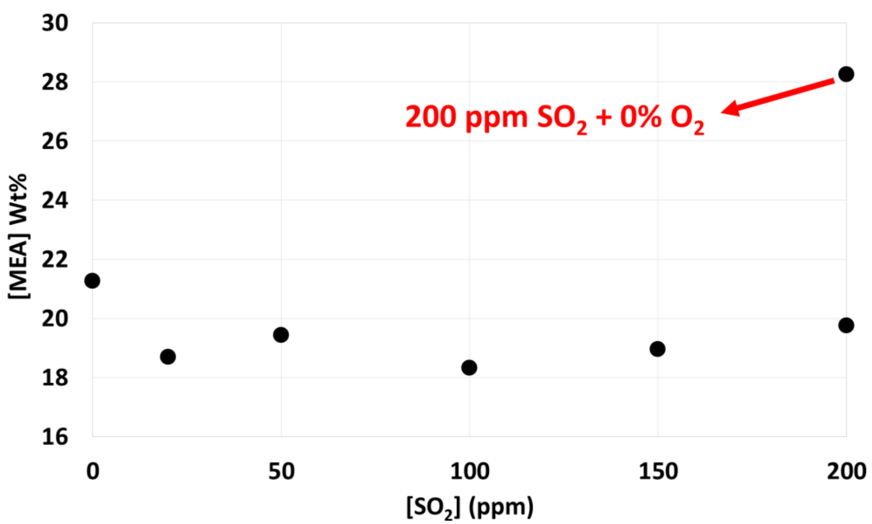
DOI: 10.1016/j.compchemeng.2015.05.003

DOI:10.1021/ie5036572

Post-combustion CO_2 capture

- Further work on amine degradation
  - Experimental study of other solvents (MDEA)
  - Kinetic modeling of mass-transfer
  - SO_2-induced degradation



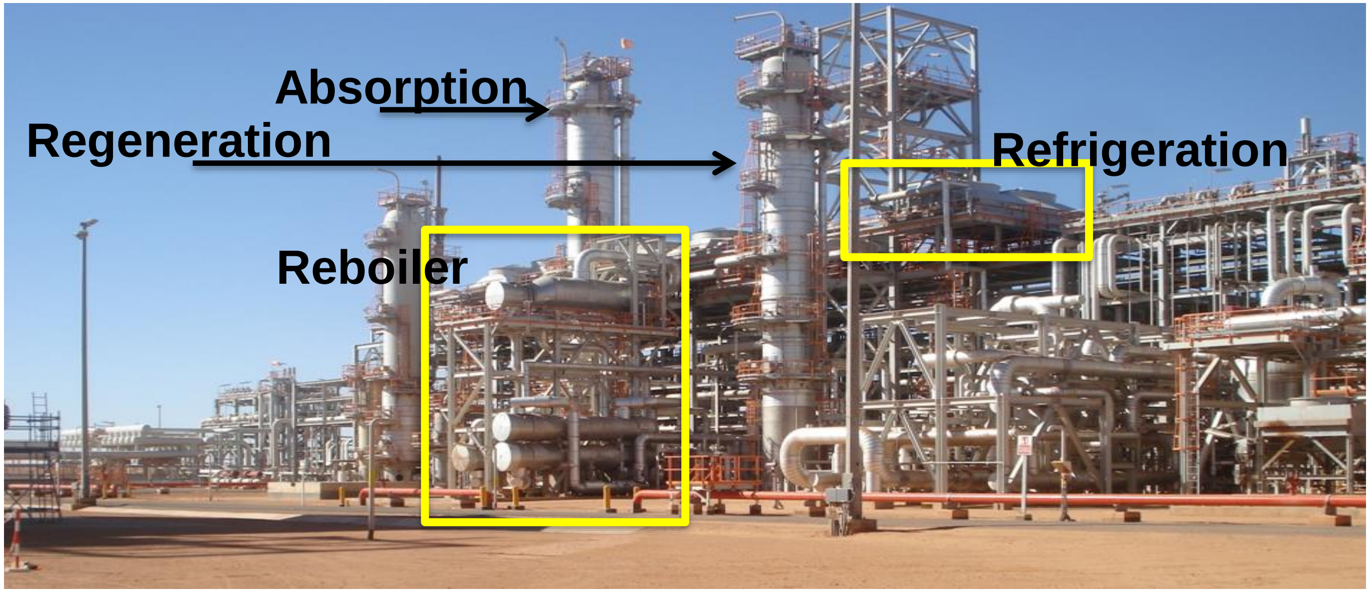


Benkoussas et al., 2018. SO2 effect on oxidative degradation of monoethanolamine for post combustion CO2 capture. GHGT-14

Pre-combustion capture

Remove C from the fuel => Natural gas sweetening

- Conventional process: absorption with solvents
- From 80 to 2 vol%; down to 50 ppm if liquefaction

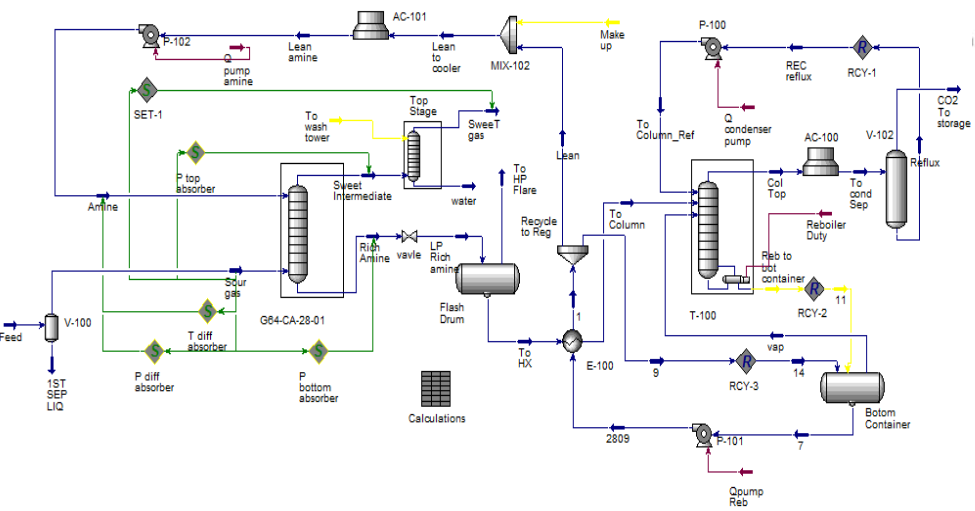


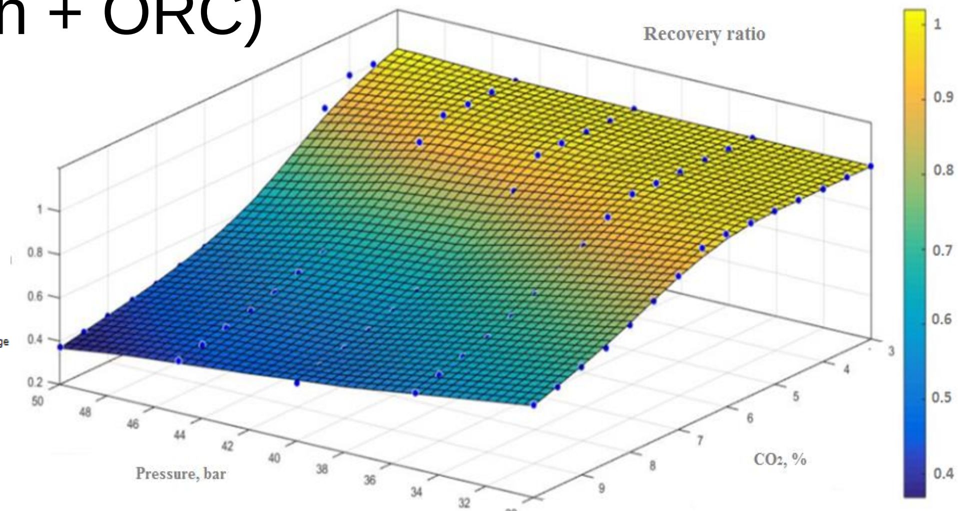
- Current PhD thesis running: Multi-objective optimization of sour natural gas sweetening processes (MDEA/DEA)
  - M. Berchiche, cotutelle with Algerian industry

Picture: Berchiche M. (2017).

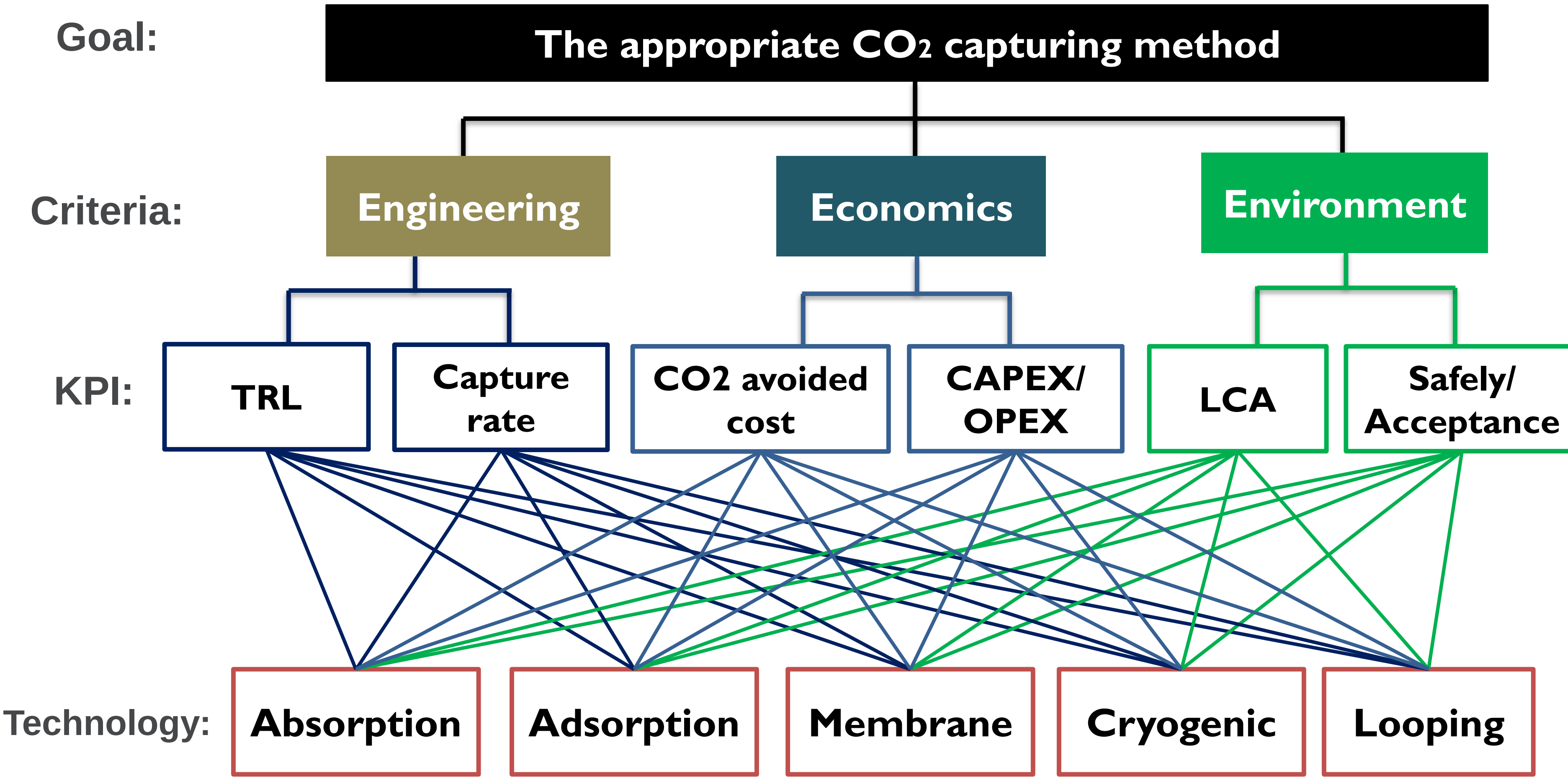
Pre-combustion capture

- Process multi-objective optimization
  - CO_2 capture for Natural gas sweetening operations
  - Energy integration (Pinch + ORC)
  - BTEX emissions + LCA

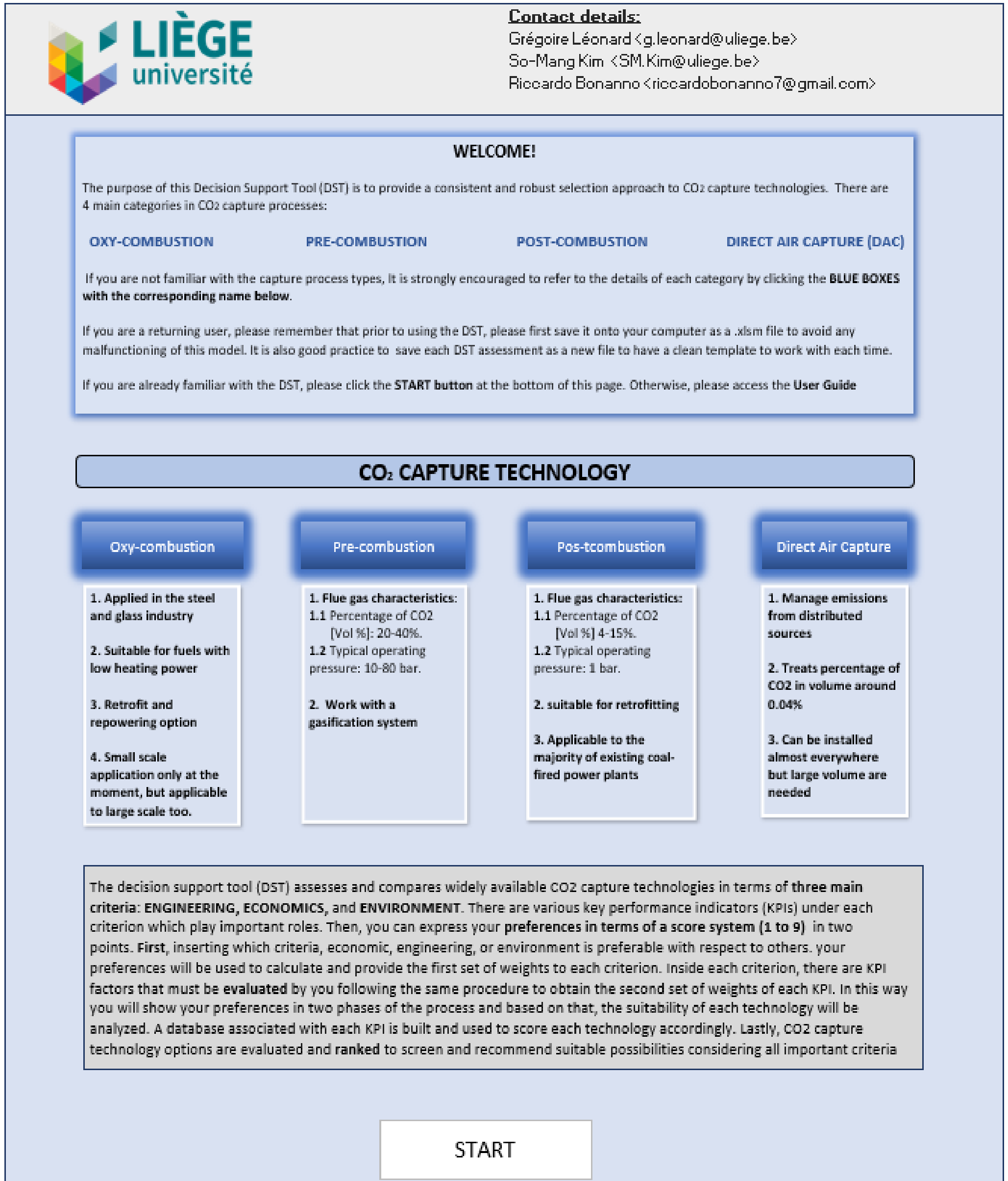




PROCURA ETF: Decision support tool



Decision-support tool



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WELCOME!

The purpose of this Decision Support Tool (DST) is to provide a consistent and robust selection approach to CO_2 capture technologies. There are 4 main categories in CO_2 capture processes:

OXY-COMBUSTION | PRE-COMBUSTION | POST-COMBUSTION | DIRECT AIR CAPTURE (DAC)

If you are not familiar with the capture process types, It is strongly encouraged to refer to the details of each category by clicking the **BLUE BOXES with the corresponding name below**.

If you are a returning user, please remember that prior to using the DST, please first save it onto your computer as a .xlsm file to avoid any malfunctioning of this model. It is also good practice to save each DST assessment as a new file to have a clean template to work with each time.

If you are already familiar with the DST, please click the **START button** at the bottom of this page. Otherwise, please access the **User Guide**

CO_2 CAPTURE TECHNOLOGY

Oxy-combustion	Pre-combustion	Pos-tcombustion	Direct Air Capture
1. Applied in the steel and glass industry 2. Suitable for fuels with low heating power 3. Retrofit and repowering option 4. Small scale application only at the moment, but applicable to large scale too.	1. Flue gas characteristics: 1.1 Percentage of CO2 [Vol %]: 20-40%. 1.2 Typical operating pressure: 10-80 bar. 2. Work with a gasification system	1. Flue gas characteristics: 1.1 Percentage of CO2 [Vol %] 4-15%. 1.2 Typical operating pressure: 1 bar. 2. suitable for retrofitting 3. Applicable to the majority of existing coal-fired power plants	1. Manage emissions from distributed sources 2. Treats percentage of CO2 in volume around 0.04% 3. Can be installed almost everywhere but large volume are needed

The decision support tool (DST) assesses and compares widely available CO2 capture technologies in terms of **three main criteria: ENGINEERING, ECONOMICS**, and **ENVIRONMENT**. There are various key performance indicators (KPIs) under each criterion which play important roles. Then, you can express your **preferences in terms of a score system (1 to 9)** in two points. **First**, inserting which criteria, economic, engineering, or environment is preferable with respect to others. your preferences will be used to calculate and provide the first set of weights to each criterion. Inside each criterion, there are KPI factors that must be **evaluated** by you following the same procedure to obtain the second set of weights of each KPI. In this way you will show your preferences in two phases of the process and based on that, the suitability of each technology will be analyzed. A database associated with each KPI is built and used to score each technology accordingly. Lastly, CO2 capture technology options are evaluated and **ranked** to screen and recommend suitable possibilities considering all important criteria

START

Decision-support tool

- Following the Analytical Hierarchy Process

4. Analytical Hierarchy Process - KPIs for Environment criteria

Table 4.1

Environment																		
Please rate importances of these KPIs																		
(j - k)																		
Criterion j	Extreme favors		Very Strong favors		Strongly favors		Slightly favors		Equal		Slightly favors		Strongly favors		Very Strong favors		Extreme favors	Criterion k
(LCA score	9	8	7	6	5	4	3	2	1	2	(●) 3	4	5	6	7	8	9	- Safety Issue)
(LCA score	9	8	7	6	5	4	3	2	(●) 1	2	3	4	5	6	7	8	9	- Public acceptance)
(Safety Issue	9	8	7	6	5	4	3	(●) 2	1	2	3	4	5	6	7	8	9	- Public acceptance)

Table 4.2

KPIs	KPIs Weight
LCA score	0.210
Safety Issue	0.550
Public acceptance	0.240

Inconsistency	0.016

Total Inconsistency	0.074

If you are satisfied with the criteria weights and KPI weights of each criterion, please click the **'Go to Results' button** to display analyzed results. If you wish to re-evaluate your preferences, please click the **'Back to Top' button** to scroll up and you may repeat the rating process.

As explained in the AHP theory page, **Pairwise matrices** can be displayed when you click the 'Show Pairwise Matrix' button provided below.

Home | Back to 'Top' | Show Pairwise Matrix | Go to 'Results'

Decision-support tool

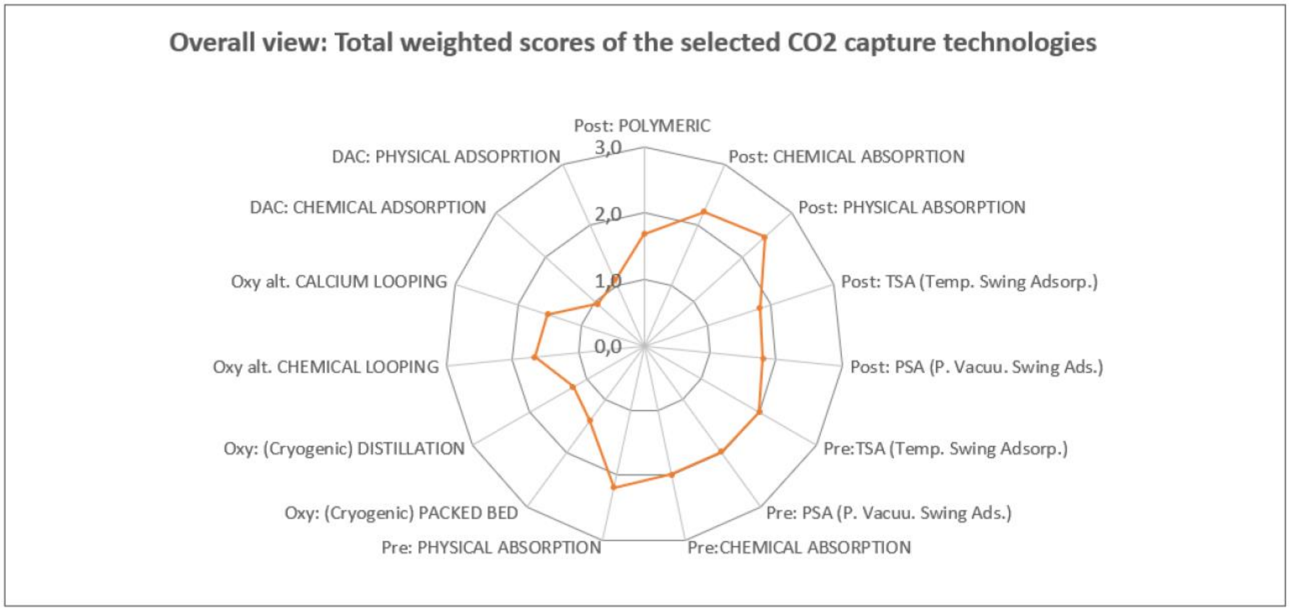
- Results display

*Please select combustion methods/technology options you wish to display

☑ Post-combustion ☑ Pre-combustion ☑ Oxy-combustion ☑ DAC

*Please select a chart type to display

Bar graph | Radar chart



If you are **NOT** satisfied with the recommendations, kindly go back to the AHP step by clicking the '**Back to AHP**' button below.
If you wish to look at the appendix of this analysis, please click '**Appendix**' button at the end of this page.

Direct Air Capture (DAC)

- Negative CO_2 emissions
  - BECCS or DAC

Elon Musk promet 100 millions de dollars à celui qui pourra l'aider à résoudre ce problème

Elon Musk @elonmusk · 22 janv. 2021
Am donating $100M towards a prize for best carbon capture technology

Elon Musk
@elonmusk

Details next week

12:08 AM · 22 janv. 2021

96,8 k 8,9 k Copier le lien du Tweet

K.S. Lackner, CNCE ASU, 2017.
https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html?smid=em-share

Direct Air Capture

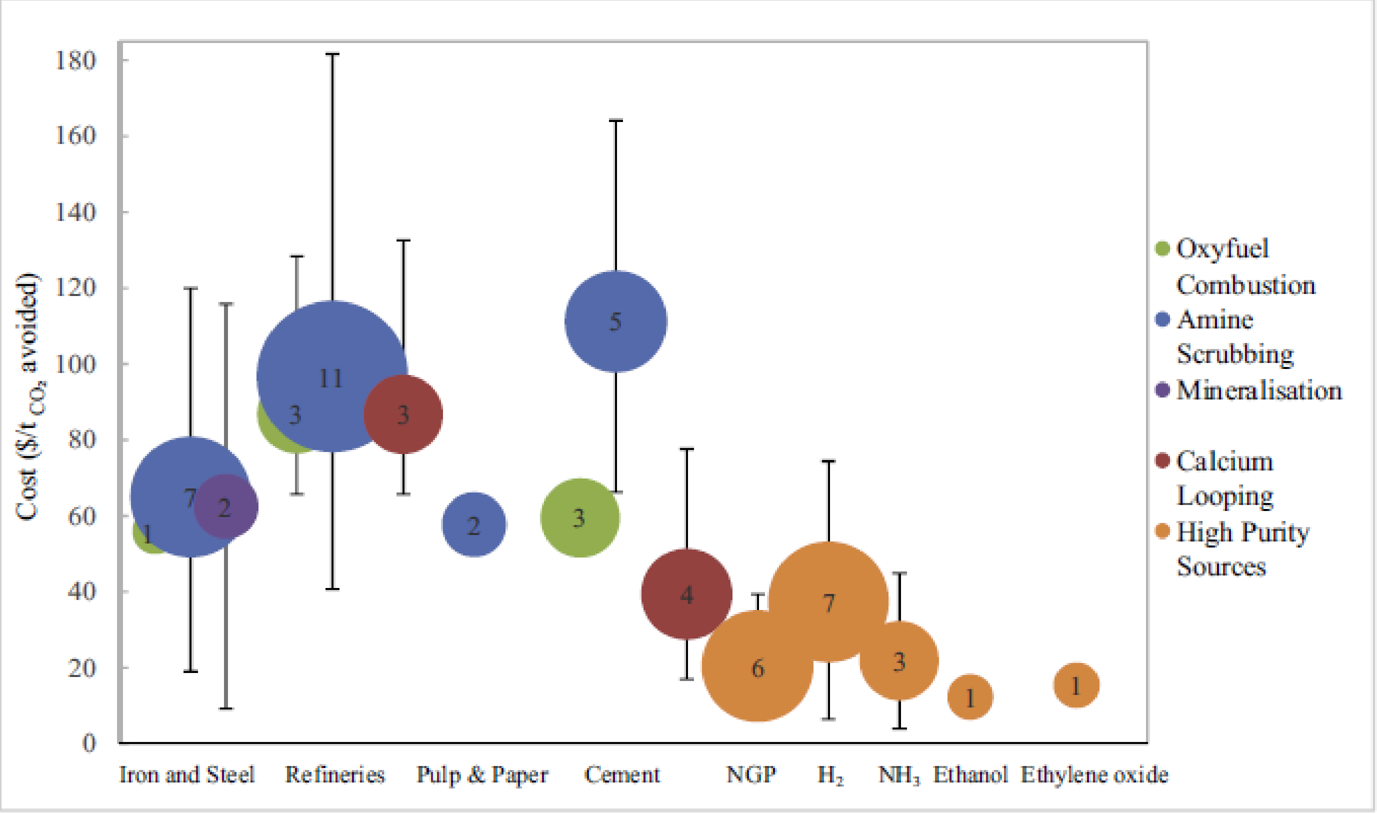
- Motivations
  - Address non-concentrated CO_2 emissions (410 ppm in the air)
  - Close the carbon cycle of synthetic fuels
  - Reduce the need for transporting CO_2
    - No Nimby effect, you can go wherever you want, incl. close to use or storage sites
  - Long-term considerations: remove C from the atmosphere

  - Adsorption / Absorption
  - Temperature-swing, moisture-swing
    - Sorbent regeneration has similar cost whatever the CO_2 concentration in the gas stream
  - Expected costs vary between 100 and 800 $/ton

www.pnas.org/cgi/doi/10.1073/pnas.1108765109
DOI: 10.1140/epjst/e2009-01150-3

Cost of CO_2 capture

- Estimated cost for different industries
  - Opex ~75% of the cost



Leeson et al, 2017, DOI: 10.1016/j.ijggc.2017.03.020
Abu-Zahra M., 2009. Carbon dioxide capture from flue gas. PhD Thesis at the Technical University of Delft, The Netherlands

CO_2 market

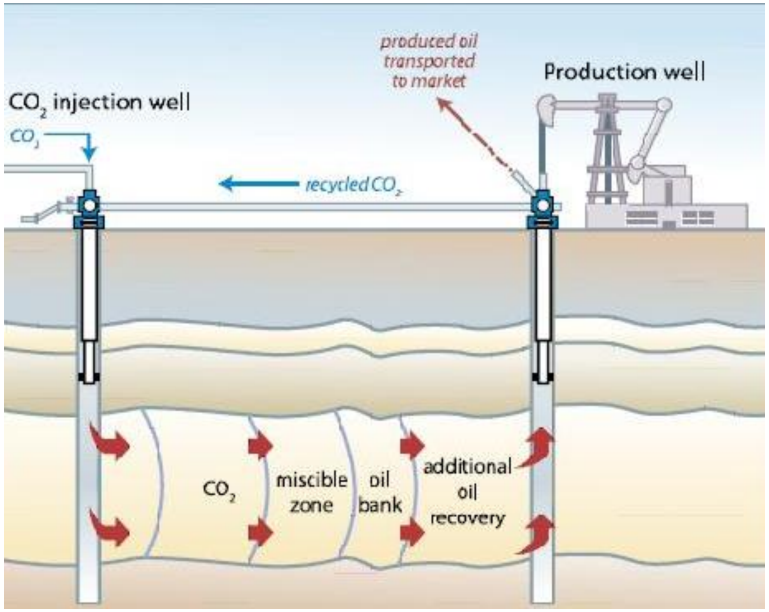
- European Emissions Trading System (ETS)
- CO_2 price now reaches > 50 €/t!

https://ember-climate.org/data/carbon-price-viewer/

3. Storage and/or re-use of CO_2 ?

Storage is state-of-the-art

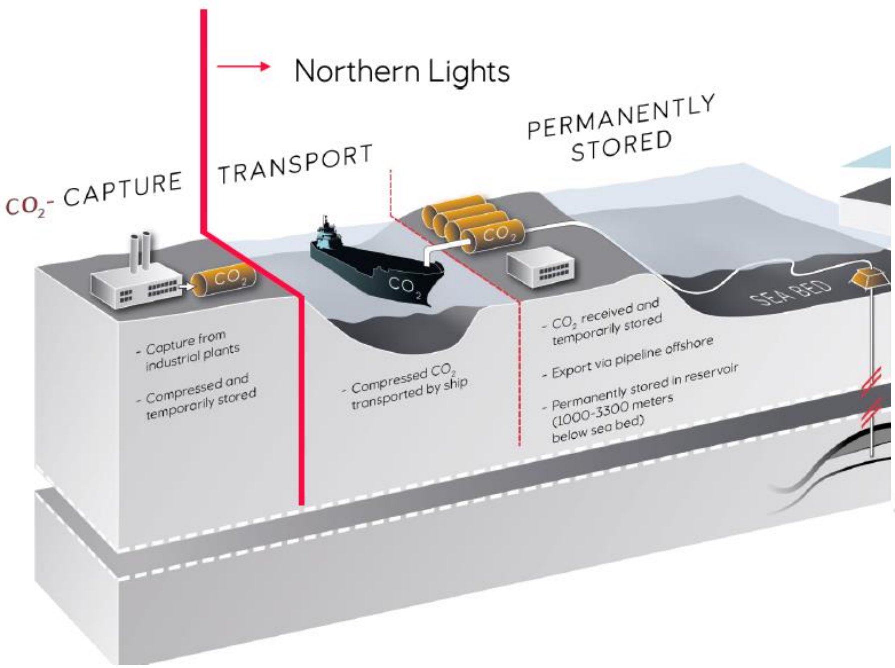
- Potential for storage exceeds by far the needs
  - 5000 – 25 000 $GtCO_2$ vs. ~ 40 $GtCO_2$/y
  - Pure storage: ~ 5 Mtpa
  - Capture and EOR: ~ 30 Mtpa in 2016
- Storage costs ~2-15 USD/t, large infrastructure costs needed!



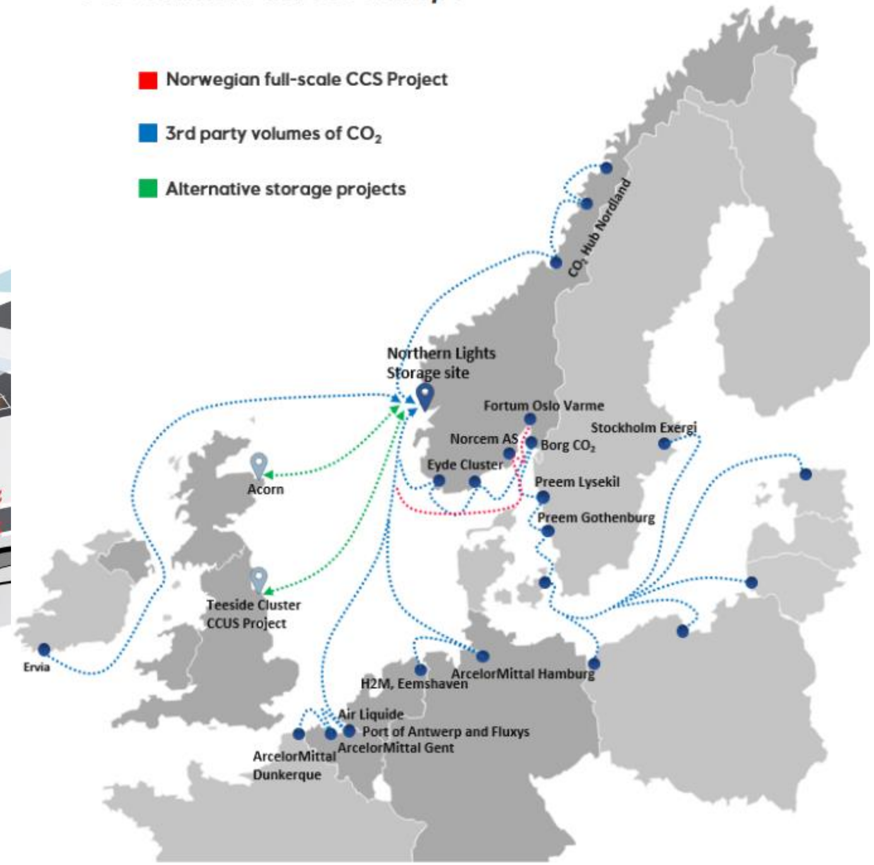
Global CCS Institute 2017
doi: 10.3389/fclim.2019.00009

Northern lights

- Norway, off-shore field, saline aquifer
- Up to 5 Mt CO_2/y

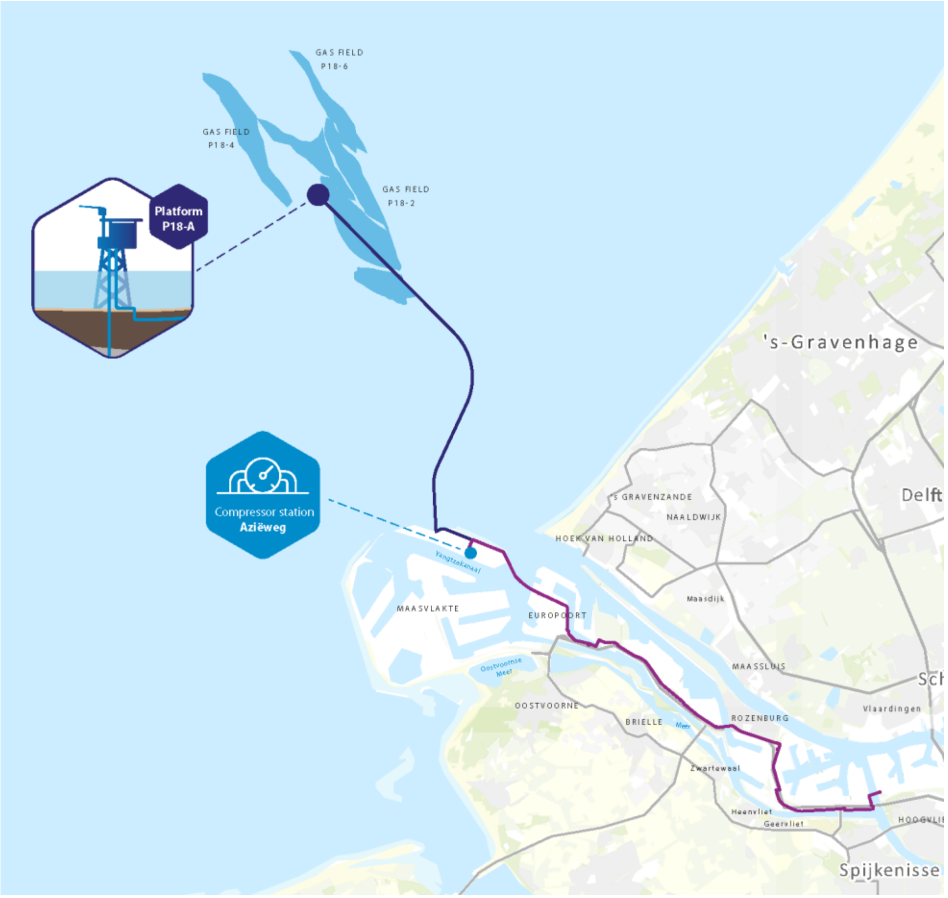


- A ship based solution means access for CO2 emitters across Europe



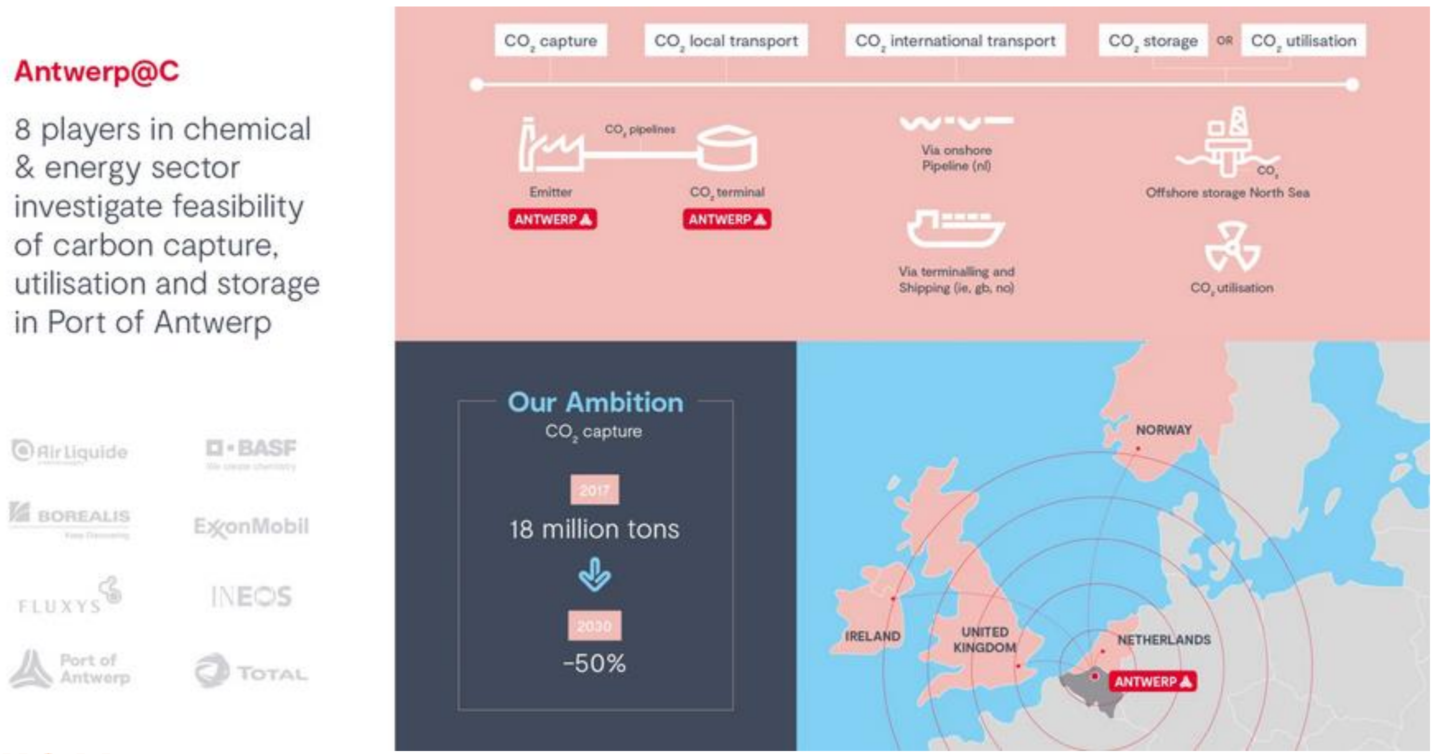
Porthos

- Rotterdam, off-shore depleted gas field
- 2.5 Mt CO_2/y



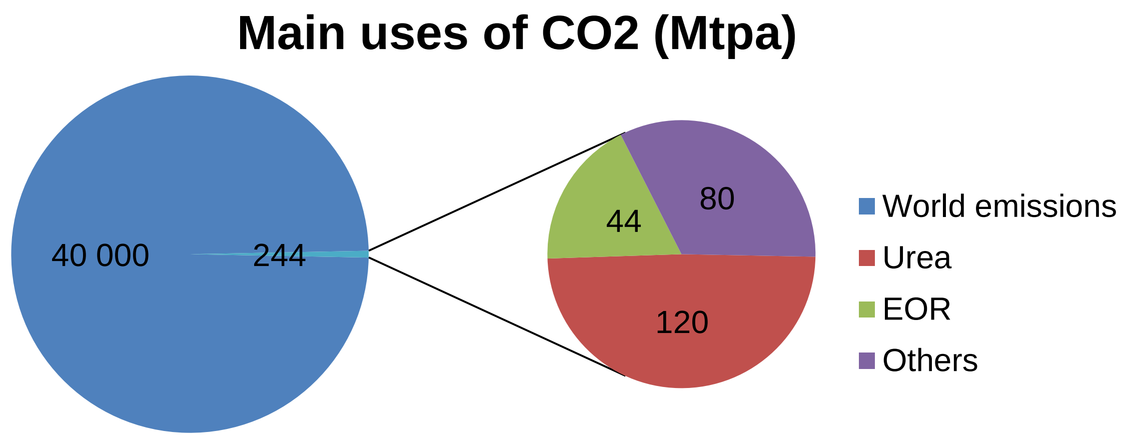
Antwerp@C

- No storage capacity offshore of Belgium
  - Antwerp@C studies the infrastructure for connection to Norway and The Netherlands
  - => Pipelines, intermediate storage, liquefaction unit…



CO_2, waste or feedstock?

- Sequestration or re-use?
  - Consider CO_2 as a resource in a Carbon-based society, not as waste



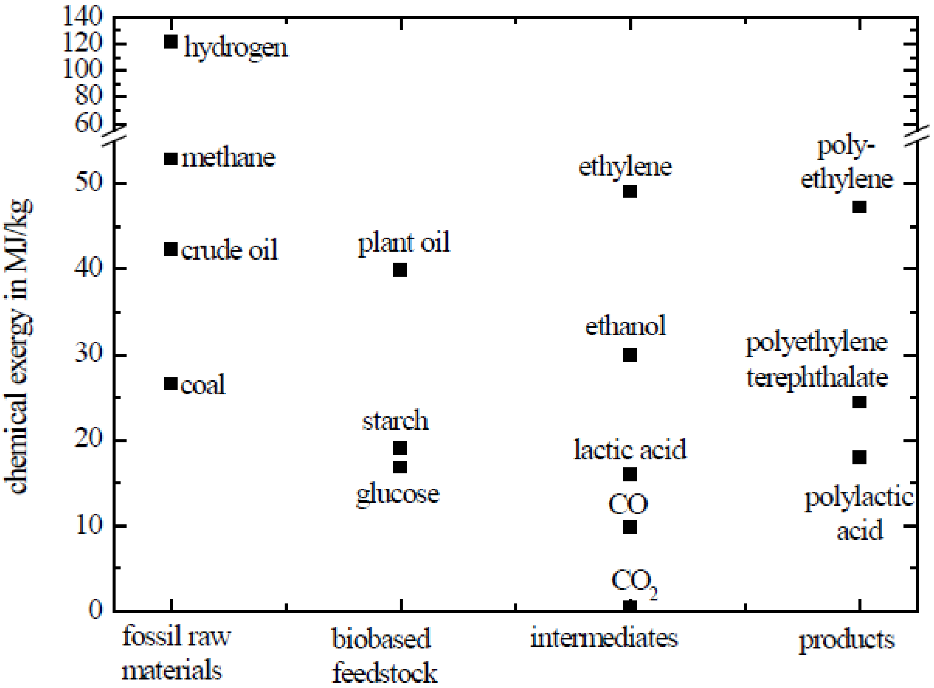
- CO_2 re-use potential up to ~ 4 – 18 Gtpa

- So far, sources for CO_2 are high-purity ones
  - Industrial (Ethanol, Ammonia, Ethylene, Natural gas…)
  - Natural (Dome)

Global CCS Institute. Global Status of CCS 2016: Summary Report.
Koytsumpa et al, 2016. https://doi.org/10.1016/j.supflu.2017.07.029

Main CO_2 re-use pathways

- Direct use, no transformation
- Biological transformation
- Chemical transformation
  - To lower energy state
    - Carbonatation
  - To higher energy state
    - Fuels
    - Chemicals
    - …



=> At large scale, need to make sure that energy comes from renewables!

CHEMICAL ENGINEERING

Frenzel et al, 2014. Doi:10.3390/polym6020327

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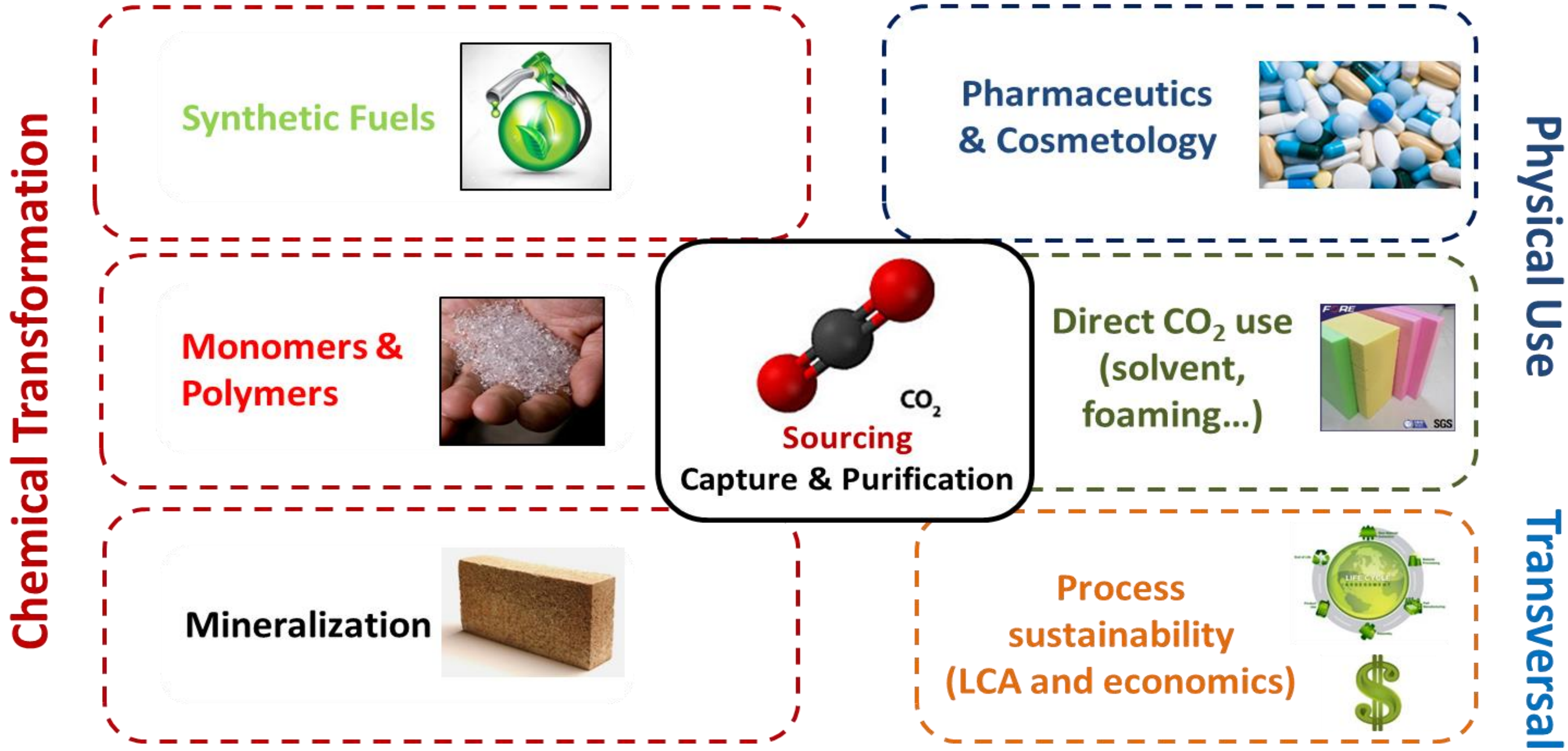
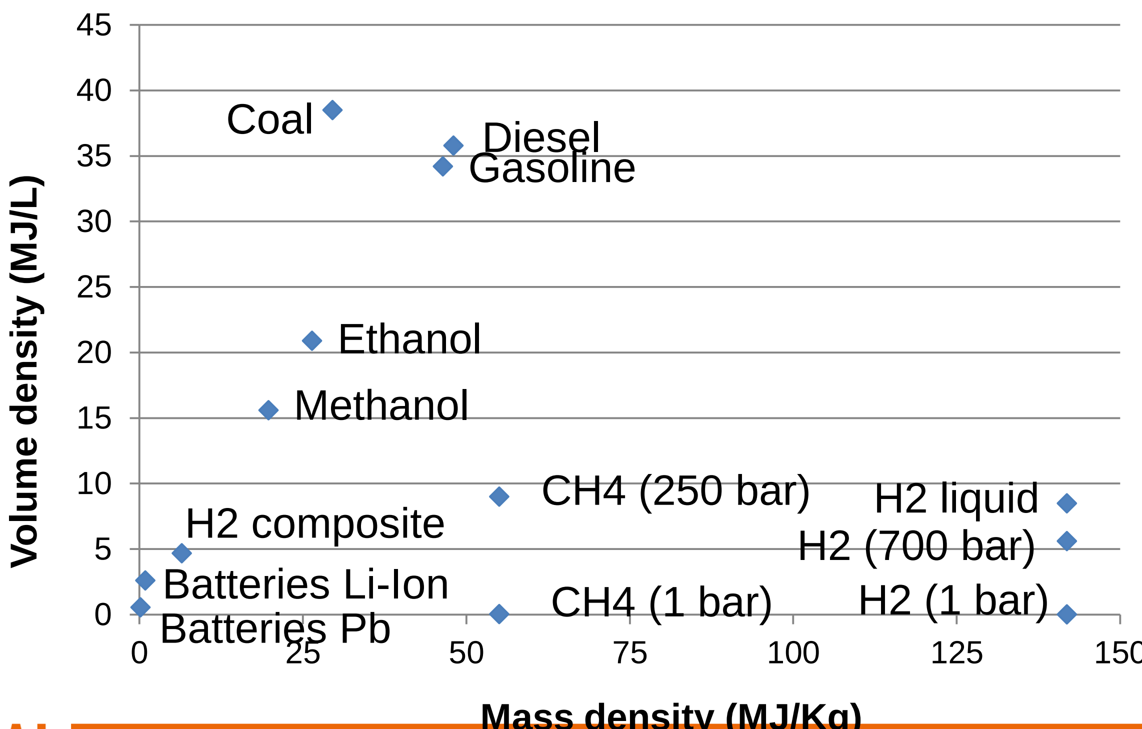
Perspective ULiège: FRITCO_2T platform

Federation of Researchers in Innovative Technologies for CO_2 Transformation



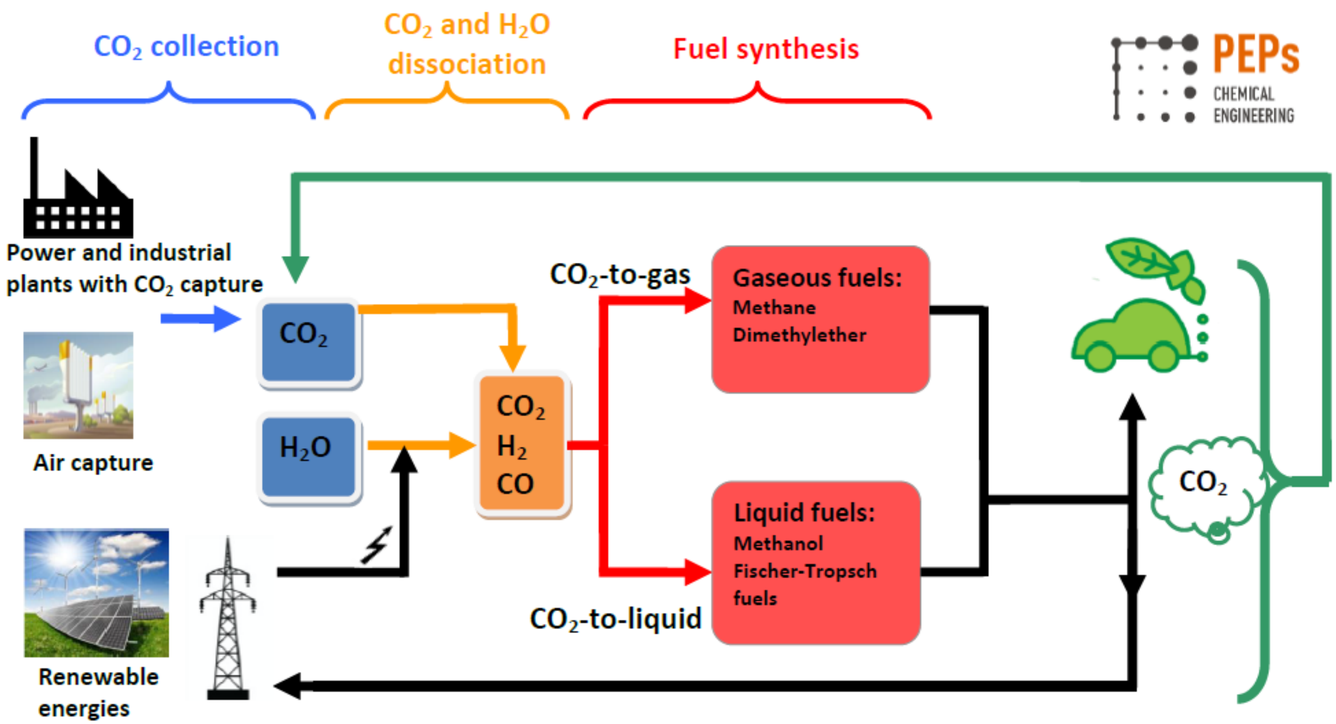
CO_2 re-use

- Our society is currently based on fossil carbon
  - Need to find replacement sources: Biomass and atm. CO_2
- C is a fantastic support for energy storage, but also a great atom for materials !



CO_2 re-use

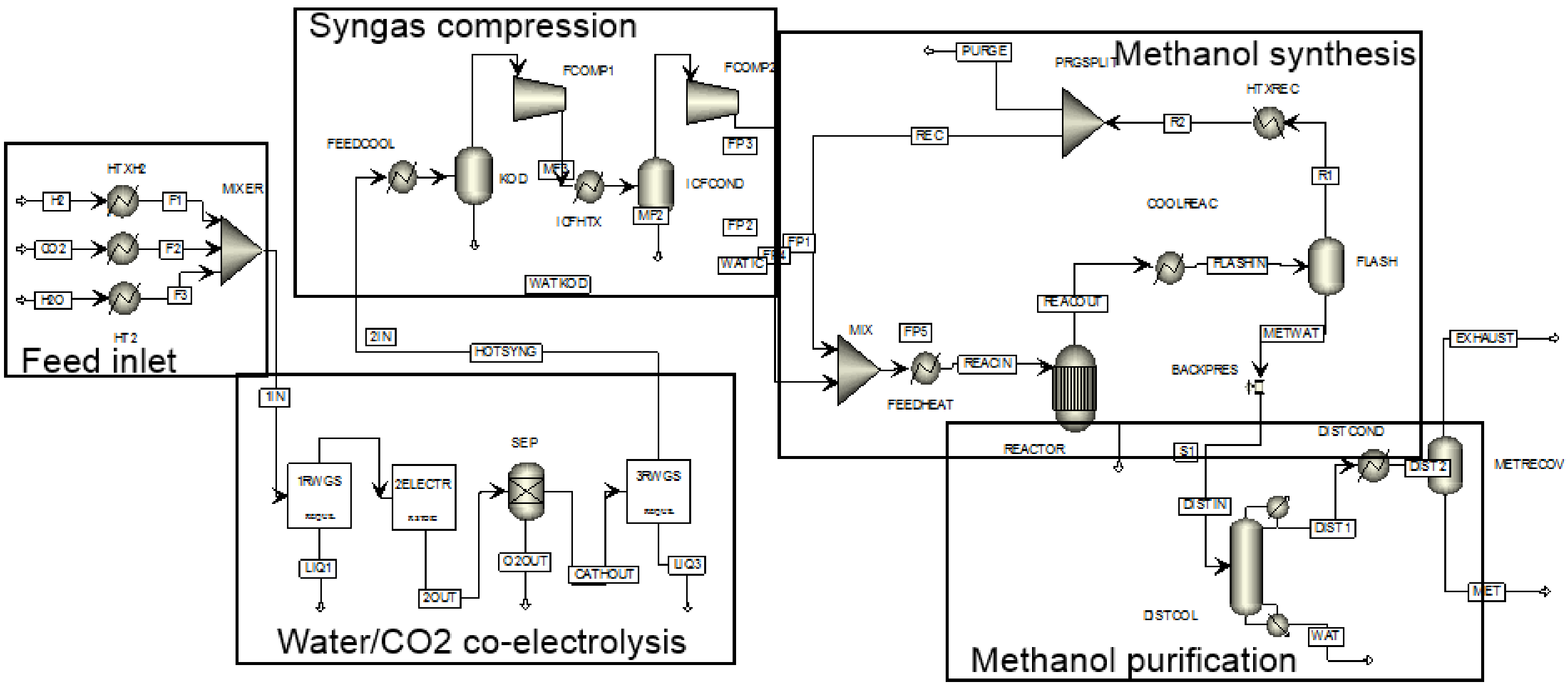
- Power-to-fuel
  - Long-term energy storage
  - => addresses time imbalance generation – consumption



=> Sustainability is possible with carbonated fuels!

CO_2 re-use

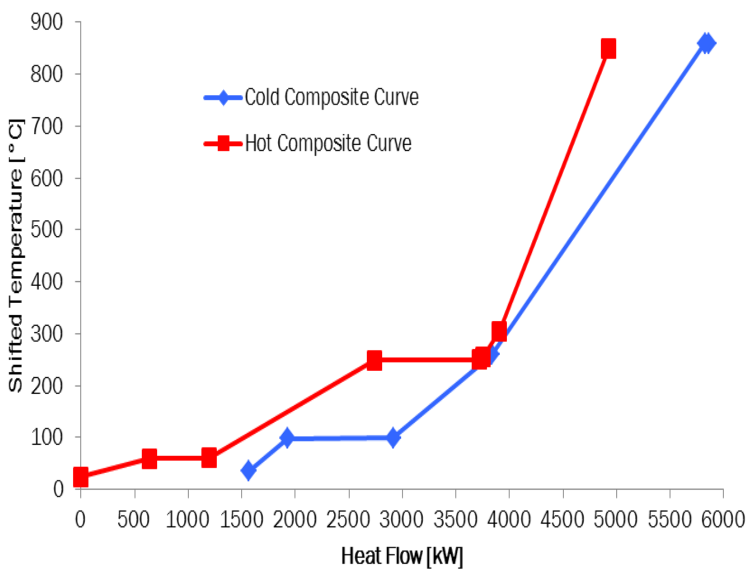
- Process integration
  - Models for electrolysis, CO_2 capture and fuel synthesis

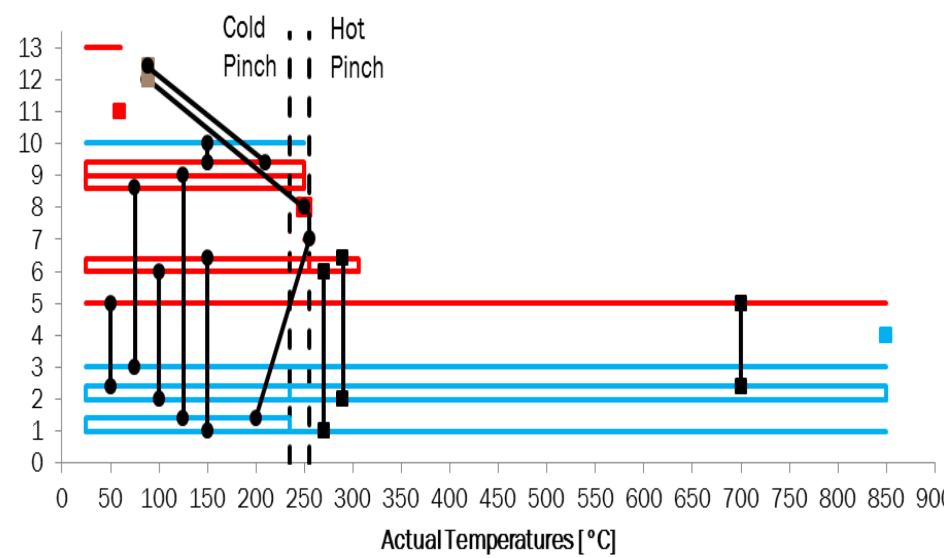


Léonard et al., 2016. Computer aided chemical engineering *38*, 1797.
DOI: 10.1016/B978-0-444-63428-3.50304-0

CO_2 re-use

- Heat integration and intensification
  - Heat integration to improve LHV conversion efficiency
  - Design of a heat exchanger network
  - ε increases from 40.1 to 53.0% !

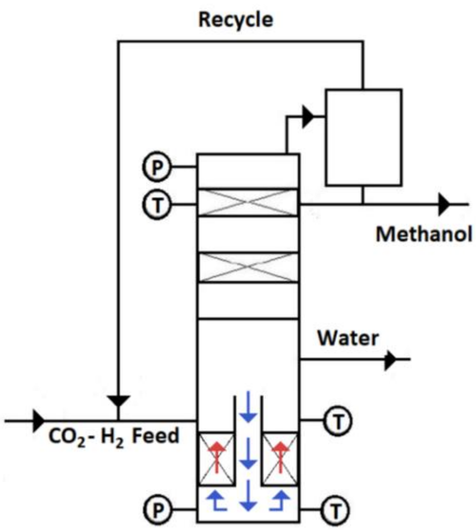


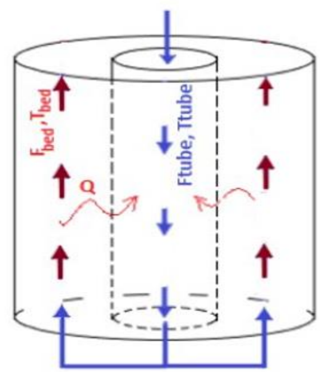


Léonard et al., 2016. Computer aided chemical engineering *38*, 1797.
DOI: 10.1016/B978-0-444-63428-3.50304-0

CO_2 re-use

- CO_2 reduction lab under construction
  - Intensification of synthesis reactor for CO_2 reduction
  - Flexibility towards input and load





$$r_{MeOH} = \frac{k'_{5a}K'_2K_3K_4K_{H2}p_{CO2}p_{H2}[1-1/K^*(\frac{p_{H2O}p_{CH3OH}}{p^3_{H2}p_{CO2}})]}{(1+K_{H2O}/K_8K_9K_{H2})(\frac{p_{H2O}}{p_{H2}}+\sqrt{K_{H2}p_{H2}}+K_{H2O}p_{H2O})^3}$$

$$r_{RWGS} = \frac{k'_1p_{CO2}[1-K^*_3(\frac{p_{H2O}p_{CO}}{p^3_{H2}p_{CO2}})]}{(1+K_{H2O}/K_8K_9K_{H2})(\frac{p_{H2O}}{p_{H2}}+\sqrt{K_{H2}p_{H2}}+K_{H2O}p_{H2O})^3}$$

Vanden Bussche K.M and Froment G.F, 1996. Journal of catalysis, 161, pp. 1-10.

4. Conclusions and perspectives

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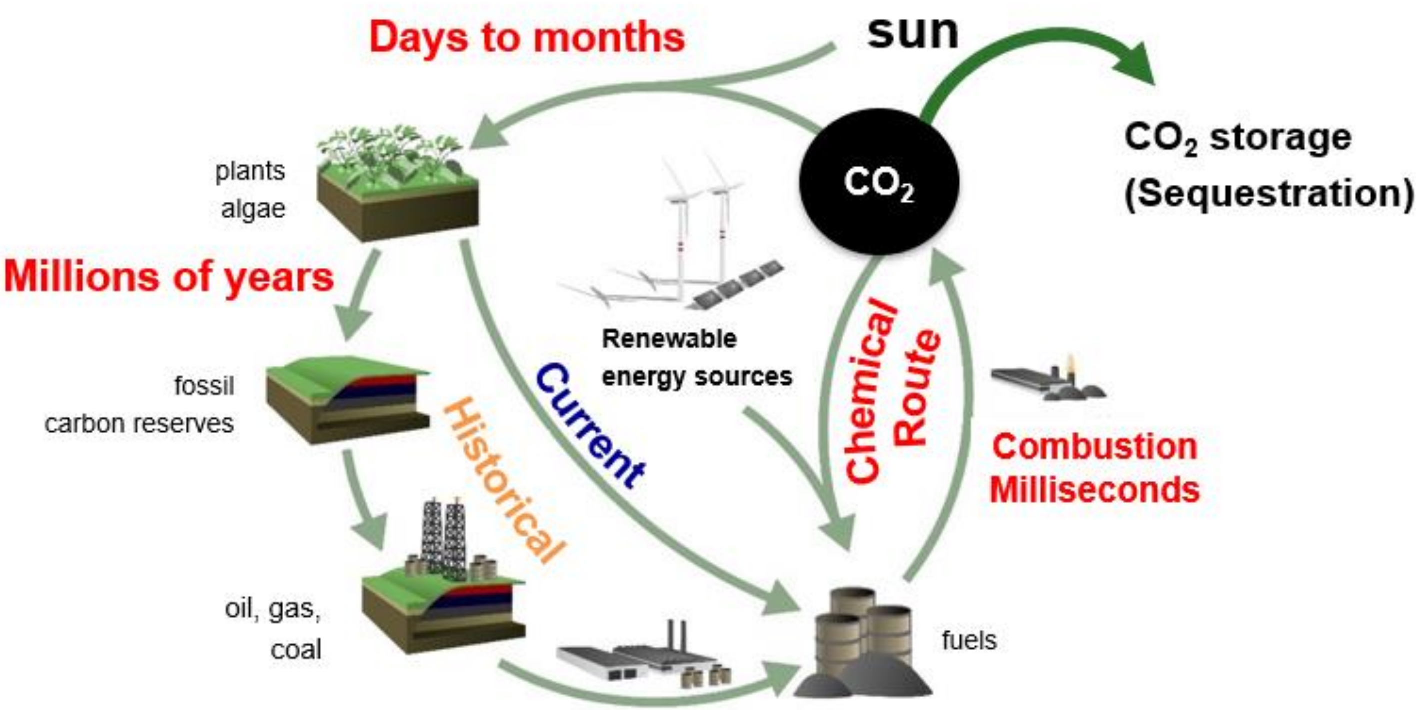
State of technology CCUS

- Capture of CO_2
  - Mature but limited application yet
- Storage
  - Commercially applied (mostly EOR)
- Re-use
  - Maturity depends on technology, from TRL 1 to 9
- Big acceleration due to Paris COP21 agreement and environmental urgency
  - European Green Deal

Perspective

- We live in a carbon-based society, with very good reasons for that !
- A CO_2 neutral future is in sight with passionating (and huge) challenges for engineers!



Martens et al., (2017) The Chemical Route to a CO_2-neutral world, *ChemSusChem*
Saeys (2015), De chemische weg naar een CO_2-neutrale wereld, Standpunt KVAB

Thank you for your attention!

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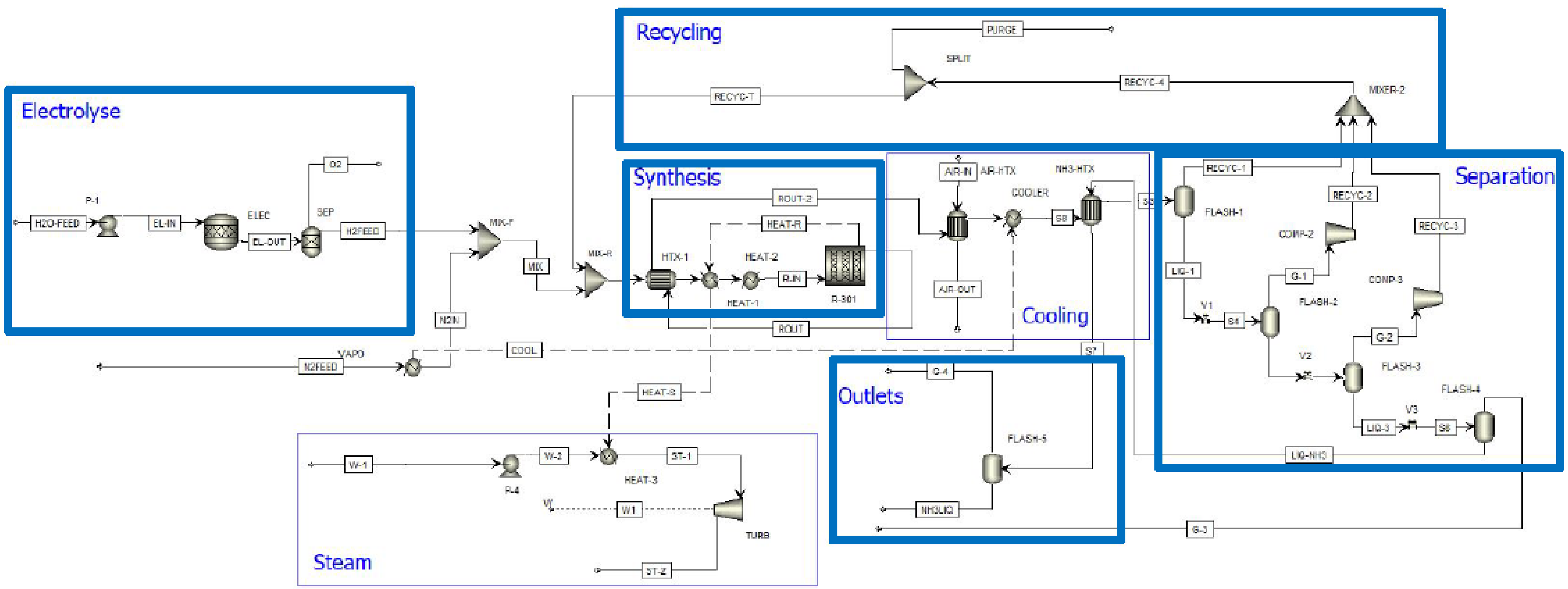
Process design for power-to-industry

- Feasibility study for green H_2 industry
  - Master’s students work – 2019-2020
  - Low carbon ammonia production in Europe



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Source: Hoxha J.-L., Caspar M., Donceel A., Fraselle J., Philippart de Foy M., Poncelet R., Léonard G., 2020. Feasibility study of low-carbon ammonia and steel production in Europe. Eceee Industrial Summer Study Proceedings.

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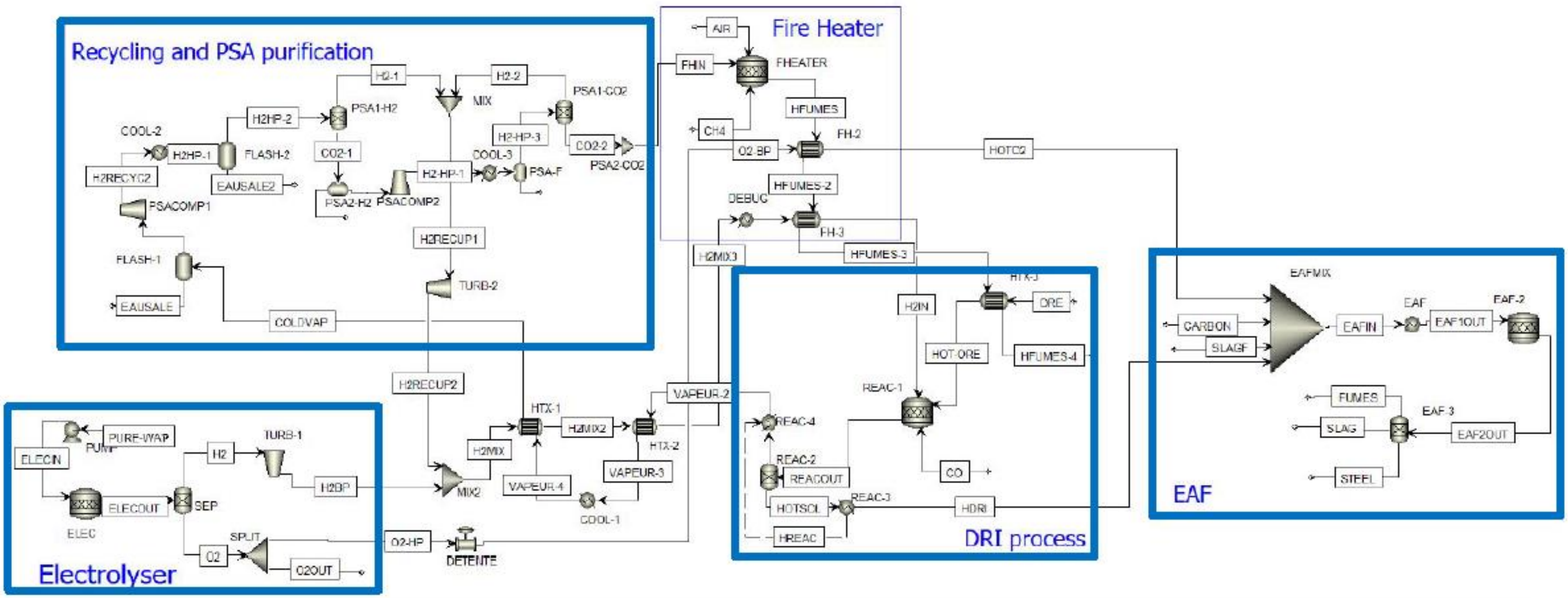
Process design for power-to-industry

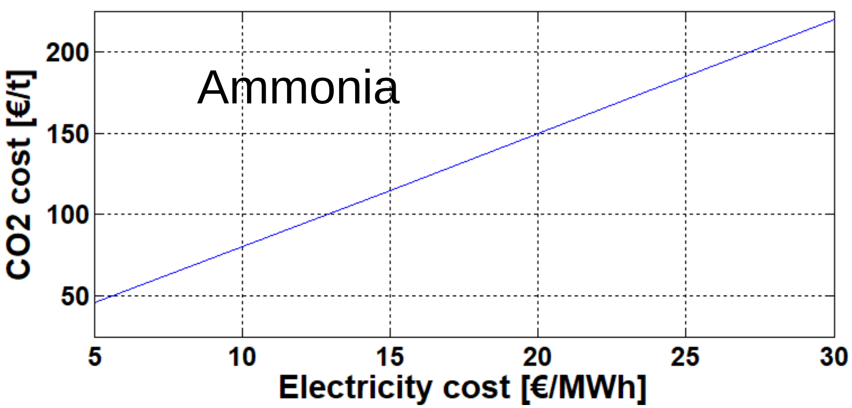
- Feasibility study for green H_2 industry
  - Master's students work – 2019-2020
  - Low carbon steel production in Europe

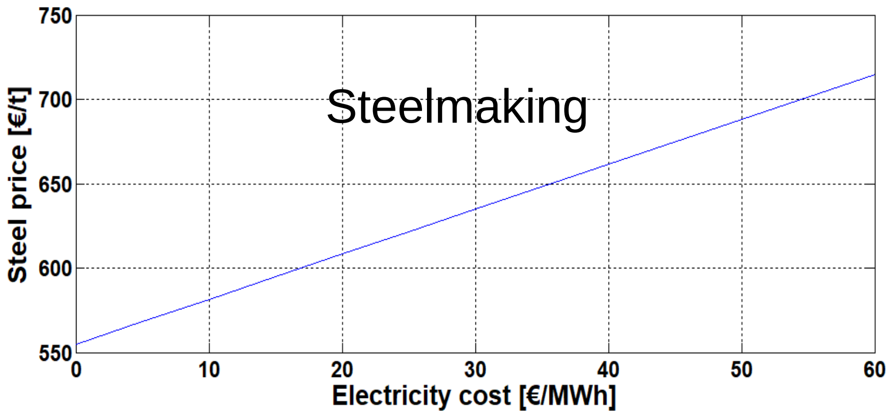


Source: Hoxha J.-L., Caspar M., Donceel A., Fraselle J., Philippart de Foy M., Poncelet R., Léonard G., 2020. Feasibility study of low-carbon ammonia and steel production in Europe. Eceee Industrial Summer Study Proceedings.

Process design for power-to-industry

- Assuming 85% efficiency, the H_2 needs in green industry would be:
  - For a typical ammonia plant (540 kt NH_3/year) => 700 MW power
  - For a typical steel making plant (1 Mt steel/year) => 400 MW power
  - Break-even costs (left: ammonia; right: steelmaking)





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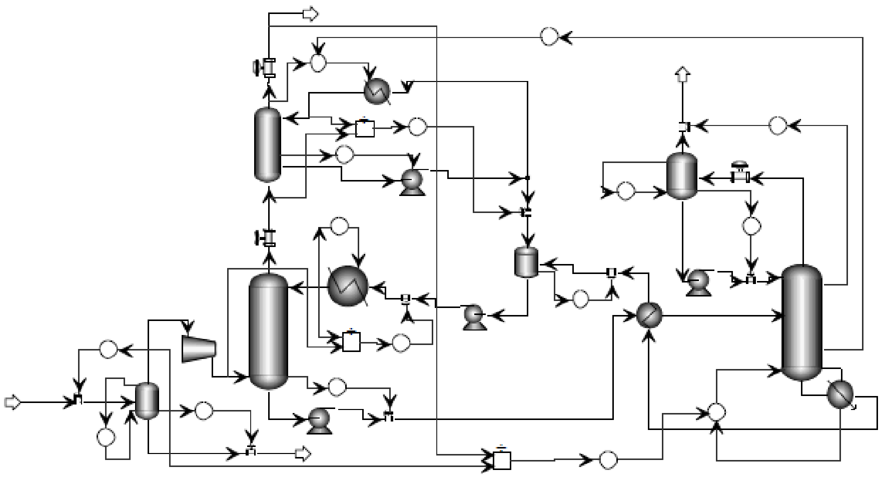
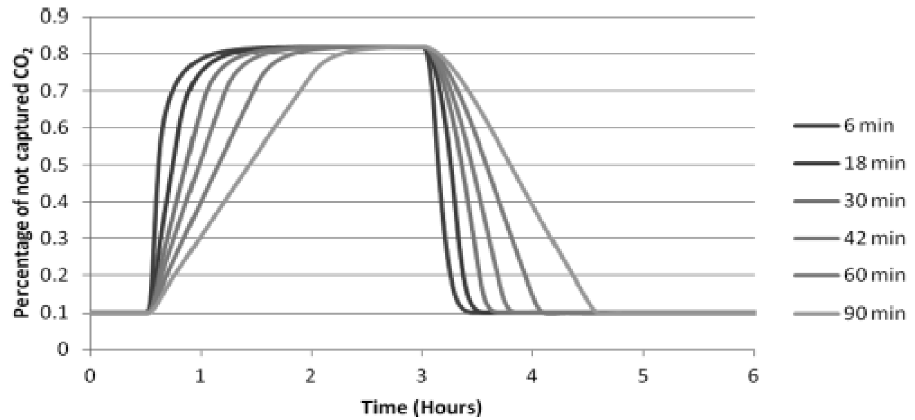
Further process modeling work

- Process dynamic modeling
  - Applied to CO2 capture





Léonard G., Mogador Cabeza B., Belletante S., Heyen G., 2013. Dynamic modelling and control of a pilot plant for post-combustion capture. Computer Aided Chemical Engineering 31, 451.

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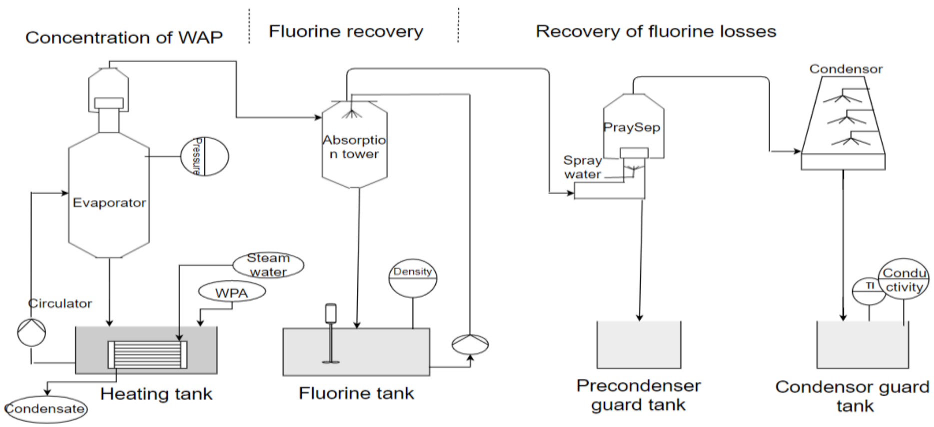
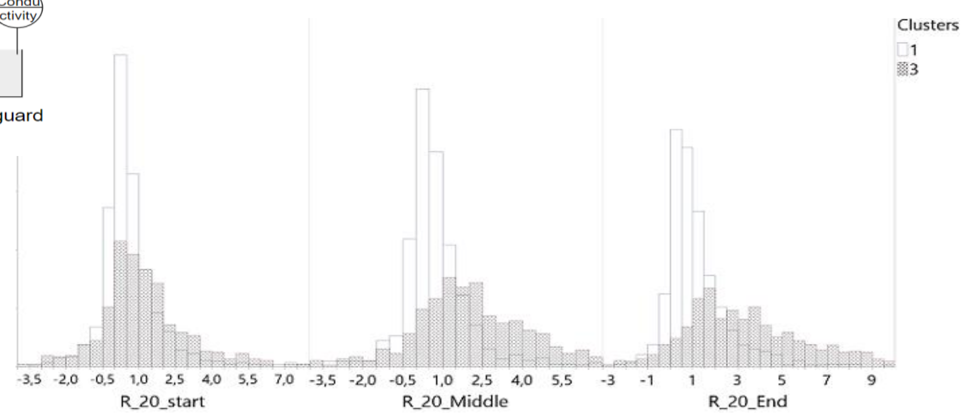
Further process modeling work

- Data treatment
  - Application of data processing and machine learning techniques for the improvement of a phosphoric acid production process
  - PhD thesis in coll. with Prayon





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Ariba H., Vanabelle P., Benaly S., Henry T., André C., Léonard G., 2021. Application of data science to study fluorine losses in the phosphate industry. Computer Aided Chemical Engineering, in press.

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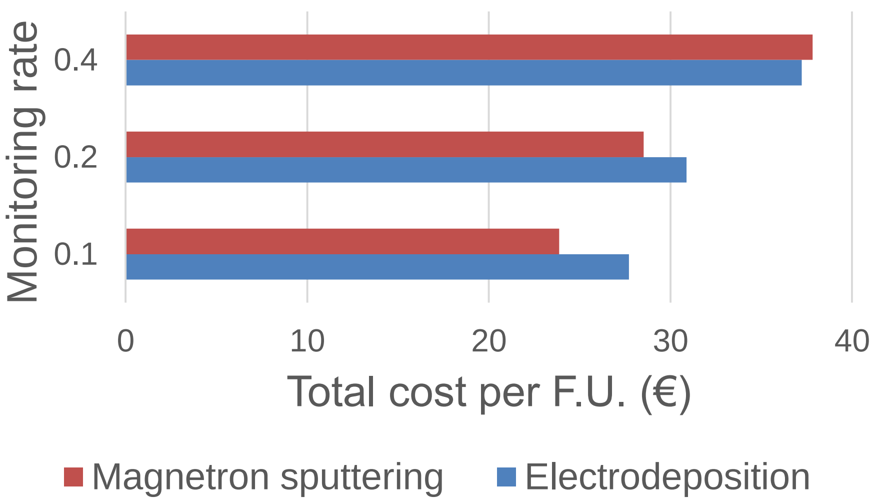
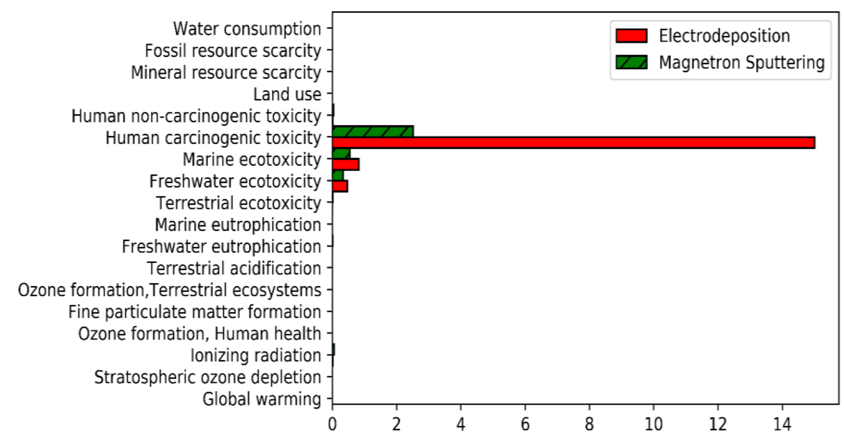
Further process modeling work

- LCA & TEA
  - Pulsatec project
  - Development of a methodology for techno-economic and life-cycle assessment of innovative technologies: case of functionalized coatings by pulsed plasma





Merlo A. and Leonard G., 2020. Development of a framework integrating TEA and LCA : advances and challenges. Oral presentation at Cape Forum 2020. http://hdl.handle.net/2268/250549

Recent initiatives

Projects recently submitted

- Direct air capture
  - Design of DAC systems based on existing gas treatment infrastructures
  - Recruitement of PhD student in progress

- Carbonation of mineral wastes
  - Accepted, start in August 2021

- CO_2 conversion to jet fuels
  - CO_2 based Fischer-Tropsch reactor design
  - Dynamic modeling

PROCURA ETF: Decision support tool

- We are convinced that CO_2 capture will play a role in future industrial systems
- But many technologies are available, and the right choice depends on many variables
  - Techno-economics and environmental footprint
  - Required purity of CO_2 ; presence of flue gas contaminants
  - …

- In the framework of the PROCURA project, we develop a decision support tool for helping local companies in their choice
  - Tool is currently at version 1.0, based on literature data
  - Next steps will refine the selection criteria, based on in-house process models (including TEA & LCA)
  - Tool will be demonstrated with Belgian case studies