Carbon capture and re-use: technological and other challenges

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ICheaP Conference - AIDIC

Naples, May 24, 2023

CHEMICAL ENGINEERING

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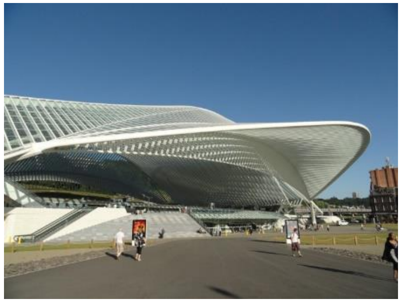
University of Liège - ULiège

- Liège: 3rd urban area in Belgium
  - ~750 000 inh.
- ULiège = a pluralist university
  - 11 faculties, 23 000+ students, 122 Nationalities

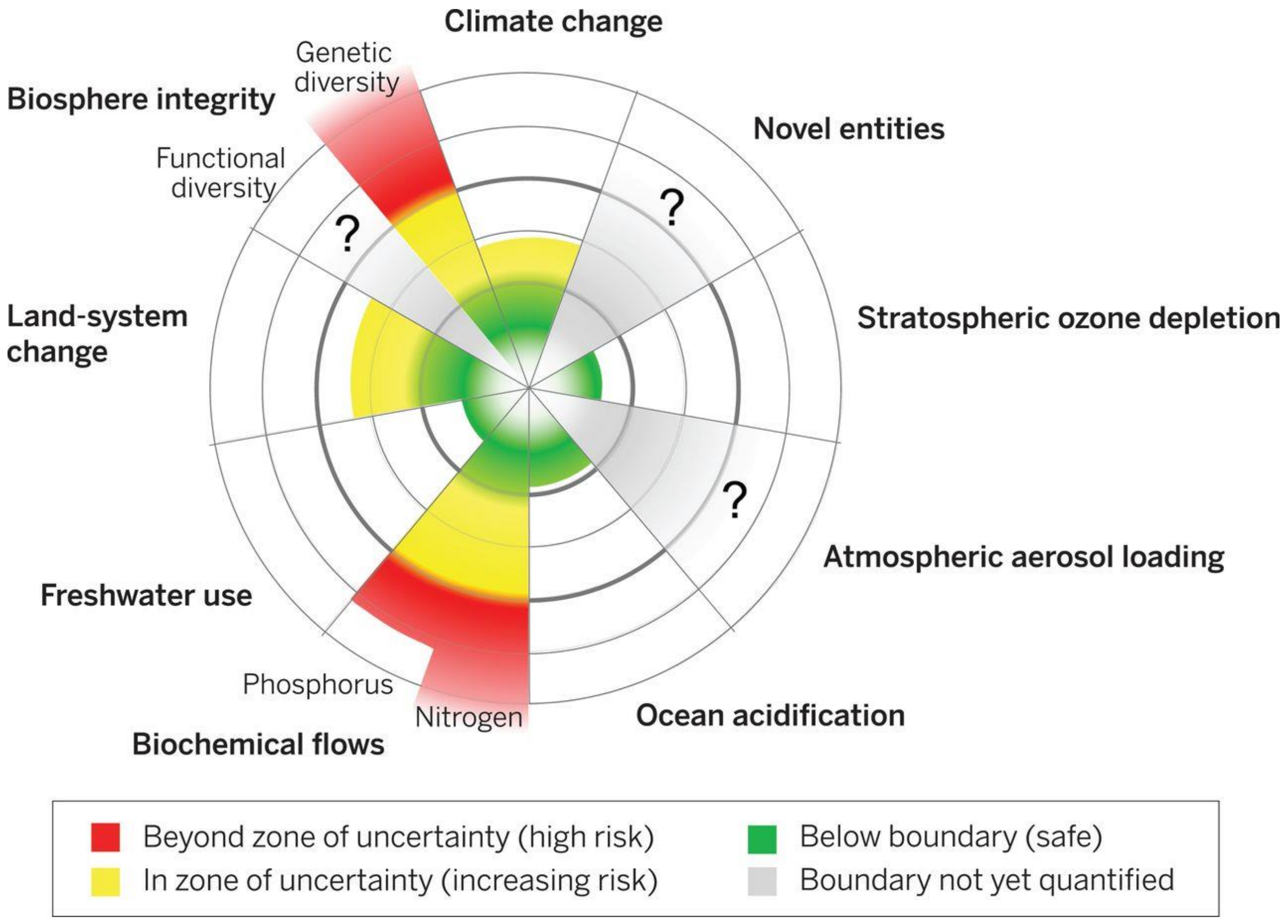


Outline

- Context and rationals
- CO_2 capture
- CO_2 re-use
- Conclusion

Sustainable development

- How to keep a safe ecosystem?



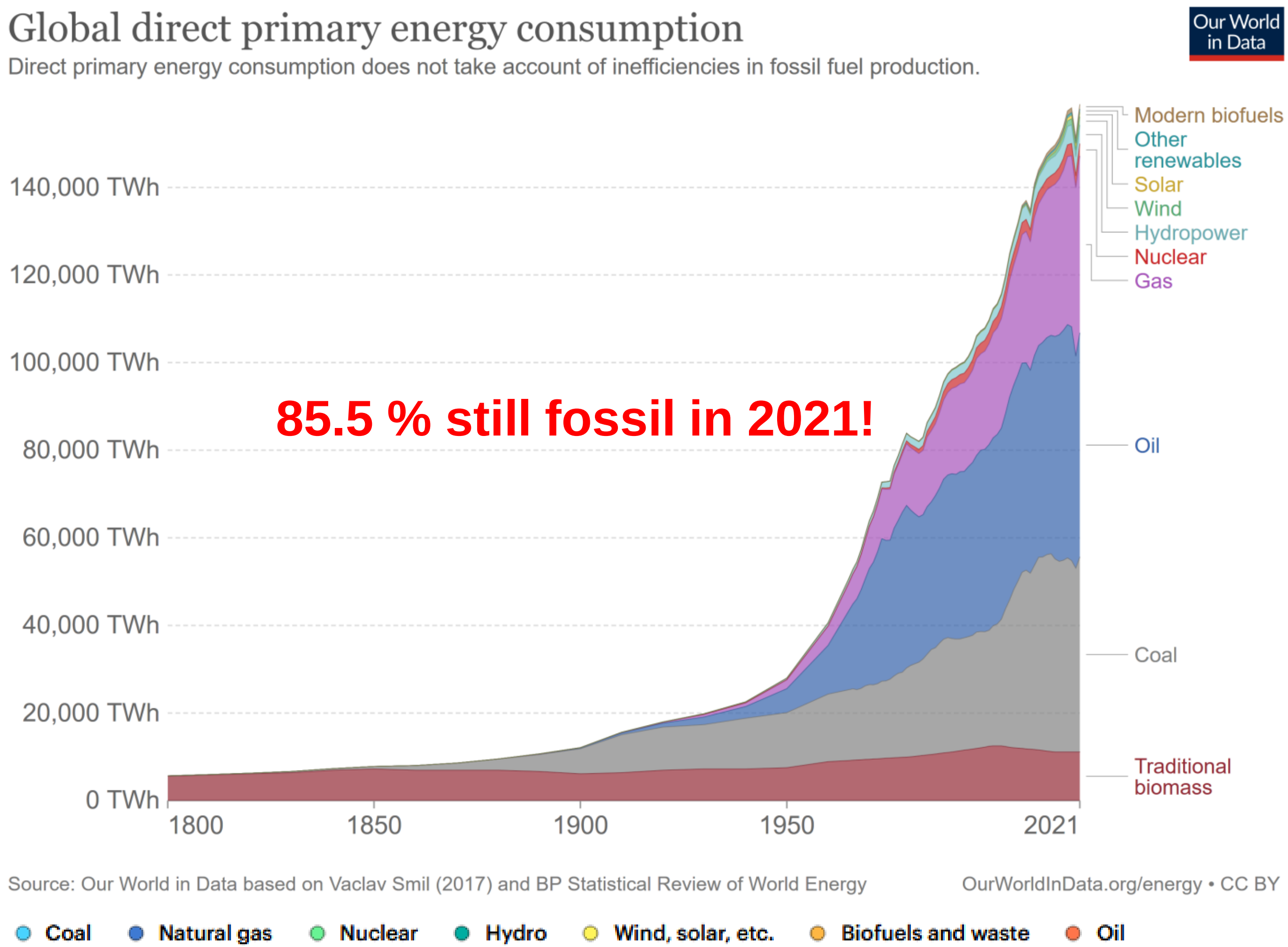
Steffen W. *et al.* (2015), *Science 347* (6223), 1259855.

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

It has to address 2 objectives in contradiction:

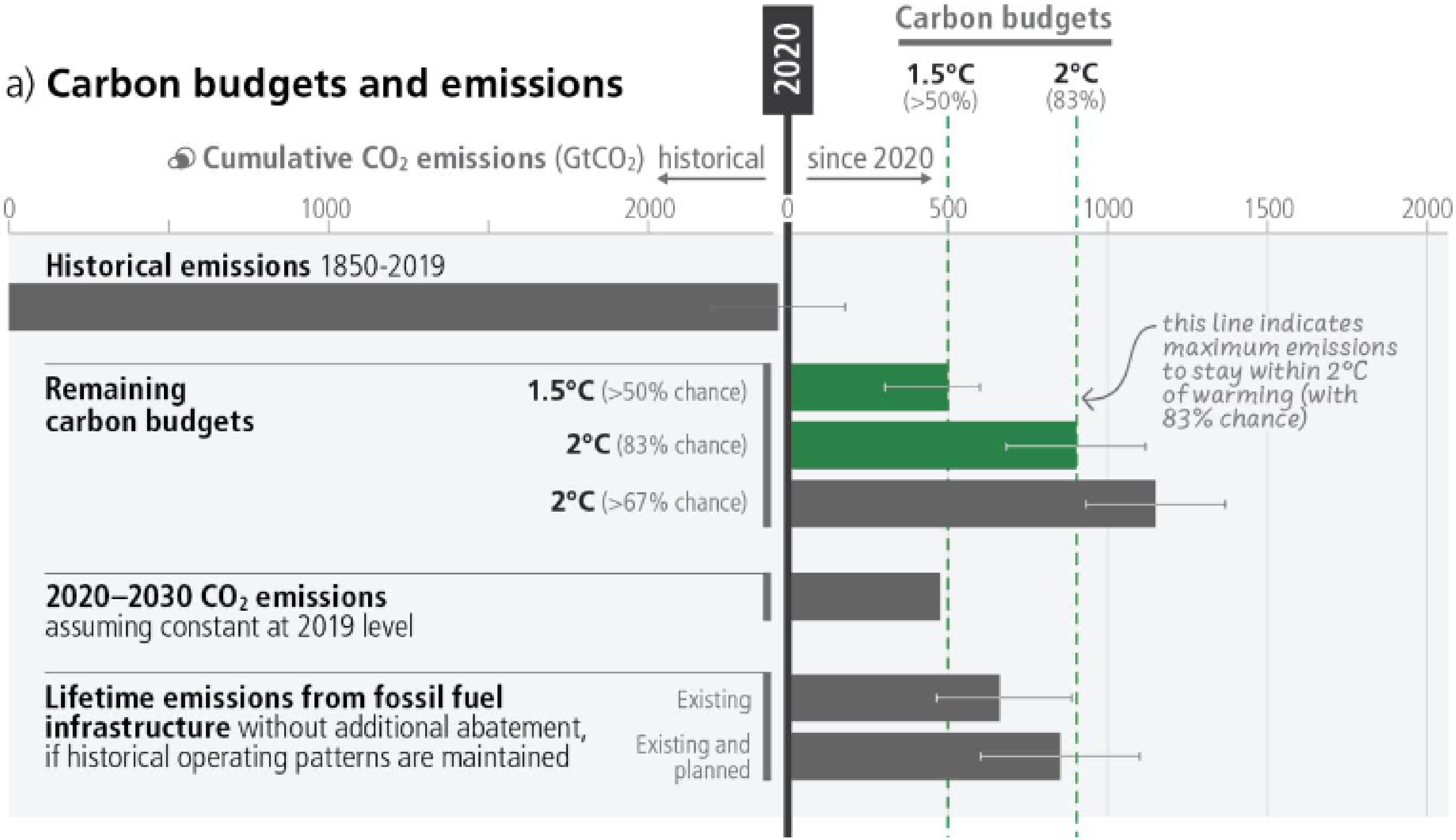
- Limit GHG emissions, and
- meet the increasing energy demand!

Meeting the increasing demand is already a challenge!



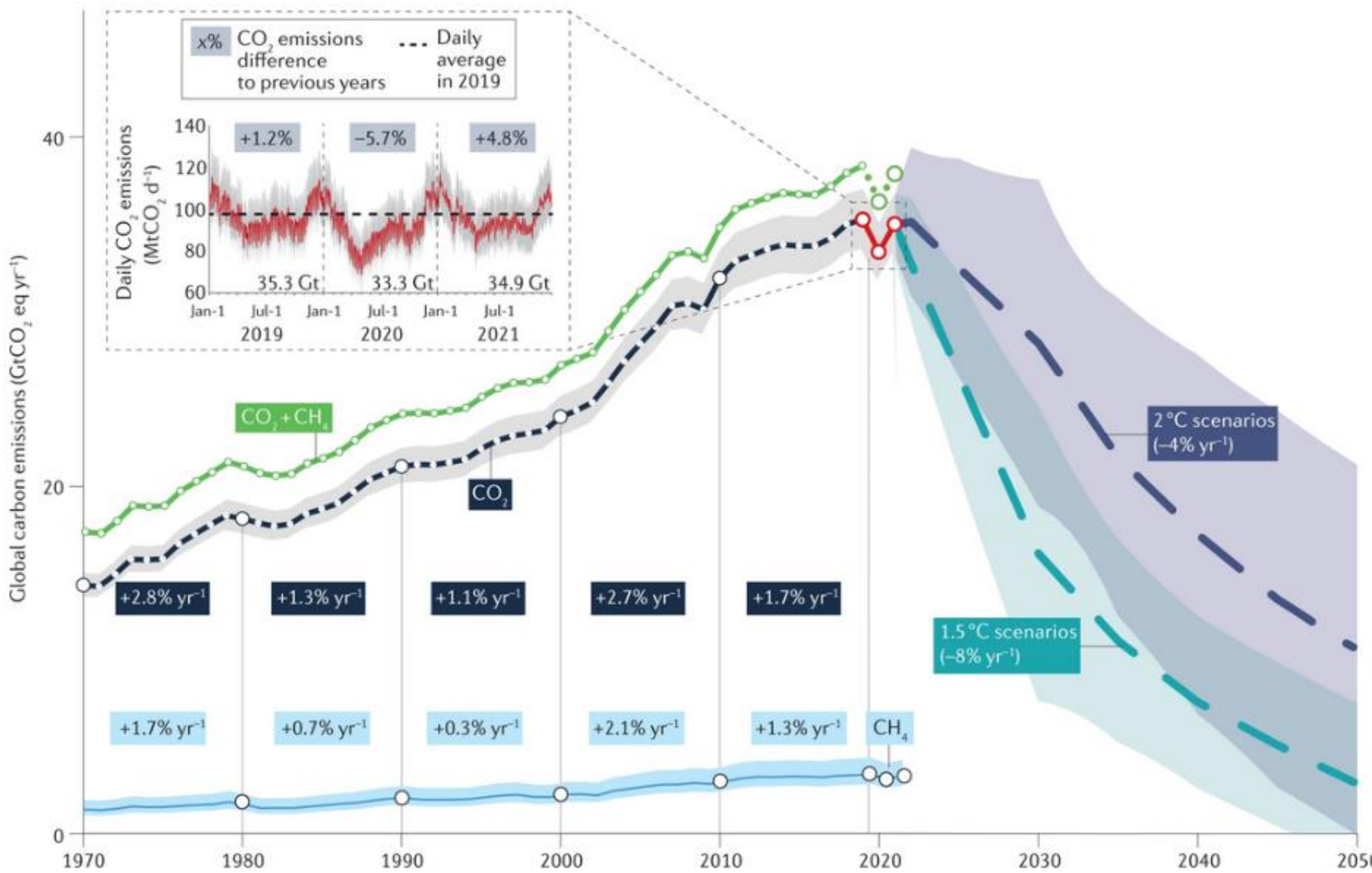
Global direct primary energy consumption. Our world in Data Available at: https://ourworldindata.org/grapher/global-primary-energy

CO_2 Budget to limit warming to 1.5°C



Are we on good tracks?

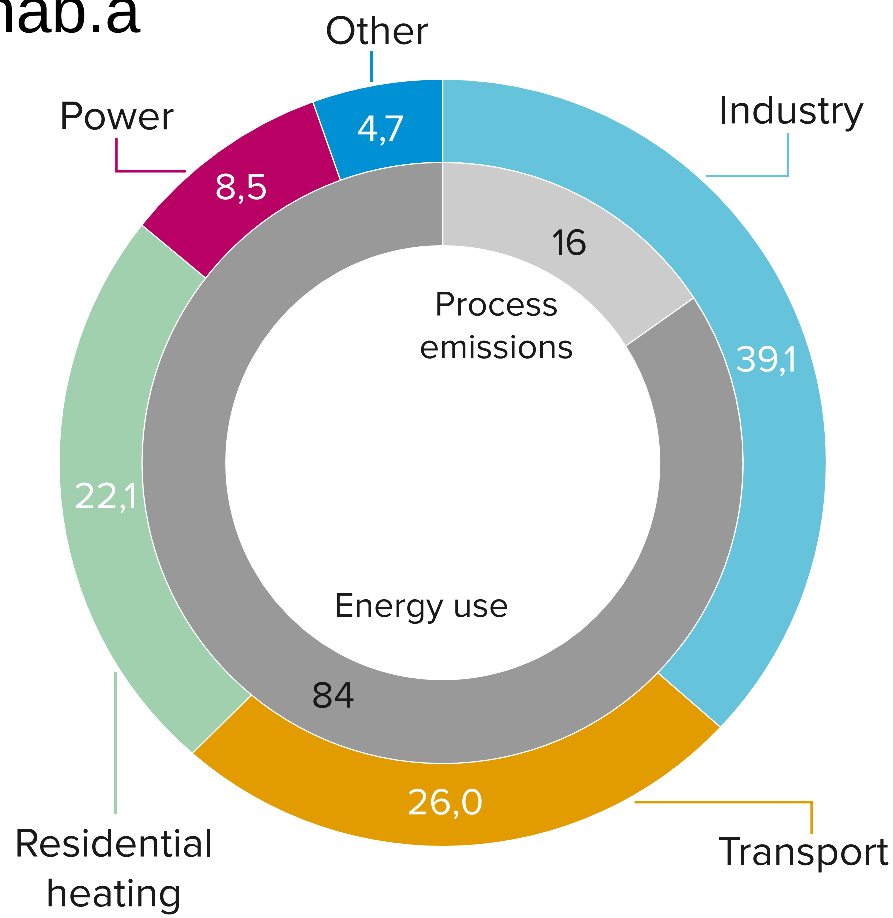
- Much greater emission reduction efforts will be required…



https://doi.org/10.1038/s43017-022-00285-w (2022)

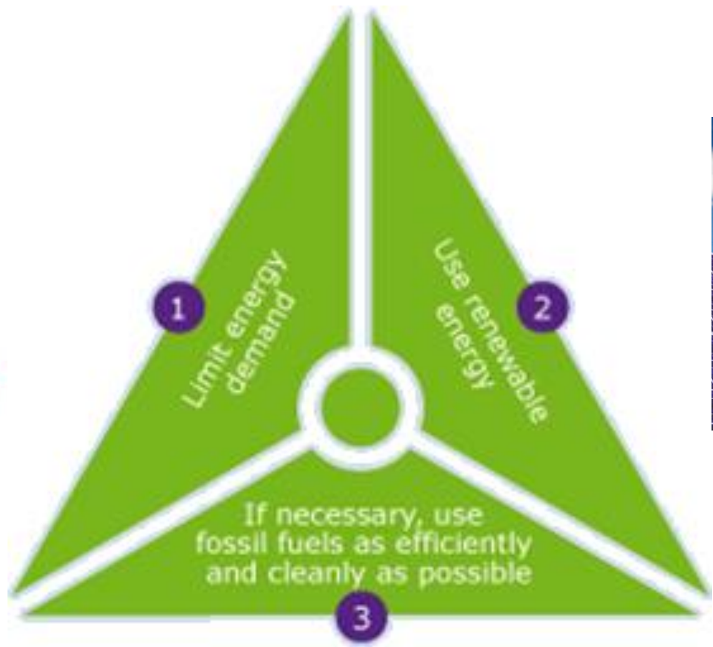
Carbon emissions in Belgium

- Belgium CO_2 emissions ~ 100 Mt/a
- This corresponds to ~ 8.6 t/hab.a
  - => 24 kg/day!!



https://www.fluxys.com/en/energy-transition/hydrogen-carbon-infrastructure#double_solution
https://ourworldindata.org/co2/country/belgium

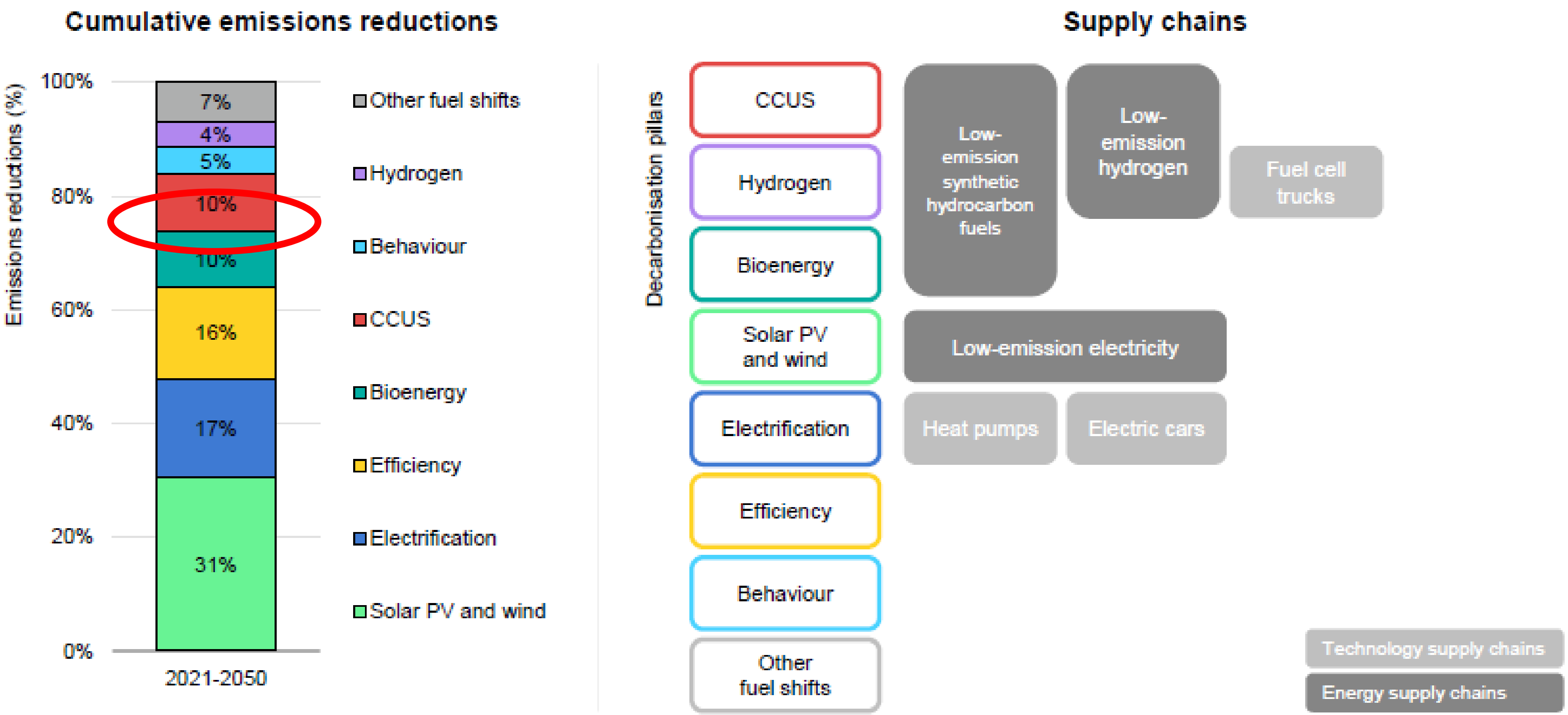
Possible technological answers: Trias Energetica



Lysen E., The Trias Energica, Eurosun Conference, Freiburg, 1996

CCUS forecasts

- IEA's Scenario Net Zero Emission 2050 (1.5°C)



=> So why isn't CCUS more implemented yet?

IEA, 2023. Energy technology perspectives report.

2. CO_2 Capture

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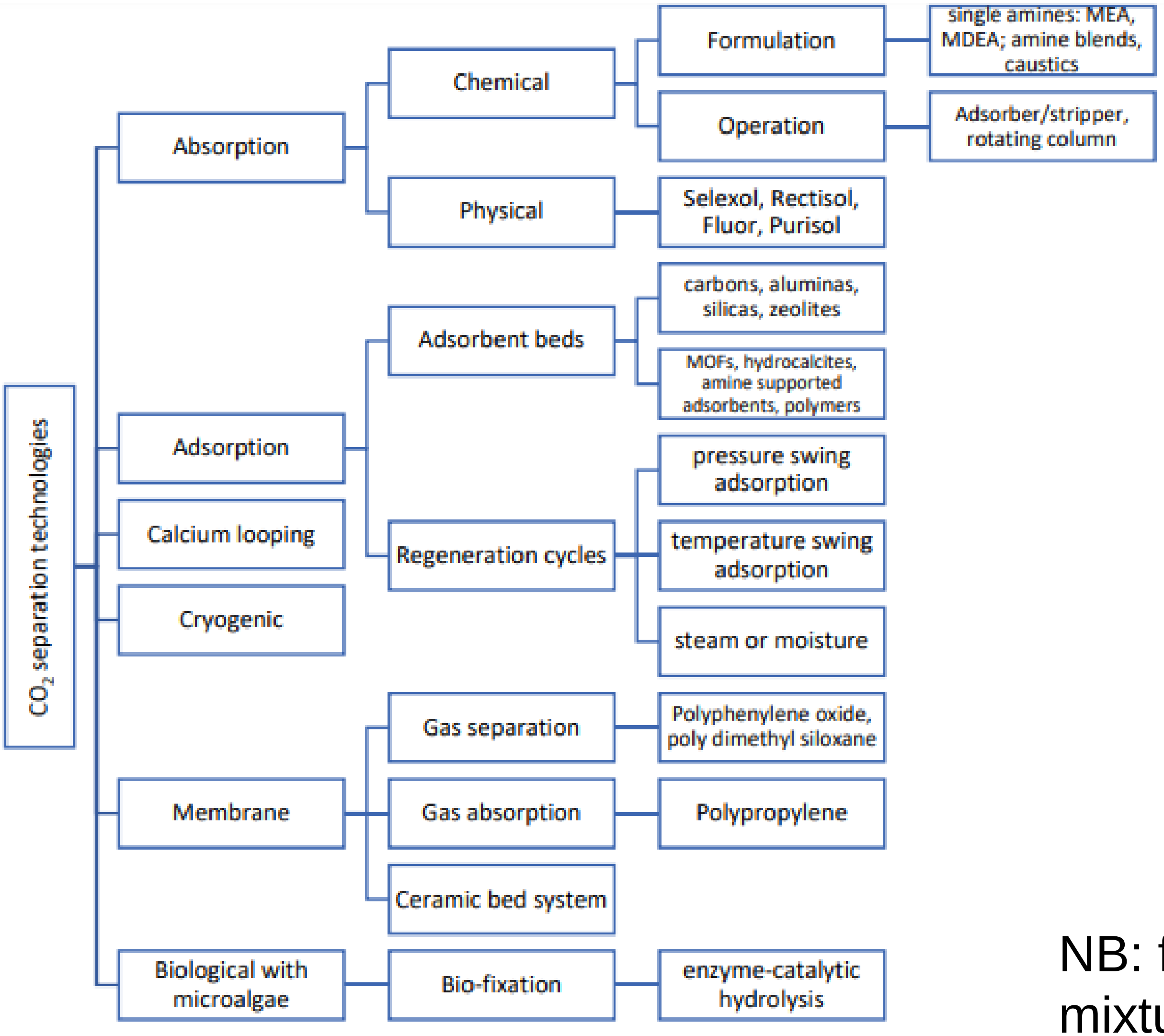
CO_2 capture

- It's a question of fluid separation!
  - Sources usually contain CO_2, N_2, H_2O, H_2, CO, CH_4, O_2, SOx …
  - CO_2 concentration varies between 0.04% and almost 100%
  - Varying maturity, "retrofitability", flexibility
  - But cost only!

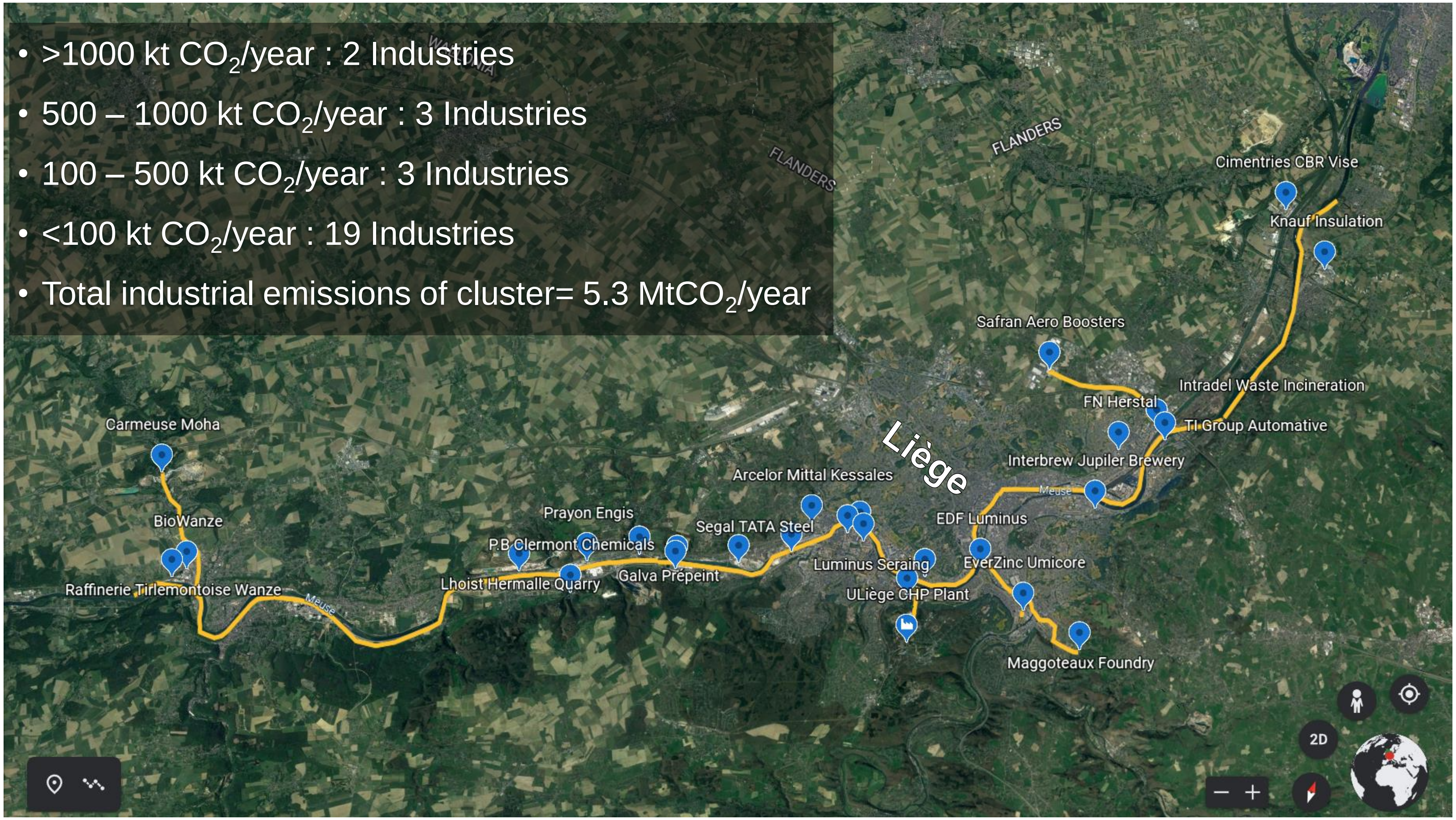
CO_2 separation technologies



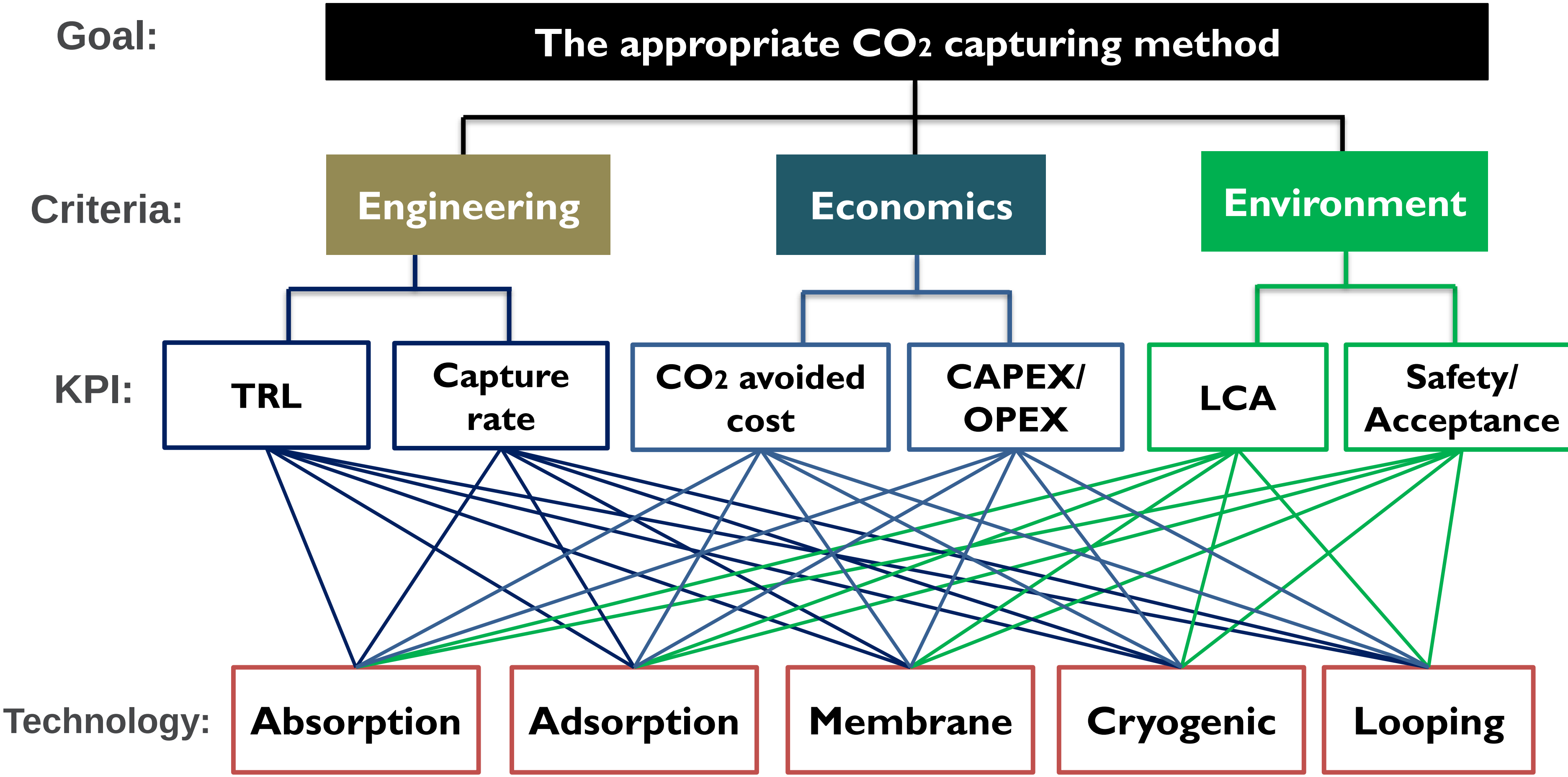
NB: first, try to avoid fluid mixtures !

Industrial Cluster in Liège – TRILATE

- >1000 kt CO_2/year : 2 Industries
- 500 – 1000 kt CO_2/year : 3 Industries
- 100 – 500 kt CO_2/year : 3 Industries
- <100 kt CO_2/year : 19 Industries
- Total industrial emissions of cluster= 5.3 MtCO_2/year



PROCURA Decision Support Tool



PROCURA Decision Support Tool

- Construction of a database using KPIs
  - Techno-economics and environmental footprint
  - TRL
  - Achieved purity of CO_2
  - Impact of flue gas contaminants
  - Part-load performances
  - …

- Calculation of KPI based on user's input and on process models (or literature)
- Weighting of scores based on user's preferences

- Result: ranking of solutions

PROCURA Decision Support Tool

- Construction of a database using KPIs

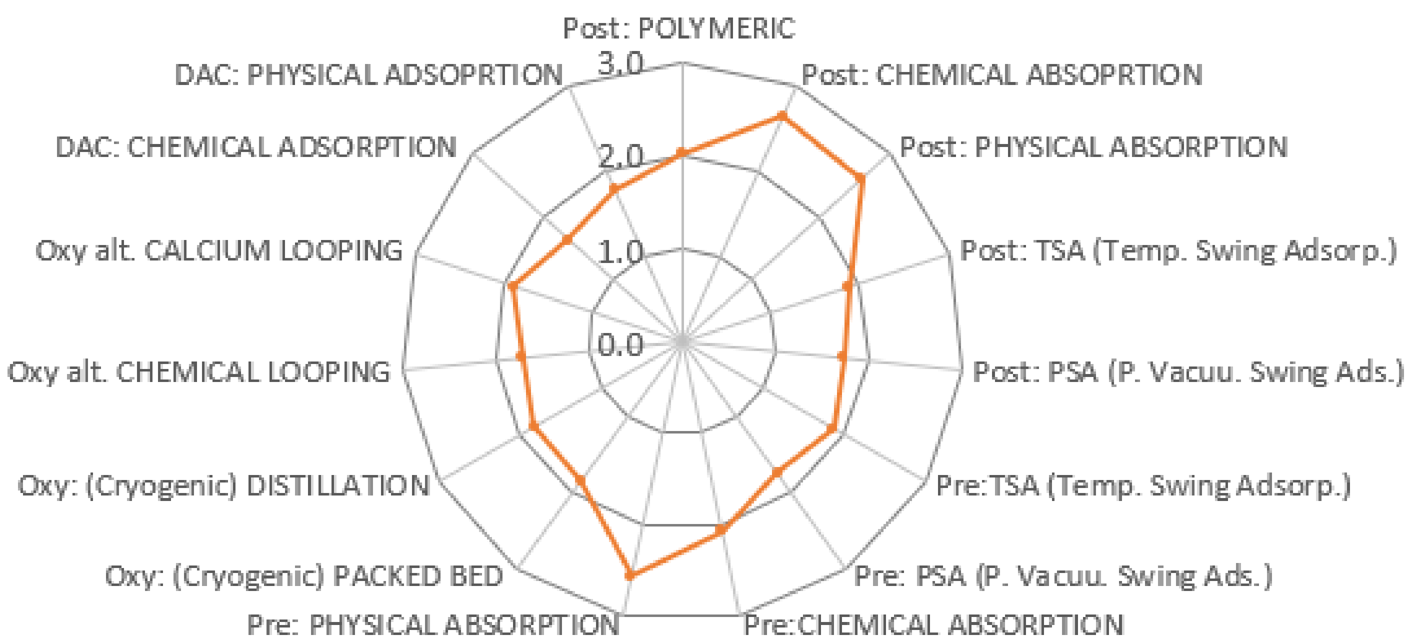
Engineering KPIs	Description/ Evaluation method	Scale	Score
TRL	TRL scale Maturity level of the technologies	< 4	0
		5 - 6	1
		7- 8	2
		9	3
Achievable Capture rate	% Percentage of CO_2 captured from the inlet stream at nominal conditions	< 50 %	0
		75 – 50 %	1
		89 – 76 %	2
		≥ 90 %	3
Thermal energy demands (LTH)	GJ/tCO_2 LP Steam (< 150 °C) to capture a specified amount of CO2 per year (E.g. 1 Mt/yr) at a specified capture rate (E.g. 90%)	>3.78	0
		2.52 – 3.77	1
		1.26 – 2.51	2
		≤ 1.25	3
OPEX per tonne of CO_2 avoided	€/tCO_2 Operative costs at nominal conditions	> 93	0
		62 – 92	1
		31 – 61	2
		≤ 30	3

PROCURA Decision Support Tool

- Weighting of scores based on user's preferences

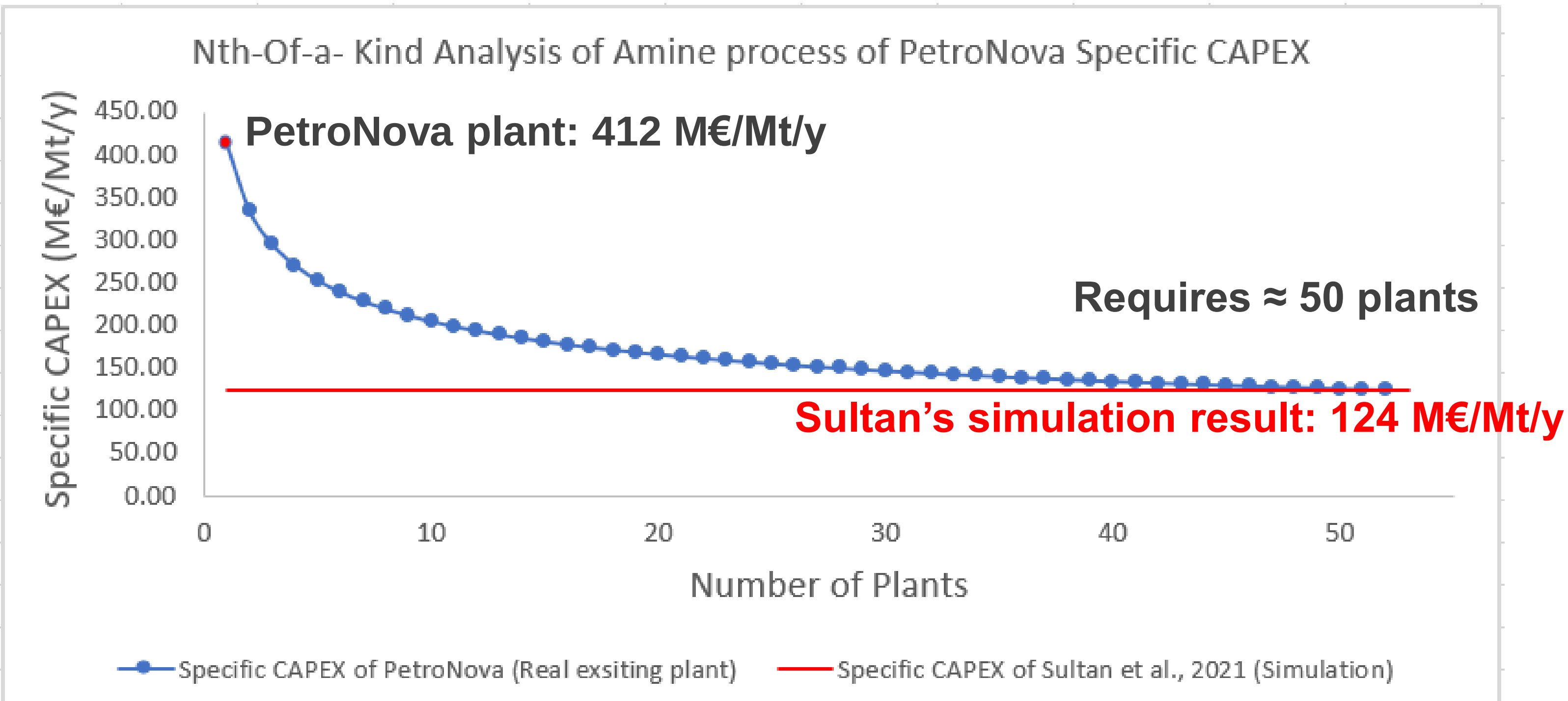
$$\textbf{Final score} = \sum_{\text{cri}} W_{\text{cri}} \cdot \{\sum_{\text{KPI}} W_{\text{KPI}} \cdot \textbf{Score}\}$$

- Ranking of results



Objective: Close the gap with reality

- Literature values or process models may be somehow inaccurate, especially at low TRL
  - Real plant costs are not available!



Sultan et al., 2021. Greenhouse Gases: Science and Technology,11(1), pp.165-182

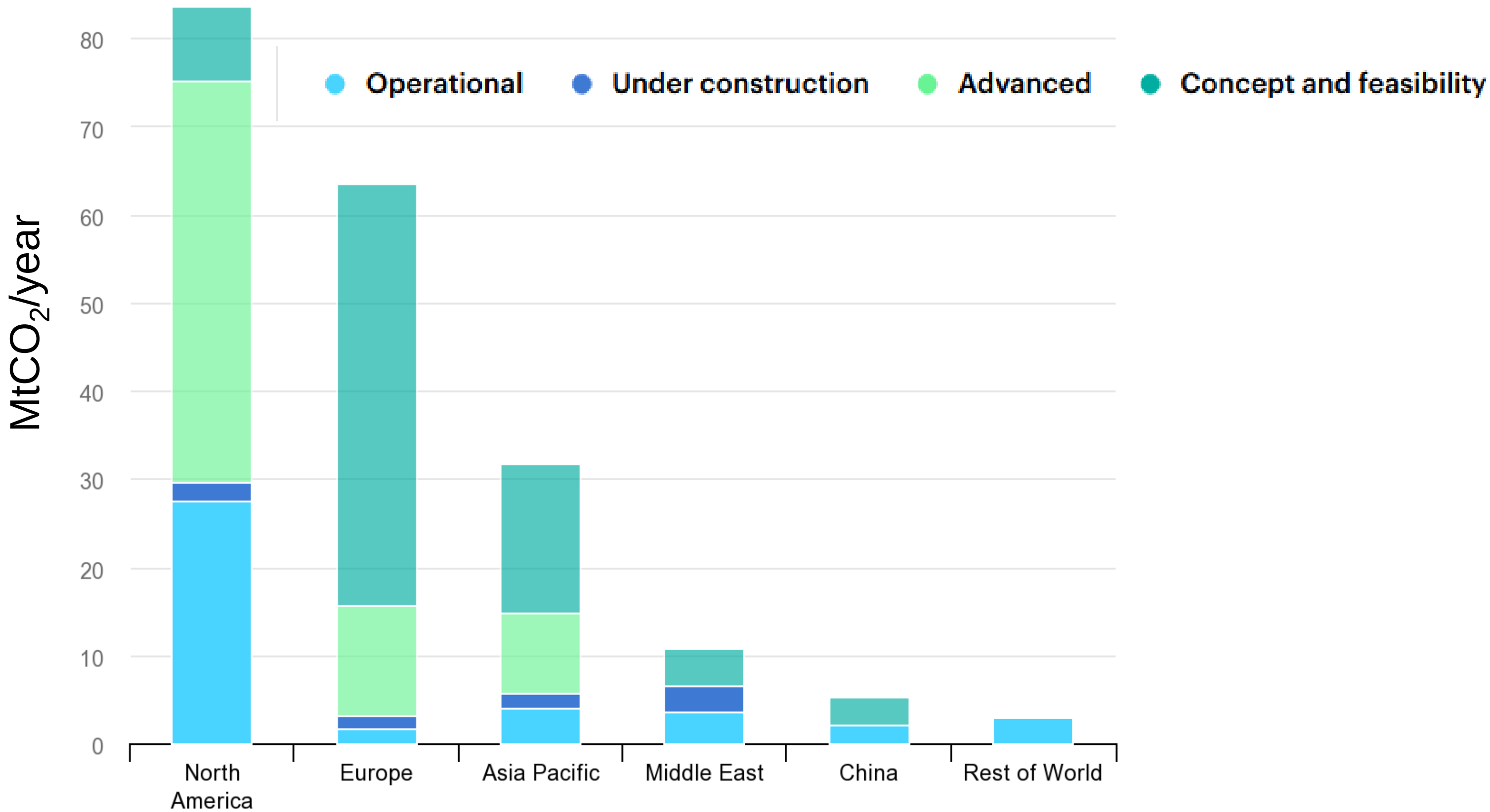
Objective: Close the gap with reality

- Scope of the study:
  - Gas pre-treatment ? Post-treatment ?
  - CO_2 captured or avoided ?
  - What about transportation and storage ?

Specification	Transport requirements
CO_2	> 95 mol-%
O_2	< 40 ppm mol
SOx (SO_3)	< 10 (< 0.1) ppm mol
NOx	< 5 ppm mol
Temperature	20 – 40 °C
Pressure	20 – 33 barg

Geological storage

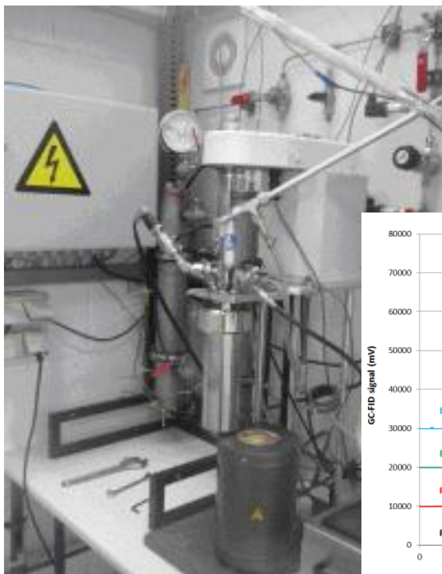
- Potential for storage exceeds by far the needs
  - 5000 – 25 000 $GtCO_2$ vs. ~ 2000 $GtCO_2$
- Storage costs ~2-15 USD/t, large infrastructure costs needed!

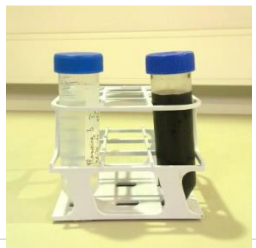


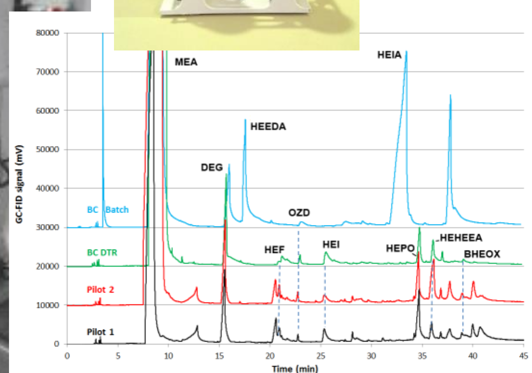
doi: 10.3389/fclim.2019.00009
IEA, CO2 storage infrastructure in development by region as of 2022

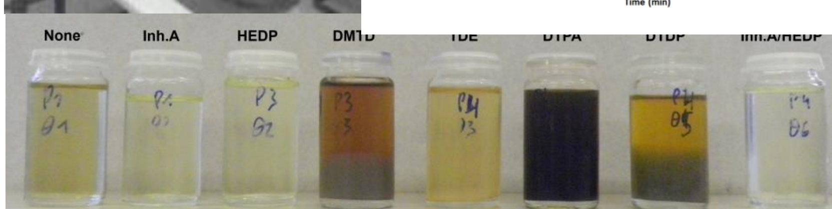
Objective: Close the gap with reality

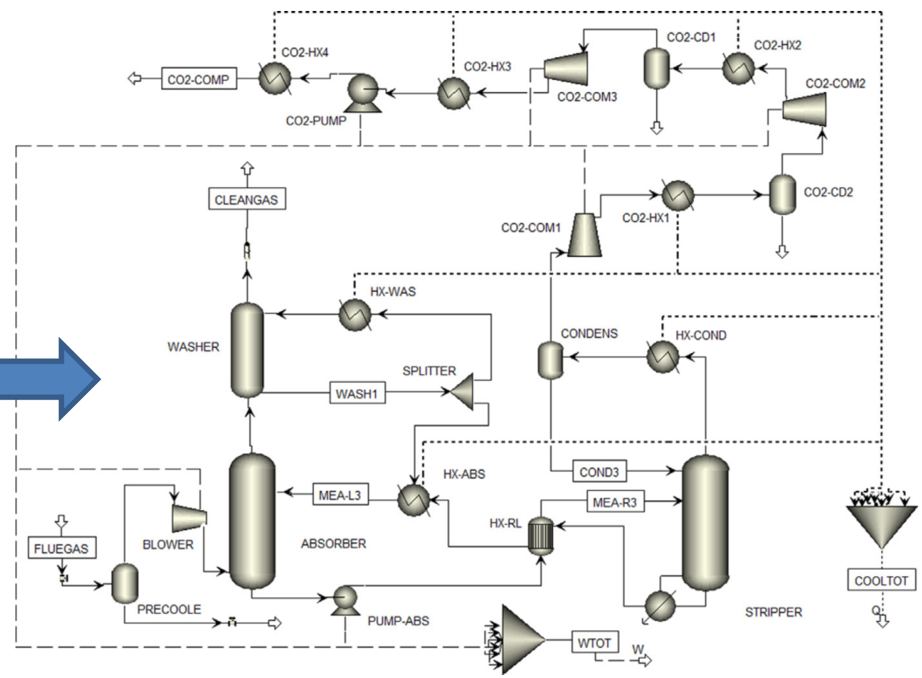
- What impact of contaminants on solvent degradation ?
  - Chemistry, kinetics, influence of O_2, T, SOx and NOx
  - Results included into a global process model











DOI: 10.1016/j.compchemeng.2015.05.003

DOI:10.1021/ie5036572

Comparison of existing technologies (SATURN)

Technology	Cryogenic	Amine (MEA)	Hot Potassium Carbonate (HPC)	Membranes
TRL	6 - 7	8+	8+	7 - 8
Capture rate (%)	90	90	80-95	60-90
Purity of CO_2 product (mol-%)	>99 (liquid)	> 99	>99 (dry basis)	>99 (liquid)
Ability to deal with SOx and NOx	Limit at 200 mg/Nm³ , but impact not clear	Max 5-10 ppm to guarantee 5 year lifetime for amines	Minimize SO_2 and NO_2 to avoid HSS	Low impact of SO_2 but SO_3 impacts membrane performances. SO_3 with water may be harmful
Water removal	Critical to remove water down to ppm level	Cooling down to absorber inlet temperature and condensation	Cooling down to absorber inlet T and condensation	Water condensation may reduce the effectiveness of the membrane.
Unit footprint ($m^2/tCO_2/d$)	2 - 3 (100 t/d)	Pilot = 15 (0,6 t/d) Industrial scale: 4,8 (50 t/d)	Pilot = 35 m² (1-2.5 t/d)	2 - 5 (200-300 t/d)
Thermal energy demand (GJ/t)	0 (full electric)	2-4	1,5 - 3	0 (full electric)
Electricity demand (kWh/t)	250-400	20-140	> 180	440-650
Minimum CO_2 concentration in feed	> 10 %	> 5 %	> 5 %	> 10-15 %
Flexibility toward varying CO_2 input	Good	Buffering needed	Buffering needed	Good

Objective: Close the gap with reality

- Liège University Campus as living lab
  - Combined Heat & Power – Wood + NG
  - District heating network – Electricity network
  - Pilot CO_2 capture plant under design (Resiliency Fund EU Green Deal)
  - Research and Education ! New Master in Energy Engineering !

To be continued…

3. Re-use of CO_2 ?

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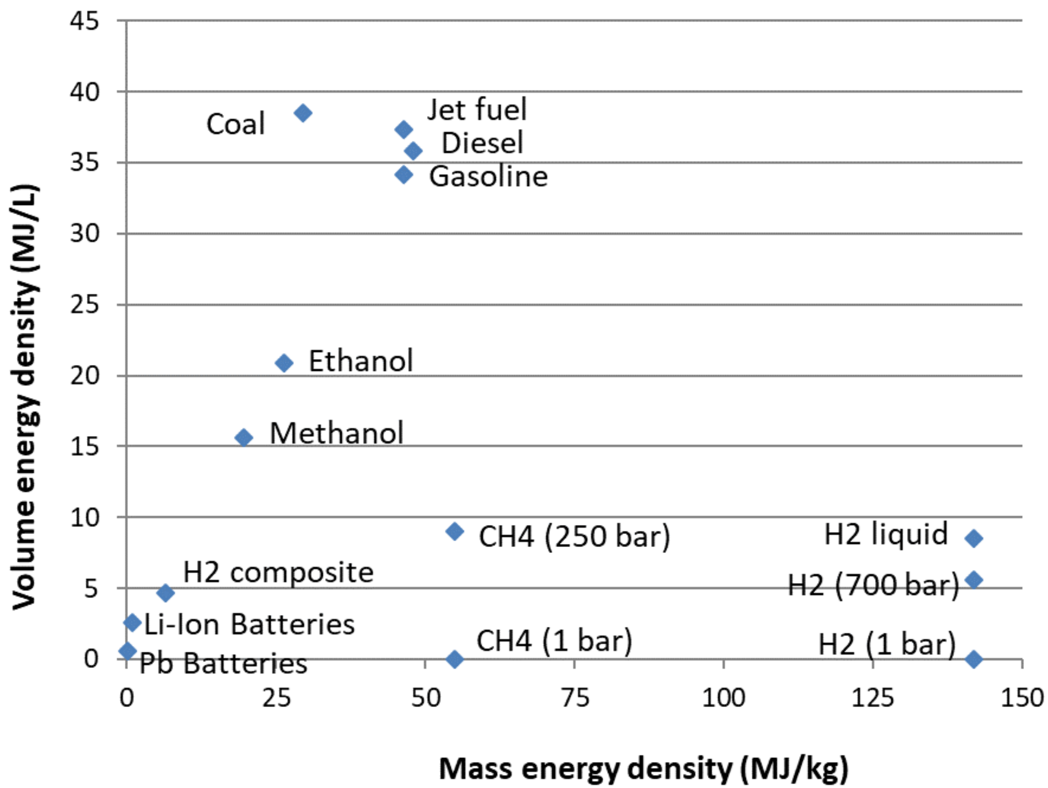
CO_2 re-use

CCUS? => CCU is a different reality compared to CCS!

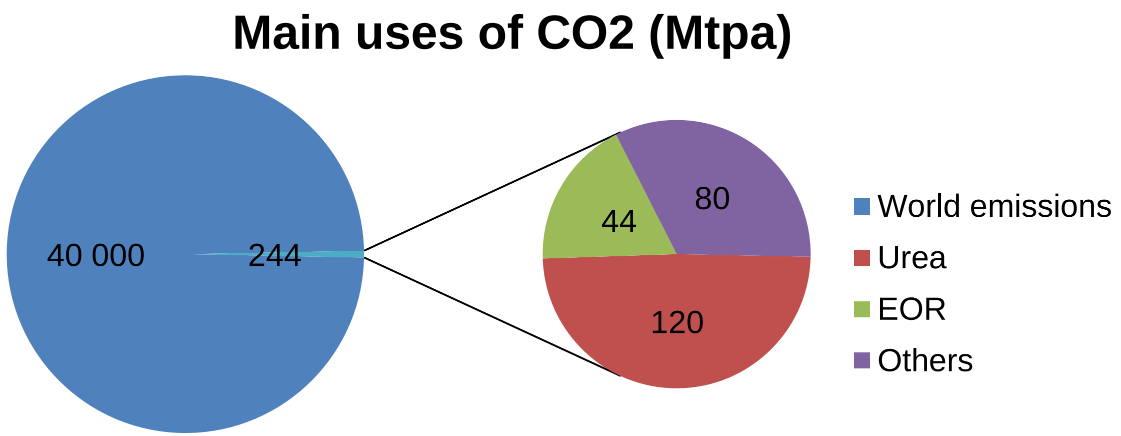
- Our society is currently based on fossil carbon
- C leads to fantastic materials and energy carriers !



=> Don't decarbonize, but instead, defossilize!

CO_2, waste or feedstock?

- Need to find replacement sources: Biomass, plastics, and CO_2



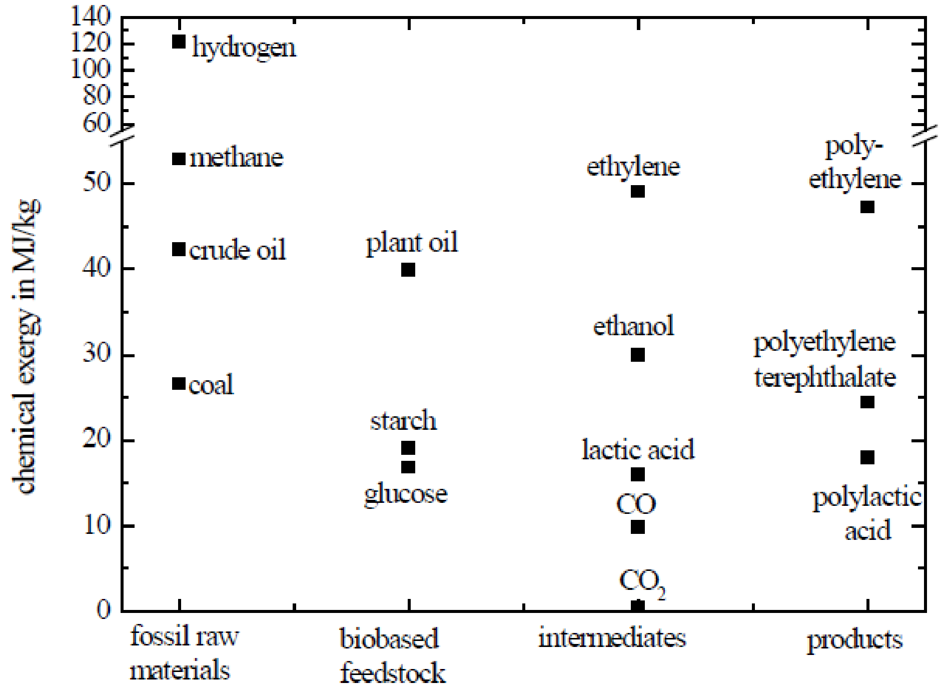
- CO_2 re-use potential up to ~ 4 – 18 Gtpa
  - From 0.6 Gtpa in 2030 to 6 Gtpa in 2050 (Galimova et al, 2023)

- So far, sources for CO_2 are high-purity ones
  - Industrial (Ethanol, Ammonia, Ethylene, Natural gas…)
  - Natural (Dome)
  - In the future: Cement, waste combustion and DAC

Global CCS Institute. Global Status of CCS 2016: Summary Report.
Koytsumpa et al, 2016. https://doi.org/10.1016/j.supflu.2017.07.029
Hepburn et al., 2019. Nature 575, 87
Galimova et al., 2023. J. Cleaner Prod. 373, 133920

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
    - …

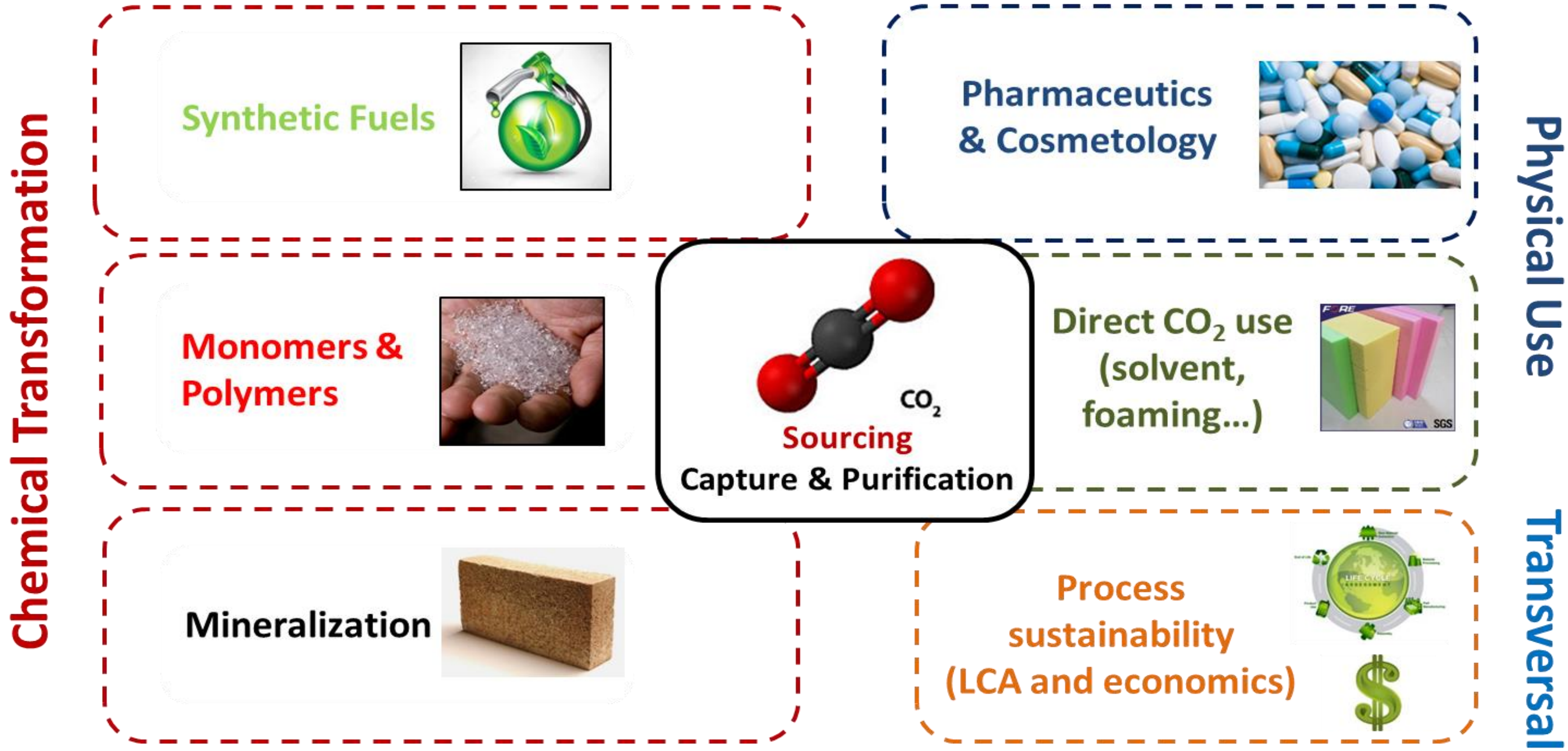


=> At large scale, make sure that the big energy demand is supplied by renewables!

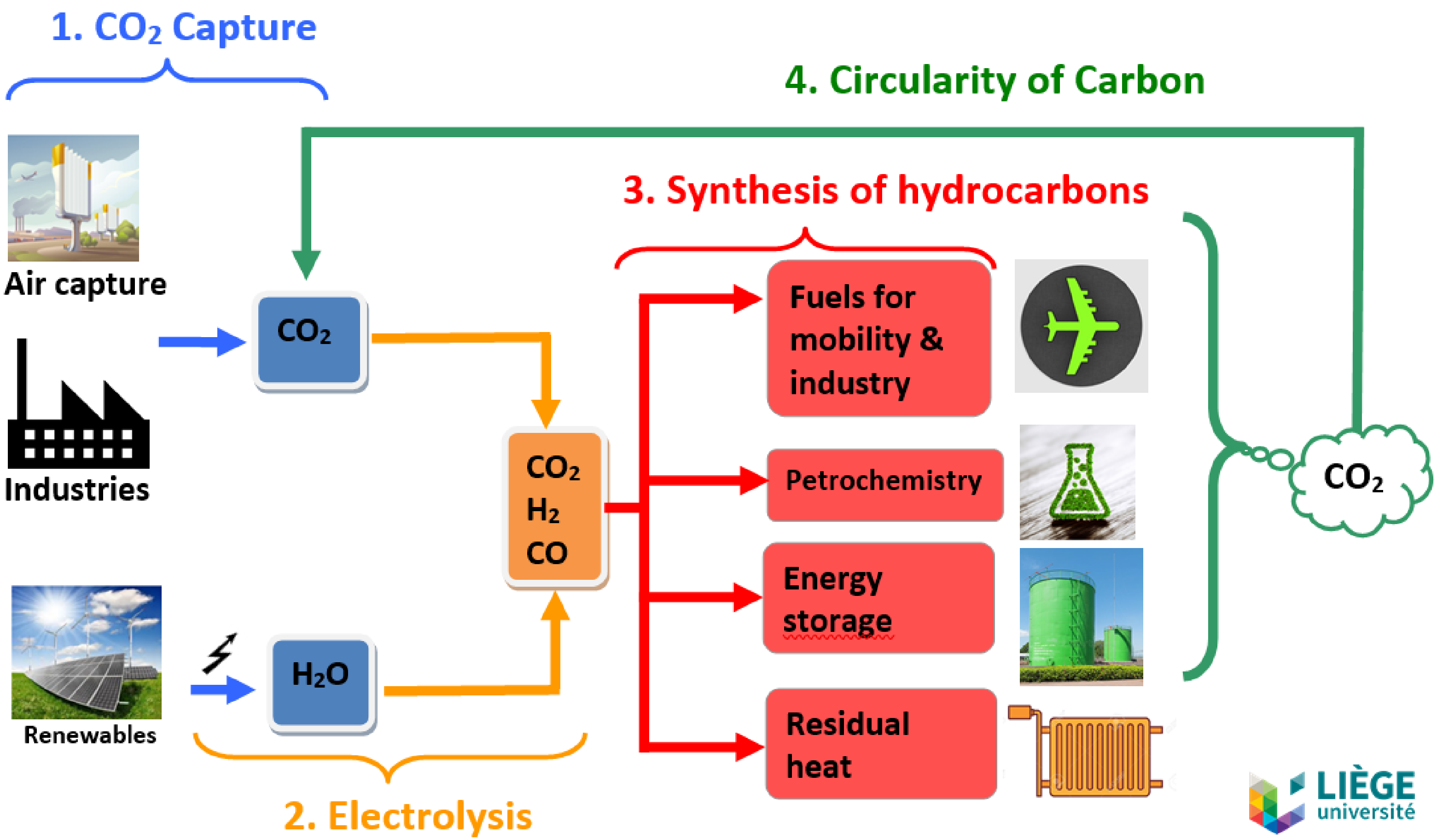
Frenzel et al, 2014. Doi:10.3390/polym6020327

ULiège: FRITCO$_2$T platform

Federation of Researchers in Innovative Technologies for CO_2 Transformation

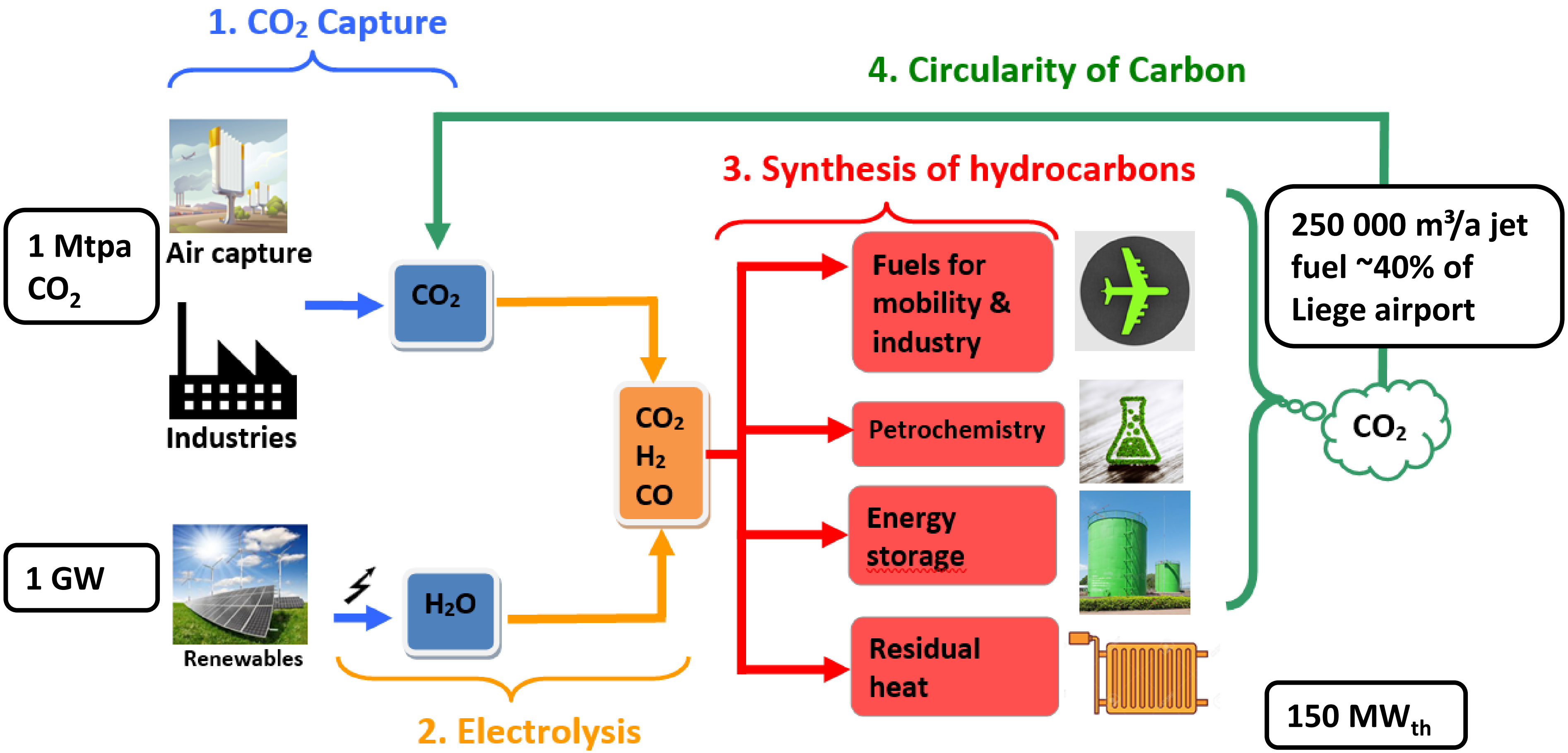


CO_2 to fuels



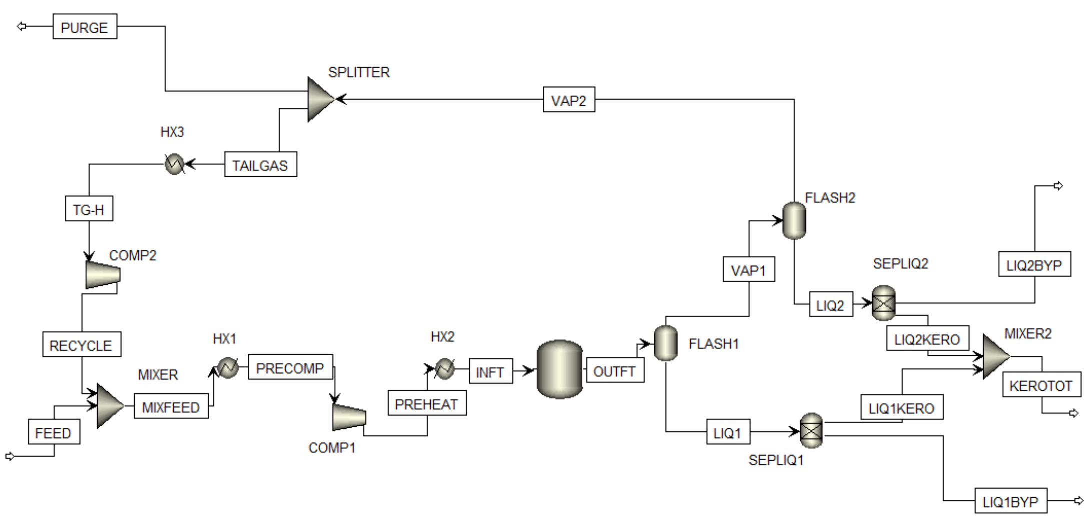
=> A sustainable energy system based on carbon is possible!

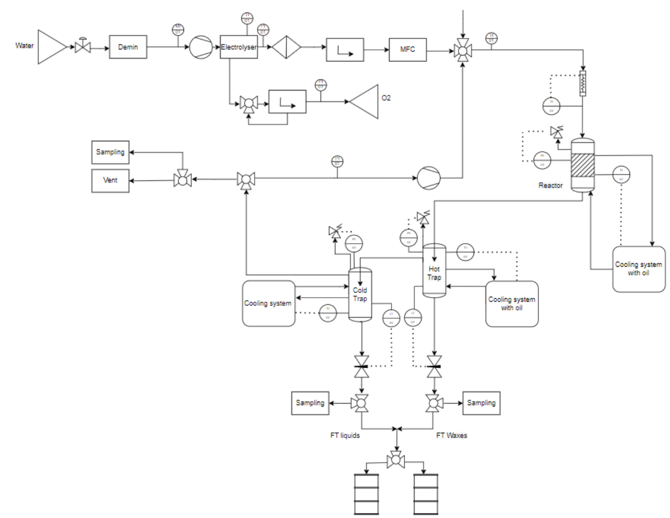
CO_2 to fuels


1. CO₂ Capture
4. Circularity of Carbon
3. Synthesis of hydrocarbons
1 Mtpa CO₂
Air capture
Industries
CO₂
CO₂ H₂ CO
Fuels for mobility & industry
Petrochemistry
Energy storage
Residual heat
250 000 m³/a jet fuel ~40% of Liege airport
CO₂
1 GW
Renewables
H₂O
2. Electrolysis
150 MWth

CO_2 to fuels

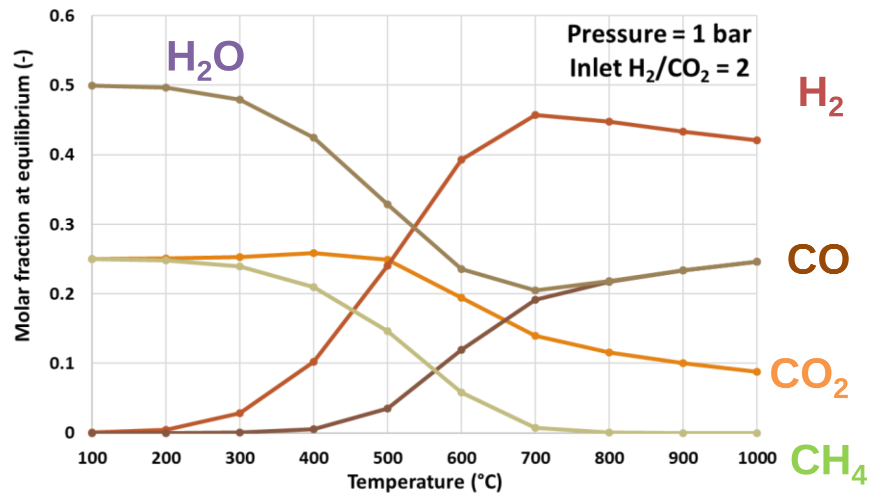
- Experimental development of a Fischer-Tropsch reactor for CO_2 to fuel
  - Electrolysis capacity of 6.6 kW (1.5 Nm³/h)
  - Reactor design and dynamic study





CO_2 to fuels

- Experimental and modelling study of a reverse water-gas shift reaction unit for integration in a Power-to-X process
  - Process optimization
  - Reactor standardization



- Alternative to the RWGS – FT
  - Development of tandem catalysts for CO_2 to Methanol then C6+ hydrocarbons
  - Collaboration with KU Leuven

CO_2 re-use

- Myth 1: We must decarbonize to achieve our climate goal
- Fact 1: CCU always requires large amounts of (renewable) energy

- Myth 2: CCU just delays CO_2 emissions and therefore—even if deployed at a large scale—will not help fight climate change
- Fact 2: Direct air carbon capture + CCS using renewable energy allows full circularity of CO_2 and water

- Myth 3: e-molecules are and will remain too expensive until at least 2035
- Fact 3: CCU allows leveraging of existing infrastructure, making the energy transition less disruptive

Mertens et al, 2023. Joule. Carbon capture and utilization: More than hiding CO_2 for some time. doi.org/10.1016/j.joule.2023.01.005

Eurecha's Student Contest Problem 2024

- Manufacturing Chemical Products from CO_2 using Renewable Energy Resources

You …

- … like modeling, simulation, and optimization?
- … want to work on sustainable solutions for future material supply?
- … want to gather experience in team-based work in chemical engineering?

→ 1st prize: 1000 € & presentation at the ESCAPE conference 2024 in Firenze, Italy
→ 2nd prize: 750 € & presentation at the CAPE Forum 2024 (place to be set)
→ Publication on the EURECHA Website

Interested? More information (to come soon):
https://www.wp-cape.eu/index.php/student-contest-problem/

Organized by: EURECHA, EFCE

https://www.wp-cape.eu/index.php/eurecha/ https://efce.info/Section_Energy.html

Sponsored by: PSE for SPEED

https://www.pseforspeed.com/

4. Conclusions and perspectives

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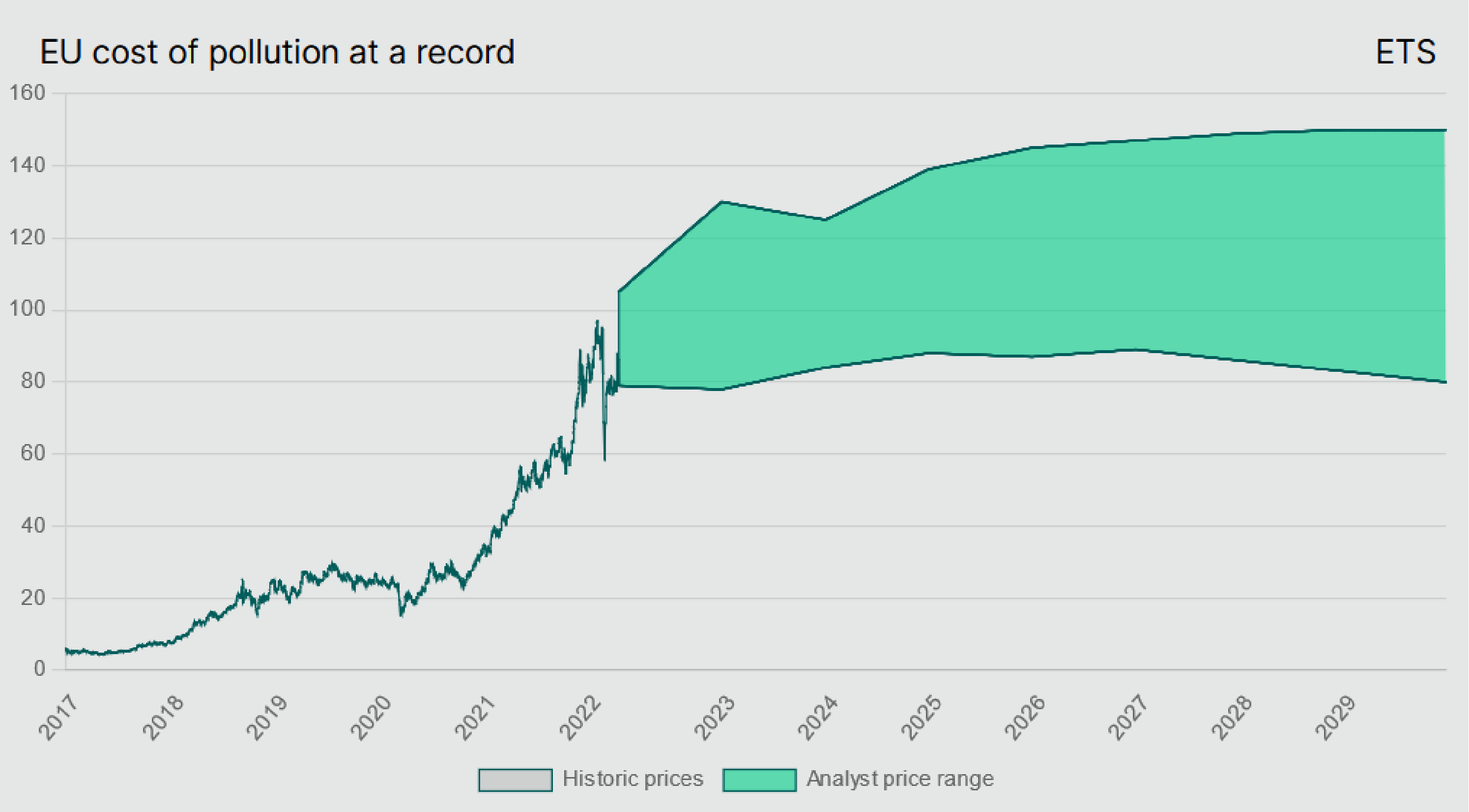
State of technology CCU - CCS

- Capture of CO_2
  - Mature but limited deployment yet
- Storage
  - Commercially applied (mostly EOR), deployment in progress
- Re-use
  - Maturity depends on technology, from TRL 1 to 9
- Big acceleration due to Paris COP21 agreement and environmental urgency, but mostly related to subsidies and regulations!
- Next steps?

=> *make it happen!*

Driver for CCU and CCS

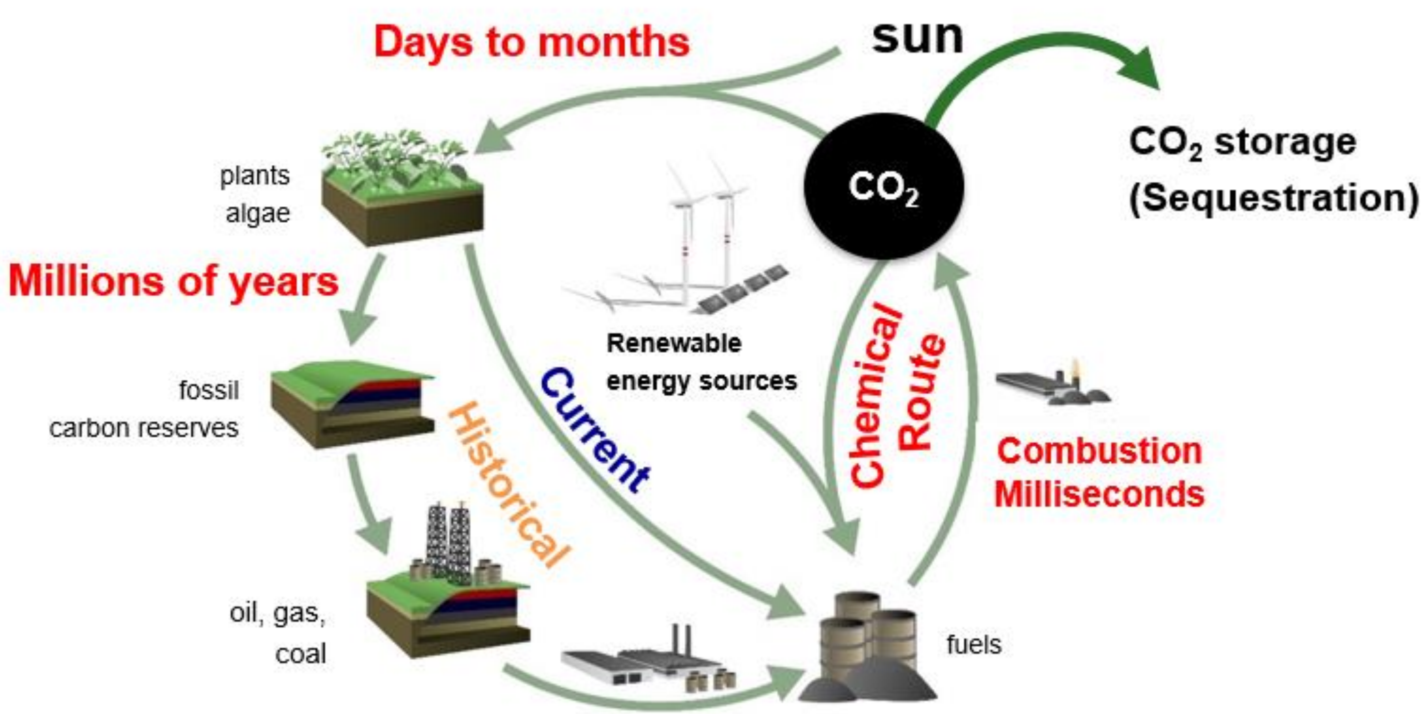
- CO_2 capture is not cheap ~ 40-60 €/t
- ETS market has dramatically increased recently !



https://akercarboncapture.com/

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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