

La transition énergétique dans l'industrie: un défi de taille!

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03/02/2026

Sommaire

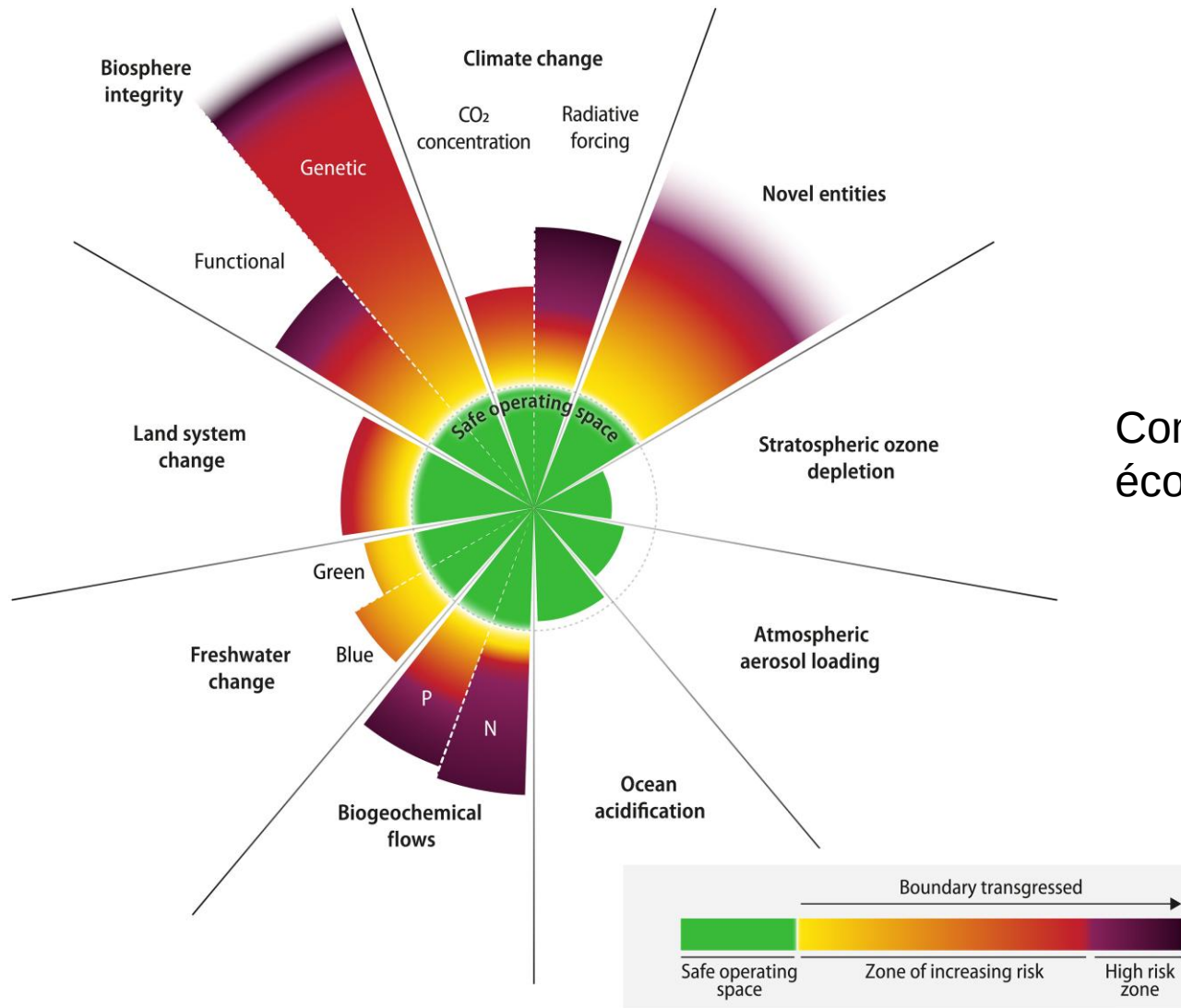
- Le contexte de la transition énergétique en chiffres
- La capture du CO₂
 - Sources concentrées
 - Emissions négatives de CO₂
- Transport et stockage du CO₂
- Tout au long de la presentation: focus sur des activités menées à l'Université de Liège
 - NB: certains slides en Anglais
 - N'hésitez pas à poser des questions

Le contexte de la transition énergétique

Structure

- Limites Planétaires et changement climatique
- La transition énergétique et les émissions de CO_2
- Le découplage
- Quelle motivation au changement? Le marché ETS
- Réponses possibles

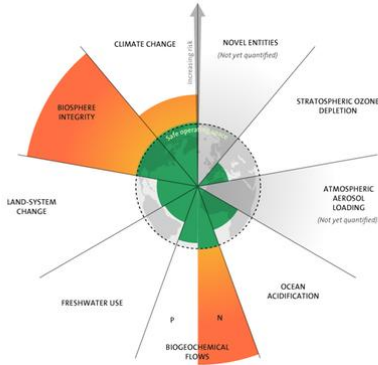
Limites planétaires



Comment garder un écosystème vivable?

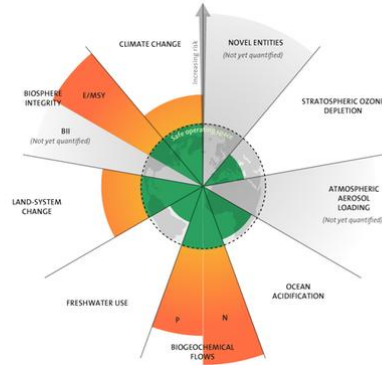
Limites planétaires

2009



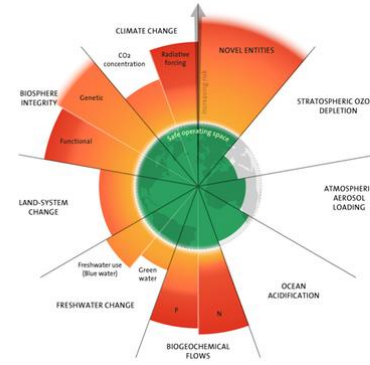
7 boundaries assessed,
3 crossed

2015



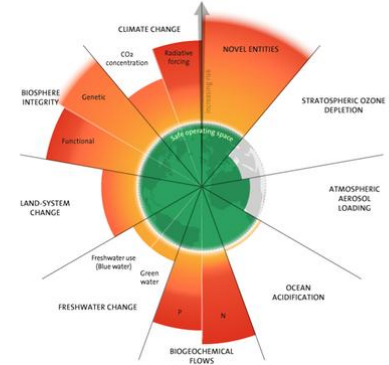
7 boundaries assessed,
4 crossed

2023



9 boundaries assessed,
6 crossed

2025



9 boundaries assessed,
7 crossed

“Crossing boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes.”

“Planetary boundaries are interdependent. We cannot consider planetary boundaries in isolation in any decision-making on sustainability.”

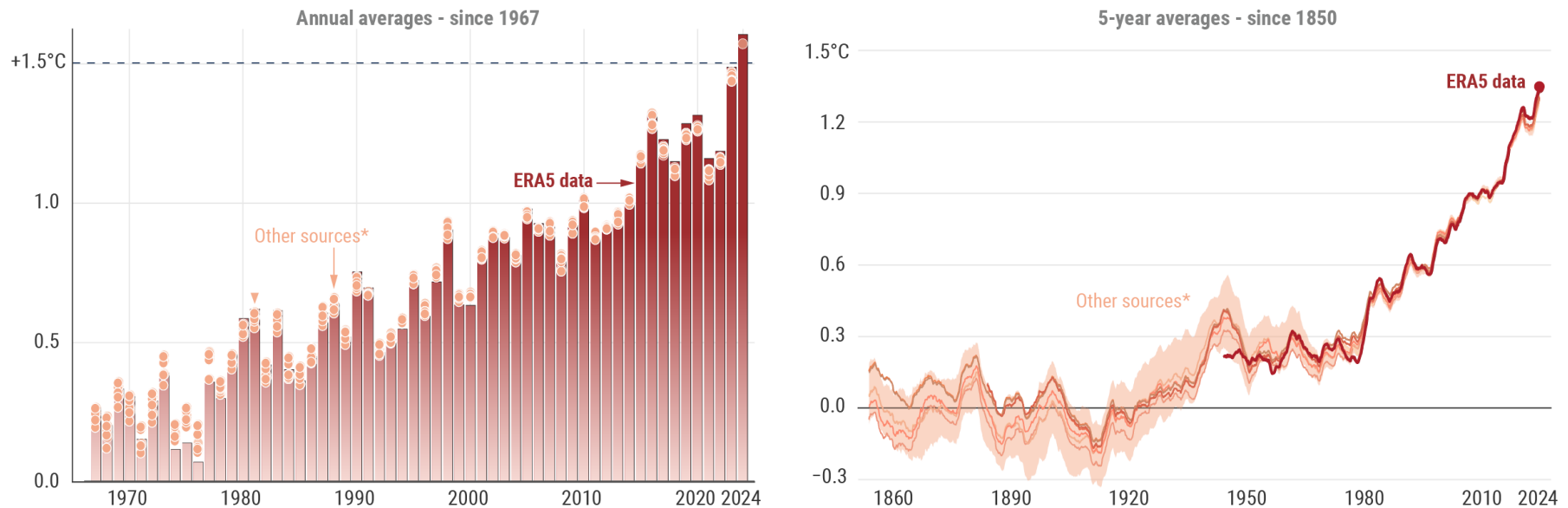
Changement climatique

2024 a été la 1ère année à dépasser le niveau de température pré-industriel de plus de 1.5°C



Global surface temperature increase above pre-industrial

Reference period: pre-industrial (1850–1900) • Credit: C3S/ECMWF



*Other sources include JRA-3Q, GISTEMPv4, NOAA GlobalTempv6, Berkeley Earth and the HadCRUT5 ensemble mean. Shading shows the range of the HadCRUT5 ensemble.



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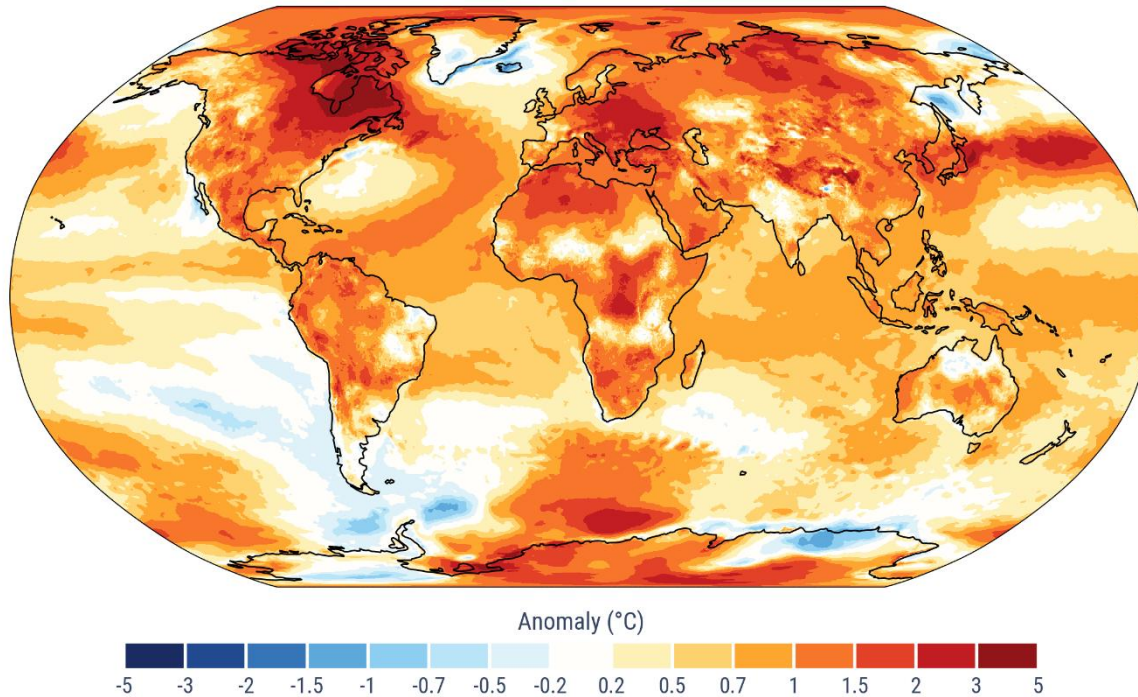
Changement climatique

Ce changement climatique n'est pas distribué uniformément!



Surface air temperature anomalies in 2024

Data: ERA5 • Reference period: 1991–2020 • Credit: C3S/ECMWF



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Changement climatique

- 2015: L'Accord de Paris

“Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change”

- 2025: COP 30 au Brazil

- Conference of Parties (COP)
- UNFCCC : United Nations Framework Convention on Climate Change

Changement climatique

- 2025: COP 30 au Brésil
 - ❑ *“Science now tells us that a temporary overshoot beyond the 1.5 limit – starting at the latest in the early 2030s – is inevitable. [...]”*
 - ❑ *Yes, the newly submitted Nationally Determined Contributions represent progress – but they still fall short of what is needed. Even if fully implemented, they would put us on a pathway well above 2 degrees of global warming. Meanwhile, the climate crisis is accelerating. [...]*
 - ❑ *Let us be clear: the 1.5°C limit is a red line for humanity. It must be kept within reach. And scientists also tell us that this is still possible. If we act now, at speed and scale, we can make the overshoot as small, as short, and as safe as possible – and bring temperatures back below 1.5°C before century’s end.”*

António Guterres, UN Secretary-General

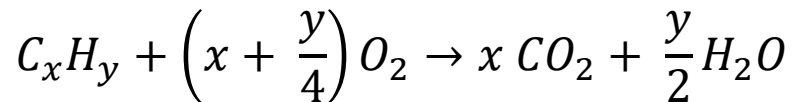


Gaz à effet de serre (GES)

- Un phénomène naturel... amplifié par les activités humaines

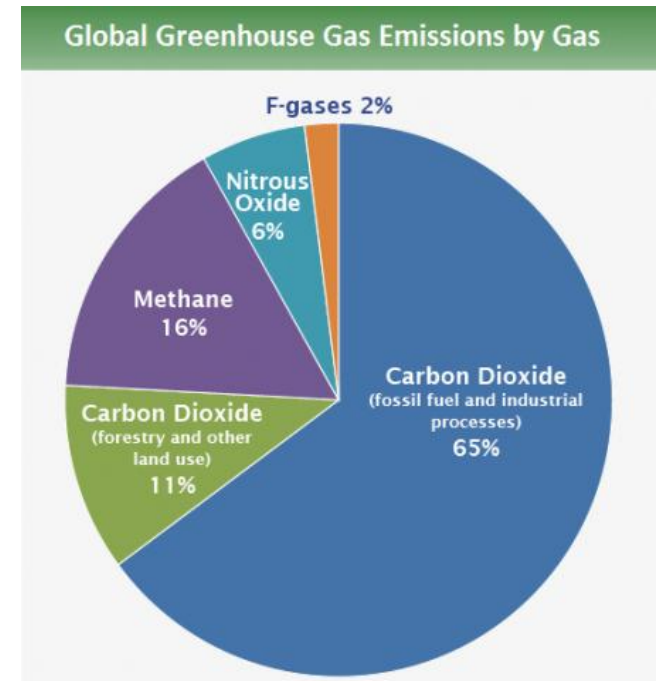


- A part l'eau, le CO₂ est le principal GES d'origine humaine



- Emissions annuelles (2023, monde):
~ 53 Gt CO₂ équivalent (CO_{2,eq})
Dont 73.7% est du CO₂ => 39 Gt CO₂

- Belgique (2023):
~ 104-106 Mt CO_{2,eq}
~ 84 Mt CO₂



Chaque tonne de CO₂ contribue au changement climatique

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO₂ emissions (GtCO₂)

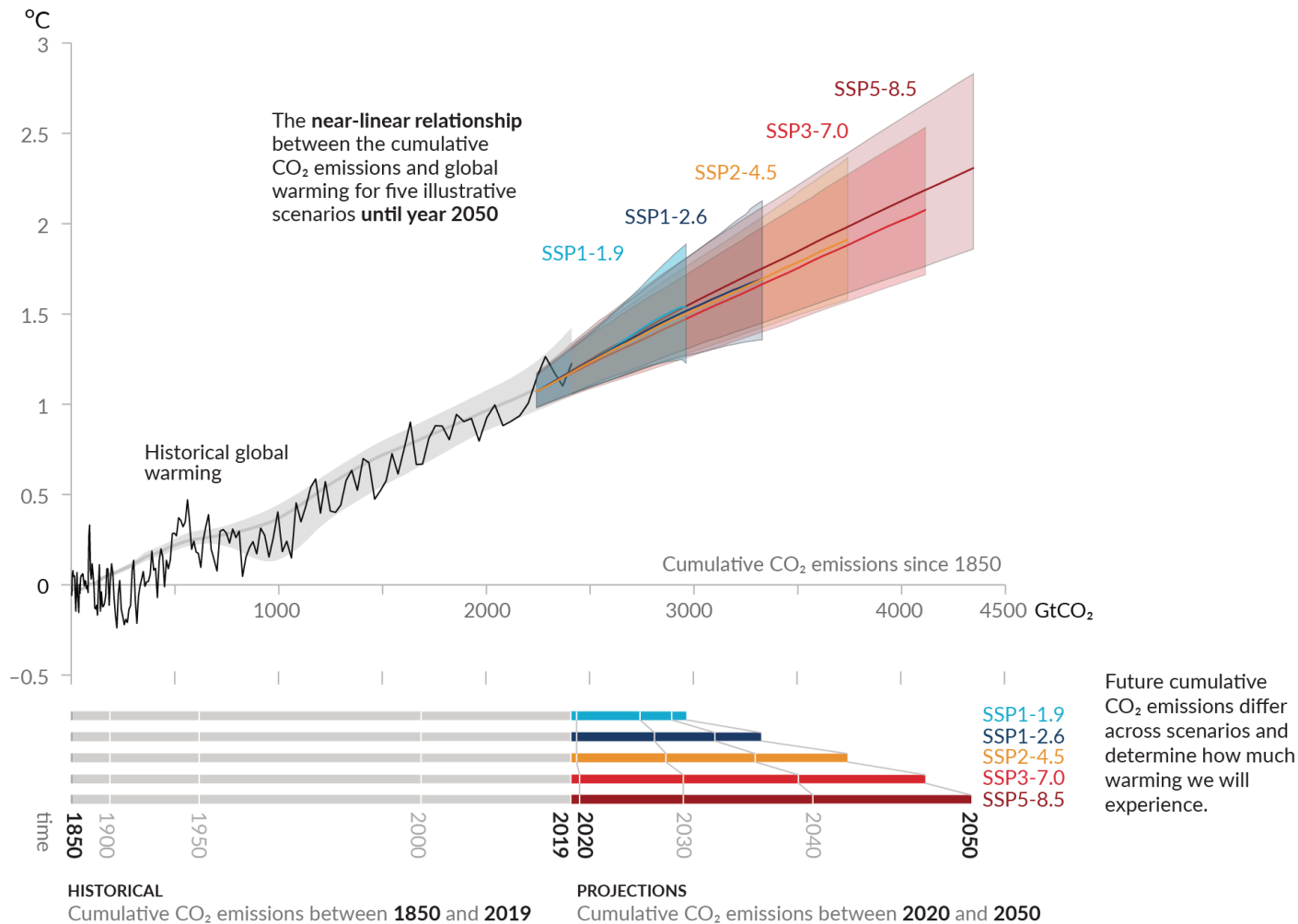


Figure SPM.10 in IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–32, doi: [10.1017/9781009157896.001](https://doi.org/10.1017/9781009157896.001).]

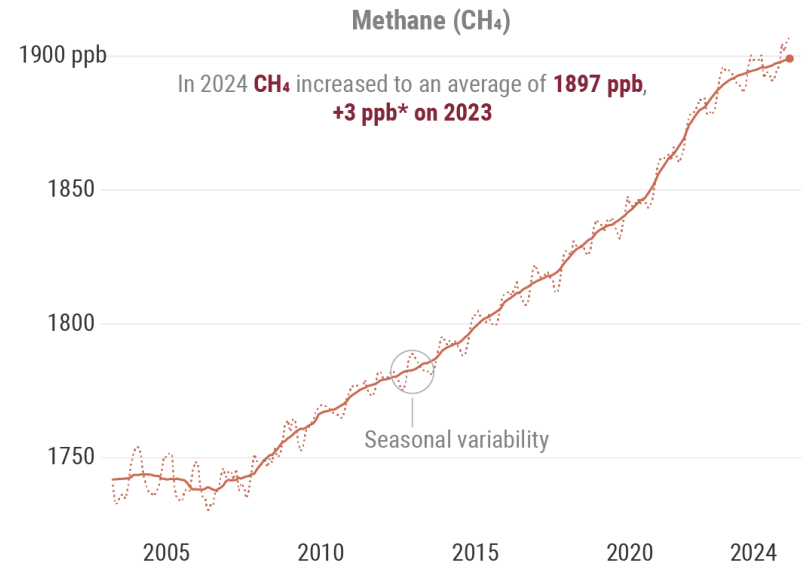
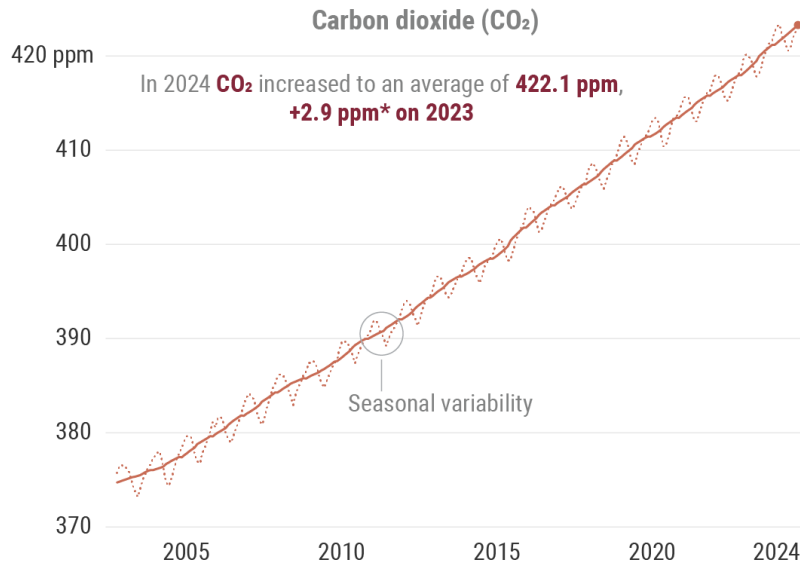


Pas que le CO₂ !



Global atmospheric concentration of greenhouse gases

..... Monthly global mean column-average concentration — 12-month average



* The uncertainty of the annual increase is CO₂ ±0.3 ppm and CH₄ ±2 ppb

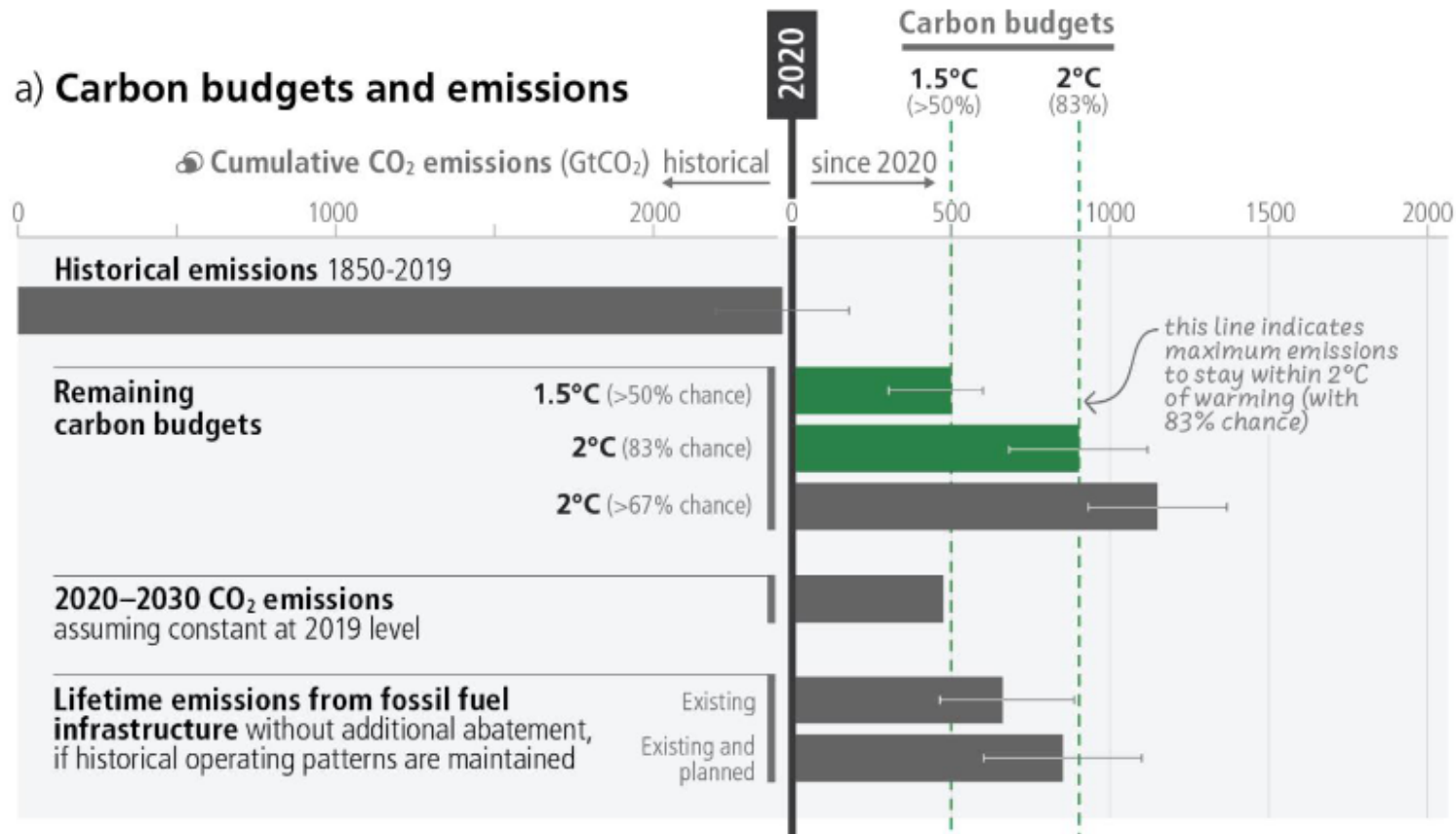
Data: C3S/Obs4MIPs (v4.6) consolidated (2003–2023), CAMS preliminary near real-time data (2024) GOSAT (CH₄) and GOSAT-2 (CO₂) records. Spatial range: 60°S–60°N over land.
Credit: C3S/CAMS/ECMWF/University of Bremen/SRON



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Il y a un budget de CO_{2,eq} pour limiter le réchauffement à 1.5°C ou 2°C



- En 2020, le budget restant était :
 - 500 Gt CO_{2,eq} pour 50% de chances de rester sous 1.5°C
 - 1150 Gt CO_{2,eq} pour 67% de chances de rester sous 2°C

~~La transition énergétique est en route ...~~ révolution



2 objectifs contradictoires:

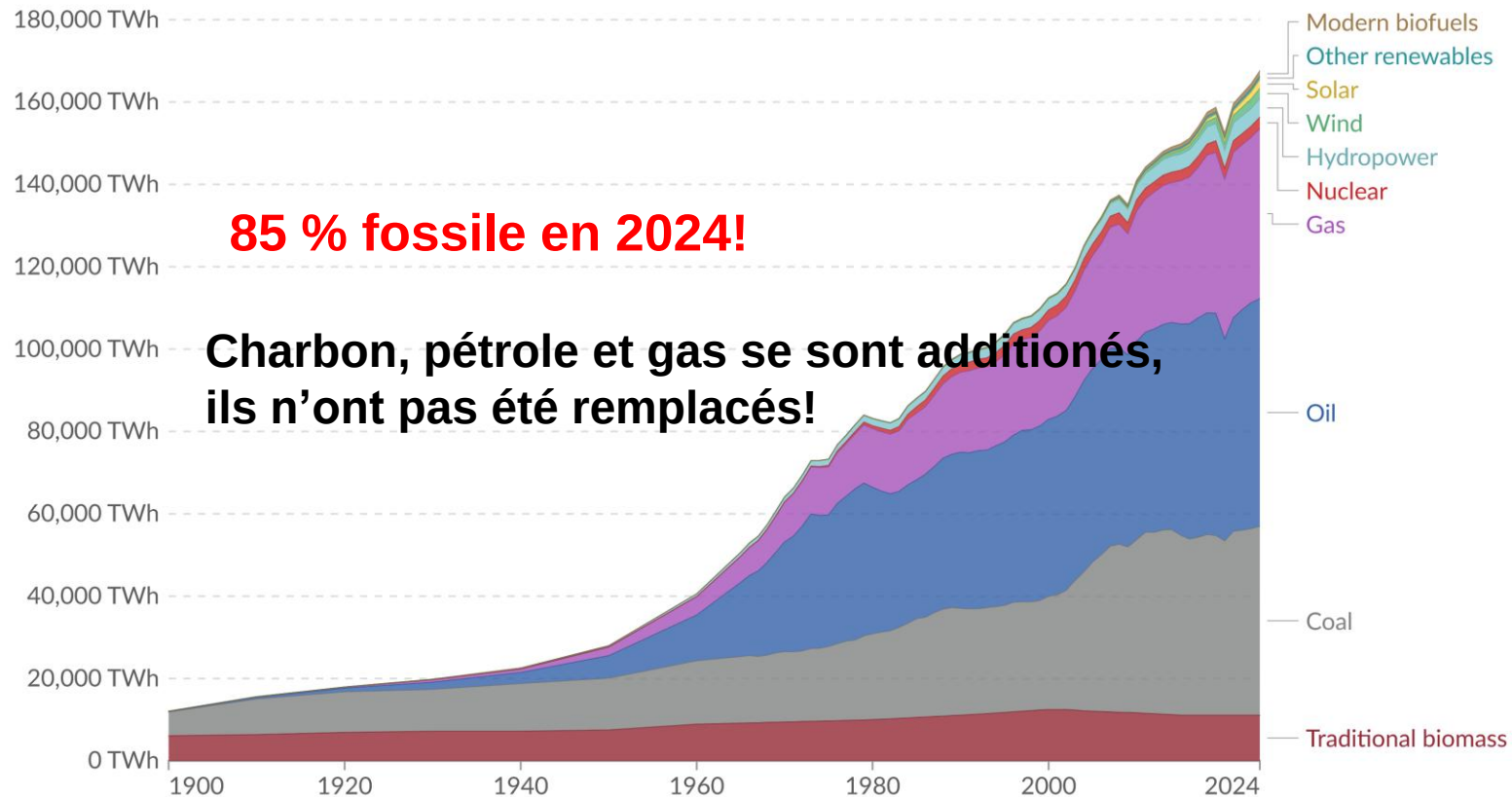
- Limiter les émissions de GES
- Répondre à la demande d'énergie, en croissance!

Répondre à la demande d'énergie est déjà un défi!

Global direct primary energy consumption

Our World
in Data

Energy consumption is measured in terawatt-hours¹, in terms of direct primary energy². This means that fossil fuels include the energy lost due to inefficiencies in energy production.



Data source: Energy Institute - Statistical Review of World Energy (2025); Smil (2017)

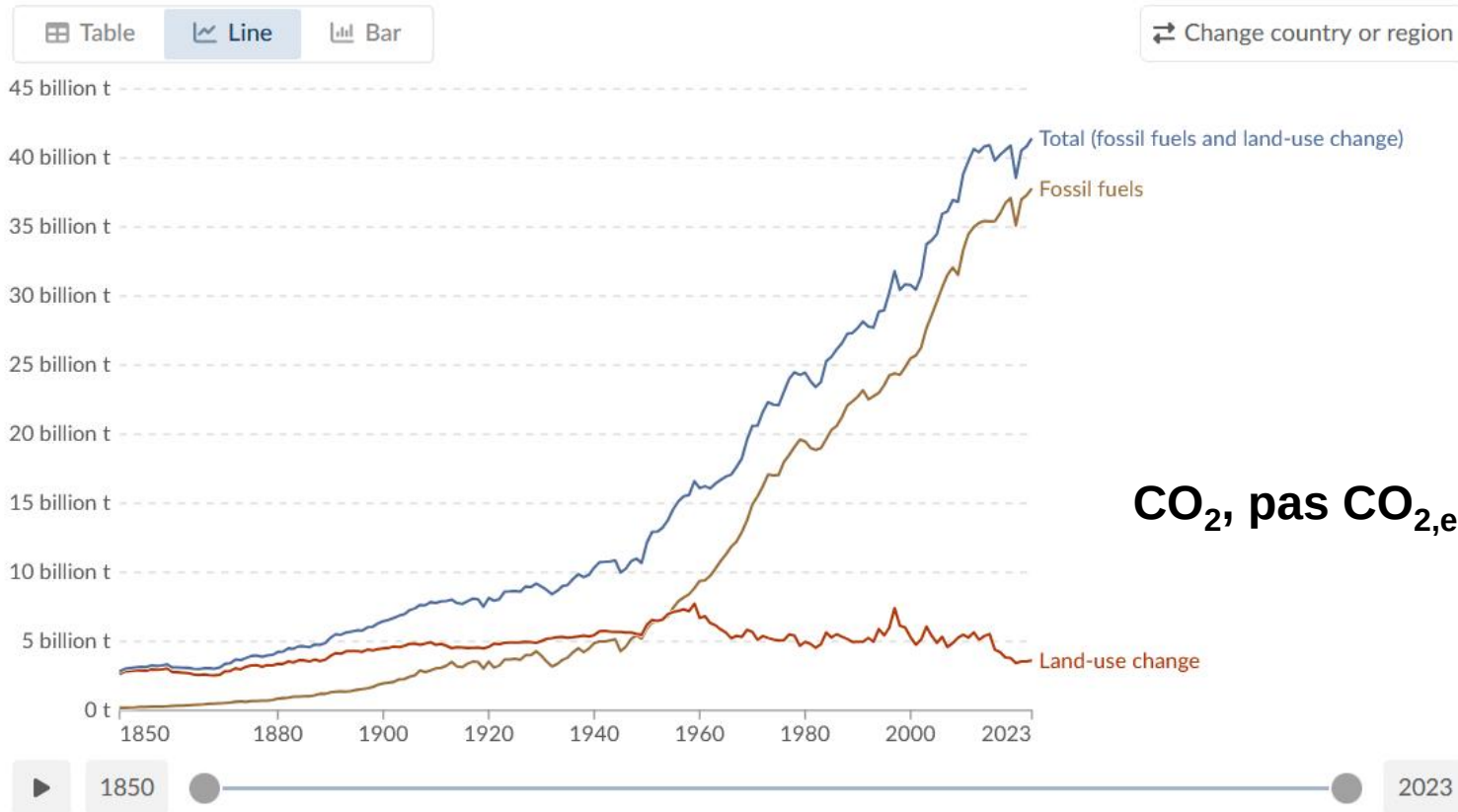
OurWorldinData.org/energy | CC BY

Note: In the absence of more recent data, traditional biomass is assumed constant since 2015.

L'augmentation de la demande énergétique est la principale raison de l'augmentation du CO₂!

CO₂ emissions from fossil fuels and land-use change, World

Our World
in Data



Data source: Global Carbon Budget (2024) - [Learn more about this data](https://ourworldindata.org/co2-and-greenhouse-gas-emissions)
OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

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Enter full-screen



Les émissions n'évoluent pas partout de la même manière!

Annual CO₂ emissions by world region

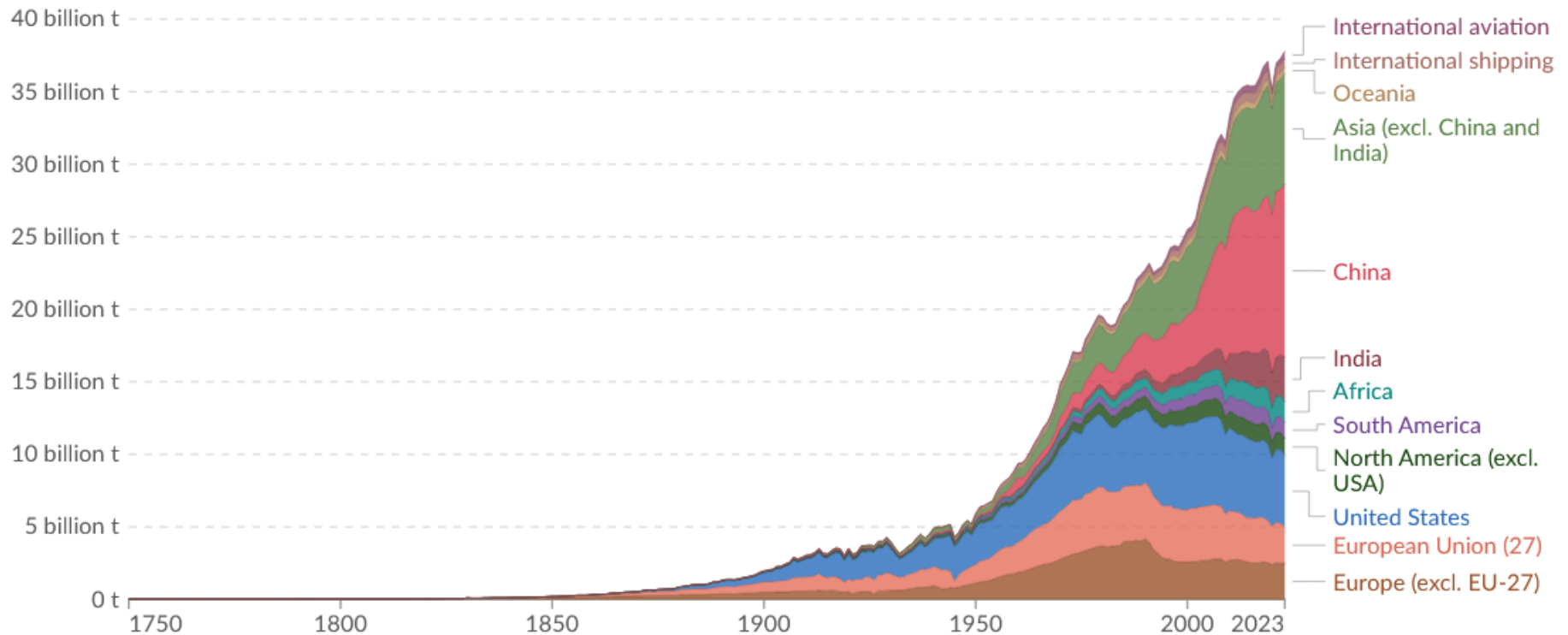
Emissions from fossil fuels and industry are included, but not land-use change emissions. International aviation and shipping are included as separate entities, as they are not included in any country's emissions.

Our World
in Data

Table

Chart

Settings



CO₂ emissions in Belgium ~83 Mtpa

Annual CO₂ emissions

Carbon dioxide (CO₂) emissions from fossil fuels and industry. Land-use change is not included.

Our World
in Data

Table

Map

Line

Bar

Edit countries and regions

Settings



CHEMICAL
ENGINEERING

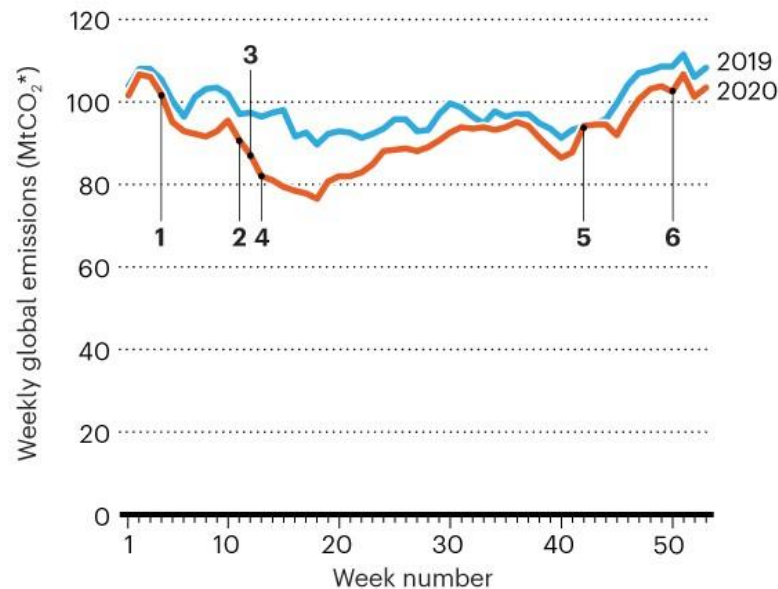
<https://ourworldindata.org/co2/country/belgium>

Impact de la pandémie

- -6.4% CO₂ sur 1 an
- Objectif de l'accord de Paris: -7.6% chaque année pendant 10 ans, pour garder 1.5°C en ligne de mire!

EMISSIONS BOUNCE BACK

After a sharp drop early in the pandemic, global CO₂ emissions rose as worldwide economic activity recovered in 2020. This trend continued even though some countries put fresh restrictions in place as coronavirus infections soared.

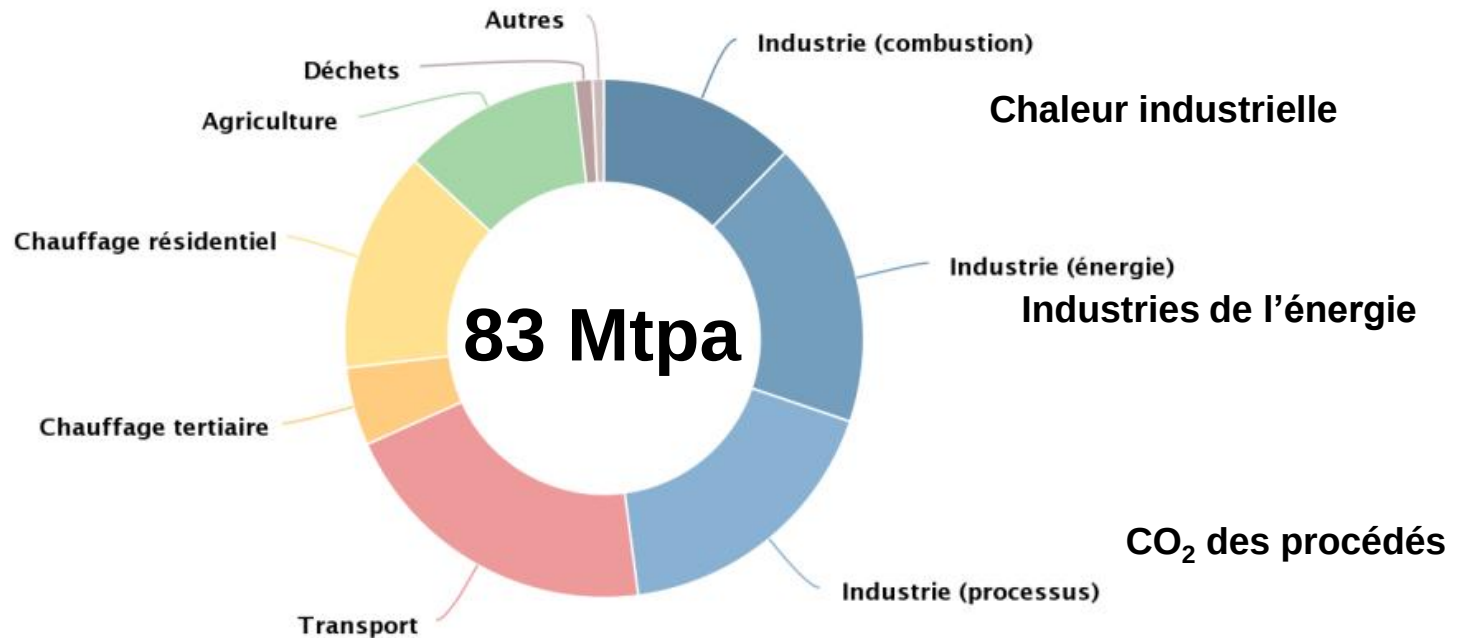


1. China imposes lockdown on Wuhan, where coronavirus was first detected.
2. Slammed by COVID, Italy issues a national lockdown.

<https://www.nature.com/articles/d41586-021-00090-3>

CO₂ emissions in Belgium

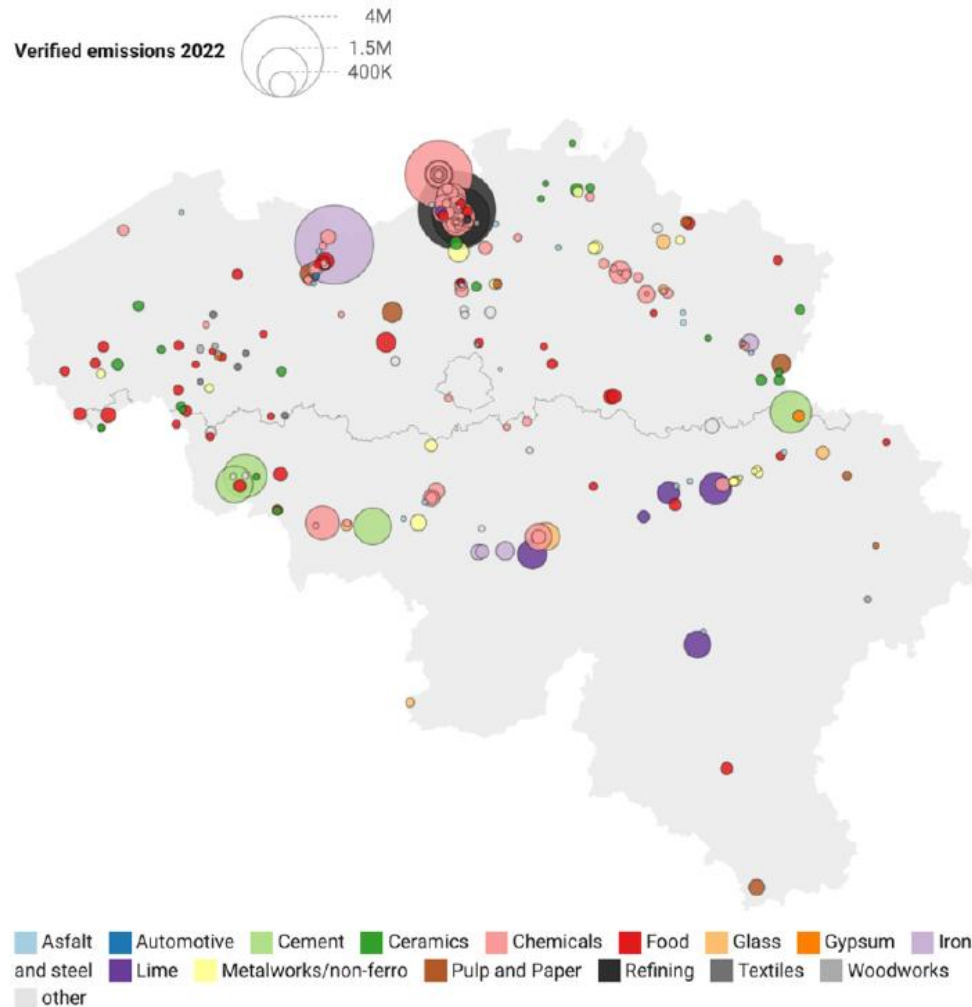
- Belgium CO₂ emissions ~ **83.4 Mt/a**
 - ~ 7.13 t/hab.a => ~ 20 kg/day!!
- **Les émissions de CO₂ en Belgique viennent à plus de 40% de l'industrie!**



climat.be



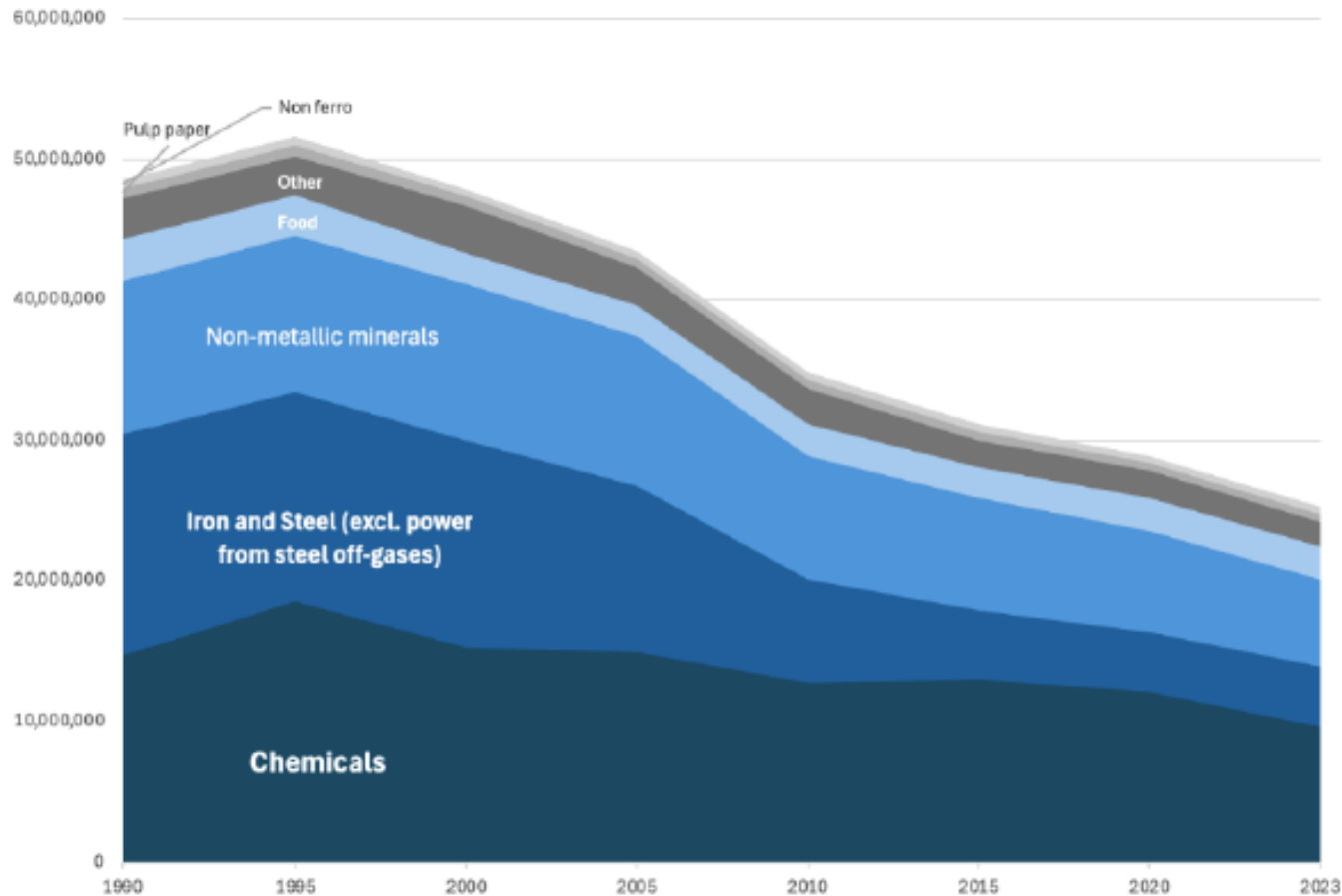
Industrial CO₂ emissions in Belgium



EU ETS installations in industry and 2022 emissions (sources: EUTL/VUB). For iron and steel this excludes emissions from waste gases for power production.



Industrial CO₂ emissions in Belgium



Evolution of industrial greenhouse gas (GHG) emissions (t CO₂-eq) - Source: Belgium, 2024, CRT



Industrial CO₂ emissions in Belgium

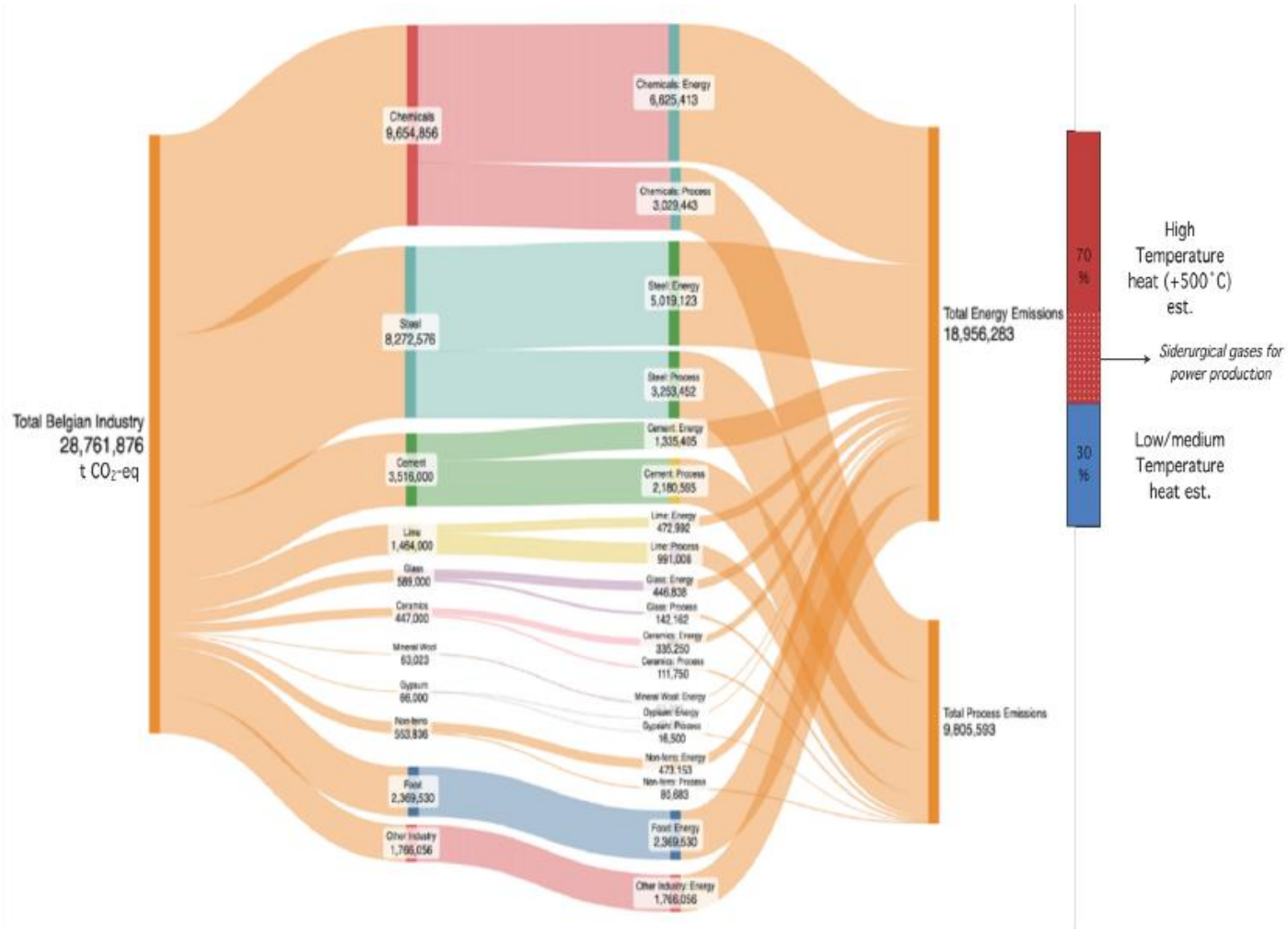


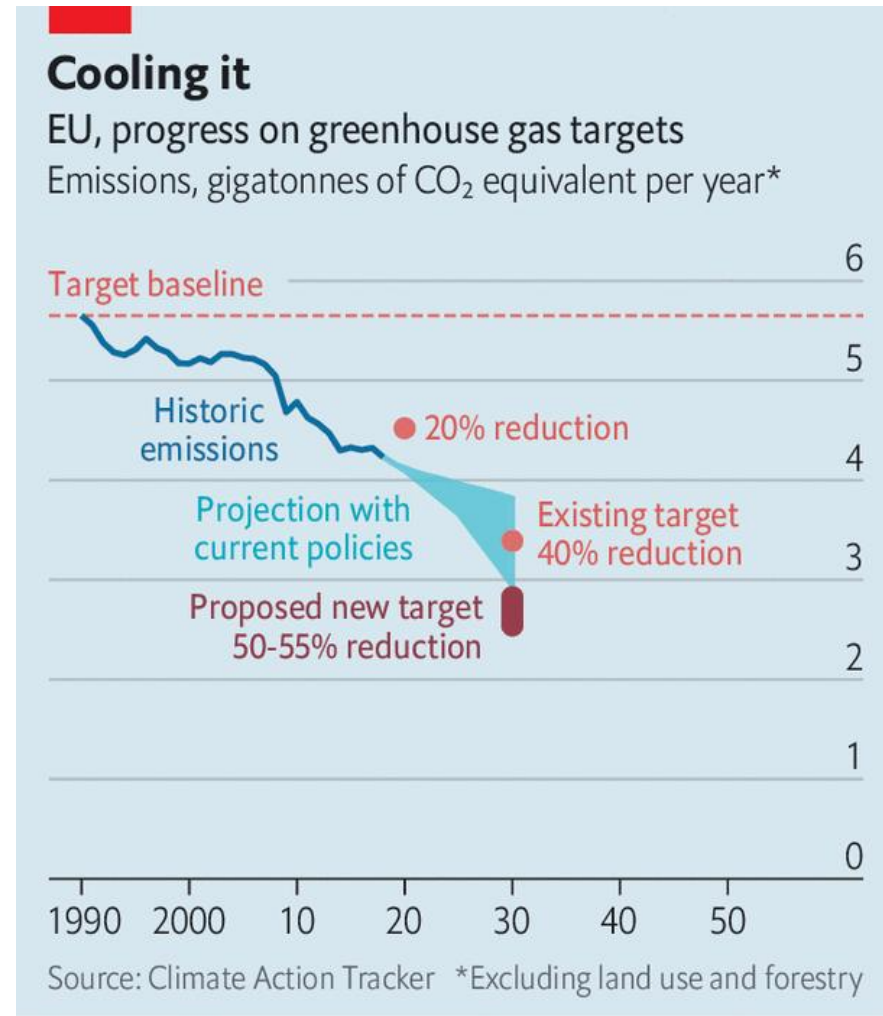
Figure 66: Industrial CO₂ emissions per sector with an estimate of process emissions and emissions related to high and low/medium heat in Belgian industry. Based on Belgium, 2024, CRT and expert guesstimates¹⁶⁹.



CO₂ targets at EU level

The European Green Deal

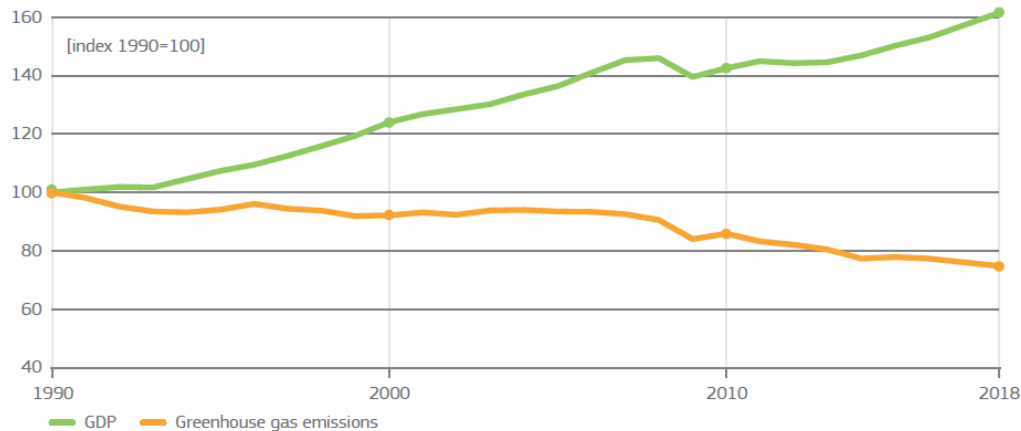
- Carbon neutrality by 2050
- - 55% CO₂ by 2030
- - 90% CO₂ by 2040



The Economist

Need for decoupling!

Between 1990 and 2018, greenhouse gas emissions **decreased by 23%**, while the economy **grew by 61%**.



EU GDP
up **61%**

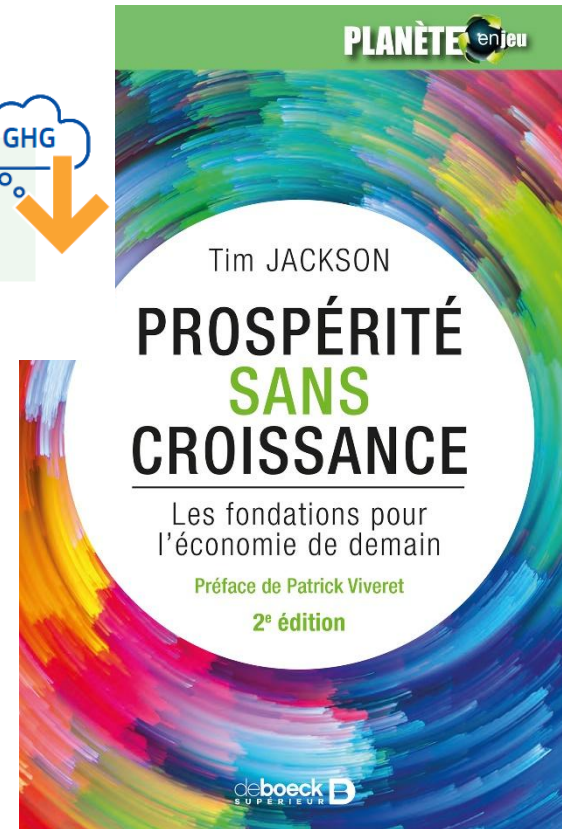
1990-2018

Greenhouse
Gas Emissions
down **23%**

1990-2018

Decoupling = society growth WITH
CO₂ reduction!

For more discussion about growth, see Tim
Jackson: “Prosperity without growth”



Kaya 's relation & decoupling

- Kaya's relation relates many techno-economical variables

$$CO_2 = \frac{CO_2}{MWh} \times \frac{MWh}{k\text{€}} \times \frac{k\text{€}}{hab} \times hab$$

Emission factor

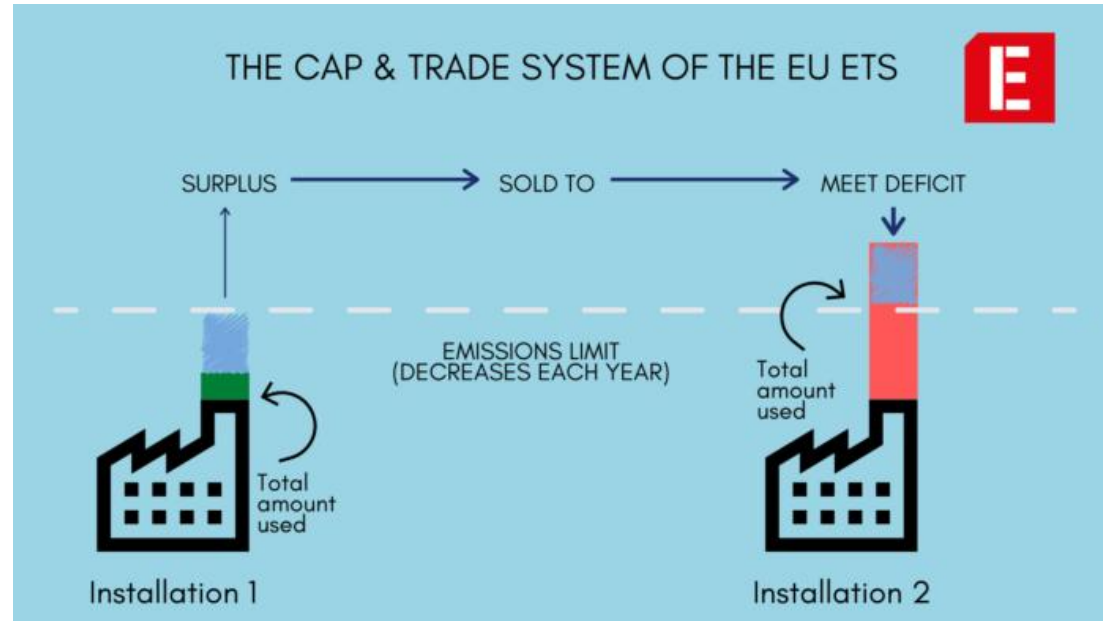
Energy Intensity

Gross Domestic Product

Population growth

Le marché du CO₂ en Europe: ETS

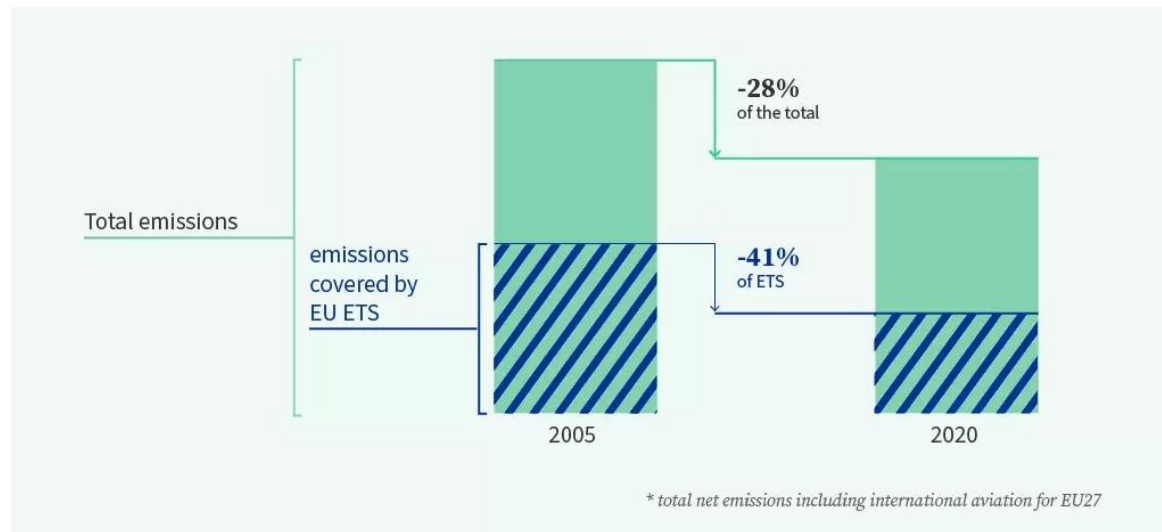
- EU Emission Trading System (ETS) ~ principale motivation pour l'industrie



- Other sectors, other drivers:
 - Monitoring of emissions out of ETS (Effort sharing)
 - Legislations with set objectives (energy efficiency, cars and truck emissions, minimal share of renewables...)
 - Support for CCUS technologies

Driver for change in industry: EU ETS

- The EU Emission Trading System (ETS) ~ Carbon Market
 - 11 000 plants in EU, 45% of EU emissions
 - Heavy industries (energy, raw materials) + commercial EU aviation
- This market is constantly evolving, with decreasing cap!

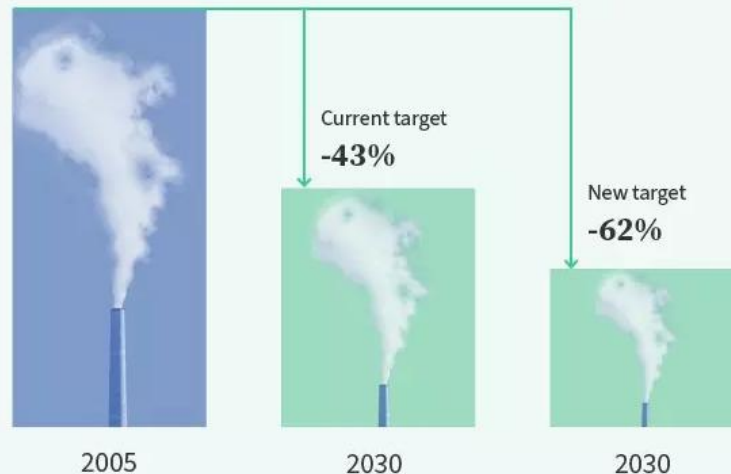


Driver for change in industry: EU ETS

- This market is constantly evolving, with decreasing cap!
 - New sectors
 - Marine transportation fuels
 - Residential energy use
 - Transportation fuels
- } ETS 2, supposed to start in 2027-28



more **ambitious** emissions
reduction **goals**

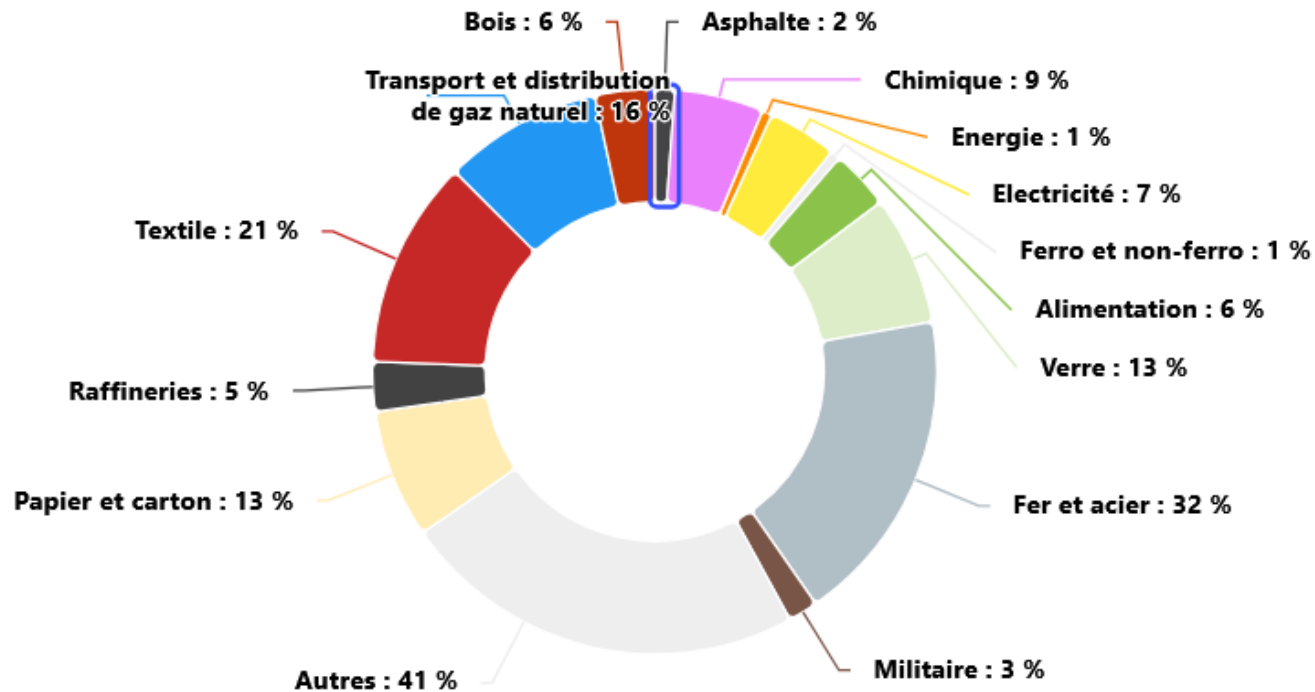


Phase 4 objectives (2021-2030)

Current ETS Industries in Belgium

Installations en Belgique par secteur

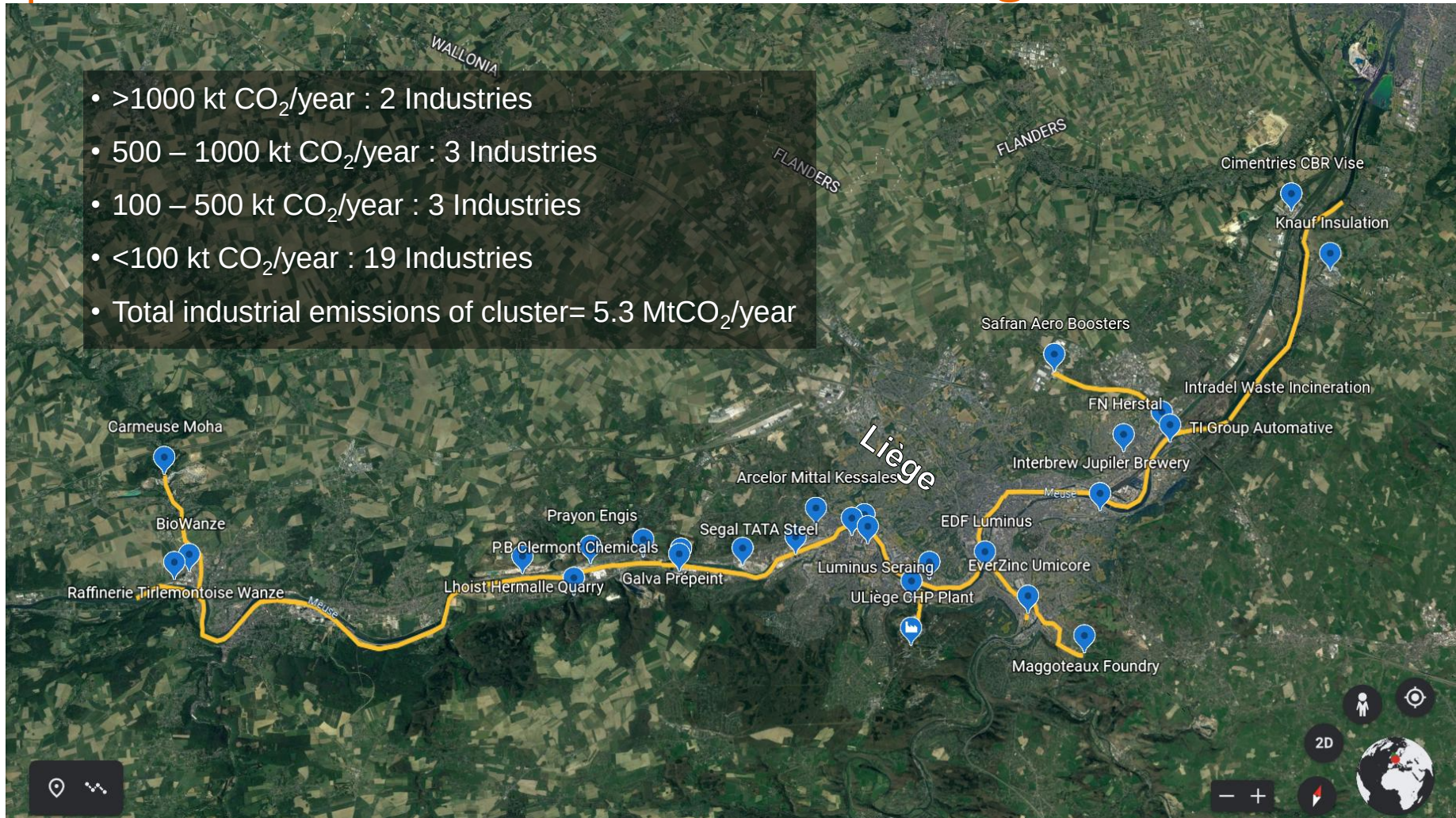
2005-2021



climat.be

Current ETS Industries in Liège area

- >1000 kt CO₂/year : 2 Industries
- 500 – 1000 kt CO₂/year : 3 Industries
- 100 – 500 kt CO₂/year : 3 Industries
- <100 kt CO₂/year : 19 Industries
- Total industrial emissions of cluster= 5.3 MtCO₂/year



=> Various emissions and site conditions !

CO₂ market

- European Emissions Trading System (ETS)
- CO₂ price reached 25 €/t last year



CO₂ market

■ La Libre Belgique, 04/05/21

- A noter qu'on voit des fumées de tours de refroidissement = de l'eau!

Les droits d'émission pour une tonne de CO₂ dépassent les 50 euros en Europe, une première

Conjoncture

La Libre Eco avec Belga

Publié le 04-05-21 à 13h17 - Mis à jour le 04-05-21 à 14h03

Les droits d'émission de CO₂ dépassent les 50 euros pour la première fois en Europe.



CO₂ market – End of 2021

- European Emissions Trading System (ETS)
- CO₂ price now reaches 65 €/t!



CO₂ market – End of 2022

- European Emissions Trading System (ETS)
- CO₂ price almost reached 100 €/t twice!
- 2 years ago, a study mentioned that this cost would be reached in 2029!



CO₂ market – Today

The price of emissions allowances in Europe

Cost per tonne of carbon dioxide produced

Europe (€/t) UK (£/t)



Source: Data provided by Montel · EU and UK Emissions Trading Scheme prices (front December contracts); UK ETS prices exclude Carbon Price Support
Due to licensing, this data is not available for download

EMBER

CO₂ market – Demain?

EU carbon price to hit €400 mark with 90% climate goal: analysts

(EurActiv, 5 Oct 2023) The European Union's new climate commissioner, Wopke Hoekstra, made written commitments on Wednesday (4 October) to defend a 90% cut in net greenhouse gas emissions by 2040, a move that financial analysts say will send EU carbon prices above the €400 mark.

Hoekstra secured backing from the Parliament's environment committee on Wednesday and was formally confirmed in his new role by the full assembly during a plenary vote in Strasbourg on Thursday.

During a Parliament hearing earlier this week, the former Dutch foreign minister came under pressure from Green and left-wing lawmakers to show his commitment to ambitious EU climate policies by taking a stance on the EU's climate target for 2040, due to be presented early next year.

His answer was unambiguous. "We will defend a minimum target of at least 90% net reduction by 2040," Hoekstra said in a written statement sent to MEPs.

The 2040 target will determine the supply of CO₂ allowances on the EU's emissions trading scheme, which puts a limit on the carbon emissions of large industrial emitters.



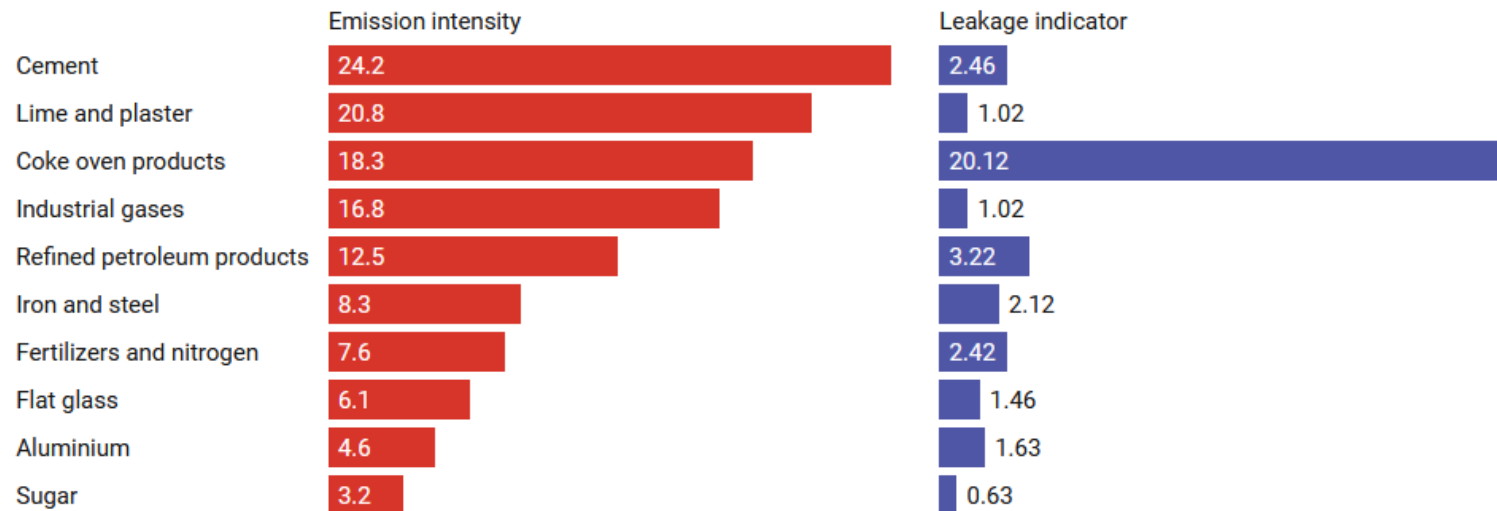
Drawback of carbon quotas?

■ Risque de fuite du carbone

□ Délocalisation de la pollution hors Europe!

Top 10 EU economic sectors with the highest emissions

The industries with the highest emissions also tend to have a high risk of carbon leakage, meaning foreign imports might be substituted for domestic production to avoid a charge for emissions. An indicator over 0.2 is considered at risk for carbon leakage.



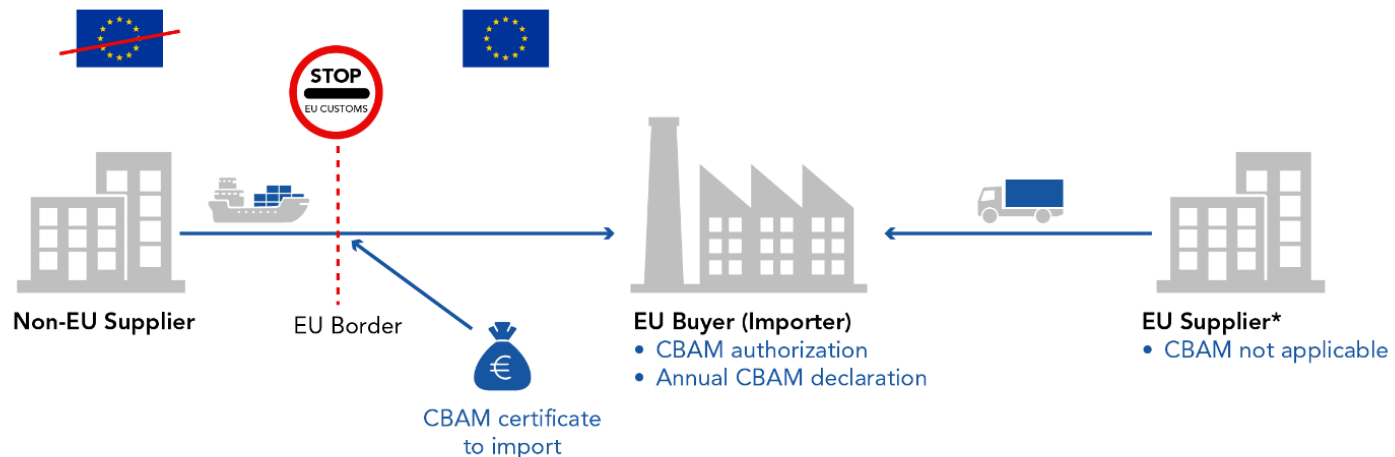
Emission intensity is the volume of emissions per unit of GDP. Coke oven products include coke, which is made from coal and used for fuel in furnaces and to manufacture iron and steel.

Chart: The Conversation/CC-BY-ND • Source: [European Commission](#) • [Get the data](#)

Réponse de l'UE : CBAM

- CBAM: carbon border adjustment mechanism
 - Applies to: Cement, Electricity, Fertilizers, Iron, steel, Aluminium, Hydrogen
 - Fully enters into force in 2026
 - But does not cover everything: no glass, lime, chemicals... !

EU Carbon Border Adjustment Mechanism simplified illustration



* Including goods originating from Iceland, Liechtenstein, Norway, and Switzerland
Source: The Conference Board, 2022

Risk of social difficulties?

- UE Answer: Social climate fund
 - Funds to support transition for poorest households
 - Social climate plans to fight energy precarity
 - Along with ETS2
 - Investments in energy efficiency, decarbonation, sustainable transportation...

What about Belgium?

■ Conventions carbonees

- ❑ Anciennement « Accords de Branche »

3 indices pour 1 trajectoire Neutralité carbone

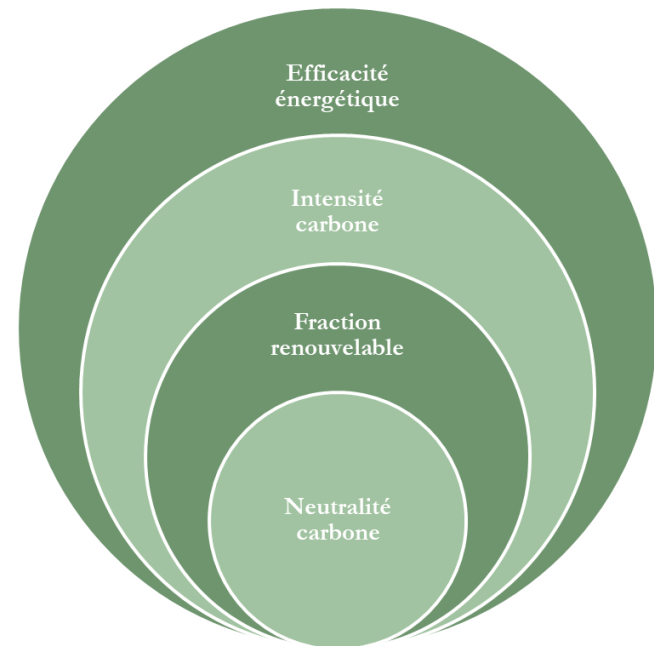
- ✓ Indice énergie
- ✓ Indice émissions
- ✓ Indice renouvelable

➤ Communauté :

3 Objectifs engageants

➤ Membre :

1 objectif engageant + 2 contributifs

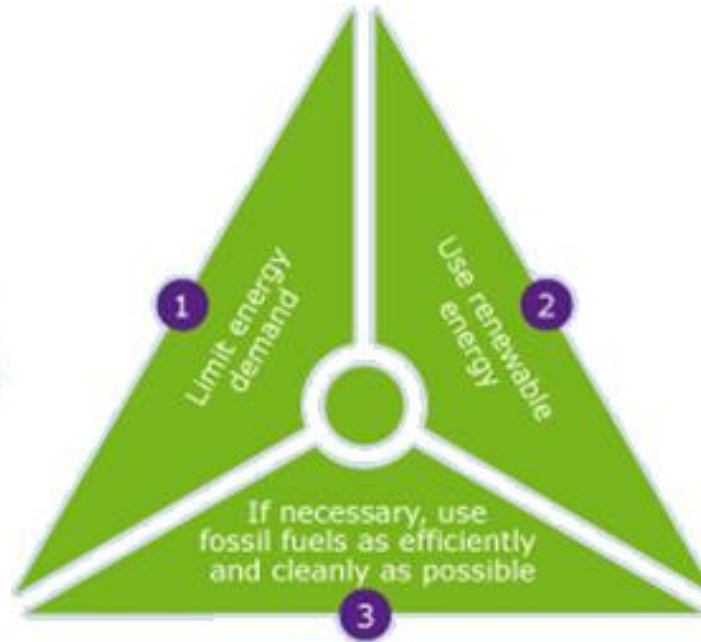


Possible answers: Trias Energetica

Eviter



Substituer

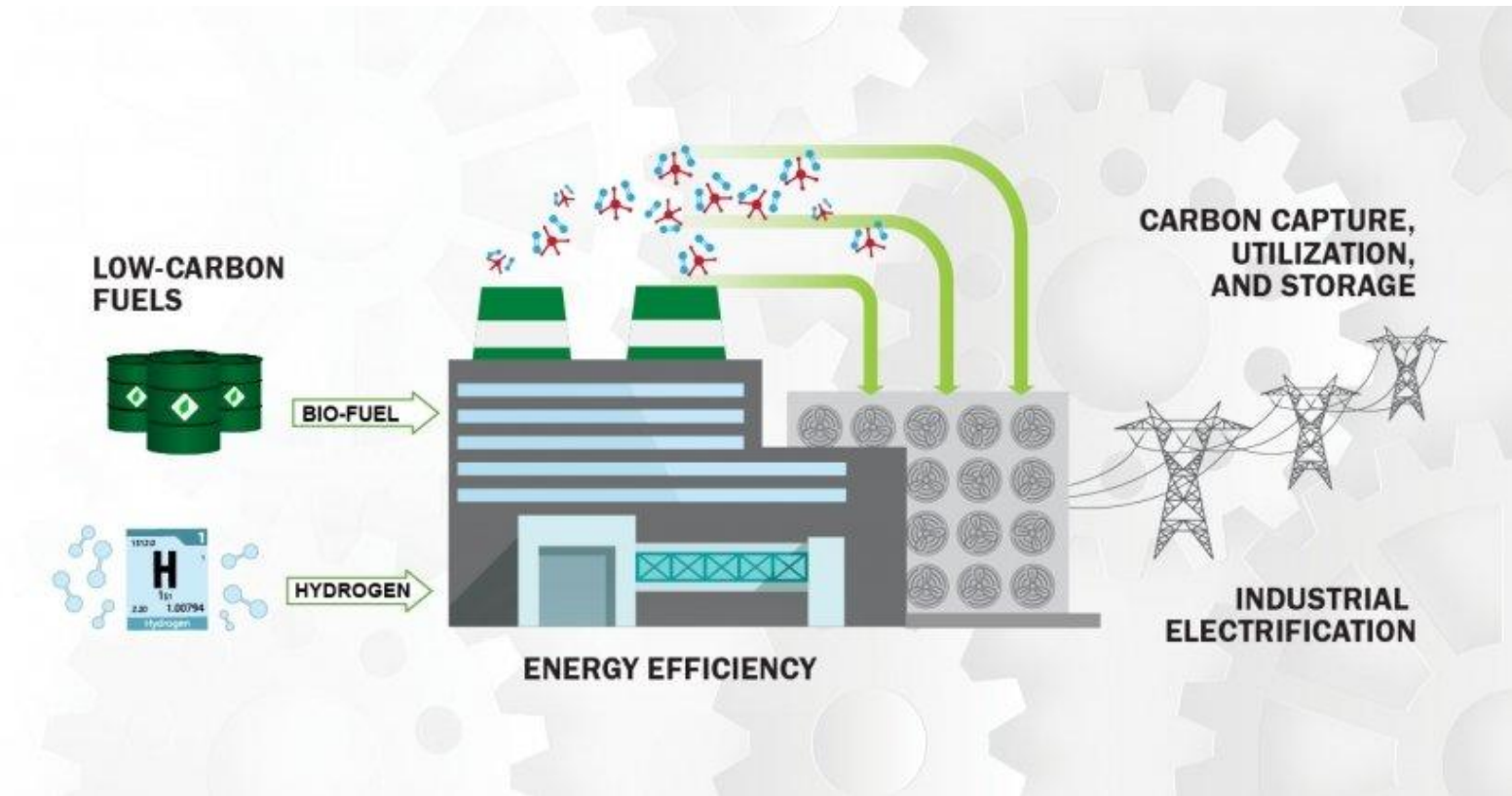


Améliorer

Action plans at EU level: Green Deal

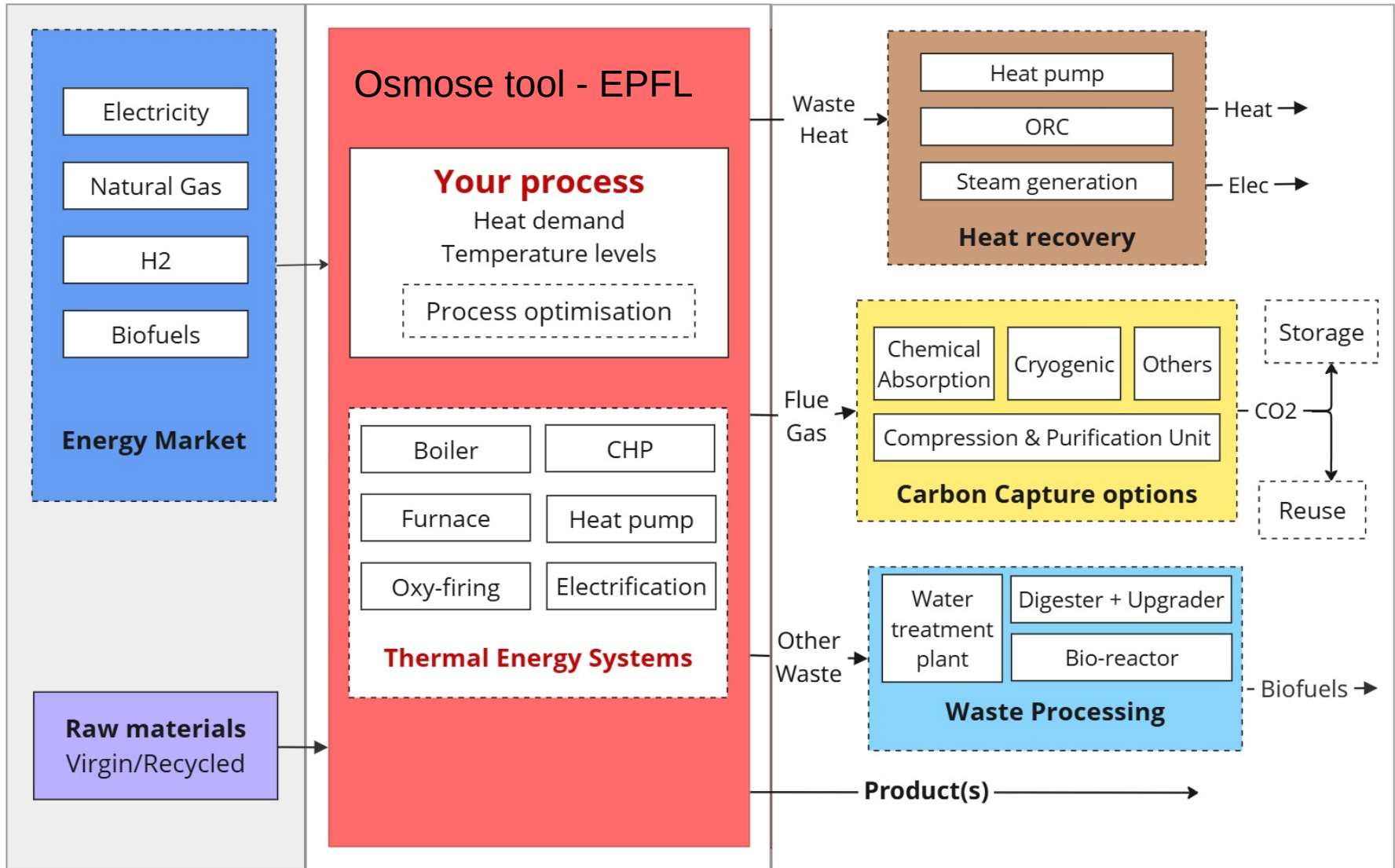


Voies de transition énergétique dans l'industrie



- Incertitudes => décision difficile!
- Besoin d'outils d'aide à la décision

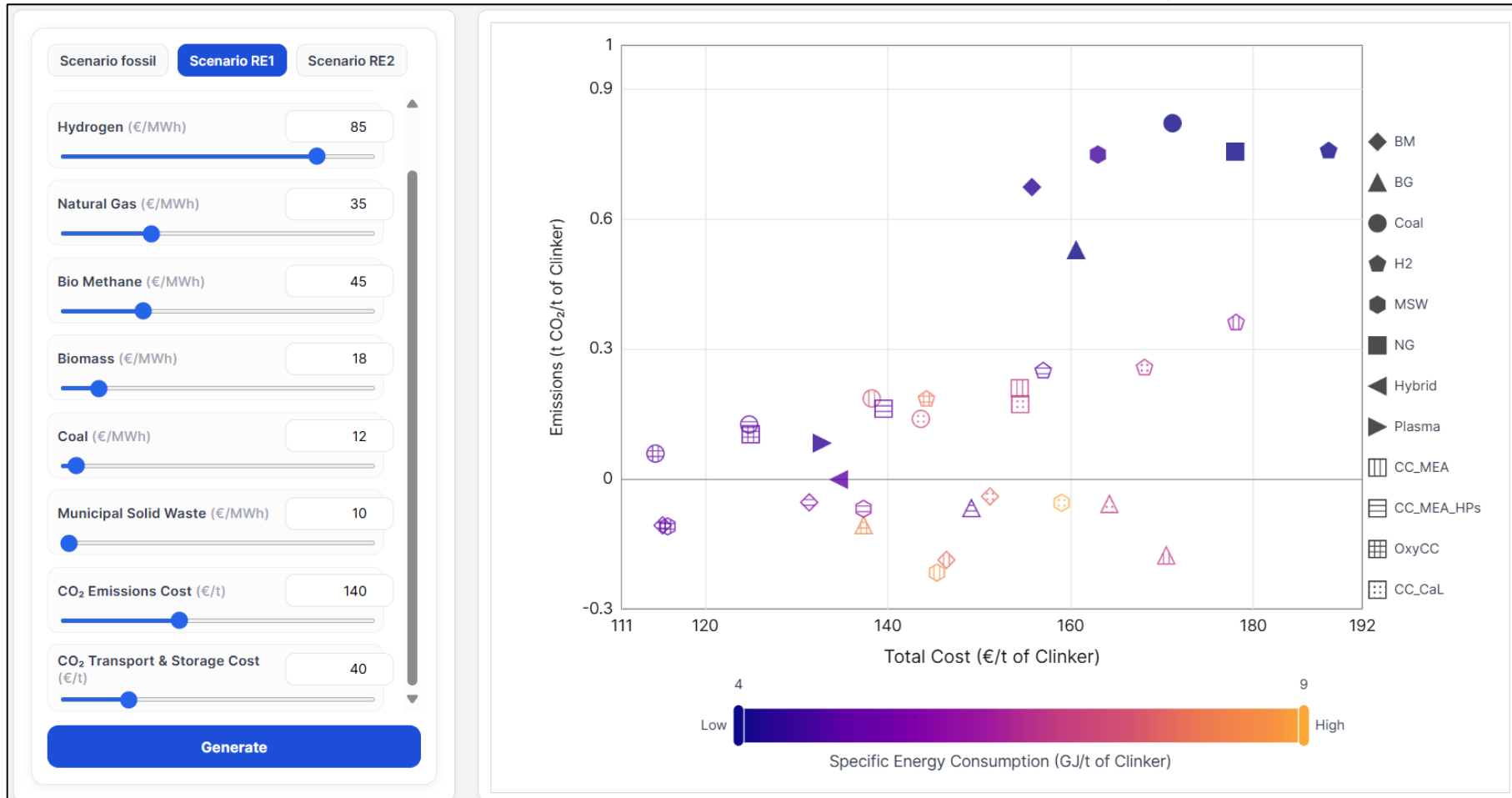
Superstructure of industrial processes (Trilate)



Techno-Strategic Assessment



ENTRAIN
Engineering



Techno-economic DST for the cement industry

Conclusion

- Limites planétaires et changement climatique
 - Il ne s'agit pas que du climat, mais de systèmes environnementaux complexes!
- Transition énergétique et émissions de CO₂
 - Les émissions de CO₂ en Belgique et dans le monde représentent un défi de taille!
- Un découplage est nécessaire
 - Pourtant, tout est lié: Economie, Energie, Politique, Société...
- Mécanisme de changement dans l'industrie: le marché ETS
 - Risque de fuite des émissions et de troubles sociaux
- Réponses possible dans l'industrie:
 - Les voies de transition énergétique
 - La capture du CO₂

CCUS = Carbon capture, carbon re-use, carbon storage

- *“Carbon Capture and Storage (including DACCS and BECCS) is central to IPCC mitigation pathways!”*

- CCS: carbon capture and storage: point-source CO₂ capture

- Remove CO₂ from concentrated gaseous effluents
- Store it underground => no climate impact anymore!
- => Fossil CO₂

- DACCS: Combine CCS with Direct Air Capture (DAC)

- DAC: get CO₂ from ambient air (420 ppm!)
- => anthropogenic CO₂

- BECCS: Biomass-enhanced CCS

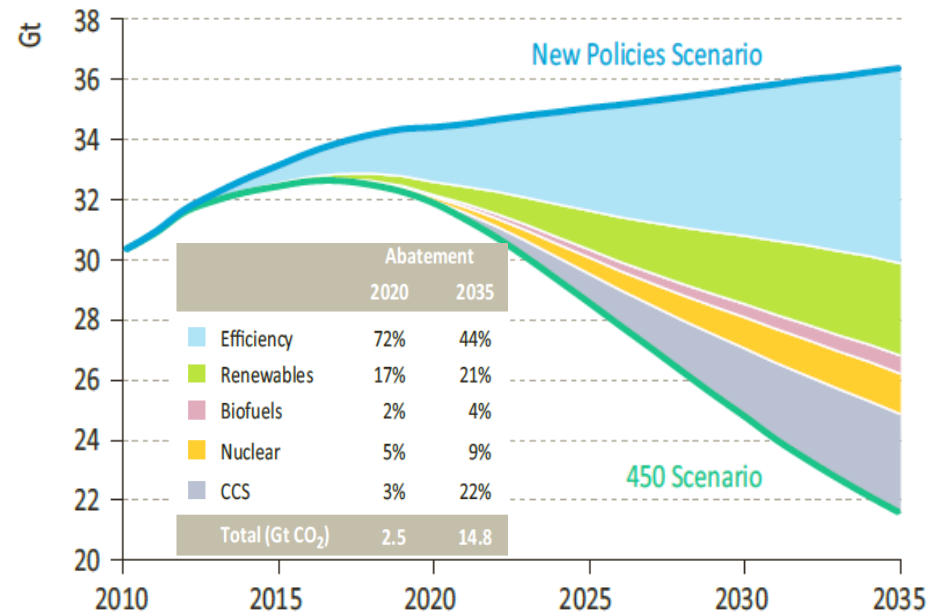
- Combine biomass combustion with CCS
- => biogenic CO₂

CDR = carbon dioxide removal
=> Net negative emissions!

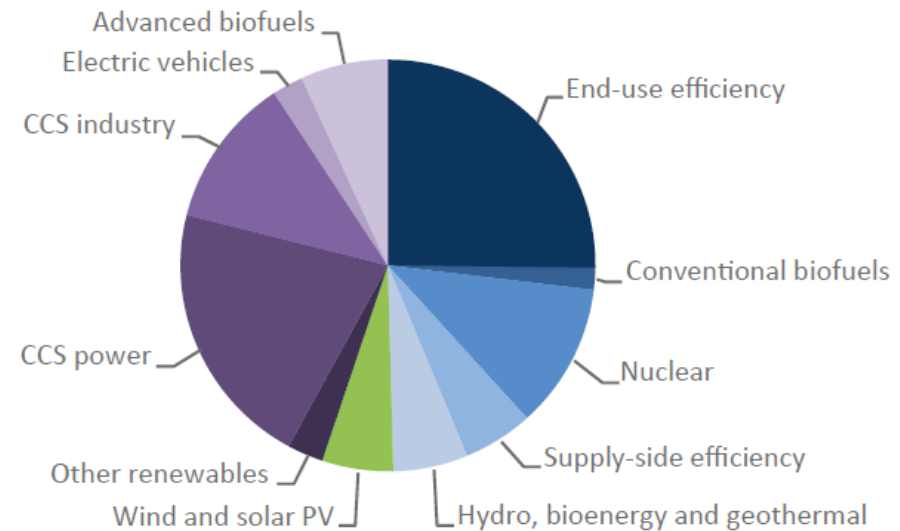


CCUS = Carbon capture, carbon re-use, carbon storage

- Bien que peu connues, ces technologies devraient jouer un rôle important pour réduire les émissions!



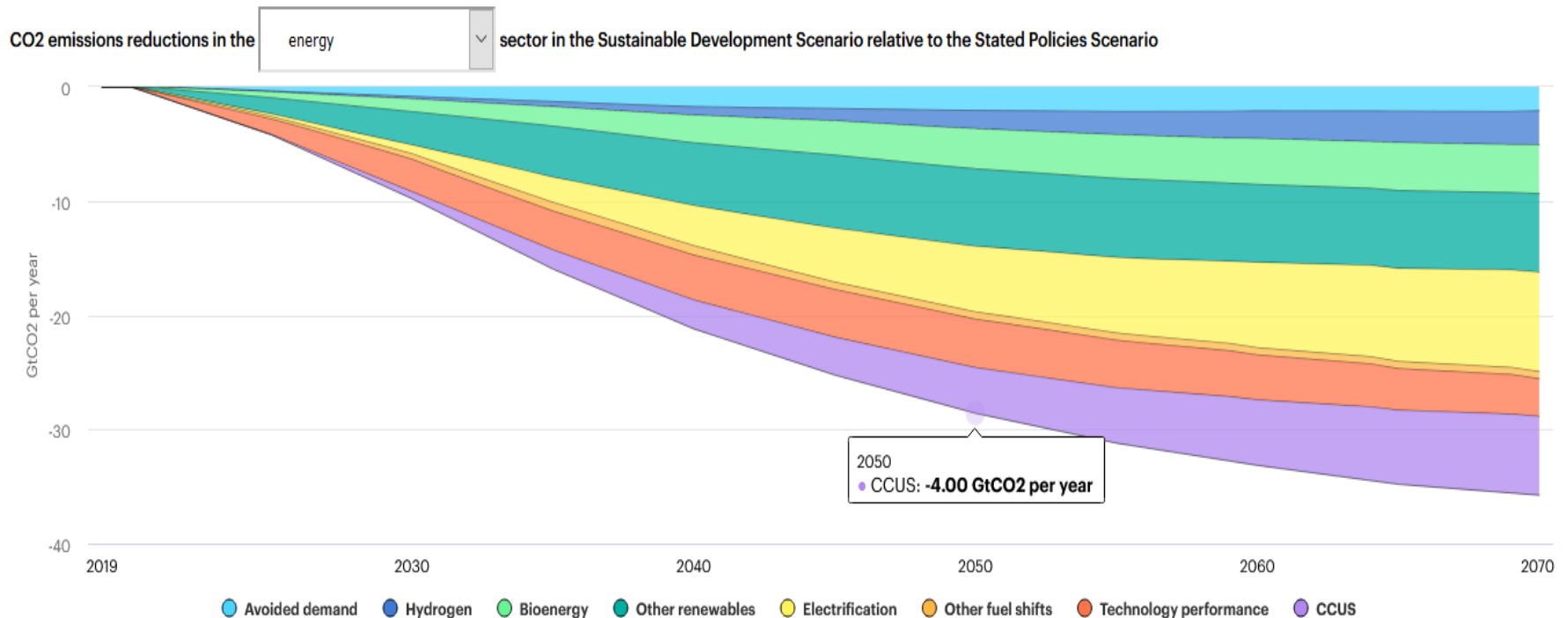
World CO₂ emissions abatement in the 450 Scenario (New Policies Scenario), IEA **2011**, WEO2011.



World CO₂ emissions abatement in the 450 Scenario (Bridge Scenario 2015-2040), IEA **2015**, WEO special report, Energy & Climate Change

Emission reductions

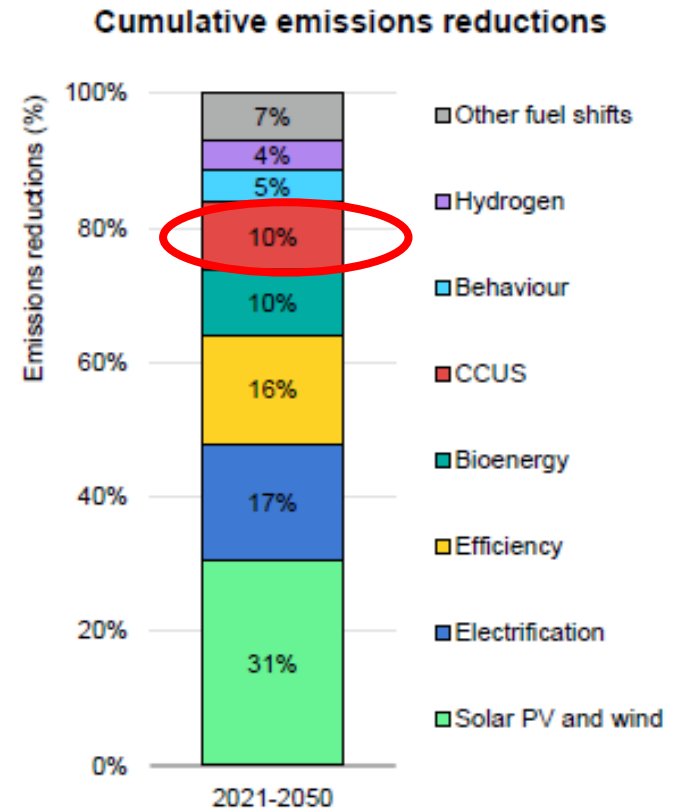
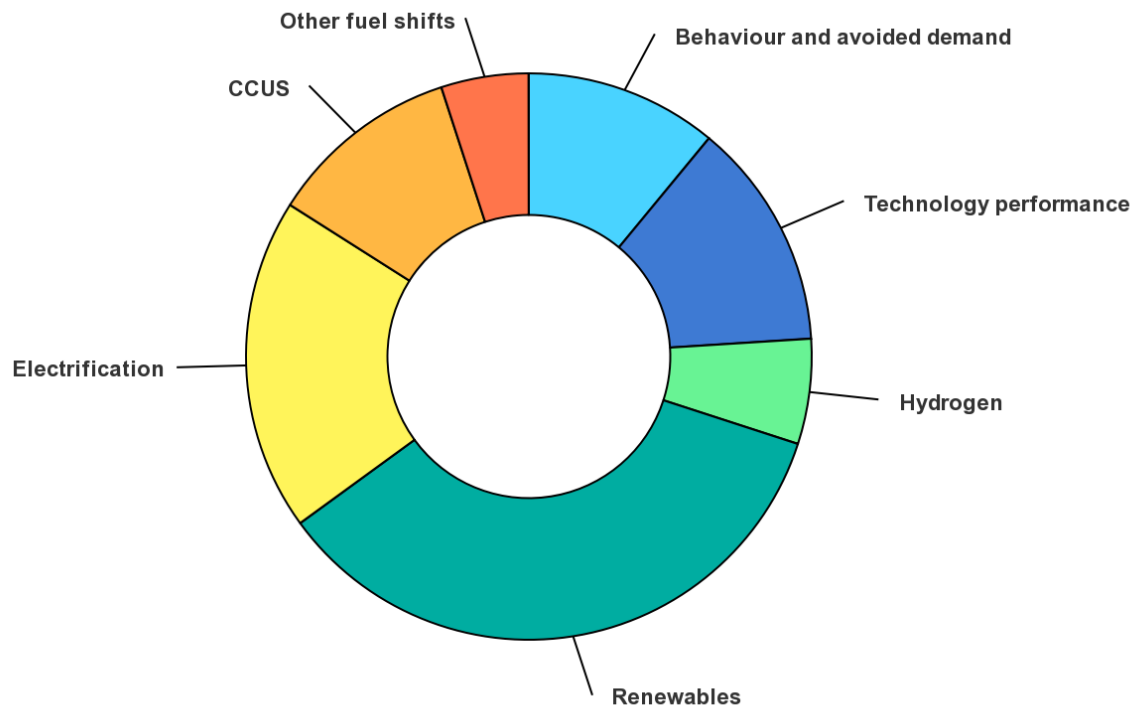
■ Role in emission reductions, 2020



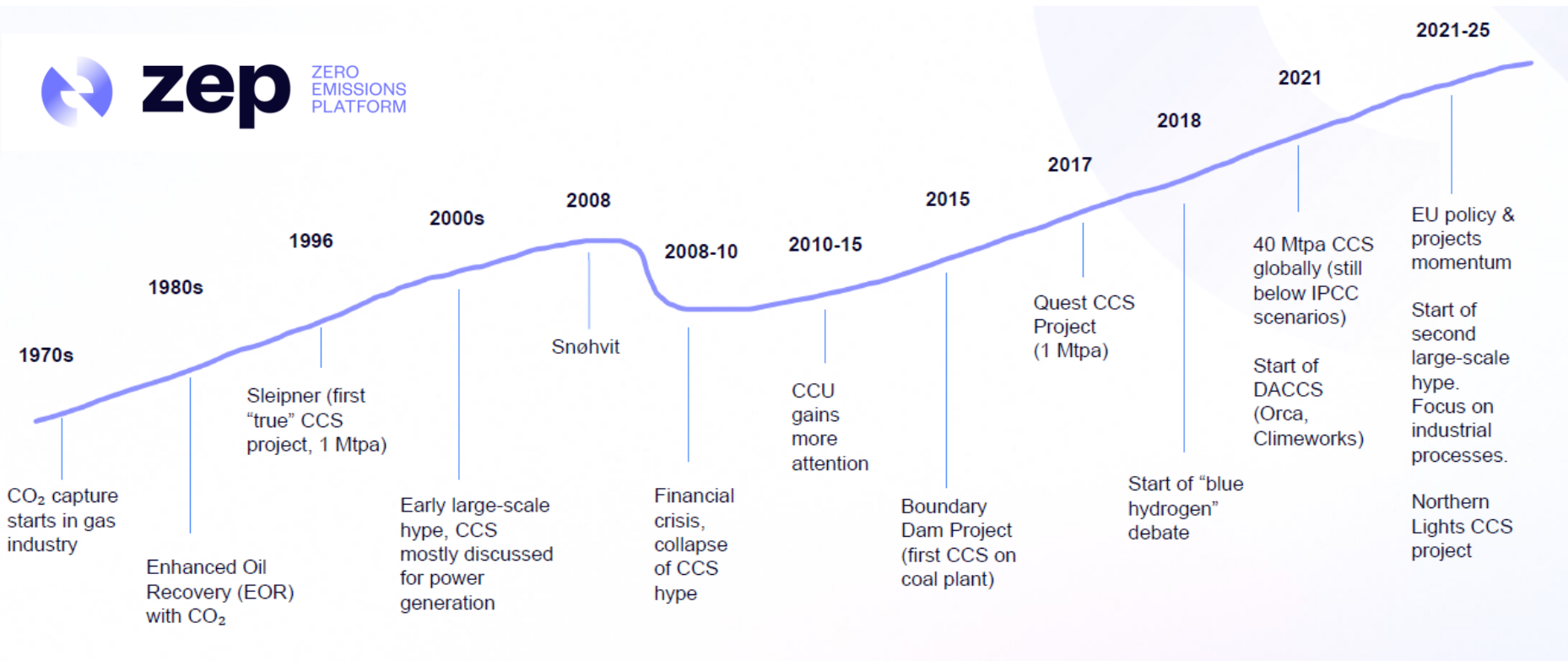
IEA. All rights reserved.

Emission reductions

■ 2023: IEA's Scenario Net Zero Emission 2050 (1.5°C)



History of CCS/CCUS



CCUS forecasts

- Quid de la Belgique?
- « *Le gaz, qui englobe à la fois les gaz de synthèse (renouvelables), le biogaz et du gaz naturel résiduel brûlé dans des unités thermiques équipées d'un système de capture et de stockage du carbone, représente un tiers (32 % à 33 %) du futur mix électrique. »*
- « *De manière générale, dans les deux scénarios [étudiés], la demande totale d'électricité augmente significativement d'ici 2050, en comparaison avec les niveaux actuels : la demande est jusqu'à trois fois supérieure à celle de 2018. »*

Source: Federal Planning Bureau, Fuel for the future, Working paper 4-20, October 2020

Point-source CO₂ Capture

CO₂ capture : une separation de fluides



La pureté des sources varie entre 0.04% et ~ 100%
En général: mélange de CO₂, N₂, H₂O, H₂, CH₄, O₂ ...

Ce n'est pas une nouvelle technologie

- Existe depuis plus de 50 ans ~ 250 Mtpa en 2016

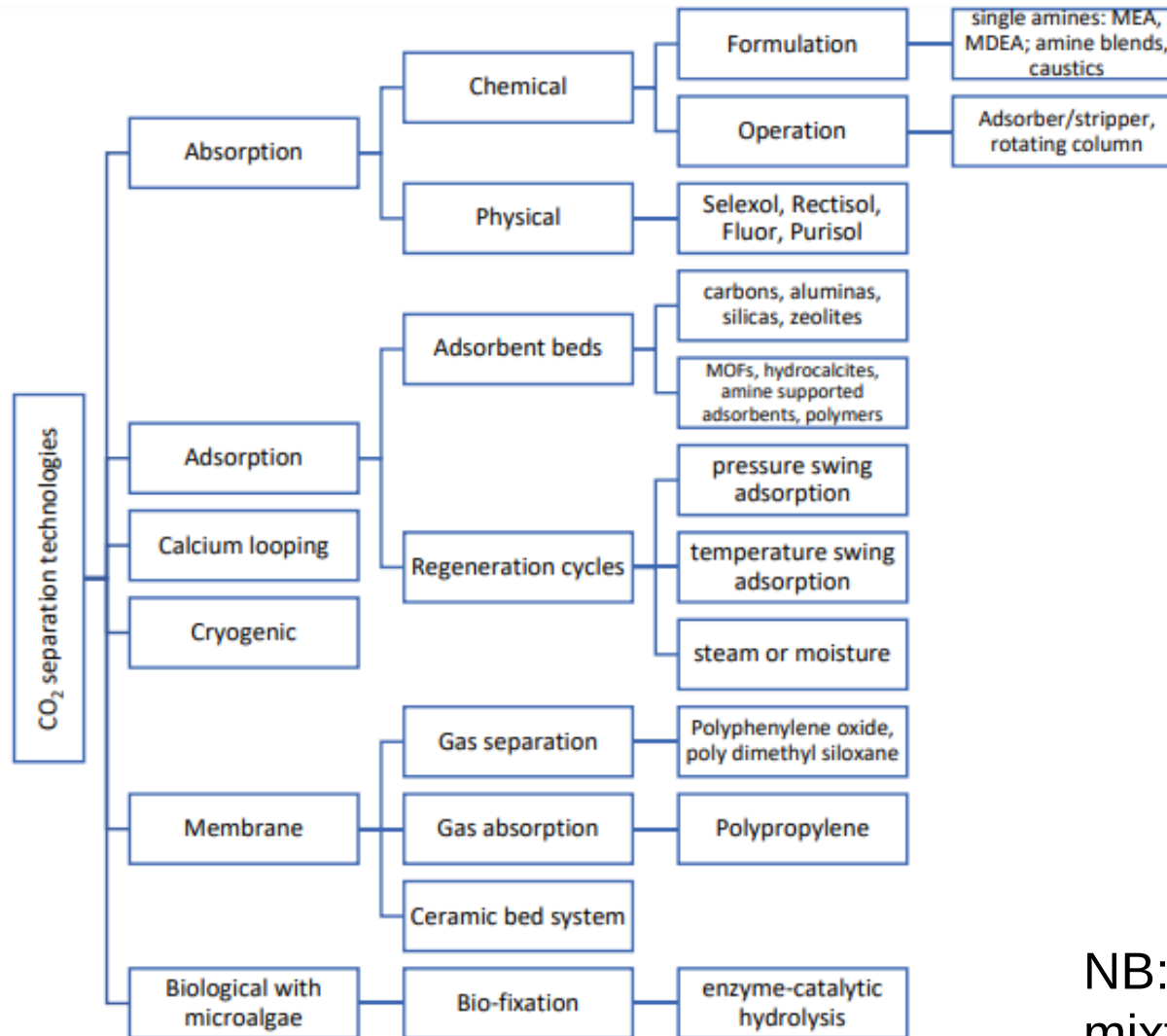


India, 2006, Urea production,
2x450 tpd CO₂



Natural gas sweetening with high CO₂ field:
1400 -2800 tpd CO₂

And various CO₂ separation technologies!



NB: first, try to avoid fluid mixtures !

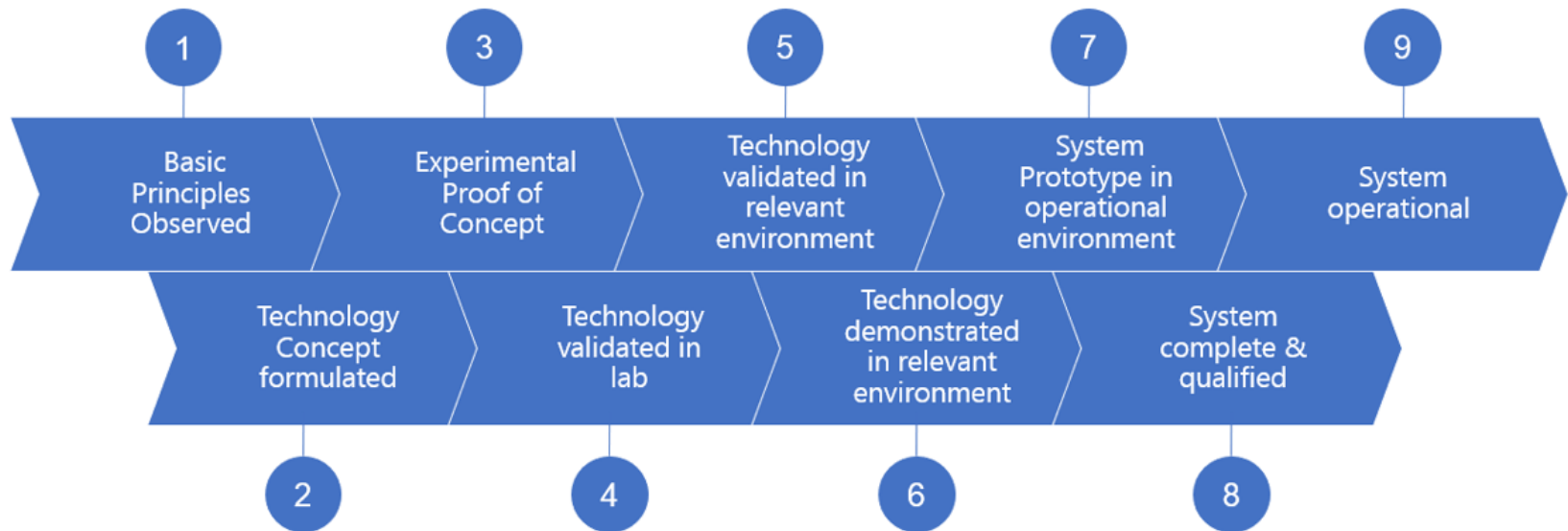
CO₂ capture benchmark – Power sector

	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

Maturity of technologies

- This can be quantified thanks to a Technology Readiness Level (TRL) scale



Source: European Commission Horizon 2020

CO₂ capture technologies maturity

Table 2 Overview of development of post-combustion capture and high-temperature solids-looping processes (based on literature review)

TECHNOLOGY		TRL AT PREVIOUS REVIEW	CURRENT TRL	CURRENT DEVELOPMENT TRAJECTORY	PREDICTED LCOE DECREASE C.F. STANDARD TECHNOLOGY
Liquid absorbents	Aqueous amine	6–9	6–9	→	Low
	Amino acid and other mixed salts	–	6	↑	Low
	Ionic liquids	1	4	↓	–
	Encapsulated absorbents	1	2–3	→	–
	Water-lean absorbents	–	5	↑	Medium
	Precipitating	4–5	4–6	→	Medium
	Liquid–liquid separating	4	4–5	↑	Low
	Catalysts	1	6	↑	Medium
Membranes	Polymeric membranes	6	6	↑	Low
	Membrane contactors	–	5–6	→	Medium
	Hybrid processes	6	6	↑	Medium
Solid sorbents	Pressure-swing adsorption (PSA) and temperature-PSA	3	6	→	Medium
	Temperature swing adsorption	1	6	↑	Medium
	Ca looping	6	6	→	Medium
Cooling and liquefaction		3	5	→	Medium
Electrochemical separation		1	4	↑	High
Algae-based capture		1	4	↓	–
Direct air capture		–	5	→	–

↑ = the technology has commercial backing, and/or large scale evaluation/ demonstration of the technology is either currently underway or planned

→ = while there may be ongoing pilot-scale demonstrations, there are no plans at present for larger-scale demonstration, or the technology is not being progressed by a commercial partner



Avantages et inconvénients

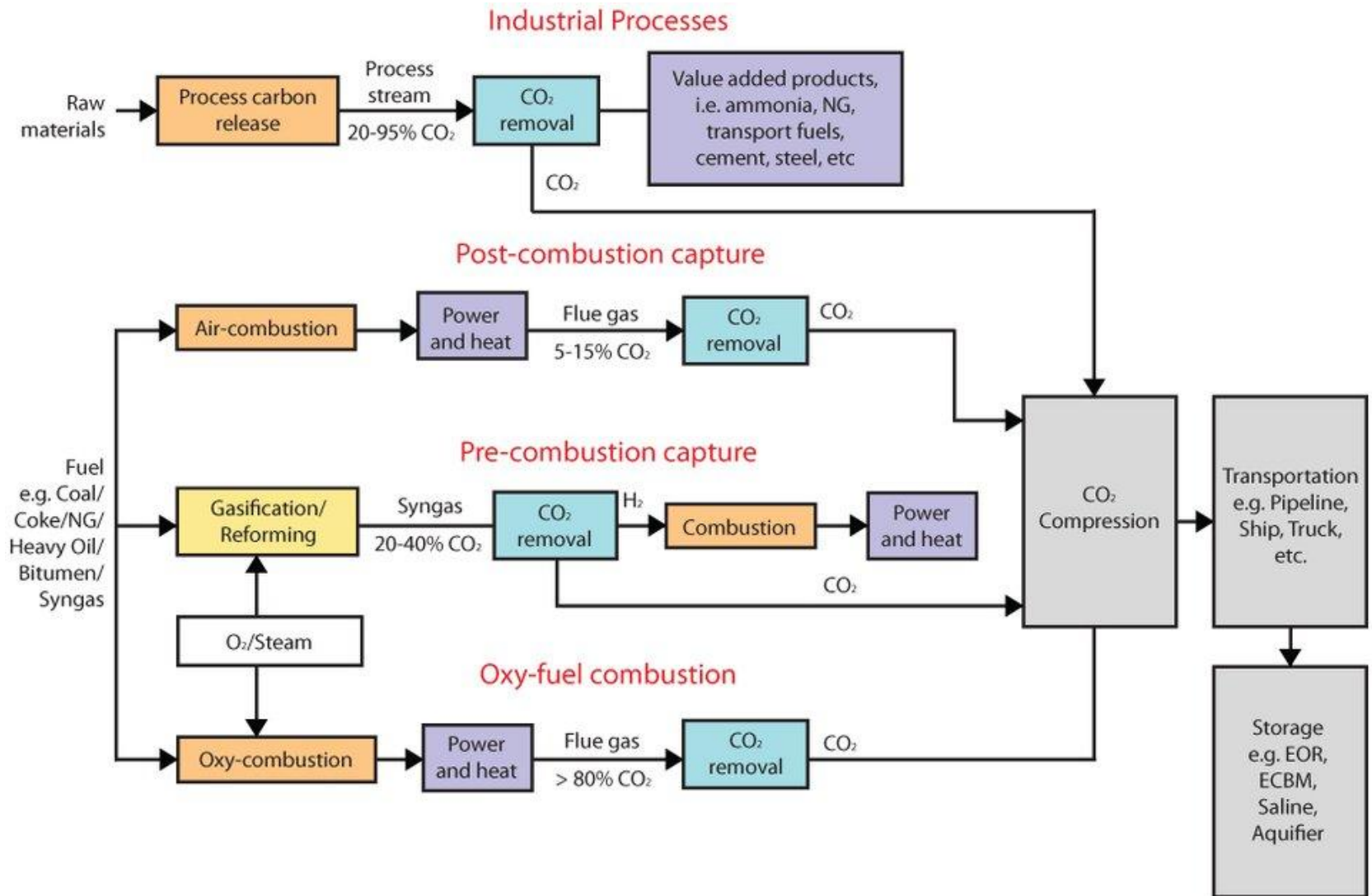
Avantages:

- Nécessaire pour le CO₂ des industries procédés
- Adaptation possible à des unités existantes
- Dynamique rapide et flexible, pilotable
- Mise à l'échelle rapide possible (end-of-pipe)
- Technologies proches de la maturité

Inconvénients:

- Investissement important en infrastructure (capture + transport + stockage)
- Coûts opératoires importants
- Technologies proches de la maturité, mais pas encore vraiment toutes commerciales
- Risque de transfert d'impact (par ex. émissions secondaires)

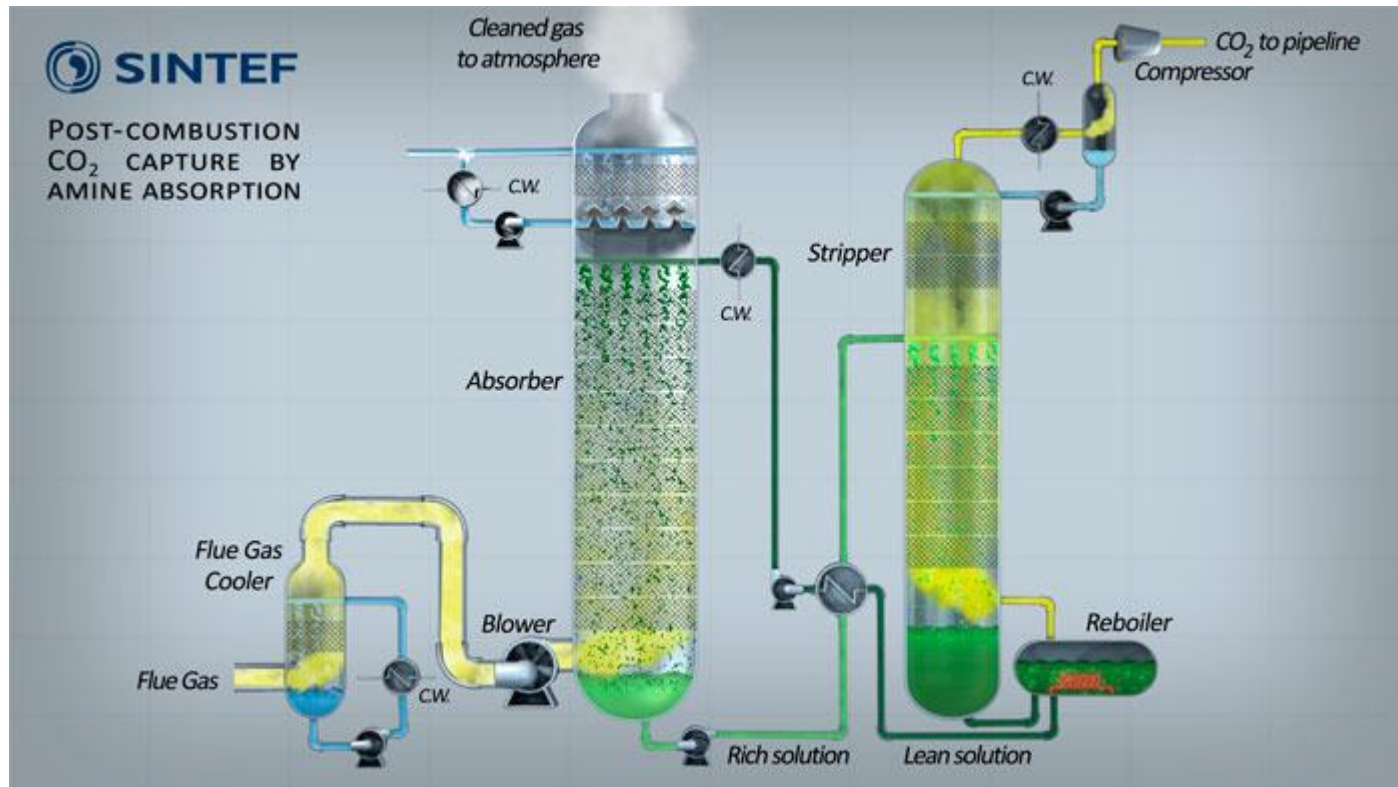
CO₂ capture configurations



Capture post-combustion

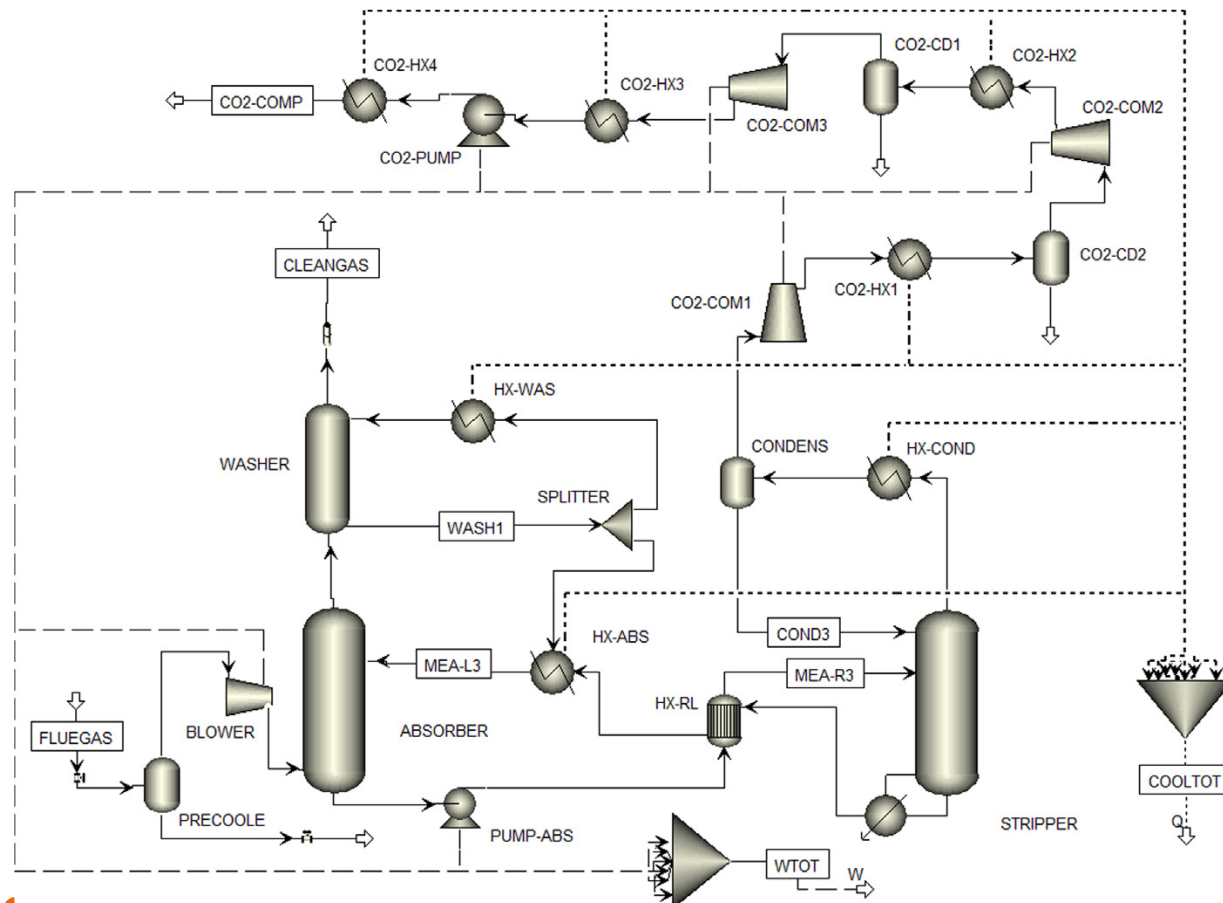
Capture de CO₂ des gaz de fumée

- Boucle d'absorption-régénération avec solvants chimiques



Capture post-combustion

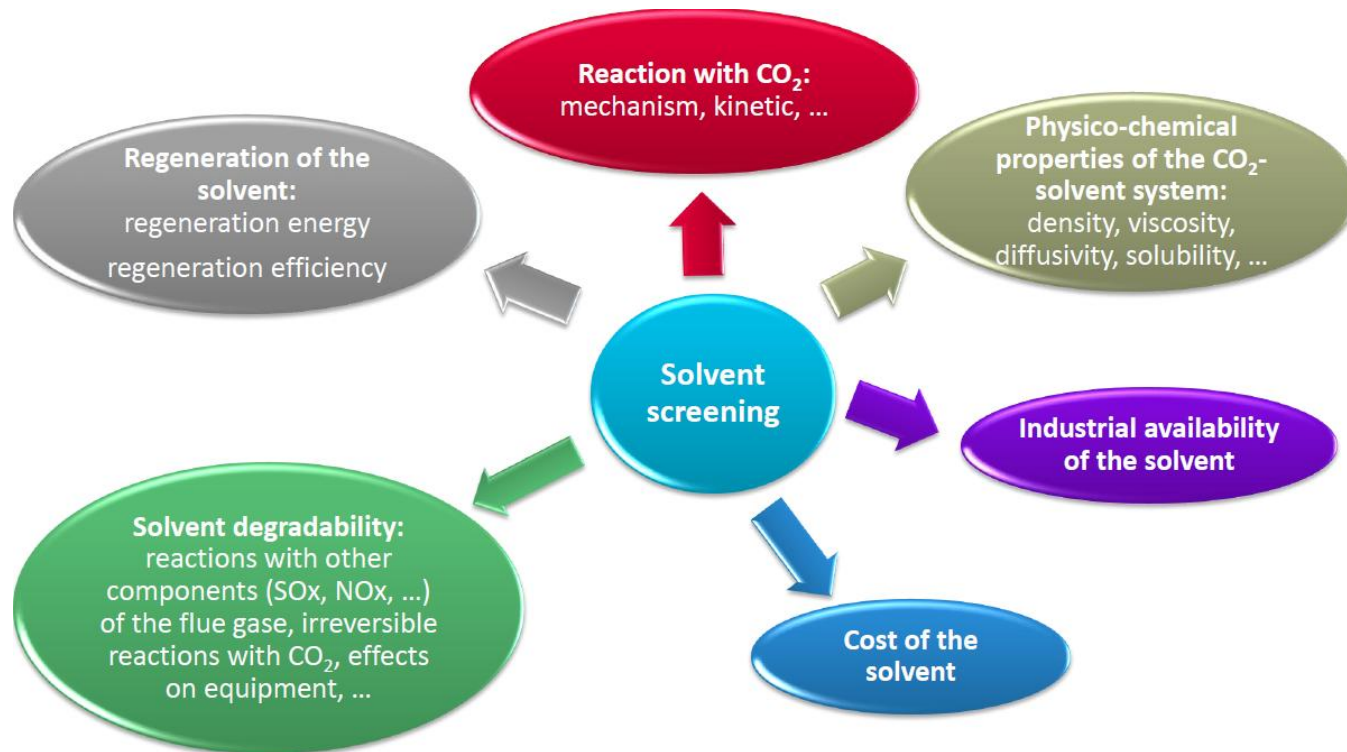
Capture de CO₂ des gaz de fumée



Capture post-combustion

Capture de CO₂ des gaz de fumée

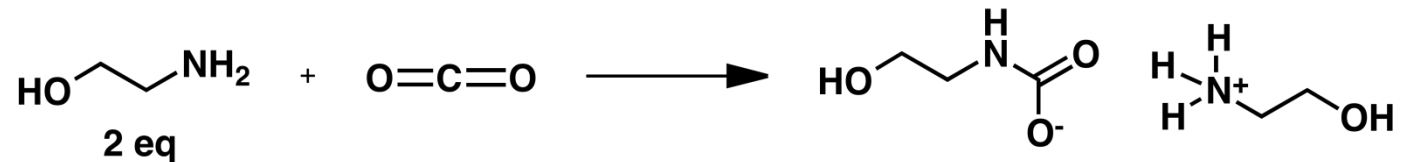
- Caractéristiques d'un solvant chimique



Capture post-combustion

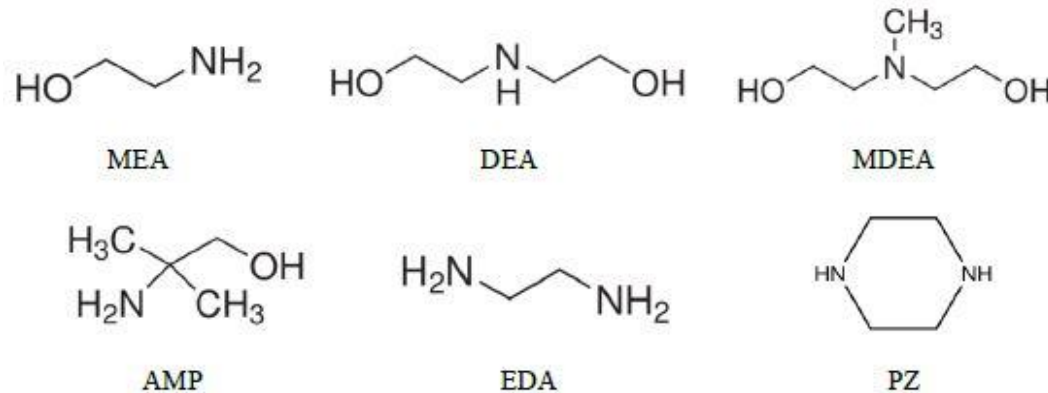
Solvant chimique

- Amines (1, 2ary) in water



- Amine (3ary) in water $R_1R_2R_3N + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons R_1R_2R_3\text{N}^+\text{H} + \text{HCO}_3^-$

- Some examples



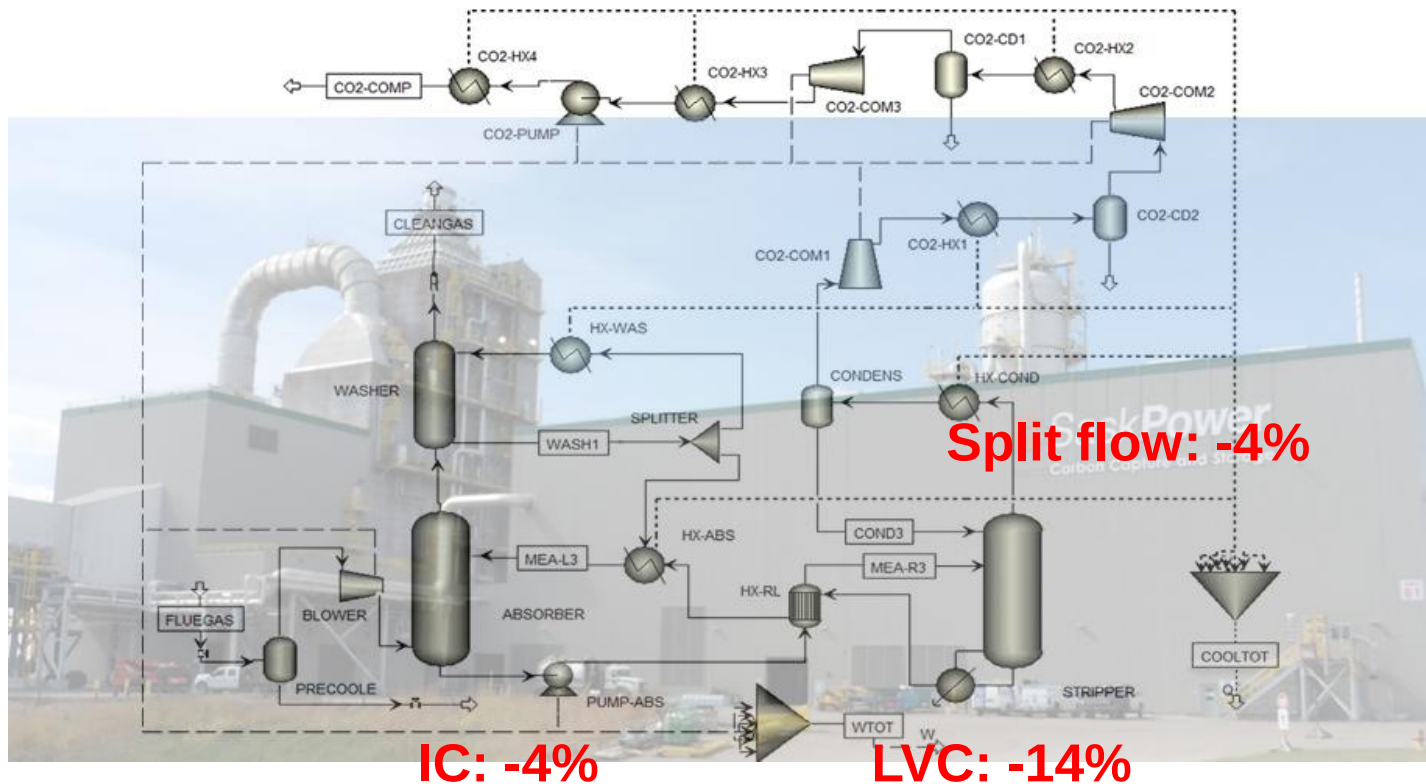
Capture post-combustion

- Echelle commerciale atteinte
 - Boundary Dam, Saskatchewan (2014)
 - Centrale charbon 160 MWe
 - 2700 tCO₂/day captured (~90% capture rate), 1 Mtpa
=> Flue gas: 180 Nm³/s ; Solvent: 550 L/s
 - Petra Nova, Texas (2017):
 - 4400 tCO₂/day, 1 milliard US\$



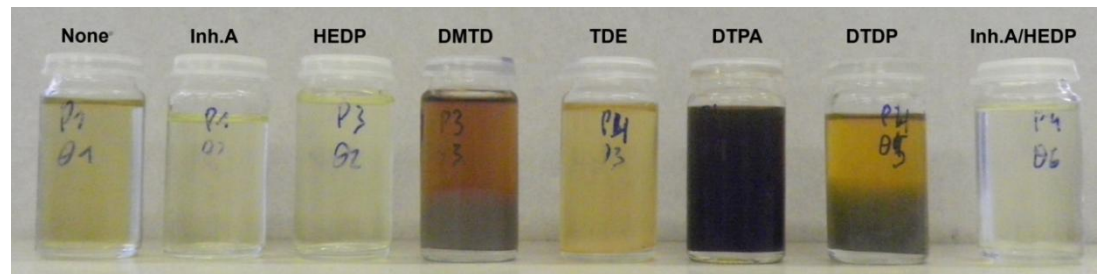
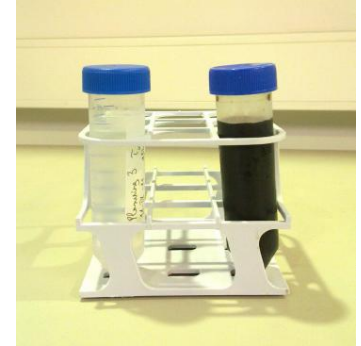
Capture post-combustion

- Focus: research at ULiège
 - Modeling and energy optimization of systems



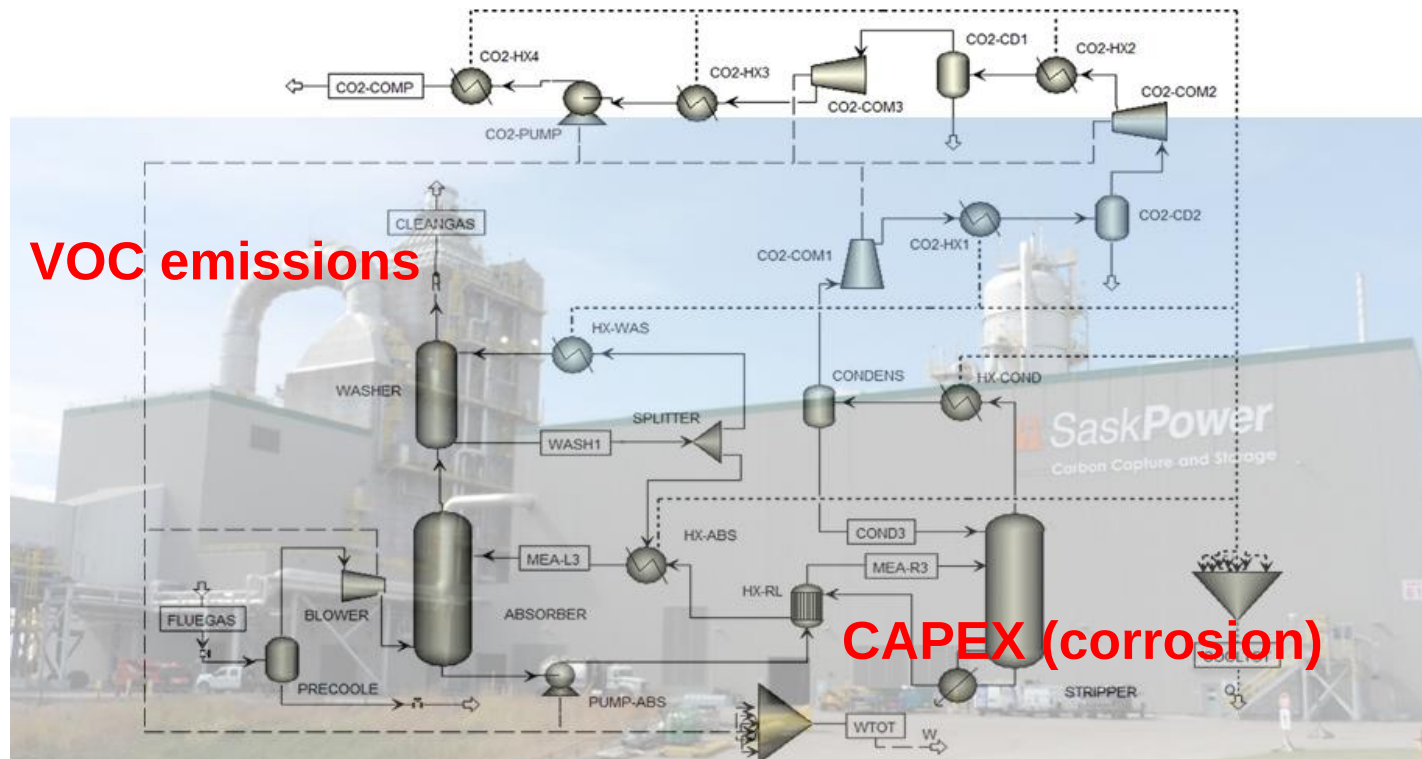
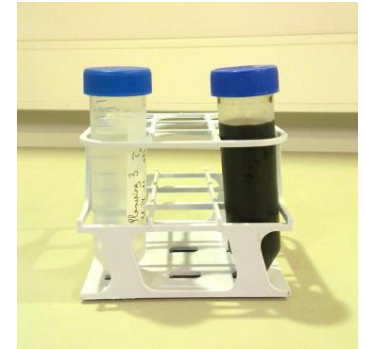
Capture post-combustion

- Focus: research at ULiège
 - Stability of chemical solvents
 - Operational issues
 - Viscosity change, decrease of solvent properties...
 - Corrosivity of amine systems
 - Emissions of VOC
 - Different types of degradation
 - Oxidative
 - Thermal
 - SO_x , NO_x ...



Capture post-combustion

- Focus: research at ULiège
 - Stability of chemical solvents



OPEX: viscosity, altered properties...

PROCURA ETF: Decision support tool

Goal:

The appropriate CO₂ capturing method

Criteria:

Engineering

Economics

Environment

KPI:

TRL

**Capture
rate**

**CO₂ avoided
cost**

**CAPEX/
OPEX**

LCA

**Safely/
Acceptance**

Technology:

Absorption

Adsorption

Membrane

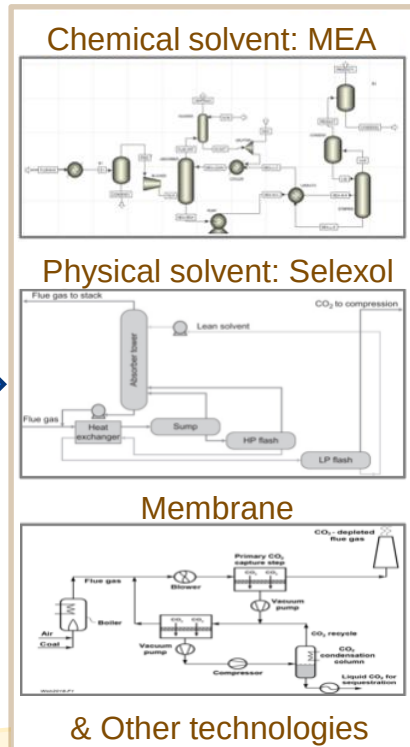
Cryogenic

Looping

■ Systematic Comparison & Assessment for Carbon Capture

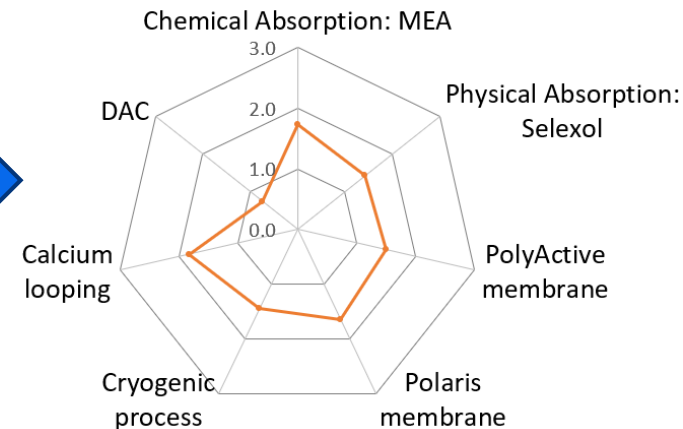
1. Emissions characterization

Engineering	Energy
TRL Purity SOx & NOx	Thermal duty Electrical duty Cooling duty
Economics	Environment
Total Cost CapEx OpEx	Carbon footprint Safety Installation area



2. Technologies database & KPI assessment

3. Score ranking

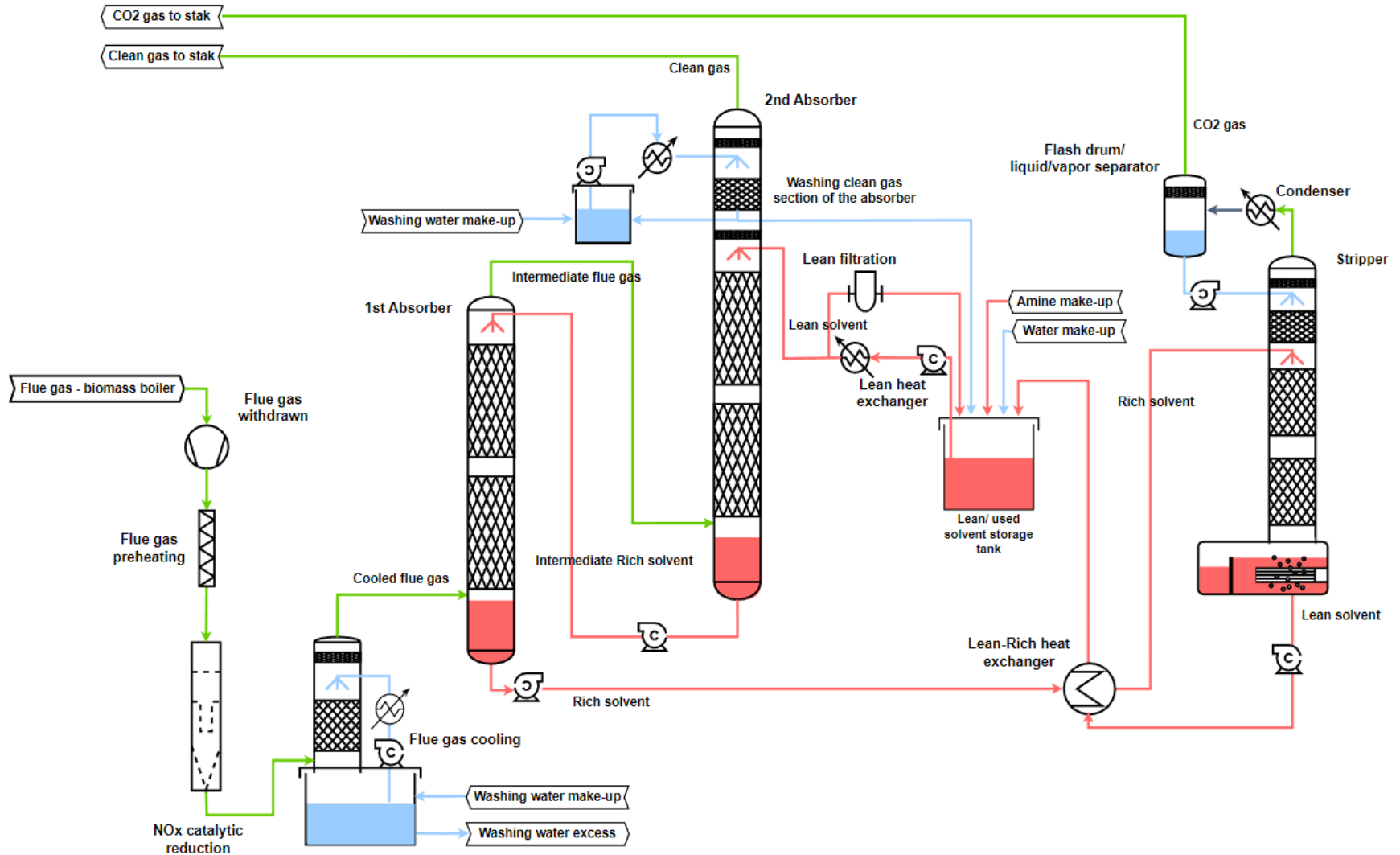


Research at ULiège: Close the gap with reality

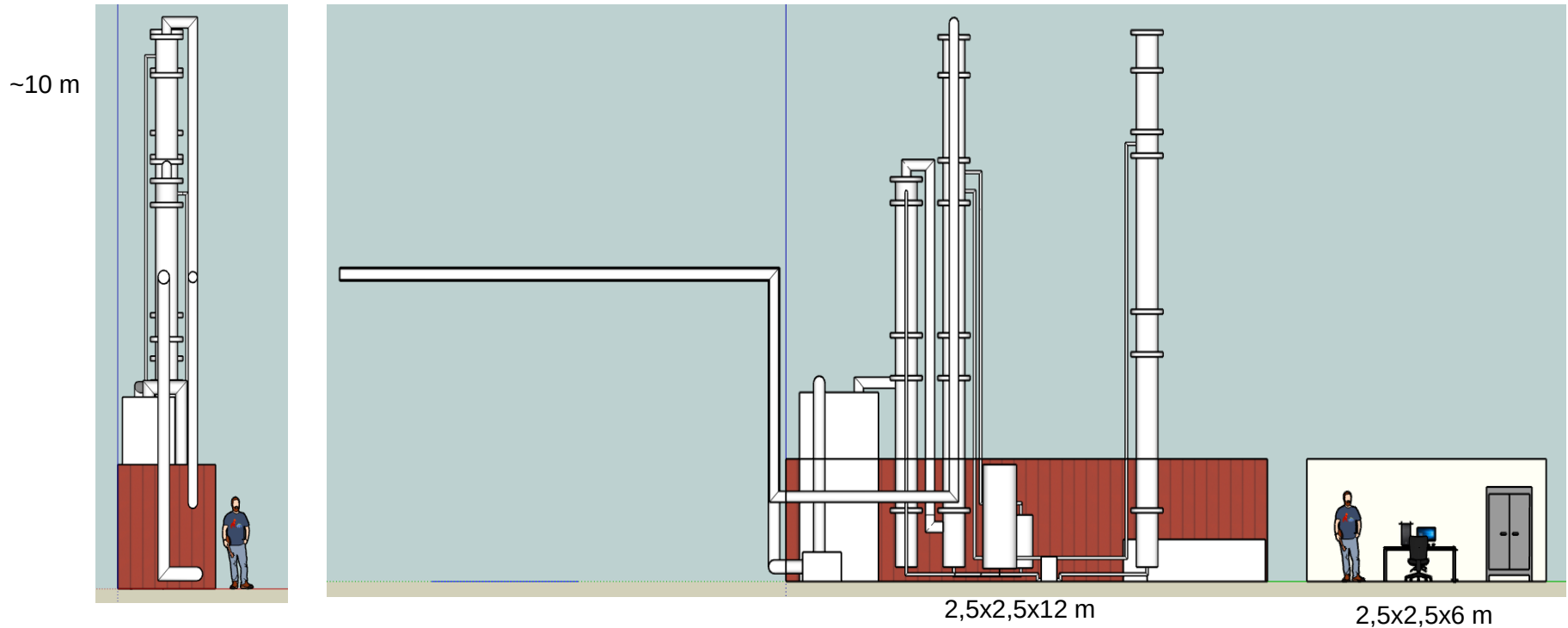
- Liège University Campus as living lab
 - ❑ CO₂ capture pilot plant under design (RRF Repower EU)
 - ❑ 1 tCO₂ per day, mobile unit
 - ❑ CHP plant – Wood pellets => **negative emissions** !
 - ❑ Research and Education ! New Master in Energy Engineering !



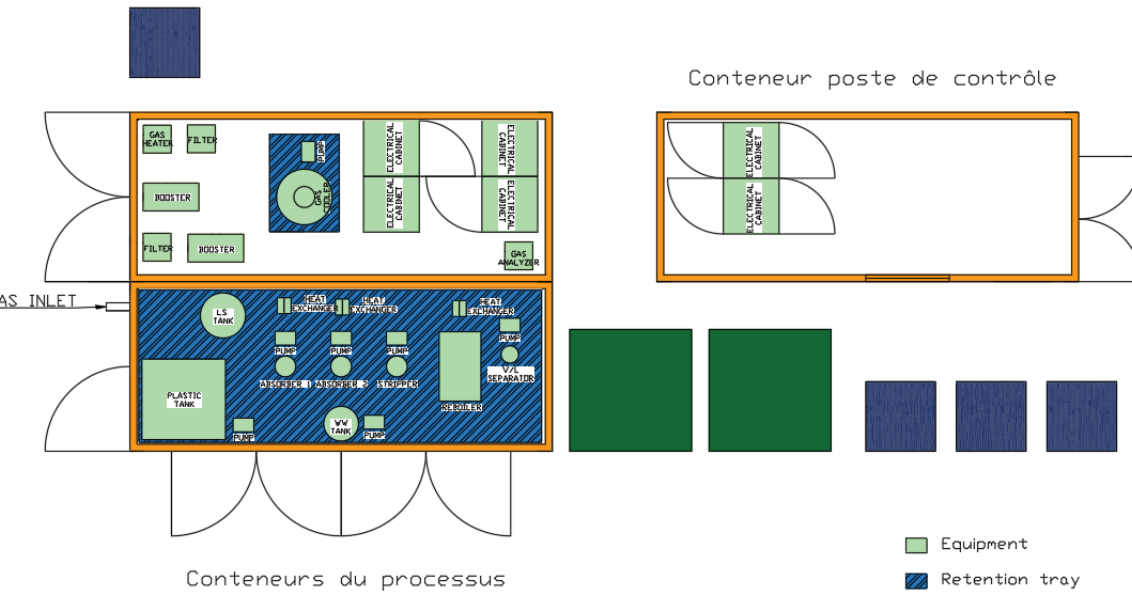
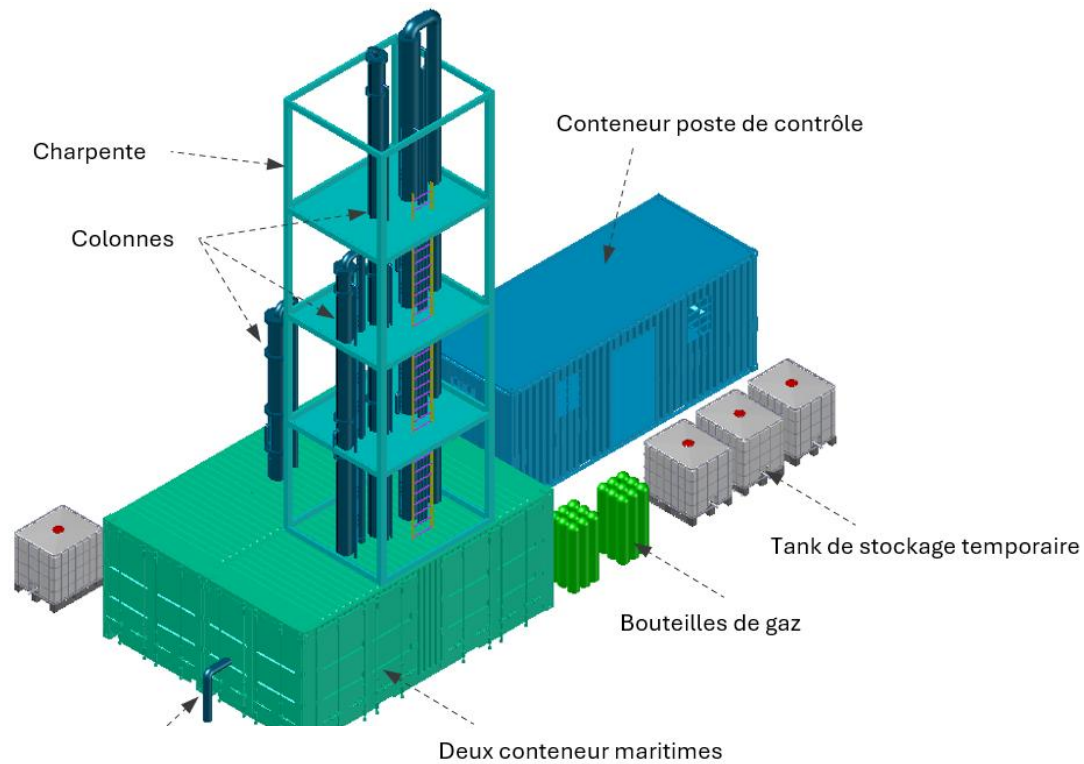
CO₂ capture mobile pilot, 1 tpd

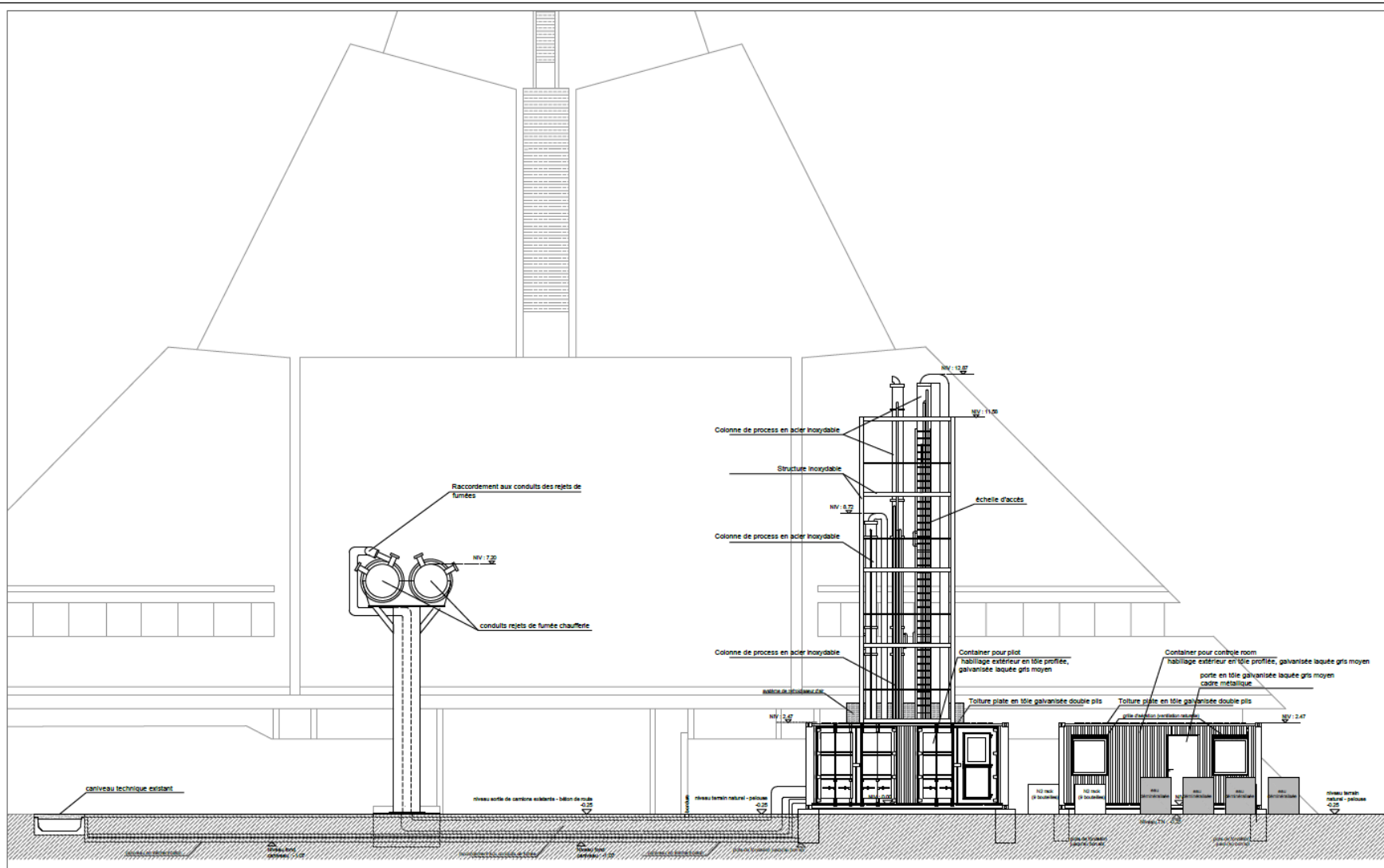


CO₂ capture mobile pilot, 2 containers



Our pilot...





ELEVATION NORD - OUEST 1/100



M. Paul ANTOINE, Ir. Architecte, Directeur adjoint de l'ARI

Patrimoine de l'Université de Liège ("ULiège" ou "Maître d'ouvrage")

Signature

ELEVATION NORD - OUEST - PILOTE DE CAPTURE CO2

BÂTIMENT B10 - chaufferie du Saint Tilman

ADRESSE Allée de la Cense Rouge n°59 - 4000 LIÈGE (Saint Tilman)

OBJET Installation de containers pour une installation pilote de capture poste-combustion de CO2

DOSSIER

Echelle 1/100

Plan dressé par : ARI

AF Marique - M. Simon

DOSSIER ARI

24.007-B10-RECUP_CO2_RRF

Les plans restent la propriété de l'auteur de projet, toute reproduction ou modification doit être autorisée par celui-ci. Les cotes sont données à titre informatif, l'entrepreneur est tenu de les confirmer sur chantier. Les entrepreneurs ne peuvent prétendre des lacunes, erreurs ou omissions figurant aux plans, toute erreur est communiquée sans délai à l'architecte.

Objectifs du pilote de capture de CO₂

❖ Objectifs de recherche

- ❑ Validation des modèles de procédé stationnaires et dynamiques
- ❑ Etudier l'impact de la composition des fumées (CO₂, SO_x/NO_x, particules) et des conditions opératoires
- ❑ Dégradation des solvants et corrosion (campagnes de plusieurs mois)
- ❑ Stratégies de contrôle avancées
- ❑ Etude de différents solvants, différentes configurations de procédés (intégration énergétique, pompe à chaleur...)
- ❑ Banc de test pour autres technologies

❖ Objectifs sociétaux

- ❑ Faciliter l'implémentation de technologies de capture de CO₂ dans les industries belges
- ❑ Enseigner et former les étudiants en ingénierie à ces technologies

Technologies d'émissions négatives

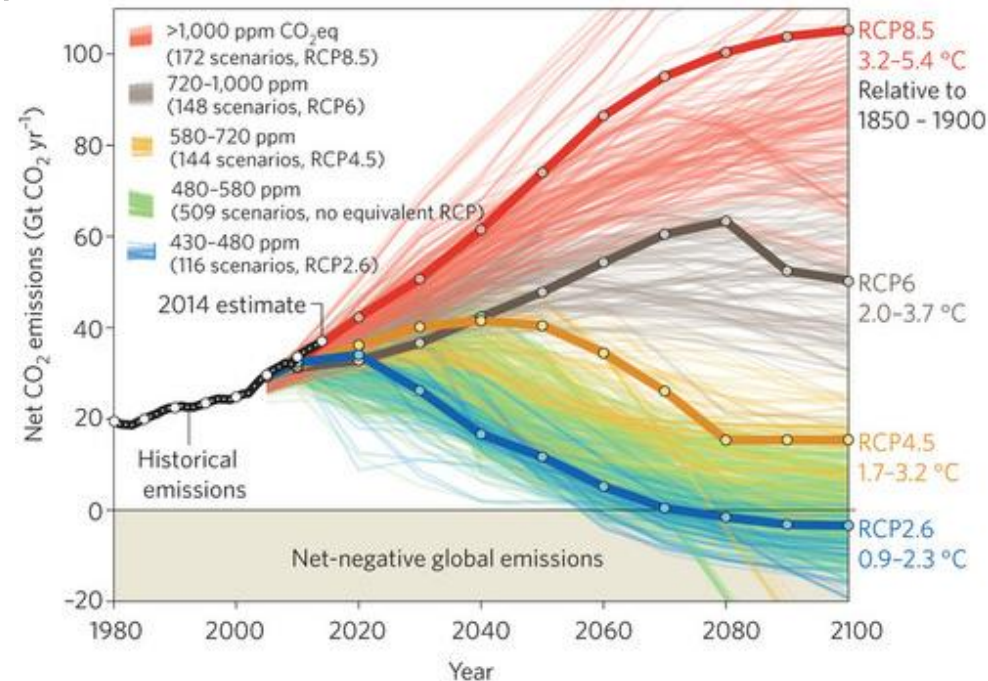
Negative emission technologies

Negative emissions technologies

- Negative CO₂ emissions
 - Use of biomass with CCS (BECCS)
 - Carbon sequestration in soils
 - Direct air capture (DACCS)

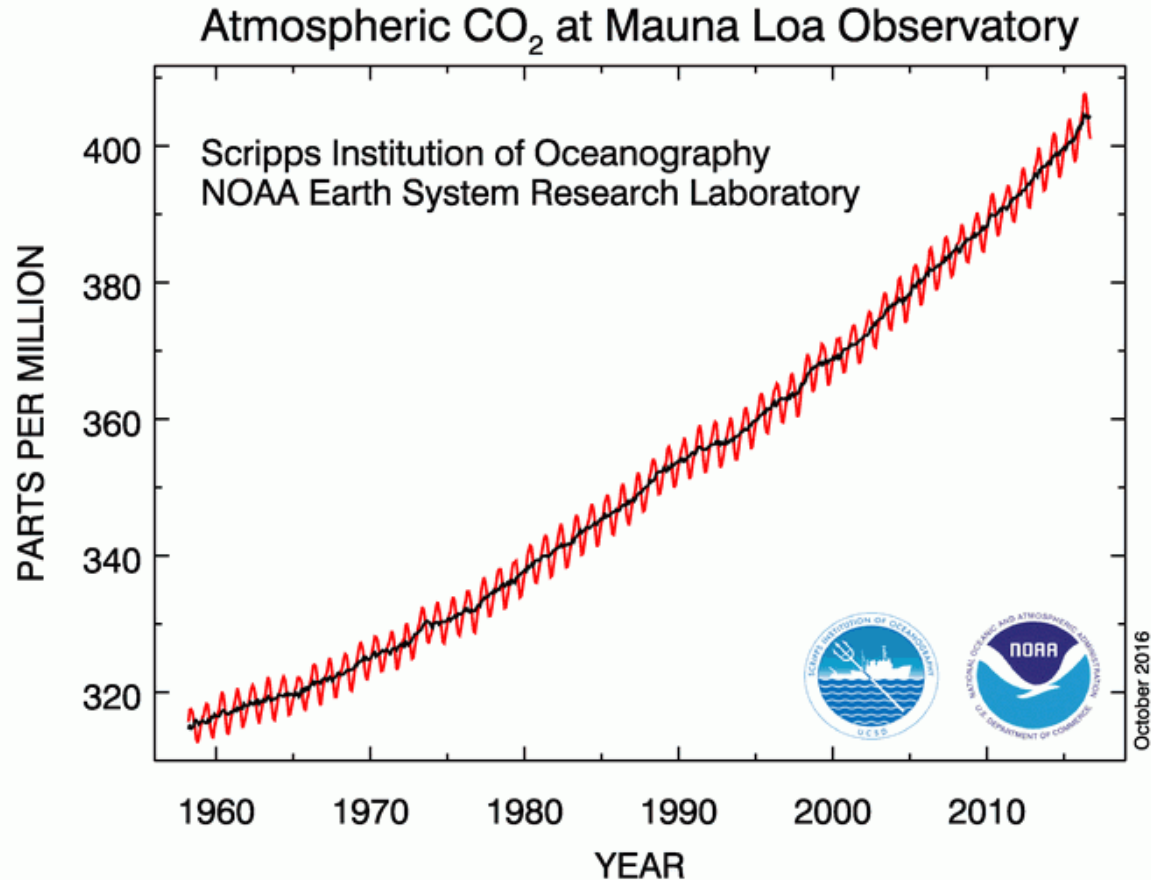
Are getting more and more present in the agenda...

But should not prevent from cutting down the emissions!!



Negative emissions technologies

- La concentration de CO₂ dans l'atmosphère atteint 425 ppm



<https://gml.noaa.gov/ccgg/trends/>

BECCS & séquestration dans les sols

- Biomass enhanced CCS (BECCS)
 - Principe: cultiver la biomasse, la brûler et capter + stocker le CO₂
 - Prêt pour déploiement, mais logistique compliquée
 - Potentiel de capture:
 - Pour 1 Gtpa (= 2.5% des émissions)
=> 30-43 Mha ~ 4% des terres cultivées
 - Potentiel < 100 US\$/ton ~ 3.5-5 Gtpa

Carbon sequestration in soils

- Sequestration as soil organic carbon
- Technical potential: 0.79 - 1.54 Gt C/y

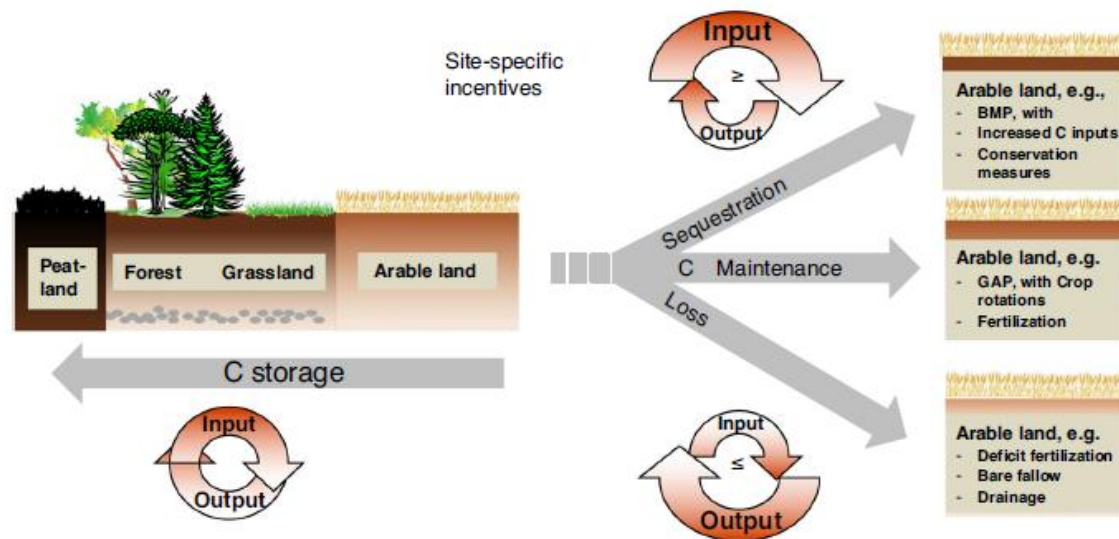
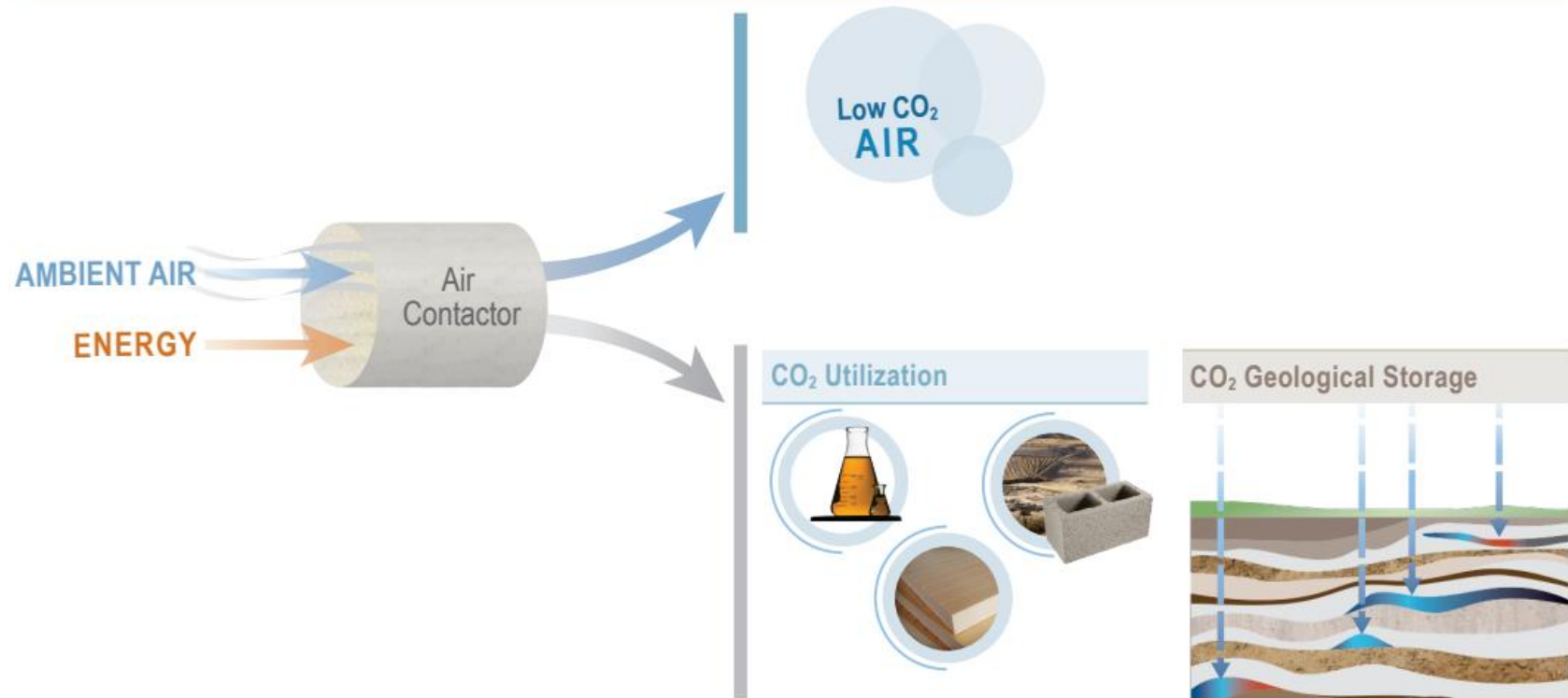


Fig. 1 Conceptualization of C sequestration potentials in arable land. Usually C is lost after land-use conversion from native ecosystems (e.g., peatlands, forests, grasslands) to arable land. Future C storage in agricultural fields then depends on agricultural management practices, with options to regain C by increasing the organic matter input relative to ongoing CO_2 release at best management practice options (BMP), to maintain C stocks by continued good agricultural practice (GAP), or to lose additional C by intensifying agriculture without additional C input, usually followed by soil degradation.

Direct Air Capture (DAC)



Direct air capture of carbon dioxide., ICEF roadmap, 2018

Direct air capture motivations

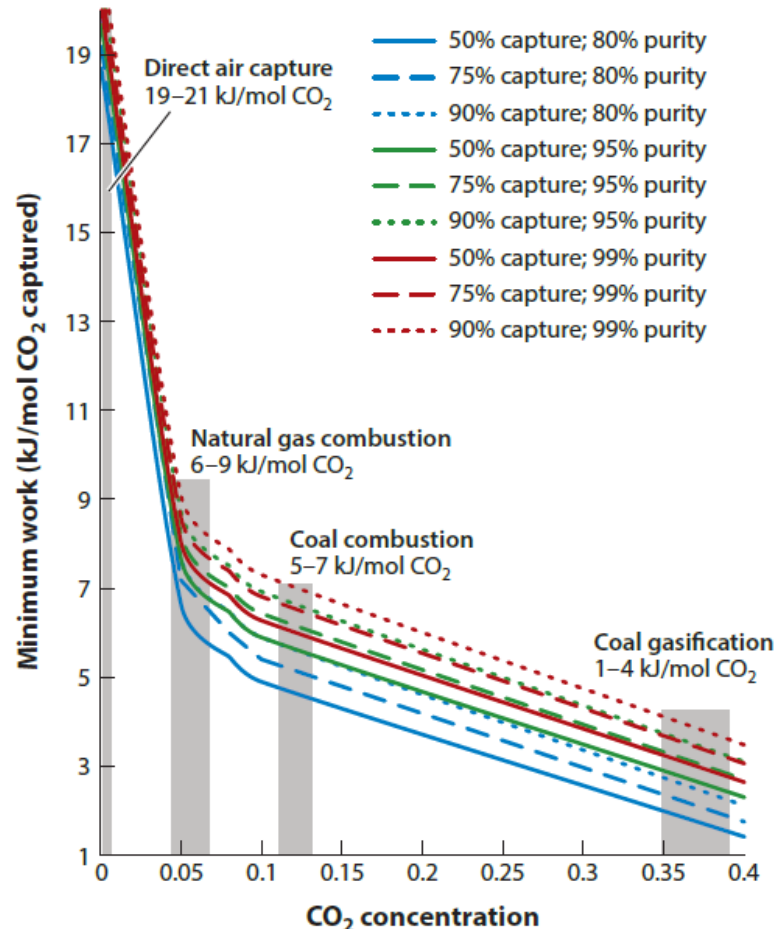
- Compensate for hard-to-abate GHG emissions (not only CO₂)
 - 20 to 40% of current emissions
 - Aviation, marine, raw materials, agriculture, potential leakage from storage
- Close the carbon cycle of synthetic fuels
 - No carbon neutrality for carbonated fuels without CO₂ capture
- Reduce the need for transporting CO₂
 - Possible to capture CO₂ anywhere, incl. close to use or storage sites
 - No Nimby effect
- Long-term considerations: remove C from the atmosphere
- Serves as a backstop technology for managing climate change

Inconvénients des technologies DAC

- Thermodynamically defavored: very dilute streams!
- DAC is more expensive
 - Climeworks: ~ 600 \$/tCO₂, but roadmap for achieving 200 \$/t
 - Carbon Engineering: objective at 94 \$/t
- DAC requires large amount of energy
 - Especially for moving the air
 - Regeneration energy similar to point-source capture

But still possible/relevant?

- The minimum work is not linearly proportional to the dilution!



Minimum work required for CO₂ capture based upon initial gas concentration, percent capture, and final purity of CO₂.
DOI: 10.1146/annurev-chembioeng-060713-040100

Direct air capture

- A growing business...



Exclusive: Carbon Engineering CEO discusses recent funding for DAC technology

By Molly Burgess | 24 April 2019



Last month, Carbon Engineering, a Canadian clean energy company announced the completion of an equity financing round of \$68m, marking the largest private investment made into a Direct Air Capture (DAC) company to date.



DAC technologies today

- Orca project, in Iceland – world's largest, 08/2021
 - Climeworks (Swiss start-up)
 - 4000 tpa CO₂ ~ Emissions of 250 US citizens
 - CAPEX: ~15 M€
 - Geothermal energy
 - CO₂ liquefaction
 - Underground mineralization



Climeworks (Switzerland)



Major hurdles...

- Uncertain business models!
- Even worse: uncertain impact on climate change!
 - Climeworks has captured 2400 t_{CO2} (cumulated value as of 2025, over several years)
 - But emissions are in the range of 1700 tpa!
 - => Social plan ongoing to decrease jobs by 106 units

<https://usbeketrica.com/fr/article/la-start-up-climeworks-ne-capture-pas-assez-de-carbone-pour-compenser-ses-propres-emissions>

https://www.lemonde.fr/planete/article/2025/05/21/capture-de-co-les-difficultes-de-climeworks-symboliques-des-turbulences-dans-l-elimination-du-dioxyde-de-carbone-dans-l-air_6607659_3244.html

La tragédie des biens publics

- Who has to pay for the carbon removal from the environment, which is a global public good?
- Solution is to establish property rights to natural resources → tradable emission allowances
- ETS market (regulated market)
- Voluntary markets
 - Soil management, forest growth, renewable energies...
 - Sell the difference between Business As Usual and upgraded situation => fair?
 - ! Certification!

Who has to pay for DAC?

- ORCA and Climeworks used to sell « CO₂ allowances » at ~1200 \$/ton
- Now, ranges between 100 and 480 €/ton
- The cost of a flight between UE and US West Coast would increase by ~1200 € (2.5 t/passenger)

 climeworks

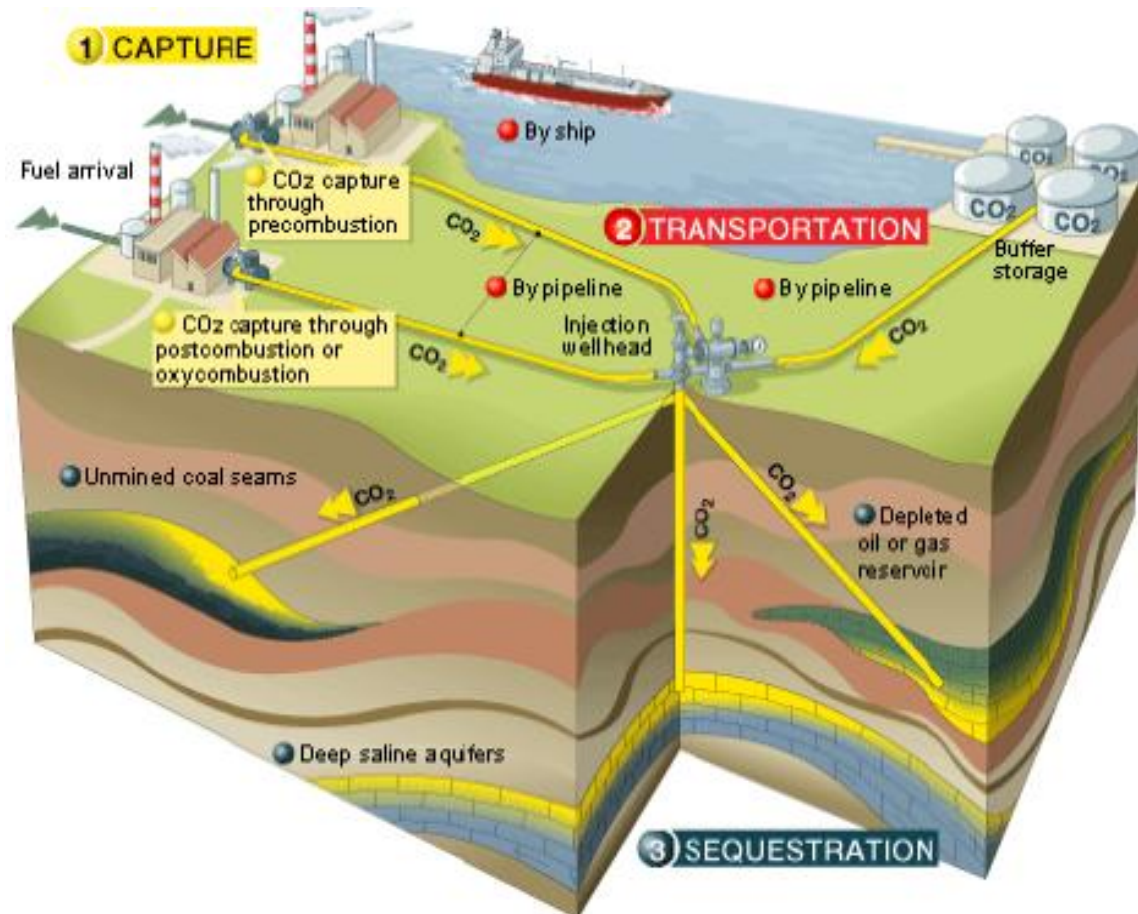
Special Expedition	Discoverer	Explorer
		
Permanently remove 50 kg of CO ₂ per month. 600 kg per year is 30 days of central heating in a home!	Permanently remove 25 kg of CO ₂ per month. 300 kg per year is 730 miles / 1,175 km driving in a car!	Permanently remove 15 kg of CO ₂ per month. 180 kg per year is 6 ½ months energy used for one light bulb!
EUR 50.- / month	EUR 25.- / month	EUR 15.- / month
Subscribe now	Subscribe now	Subscribe now

<https://climeworks.com/actnow>

Transport du CO₂

Integrated chain

Capture – Transport – Séquestration



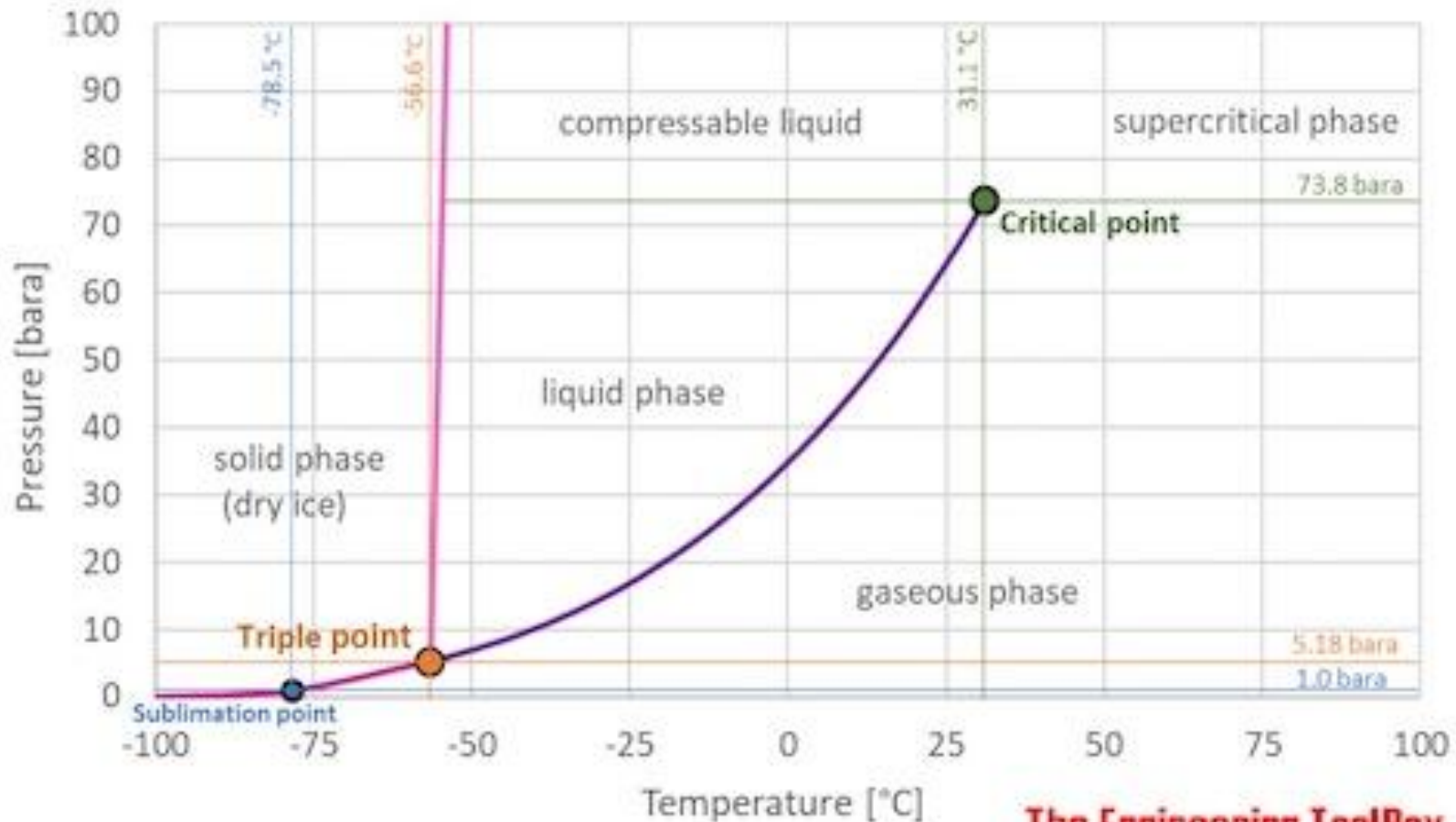
Transport du CO₂

- Par bateau:
 - 100 000 tonnes transportées/year (~1000 tCO₂/bateau)
 - CO₂ liquéfié (-30°C, 15 bar)
 - Technologie proche du LPG
- Par pipeline:
 - CO₂ supercritique (100 bar)
 - > 6500 km de pipelines depuis les années 1970 (EOR)



Diagramme de phase du CO₂

Carbon dioxide phase diagram



The Engineering ToolBox

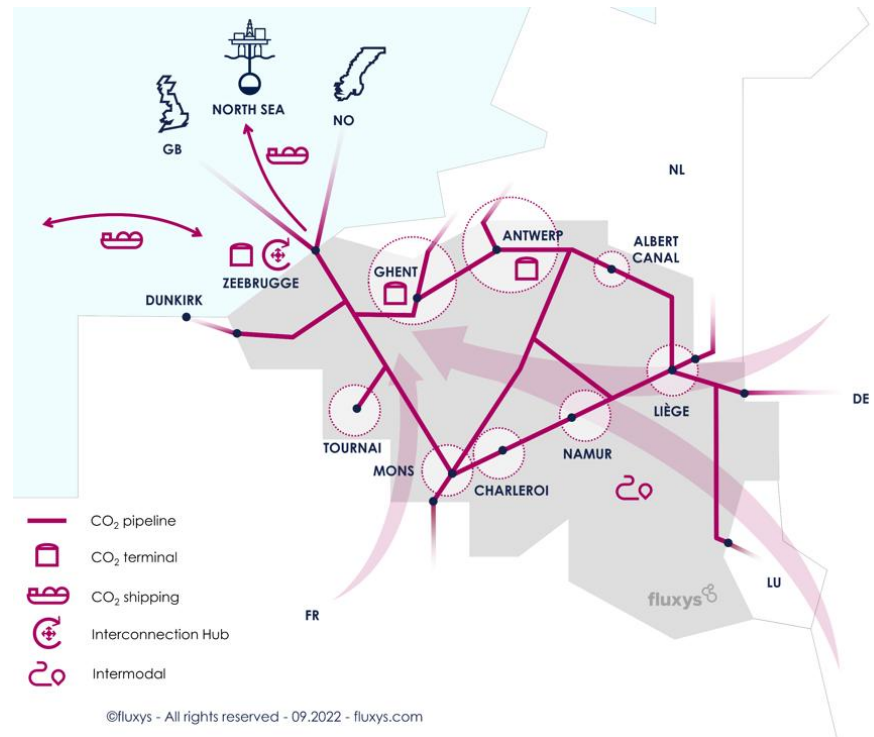
www.EngineeringToolBox.com

Transport du CO₂

- Provisional specifications for CO₂ transport in Belgium
 - Gaseous to avoid corrosion issues

Compounds	Specification 95	Specification 99
CO ₂ [mol-%]	> 95	> 99
O ₂ [ppmv]	< 40	
N ₂ [mol-%]	< 2	< 0.5
H ₂ O [ppmv]	< 40	
SOX [ppmv]	< 10	
NOX [ppmv]	< 5	

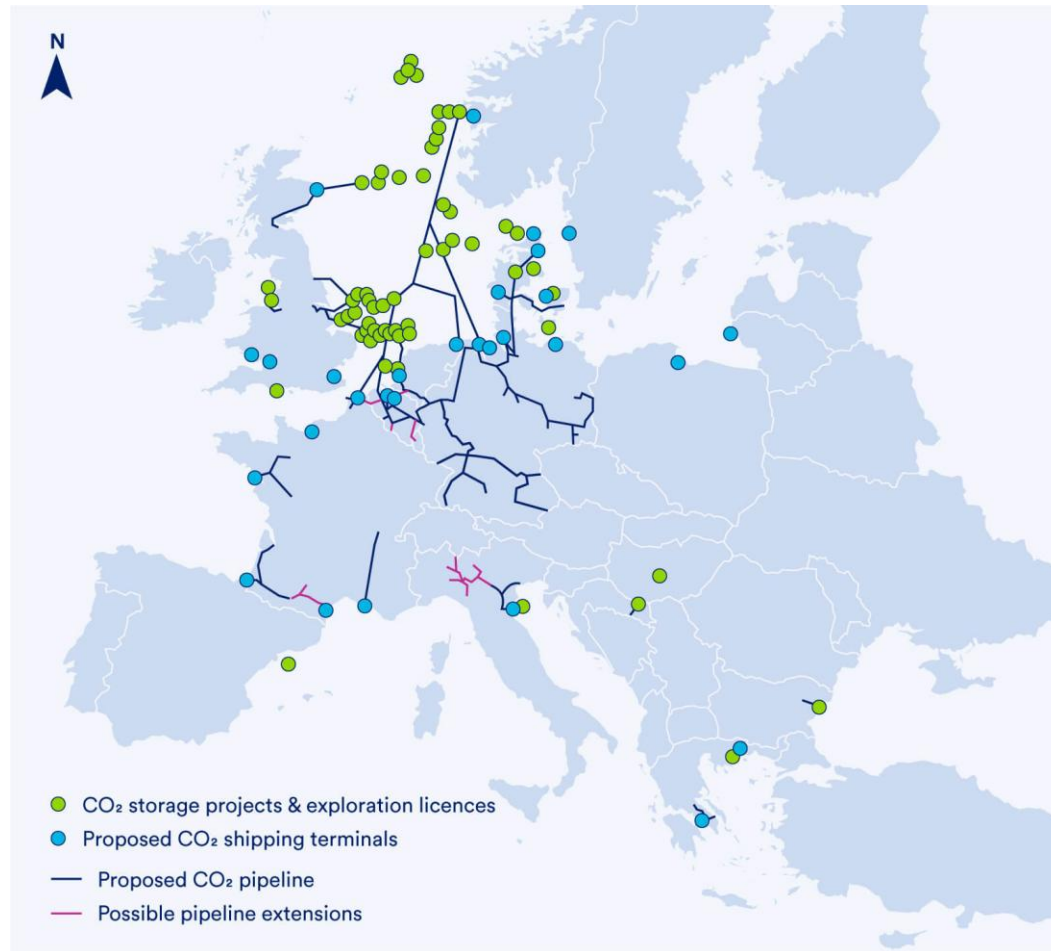
Parameters	Units	Operating conditions
Pressure	barg	Up to 35
Temperature	°C	5-40



Fluxys CO₂ mature backbone for 2050

Les infrastructures sont un atout clé!

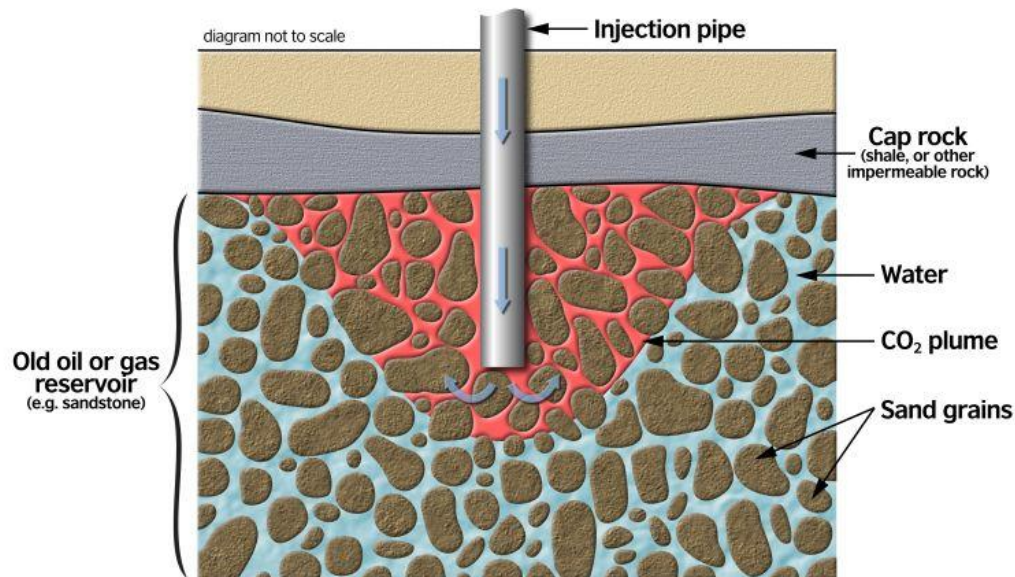
■ Proposition en Europe



Séquestration du CO₂

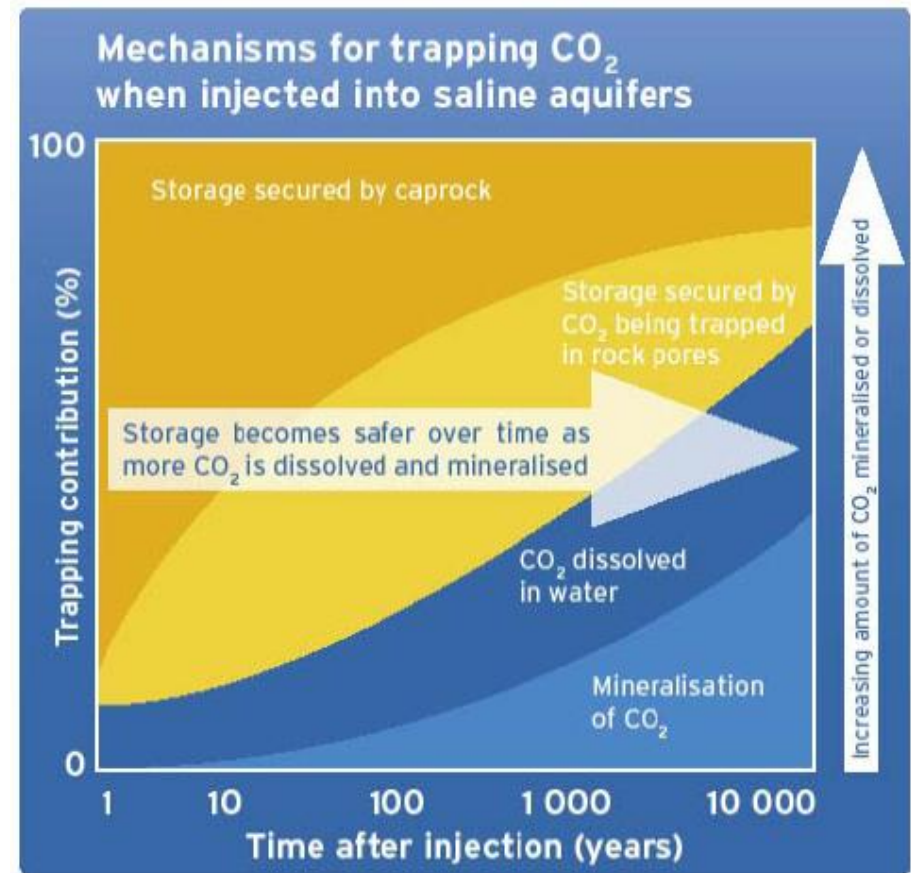
Sites possibles

- Aquifères salins: large capacity, geology less well-known, reservoir properties under study
- Champs épuisés de gaz et pétrole: Limited capacity, but geology is well-known, storage safety has been proven
- Veines de charbon: limited capacity, low permeability, possibility to recover methane



Qu'arrive-t-il au CO₂ en sous-sol?

- CO₂ diffuses in the geological formation and is trapped under the cap
- It then get stuck in smaller porosities
- It dissolves and gets mineralized
- Long time-scale!



Quelques exemples

■ In-Salah, Algeria

- 3.8 Mt CO₂ injected 2004 - 2011
- Former gas reservoir (1900 m deep)
- Injection paused, soil integrity being studied
- Constant monitoring

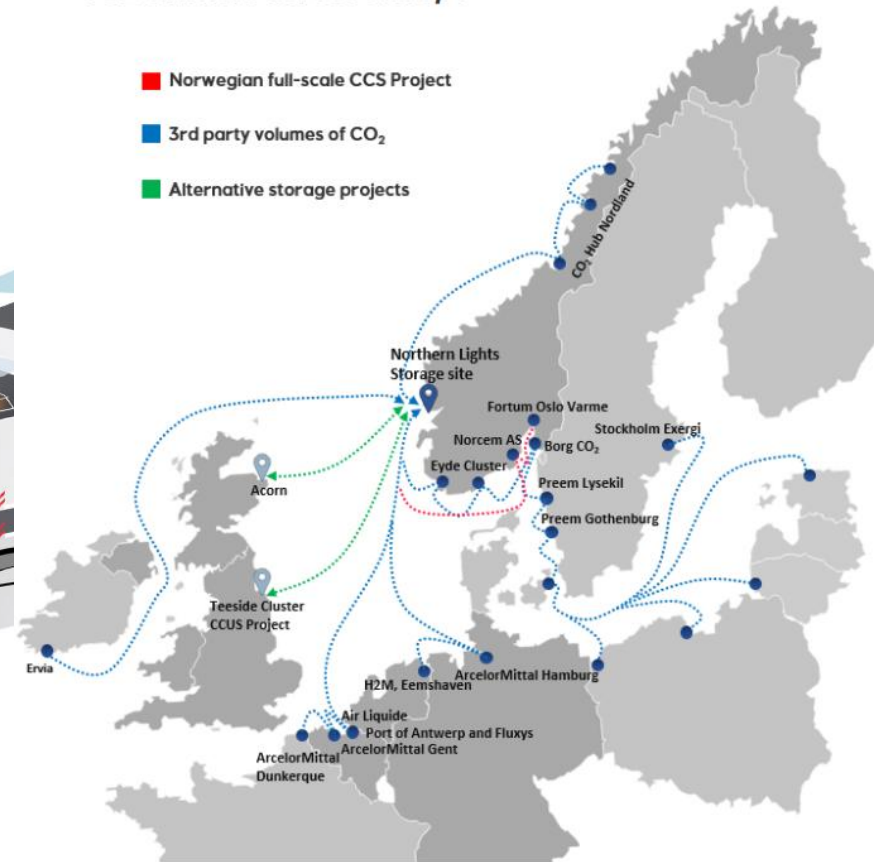
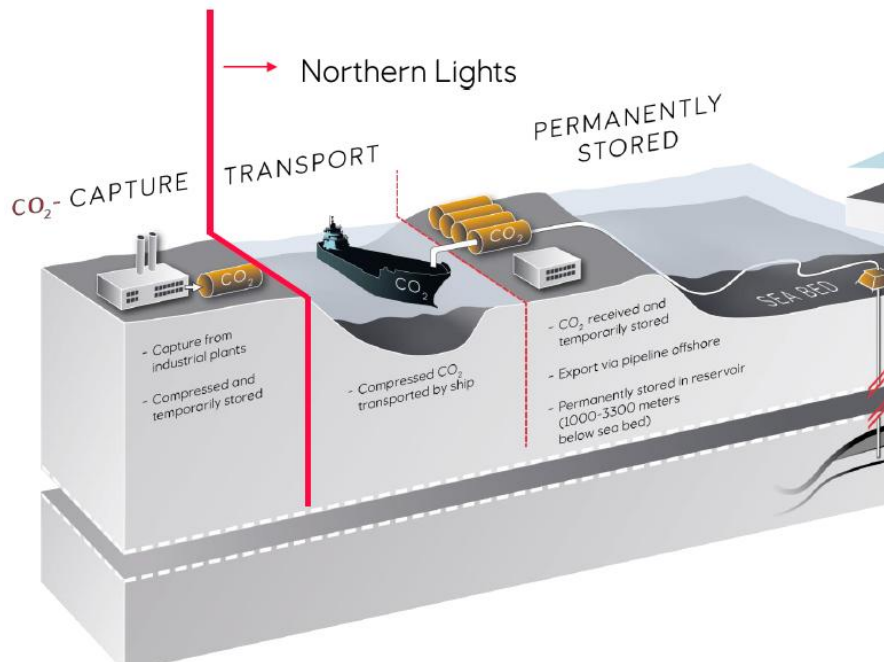
■ Sleipner, Norway

- ~ 1 Mtpa from 1996
- Saline aquifer (800-1000 m deep)
- Offshore of Norway's coast
- > 17 Mt injected

Northern lights

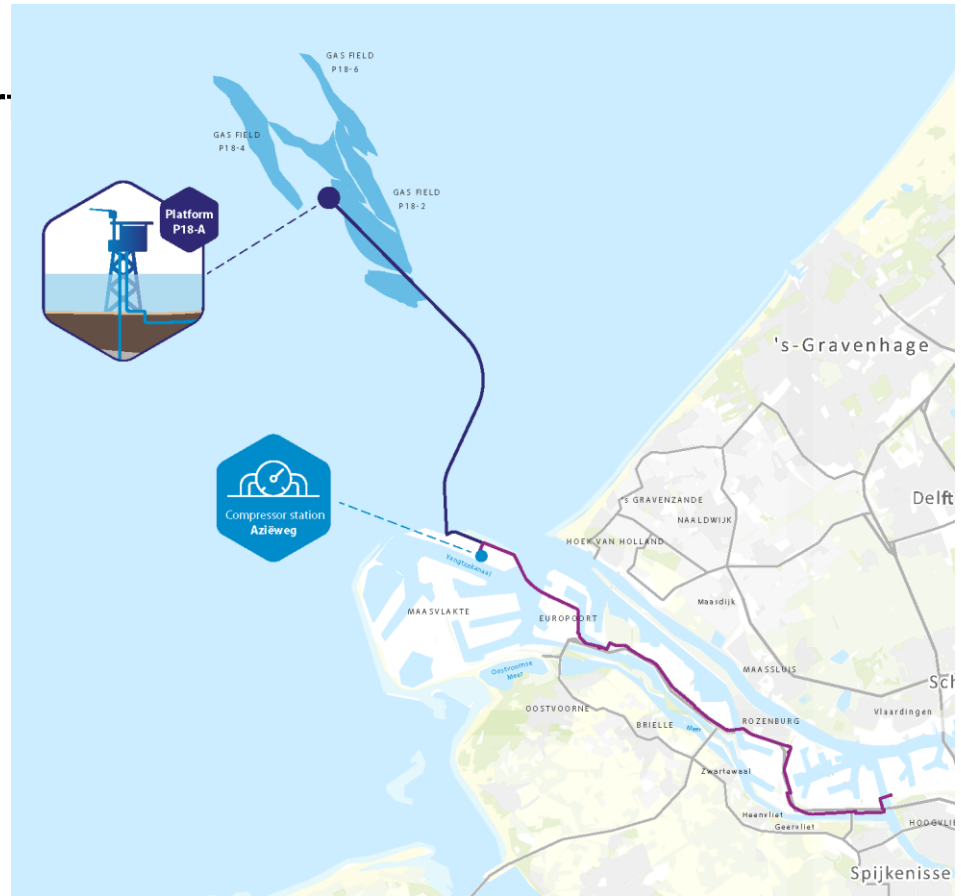
- Norway, off-shore field, saline aquifer
- Up to 5 Mt CO₂/y

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



Porthos

- Rotterdam, off-shore depleted gas field (3-4 km undersea)
- JV EBN, Gasunie, Port of Rotterdam
- 2.5 Mt CO₂/y
- Operation: 2026-2041
 - => 37 Mt in total
- 1.3 bn€ investment
- Aramis + Athos are parallel projects

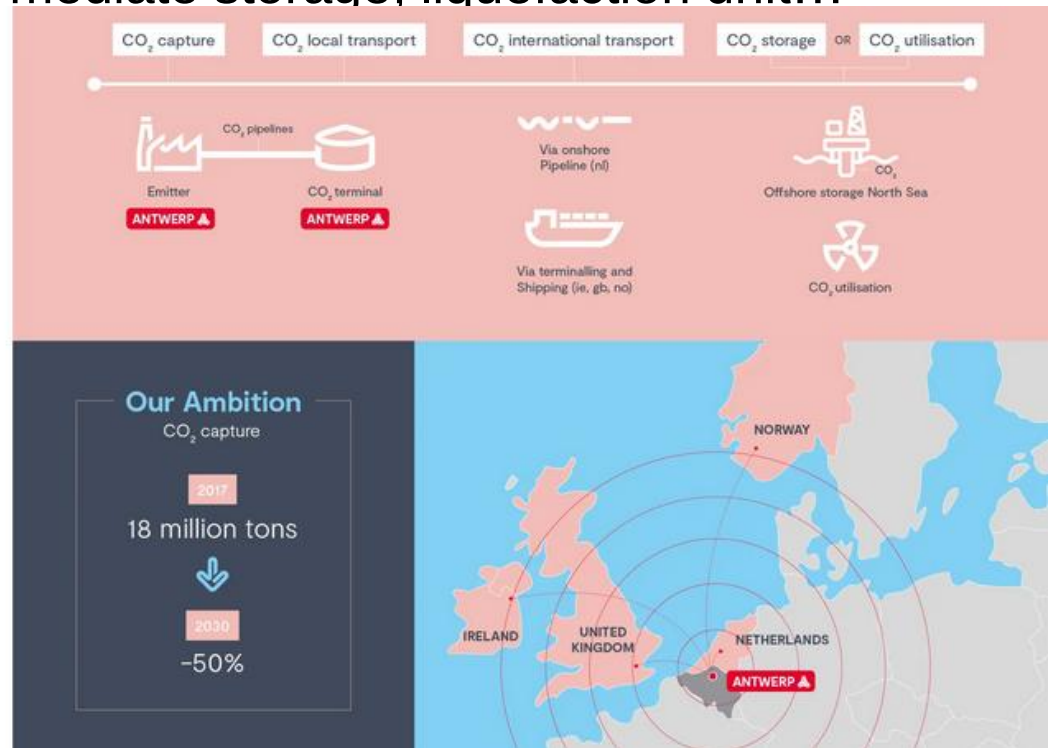


Antwerp@C

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

Antwerp@C

8 players in chemical & energy sector investigate feasibility of carbon capture, utilisation and storage in Port of Antwerp



Greensand

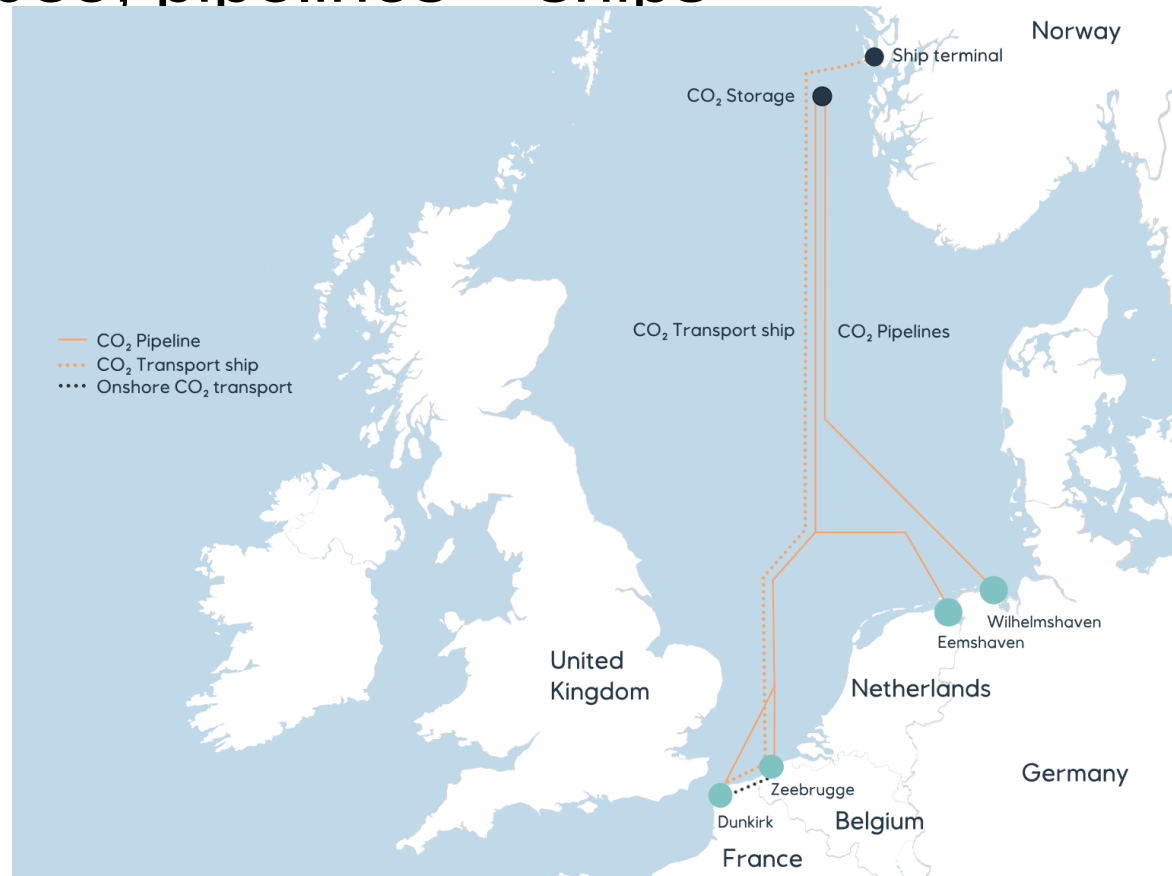
- CO₂ captured at Ineos Oxide, Zwijndrecht
- Depleted oil reservoir 1800 m deep, offshore of Denmark

Greensand CCS pilot



CO₂ Highway

- 15-30 Mtpa CO₂ transport and storage capacity by 2035, pipelines + ships

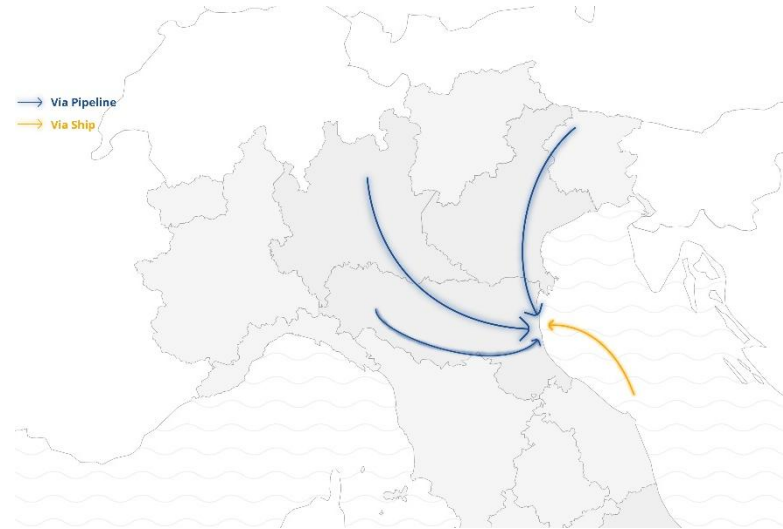


<https://www.equinor.com/energy/smeaheia>

115

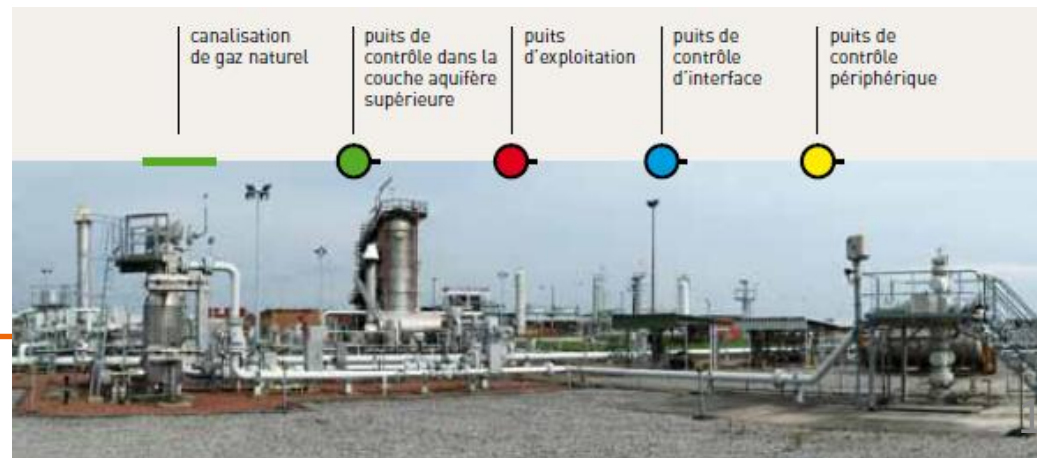
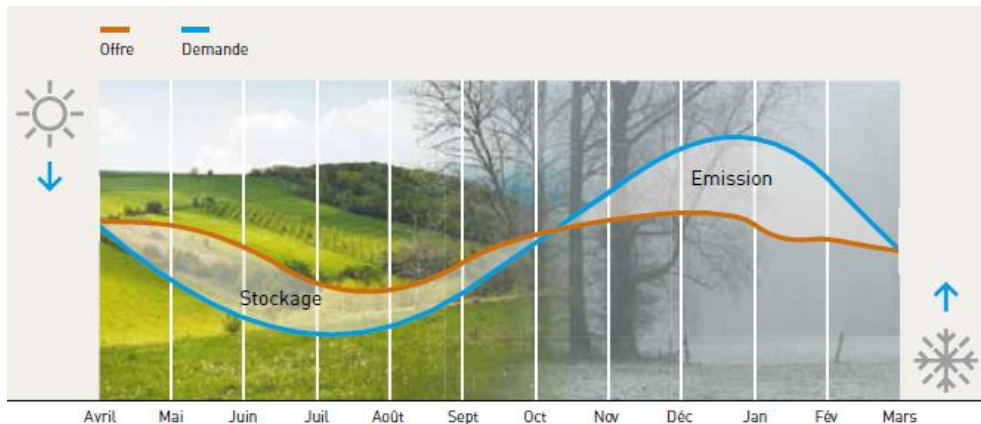
Ravenna CCS

- Italian joint venture: ENI + Snam
 - Start in 2027
 - 4 Mtpa by 2030, > 16 Mtpa after 2030
 - More than 500 Mt total storage capacity
- Depleted natural gas reservoirs under Adriatic sea (about to be phased out)
- ~10% of existing facilities (pipelines + offshore) will be converted to CCS



Est-ce dangereux ?

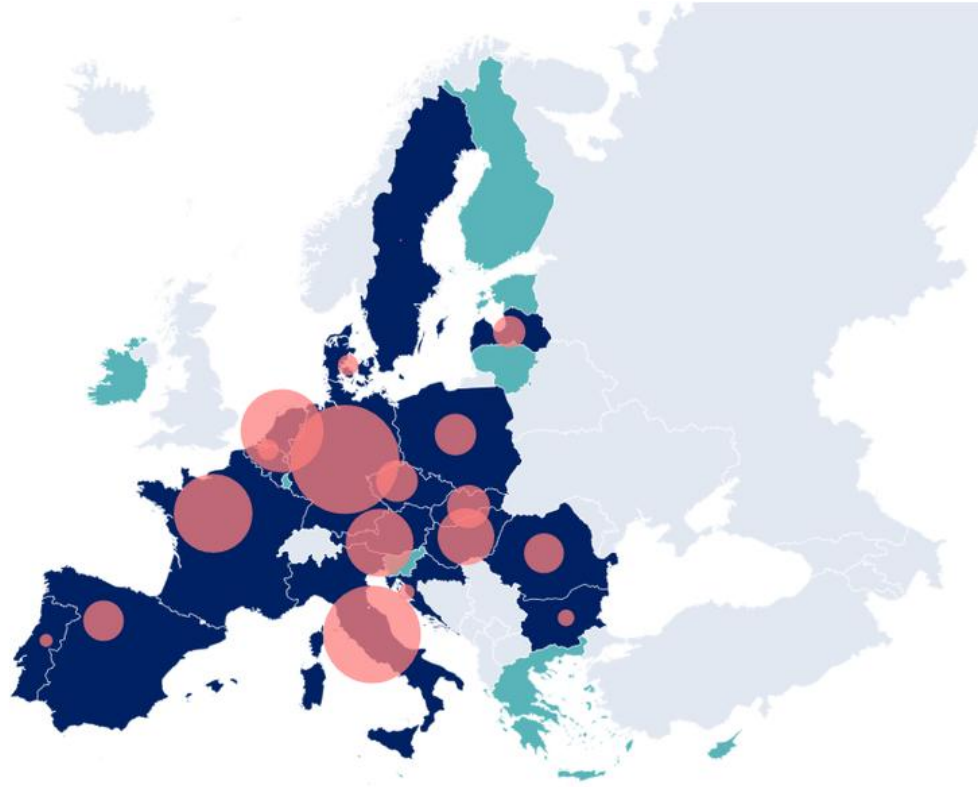
- Ce n'est pas une nouvelle technologie!
 - Exemple: Stockage saisonnier de gaz naturel à Loenhout (Anvers), capacité de 9 TWh



Source : www.fluxys.com

Est-ce dangereux ?

■ Sites de stockage de gaz naturel



Capacité de stockage de gaz des États membres de l'UE. En vert les États membres en incapacité de stocker (soit Chypre, l'Estonie, la Finlande, la Grèce, l'Irlande, la Lituanie, le Luxembourg, Malte et la Slovénie), en bleu ceux qui sont en capacité. © Conseil de l'UE

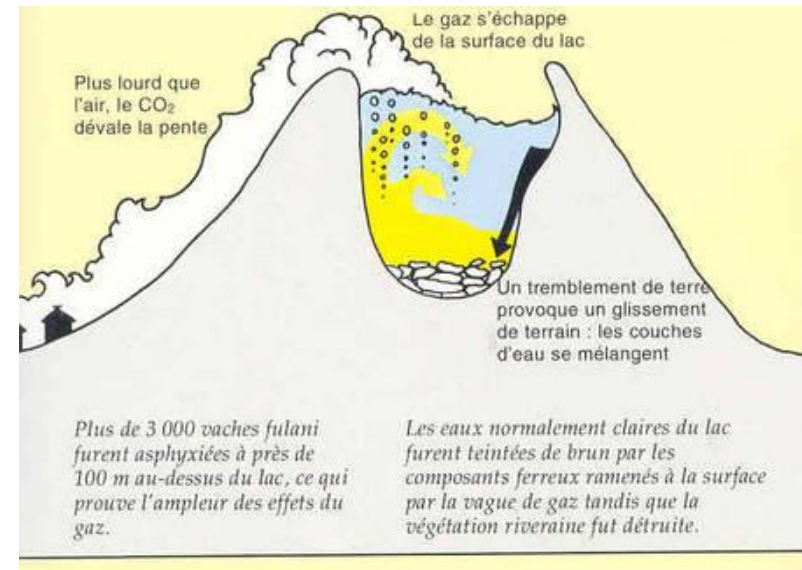
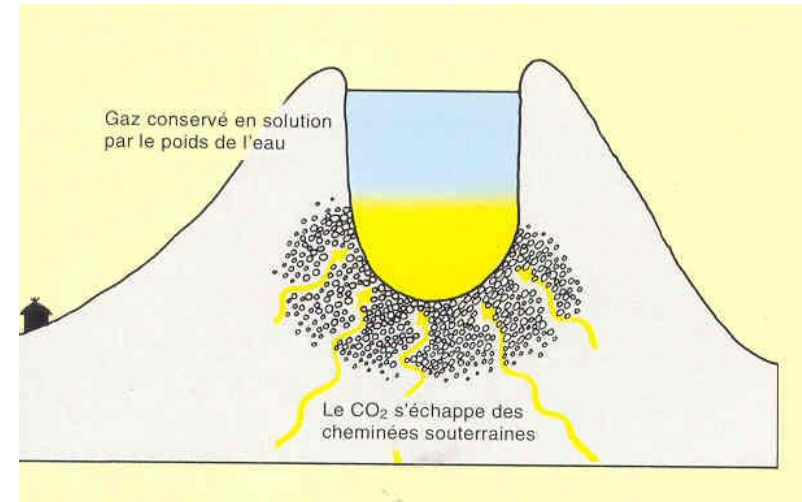
Source : www.trends.levif.be

Est-ce dangereux ?

■ Lac Nyos

- ❑ Cameroun, 1986
- ❑ CO₂ from volcanic source
- ❑ Almost 1700 fatalities

=> Risk management!

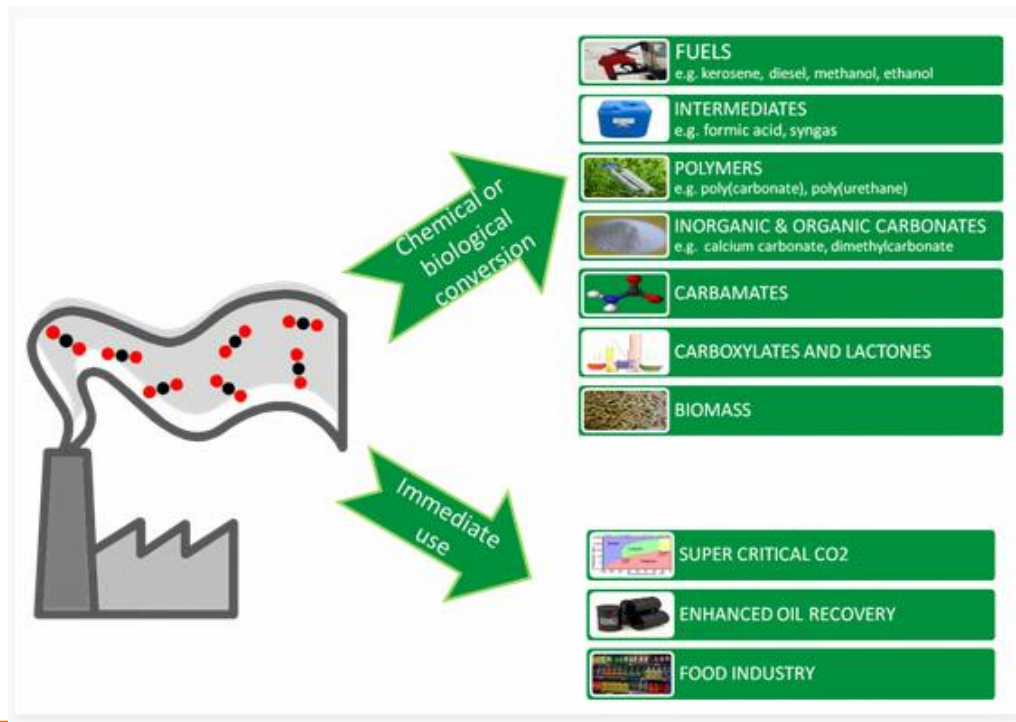


Utilisation du CO₂

Les molécules carbonées sont une richesse!

But where to get the carbon from, if not from fossils?

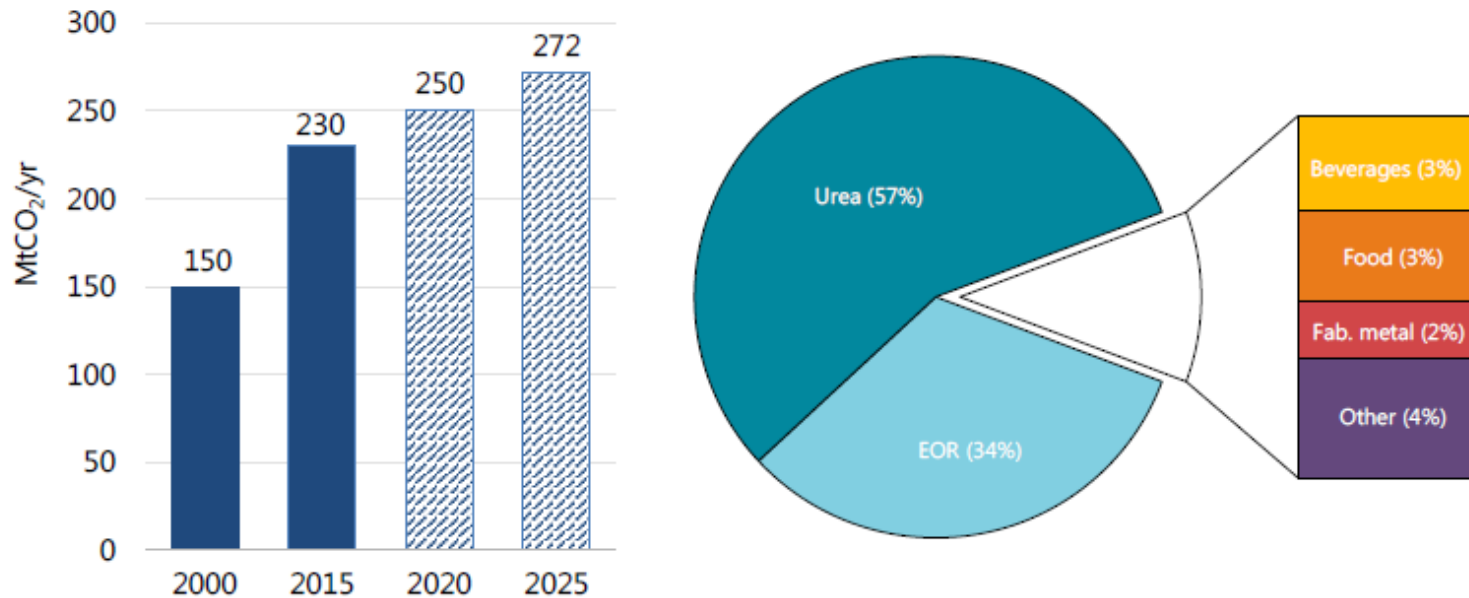
- Biomass: yes, but limited supply
- $\text{CO}_2 \Rightarrow$ leads to almost all petrochemical products!
+ energy-intensive!



Source: CO2Chem

Le CO₂ : un déchet ou une matière première ?

Figure 1. Growth in global demand of CO₂ over the years (left); breakdown of demand in 2015 (right)

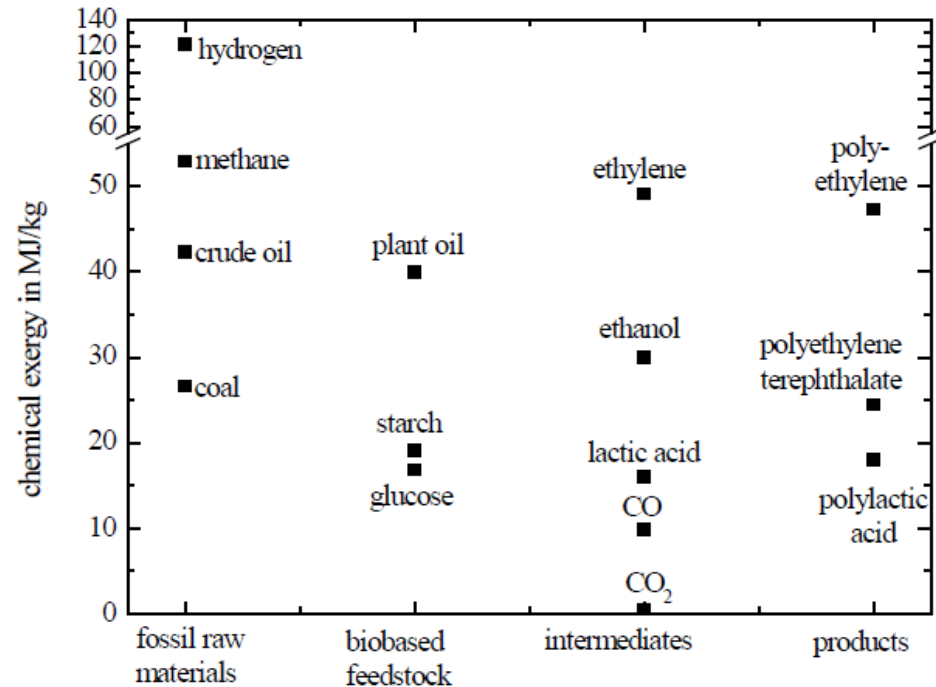


Note: Projections for future global CO₂ demand are based on an average year-on-year growth rate of 1.7%.

Sources: Analysis based on ETC (2018), *Carbon Capture in a Zero-Carbon Economy*; IHS Markit (2018), *Chemical Economics Handbook – Carbon Dioxide*; US EPA (2018), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016*.

Principales voies d'utilisation de CO₂

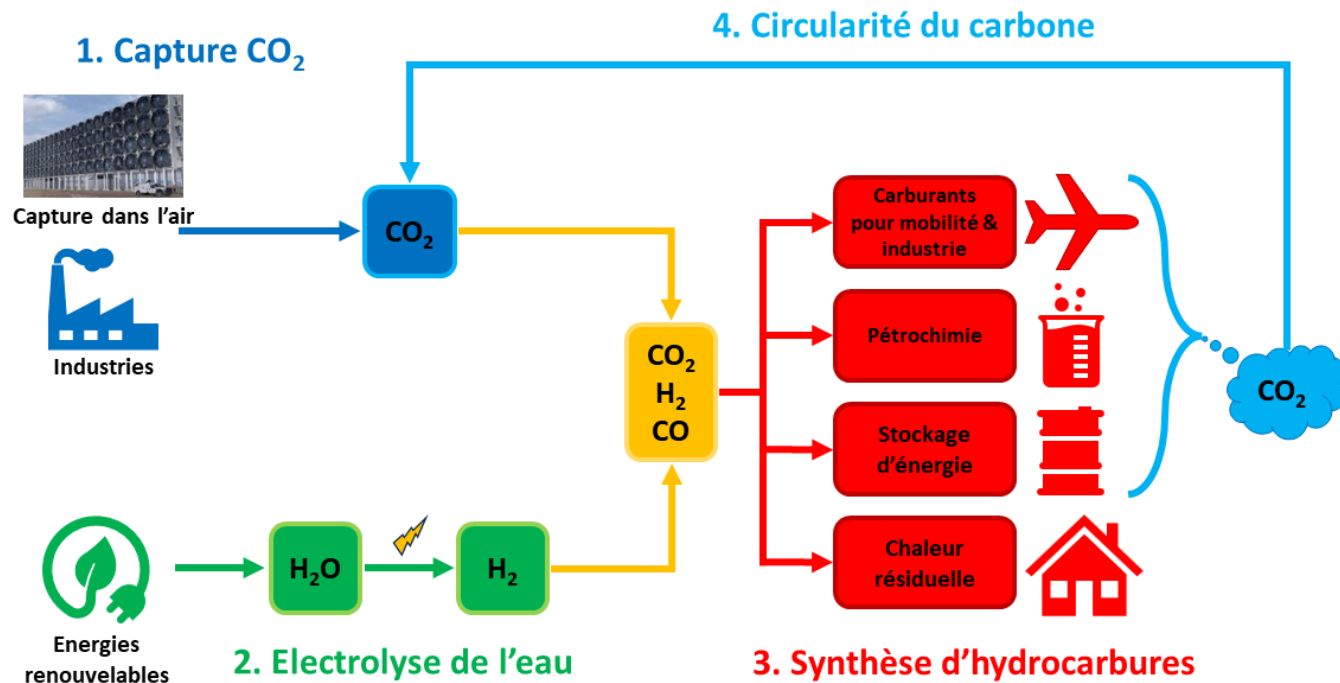
- Direct use, no transformation
- Biological transformation
- Chemical transformation
 - To lower energy state
 - Carbonatation
 - To higher energy state



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

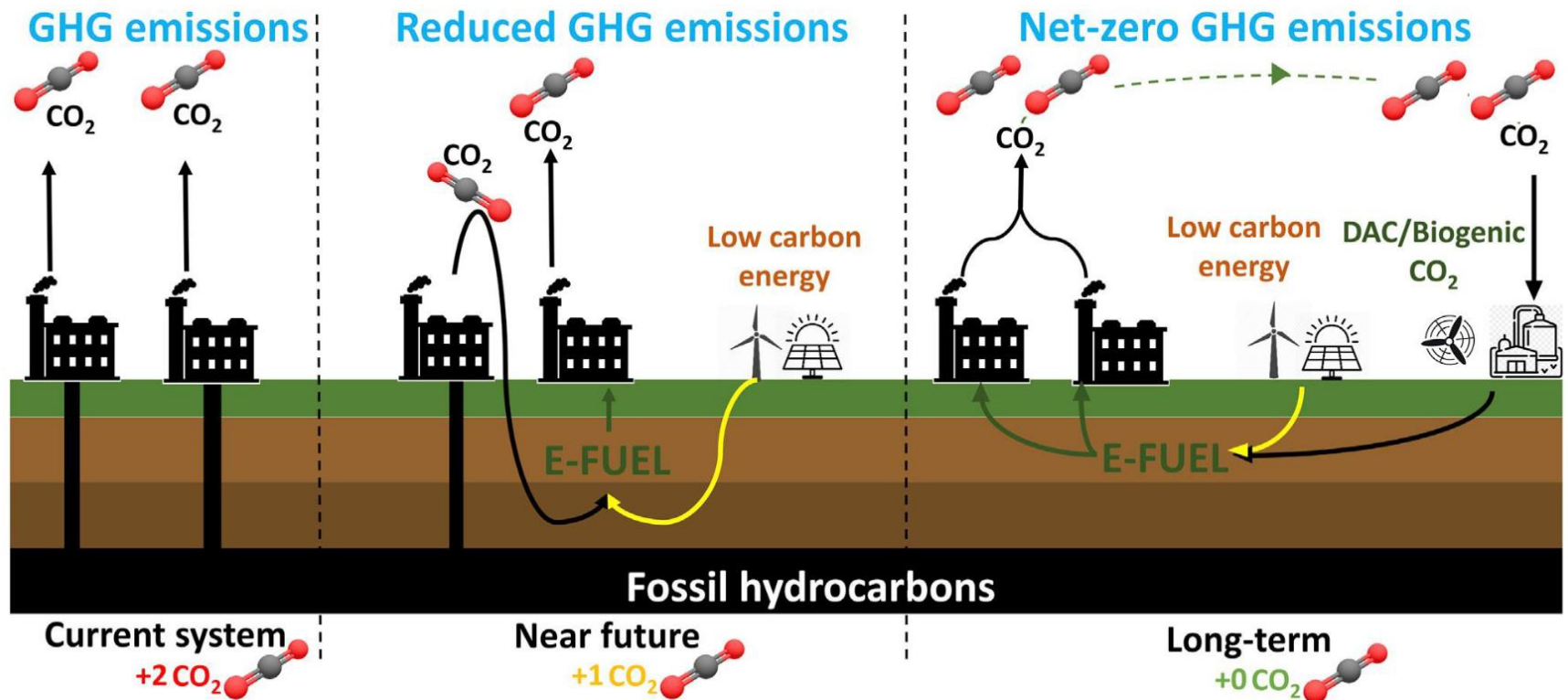
CO₂ to fuels

■ Power-to-liquid, power-to-gas



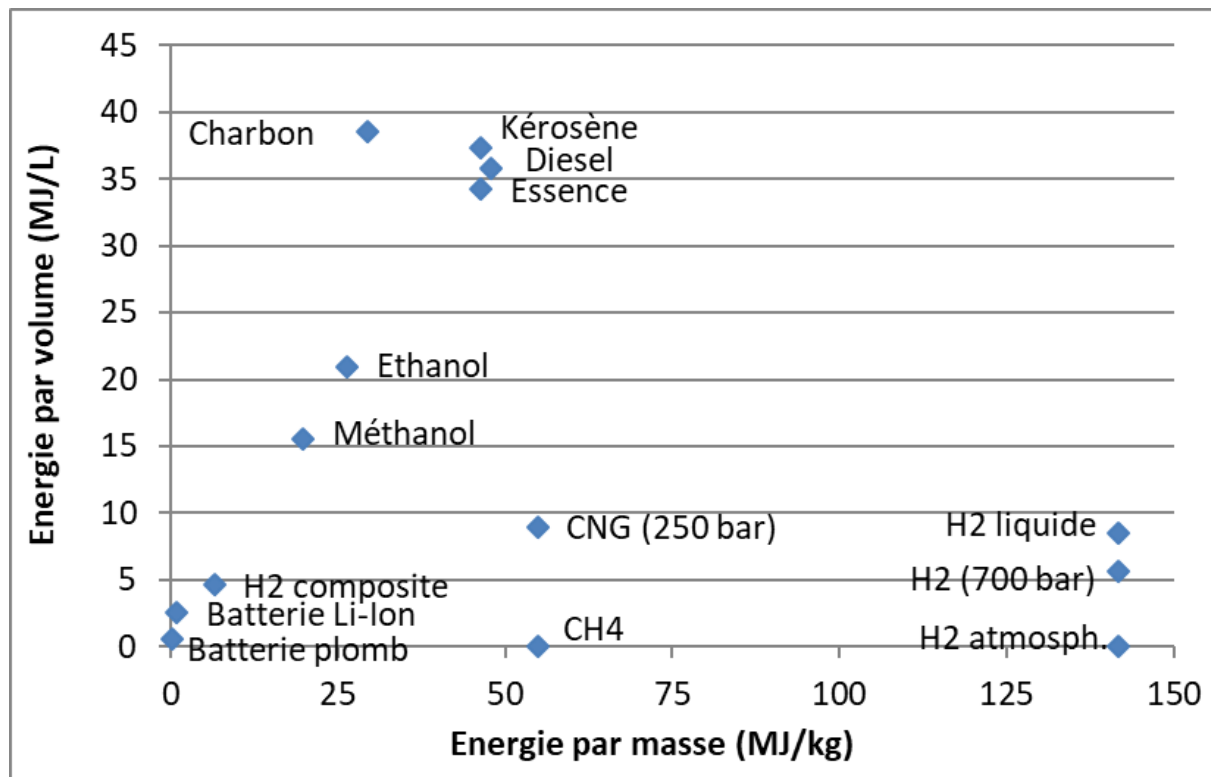
- Avantage décisif : une fantastique densité énergétique!
- + un système durable est possible!

The principle of CO₂ to fuels



Energy storage

- E-fuels chemical storage: a fantastic energy density!
 - => Interseasonal energy storage becomes possible



Energy storage

- Quick calculations
 - How many cars tanking at the same time are needed to develop a power of 3 GW_{th} ?
 - 1 L/s gasoline transfer
 - Gasoline $\sim 35 \text{ MJ/L}$

Energy storage

- Quick calculations
 - How many cars tanking at the same time are needed to develop a power of 3 GW_{th} ?
 - 1 L/s gasoline transfer
 - Gasoline $\sim 35 \text{ MJ/L}$
 - $\Rightarrow 1 \text{ car tanking} = 35 \text{ MW}_{\text{th}}$
 - $3 \text{ GW}_{\text{th}} \sim 85 \text{ cars}$
 - NB: note that a car has $\sim 70\text{-}110 \text{ hp}$ (horsepower) $\sim 50\text{-}80 \text{ kW}$

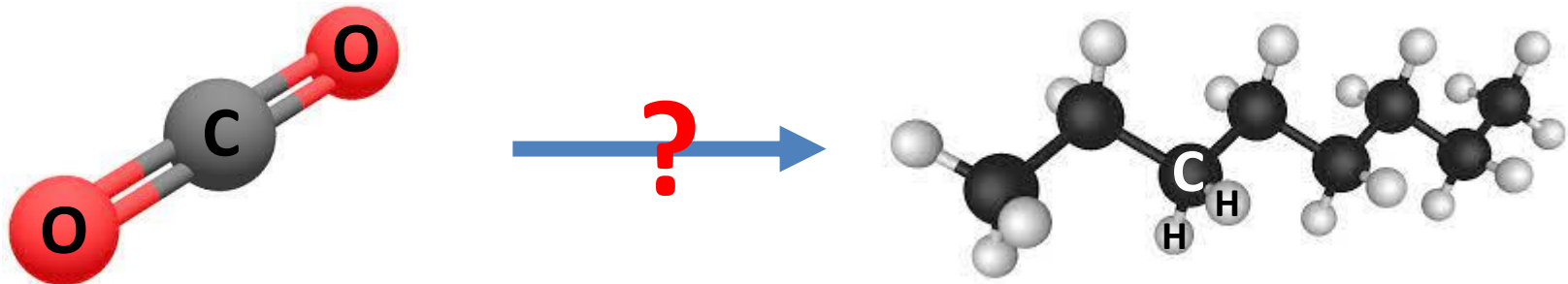
Energy storage

- Quick calculations
 - What would be the hourly gage for one worker based on fossil fuel cost?
 - Physical activity ~ 300 W
 - Cost of one barrel (159 L oil @ 40 MJ/L) ~ 50 USD

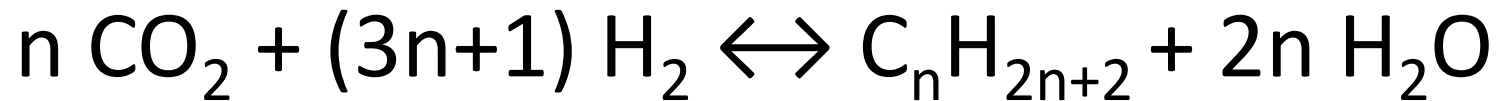
Energy storage

- Quick calculations
 - What would be the hourly wage for one worker based on fossil fuel cost?
 - Physical activity ~ 300 W
 - $1 \text{ h} = 300 \text{ Wh} = 0.3 \text{ kWh} = 1.08 \text{ MJ}$
 - Cost of one barrel (159 L oil) ~ 50 USD
 - $159 \text{ L oil @ } 40 \text{ MJ/L} = 6360 \text{ MJ}$
 - $\Rightarrow$ 1 hour of human work at standard fossil energy prices
 $= 1.08 \text{ MJ} * 50 \text{ USD}/6360 \text{ MJ} = 0.0085 \text{ USD}$

From CO₂ to fuel...

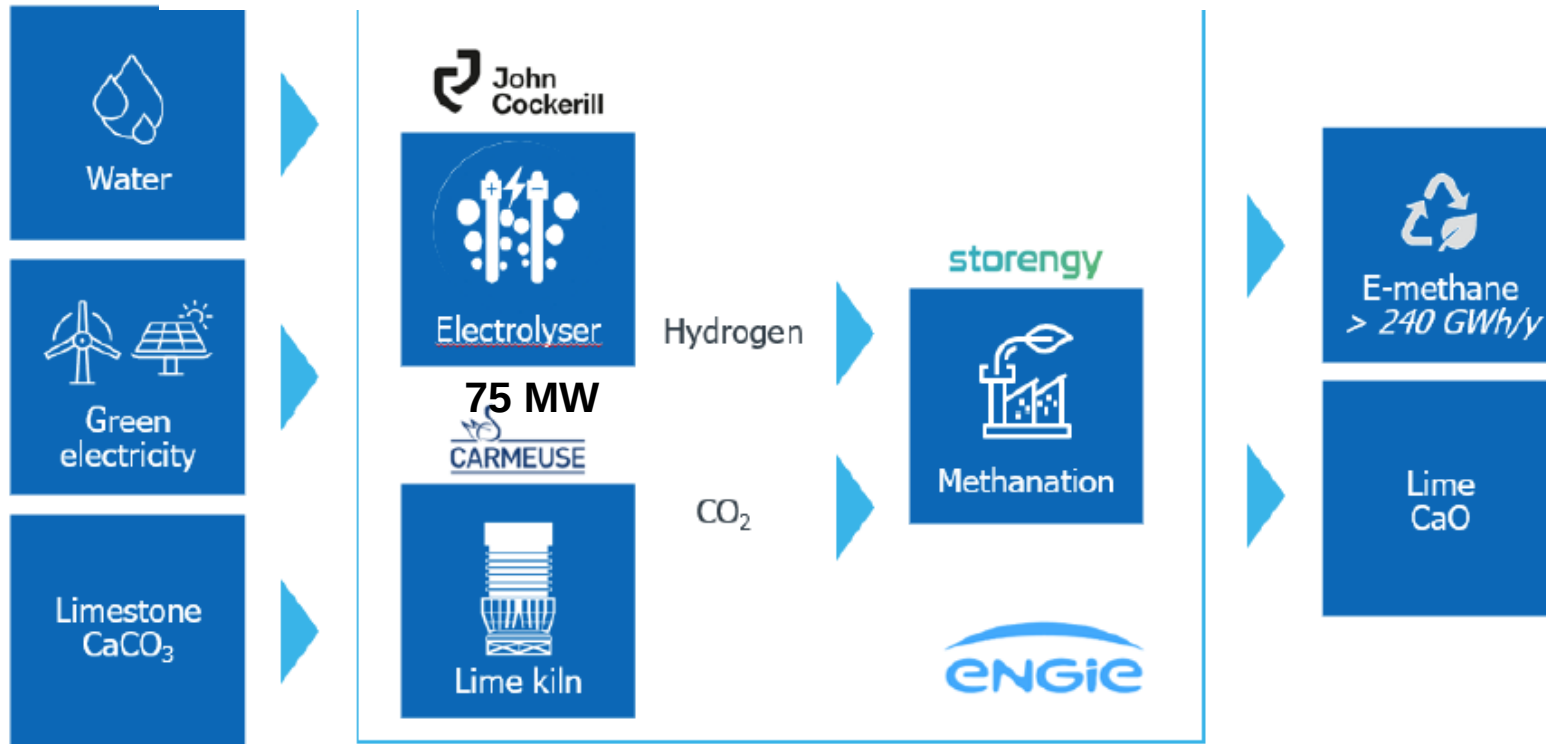


Use of H₂ !



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

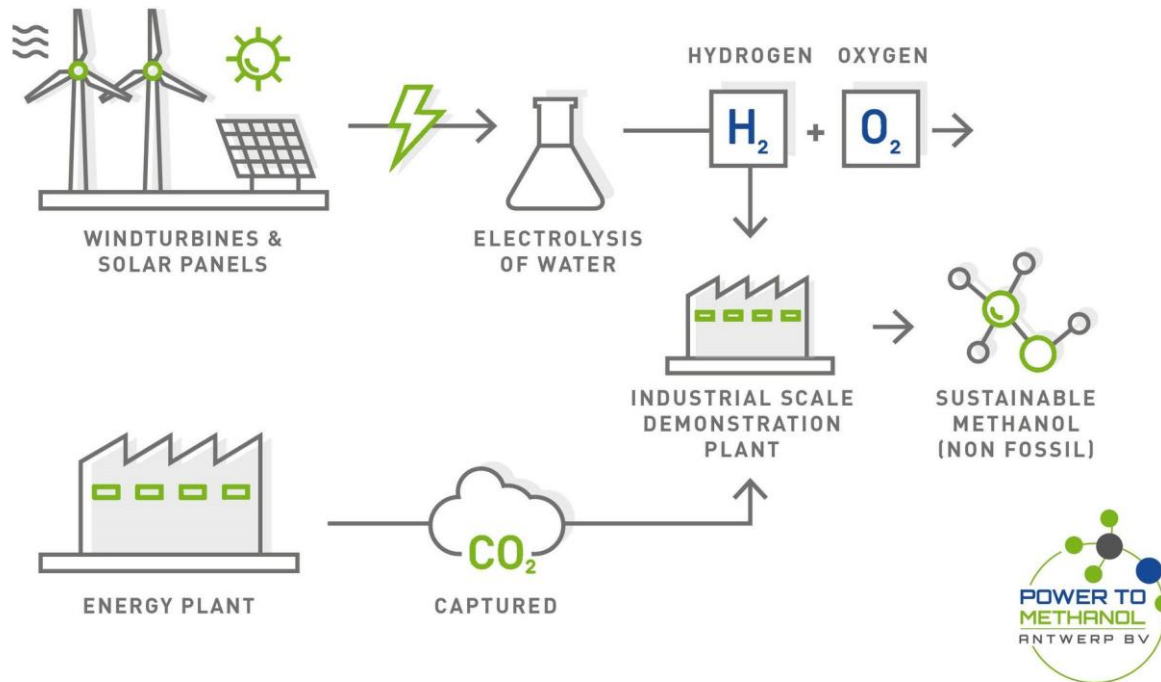
CO₂ to methane: Columbus project



But project cancelled in 2024, due to economic and regulatory considerations!

Power-to-methanol in Antwerp

- 8000 tpa of methanol
 - Commissioning planned in 2023, but now in the fridge...



2024: Termination of Power to Methanol Antwerp BV due to economic challenges and high energy costs

Ups and downs...

- ***“Ørsted opens a new era in green shipping by breaking ground on Europe’s largest e-methanol project”***
 - *“FlagshipONE will start production in 2025 when it will produce 50 000 t of e-methanol yearly”*
 - 24.05.2023 16:27
- ***“Ørsted cancels FlagshipONE amid slow growth of liquid e-fuel market”***
 - Aug 16 2024

CO₂ to fuels

- Transport applications of CO₂-sourced fuels
 - Ferries (Methanol, Stena, 24 MW)
 - Trucks (DME, Volvo)
 - Cars (GEM fuels, Gely...)

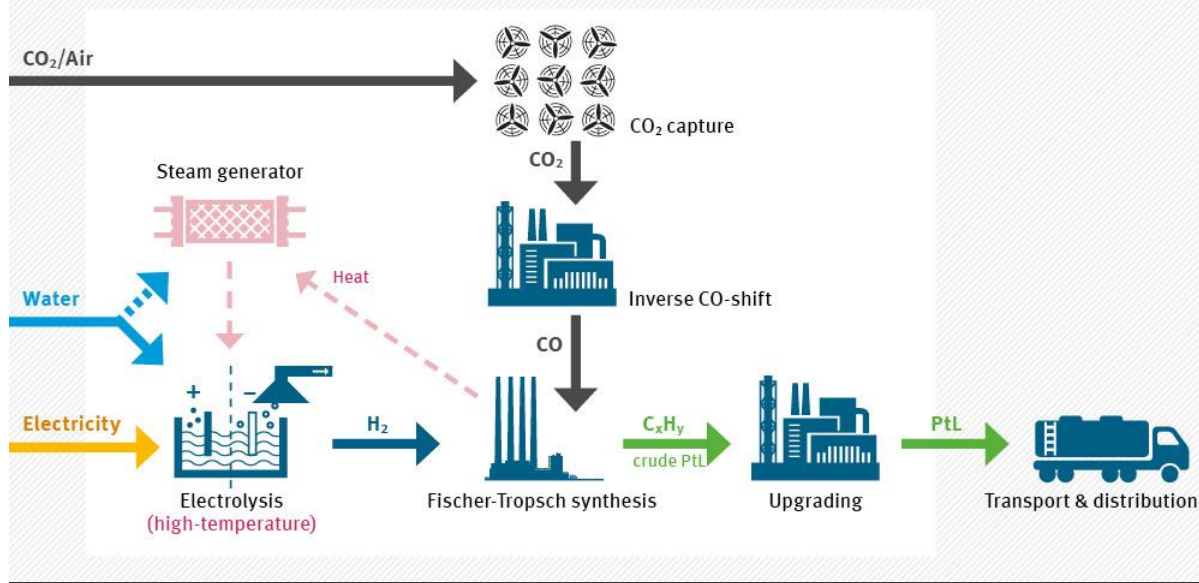


CO₂ to fuels

- Fischer-Tropsch fuels
 - Similar to gasoline, complex mixture
 - Sunfire: 58 m³/a, Efficiency ~70%

Figure 3

PtL production via Fischer-Tropsch pathway (high-temperature electrolysis optional)



Source: LBST

Figure 5

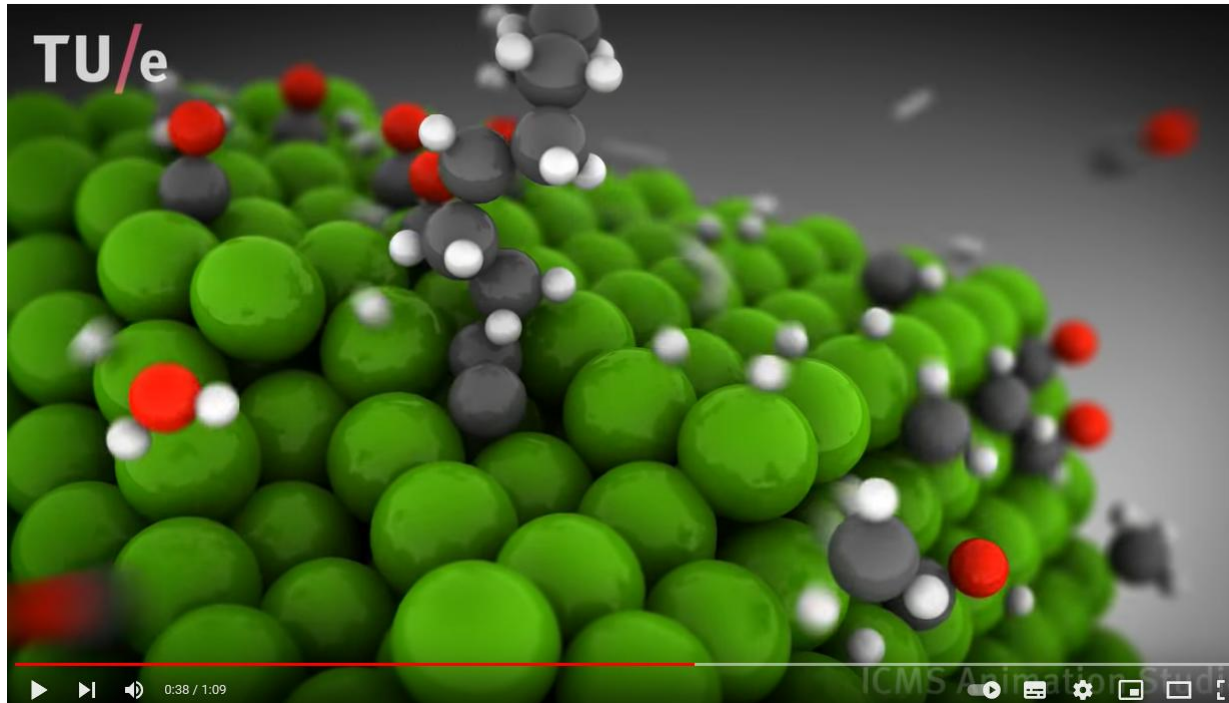
Sunfire PtL demonstration plant (top)
using high-temperature electrolysis (middle)
for the production of Fischer-Tropsch crude (bottom)



Sources: top: sunfire GmbH Dresden/CleantechMedia; sunfire GmbH Dresden/reneDeutsch.de

CO₂ to fuels

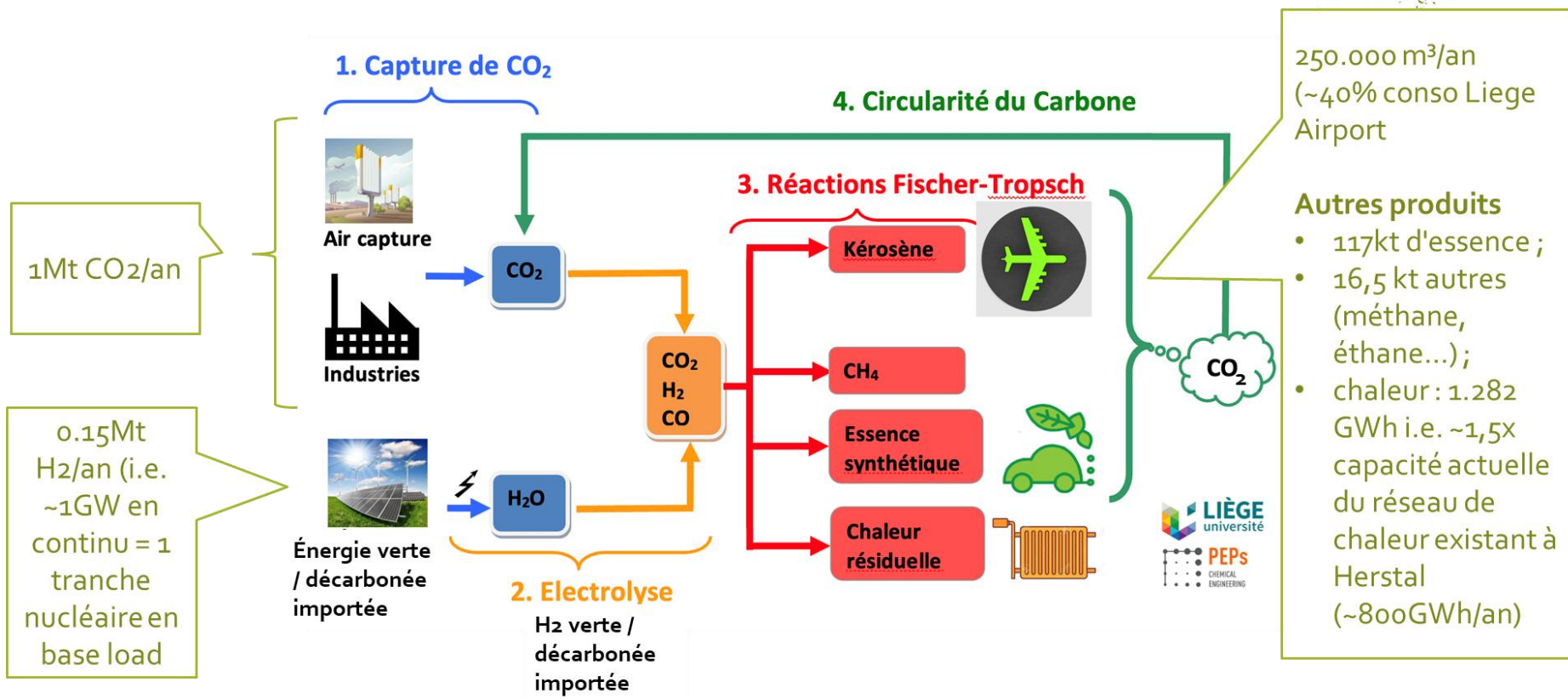
- Chain growth mechanism



https://www.youtube.com/watch?v=44OU4JxEK4k&ab_channel=ICMS

CO₂ neutral kerosene (SAF)

Capture de CO₂ + électrolyse + synthèse Fischer-Tropsch

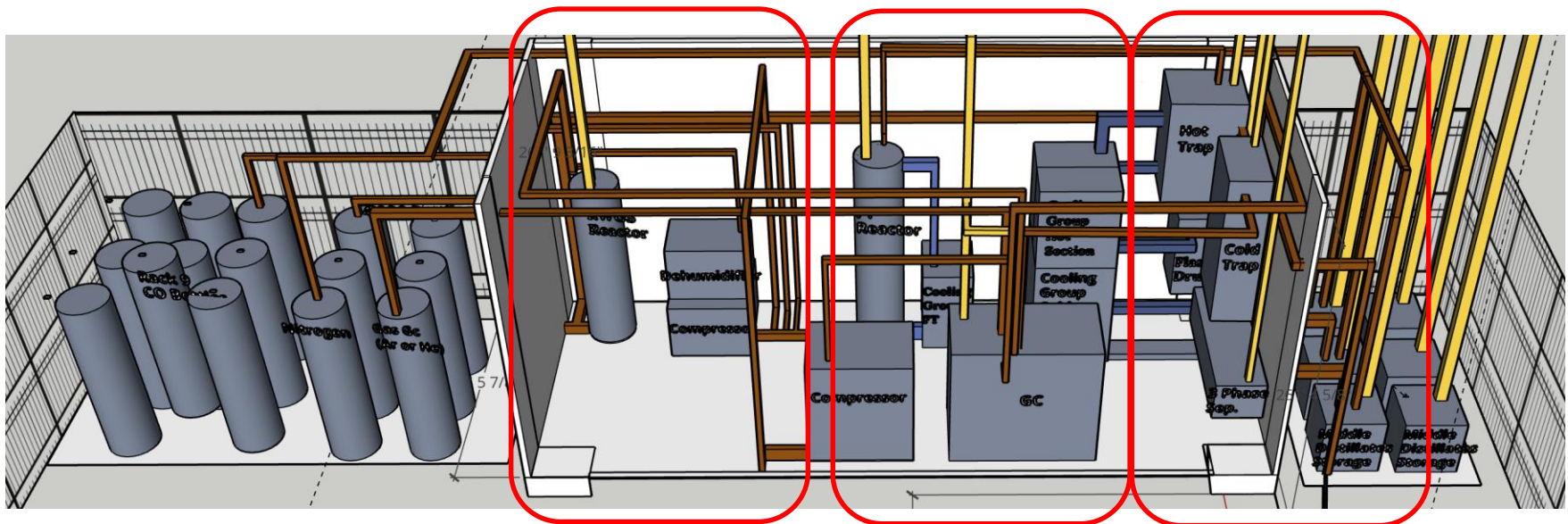


Laboratoire de synthèse d'e-fuels

- Objective: convert CO₂ into e-kerosene



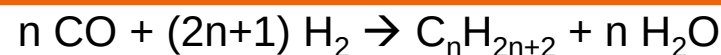
Total H₂ production = 1.5 Nm³/h



RWGS

FT

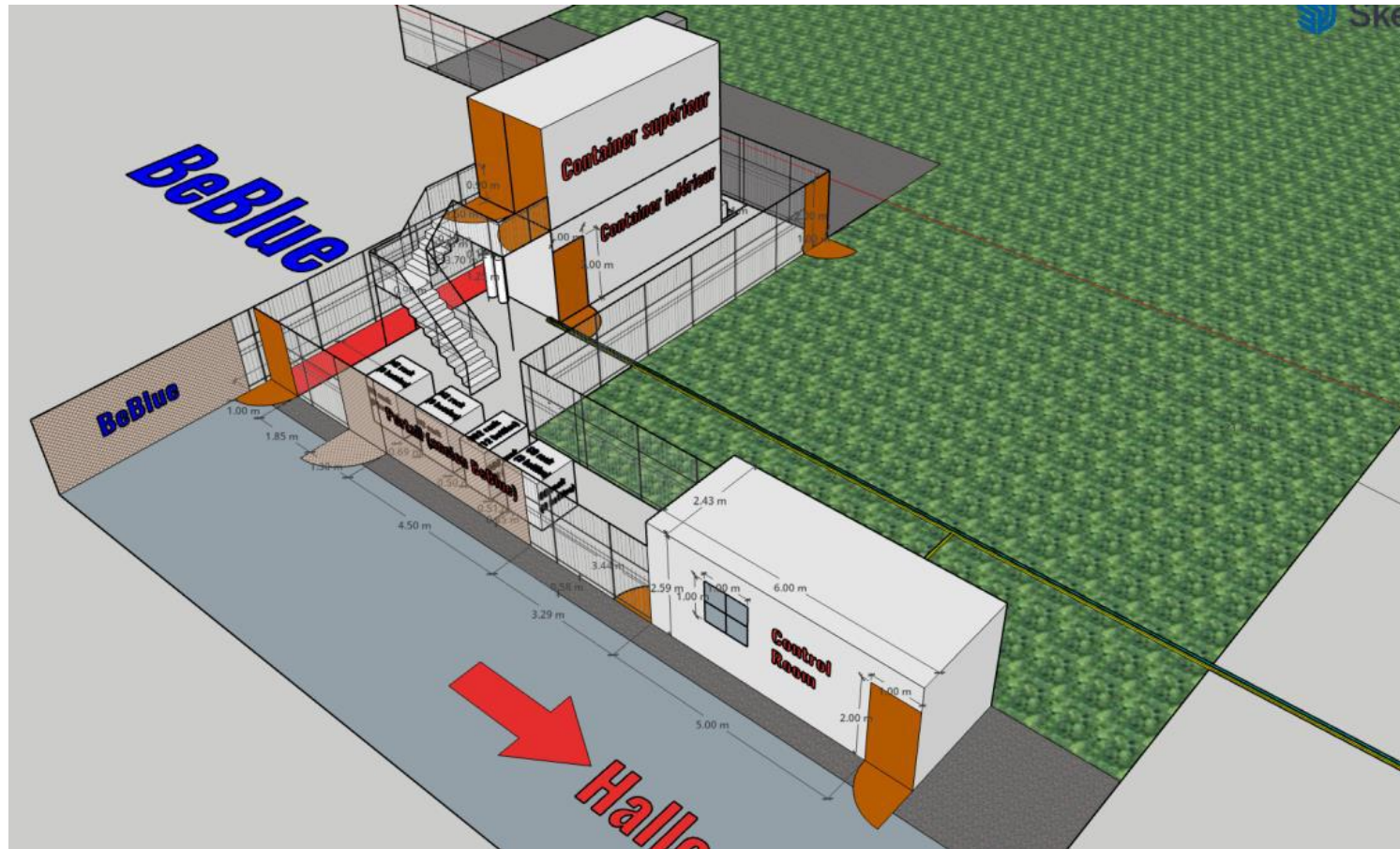
Separation



140

Laboratoire de synthèse d'e-fuels

- Urbanism permit just granted !

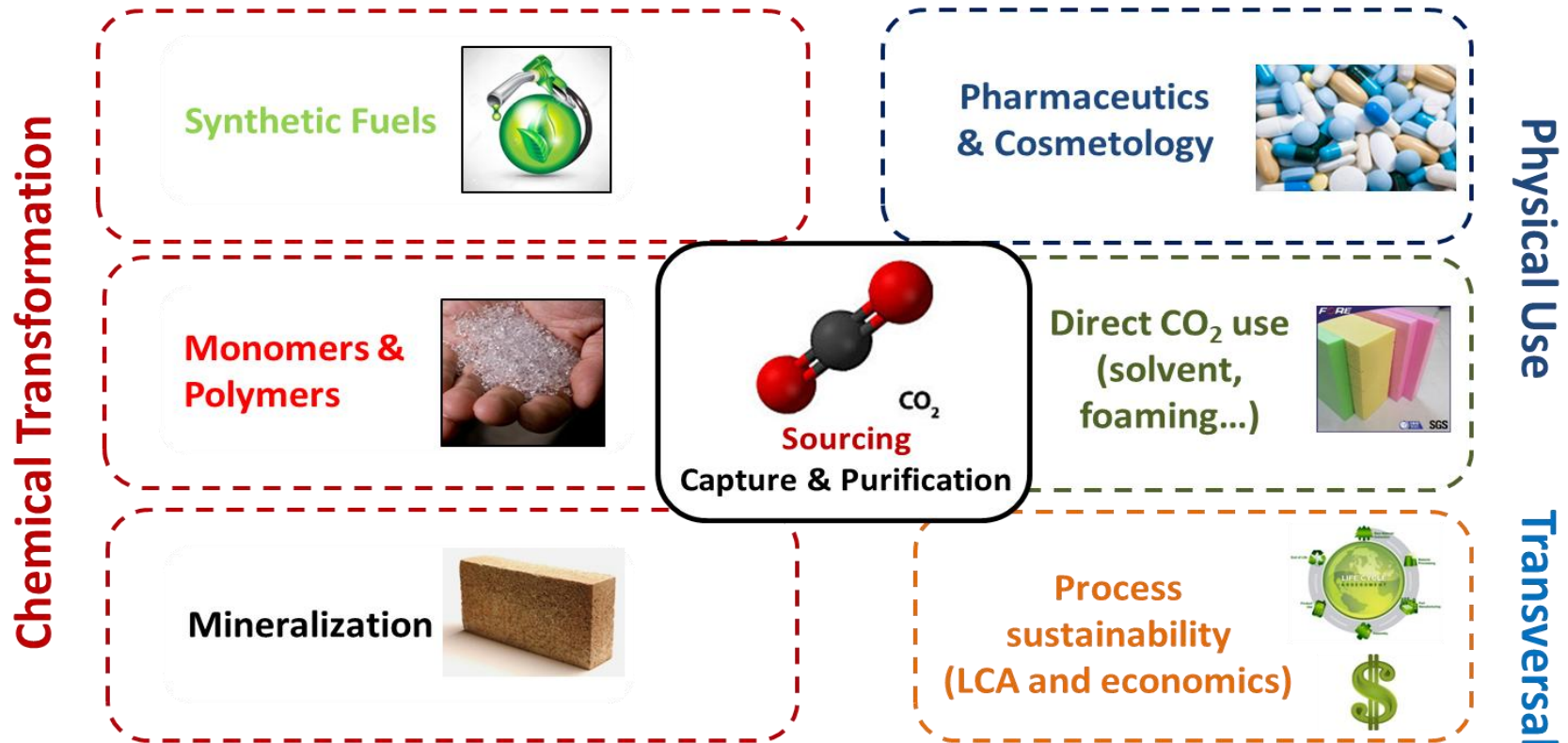


CO₂ to fuels

- Potential market is larger than for petrochemistry!
 - But high energy cost and lower added-value products
 - => Need for renewable energy to make it sustainable
- Critical issues
 - Variability of energy source
 - Capital cost
 - Conversion efficiency
 - Power-to-methanol @ CRI => 4000 T/a, Efficiency ~50%
 - Power-to-diesel @ Sunfire => 58 m³/a, Efficiency ~70%

CCU: The FRITCO₂T Platform

Federation of Researchers in Innovative Technologies for CO₂ Transformation



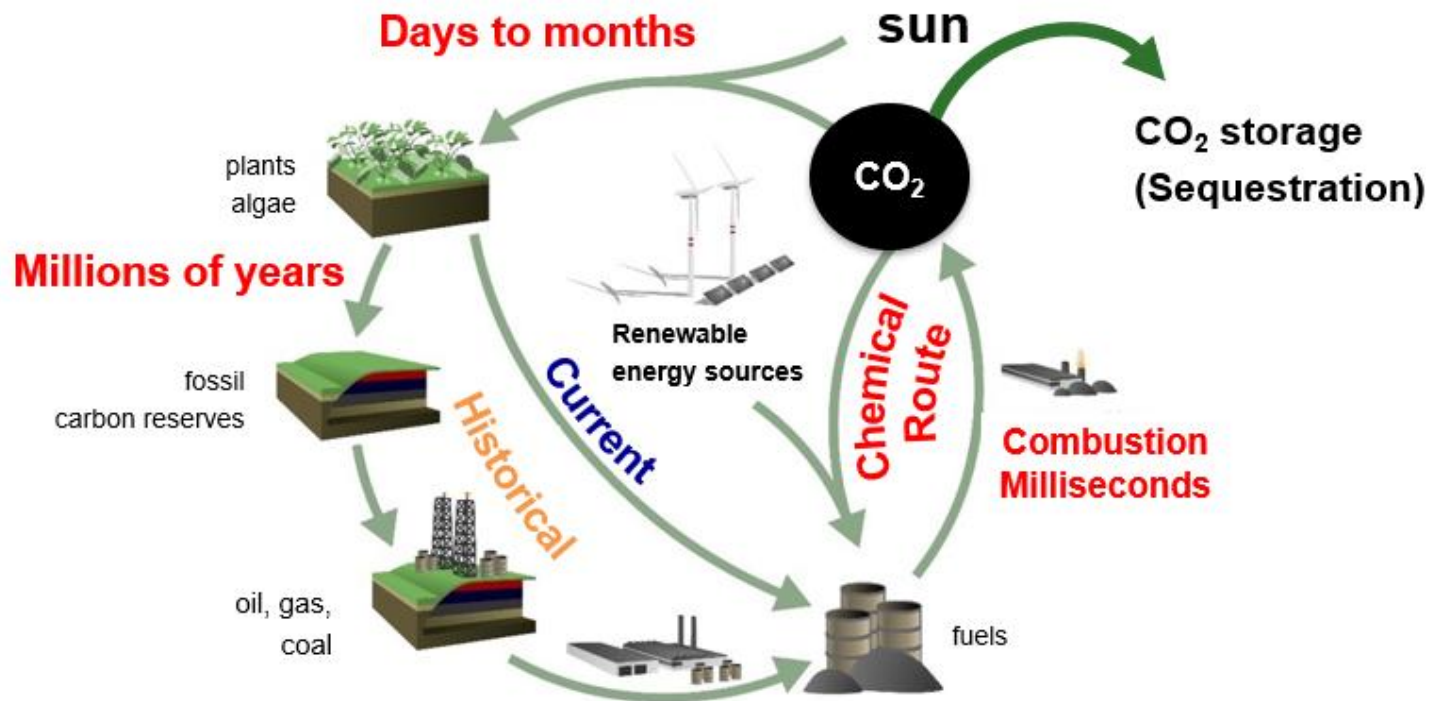
Conclusions and perspectives

State of technology CCUS

- Capture of CO₂
 - Mature but not commercially applied yet
- Transport of CO₂
 - Commercially applied
- Storage
 - Commercially applied (mostly EOR), interest rising
- Re-use
 - Maturity depends on technology, from TRL 1 to 9
- Big acceleration due to Paris COP21 agreement
 - European Green Deal

Perspective

- We live in a carbon-based society, with very good reasons for that !
- A CO₂ neutral future is in sight with passionating (and huge) challenges for engineers!



Merci pour votre attention!
