



WEBINAR HEEREMA
**CARBON CAPTURE AND UTILISATION:
A VISION**

TNO innovation
for life

Earl Goetheer



Chemical Engineer

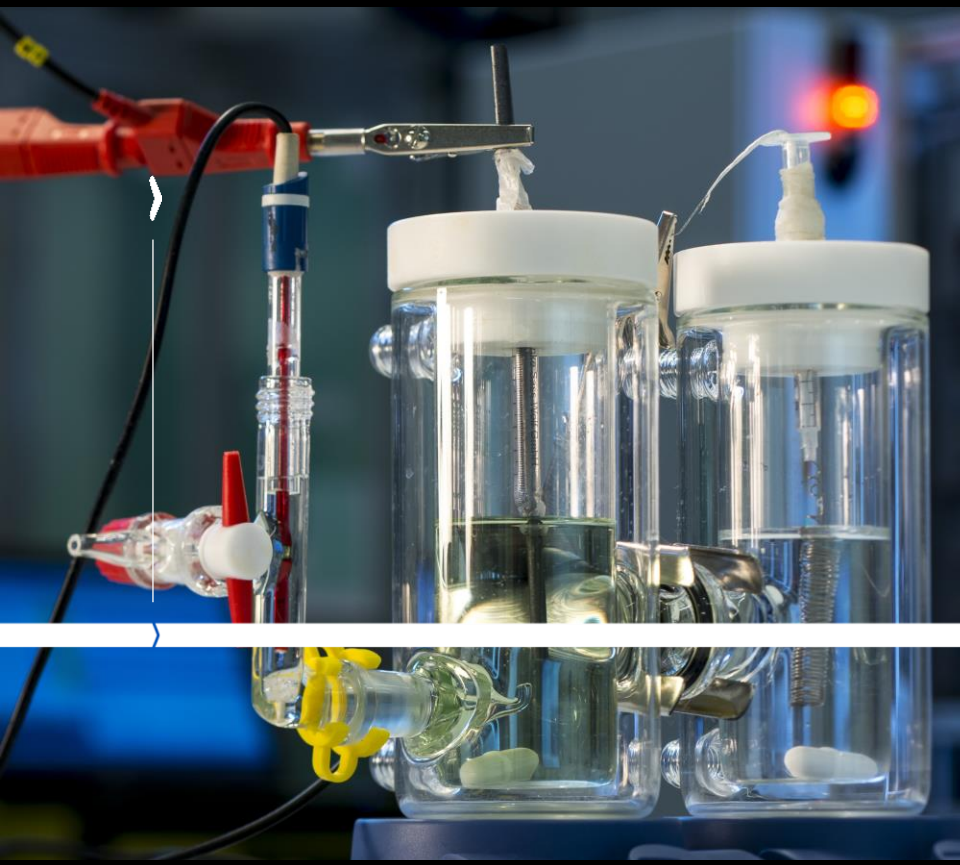
Principal scientist Process Technology TNO

Part-time professor TUDelft
CO₂ utilisation/mechanical engineering

EARL GOETHEER

“BRIDGING SCIENCE WITH TECHNOLOGY”





CIRCULAIR CARBON

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The Rodney & Otamatea Times

WAITEMATA & KAIPARA GAZETTE.

PRICE—10s per annum in advance

WARKWORTH, WEDNESDAY, AUGUST 14, 1912.

3d. per Copy.

Science Notes and News.

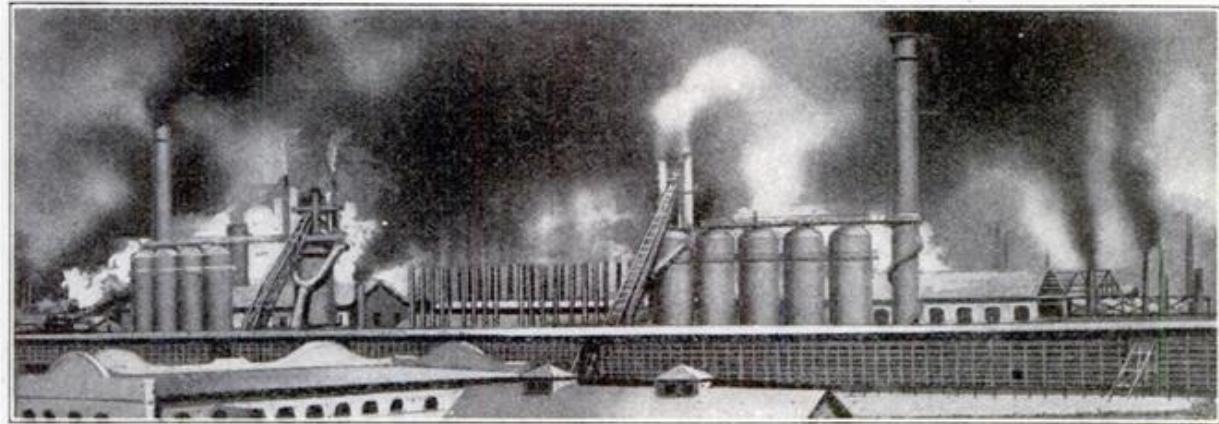
COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

← 1912 !!

POPULAR MECHANICS

341



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NIEUWE APELDOORNSCHE COURANT VAN VRIJDAG 8 JANUARI 1932.

Koude en beschaving.

Londen, 5 Jan..... Dr. Robert Innes, een bekend Engelsch astronoom en meteoroloog, heeft in een zitting van de British Astronomical Association verklaard dat het klimaat van de wereld geleidelijk warmer wordt en dat de oorzaak daarvan te zoeken is in de toegenomen beschaving!

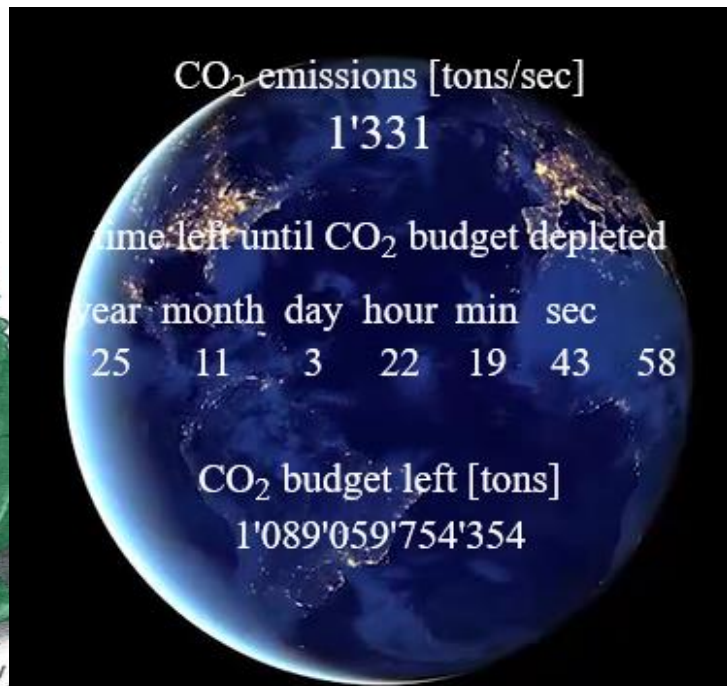
Het klimaat, verklaarde dr. Innes, wijkt af van den toestand van de atmosfeer. Kool-dioxide in de lucht heeft hetzelfde effect als een deken — het maakt het weer warmer. De bezigheden van den beschaafden mensch — het verbruik van steenkolen en benzine bijvoorbeeld — veroorzaken kool-dioxide. Indien deze theorie juist is, dan beteekent dit, dat wij geen ouderwetsche strenge winters meer krijgen en dat de zomers geleidelijk warmer worden.

“Human activity, by using coal and gasoline, is creating carbon dioxide. In case this theory (greenhouse effect) is correct, this means that we are not going to have strong winters anymore and that summers will gradually get warmer”.

Sense of Urgency



“All I’m saying is **NOW** is the time to develop the technology to deflect an asteroid”



Carbon Clock

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Outline





So
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Som
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surfa
warm



IPCC 5th Assessment Report:

"Atmospheric concentrations of carbon dioxide unprecedented in at least the last 800,000 years. Warming increases the likelihood of severe, persistent, and irreversible impacts on natural and human systems."

IPCC 4th Assessment Report:

"warming of the climate system is unequivocal, and is likely to continue for many decades to centuries, with a capacity of natural, managed and human systems to adapt to it being limited."

IPCC 3rd Assessment Report:

"Observations show Earth's surface is warming at a rate that is projected to continue at a more rapid rate than that experienced in the 20th century."

IPCC 2nd Assessment Report:

"The balance of evidence shows a clear human influence on global climate, and the risk of severe impacts is increasing."

IPCC 1st Assessment Report:

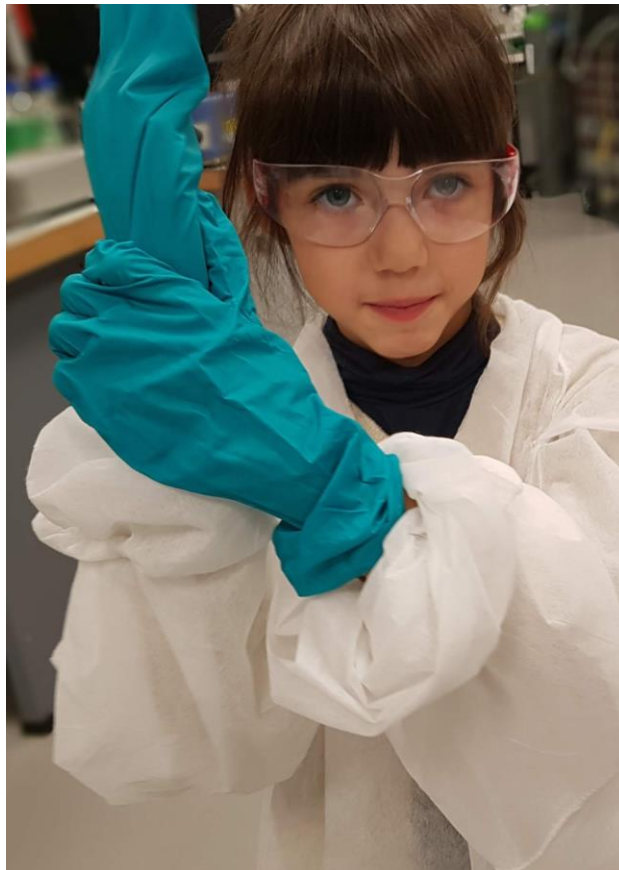
"global mean surface temperature increased by 0.3 to 0.6°C over the past 50 years."

Star Wars movie

Neil Armstrong step onto the moon



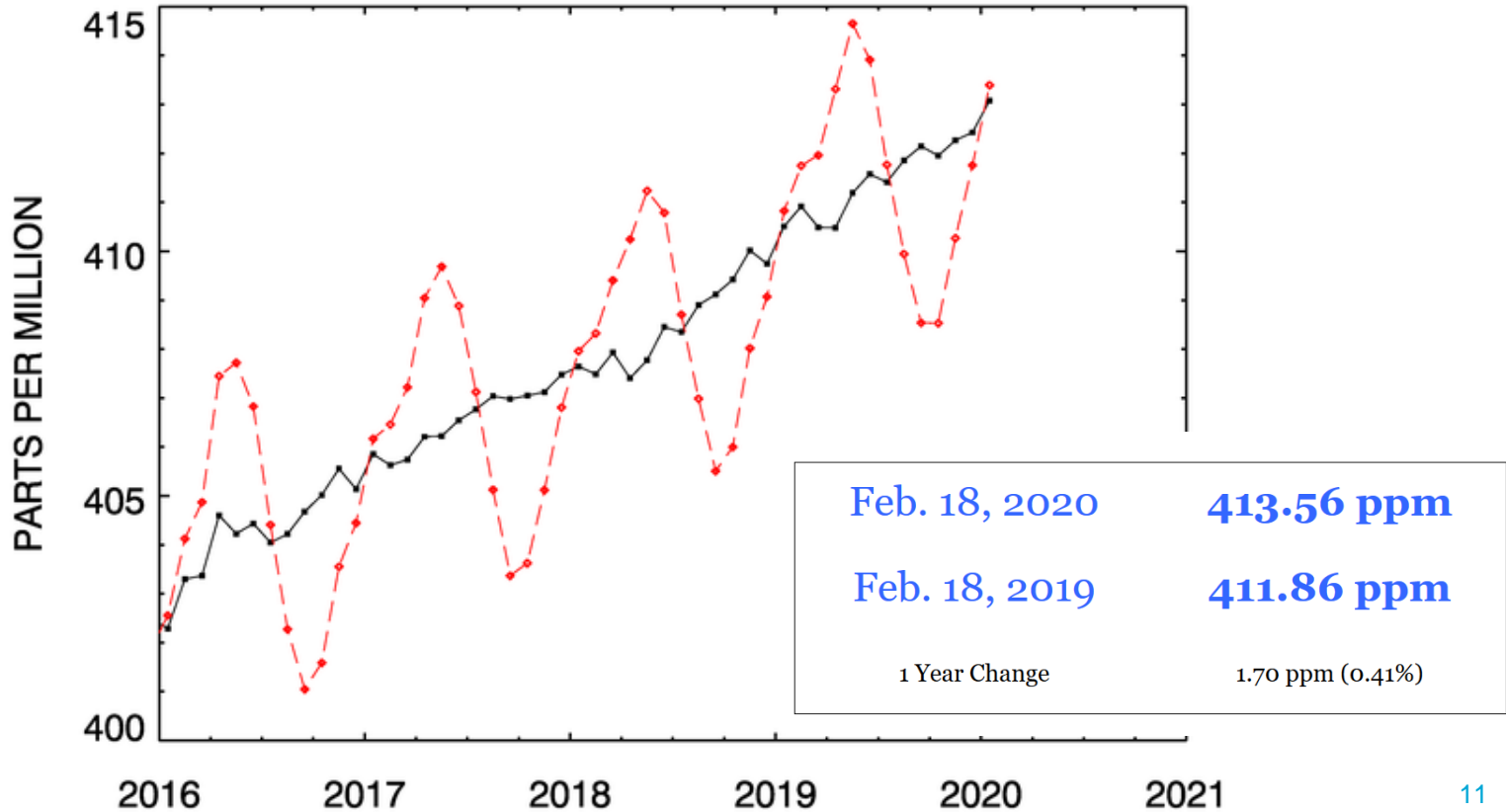
1958



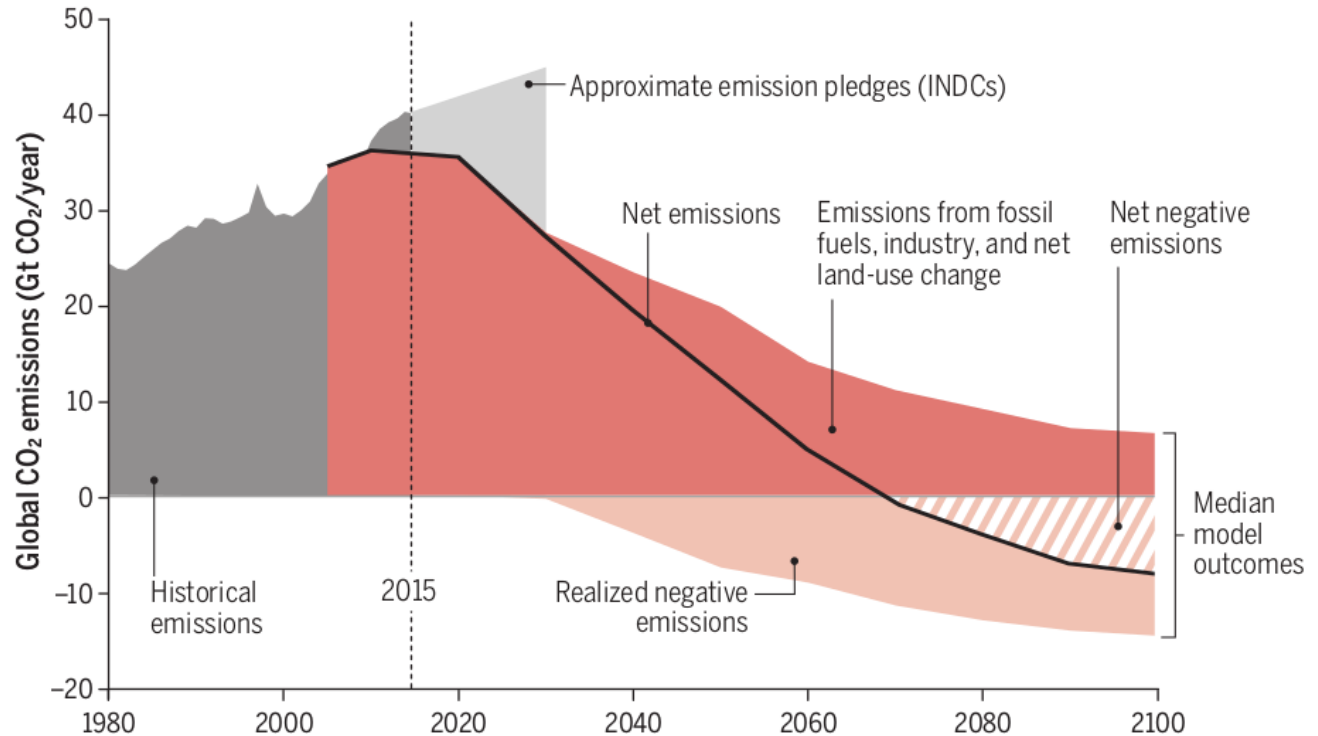
Present



RECENT MONTHLY MEAN CO₂ AT MAUNA LOA



No quick fixes: negative emissions



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Carbon neutrality by 2050

Carbon neutrality manifested in political agendas and corporate mission statements



European Green Deal
European Commission

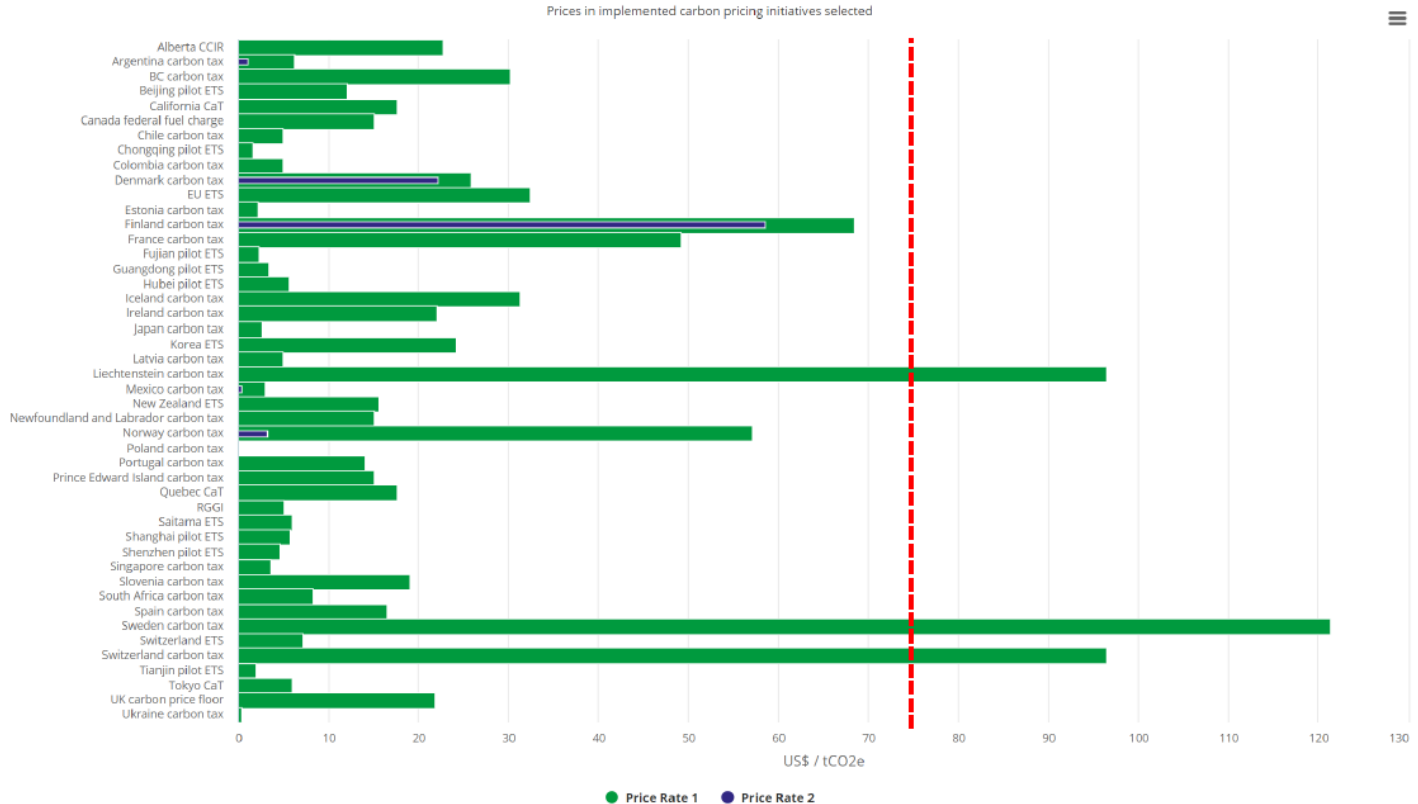


Klimaat-akkoord
The Netherlands

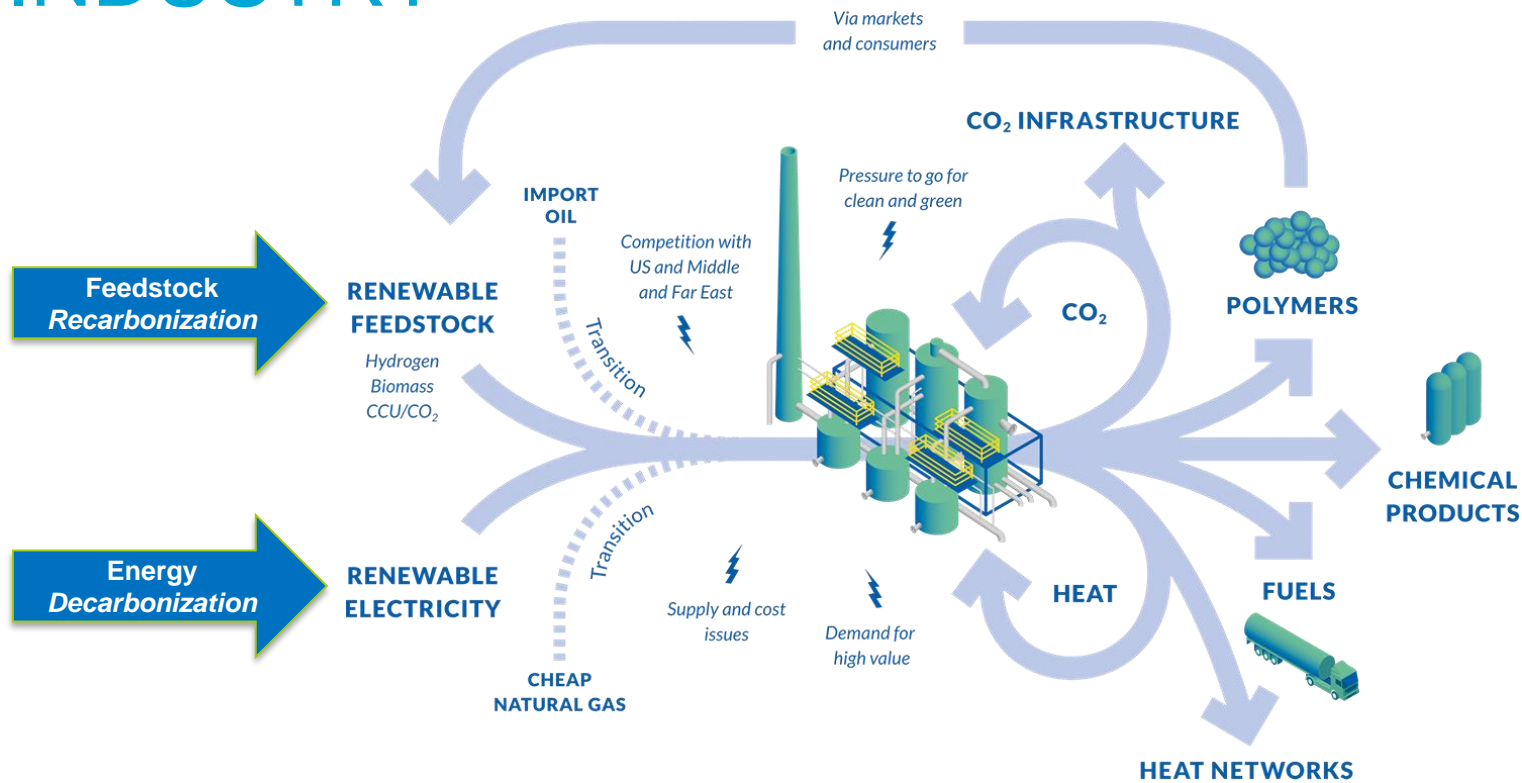


Mission Statements
...and many more

Global carbon tax will unlock innovation



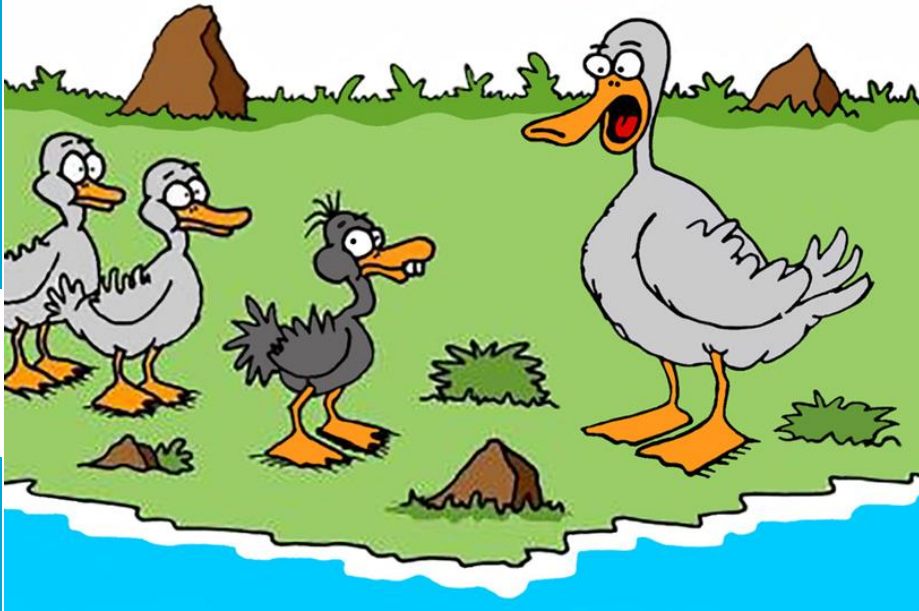
CHALLENGES ENERGY & CHEMICAL INDUSTRY



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FOR THE LAST TIME, CCS!
YOU'RE NOT A SWAN! YOU'RE
JUST UGLY!



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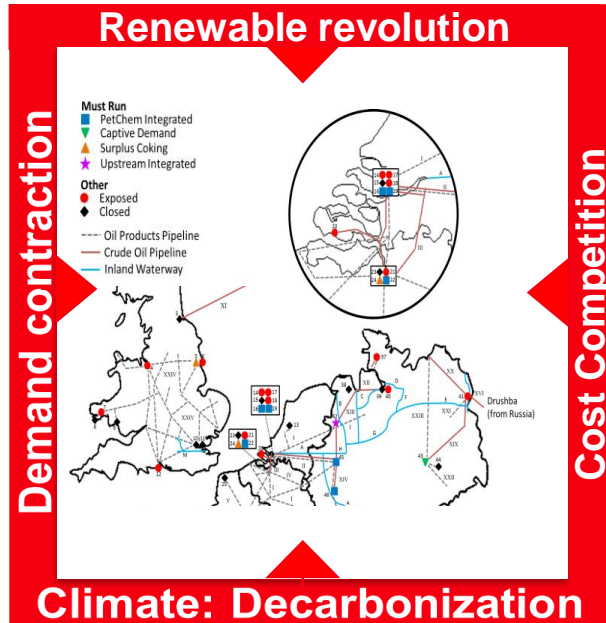
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AVR: CO₂ capture for utilisation



Industrial Clusters under High Pressure



- **40% of total CO₂ emissions related to industrial clusters.**
- **In Rotterdam:**
 - 250+ Billion Euro capital assets.
 - 450 Mtonnes material flow in 2015.
 - 6,000 ha of industrial sites.
 - >90,000 employed overall in harbor (20,000 @ industrial cluster)



Porthos (Rotterdam)



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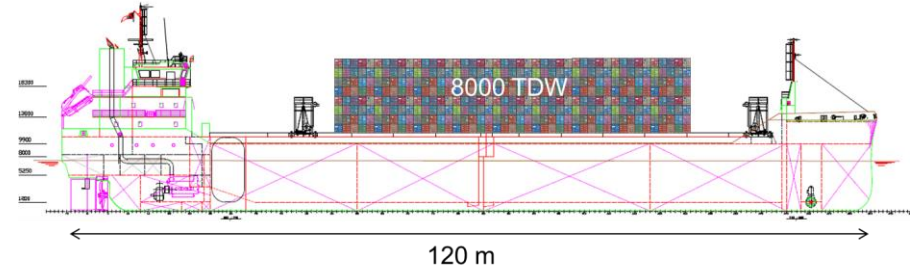
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A 3D cutaway illustration of a ship's deck. The deck is populated with various pieces of equipment, including several large white cylindrical tanks, two prominent yellow and blue cylindrical tanks, and various pipes and mechanical components. In the background, there are some green and blue structures that look like small trees or ventilation units. The ship's hull is visible on the right side, showing a funnel and other deck structures. The overall scene is set against a white background.

CAN I CAPTURE CO₂ ONBOARD OF SHIPS?

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DESIGN BASIS



Cargo ship with a 3000 kW Wärtsilä 6L34DF engine



Fueled by LNG



+ CO₂ capture and storage



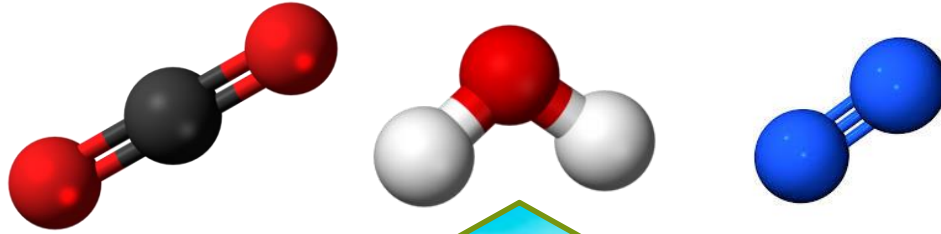
COST ESTIMATE

- › CAPEX = 8 million Euros (close to the cost of the ship itself)
- › Cost of CO₂ captured = 79 €/tonne CO₂
 - CAPEX = 75 €/tonne CO₂
 - OPEX = 4 €/tonne CO₂
- › Food-grade CO₂ price ca. 80 €/tonne
- › Cost of CO₂ capture and compression €/tonne:
 - Power plants = 40-60
 - Cement = 60-70



Grand challenge: Man On The Moon

FUTURE



Renewable production of fuels and (platform) chemicals from CO₂, water and nitrogen based on photochemistry, electrochemistry, biotechnology

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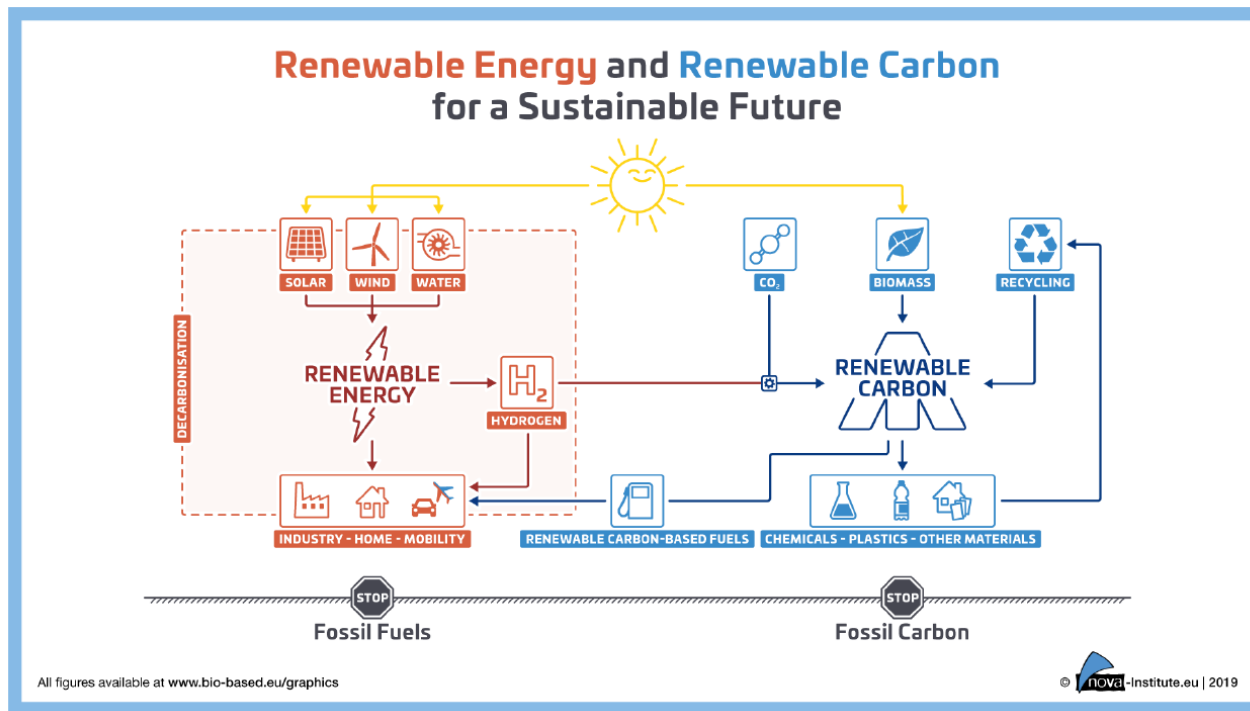
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Synthetic fuels		Platform chemicals		Complex molecules	
<i>hydrogen</i>	<i>carbonmonoxide</i>	<i>alkanes</i>	<i>alcohols</i>	<i>carbohydrates</i>	<i>lipids</i>
<i>ammonia</i>	<i>Fisher-Tropsch</i>	<i>ethers</i>	<i>carboxylic acids</i>	<i>proteins</i>	<i>nucleic acids</i>

* Modified from NWO solar fuel



Circular carbon



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Conversion Technologies



1. Catalytic Hydrogenation

2. Direct Electrochemical

3. Polymerization

4. Biochemical

5. Mineralization



e-Refinery TU Delft

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Technology potential and overview of players

Mineralization Commercial today

- But low value products;
- Select best regional product fit

Microbial no advantage for bulk v.s. T/C*

Focus on high value products:

- Single cell Proteins
- Longer chains, functional
- Direct conversion of flue gases promising

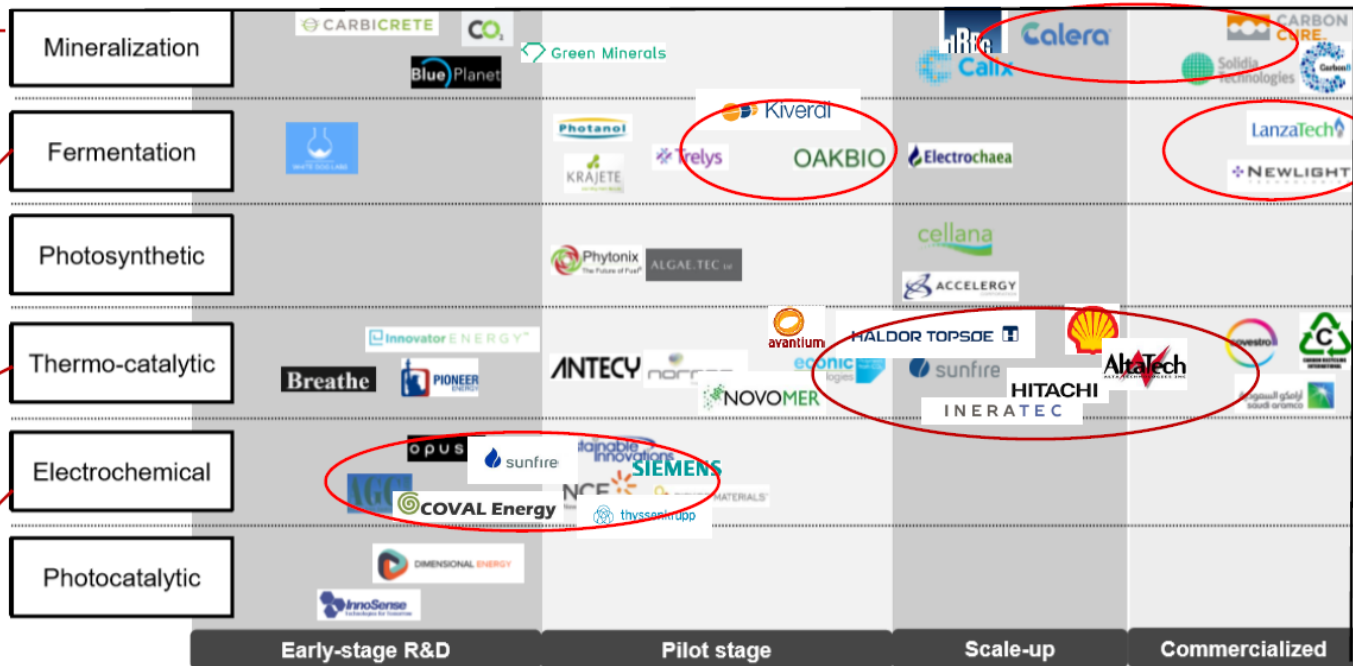
T/C* Bulk and Fuels unprofitable as yet

Focus on high value products

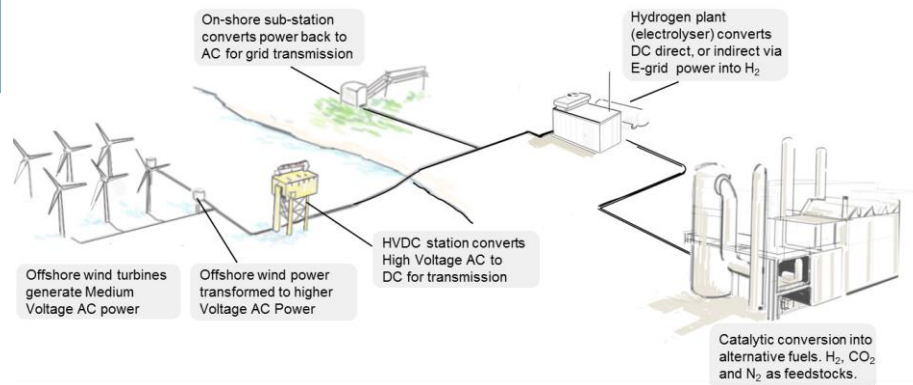
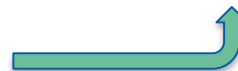
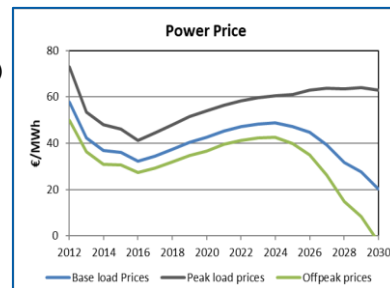
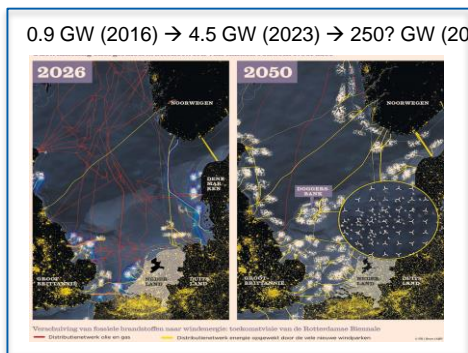
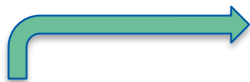
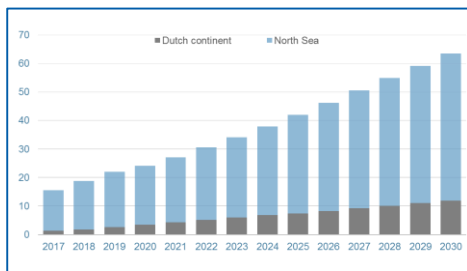
- Many players (Established and new)
- Focus polymers/materials/solvents
- Well-known chemical processes, new catalysts

Electrochemical: earlier stage but promising

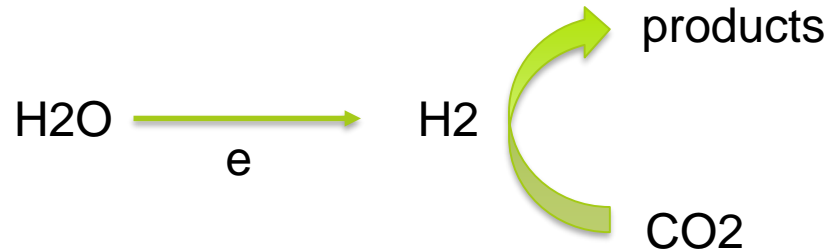
- Energy efficient (except for e.g. methanol)
- CO, Formic, Oxalic acid
- Fieldlab IE projects



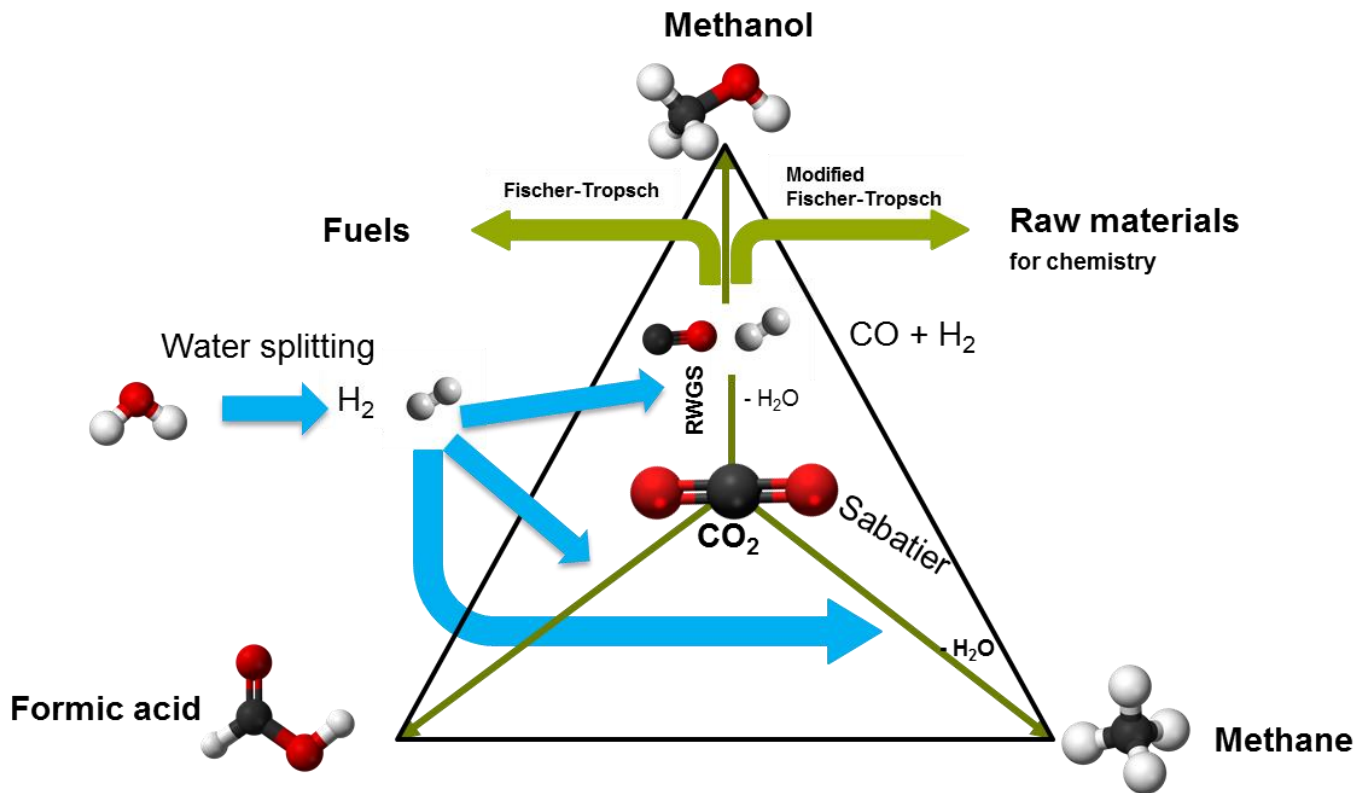
Renewables will create opportunities



Direct versus Indirect



Indirect

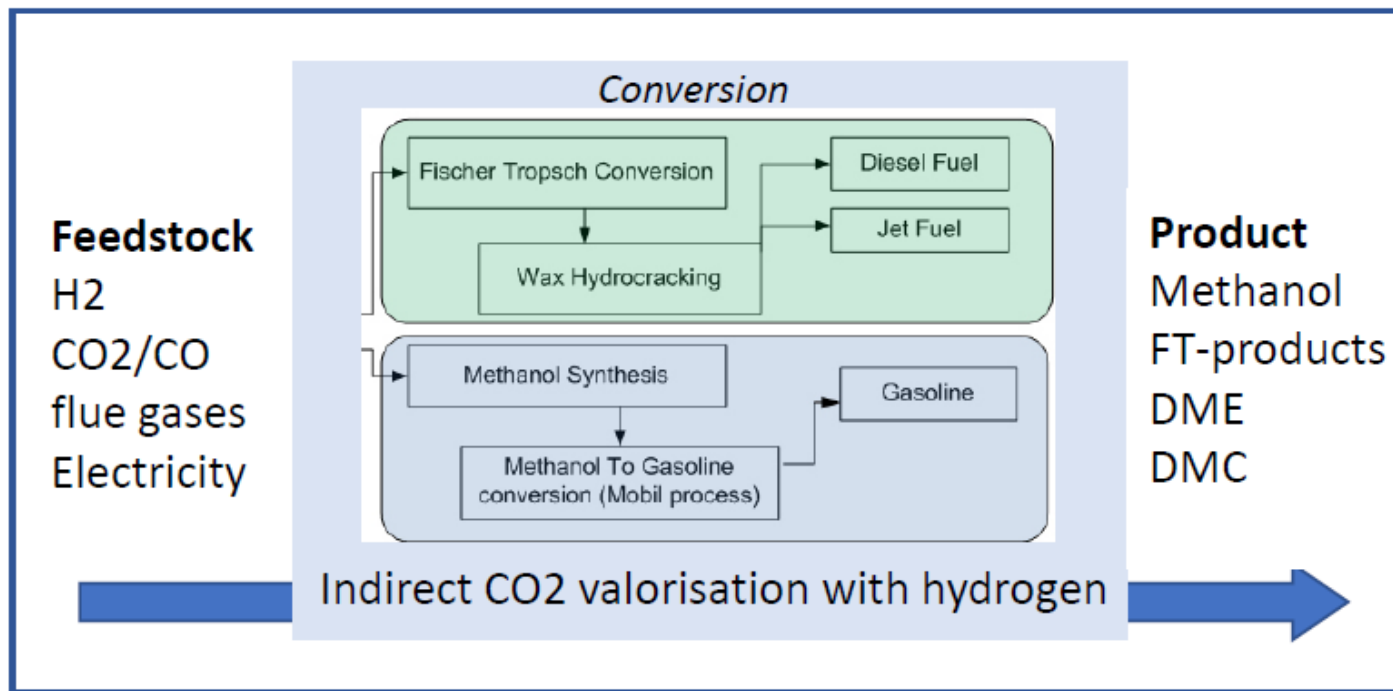


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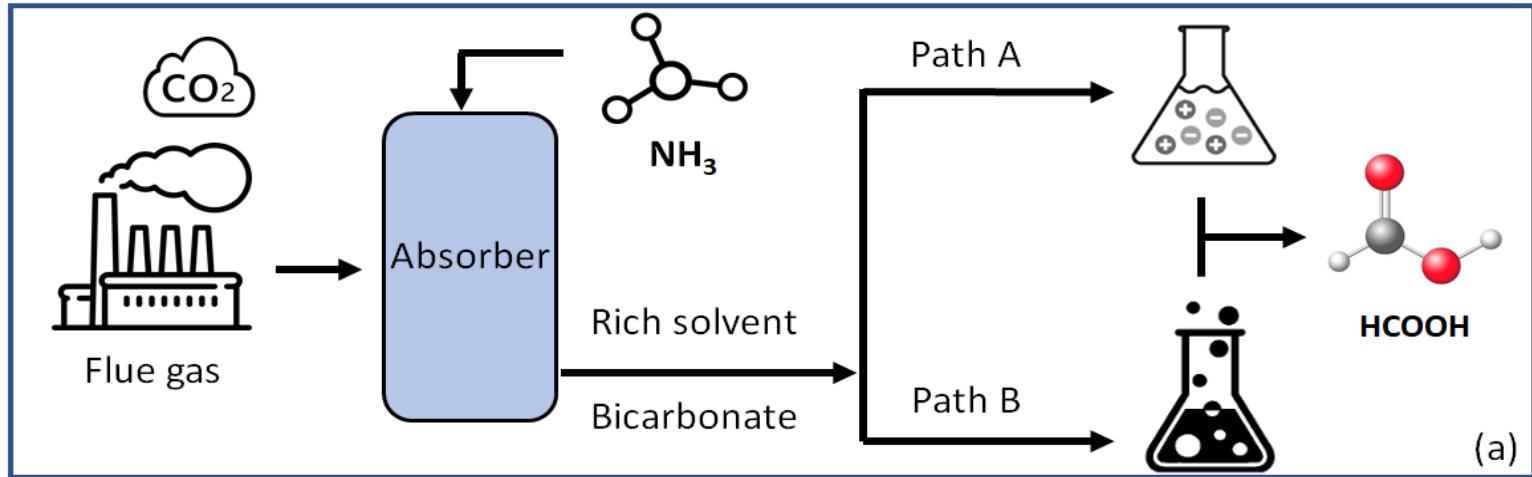
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Fransesc Sastre

CO2 to fuels

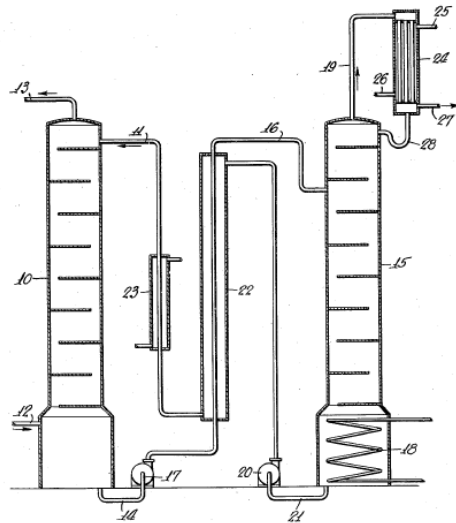


Indirect Integration

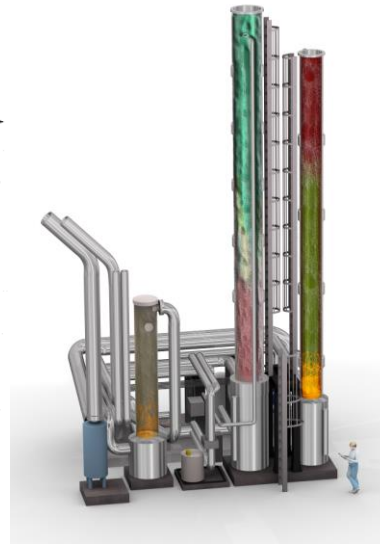


Post combustion CO₂ capture Ammonia as capture solvent

1930



Generic pilot plant



Capture system based on NH₃

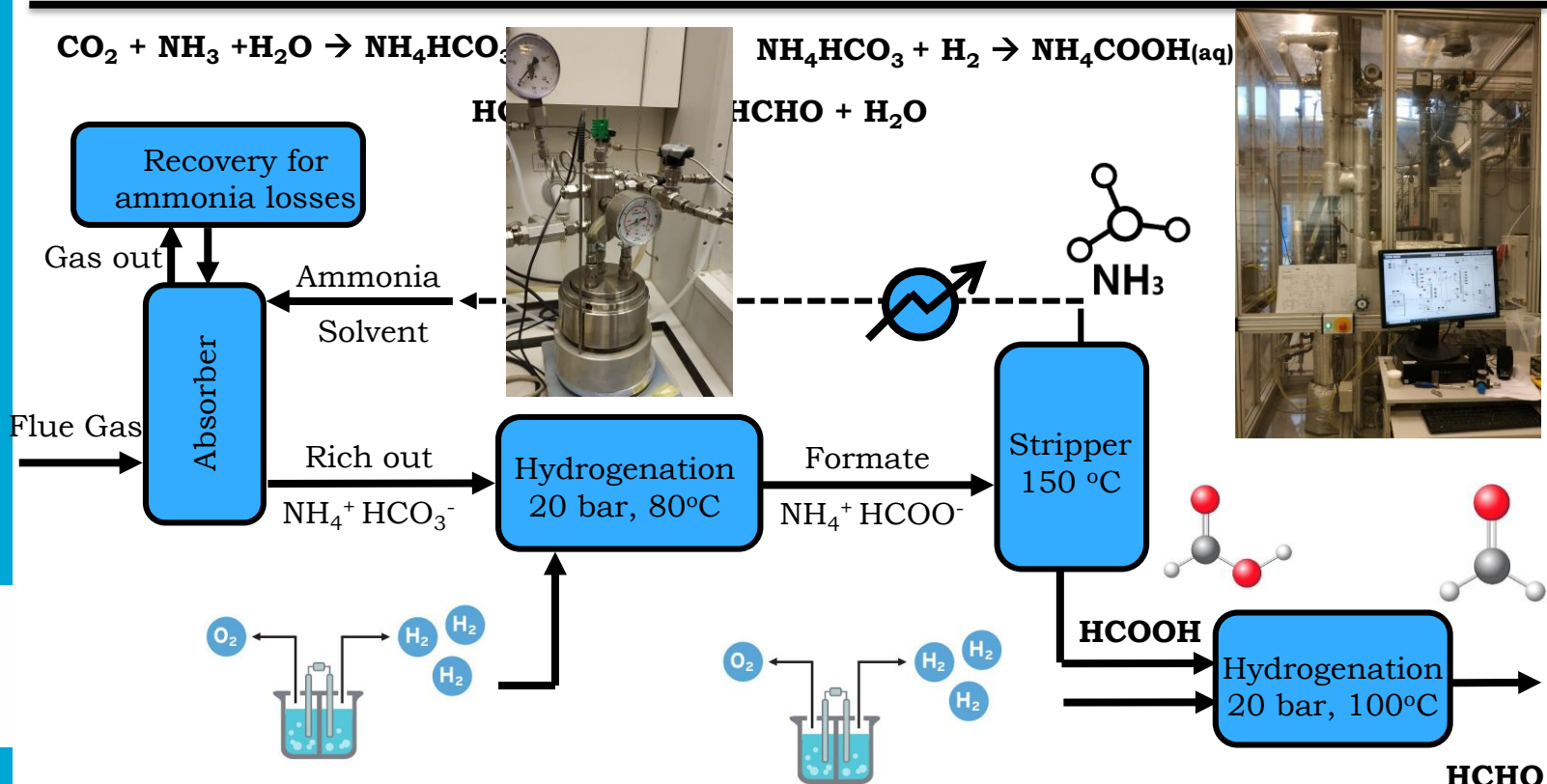


Courtesy TCM

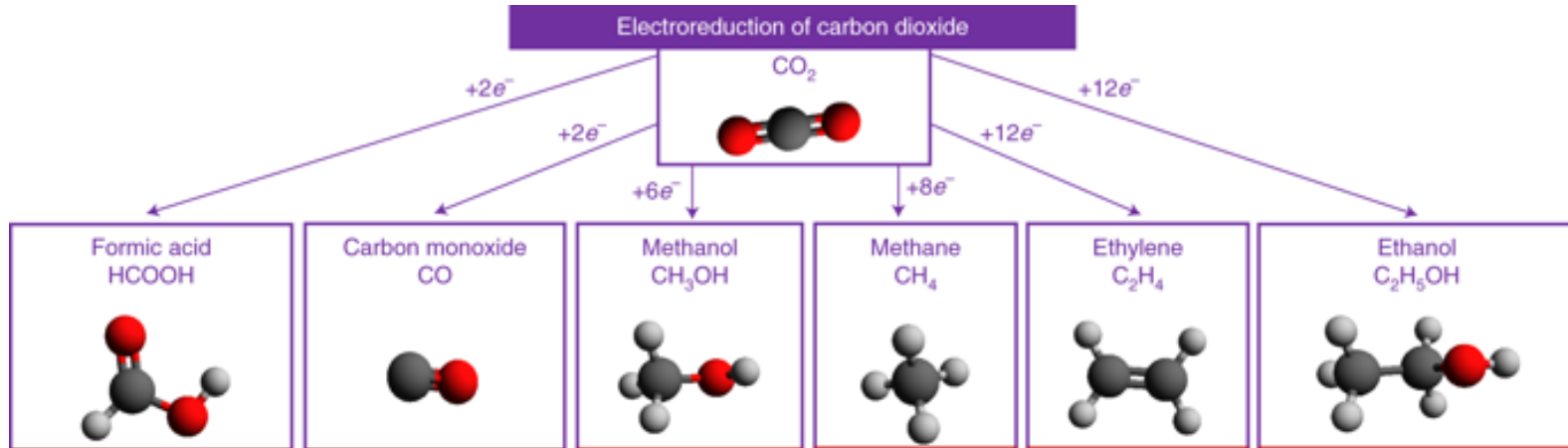
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Description of the system



Direct electrochemistry



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UP OF GDE – CO₂ to HCOOH

Interreg
2 Seas Mers Zeeën
European Regional Development Fund



PILOT DEMONSTRATOR
TRL 5
CO₂ TO FORMIC ACID
SCALE: 1 Kg/h



10 cm²



100 cm²



stack

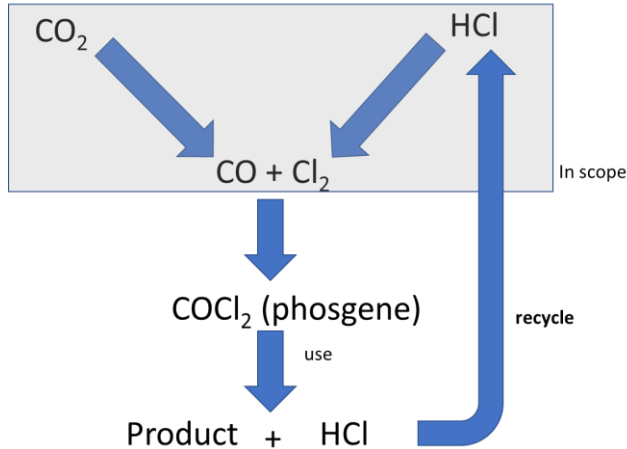
Project partners:



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Increasing total efficiency – Paired electrolysis



- Paired electrolysis concept to produce **2 value-added** products using the **same energy cost** involved in the production of only one product.
- Combining oxidation and reduction reactions to improve the **economically feasibility** of the processes.
- A major challenge for paired electrolysis is ensuring that the **reaction conditions are suitable for both chemical transformations**

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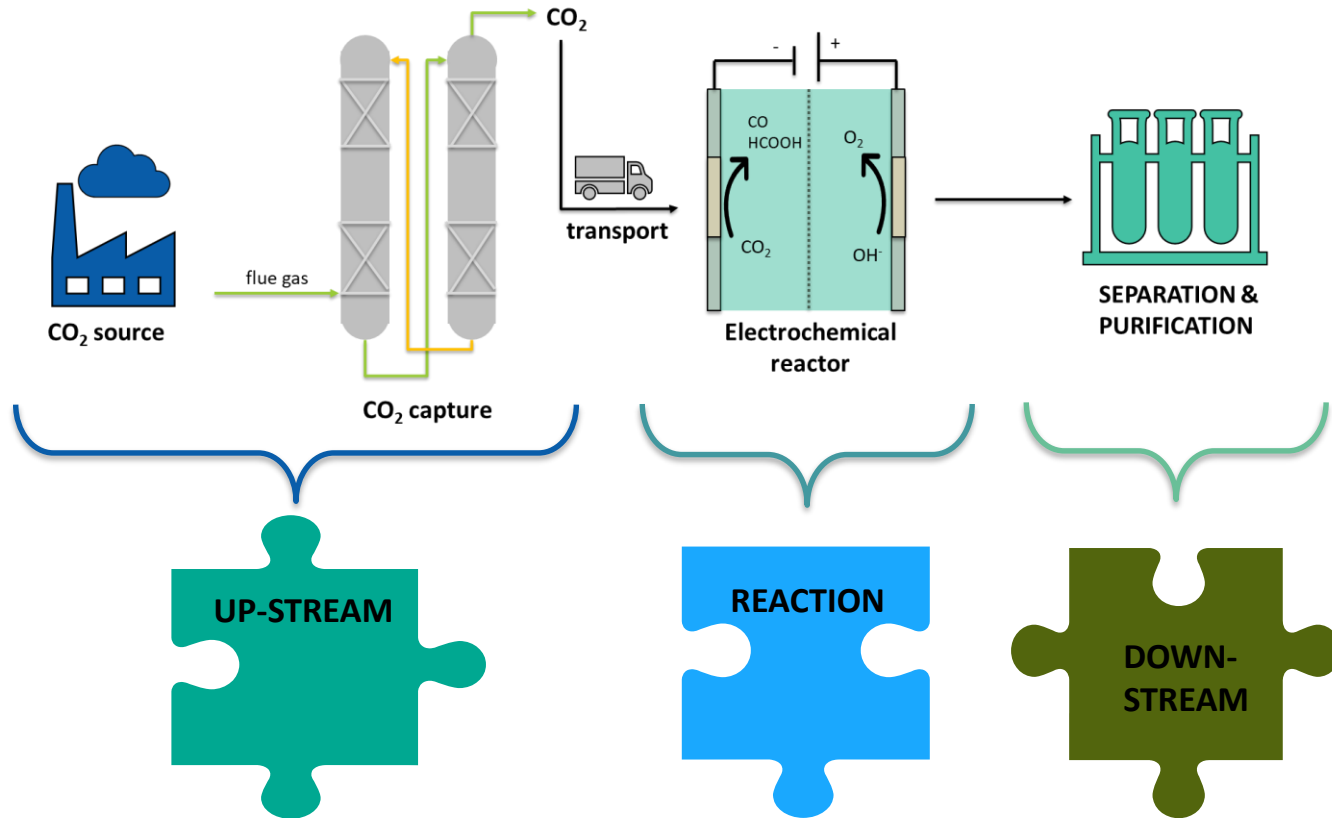
E-COUCH



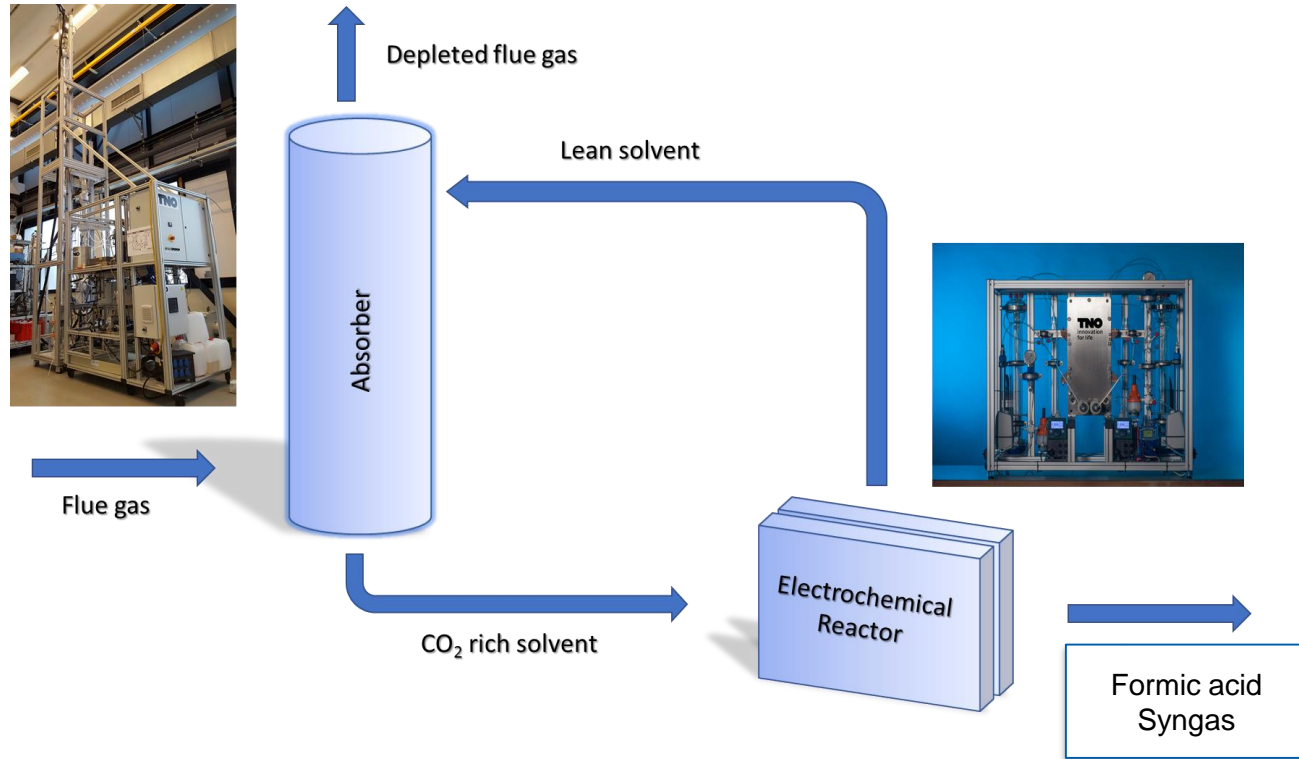
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Process and system integration



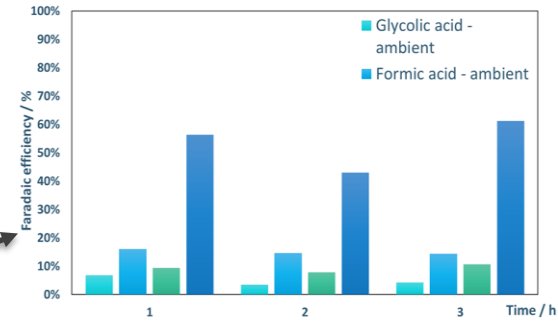
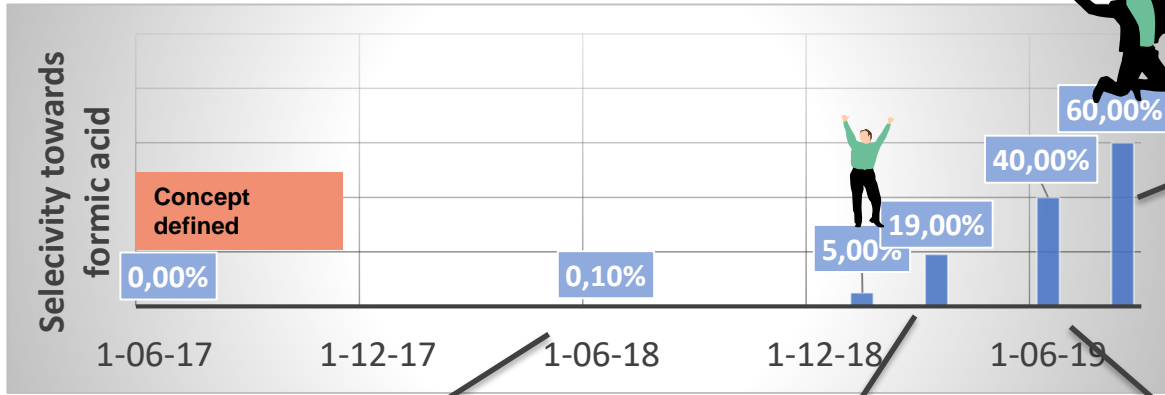
Integration of CO₂ capture & conversion



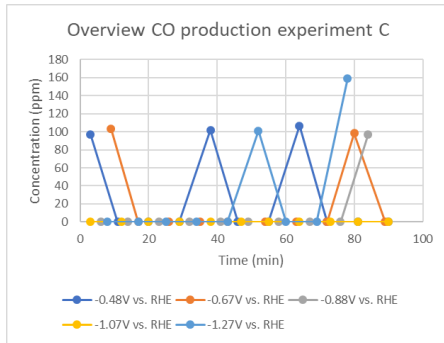
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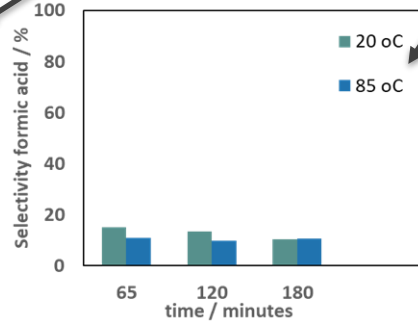
CO₂ Electrolysis from capture solvents



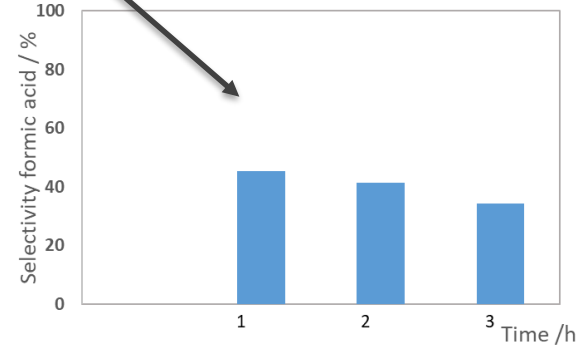
Organic capture solvent B



Aqueous capture solvent A



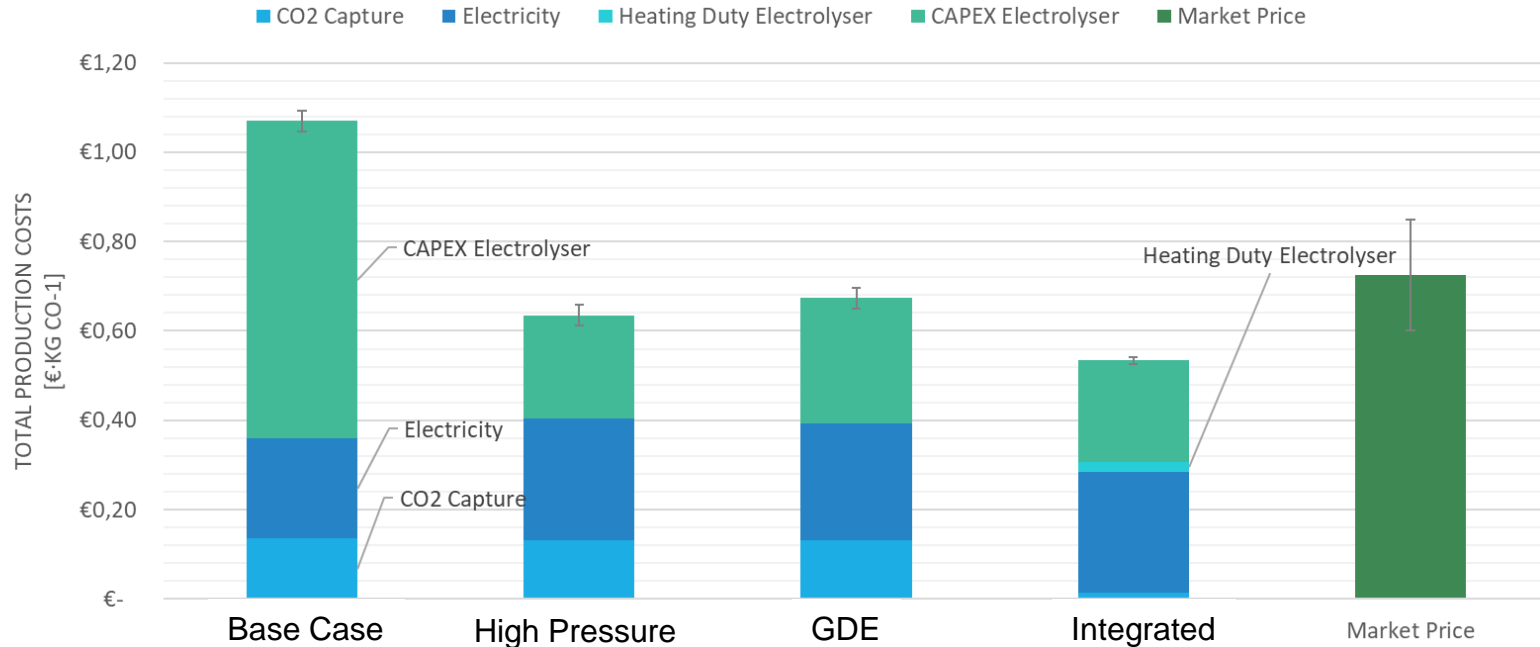
Aqueous capture solvent B



Low aqueous capture solvent B

What if we make CO

Techno-economic Comparison for CO Production



The Stone Age didn't end for lack of stone,
and the oil age will end long before
the world runs out of oil.

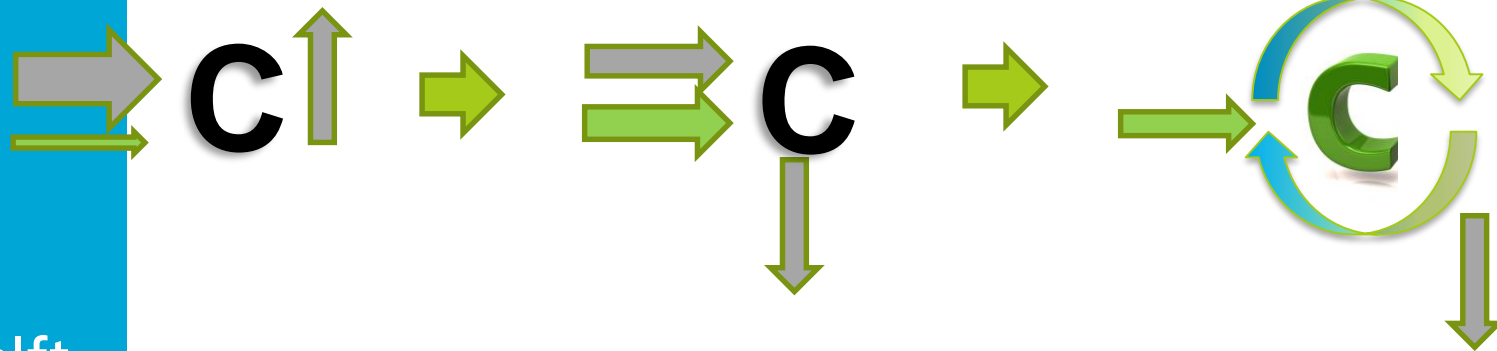


- Sheik Ahmed Zaki Yamani

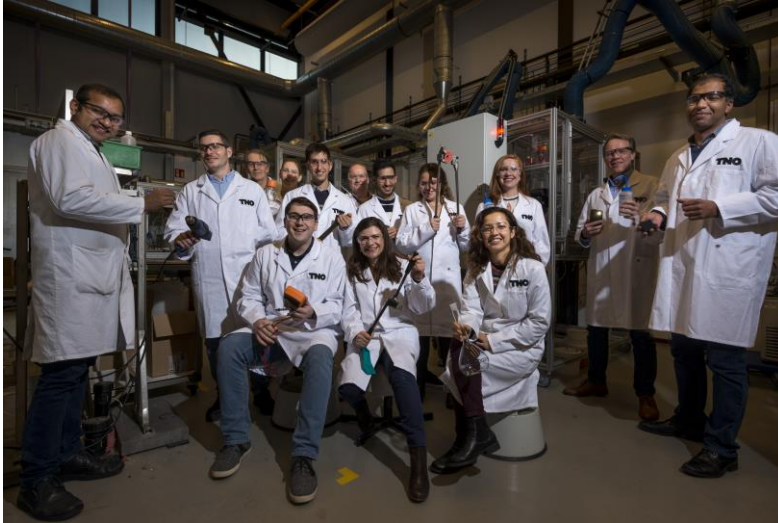
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Summary: the future is circular



Let's energize innovation together!



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