ENGIE Research

Emerging Sustainable Technologies

Report from 2020 Technology Watch

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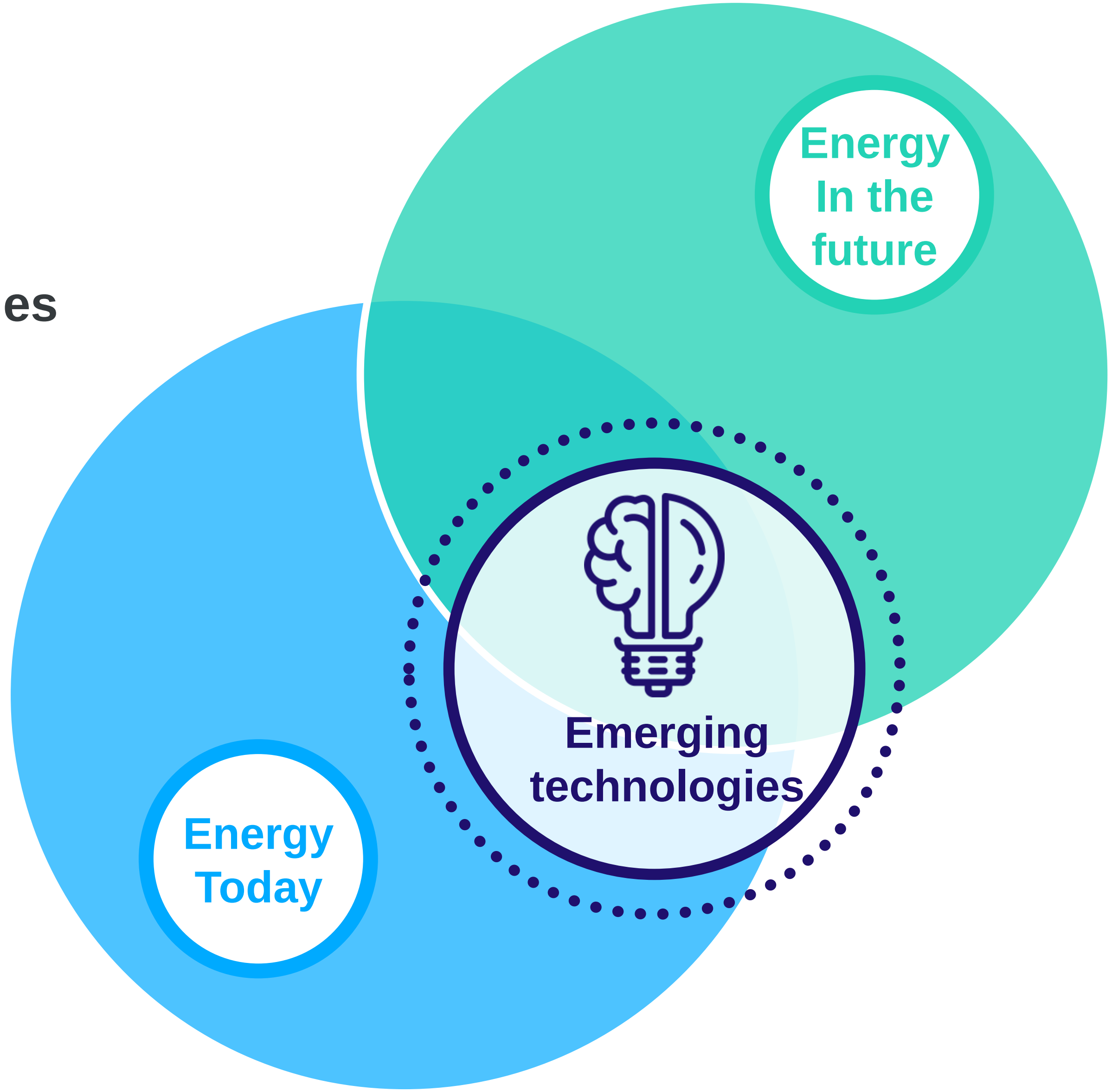
Just before the start...

Objective of this document

Present a selection of emerging technologies that:

- Impact Energy today
- Very likely will impact Energy in future
- May impact Energy directly or indirectly even though today they seem far away from our current and 'planned' future activities…

So where possible link is made with our activities but not always straightforward TODAY…



Introduction

Green energy is the key enabler for solving the top 10 issues that we face

Only 25 % of the required CO_2 emissions to meet carbon neutrality can be achieved using mature technologies

CO_2 as a resource will be part of the portfolio of technologies required to meet carbon neutrality

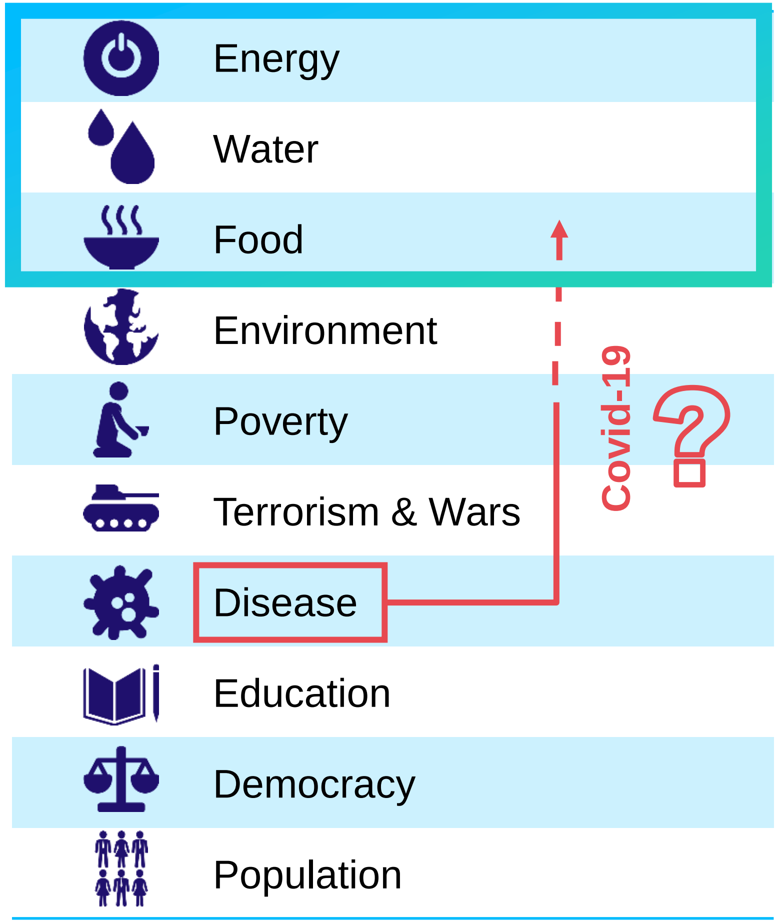
Green energy is the key enabler for solving the top 10 issues that we face

We need to adress the first three structural challenges to ensure having the means to fight the other ones!

1986 Nobel Prize-winning chemist, Professor Richard Smalley identified what he felt were the top 10 issues facing the world and their link with energy:

"Clean water is a great example of something that depends on energy. And if you solve the water problem, you solve the food problem."

R. Smalley, Lecture at NREL In Golden, Colorado, 2003

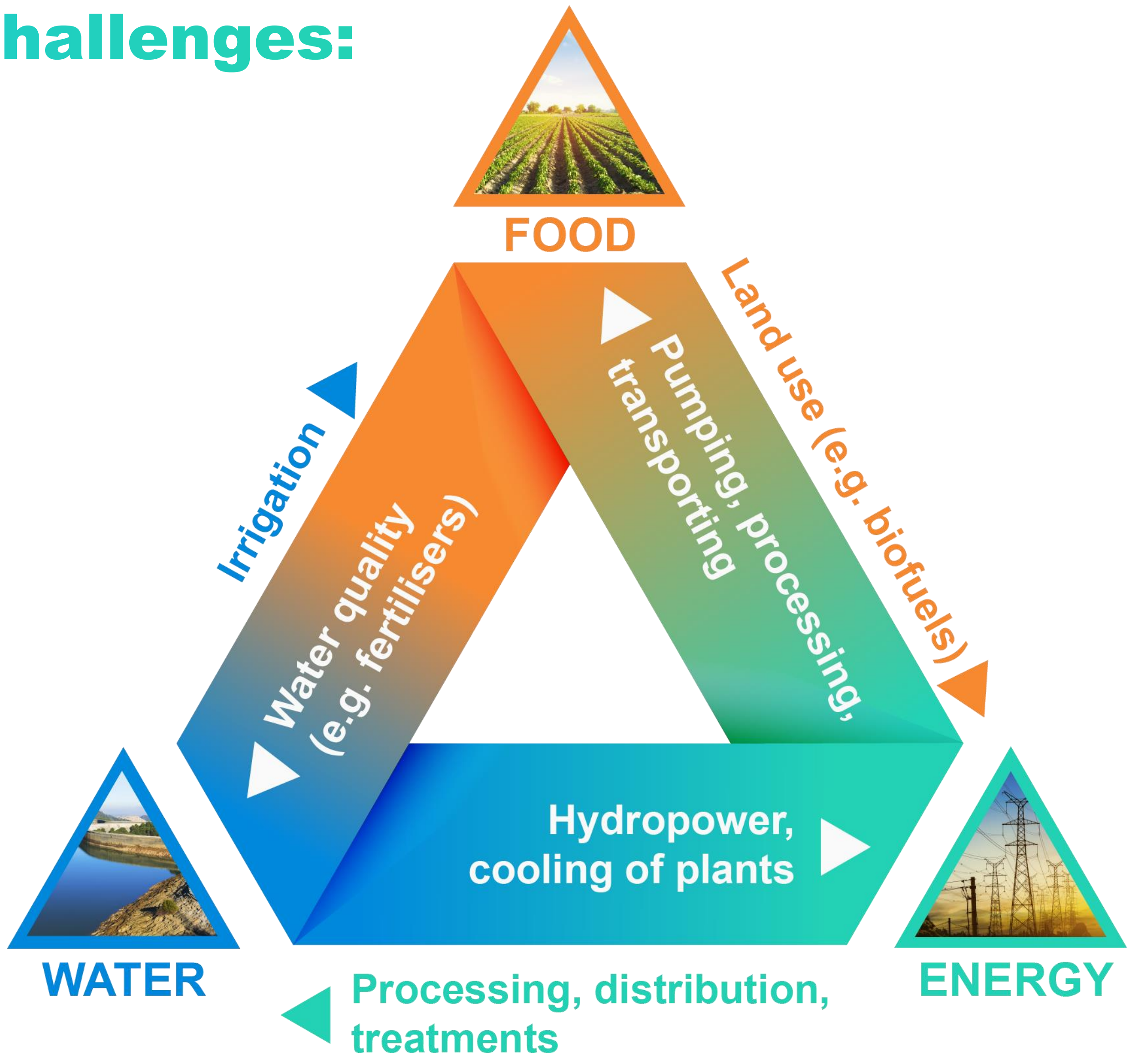


Let's focus on the first 3 challenges: the nexus approach

Water ▶◀ Food: Water is the keystone for the entire agro-food supply chain.

Food ▶◀Energy: Energy is an essential input throughout the entire agro-food supply chain, from pumping water to processing, transporting and refrigerating food.

Energy▶◀ Water : While water plays a key role in energy production, energy is required to process and distribute water, to treat wastewater, to pump groundwater and to desalinate seawater.

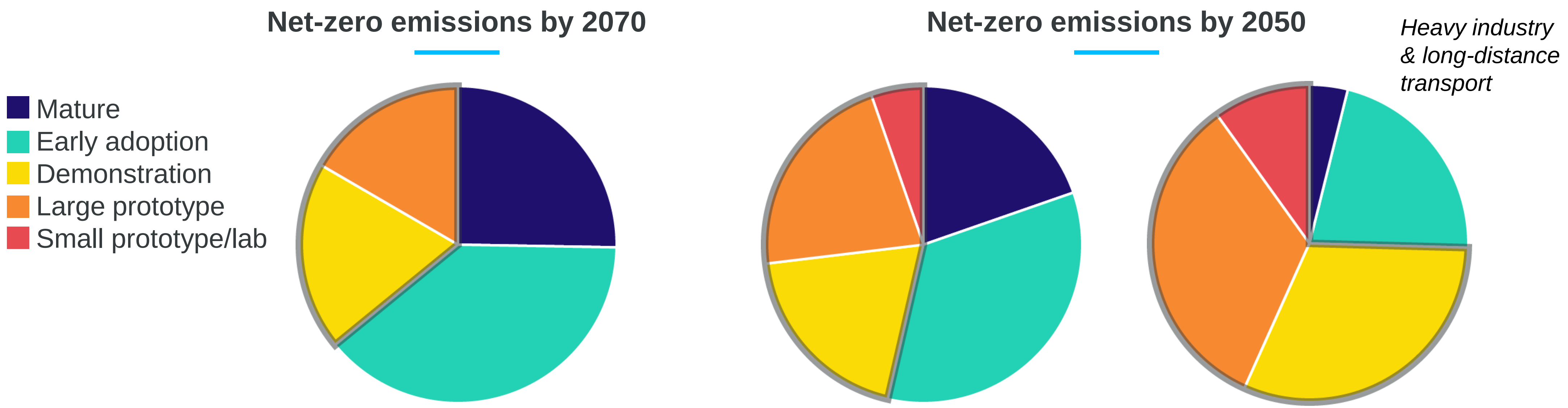


Source [1]

More than half of the emissions reduction will have to come from not mature technologies

We need to need to speed up R&D and Innovation!

Cumulative emissions reductions to baseline trends by technology maturity



"CCUS, batteries and H_2 are today where PV was 10 years ago. Governments need to support their development now."

Fatih Birol, IEA, 2020

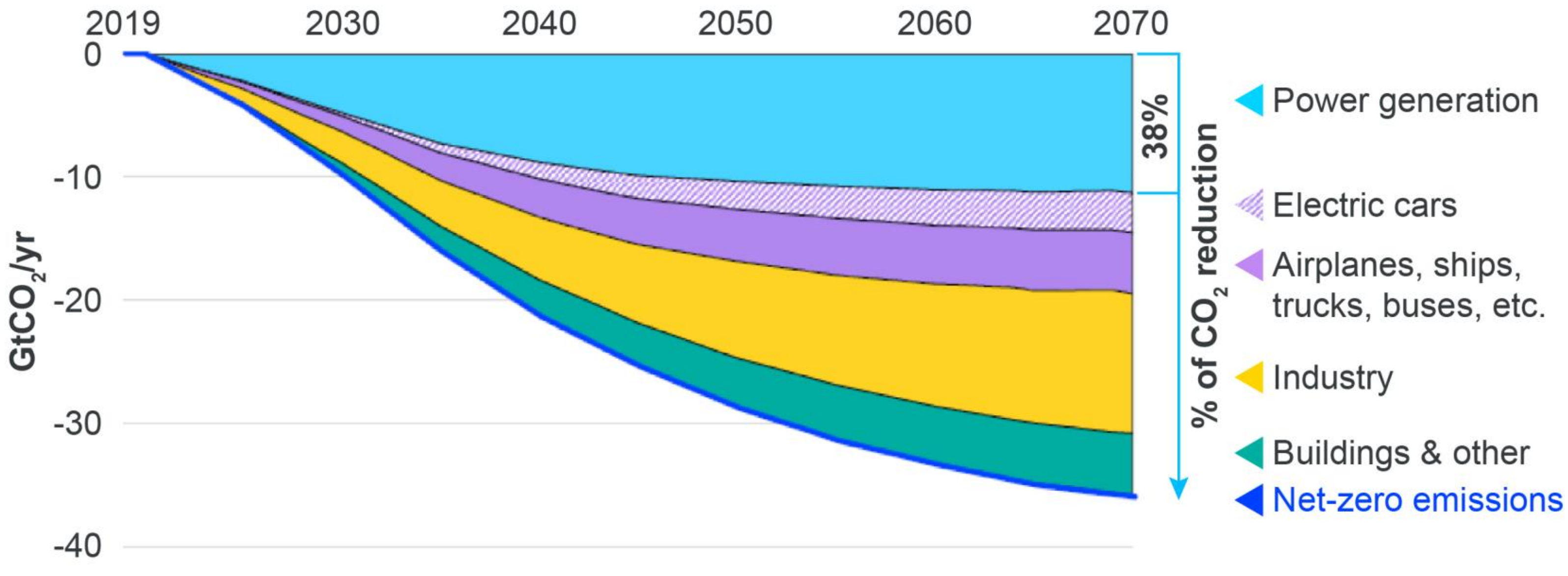
iea

Source [2]

For these non-mature technologies, green electricity generation is crucial but not sufficent as it will only reduce our overall emissions by 38%

We will need also green molecules (gases/liquids) for industry, building and transport

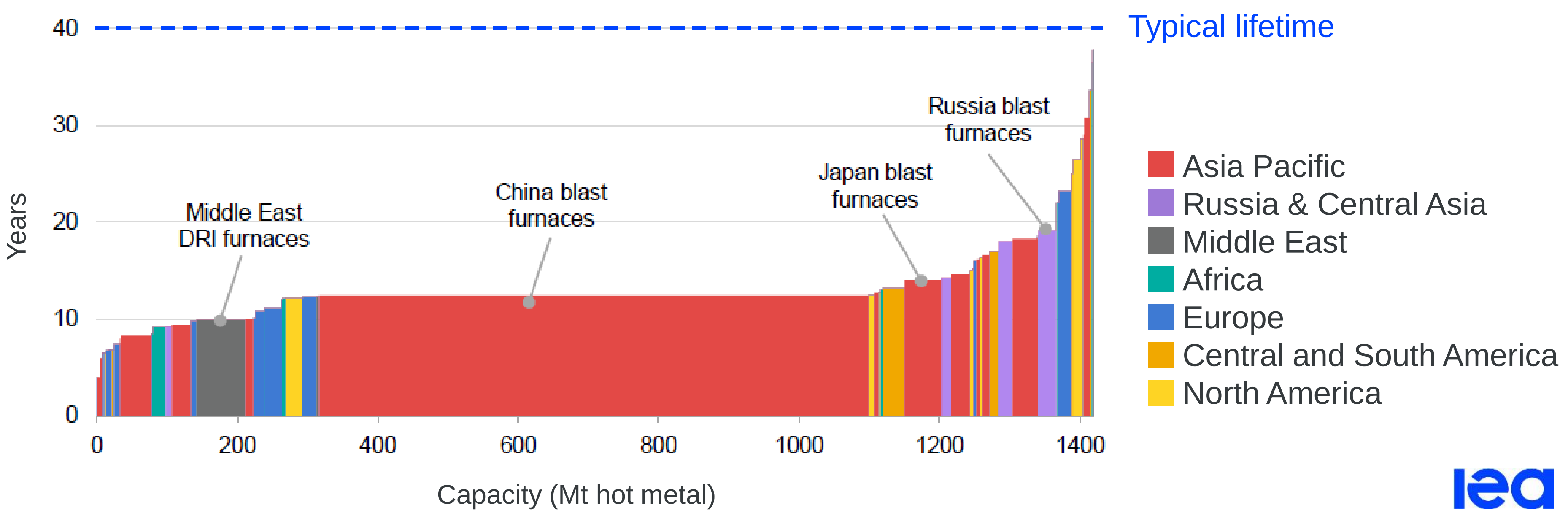
Global CO_2 emissions redutions in the Sustainable Development Scenario, relative to baseline trends



Source [2]

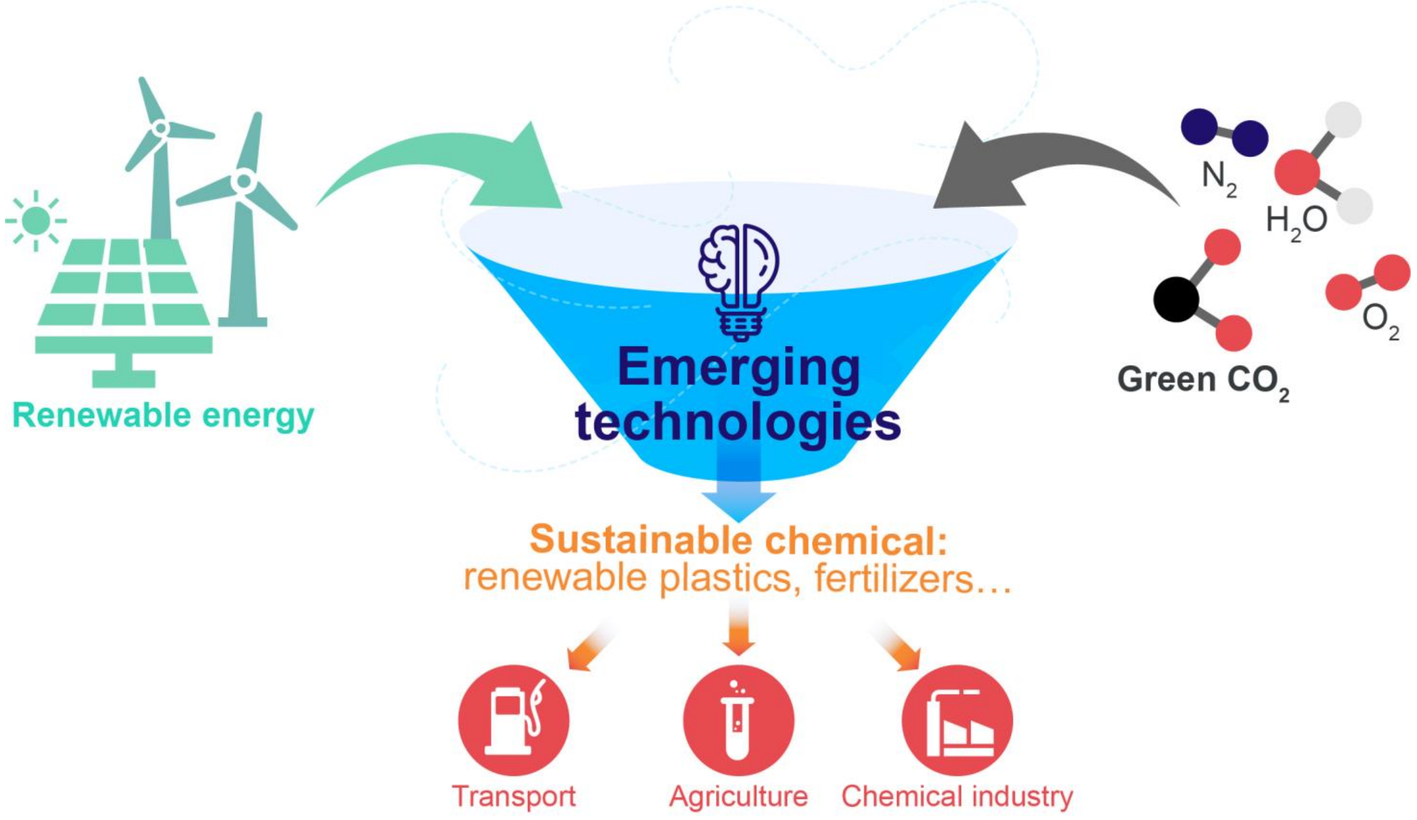
We must not only build new clean aluminium, cement, iron and steel, chemical plants BUT must address emissions from EXISTING infrastructure since many assets are still young! CCUS and H_2 will be required

Age profile of steelmaking from iron ore



Source [2]

Why the carbon neutral energy transition will require lots of Carbon (C)? CO_2 as a resource will be part of the portfolio of technologies required to meet carbon neutrality



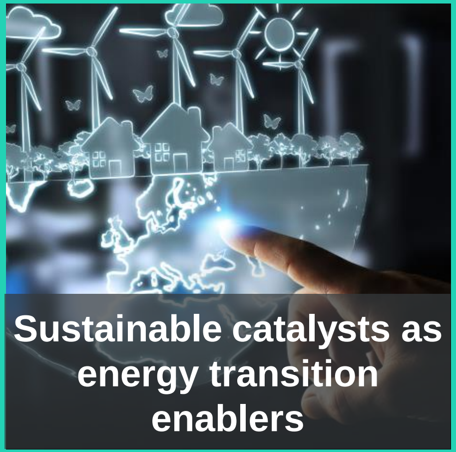
Modified from Source [3]

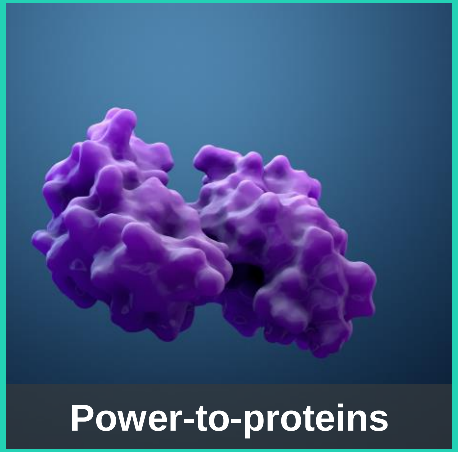
BUT "Due to efficiency losses in capturing and converting atmospheric CO_2, the production of renewable molecules will increase the overall demand for renewable energy drastically."

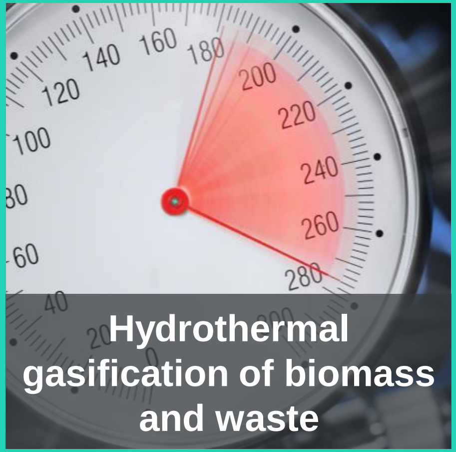
Mertens, Belmans and Webber, 2020

Sources [3], [4]

Emerging Sustainable Technologies







1

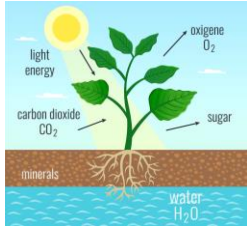
Direct air capture for circular carbon economy

CO_2 capture from the air: myth or reality?

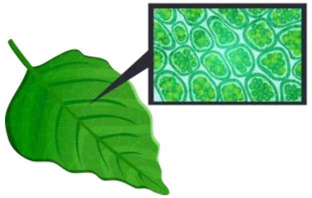
Technology wise, a reality

- Carbon dioxide can be removed from ambient air through **chemical processes based on acid-base reactions**. Direct Air Capture (DAC) is comparable to the respiratory system or the photosynthesis.

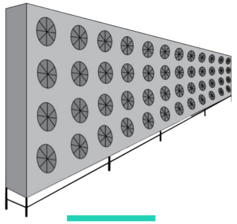
SYSTEM
The system moves the air to the process
Tree



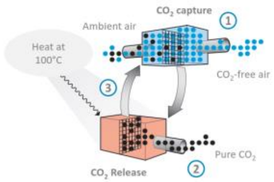
PROCESS
The process releases captured gases from the material
Photosynthesis



MATERIALS
Where the chemistry happens: capacity and selectivity
Chlorophyll



SYSTEM
Fans are processing air through large contactor arrays



PROCESS
Cyclic process: absorption on materials and desorption by heat

MATERIALS
Contactor: solvent or solid sorbent

Modified from Source [5]

	Liquid adsorbent and regeneration at high T°C (900°C)	Solid adsorbent and regeneration at low T°C (80-100 °C)
Amine based		CLIMEWORKS; skytree; Global Thermostat – The Carbon Negative Solution
Non-amine	OrigenPower; Carbon Engineering	carbyon – Closing the CO_2 cycle.

Sources [5], [6]

Why capture from the air when there are so many concentrated CO_2 sources?

Advantages

- DAC can capture the CO_2 emitted by decentralized sources (e.g. transport)
- It can be **decentralized towards sites that offer a cheap source of renewable electricity and heat**
- Deployed closed to CO_2 storage sites, DAC becomes a Negative Emission Technology (NET)
- Its modular construction means many of them can be built which can drive down cost

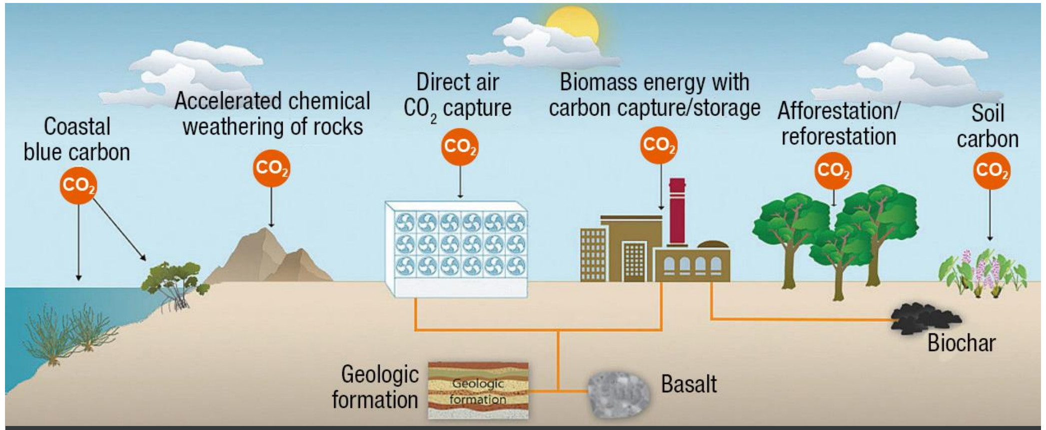
Challenges

CO_2 in the atmosphere is highly diluted (~400 ppm):

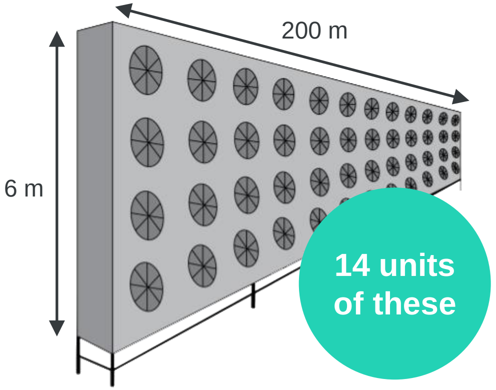
- Large energy footprint
- Cost
- Large land footprint

These challenges can be overcome by:

- Contactor development
- Low carbon energy, such as waste heat in the case of low temperature DAC



DAC with storage can be a NET, next to bio-CCS, carbon soiling, reforestation



Modified from Source [9]

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Petra Nova – 1.4 Mt CO_2/year
115 m tall, 20 m large absorber

Sources [8], [9]

CO_2 capture from the air: myth or reality?

Next 5-10 years a major milestone to go from myth to reality

The leading DAC technology developers are all striving for the first large scale demonstration where the economics and technology performances will be proven in an integrated business model (Enhanced Oil Recovery,e-fuels). 2025 will be a major milestone for DAC.

Roadmap	**< 2015**	**2015- 2020**	**2025**	**2030**
	Prototype	**Pilot**	**Demo**	**Commercial**
Tons/year	1	1000	10,000	> 1,000,000
Proof	Material	Technology	Economics	Profit & Impact

© climeworks.com

Source [7]

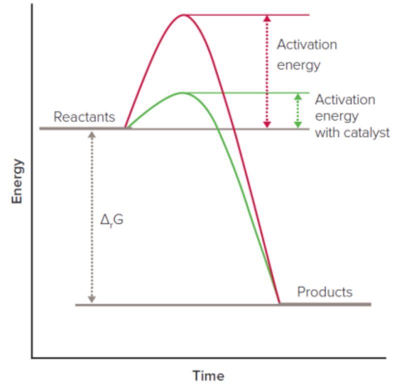
5

Sustainable catalysts as energy transition enablers

Catalysis is a key enabling technology for energy transition

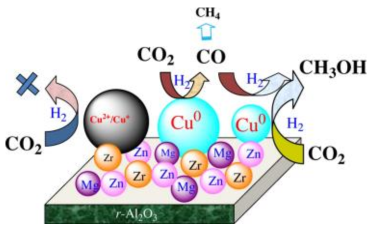
- Both energy (heat, electrons, photons) and catalyst are required to convert thermodynamically stable molecules, i.e. H_2O and CO_2, into value-added products.
- Catalysts are chemical substances **increasing the reaction rate without being consumed** to reach the chemical equilibrium at a suitable temperature.They do not change the thermodynamics and can be used cyclically.
- **Its performance is driven by:**
  - Its composition (nature of the metal, enzyme…)
  - Structure / morphology / microstructure
  - Type and nature of support
  - Immobilization method
- A catalyst is specific for each final product, reaction conditions and type of process:

Comparison of activation energy with (green) and without (red) a catalyst



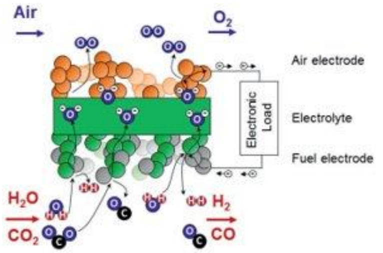
Thermocatalytic conversion

Metallic Cu catalyst



CO_2 hydrogenation into methanol

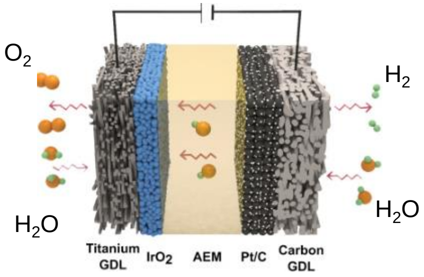
Metallic Ni supported on YSZ ceramic



Production of syngas by Solid Oxide Electrolysis (SOEC) at High Temperature

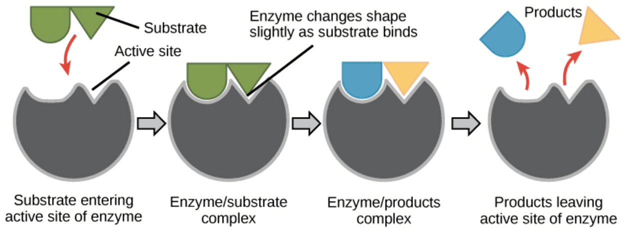
Water electrolysis

Pt/IrO_2 catalyst



H_2 production from water electrolysis

Biocatalytic conversion



Sources [28], [29], [30], [31]

Platinum group metal (PGM) catalysts dominate today's applications

CHALLENGES

- Even at high production volumes, the PGM catalyst is expected to represent a significant part of the fuel cell cost.
- The wide development of **electrochemical processes, that bridge the molecule-based economy with a green electricity production** should avoid the intensive use of PGM materials. As such, a large scientific effort is devoted to the development of low-PGM and PGM-free catalysts.
- Developments of new catalytic materials with improved performance are focused on composition and microstructure.

2018 PEMFC Stack Cost Breakdown

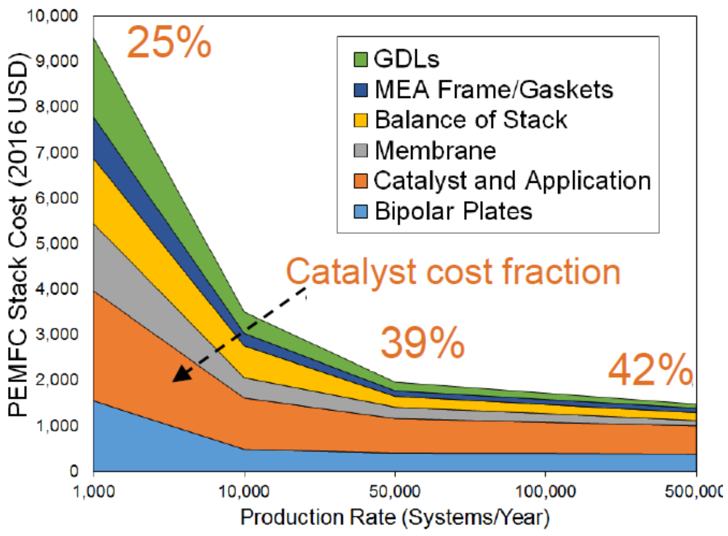
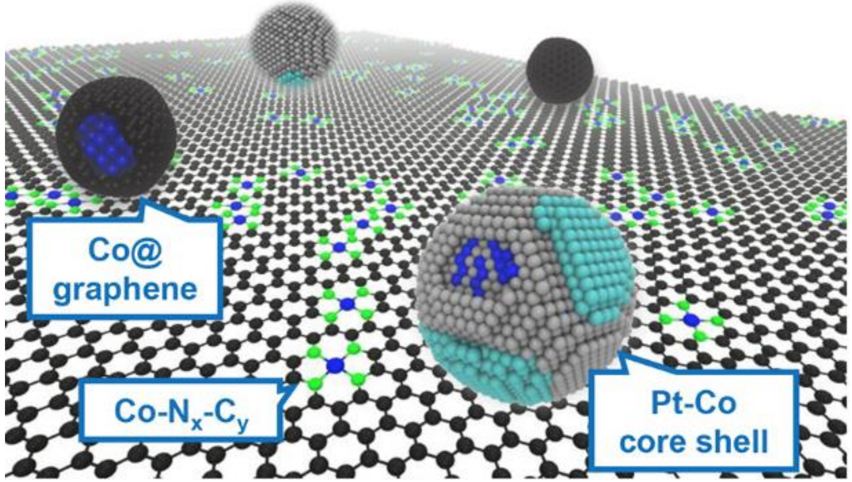


Illustration of the microstructure of a low PGM catalyst



Platinum group metal

Ru Ruthenium 101.07	**Rh** Rhodium 102.91	**Pd** Palladium 106.42
Os Osmium 190.23	**Ir** Iridium 192.22	**Pt** Platinum 195.08

Sources [32], [33]

Conventional catalysts

- ☒ Fossil fuel feedstock
- ☒ Harsh reaction conditions
- ☒ Low process flexibility
- ☒ Low catalyst activity
- ☑ Abundant and cheap materials

H_2 + N_2 → **Fe** (Iron, 55.845), 300-600°C, 150-250 bar → NH_3

H_2 + CO → **Ni** (Nickel, 58.693), 400-600°C, 5-20 bar → CH_4

H_2 + CO → **Cu** (Copper, 63.546), 250-300°C, 50-100 bar → CH_3OH

Alternative catalysts

- ☑ Renewable feedstock
- ☑ Mild reaction conditions
- ☑ Higher process flexibility
- ☑ Higher catalyst activity
- ☒ Rare and expensive materials

H_2 + N_2 → **Ru** (Ruthenium, 101.07), <400°C, <20 bar → NH_3

H_2 + CO_2 → **Rh** (Rhodium, 102.91), 125°C, 2 bar → CH_4

H_2 + CO_2 → **Pd** (Palladium, 106.42), <250°C, <30 bar → CH_3OH

Tomorrow’s catalysts

- ☑ Renewable feedstock
- ☑ Mild reaction conditions
- ☑ High process flexibility
- ☑ High catalyst activity
- ☑ Non-transition metals

H_2 + N_2 → **Li** (Lithium, 6.941), 250°C, 10 bar → NH_3

K Potassium 39.098

Cs Cesium 132.91

Na Sodium 22.989

...

Sources [36], [37]

Future catalyst will have to be based on earth-abundant materials and will require to work at moderate pressure and temperature ultimately

The biocatalytic approach could allow the convergence of both approaches

ADVANTAGES

Mimicking the reactions taking place in living organisms, biocatalysis has many attractive features in the context of green and sustainable chemistry:

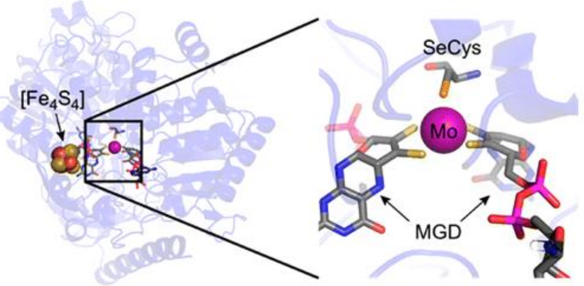
- Mild reaction conditions: ambient temperature and pressure
- High flexibility
- Efficient
- Highly selective
- Sustainable : biodegradable catalyst (enzyme)

CHALLENGES

- Recycling biocatalysts
- Development of more stable biocatalysts according to two different approaches:

- Keep wild type organisms / enzymes and select organisms that live in extreme environments as these will be naturally more stable.
- Engineer it using genetic tools

Formate dehydrogenase with focus on the active site of Mo for the CO_2 reduction into formate



Over the last few years, an increasing number of pilot and demonstration emerges.

Power-to-Methanol Methanol

Thermocatalytic hydrogenation
8000 tpa

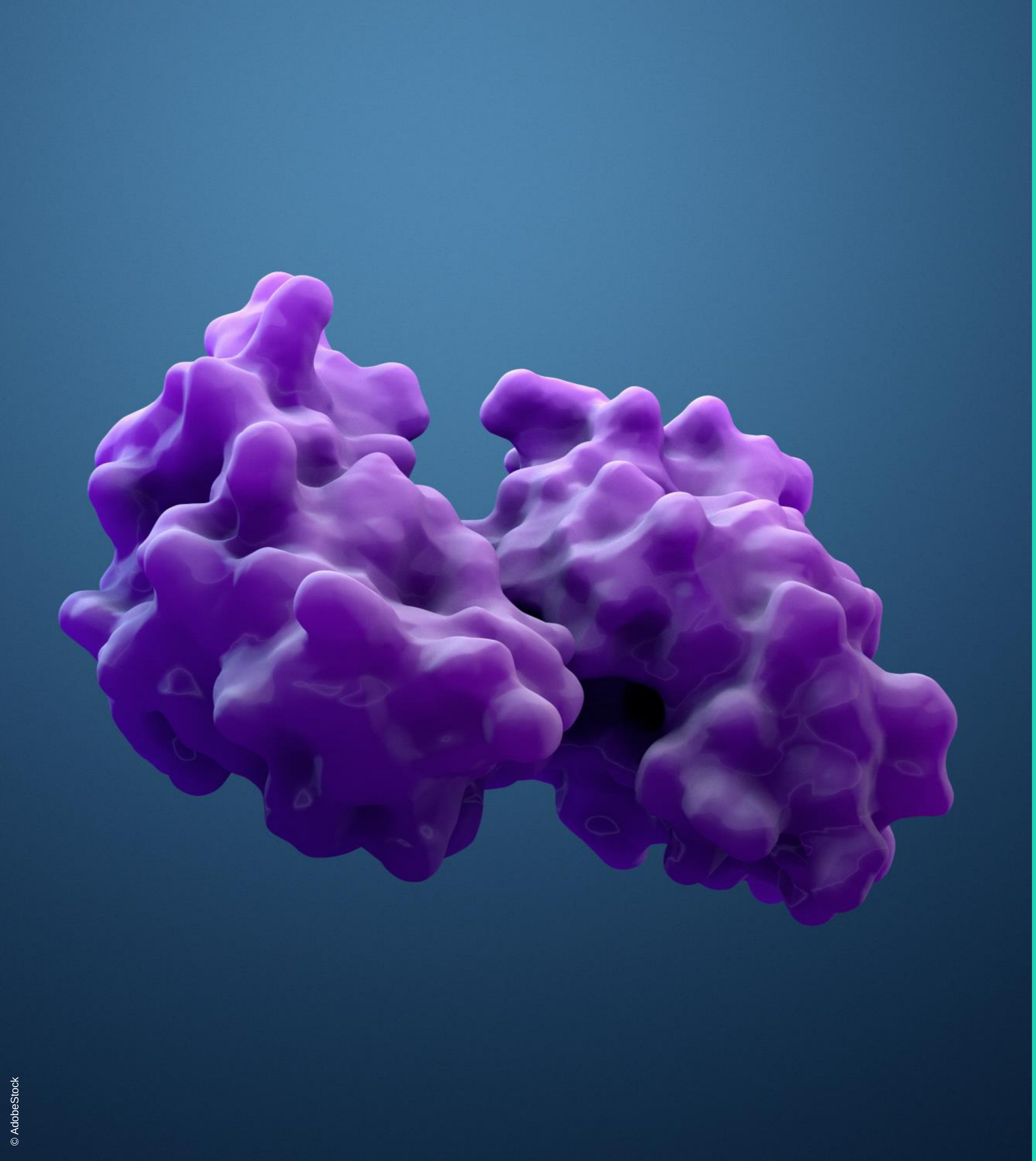
North-C-Methanol Methanol

Thermocatalytic hydrogenation
45000 tpa

Power-to-gas Hycaunais E- methane

Bioconversion
H_2 electrolyser @ 1MWe

Source [36]



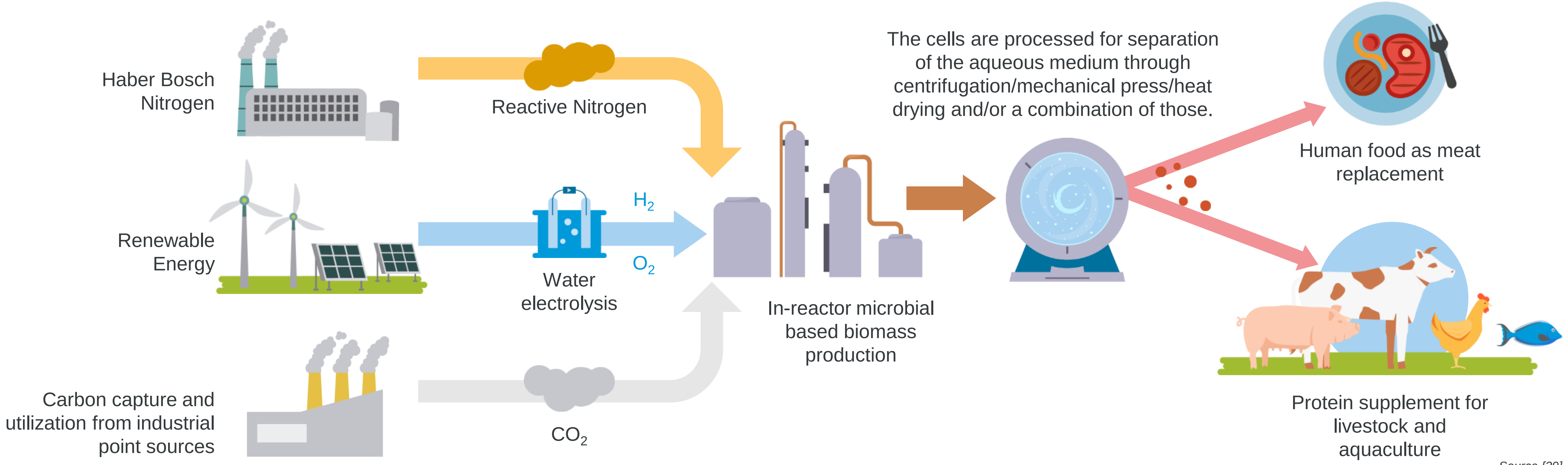
6

Power-to-proteins

Power-to-proteins approach consists in the production of a protein-rich material by bacterial cultures using electrolytic H_2 as energy source

- Commonly used microorganisms are **hydrogenotrophs** like *Cupravidius necator*, *Rhodococcus opacus* or *Hydrogenobacter thermophiles*. These bacteria **oxidize hydrogen** in anaerobic conditions **to power their metabolism** and **accumulate proteic biomass** at high rates (kg/m³.h scale)

Power-to-protein concept for food/feed production: a process that decompartmentalize energy, biology and agriculture sectors.

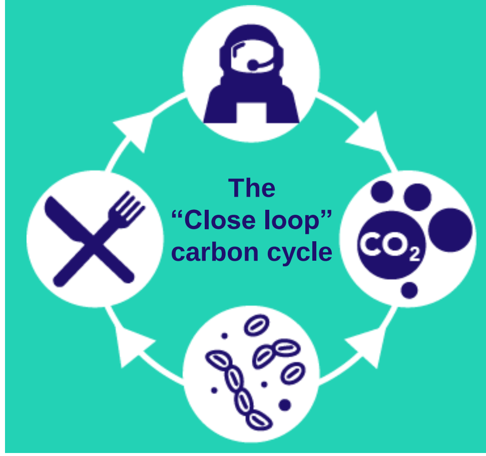


Source [39]

This no-brainer protein production pathway remains to be demonstrated economically at scale and socially accepted

Parameter	Animal based	Vegetable based	Microbial
Land footprint	High and only arable	Medium and only arable	Low and can be barren
Water use	High	High	Low
Greenhouse gases footprint	High	Medium	Low
Production time	Days to years, non seasonal	Months, seasonal	Days, non seasonal
Proteic efficiency	Low	Low	High
Nutrients environment spillover	Large, linked to vegetal feed needs	Large, through N emissions when fertilisers are applied	Close to 0
Resilience towards climate change	Low due to ecosystems change		High as it is decoupled from the environment
Pesticide and antibiotics use	Yes		No
Sterile environment	No	No	Yes

Comparison of animal, vegetable and bioconversion protein production pathways.



Food for astronauts?

Food cargo is a large expenditure when it comes to space exploration. Producing it autonomously is thus a huge opportunity. Power-to-proteins was actually initially developed for that application by NASA and still viewed as a long-distance space exploration enabler.

CHALLENGES:

- **Foremost challenge is to make it renewable and economical as hydrogen is the main cost**
- **Social** acceptance of eating a microbe or eating meat produced on microbes.

Sources [40], [41]

A dynamic portfolio of start-ups developing the subject at different stages and with different focuses. Oil and gas as well as electricity utilities are partnering

Start-ups

- novonutrients – feed from CO_2
- Deep Branch Biotechnology
- Avecom Bioproducts & Apps
- Kiverdi
- Solar Foods

In partnerships with

- Chevron
- Shell
- fortum
- drax
- esa
- engie

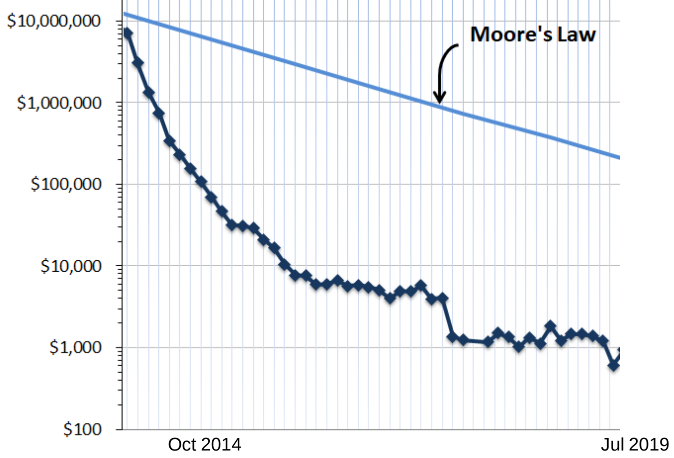
The steadily growing biotech economy is experiencing an ever growing momentum pulled by key enabling technologies to harness biology without wasting resources

Biotechnologies have been ever rising since a couple of decades through 3 main different sectors: **Industrial**, **pharmaceutical** and **agricultural applications**. Today, pharma sector is leading but the grow is cross sectorial.

Currently, an **even stronger development** of the sector is observed due to several factors:

- **Dropping DNA sequencing costs to access massive information**
- **Artificial intelligence** (especially machine learning) developments to **manage the massive amount of data**
- **CRISPR/Cas9** development, a genetic editing tool to **screen large number of precisely edited mutants**
- Laboratory increasing **automatization** capacity

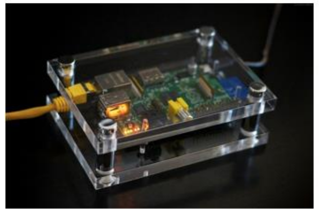
Cost per Human Genome Sequenced

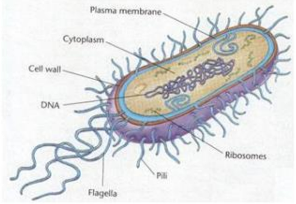


Nobel Price in Chemistry 2020: Emmanuelle Charpentier and Jennifer Doudna.

Similarities with the informatics wave?

Actors in the field sometimes compare this evolution to the computer and IT revolution that occurred the past decades as both show **impressive growth and several similar concepts**





“Blank” chassis	“Evolutionary” based chassis
Constructed by modules (parts)	
Behavior code based	
Non self replicative	Self coding and self replicative
Possible contamination by external code	
Similarities with IT exists but fundamental differences	

Sources [40], [41], [42]

7

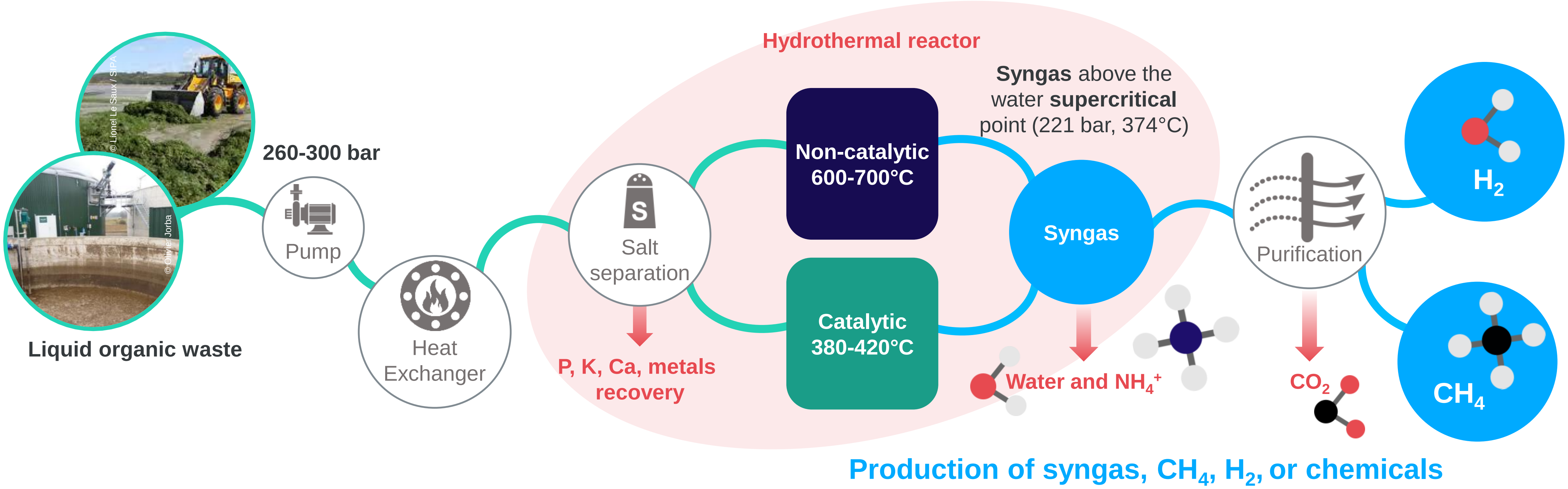
Hydrothermal gasification of biomass and waste

Hydrothermal Gasification converts liquid organic waste into green gases in contrast to pyrogasification processes which valorizes dry organic waste

What is a liquid organic waste?

- Biomass or waste having a dry matter range of 5-50 wt%
- Organic fraction in the dry matter is higher than 50 wt%
- Liquid organic waste must be pumpable to reach high pressure required by the process

Hydrothermal Gasification is gasification in hot compressed water which uses water in a supercritical state



- Raw syngas can be valorized either directly for heat and/or electricity production, or purified to clean CH_4 or H_2, or converted into **chemicals.**
- CH_4 content reaches 50-60% in catalytic conversion, and up to 90% when H_2 is co-injected in the gasifier
- H_2 concentration can achieve 50-75% in syngas

Sources [45], [46], 47]

Hydrothermal Gasification is either a complementary or competitive alternative pathway for green gas production from organic waste

ADVANTAGES

- Complementary to **pyrogasification process** which valorizes dry organic waste and to **anaerobic digestion (AD)** by valorizing liquid digestates in saturated spreading zones
- Efficient production of **CH_4 or H_2** depending on the operating conditions and process chain (CH_4 production is doubled compared to **AD**)
- Fast conversion (<10min) ➔ **compact units** (10 times more compact than AD)
- Co-production of minerals (P, K, Ca) and NH_4+ possibly valorized as fertilizer ➔ **extra-revenues**
- Low quantity of **final solid residue** generated
- No problem by using only one type of feedstock contrary to AD

CHALLENGES

- Operating with high pressure and high temperature
- **Optimisation of minerals separatio**n to avoid plugging of the gasification reactor
- Preventing from catalysts **deactivation by poisoning** (sulfur compounds) and **plugging** (minerals precipitation)
- Scaling-up and simplifying the installation operation
- Potentially in competition with anaerobic digestion since both sectors valorize **liquid organic fuels**
- Uncertainty on profitability due to costly alloys for reactor and equipment to withstand operating conditions and **corrosion**

Sources [47], [48], [49], [50], [51], [52], [53], [54]

Gas companies and transport infrastructures are involved in the development of the sector by providing support to technology developers and to initiate pilot or demonstration projects

GRTgaz

FROM RESEARCH TO INDUSTRY cea tech

PAUL SCHERRER INSTITUT PSI

KIT Karlsruhe Institute of Technology

SCW Systems clean energy technology & gasunie crossing borders in energy

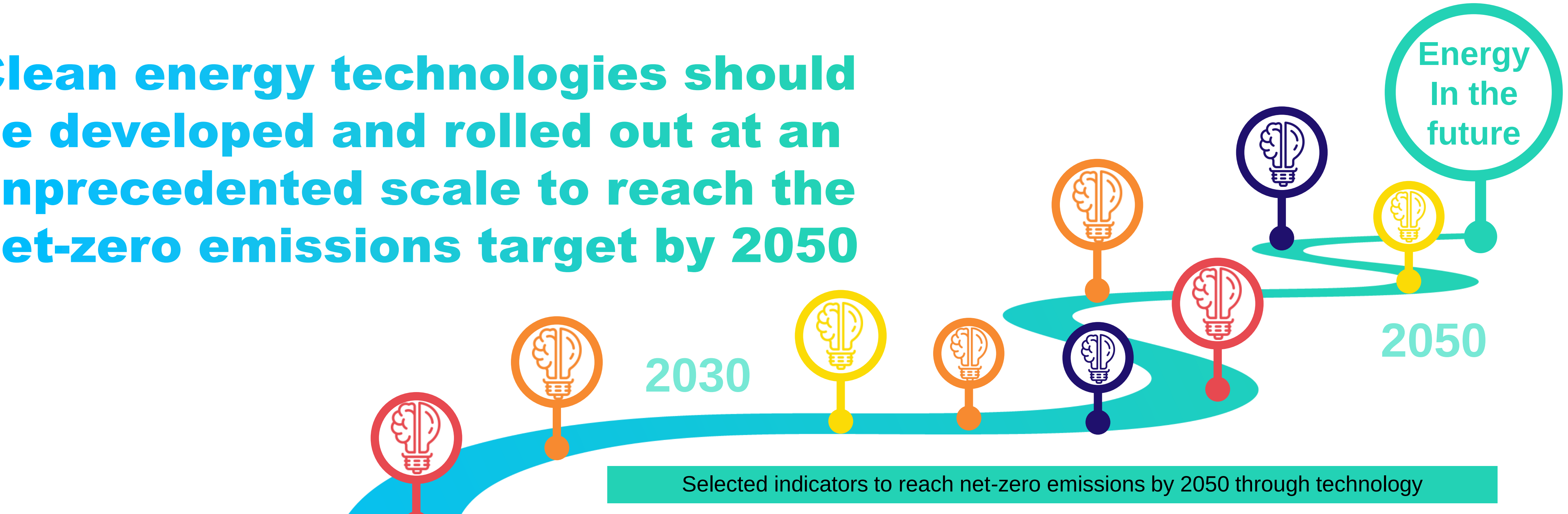
PAUL SCHERRER INSTITUT PSI & TreaTech

Bright Circular

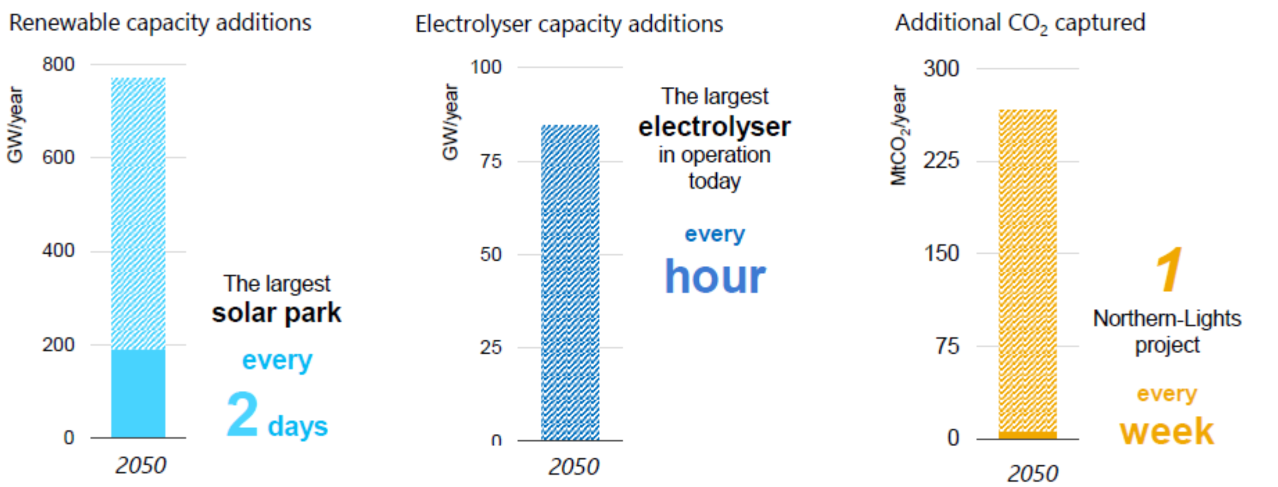
ENGIE

Conclusions

Clean energy technologies should be developed and rolled out at an unprecedented scale to reach the net-zero emissions target by 2050



Selected indicators to reach net-zero emissions by 2050 through technology



Source [3]

Research

Discussion / Questions

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[1] Smalley R.E., 2005. Future Global Energy Prosperity: The Terawatt Challenge. *MRS Bulletin,* Vol. 30, 6, 412-417.

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