RESEARCH &
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# EMERGING SUSTAINABLE TECHNOLOGIES

EDITION 2023

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# AGENDA

# FROM CLIMATE SCIENCE TO CLIMATE ENGINEERING

Scientists ask the question “what?” and they’ve done a very good job of modelling the climate and pointing out likely scenarios, stated John Anderson, the president of the US National Academy of Engineering’ in an interview in September 2022 (Engineering the Transition to Net-Zero Carbon Emissions | National Academies).

Engineers differ in that they ask the question “how?” Now that we know what the goals are, we have to ask how we can achieve those goals – by what paths can we attain the net-zero carbon emission economy?’, he asked.

The storm is coming, and the time for action is now.

The latest IPPC WGIII report, published in spring 2022, leaves no scientific doubt that the current climate change is man-induced. The sense of urgency increased further over the summer 2022 due to more extreme weather events such as wildfires and floods worldwide, and an exceptionally severe drought in Europe. The challenge lies not so much in developing technologies from scratch as in upscaling what already exists in labs at universities, research centres, start-ups and companies. The ‘industrialisation’ of those technologies poses a great challenge: just showing that a technology works in the lab or small pilot is not sufficiently convincing for a company to take up the technology and deploy it massively.

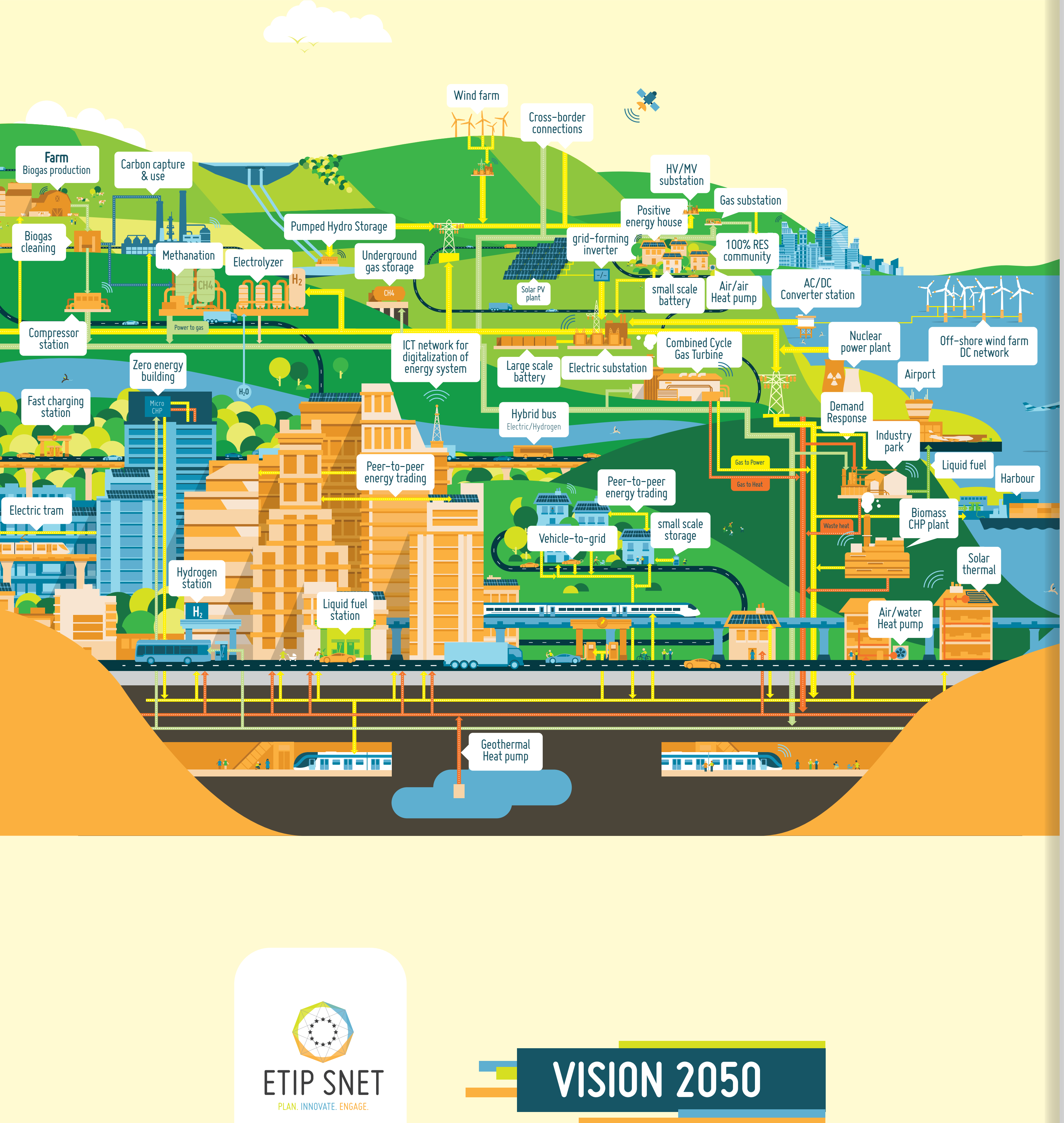
In many cases, there is a significant ‘business gap’ making the technology unattractive to companies due to the associated high financial risk. But it is not unthinkable that society, due to this heightened sense of urgency, will at some point no longer tolerate the ‘excuse’ of this business gap and force the large-scale deployment of the necessary technologies, despite the financial risks.

This could become the case in particular for sectors like aviation, shipping, the steel and cement industries, long distance transport of (renewable) energy and long-term storage of (renewable) energy. These sectors account for roughly one third of our energy needs. Significant thermodynamic constraints need to be addressed in the search for solutions. But even if we cut emissions now, extreme events – such as floods, droughts, tornadoes and Arctic ice loss – are not going to disappear in the coming years, or even decades. So we will need to adapt whilst continuing to develop at the same time further the many climate actions that we have already identified to reach our objective of a net zero carbon society.

In addition, we need to consider efforts on climate engineering, and have an open and scientific discussion about the risks and benefits of this approach which are not yet fully understood. Our decision to include the (sometimes) taboo topic of geo-engineering in this document is meant as a contribution to that discussion. The topic should absolutely not be considered as a way forward to continue using fossil fuels in future. Afforestation and reforestation, for example, show great potential but, although less controversial than some other ideas, they still need to be carefully evaluated with respect to their impact on the local environment. This also goes for several other climate engineering technologies that seem promising but need to be carefully examined as to their long-term impacts. To be clear, climate engineering should never be seen as a “silver bullet”, a single quick solution to the planet’s problems and certainly not as an excuse to continue our fossil fuel based economy. But as society pushes forward with the fight against climate change, we may have to consider it as a potential solution– and one that may become necessary to reach our climate targets. This is why we need this discussion.

ENGIE, a leader in the world’s energy transition, promotes in-depth collaboration across all sectors and countries, and between companies and industries, to tackle the problems we jointly face and to implement solutions. The challenge ahead is too large for one company, one industry, one country, even one continent, alone. We wrote this document in the hope of inspiring everyone who wants to be part of this transition. It is, in short, a call for global collaboration across all boundaries.

**Jan Mertens**,
Chief Science Officer ENGIE, Professor at Ghent University



# INTRODUCTION

## The Energy Transition: an integrated system of systems.

The success of any carbon neutral energy transition requires orchestrating a complex network of different technologies that will all be integrated. In all this, energy efficiency and circularity will remain important, and more thought must be given to how the waste of one industry can serve as input for another. This industrial symbiosis will not only require technical solutions but also non-technical ones such as regulatory frameworks. Biogas is an interesting example of circular thinking, especially using biowaste as a feedstock. No doubt electricity will play a crucial role and a much bigger one than today. It will be integrated not only from a demand-side management point of view: ie. matching consumption with production but it will also be closely linked to the gas grid and vice versa. Molecules, made either from biomass or from renewable electricity, will be required not only for long term renewable energy storage and transport but also for some hard to abate industries (cement, steel, glass,…) and heavy mobility (shipping, aviation,…).

The complex integration of all these technologies and their orchestration is nicely depicted in the ETIP SNET VISION 2050 figure. It shows that major investments for the large-scale deployment of energy conversion and storage devices, the upgrade and extension of the energy networks, and the use of digital solutions will be crucial. In the animated version of ETIP SNET graphic, we positioned our selection of emerging sustainable trends and technologies presented in this document. This reminds us that what we present here in this document is just a (small) part of the entire network of integrated technologies. This interconnection and industrial symbiosis including the connection between electricity and molecules, a concept which we called ‘CirculAir’ fuels, is explained here in detail.

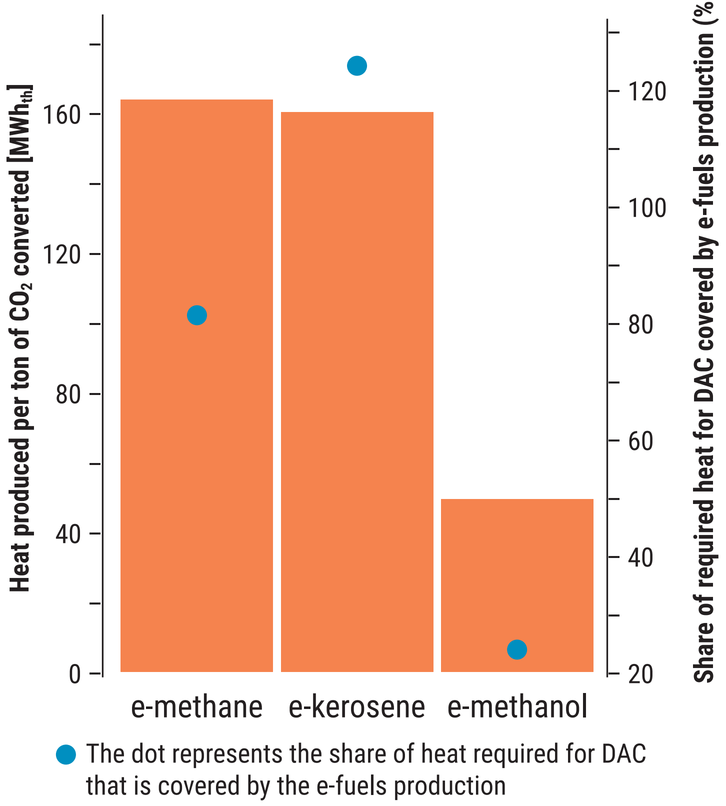
# CirculAIR fuels: converting low-carbon electricity to e-fuels in a fully circular manner!

## The reaction between $CO_2$ and $H_2$ towards e-fuels yields water which can be used to produce $H_2$. It also produces heat which can be used to capture the $CO_2$ from the air.

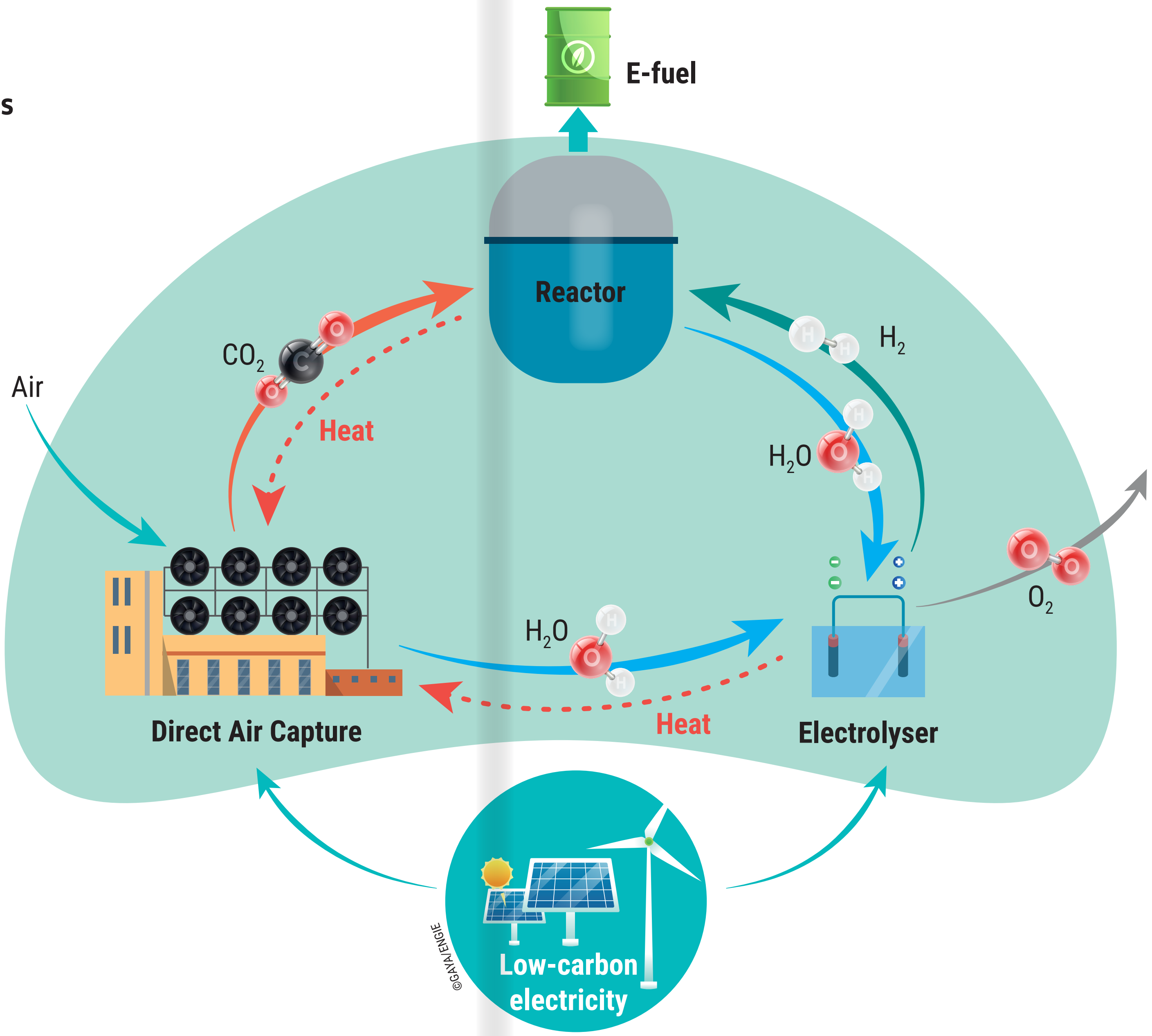
**The heat available from the e-fuels synthesis together with heat recovered from the water electrolysis suffices to run the Direct Air Capture (DAC).**
E-fuels synthesis is exothermic, producing heat (and water).

| | |
|---|---|
| **Methane**: $CO_2 + 4\ H_2 \rightleftharpoons CH_4 + 2\ H_2O$ | **-164 kJ/mol of $CO_2$** |
| **Methanol:** $CO_2 + 3\ H_2 \rightleftharpoons CH_3OH + H_2O$ | **-49.5 kJ/mol of $CO_2$** |
| **Kerosene:** $12\ CO_2 + 37\ H_2 \rightleftharpoons C_{12}H_{26} + 24\ H_2O$ | **-160 kJ/mol of $CO_2$** |

↑
*$C_{12}$ taken as average on the kerosene interval ($C_8$-$C_{16}$)*



Share of required heat for DAC covered by e-fuels production (%).



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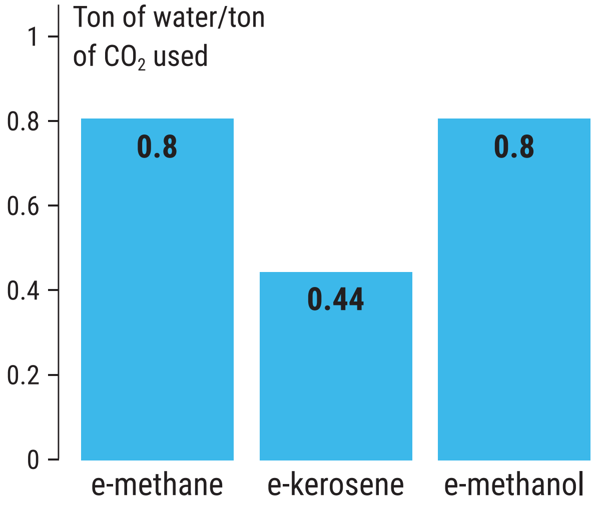
E-fuels synthesis is exothermic, producing heat (and water).

**The water available from the e-fuels synthesis together with water recovery from DAC suffices to run the water electrolysis for $H_2$ production.**
Despite water production during e-fuels production, the overall water balance is negative due to water required to produce $H_2$:

**Methane**: $2\ H_2O + CO_2 \rightarrow CH_4 + 2O_2$
**Methanol:** $2\ H_2O + CO_2 \rightarrow CH_3OH + \frac{3}{2}O_2$
**Kerosene:** $13\ H_2O + 12\ CO_2 \rightarrow C_{12}H_{26} + \frac{37}{2}O_2$



Amount of water needed per ton of $CO_2$ used to produce different e-fuels (in ton water).

## What are the advantages of converting low-carbon electricity to e-fuels in a fully circular manner?

First of all, low-temperature DAC solutions can today capture, depending on the climatic conditions, between 0.8 and 2 tons of water [1-2-3] per ton of $CO_2$.

In addition, comparing this to the water requirements (see figure above) shows that there is enough water that can be harvested from the air for the e-fuels production. If required, more water could be harvested from the e-fuel synthesis.

Particularly in arid areas, this is very relevant since access to clean water will be an appealing co-benefit from the pathway to a Power-to-X economy.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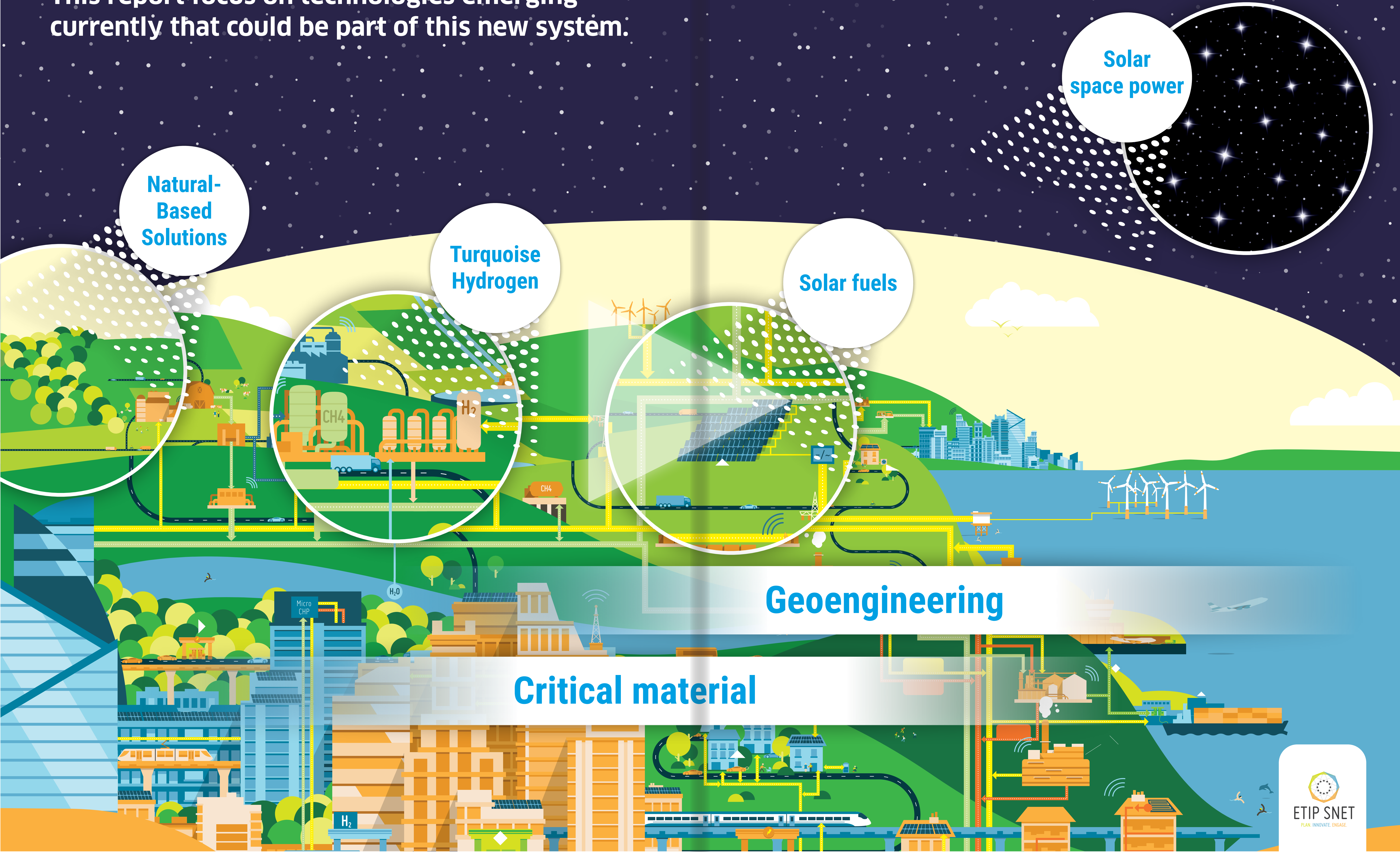
## What are the challenges to meet circularity?

Much research as well as business challenges remain to be investigated:
- possibility of a slight rise in temperature of the water electrolysis,
- co-capture of water and $CO_2$ from DAC,
- water recovery and required purity.

Identifying the best process to produce e-fuels: biological versus catalytic methanation of $CO_2$ and $H_2$ into e-fuels, co-electrolysis of water of $CO_2$ into e-fuels...

In term of economics, we need to compare the cost of the $CO_2$ from DAC versus seawater versus biogenic. The cost of renewable electricity and access to abundant cheap renewable electricity are key as well. Finally, from a market point of view which e-fuel is best suited to which application.

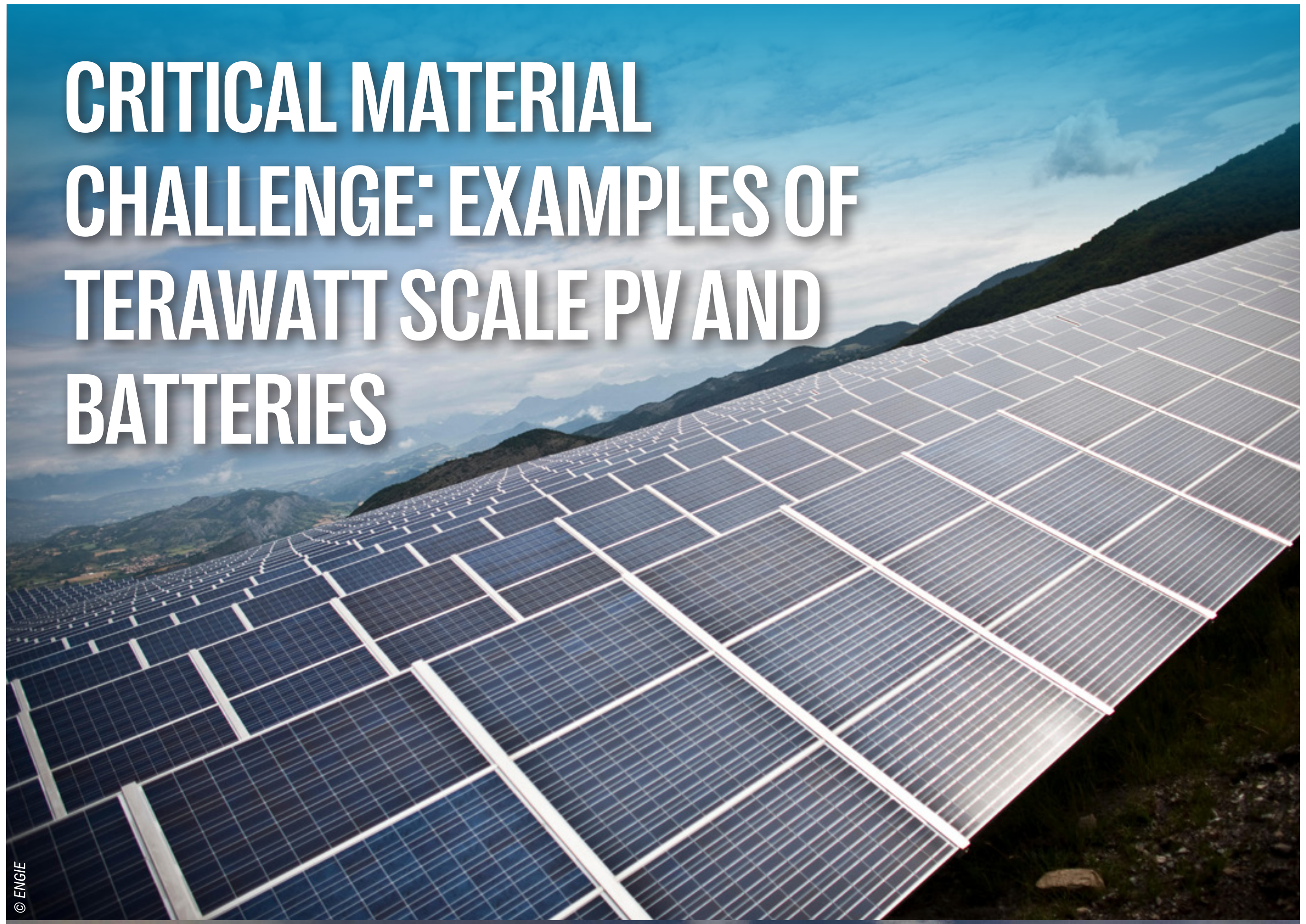
This report focus on technologies emerging currently that could be part of this new system.



# 1

# EMERGING TRENDS

## CRITICAL MATERIAL CHALLENGE: EXAMPLES OF TERAWATT SCALE PV AND BATTERIES



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## GEOENGINEERING FOR CLIMATE CHANGE GAINING TRACTION

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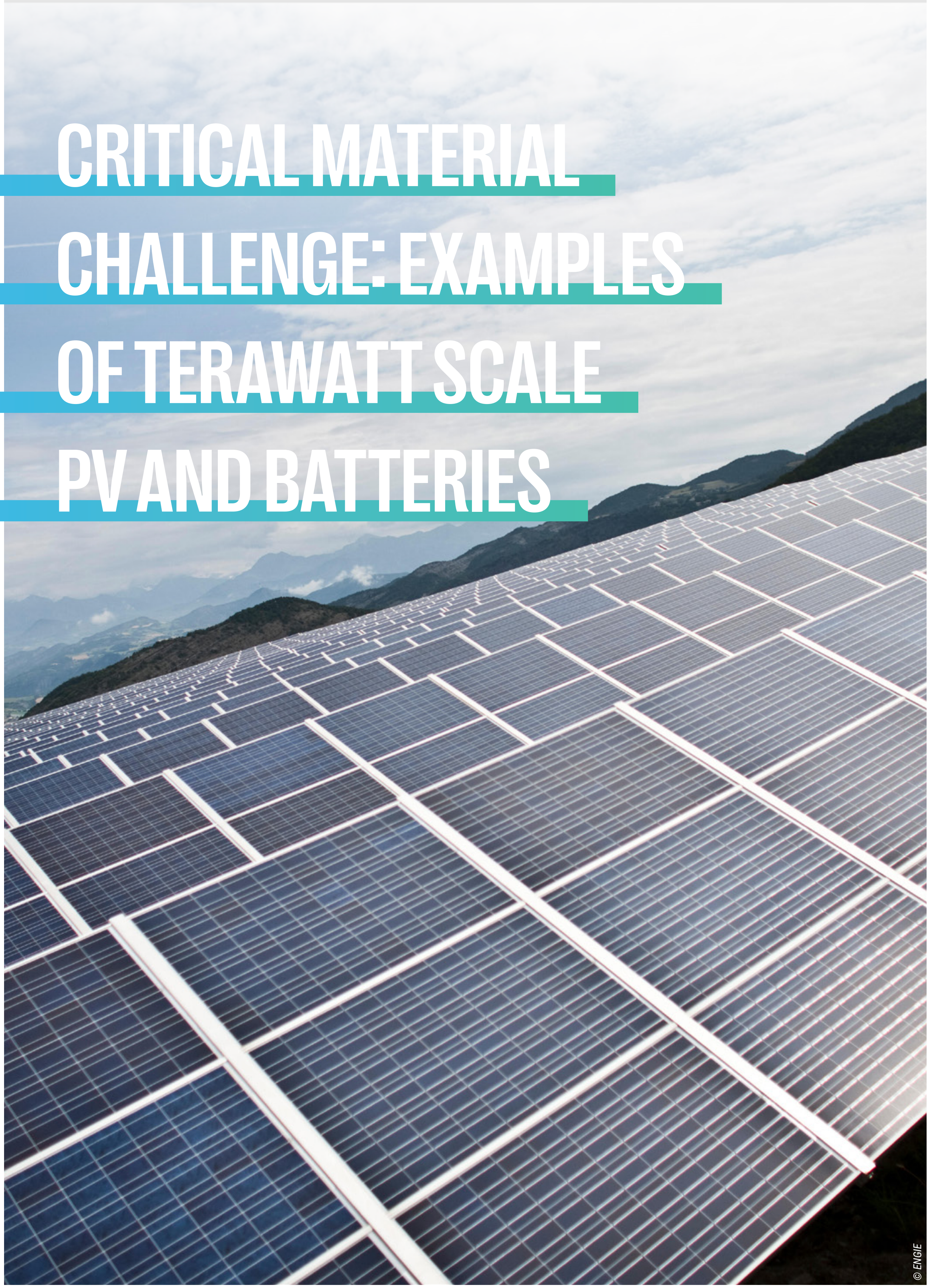
# CRITICAL MATERIAL CHALLENGE: EXAMPLES OF TERAWATT SCALE PV AND BATTERIES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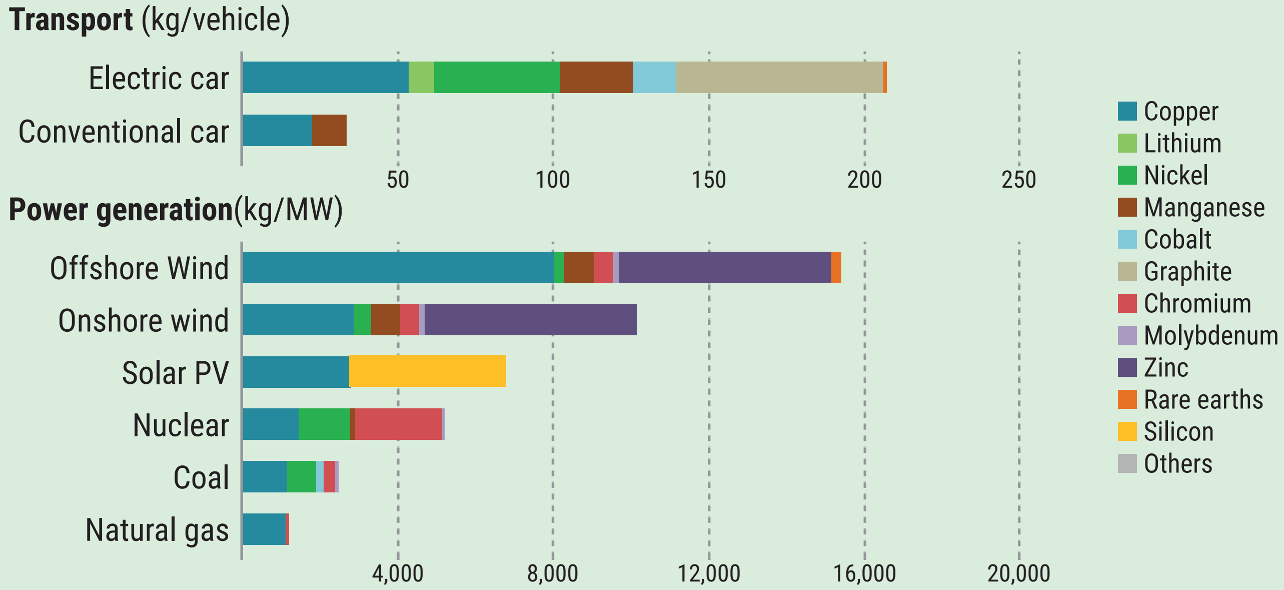
## The energy and mobility transition is metal intensive and faces sustainability challenges. Exponential increase of renewables raises critical material issues.

| 2022 Solar power reaches 1 TW milestone. [1] |

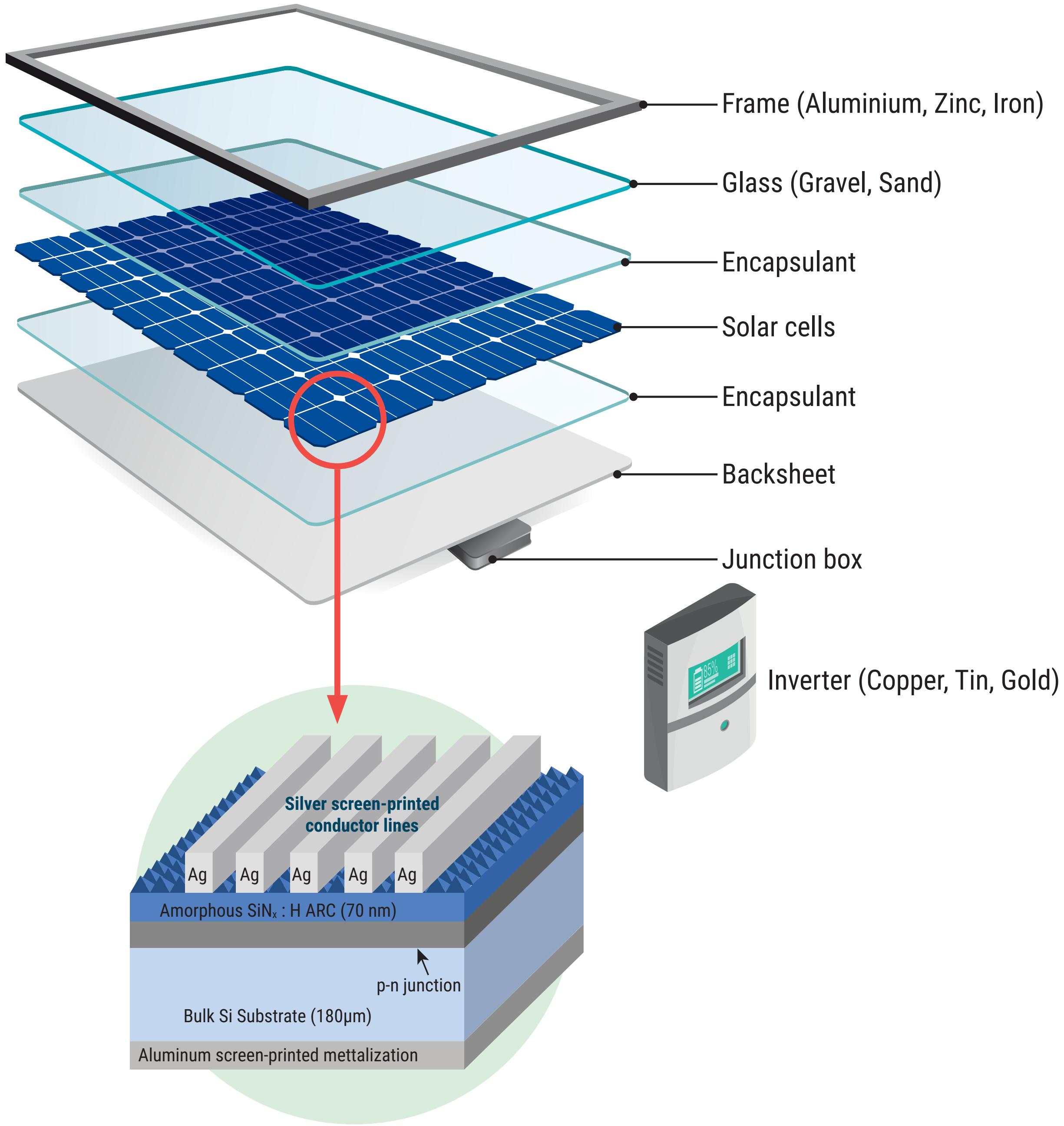


*Notes: kg = kilogramme; MW = megawatt. Steel and aluminium not included.*

| Minerals used in selected clean energy technologies. [2] |

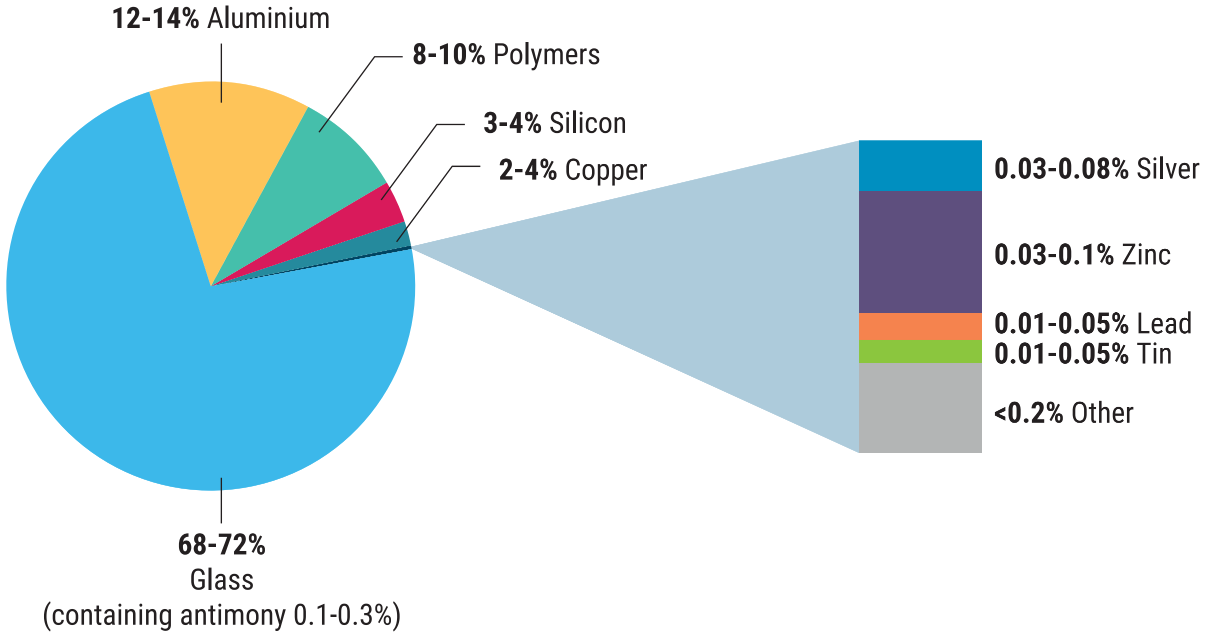
# What is inside photovoltaïc panels?

**PV panels mainly rely on the Crystalline Silicon (c-Si) technology. This technology represents around 95% of the market share and is expected to stay the dominant technology in the near future in addition to more emerging ones such as: Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Perovskite.** [3]



| The structure of c-Si solar module: most minerals are used to produce PV cells. [4-5] |

C-Si cells dominate the PV market and glass is the main processed material in terms of weight, while polysilicon and silver are most important in terms of value.



| Typical weighted composition of a c-Si PV module – PERC technology. [6] |

Environmental footprints were reduced by 60-75% since 2011*. [7]

| Impact category | Value | Unit | Change since 2011 |
|---|---|---|---|
| **GHC emissions** | 42.5 | $gCO_2$-eq | -60% |
| **Fossil fuels** | 0.54 | MJ | -55% |
| **Particulate matter** | 3.63 | $10^{-9}$ disease incidences | -69% |
| **Acidification** | 0.36 | mmol H+-eq | -63% |
| **Water scarcity** | 7.49 | L water-eq | -75% |

| The Life-cycle environmental impacts of 1 kWh AC electricity. [7] |

**TECHNOLOGY DEMAND TREND**

**167 GW**
EU 2020

**x 6**

**1,043 GW**
EU 2050

**Main raw materials involved*:**

- Aluminium
- Borate
- Copper
- Germanium
- Gold
- Iron
- Lead
- Nickel
- Silicon
- Silver
- Tin
- Zinc

** In red: critical raw materials according to EUC 2020 CRM supply rick assessment.*

*Source [8-9]*

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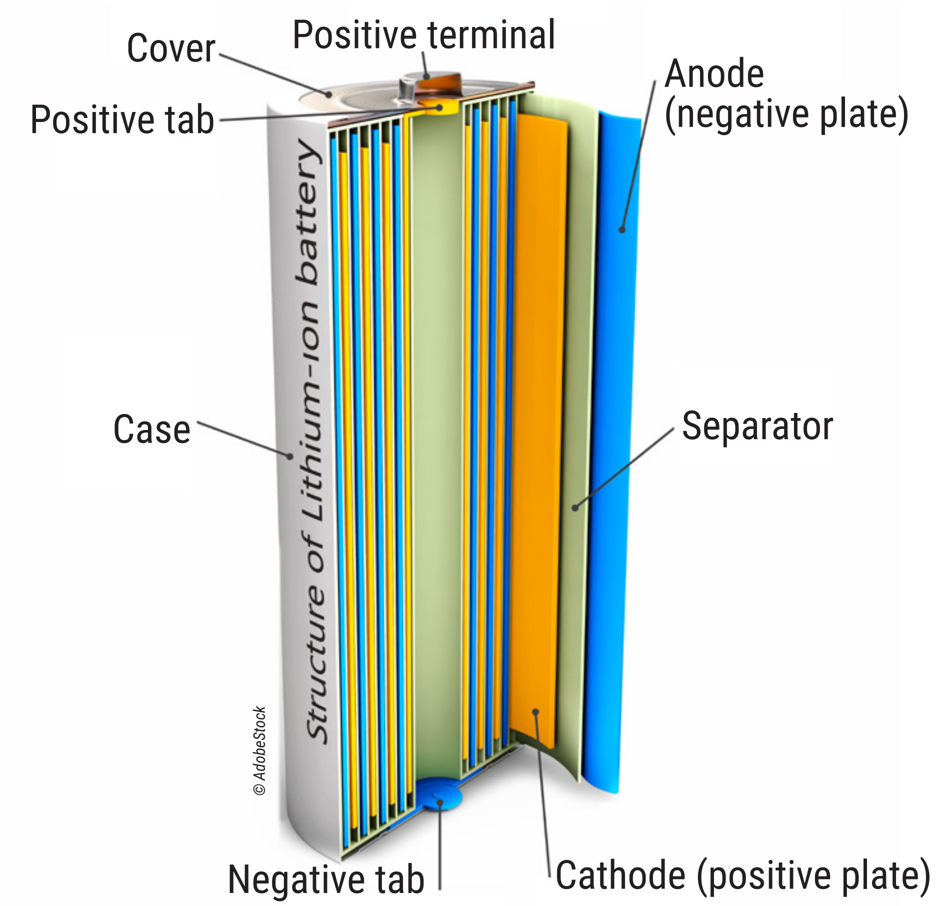
**The assessement was based on data from 2017-2019 with a module efficiency of 19.5, an average European annual yield of 975 kWh/kWp, assuming 0.7%/yr linear degradation rate, 30 year lifetime for the panel and 15 year for the inverter.* [6]

# What is inside a Li-ion battery?

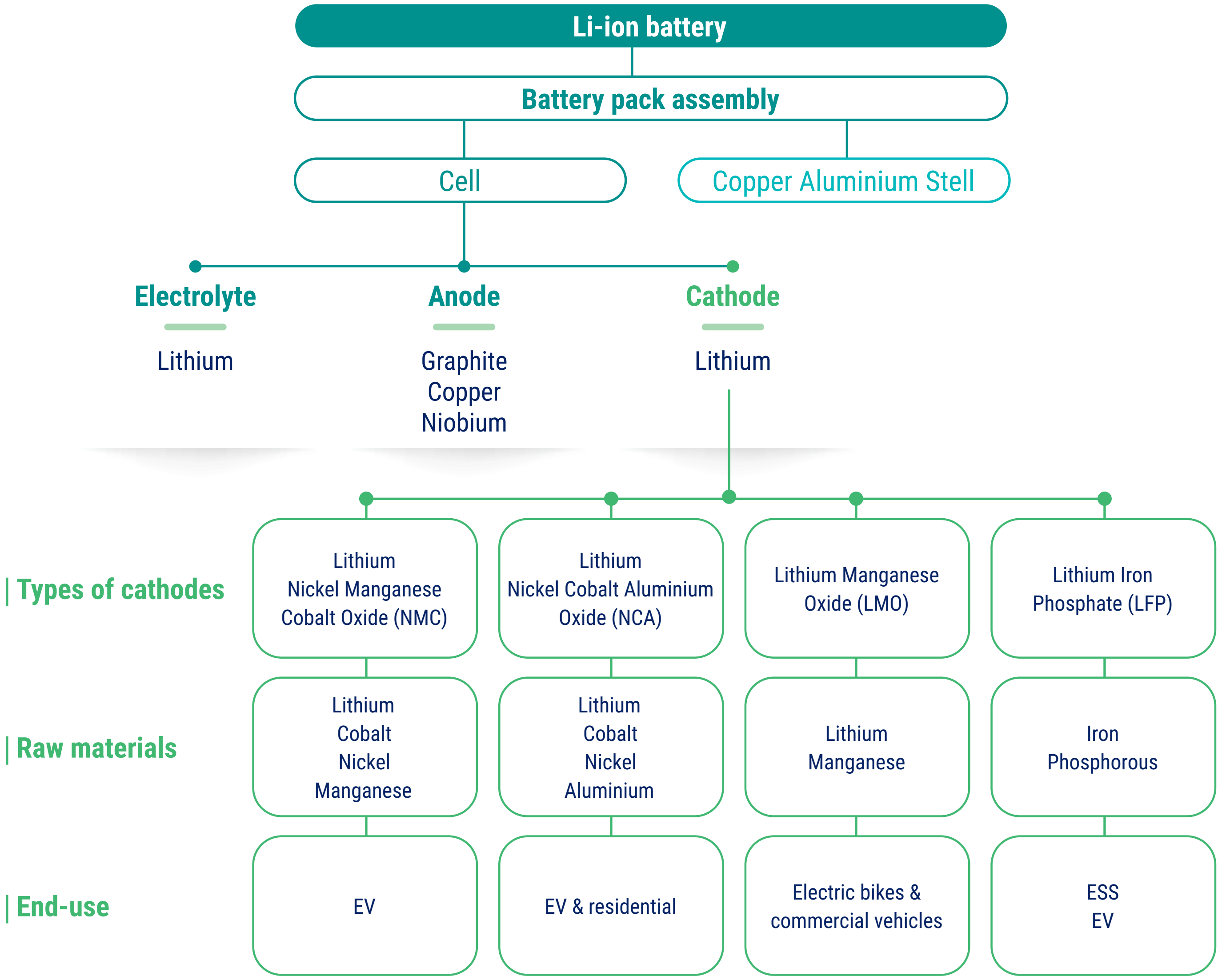
**The Li-ion battery is the most versatile battery, continuously evolving, aiming at ever-higher performance while mitigating safety issues and critical material issues.**



| **Lithium Cell Structure.** |

A Li-ion battery is composed of an anode a cathode and a separator in an electrolyte. Different kinds of cathode exist, which allow a different energy density, lifetime, thermal stability and specific power performance for the battery. Hence they are used in different applications.

Cathodes contain most critical materials Lithium, Cobalt and Nickel in different proportions.



| | | | | |
|---|---|---|---|---|
| **Types of cathodes** | Lithium Nickel Manganese Cobalt Oxide (NMC) | Lithium Nickel Cobalt Aluminium Oxide (NCA) | Lithium Manganese Oxide (LMO) | Lithium Iron Phosphate (LFP) |
| **Raw materials** | Lithium<br>Cobalt<br>Nickel<br>Manganese | Lithium<br>Cobalt<br>Nickel<br>Aluminium | Lithium<br>Manganese | Iron<br>Phosphorous |
| **End-use** | EV | EV & residential | Electric bikes & commercial vehicles | ESS<br>EV |

| **Diagram showing different raw materials involled in Li-ion battery.** *Inspired by [8]* |

**TECHNOLOGY DEMAND TREND**

**19 GWh** EU 2020 → **x 37** → **700 GWh** EU 2050

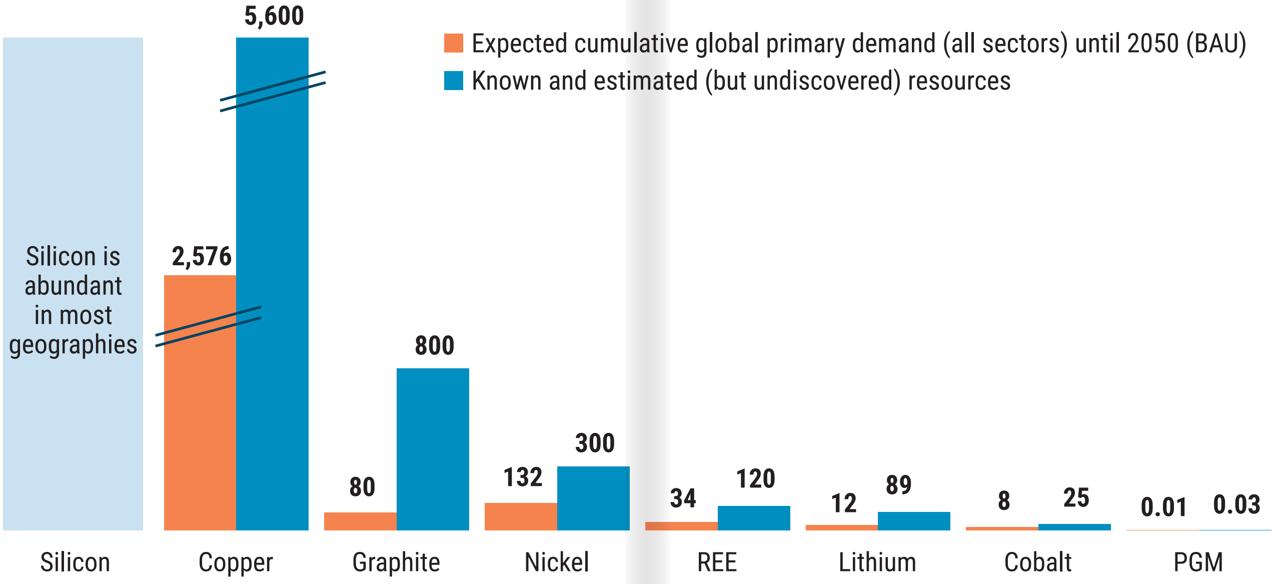
**Main raw materials involved*:**

- Bauxite
- Cobalt
- Copper
- Fluospar
- Iron ore
- Lithium
- Manganese
- Natural graphite
- Nickel
- Niobium
- Phosphorus
- Silicon metal
- Titanium

** In red: critical raw materials according to EUC 2020 CRM supply rick assessment.*

*Source [8-9]*

# Renewable energy solutions rely on metals that are plentiful in earth's crust but bottlenecks might arise from geographical concentration, lack of mining capacity, company concentration as well as geopolitical, environmental and social risks.



| **World resources known and undiscovered remaining resources in earth's crust, in metric megatons.** [10] |

## Challenges for photovoltaïc panels

### Raw materials

- Borates: 42% of global supply comes from Turkey, 0 % from EU.
- Germanium: 80% of the production from China.
- Indium: China is the top producer.

### Processed materials

- China covers about 70% of polysilicon production capacity.
- Europe currently has 26 GW capacity of polysilicon production and it is then exported to China for further processing.
- Shortages and price volatility expected for polysilicon.

### Components

- China's role is quasi-monopolistic at this stage: wafer production being the most concentrated, 97% of global capacity is in China.
- Even concentrated within China: 42% of the capacity in one single Chinese province and 14% in one single facility in 2021.
- According to building capacity planned, it is likely to remain as such.

*Source [1-2-8-9]*

## Challenges for Li-ion battery

### Raw materials

- **High geographical concentration** of extraction:
  - Niobium: 92% from Brazil,
  - Cobalt: 70% from **Democratic Republic of Congo (DRC)**,
  - Graphite: 71% from China,
  - Lithium: 50% from Australia,
  - Phosphor: 72% of EU demand from Kazakhstan).
- **Resources are sufficient but limited extraction capacity** in the mid-term (especially for Lithium).
- Lithium, Cobalt and Graphite demand is expected to be **90**, **18 and 2 times current production,** respectively.

### Processed materials

- 50-70% of lithium and cobalt are refined in China with Finland, Canada and Norway being the other top suppliers for cobalt.
- The EU's refining operations are placed in Finland and Belgium supplying 70% of current domestic demand (7).

### Components

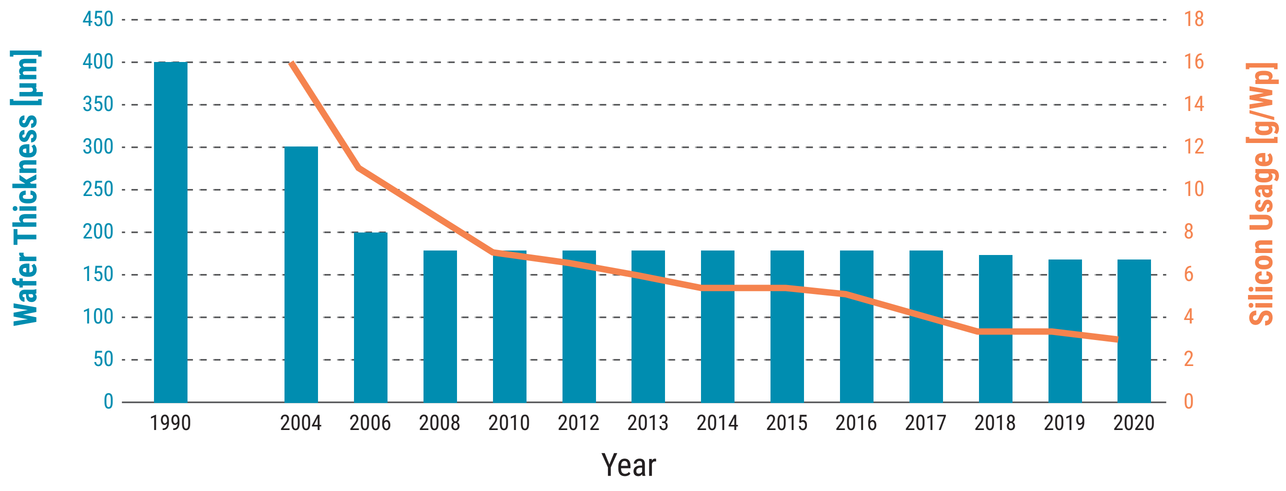
- **China** is home to 70% and 85% of cathodes and anodes production capacity respectively.
- **Korea and Japan** also play a large role.
- **Europe lacks capacity** to produce components.

*Source [1-2-8-9]*

# However, solutions exist to mitigate the material scarcity and hence reduce the risk of shortages.

## 1. Reduction of material and development of improved and more sustainable design.

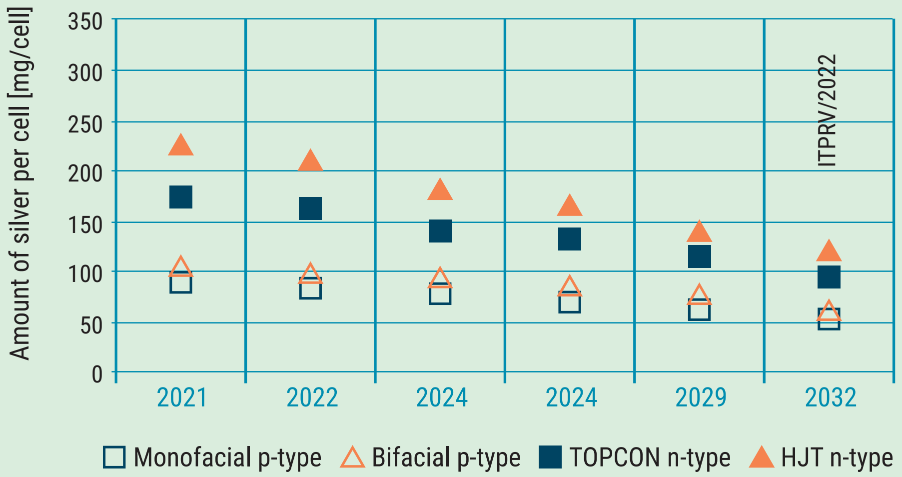
The cost and efficiency of solar panels have improved in recent years and are expected to continue to do so over the next decades. For example, wafer thickness reduction has decreased the raw materials quantity need of silicon and silver.



**Wafer thickness (µm) and silicon usage (g/Wp) have drastically decreased all along the years.** [3]

The silver amount per cell fell by 80% since 2008 thanks to a better metallization pastes and is expected to further decrease by 25% in 2030.

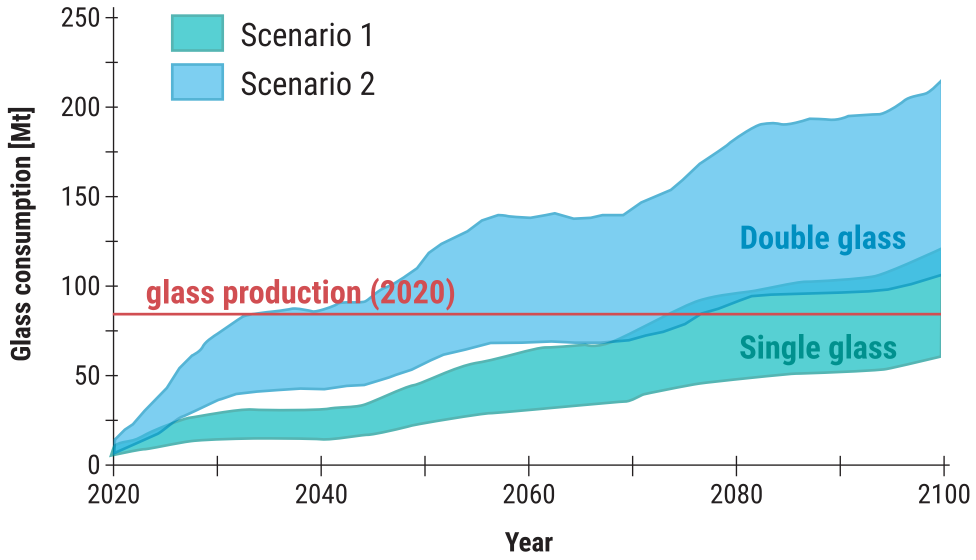
**Evolution of the silver amount per cell (mg/cell).** [11]



### Continued technological progress at current rates would be sufficient to stay within reasonable boundaries for reaching the 20-80 TWp photovoltaics by 2050.

On the one hand, glass demand might still exceed current float glass production. Depending on whether single glass or double glass modules are assumed, current glass demand for PVs is in the same order of magnitude as current global float-glass production or significantly exceeds current production.
From a resource perspective, this is probably not critical since sand reserves for glass manufacturing are abundant and widespread and glass can be also be recycled, but it certainly requires a serious expansion of production facilities within the next ten years.

On the other hand, silver consumption could be kept at current levels.



**Glass consumption for PV module fabrication.** [12]

(calculated with the REMIND model, scenario 1 & 2 describes favorable or not PV deployment with limiting climate change to 1.5 °C; Assumptions: system lifetime of 25 years; single glass = glass/backsheet module; double glass= glass/glass module).

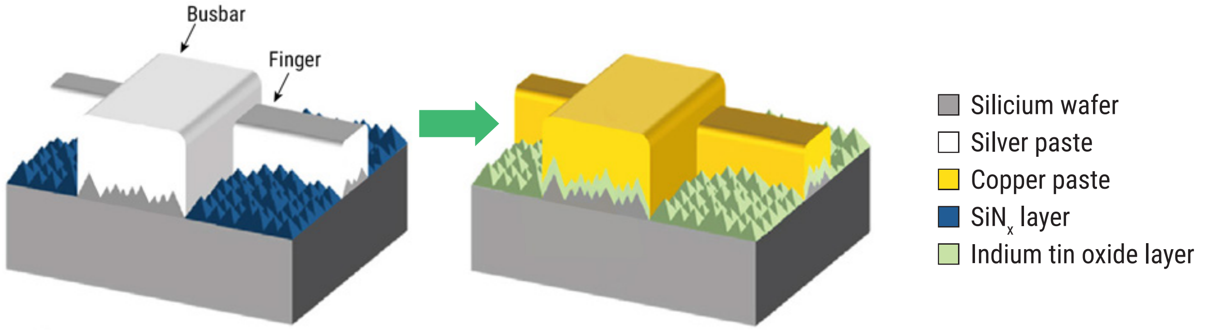
**Example of eco-design. New module technology (NICE) without encapsulant, soldering and lamination allowing an increased robustness and a 100% recyclable panel.** [13]

APOLLON SOLAR

# 2. Materials substitution as an alternative to reduce the resource supply pressure.

## Photovoltaïc panels

Substitution of silver by copper would lead to direct financial savings and reduce the supplies scarcity, assuming it does not reduce efficiency.[15]



**Substitution of silver by copper during the cell metallization step.**[15]

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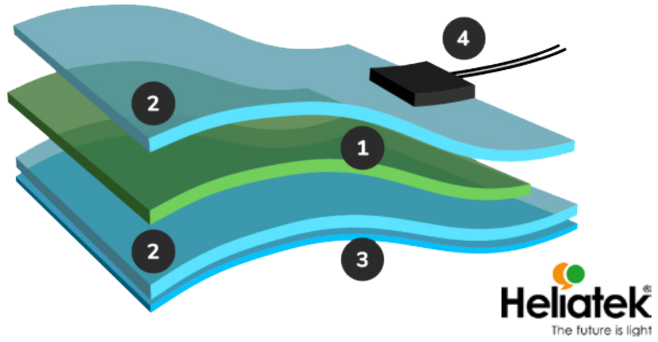
**Heliatek's lightweight PV modules on ENGIE Laborelec's building, Linkebeek, Belgium.**

Organic photovoltaics (OPV) uses materials from the field of organic chemistry to convert sunlight into electrical energy.

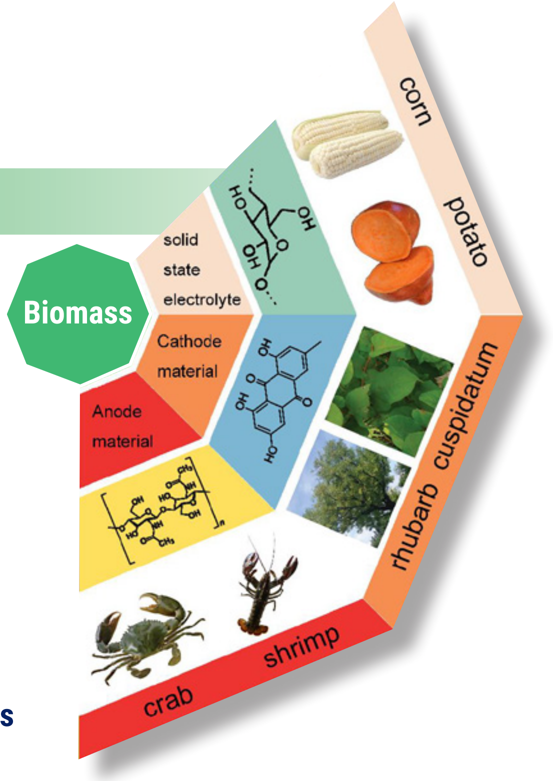


1. Carrier film with a vapor deposited organic stack
2. Encapsulation to protect the organic stack against environmental influences
3. Integrated backside adhesive
4. Junction box with cables

*Source [16]*

## Li-ion battery

**Biomass based sourcing:** Biomass-derived materials that range from inorganic multi-dimensional carbons to renewable organic biomolecules or biopolymers can contribute towards "green battery" systems, serving as sustainable battery components[35]. However, large demand for them could raise environmental and ethical issues if they compete with the feed and food industry.



**Biomass-based materials for green lithium secondary batteries.**[17]

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**Use of Lithium Ferrous Phosphate (LiFePO4 or LFP) at the cathode:** Li-ion batteries and LFP batteries both fall under the class of Lithium batteries but LFP have a long life span, requiring fewer battery changes.

**Sodium (Na)-ion battery:** A sodium-ion battery is a type of rechargeable battery that uses sodium-ions as its charge carriers. This type of battery is in a developmental phase, but may prove to be a cheaper way to store energy than commonly used lithium-ion batteries. Sodium-ion batteries have been gaining attention thanks to the natural abundance and low toxicity of sodium resources. There are still energy density and safety issues.

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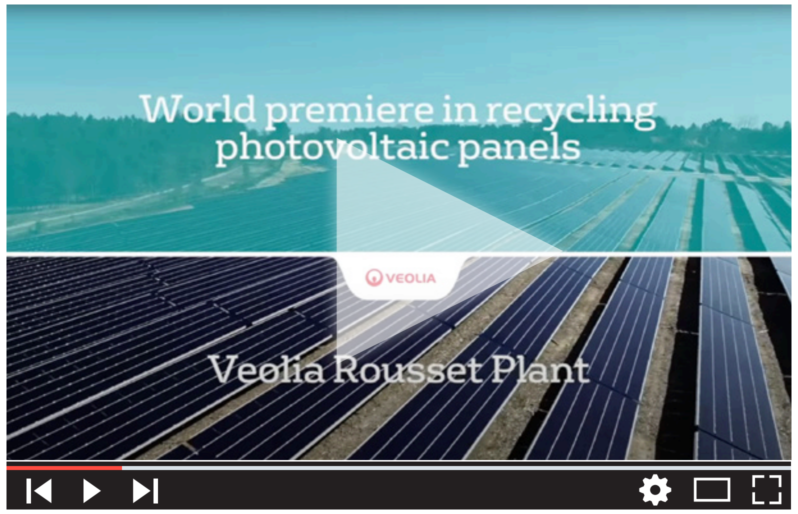
# 3. Circular use of critical raw materials to reduce primary resource use and waste production.

## Photovoltaïc panels

Presently, most of the recycling processes achieve high recovery of glass and aluminum (around 80%), moderate recovery of copper (around 40%), but do not recover silver and high-purity silicon as it requires a costly and difficult thermal treatment to remove the polymer encapsulant.
However, the following pilot project is on track:



**Video explaining the new recycling plant of Veolia [17]. They developed a plant allowing to achieve a 95% recycling efficiency with both recovery of Ag and Si. The PV recycling industry is expected to drastically grow in the future, ensuring a large economy of volume. [18]**

## Li-ion battery

**Recycling rates** of Li-ion batteries will improve thanks to an emerging direct recycling process (does not break down but regenerates the cathode material). Lithium recycling rate as an input is close to 0 today.

**Spent EV batteries** still have around 80% of their usable capacity, they can be repurposed for less demanding second life applications, typically in stationary storage.

**US-based Redwood Materials claims to be able** to recycle 95% of the metals used in lithium ion batteries, at lower cost than virgin materials. Volkswagen USA, Toyota, Ford and Volvo are its main sources of supply [10].

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Recycling will be imposed by regulations whatever the element present.

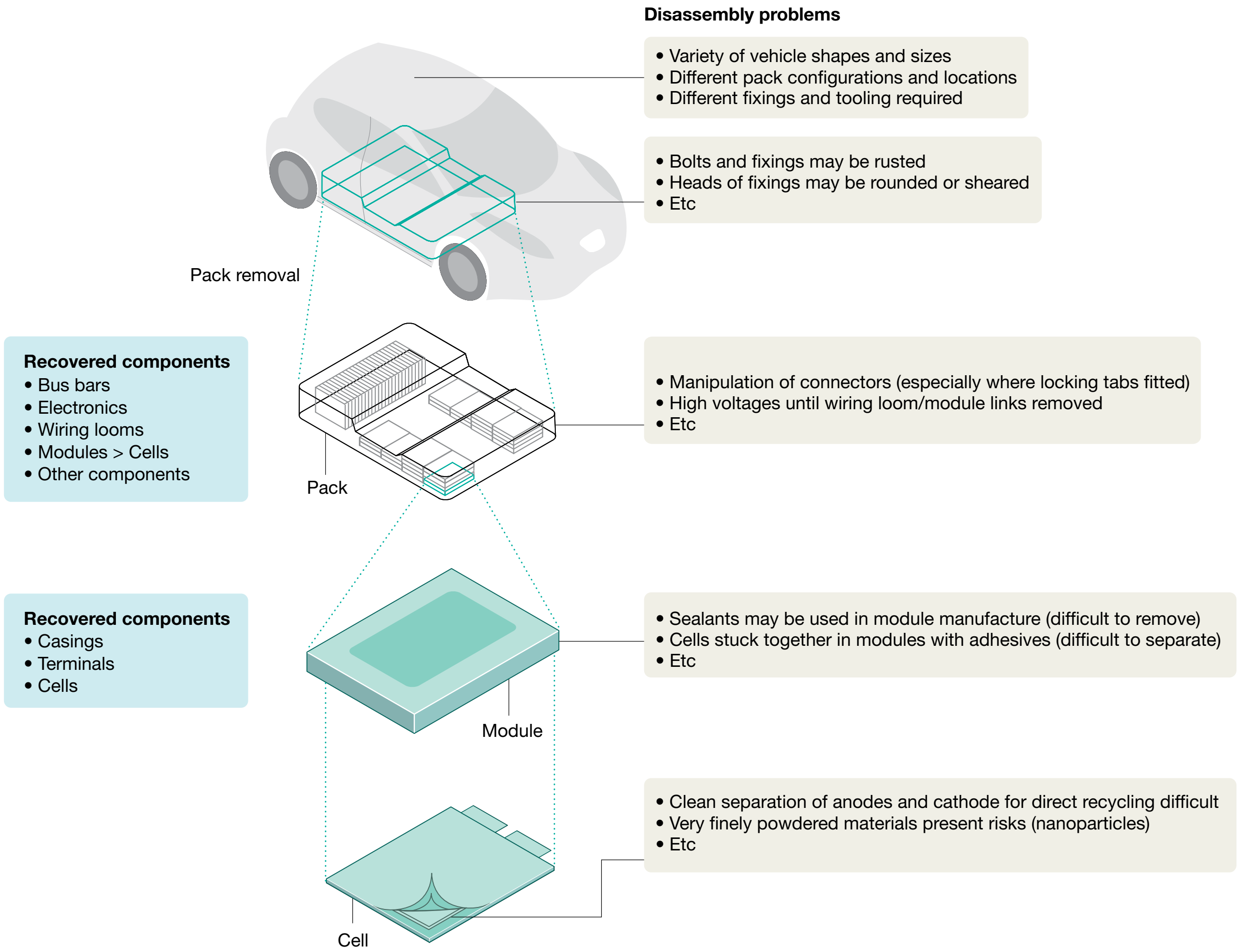
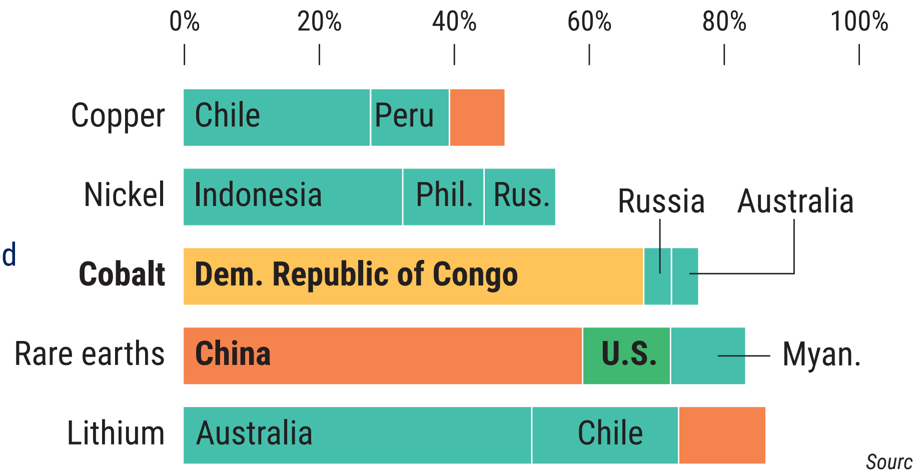


**Diagram showing challenges of disassembly at different levels of scale.** *Inspired by [19]*

# 4. Production of key mineral resources: toward more independence through a worldwide reflection of relocalization.

**Where clean energy metals are produced**

Production of key mineral resources is highly concentrated today. Charts show top three producers.



*Source [20]*

# GEOENGINEERING FOR CLIMATE CHANGE GAINING TRACTION

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## Climate geoengineering solutions to reach the Paris agreement temperature goals is not a taboo anymore.

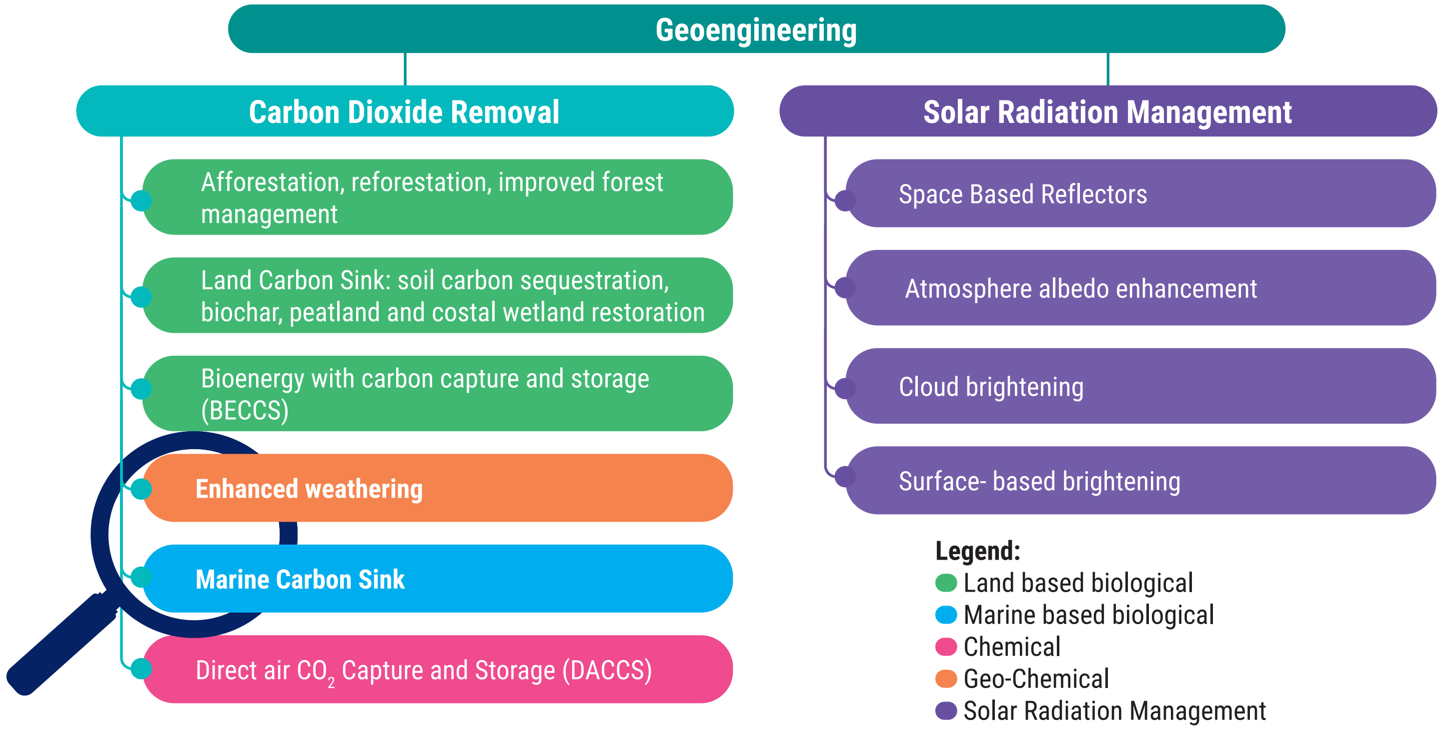
Recognition of the climate change challenge has given increased momentum to often controversial discussions about two additional possible approaches to limiting climate change:

- greenhouse gas removal from the ambient atmosphere, particularly $CO_2$ as the most important climate forcer called Carbon Dioxide Removal (CDR)
- intentionally reducing or reflecting solar radiation back into space to minimize global warming.

These proposed approaches have been referred to collectively under various names, including geoengineering, climate engineering, and climate interventions. [1-2-3-4]

Although none of the proposed techniques exists yet at scales sufficient to affect the global climate, their place in climate change scenarios and policy discussions is increasing (i.e. extensive application of techniques for removing $CO_2$ from the atmosphere in a scenario of the Intergovernmental Panel for Climate Change (IPCC)).

**So geoengineering is a generic word referring to heterogeneous technologies not perceived by the public in the same way. Some are very controversial, others much less so. Risks and benefits of this approach are not yet fully understood by the scientific community and are getting more and more attention.**



**Geoengineering**

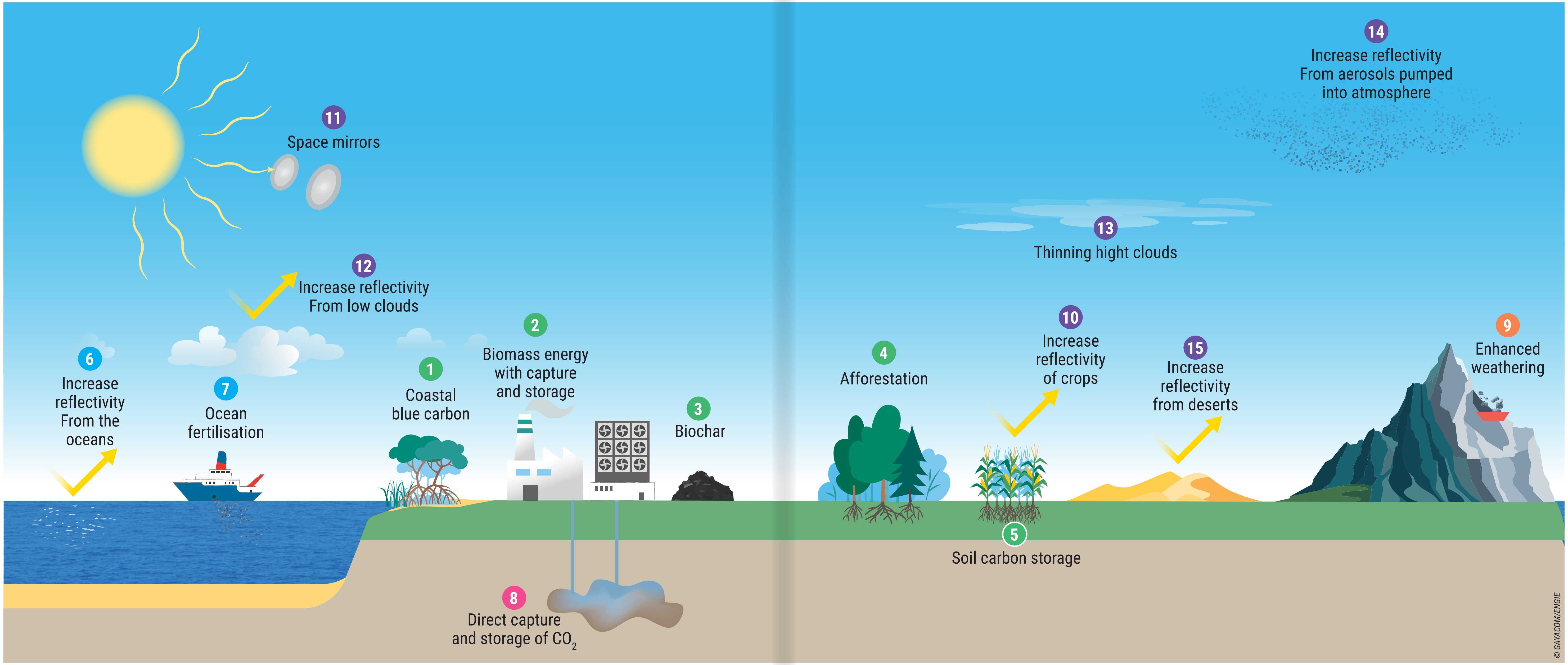
**Carbon Dioxide Removal**
- Afforestation, reforestation, improved forest management
- Land Carbon Sink: soil carbon sequestration, biochar, peatland and costal wetland restoration
- Bioenergy with carbon capture and storage (BECCS)
- **Enhanced weathering**
- **Marine Carbon Sink**
- Direct air $CO_2$ Capture and Storage (DACCS)

**Solar Radiation Management**
- Space Based Reflectors
- Atmosphere albedo enhancement
- Cloud brightening
- Surface- based brightening

**Legend:**
● Land based biological
● Marine based biological
● Chemical
● Geo-Chemical
● Solar Radiation Management

| **Geoengineering techniques overview based on litterature review.** [2] |

# Geoengineering proposals.



*Inspired by [5-6]*

① **Coastal blue carbon** (Reforestation/ Mangrove restoration)

② **Biomass energy with capture and storage** (Using biomass for energy and capturing the $CO_2$)

③ **Biochar** (Carbon-rich charcoal from burnt crops added to soil)

④ **Afforestation** (Planting vast forests)

⑤ **Soil carbon storage**

⑥ **Increase reflectivity from the oceans** (Microbubbles increase reflexivity)

⑦ **Ocean fertilisation** (Incressing population of carbon-absorbing plankton)

⑧ **Direct capture and storage of $CO_2$**

⑨ **Enhanced weathering**

⑩ **Increase reflectivity of crops**

⑪ **Space mirrors**

⑫ **Increase reflectivity from low clouds** (e.g by spraying salt into him)

⑬ **Thinning hight clouds** (Clouds act as a blanket, retaining heat)

⑭ **Increase reflectivity from deserts** (Using highly reflective materials)

⑮ **Increase reflectivity from aerosols pumped into atmosphere**

**Legend:**
● Land based biological
● Marine based biological
● Chemical
● Geo-Chemical
● Solar Radiation Management

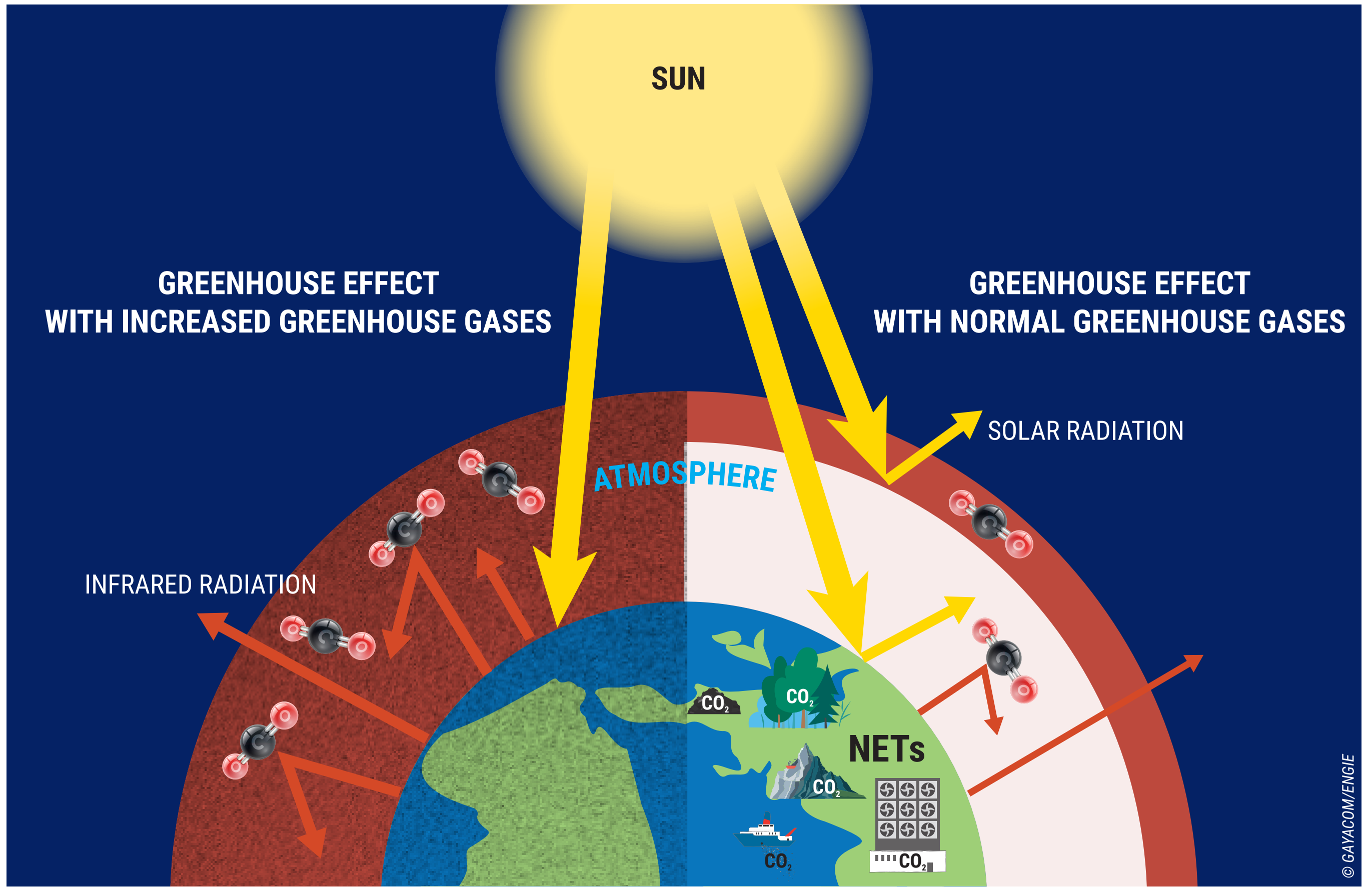
# How these approaches work

## Carbon Dioxide Removal (CDR)

CDR refers to the process of removing $CO_2$ from the atmosphere which produces global warming through greenhouse effects. Since this is the opposite of emissions, practices or technologies that remove $CO_2$ are often described as achieving 'negative emissions'. The process is sometimes referred to more broadly as greenhouse gas removal if it involves removing gases other than $CO_2$. There are two main types of CDR:

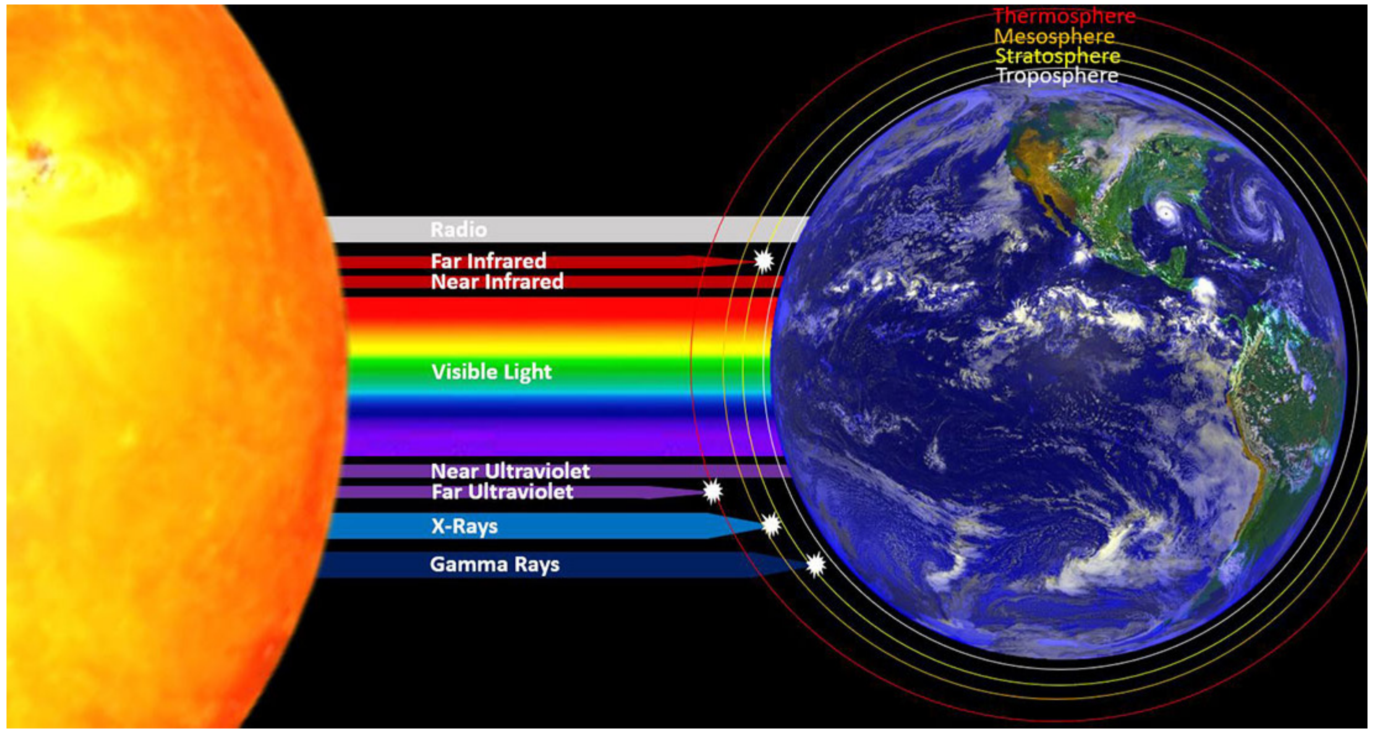
- enhancing existing natural processes that remove carbon from the atmosphere (e.g., by increasing its uptake by trees, soil, or other 'carbon sinks'),
- using chemical processes to, for example, capture $CO_2$ directly from the ambient air and store it elsewhere (e.g., underground). [7]

Negative Emissions Technologies (NETs) are technologies involved in CDR processes.



*Inspired by [8]*

Removing $CO_2$ from the atmospheric stock through its transfer in the biologic and geologic stock decreases the concentration and consequently the greenhouse effect.



**Absorption of solar radiation in the atmosphere [9] based on NASA.**

## Solar Radiation Management (SRM)

Solar radiation management (SRM) or solar geoengenering (SG) goal is to decrease the amount of absorbed solar radiation through an increase in albedo* [10]. It aims to reflect away a very small fraction of sunlight back to space to partially offset the energy imbalence caused by accumulating greenhouse gases [11].

---

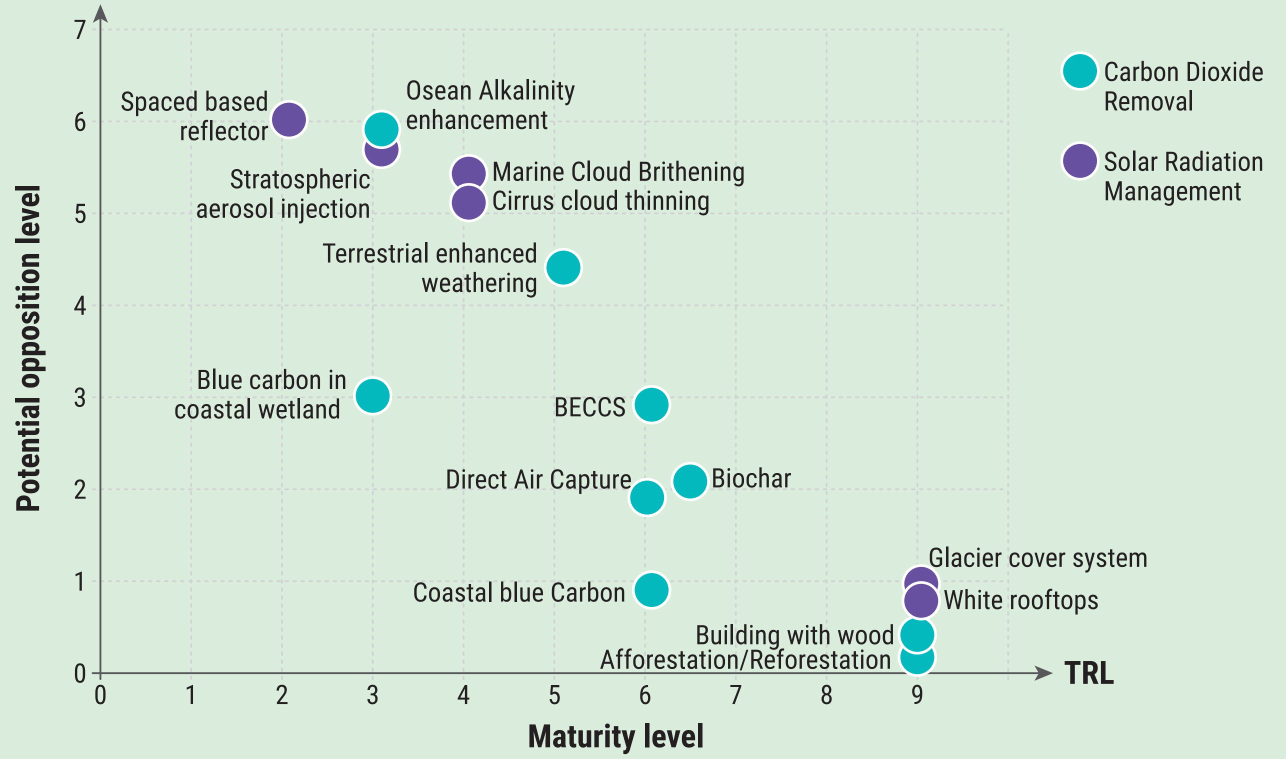
* *Albedo is the amount of sunlight (solar radiation) reflected by a surface*

**BENEFITS PUT FORWARD BY PROPONENTS**

| CDR | SRM |
|---|---|
| ● CDR is a key element in scenarios that likely limit warming to 2°C or 1.5°C by 2100 (high confidence). [12]<br>● It offers the potential to slow the growth and reverse the increase of $CO_2$ concentrations in the atmosphere. [10]<br>● Bridging technologies to wait for large deployment of low carbon technologies (e.g. DAC, CCUS). [13]<br>● Some nature-based technologies are better accepted (afforestation and reforestation) and are at a higher stage of maturity. | ● Quickly reduces surface air temperatures, which could reduce or reverse negative impacts of global warming. [14]<br>● Technology to limit the sea level rise. [15]<br>● Offers rapid climate change abatement in a world where neither mitigation or adaptation can adequately address climate change. [16] |

Geoengineering should not in any way slow down the carbon neutral energy transition and the deployment of renewable electricity and gases. It should never be used as an excuse to continue using fossil fuels! It is more like an emergency brake we may need to deploy to ensure we reach the 1.5 °C or 2 °C...

## For supporters of geoengineering, global change in humans' behavior in the short term is a riskier bet than geoengineering development facing the climate emergency.



**The potential opposition level of geoengineering solutions according to their maturity level**

*(ENGIE inspired by [17])*

Carbon geological storage solutions are controversial compared to processes like afforestation, more mature options with a higher level of acceptability.

Low maturity technologies such as the injection of aeorosol into the atmosphere, are already controversial despite the fact that they are not well known. This could limit investments to avoid social risks.

## At this stage 3 main controversial aspects of geoengineering can be identified.

### Social acceptability

Many environmental NGOs advocate for **a transformation of society rather than the development of compensatory technologies**. For example, WWF summarized its position as follows: "Thinking that we will be able to continue on a "business as usual" scenario without changing our behaviors and way of life just relying on geoengineering is a lie. We need to reduce our anthropogenic input to climate change, and not try to fix it using dispendious technologies and spending funding that are crucially needed for both mitigation and adaptation measures [18]. **Some technologies will not have the support of key stakeholders.** This is particularly the case for solar geoengineering and geological storage. **Afforestation avoids this type of criticism**. On the other hand, geoengineering advocates argue that potential short-term human behavior change is a riskier bet than geoengineering, with regard to the climate emergency.

### Risk and impact

There are also many controversies among scientists about the **effects of geoengineering and its risks**. Risks include **technological immaturity** and **impermanence, high financial costs, and environmental destruction for SRM** (air quality and atmospheric pollution [11], on ocean and vegetation [16]).

For CDR, uncertainties are more about the **permeability and stability of non-biobased storages** (risks of leakage, seismic activity, and water contamination) [19-20]. while SRM's uncertainties relate more to the climatic effects globally. To date, these uncertainties do not allow the IPCC to take these technologies fully into account in its scenarios (except for afforestation) [4]. Scientists are not aligned on the benefits of several geoengineering technologies. Therefore, risk of controversy is emphasized by technical debate. It should be noted here **that afforestation and reforestation do not fall under this type of debate** although many scientists warn that they are not a miracle solution and question the idea of a compensatory balance [21].

### Policy and governance issues

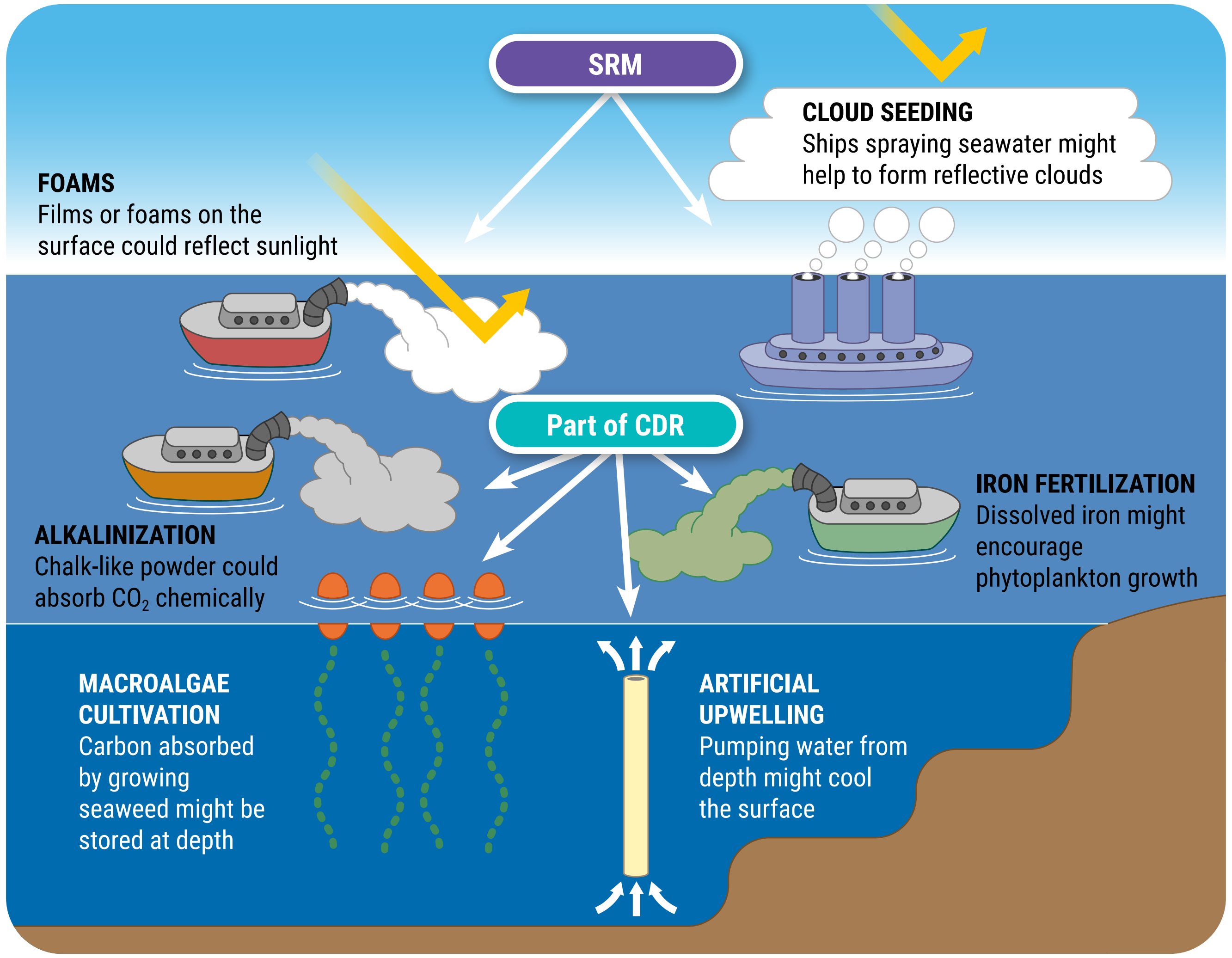
Finally, **geoengineering also raises issues of policy and governance**. Development of technologies with global impact should require the establishment of an international governance for cooperation and regulation (including experimentation,e.g. injection or spraying of molecules) [14]. For CDR, land use arbitration and mediation is an additional issue: geoengineering technologies vs agriculture, fisheries [10-3] or local economy [10-17]. The measurement and assignment of credit for $CO_2$ captured could be done unilaterally [10-16].

# Example of marine carbon sink.

## Dozens of marine engineering approches have been proposed to store $CO_2$ in or below the oceans, or to alter seas to cool the planet and few scientific tests have been performed on methodology up to now.

Focus on ocean fertilization: Marine **phytoplankton** has a crucial role in the global **carbon cycle**. Its photosynthesis consumes not only $CO_2$ but also macronutrients (e.g., nitrogen–N–and phosphorus–P) and micronutrients (e.g., iron–Fe). **Ocean fertilization** proposes the addition of nutrients to the ocean surface, which ultimately controls the amount of carbon that is sequestered. Since the levels of N and P are usually greater than Fe levels, the addition of Fe into the ocean can stimulate photosynthesis and enhance carbon sequestration. [22]

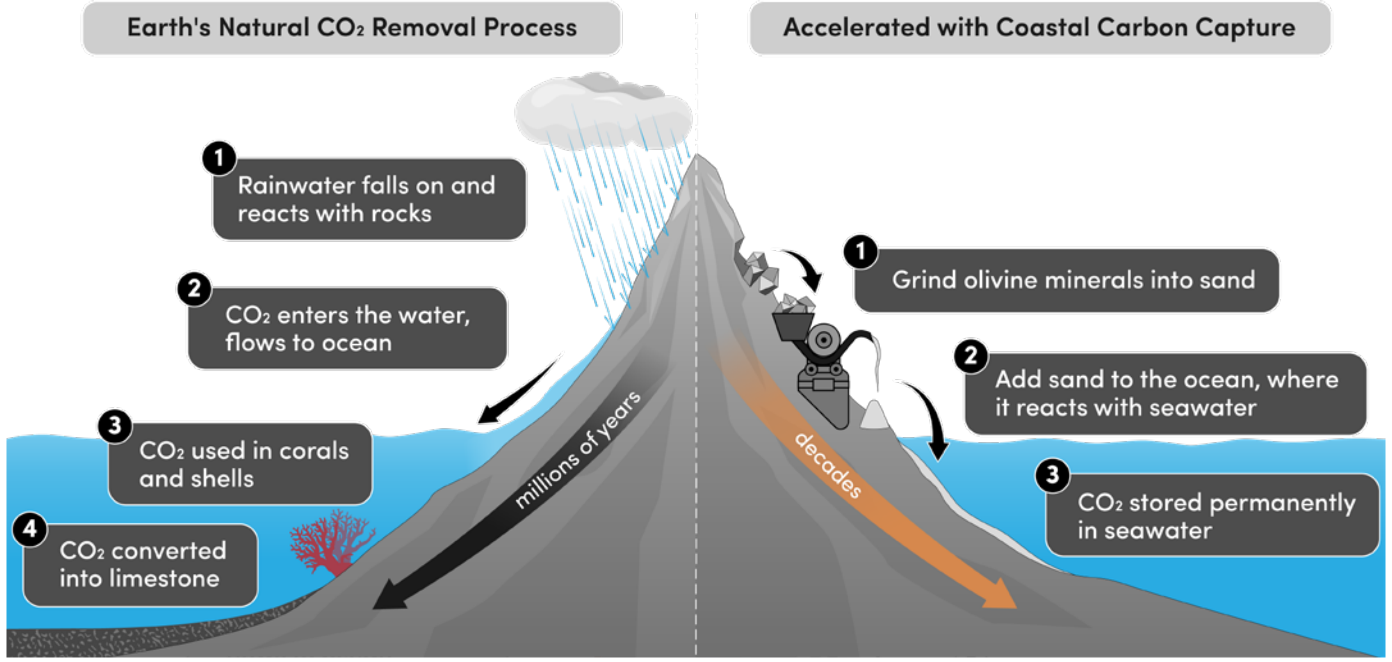
**Who gives the authorization to carry out this type of action?**
**The precautionary principle should be applied.**



| Panorama of Marine engineering solutions. [23] |

# Example of enhanced weathering.

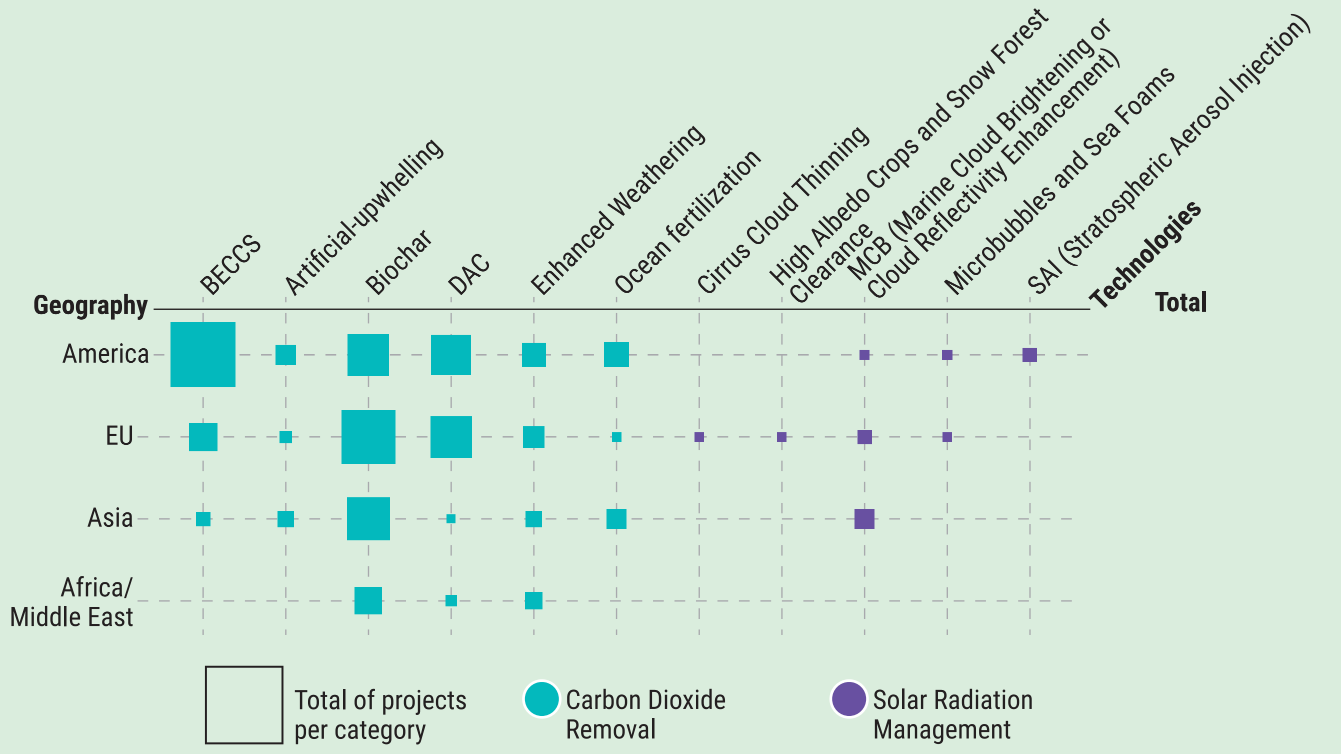
## This is a natural process whereby rocks are broken down by rainwater, extreme temperatures or human activity. It takes place over millions of years, constituting an important carbon sink.



| Description of enhanced mineral weathering. [24] |

| Rocks are ground into fine particles and spread across large spans of land or the ocean to speed up the natural process. [25] |

## More than 1,700 projects have been identified all over the world. The USA and Europe are the main developers of CDR to deal with their commitment to carbon neutrality by 2050, followed by Asia.



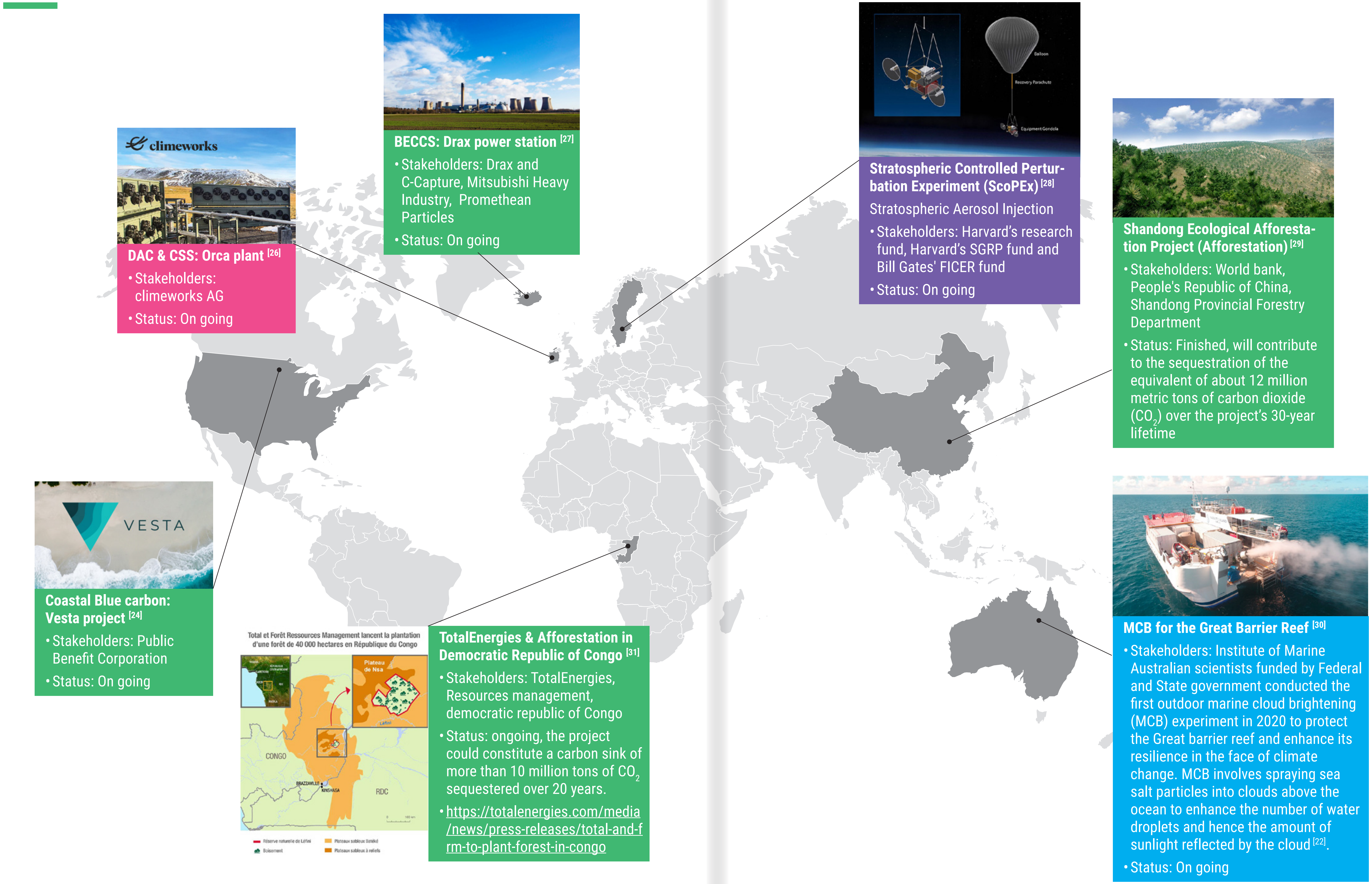
| **Distribution of geoengineering projects (completed, ongoing and planned) over the world.** |

Note: To date, there is no exhaustive scientific database listing all the projects that could be considered as geoengineering. So this graph is based on a database of whistleblower organizations: ETC Group and the Heinrich Böll Stiftung (https://map.geoengineeringmonitor.org). Even if reforestation and afforestation projects are not mentioned, as they benefit from a greater social acceptability, it gives a controversial technologies overview. The technological categorization is based on stated activities by the project owner.

| **DAC & CSS: Orca plant.** [26] |

| **BECCS: Drax power station.** [27] |

# Main representative geoengineering projects.



**DAC & CSS: Orca plant** [26]

- Stakeholders: climeworks AG
- Status: On going

**BECCS: Drax power station** [27]

- Stakeholders: Drax and C-Capture, Mitsubishi Heavy Industry, Promethean Particles
- Status: On going

**Coastal Blue carbon: Vesta project** [24]

- Stakeholders: Public Benefit Corporation
- Status: On going

**TotalEnergies & Afforestation in Democratic Republic of Congo** [31]

- Stakeholders: TotalEnergies, Resources management, democratic republic of Congo
- Status: ongoing, the project could constitute a carbon sink of more than 10 million tons of $CO_2$ sequestered over 20 years.
- https://totalenergies.com/media/news/press-releases/total-and-frm-to-plant-forest-in-congo

**Stratospheric Controlled Perturbation Experiment (ScoPEx)** [28]

Stratospheric Aerosol Injection

- Stakeholders: Harvard's research fund, Harvard's SGRP fund and Bill Gates' FICER fund
- Status: On going

**Shandong Ecological Afforestation Project (Afforestation)** [29]

- Stakeholders: World bank, People's Republic of China, Shandong Provincial Forestry Department
- Status: Finished, will contribute to the sequestration of the equivalent of about 12 million metric tons of carbon dioxide ($CO_2$) over the project's 30-year lifetime

**MCB for the Great Barrier Reef** [30]

- Stakeholders: Institute of Marine Australian scientists funded by Federal and State government conducted the first outdoor marine cloud brightening (MCB) experiment in 2020 to protect the Great barrier reef and enhance its resilience in the face of climate change. MCB involves spraying sea salt particles into clouds above the ocean to enhance the number of water droplets and hence the amount of sunlight reflected by the cloud [22].
- Status: On going

# 2

# EMERGING TECHNOLOGIES

NATURAL-BASED SOLUTIONS

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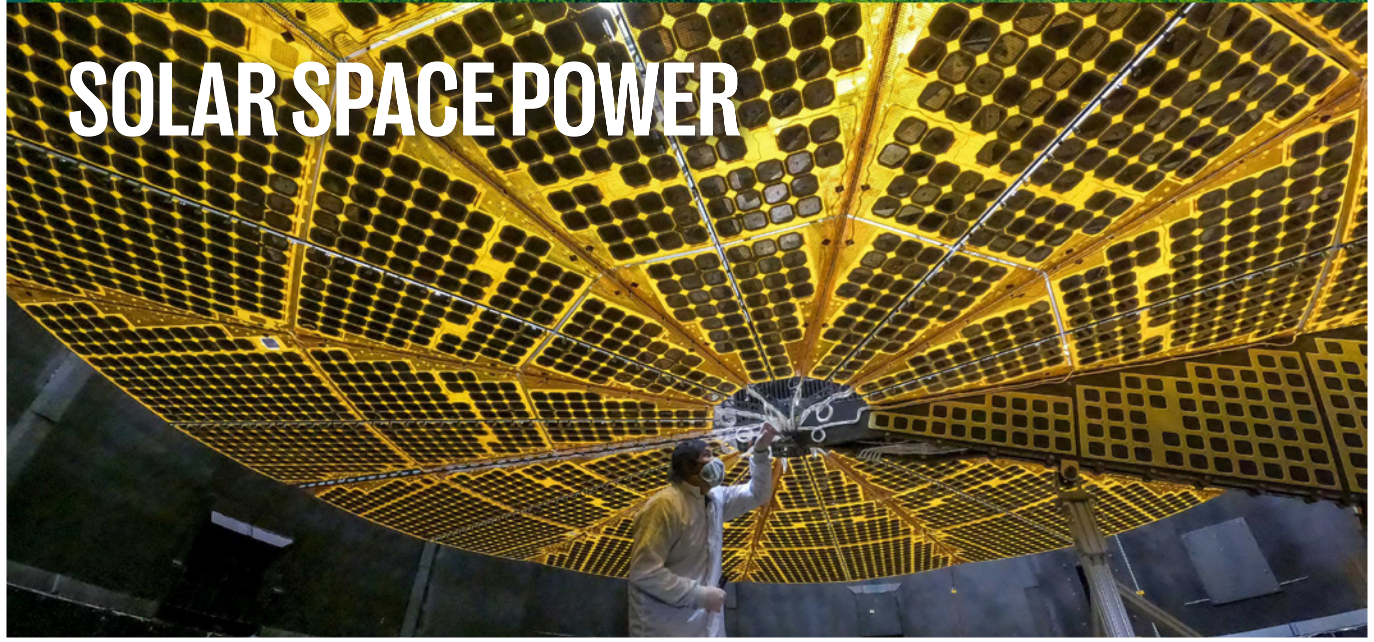
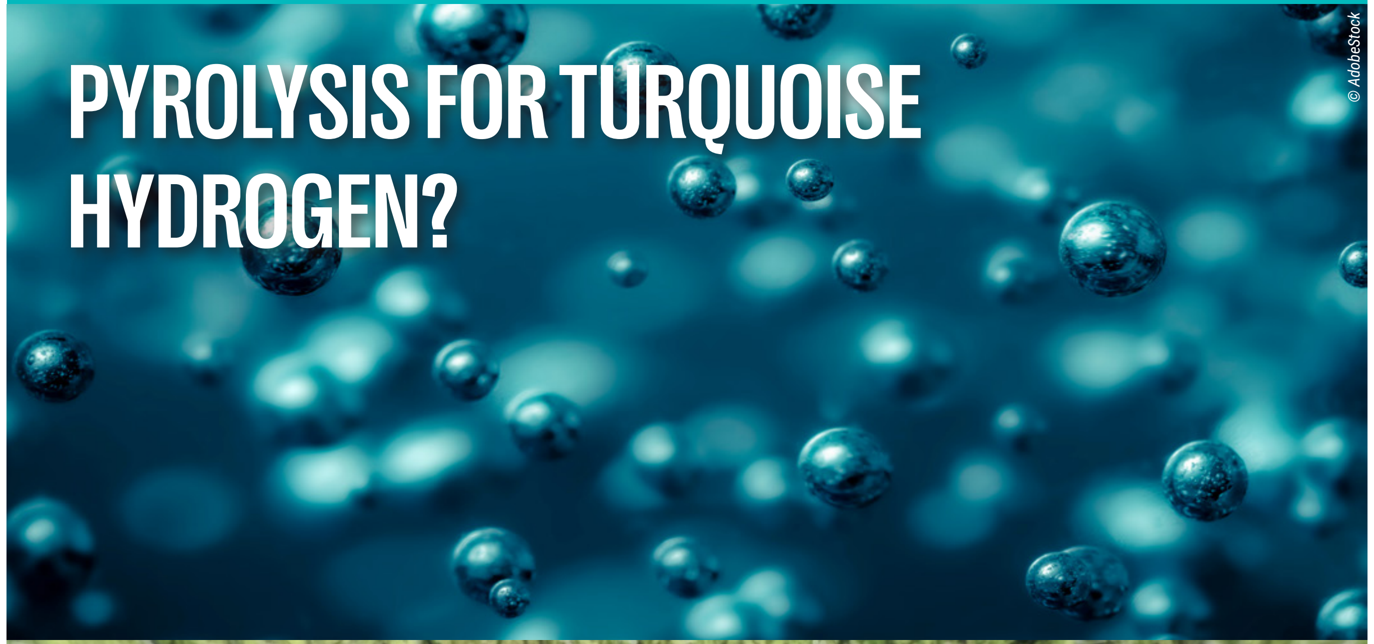


SOLAR SPACE POWER



PYROLYSIS FOR TURQUOISE HYDROGEN?

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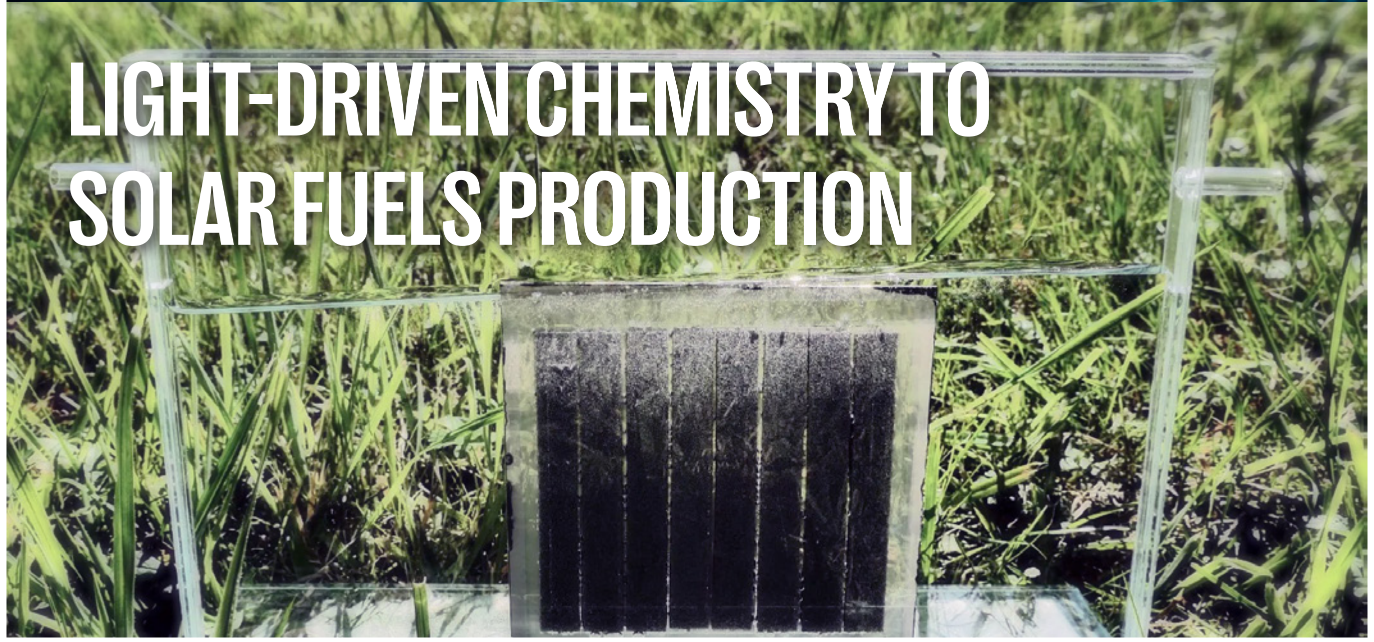

LIGHT-DRIVEN CHEMISTRY TO SOLAR FUELS PRODUCTION

# NATURAL BASED SOLUTIONS

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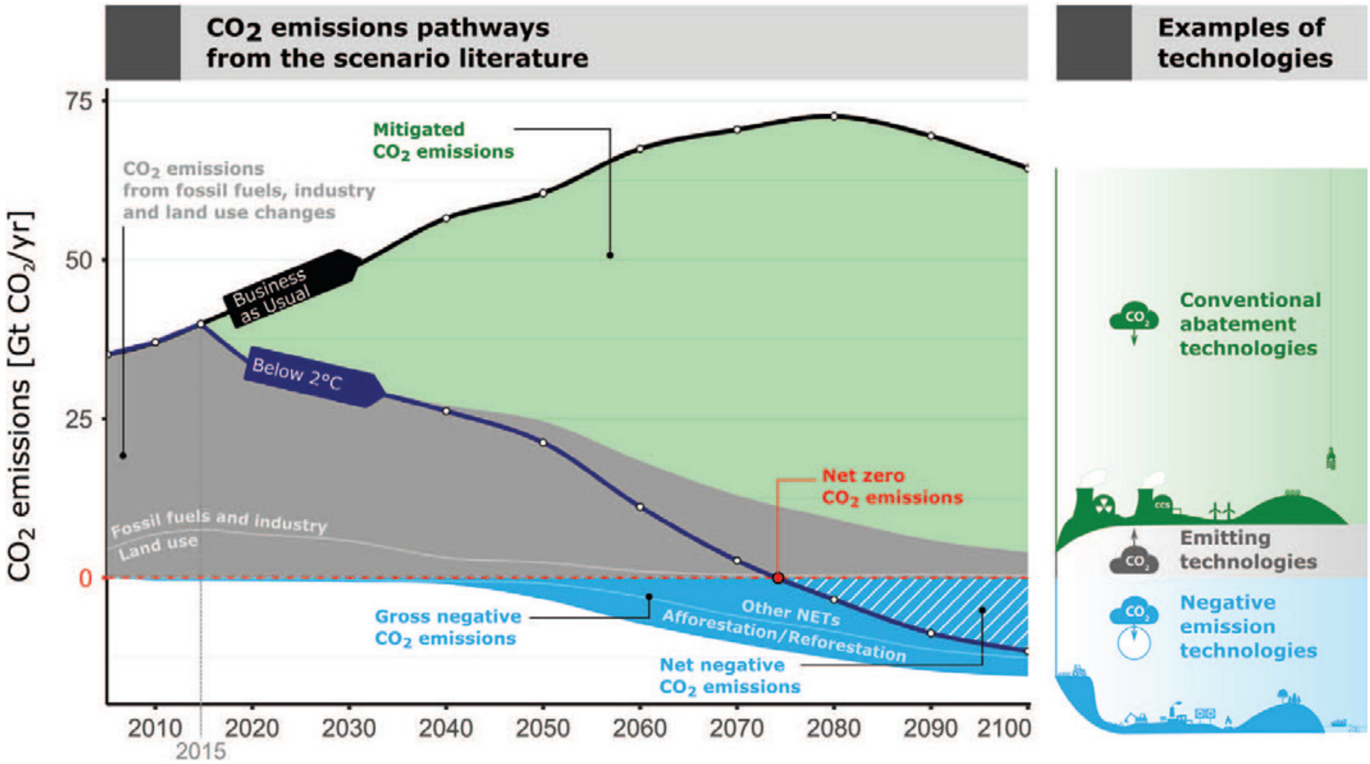
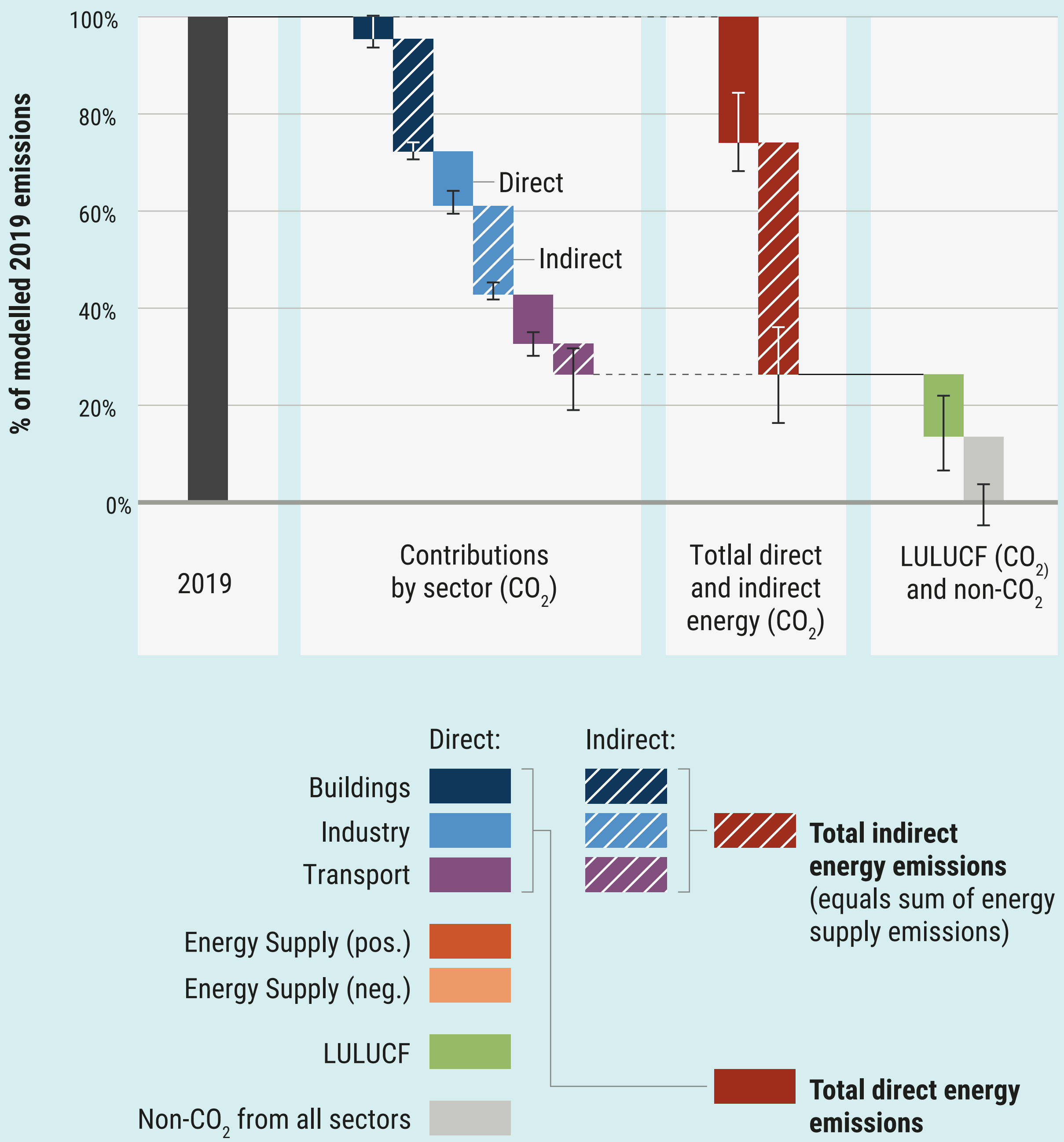
## Recently recognized by the IPCC and IEA as necessary to offset hard-to-abate emissions and eventually, to go beyond net-zero, Negative Emissions Technologies will play a main role but Natural-Based Solutions (NBS) even more.



“Global emission levels turn net negative towards (hatched blue area) the end of the century to compensate for earlier carbon budget overshoot. Cumulative gross negative emissions represented by the entire blue area. The exemplary scenarios ‘business as usual’ and ‘below 2 °C’ were constructed using data from the LIMITS database (https://tntcat.iiasa.ac.at/LIMITSDB/). Gross positive and negative $CO_2$ emissions from land-use changes labelled as ‘land use’ (bottom grey shaded area) and ‘afforestation/reforestation’ (bottom blue shaded area) were inferred from net land-use changes emissions to account for current afforestation and reforestation efforts and differentiate between negative emissions from land-use changes and other NETs.”

| $CO_2$ net emissions over time, involving both reduction (green) and removal (blue). [1] |

# 13% of $CO_2$ mitigation options should come from Natural-Based Solutions to reach global net zero GHG emissions.



Direct = demand-side; Indirect =supply-side $CO_2$ emissions reductions.
LULUCF: Land Use, Land-Use Change, Forest, encompass removals mainly from forests, but also from cropland, grasslands, wetlands, settlements and other lands.

**Contributions to reaching net zero GHG emissions (for all scenarios reaching net-zero GHGs).** [2]

**NATURE is the forgotten solution representing 37% of the climate solution.** *Inspired by [3-4]*

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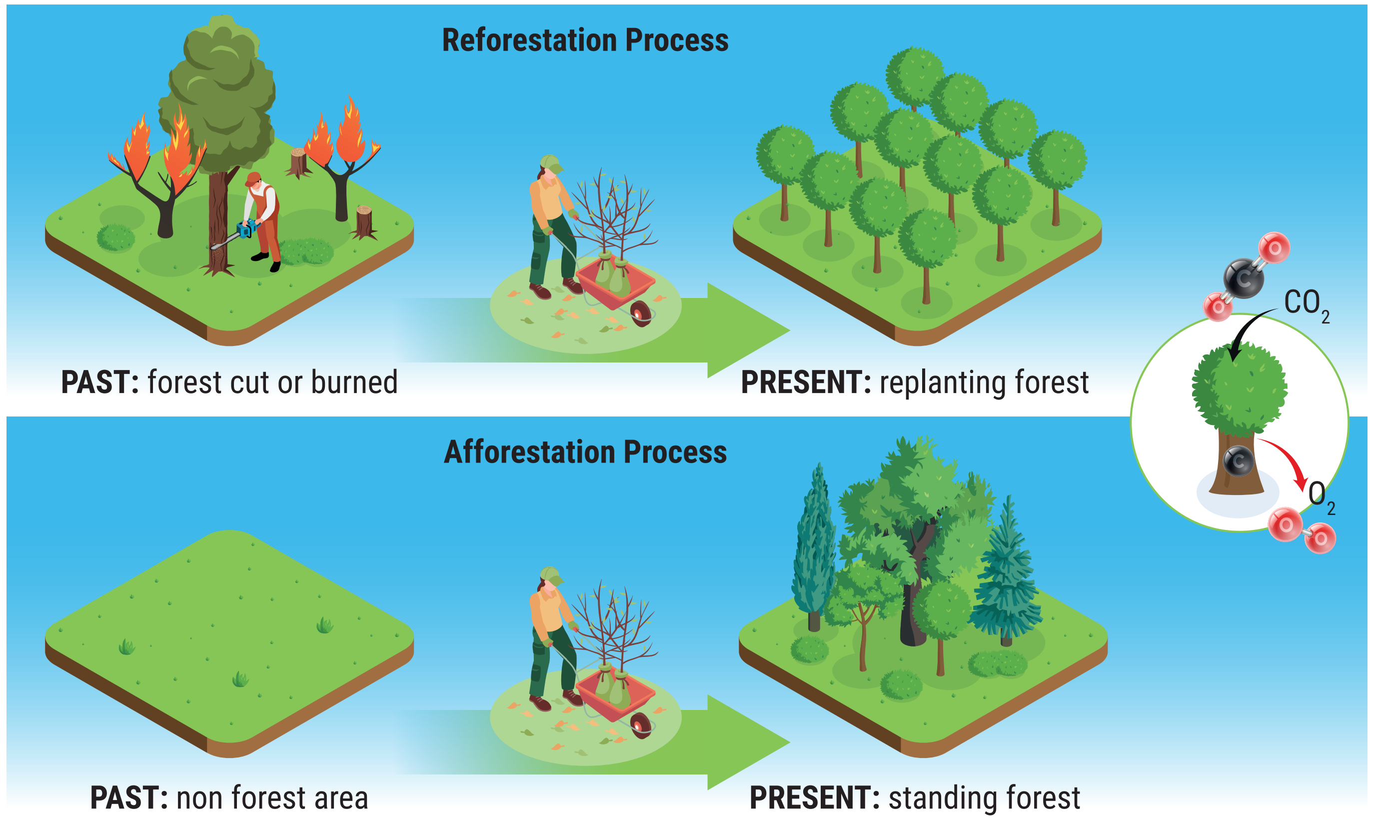
# Afforestation/Reforestation (A/R)

## A/R has a big potential that is limited by the suitable area for tree plantation, taking into account the albedo issue and competition with food production.

**TRL 8-9**



*Inspired by [5]*

Reforestation consists of land-use and management practices within forests, i.e. planting new or extending existing forests to increase the total inventory of carbon in this forest. There are two types of reforestation:

- Urban reforestation = tree planting in developed areas. The purpose depends on the city's needs: modify the climate, improve air quality, provide more shady areas or enhance the appearance of the environment.
- Rural reforestation = Huge numbers of trees planted in areas that have suffered deforestation, places which were once forests, jungles or covered with semi-arid vegetation. [5]

Afforestation consists of planting trees in non-forest areas.

**POTENTIAL:**

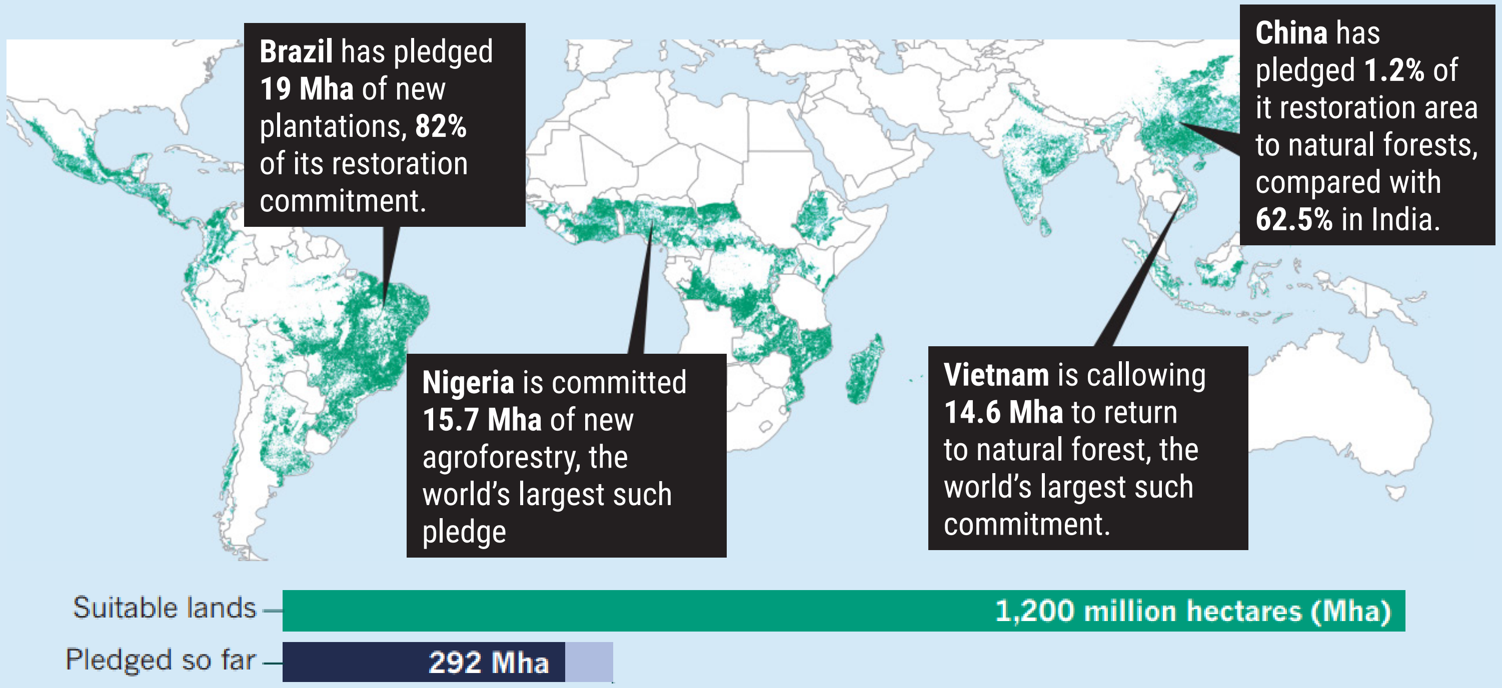
**3-10 Gt $CO_2$/year by 2030**

### ADVANTAGES

- Enhanced employment and local livelihoods, improved biodiversity.
- Improved renewable wood products provision.
- soil carbon and nutrient cycling. Possibly less pressure on primary forest.

### CHALLENGES

- Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.
- Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production. [2]



**Brazil** has pledged **19 Mha** of new plantations, **82%** of its restoration commitment.

**Nigeria** is committed **15.7 Mha** of new agroforestry, the world's largest such pledge

**Vietnam** is calling **14.6 Mha** to return to natural forest, the world's largest such commitment.

**China** has pledged **1.2%** of it restoration area to natural forests, compared with **62.5%** in India.

**| Overview of high potential regions for A/R. [7] |**

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## Forest experts develop new business supported by financial actors to provide carbon removal solutions based on afforestation/reforestation projects.

**“AXA IM Alts, ENGIE and The Shared Wood Company join forces to develop nature-based solutions project.**

The newly incorporated French company The Shared Wood Company (SWC), which was created by experienced forestry experts, develops nature-based solutions projects primarily located in Africa, Latin America and Europe. SWC will benefit from AXA IM Alts’ impact investing and project finance capabilities and ENGIE’s expertise in carbon markets and risk management.” [8]

PRESS RELEASE HERE

**“Gabon: TotalEnergies and Compagnie des Bois du Gabon Join Forces to Develop a New Forest Management Model Combining Wood Production and Carbon Sinks.”** [9]

PRESS RELEASE HERE

## How can building with timber help us to achieve our net zero goals?

According to the UK Green Building Council, the built environment accounts for 40% of all the UK’s carbon emissions. [10]
Wood has a role to play in helping to decarbonise the structural fabric of new and existing homes and the construction industry as a whole.

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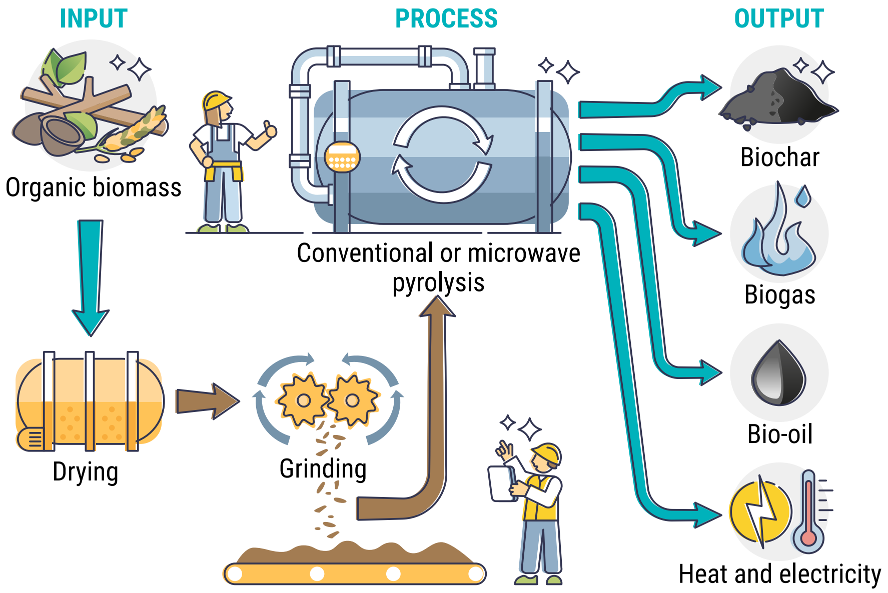
## Biochar
## The new black gold for the climate that makes industries dream of decarbonization?

**TRL 6-7**

**POTENTIAL OF CARBON REMOVAL:**
**0,2 to ~1 Gt $CO_2$/year by 2030**

Biochar is formed by recalcitrant (i.e., very stable) organic carbon obtained from pyrolysis, which, applied to soil, can increase soil carbon sequestration leading to improved soil fertility properties. Permanence depends on soil type and biochar production temperatures, varying between a few decades and several centuries [11].
Biochar is obtained from wood residues (natural or industrial residues from the maintenance of forests, agriculture or the wood industry, such as bark, harvest wood or straw) or residues of dry crops (such as the hulls of coffee beans for example). They are heated to approximately 500 degrees, in the absence of oxygen, in order to avoid their combustion which would reduce them to ashes [12].

Biochar takes the form of a black powder.



Example of pyrolysis technology, an authothermal technology. [13]

### ADVANTAGES

- Increased crop yields and reduced non-$CO_2$ emissions from soil and resilience to drought.

### CHALLENGES

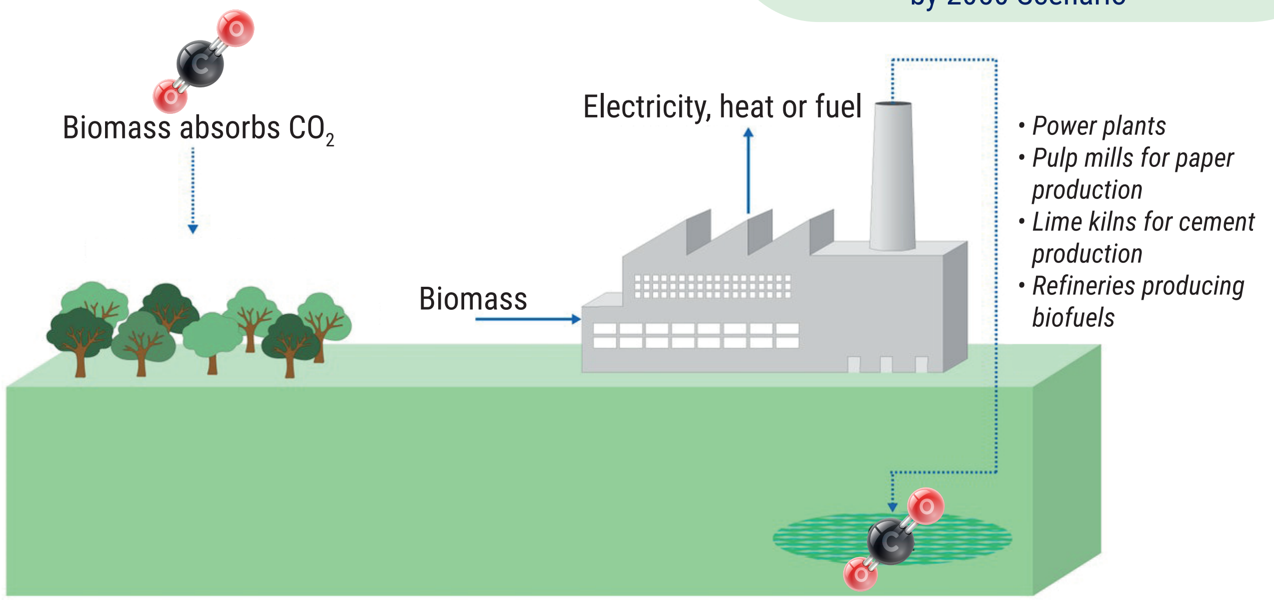
- Potential estimation considering limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application to agricultural soils under field conditions.

---

## BioEnergy Carbon Capture and Storage (BECCS)
## Primarily developed for ethanol production with large infrastructures, BECCS has an interesting potential that is limited by the production of sustainable biomass.

**POTENTIAL OF CARBON REMOVAL:**
**~250 Mt $CO_2$/year by 2030** in the Net Zero Emissions by 2050 Scenario [14]

**TRL 8-9**



Example of BECCS process. [15]

BECCS consists in the capture of $CO_2$ that is co-produced from biomass transformation into an energy vector, not the $CO_2$ produced from the utilisation of the energy vector. This encompasses various processes (combustion, fermentation, carbonisation, liquefaction, gasification, etc.). The $CO_2$ is then treated to be injected into an underground storage.

Many energy vectors can be produced through biomass processing but those that are most relevant for NETs are fermentation (to bioethanol or biomethane) and combustion based (to heat/electricity). [15]

### ADVANTAGES

- Reduction of air pollutants; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity.

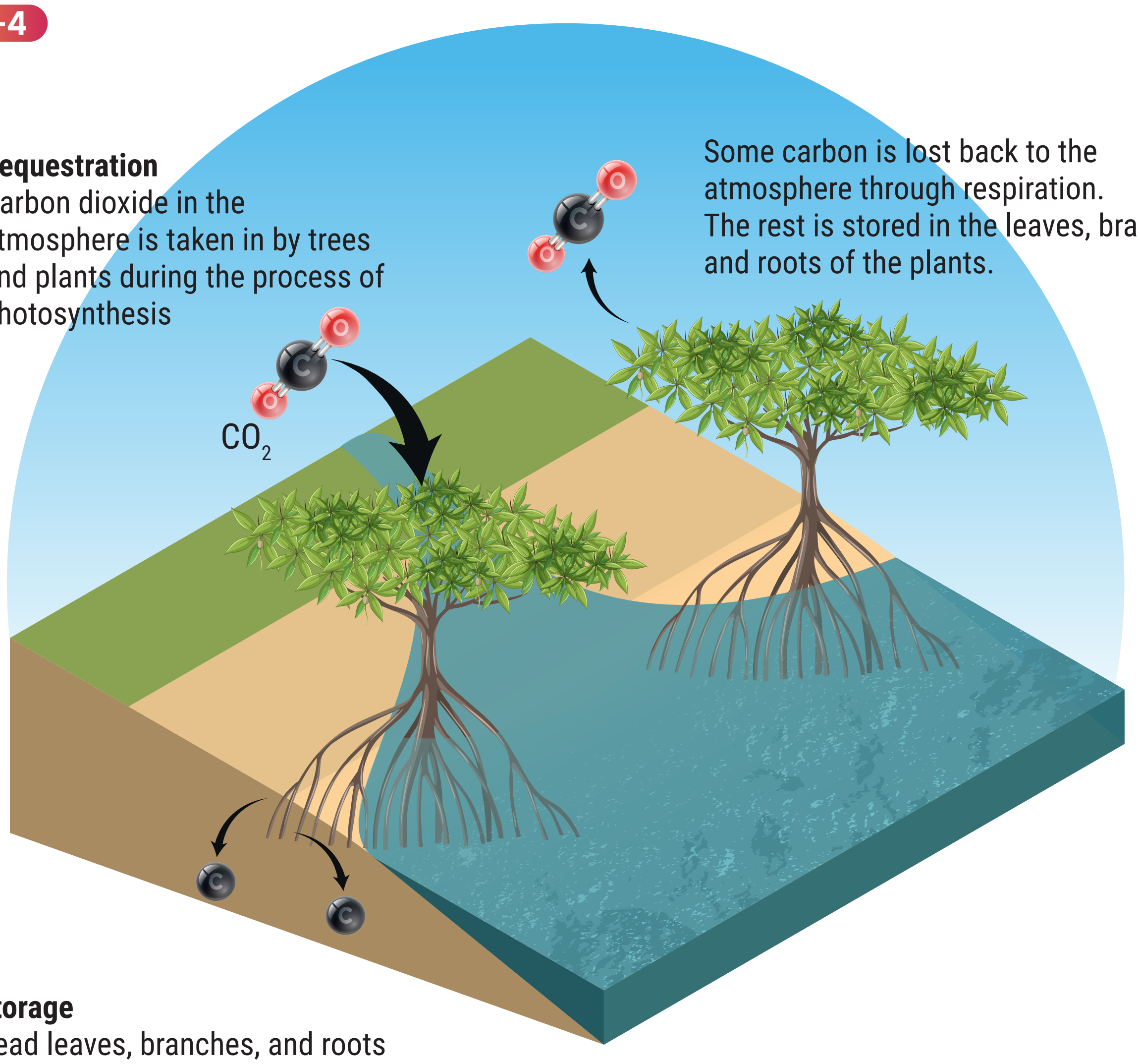
### CHALLENGES

- Inappropriate deployment on a large scale leads to additional land and water use to grow biomass feedstock. [2]

## Coastal blue carbon

## This is the carbon captured by living coastal and marine organisms and stored in coastal ecosystems such as mangroves, seagrass beds, salt marshes.

TRL 2-4

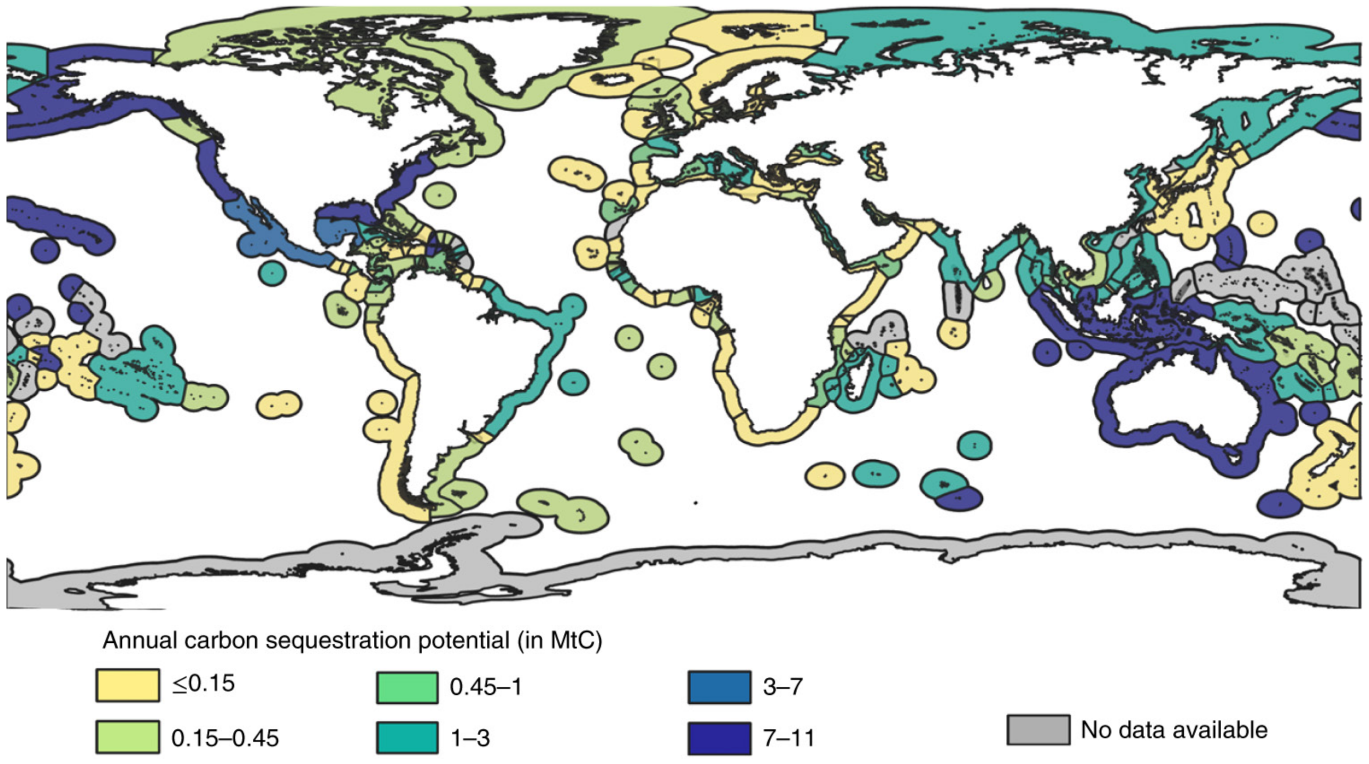


**Sequestration**
Carbon dioxide in the atmosphere is taken in by trees and plants during the process of photosynthesis

Some carbon is lost back to the atmosphere through respiration. The rest is stored in the leaves, branches, and roots of the plants.

**Storage**
Dead leaves, branches, and roots containing carbon are buried in the soil, which is frequently, if not always, covered with tidal waters. This oxygen-poor environment causes very slow break down of the plant materials, resulting in significant carbon storage.

| Coastal Blue Carbon process for carbon storage. [16] |



| Mean annual blue carbon sequestration potentials. [17] |

“Globally, coastal ecosystems contribute a mean ± s.e.m. of US\$190.67 ± 30 bn yr−1 to blue carbon wealth. The three countries generating the largest positive net blue wealth contribution for other countries are Australia, Indonesia and Cuba, with Australia alone generating a positive net benefit of US\$22.8 ± 3.8 bn yr−1 for the rest of the world through coastal ecosystem carbon sequestration and storage in its territory.” [17]

### ADVANTAGES

- 726 tonnes of coal are offset by one hectare of mangrove.
- Every year, coastal wetlands sequester enough CO$_2$ to offset the burning of over 1 billon barrel of oils.
- In some areas, one hectare of seagrass can store 2 times the carbon captured by an average terrestrial forest.
- Although covering less than 1% of the ocean they store over 50% of the seabed’s rich carbon reserves. [18]

### CHALLENGES

- If degraded or lost, coastal blue carbon ecosystems are expected to release most of their carbon back to the atmosphere.
- Risk of increased CH$_4$ emissions.
- Effect of shoreline modifications on sediment redeposition and natural marsh accretion.

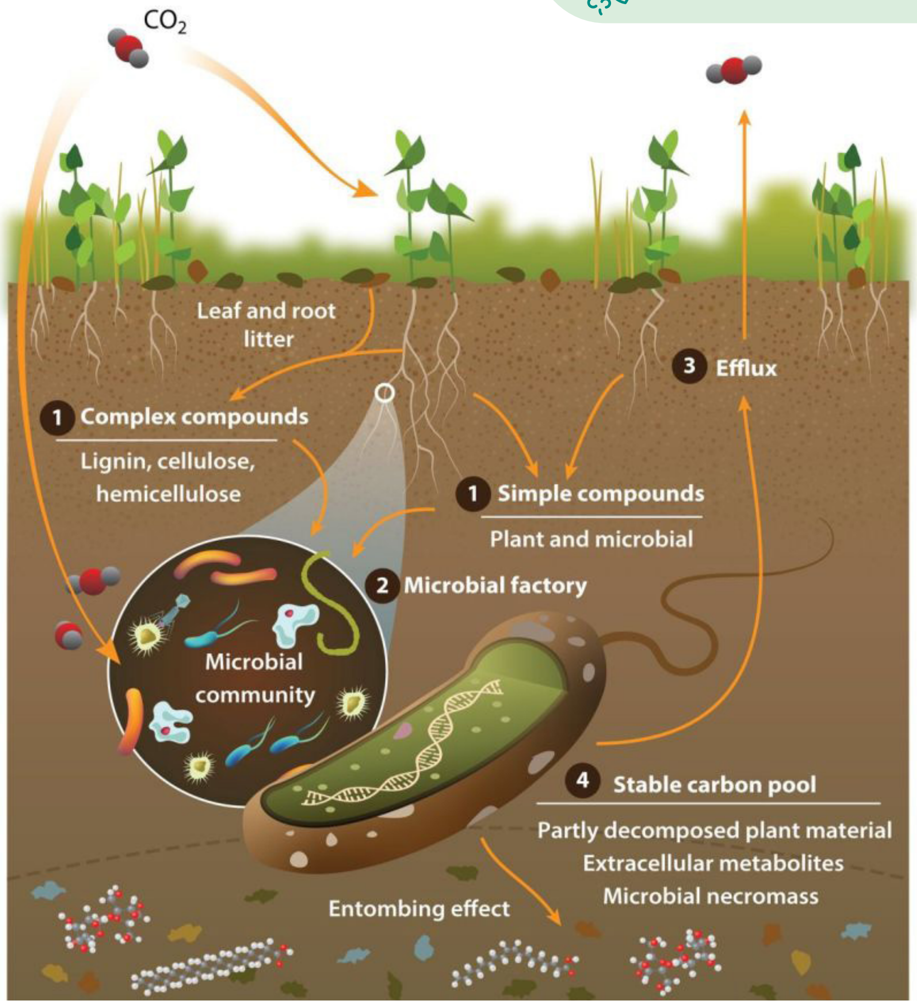
# Soil Carbon Storage (SCS)

## This refers to the increase of soil organic matter though specific agricultural management practices: reduced tillage, use of cover crops, agro-forestry, use of compost, etc.

**In development TRL 8-9**

**POTENTIAL OF CARBON REMOVAL:**

**: 0,6 to mor than 3 Gt $CO_2$/year**



*Source [19]*

### ADVANTAGES

- Improved soil quality, resilience and agricultural productivity.

### CHALLENGES

- Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.

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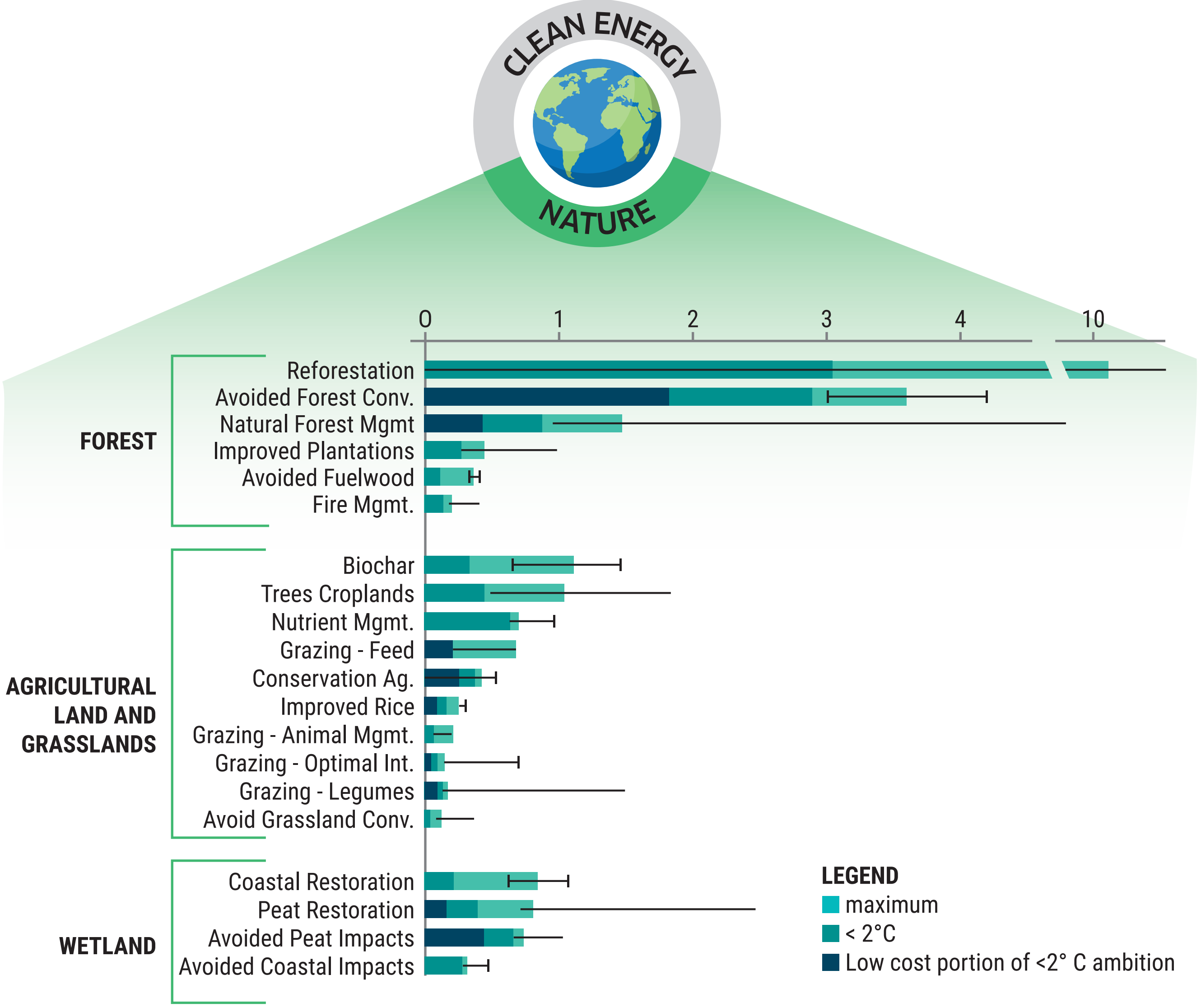
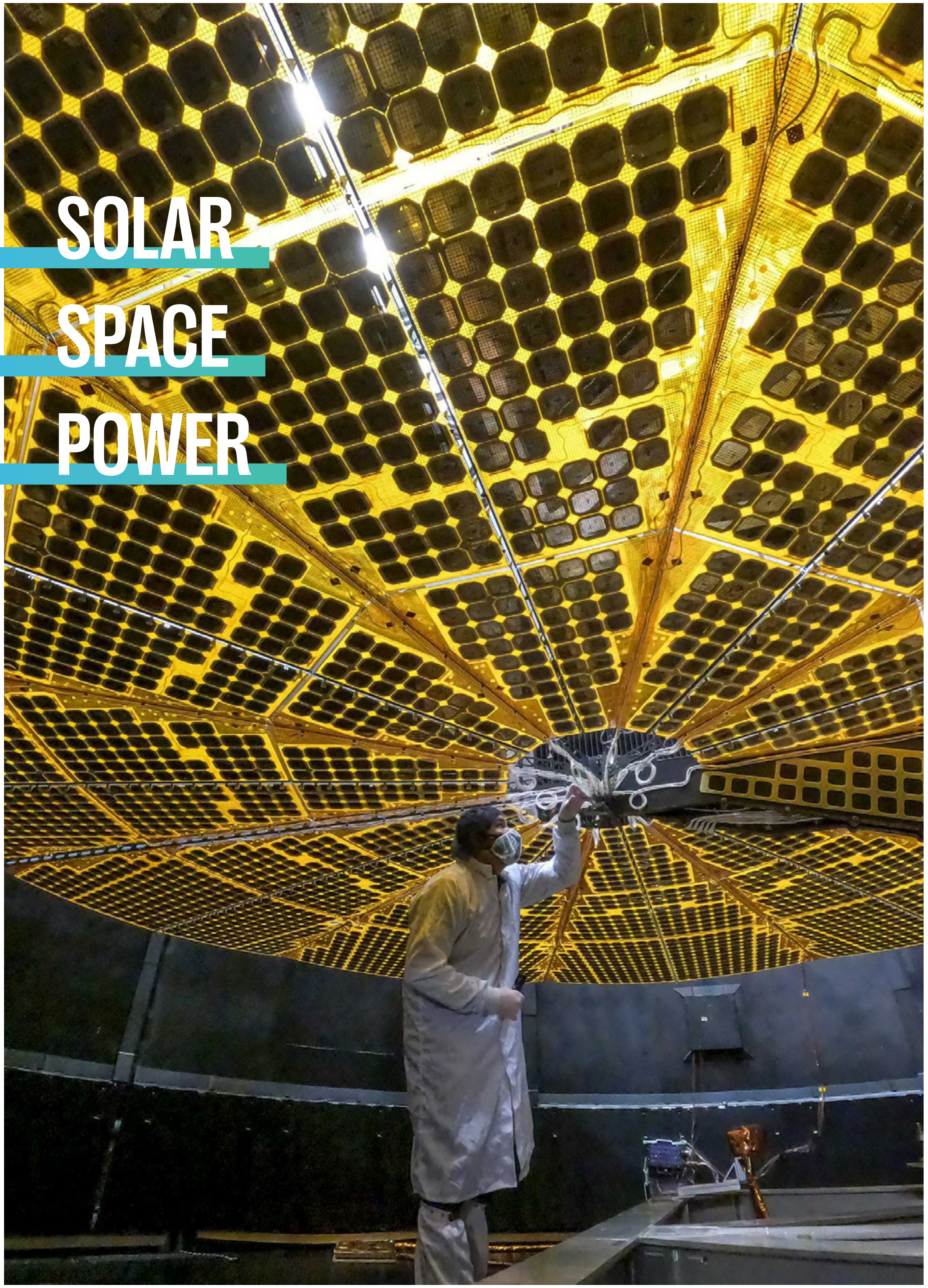
## As they conserve or expand ecosystems, NBS protect biodiversity against both climate change and habitat loss. On a 2030 horizon forests represent the best solution to store carbon massively.



| **Natural climate solutions: climate mitigation potential in 2030 (Gt $CO_2$e).** *Adapted from [20-21]* |

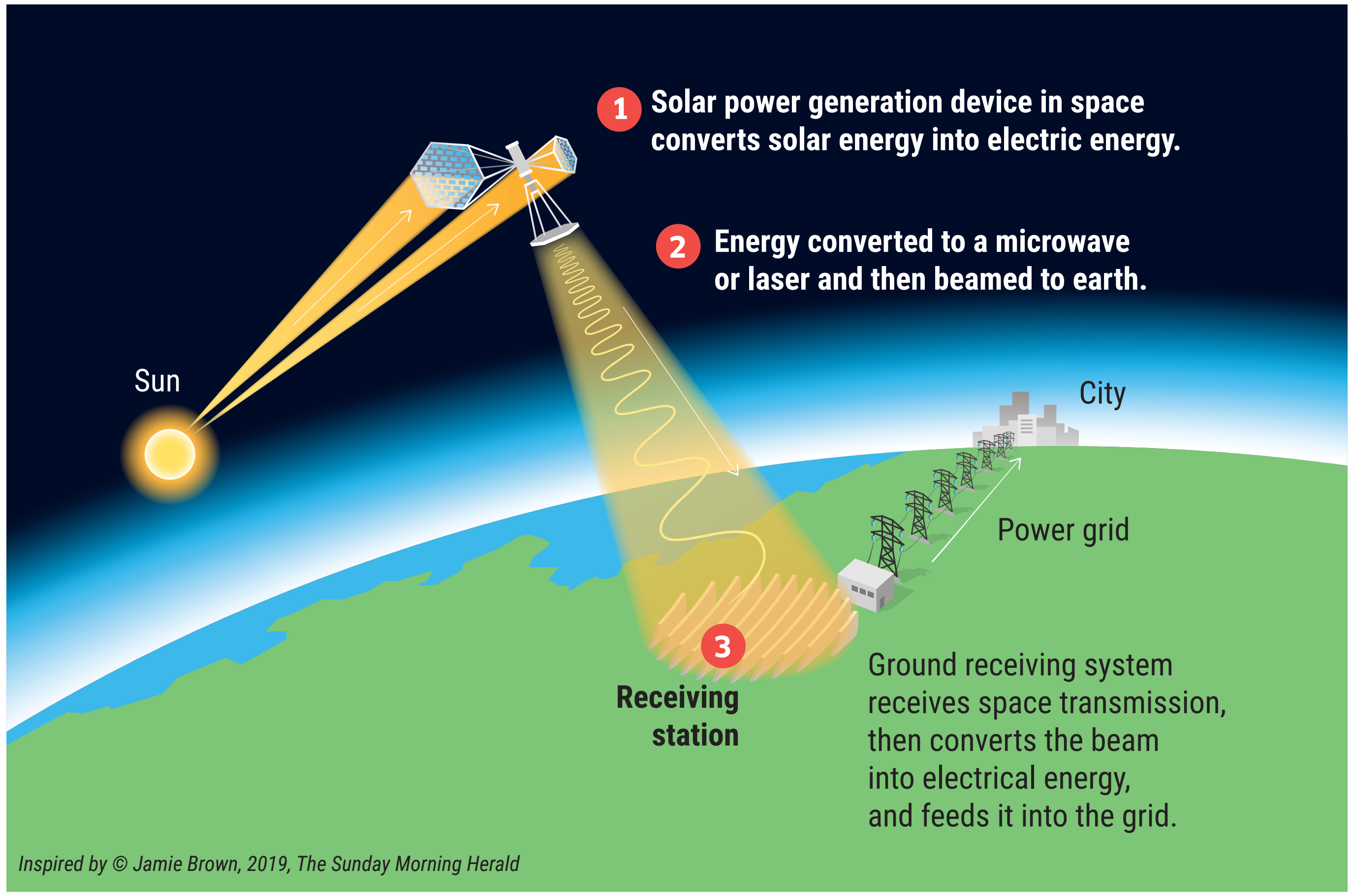
The removal and storage of $CO_2$ through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, $CO_2$ stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinisation) and as carbon in biochar is less prone to reversal. [2]

# SOLAR SPACE POWER



## Can we use Solar Power in Space to supply energy for Earth's consumption?

The concept of Space Based Solar Power (SSP) systems is to collect solar power in high earth orbits* and then transmit it wirelessly to Earth.



① Solar power generation device in space converts solar energy into electric energy.

② Energy converted to a microwave or laser and then beamed to earth.

Ground receiving system receives space transmission, then converts the beam into electrical energy, and feeds it into the grid.

*Inspired by © Jamie Brown, 2019, The Sunday Morning Herald*

①
Solar power is collected by a solar power satellite which converts solar rays into electric energy.

②
The electric energy is then converted into another form of energy (such as microwaves (MPT) or laser (LPT)) which can be transmitted wirelessly through the atmosphere by antennas.

③
The ground-based receiving antennas, called rectennas, will convert the energy back into electrical energy before feeding it into the grid.

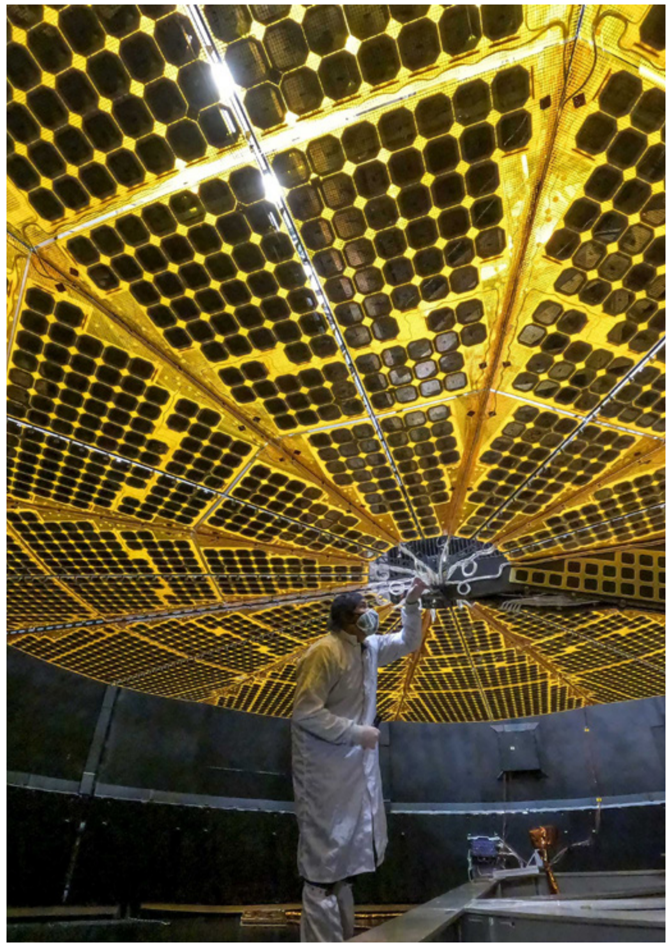
---

* *Geostationary Earth Orbit (GEO) or Low Earth Orbit (LEO).*

## Over the past decade, advances within the space industry make SSP systems technically feasible, and potentially before 2050 [1] due to:

- **Decrease of space launch costs** thanks to ground-breaking commercial space firms like SpaceX or Blue Origin. Launch costs have already been reduced by 90%[1] and space hardware costs by 99%. [2-3]
- **Emerging technologies**: space robotics, more efficient PV technologies, lighter solar power satellites and others hold promise for the cost-effective manufacturing and deployment of exceptionally large space structures in the near term.[2]
- **Increase of strategic interests**: "Other nations may see strategic advantages and global influence in being able to develop a source of abundant affordable energy which could potentially be beamed anywhere in the world." [1]

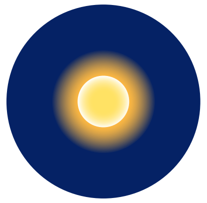
SpaceX Falcon 9Reusable launch vehicle [SpaceX].



Deployable solar panels developed by NASA [NASA].

PRESS RELEASE HERE

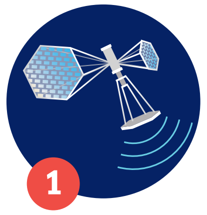
# Different concepts of SSP are being developed but they all rely on the same building blocks.



**The Sun**

The Sun has the power to supply 2,880 trillion light bulbs [7] for billions of years.

There is 100 times more solar energy available from a narrow strip around the earth at GEO , than the forecast global energy demands of humanity in 2050 [1].



**Space-based solar panels**

Enormous structures composed of solar reflectors allow the consistent reflection of sunlight onto solar panel arrays to maximise the produced electrical energy.

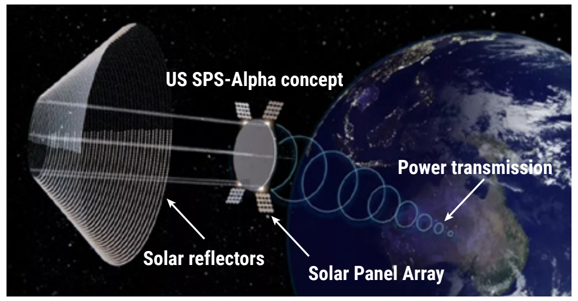
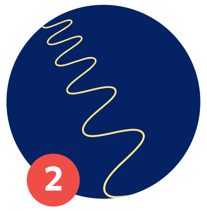


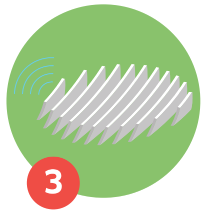
*Illustration of the SPS-ALPHA («Solar Power Satellite by means of Arbitrarily Large Phased Array») system beaming energy to Australia. (Image credit: John Mankins/Artemis Innovation Management Solutions)*



**Microwave energy transfer**

The electrical energy is converted into a high frequency radio-wave that will allow the transfer of energy to Earth using transmitting antennas:

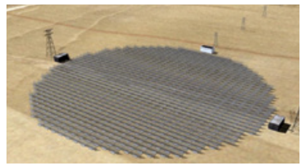
- Specific frequency to be used,
- Safe as the intensity of the beam will be reasonable,
- Negligible absorption / heating inducing no heating in the atmosphere. [2]



**Ground station**

The radio-wave captured by a ground station of rectennas.

This will need to have a diameter of several kms to capture the complete wave.



Ground station [2]

Rectennae [5]

**Existing infrastructure & Homes and businesses**

The energy is then shared into the existing electric infrastructure leading to homes and businesses.

Direct Current or Alternative Current is fed into the local grid. [2]

# The technology's maturity is progressively increasing but still faces multiple challenges.

## The technology currently faces multiples challenges on different aspects that will need to be solved for future implementation.

*Inspired by [1]*

**P Political**

Integrating this technology into the current energy policy at an international level?

**T Technical**

Reaching maturity such as wireless transmission efficiency, deployable solar panels, in-orbit maintenance or life in space environment.

**L Legal and Regulation**

Managing the spectrum of wireless power transmission, managing the risks of orbital congestion.

**E Environmental**

- Environmental impact of rectenna site, launches…
- End-of-life strategy and carbon impact of such technology in term of manufacturing.
- Hazards could cause damage to the solar panels, such as **space debris and extreme solar radiation** [9].

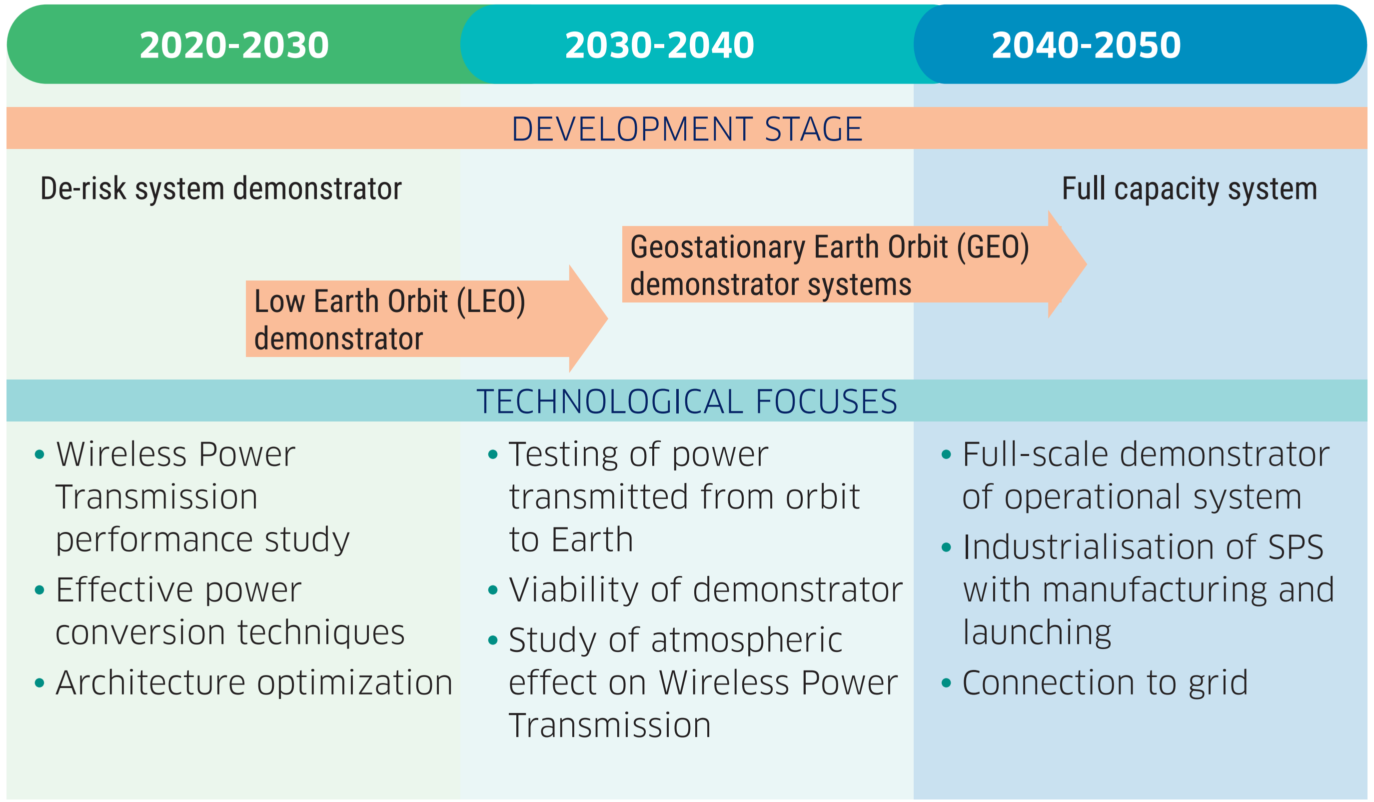
**S Societal**

Public acceptance of this new technology, managing the long term safety for the beaming and large area for rectenna occupation.

**E Economic**

- Electricity cost of this technology compared to other renewable.
- Cost of launching panels to space and transport costs of infrastructure.

## A broad number of companies have drawn up development roadmaps with the most ambitious ones aiming at an industrial application in the coming decade while the general understanding is to have full capacity systems by 2050.



| 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|
| DEVELOPMENT STAGE | | |
| De-risk system demonstrator<br>Low Earth Orbit (LEO) demonstrator | Geostationary Earth Orbit (GEO) demonstrator systems | Full capacity system |
| TECHNOLOGICAL FOCUSES | | |
| • Wireless Power Transmission performance study<br>• Effective power conversion techniques<br>• Architecture optimization | • Testing of power transmitted from orbit to Earth<br>• Viability of demonstrator<br>• Study of atmospheric effect on Wireless Power Transmission | • Full-scale demonstrator of operational system<br>• Industrialisation of SPS with manufacturing and launching<br>• Connection to grid |

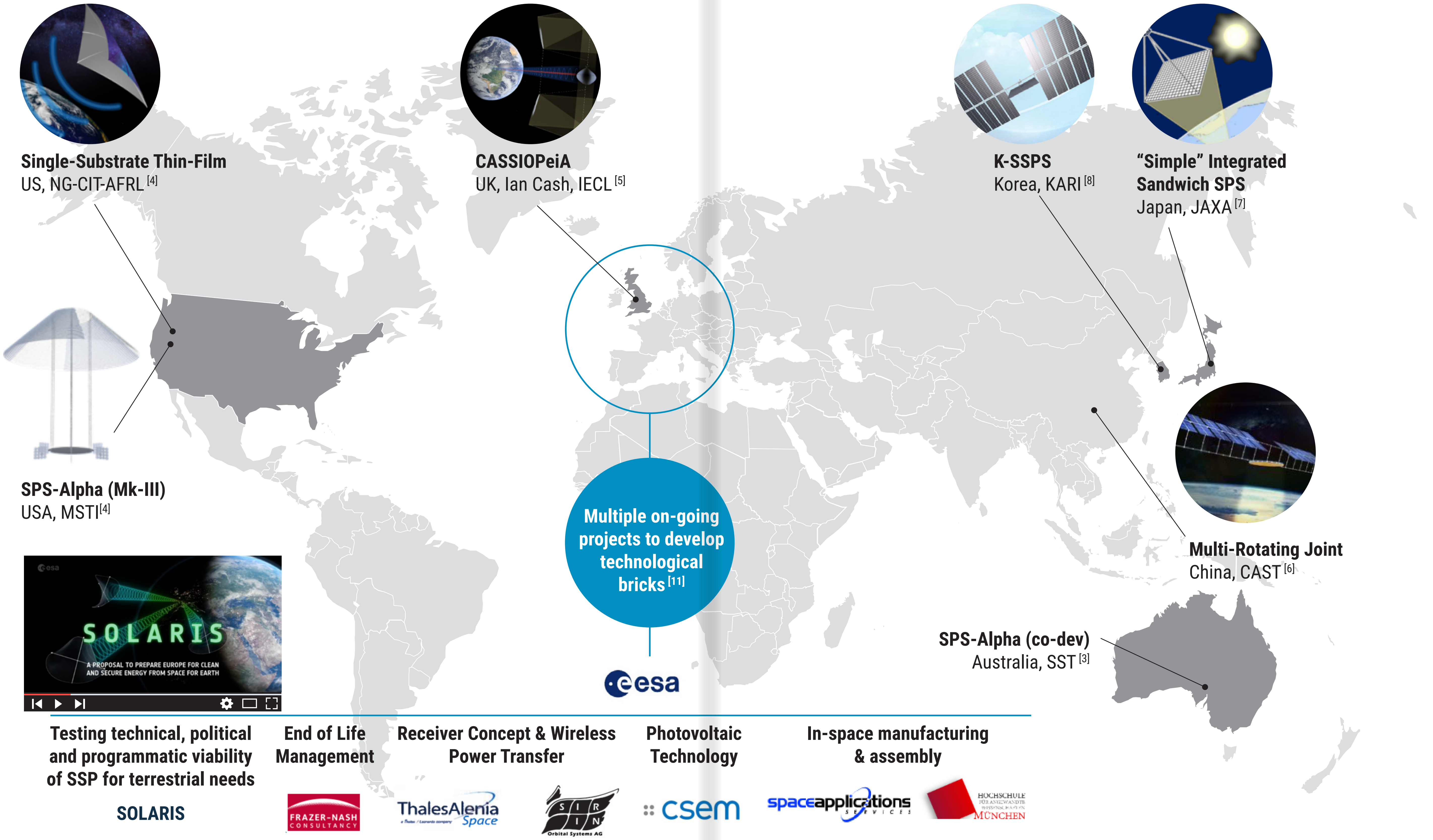
*Inspired by the developpement programms from [1-3-6-7-8]*

# Continuous green energy production with no GHG emissions make SSP a credible candidate in the carbon neutrality race.

**ADVANTAGES**

- **Low carbon payback period: The space-based solar power will generate 0% greenhouse gas emissions on Earth during its operation.** [1-7-9]
- **No intermittency : This technology can generate continuous electricity, 24 hours a day as, unlike Earth, the space environment does not have night and day, and the satellites are in the Earth's shadow for only a maximum of 72 minutes per night.** [1-9-10]
- **Competitive energy production: The efficiency of solar panels will also be much higher than Earth's applications, and have a favourable estimated LCOE compared to current technologies used on Earth.** [1-9]

# Different concepts of SSP are currently being developed over the world.



**Single-Substrate Thin-Film**
US, NG-CIT-AFRL [4]

**CASSIOPeiA**
UK, Ian Cash, IECL [5]

**K-SSPS**
Korea, KARI [8]

**"Simple" Integrated Sandwich SPS**
Japan, JAXA [7]

**SPS-Alpha (Mk-III)**
USA, MSTI[4]

**Multiple on-going projects to develop technological bricks** [11]

esa

**Multi-Rotating Joint**
China, CAST [6]

**SPS-Alpha (co-dev)**
Australia, SST [3]

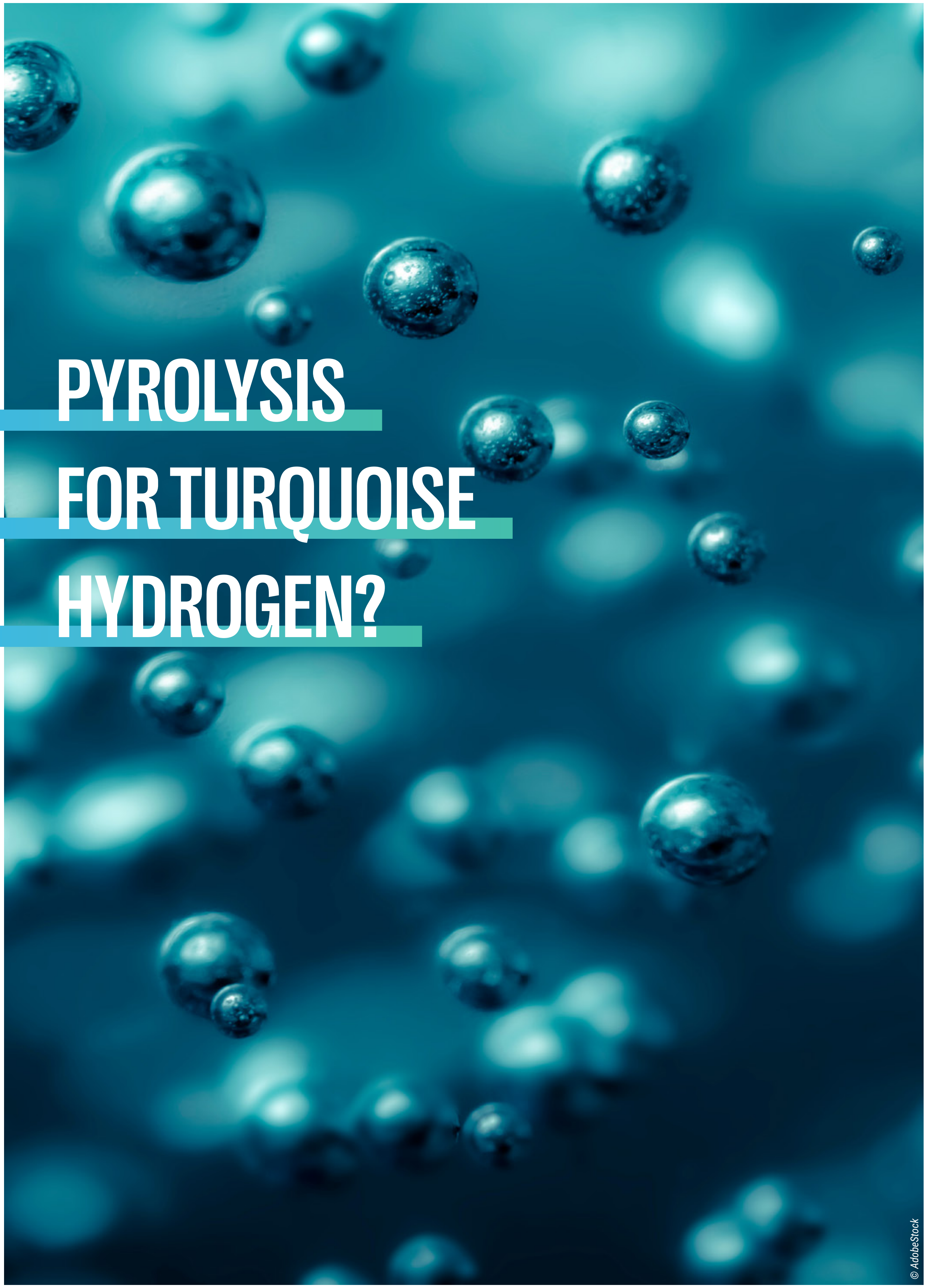
**Testing technical, political and programmatic viability of SSP for terrestrial needs**
SOLARIS

**End of Life Management**
FRAZER-NASH CONSULTANCY

**Receiver Concept & Wireless Power Transfer**
ThalesAlenia Space
SIRIN Orbital Systems AG

**Photovoltaic Technology**
csem

**In-space manufacturing & assembly**
spaceapplications SERVICES
HOCHSCHULE MÜNCHEN

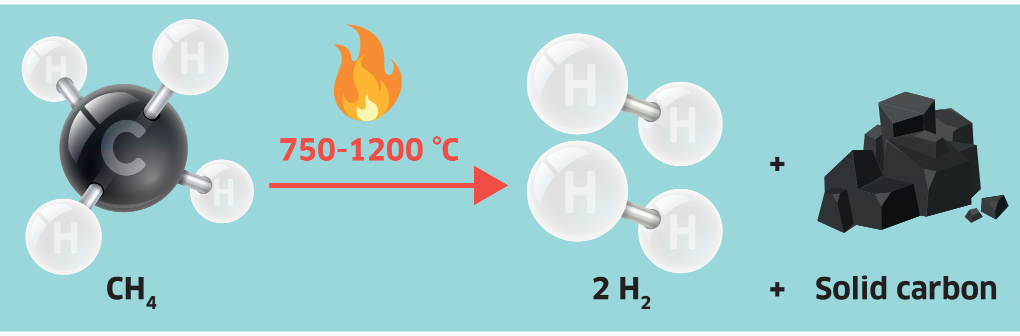


# PYROLYSIS FOR TURQUOISE HYDROGEN?

© AdobeStock

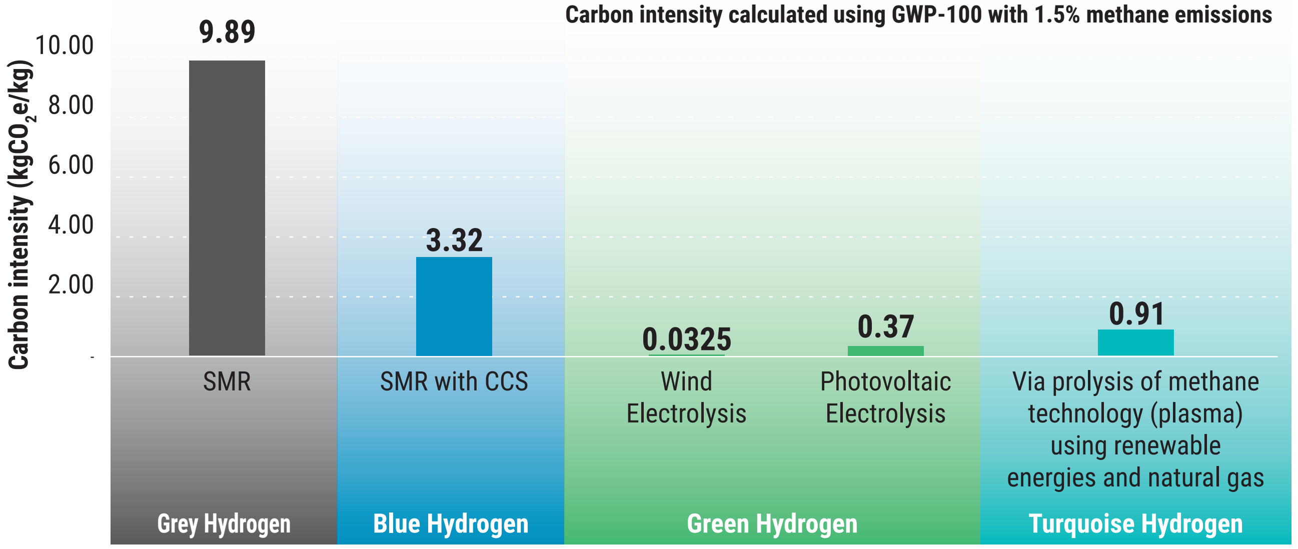
## Methane pyrolysis is a set of emerging technologies that allow hydrogen production while avoiding $CO_2$ emissions. Carbon is stored in a solid form.

### Commonly named ”Turquoise hydrogen”, methane pyrolysis is the conversion of natural gas into hydrogen and solid carbon.



~3 kg of solid carbon produced per 1 kg of hydrogen

**Methane pyrolysis could present an alternative way to produce low-carbon hydrogen**, while benefiting from existing gas natural infrastructure and perpetuating its usage.



| **Comparison of grey, blue, green and turquoise hydrogen carbon intensity.** *Adapted from source [1]* |

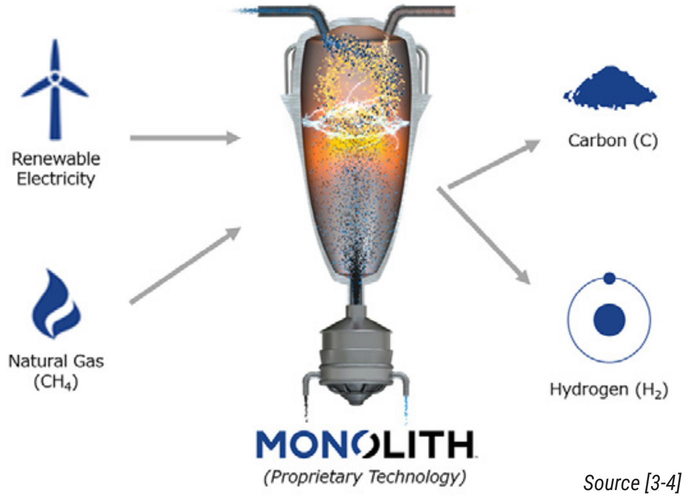
Using fossil natural gas, turquoise hydrogen performs significantly better than both grey and blue hydrogen, but less than wind electrolysis having almost negligible production emissions. Variability of carbon intensity for pyrolysis processes will depend a lot on up-stream emissions from natural gas supply chain and down-stream emissions from solid carbon valorisation.

# Several technology families allow turquoise hydrogen production all based on the same challenge: how to control reactions at high temperature?

| | ① **Plasma Pyrolysis** | ② **Thermal Pyrolysis** | ③ **Catalytic Pyrolysis** |
|---|---|---|---|
| Description | Electric power ignites a plasma in $CH_4$ gas generating $H_2$ and solid C | Molten media (salts or metals) baths to decompose $CH_4$ into $H_2$ and solid C | Catalytic decomposition of $CH_4$ in a fluidized or fix bed |
| Development status | **Commercial demonstrator** | **Lab scale** | **Demonstrator** |
| TRL | **TRL 5-9** | **TRL 3-5** | **TRL 4-7** |
| Current max $H_2$ capacity | ≈ 104 kg $H_2$ / day (MONOLITH) | ≈ 10 kg $H_2$ / day (Lab scale – C-ZERO) | ≈ 103 kg $H_2$ / day (HAZER) |
| Conversion rate (NG to $H_2$) | ~ 85% | ~ 75% | ~ 85% |
| Electrical consumption (kWh/ kg $H_2$) | >10 | Unknown | > 10 (HAZER) |
| Stakeholders | MONOLITH<br>KIT<br>DBI GUT<br>POLITÉCNICA<br>PLENESYS<br>ENGIE<br>TNO<br>spark | MITSUBISHI HEAVY INDUSTRIES<br>C ZERO<br>BASF<br>Linde<br>thyssenkrupp<br>hte<br>BFI<br>tu dortmund | GAZPROM<br>HazerGroup |

*Source [2]*

## ① Plasma Pyrolysis

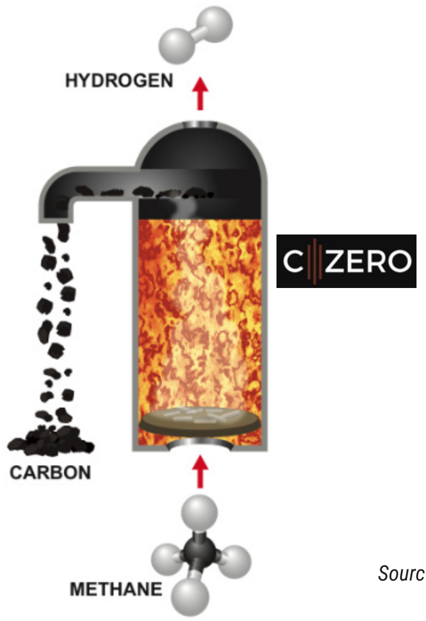


*Source [3-4]*

Utilized a plasma torch where methane pyrolyzes at 1000°C (cold plasma) - 2000°C (hot plasma).

Cold plasma leads to conversions less that 50% without the presence of catalysts while hot plasma results in conversion over 90%.

## ② Thermal Pyrolysis

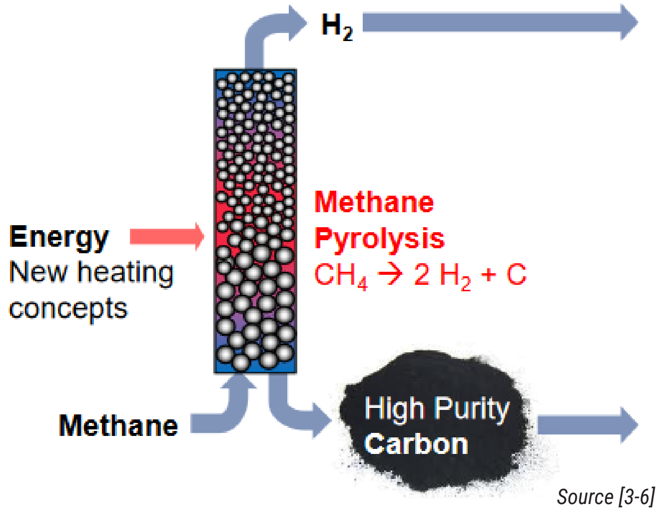


*Source [3-5]*

Uses mosten media reactors (salt and or metal) which enhances the heat transfer between the gas bubbled and the molten media.

Operating temperature is around 1000°C.

## ③ Catalytic Pyrolysis



*Source [3-6]*

Methane breaks down into hydrogen and carbon over a carbon or metal catalyst (nickel- or iron-based) at a temperature between 650-1100°C.

BASF Linde thyssenkrupp
hte BFI tu dortmund

## Depending on carbon quality, several carbon valorisation paths are possible.

### Currently, carbon is mainly used as activated carbon or for batteries.


© Bing

“Activated carbon is used to purify liquids and gases in a variety of applications, including municipal drinking water, food and beverage processing, odor removal, industrial pollution control.” [7]

www.lerepairedesmotards.com © Alexis Ferrant

The addition of carbon black or graphite is optional at the anode, but mandatory at the cathode. Carbon black is used for its conductivity and corrosion resistance.

**Carbon Disruptive applications will be necessary to expand a solid carbon market in the future if $H_2$ demand is satisfied by methane pyrolysis. Indeed, the current carbon markets are either small or not mature.**


© AdobeStock

**Reinforce mine shafts to prevent sinkholes in mines in Germany.**


© Shutterstock

**Reinforce asphalt providing higher resistance to mechanical and thermal distresses.**


© Pixabay

**As a filler in concrete, after validation in pilots.**


© Wikipedia

**Sequestered in open pit mines.**

## Why is methane pyrolysis attractive?

### ADVANTAGES

- No direct $CO_2$ created in the process - carbon captured as solid carbon.
- Competitive solution requiring less energy than Steam Methane Reforming (SMR).
- Production on site (limited land footprint, no added infrastructure, no water use).
- Technology under development to target commercial scale by 2026.
- A complement to green $H_2$ when renewable energy is not affordable/available and natural gas accessible at a good price.

### CHALLENGES

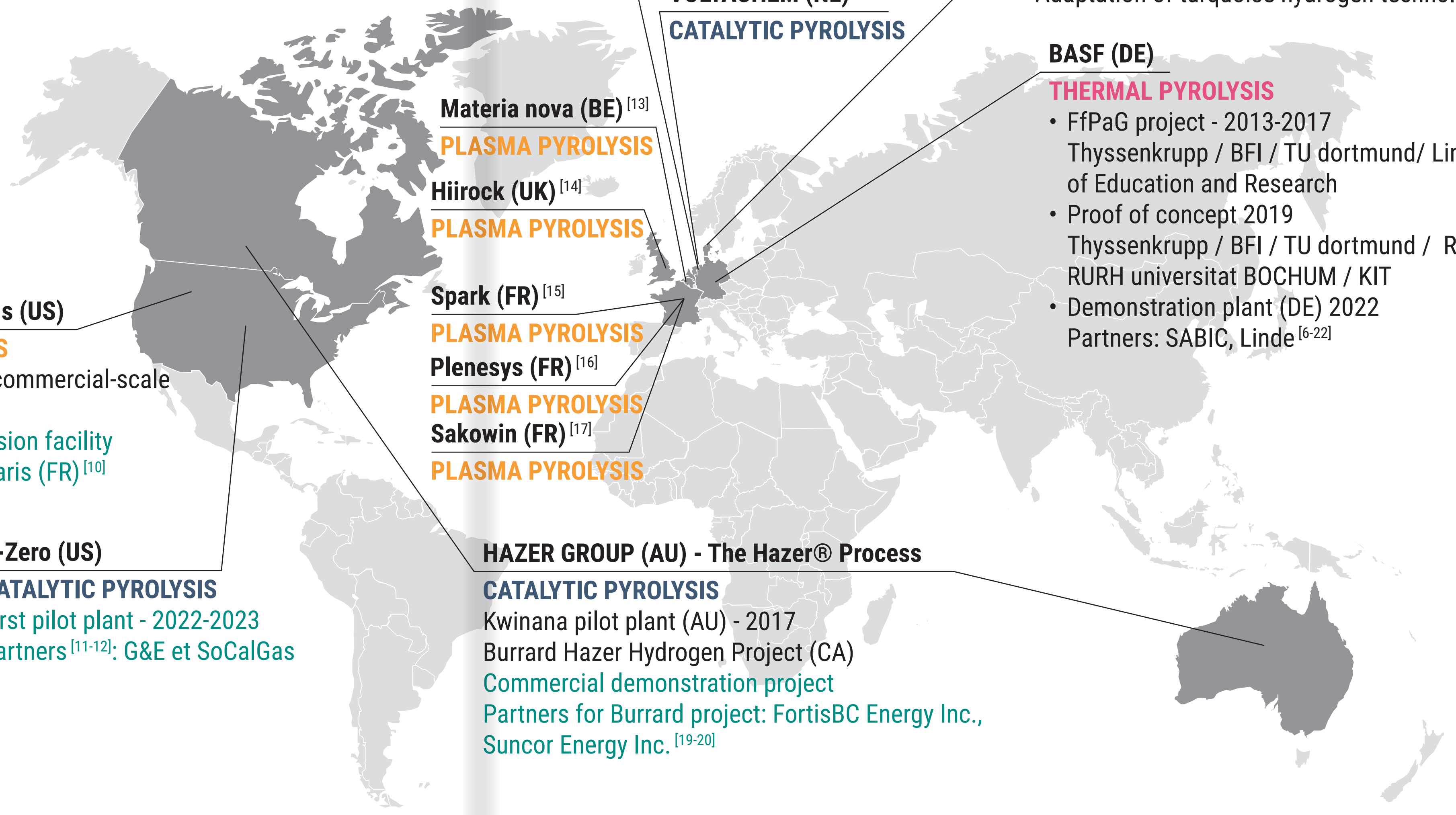
- Manage $CH_4$ emissions along the supply chain and during conversion.
- Still use of fossil energy.
- Deal with carbon valorization.
- Optimize energy integration .
- Maximise energy efficiency in a high temperature process (750 – 1200°C).
- Manage carbon storage? Size & quality issues.
- Plasma technologies require electricity thus presenting less interest to complement electrolysis in regions lacking affordable renewable electricity.

Sources [3-4-5-6-8-9]

**Using biomethane or e-methane will lead to a negative hydrogen carbon-intensity making turquoise hydrogen a game-changer for the energy transition**

“Using renewable-natural-gas with a feedstock percentage as low as 8-18% leads to a negative hydrogen carbon-intensity (reaching -4.09 to -10.40 kg $CO_2$ eq/kg $H_2$ at 100% renewable natural gas), the lowest compared to grey, blue, and green hydrogen.” [1]

## Given current technology maturity, the first commercial roll-out would be expected to start in 2023 for the catalytic technology. Other ones are expected to be built on a commercial scale between 2025 and 2035.



**MONOLITH Materials (US)**
PLASMA PYROLYSIS
Olive Creek 1: First commercial-scale plant 2016-2020
Olive Creek 2: Extension facility
Partner: Mines de Paris (FR) [10]

**C-Zero (US)**
CATALYTIC PYROLYSIS
First pilot plant - 2022-2023
Partners [11-12]: G&E et SoCalGas

**TNO (NL)** [18]
CATALYTIC PYROLYSIS

**VOLTACHEM (NL)** [18]
CATALYTIC PYROLYSIS

**Materia nova (BE)** [13]
PLASMA PYROLYSIS

**Hiirock (UK)** [14]
PLASMA PYROLYSIS

**Spark (FR)** [15]
PLASMA PYROLYSIS

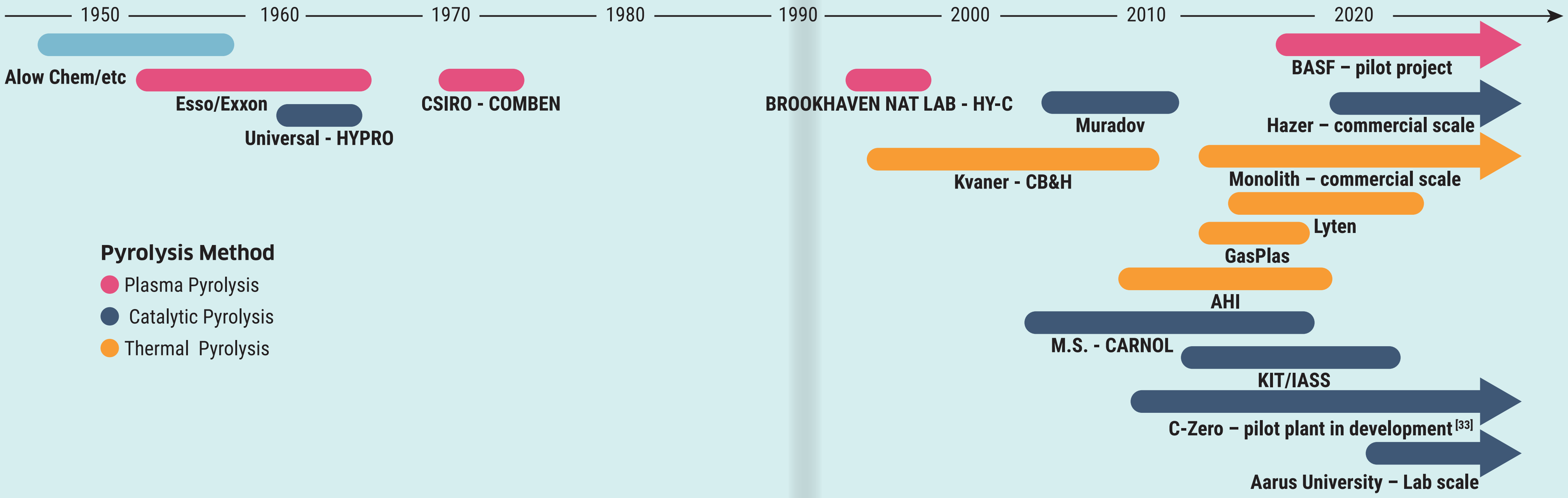
**Plenesys (FR)** [16]
PLASMA PYROLYSIS

**Sakowin (FR)** [17]
PLASMA PYROLYSIS

**Aarhus University (DK)** [21]
CATALYTIC PYROLYSIS
- Adaptation of turquoise hydrogen technology to biogas - 2025

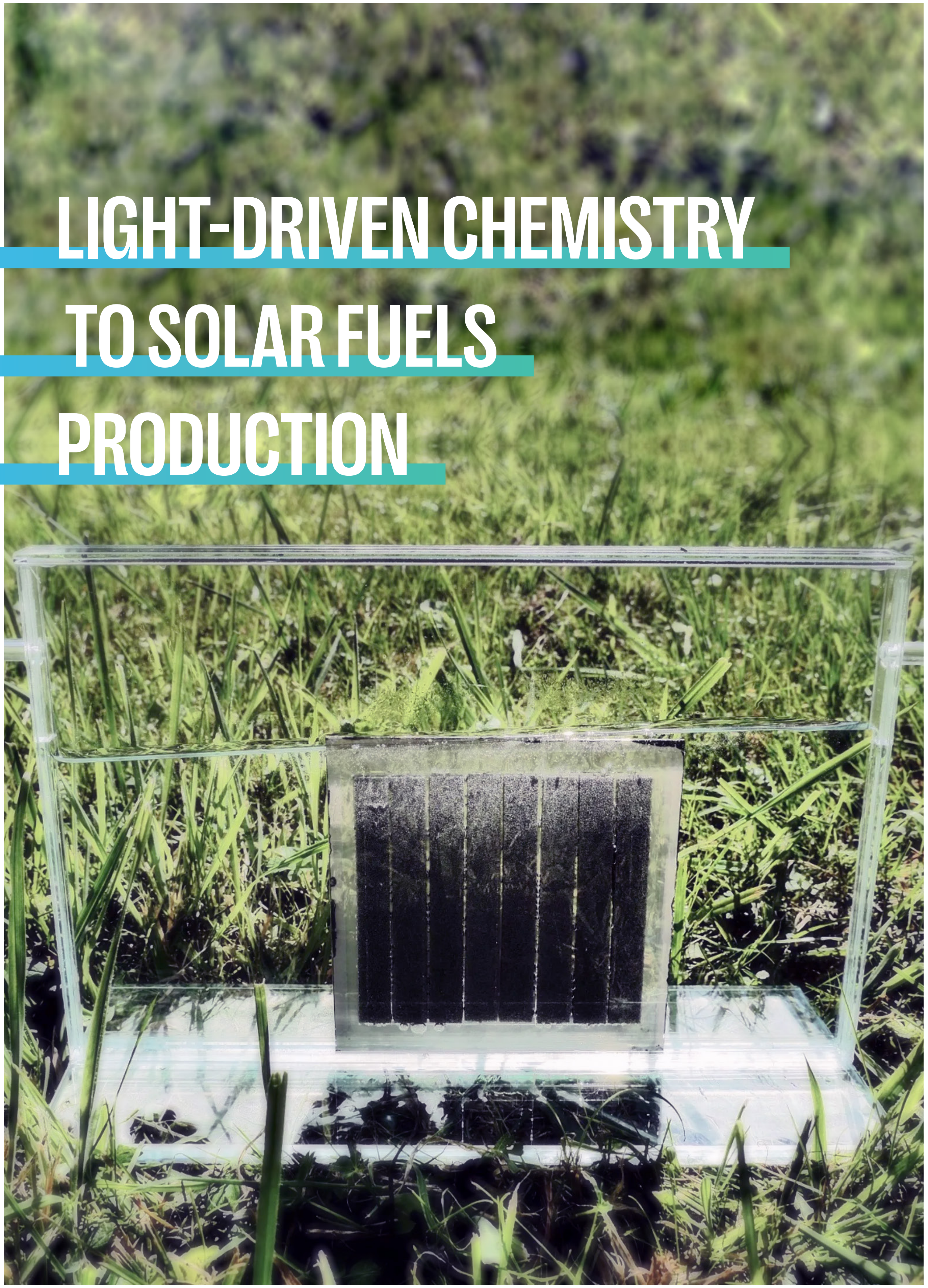
**BASF (DE)**
THERMAL PYROLYSIS
- FfPaG project - 2013-2017
  Thyssenkrupp / BFI / TU dortmund/ Linde/ hte / Federal Ministry of Education and Research
- Proof of concept 2019
  Thyssenkrupp / BFI / TU dortmund / RUB / RURH universitat BOCHUM / KIT
- Demonstration plant (DE) 2022
  Partners: SABIC, Linde [6-22]

**HAZER GROUP (AU) - The Hazer® Process**
CATALYTIC PYROLYSIS
Kwinana pilot plant (AU) - 2017
Burrard Hazer Hydrogen Project (CA)
Commercial demonstration project
Partners for Burrard project: FortisBC Energy Inc., Suncor Energy Inc. [19-20]



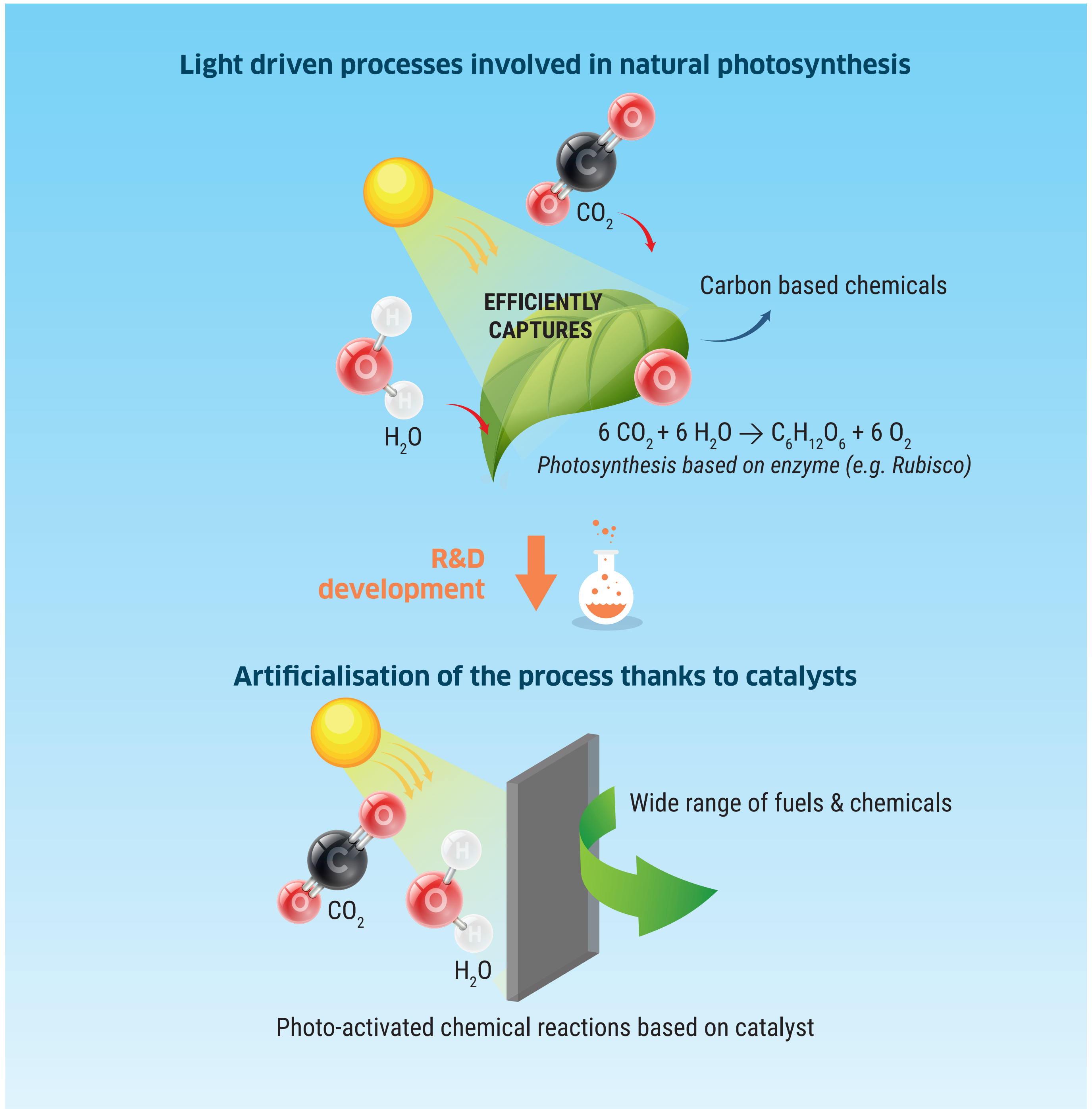
*Updated from [6]*

# LIGHT-DRIVEN CHEMISTRY TO SOLAR FUELS PRODUCTION



## Light-driven chemical synthesis.

"Photosynthesis efficiently captures solar energy, but its subsequent conversion into chemical energy in the form of biomass is limited in terms of efficiency in the range between 1 to 4%. Re-routing of photosynthetic electron transport and reducing power directly into desired pathways offers a sustainable production of high-value products." [1]

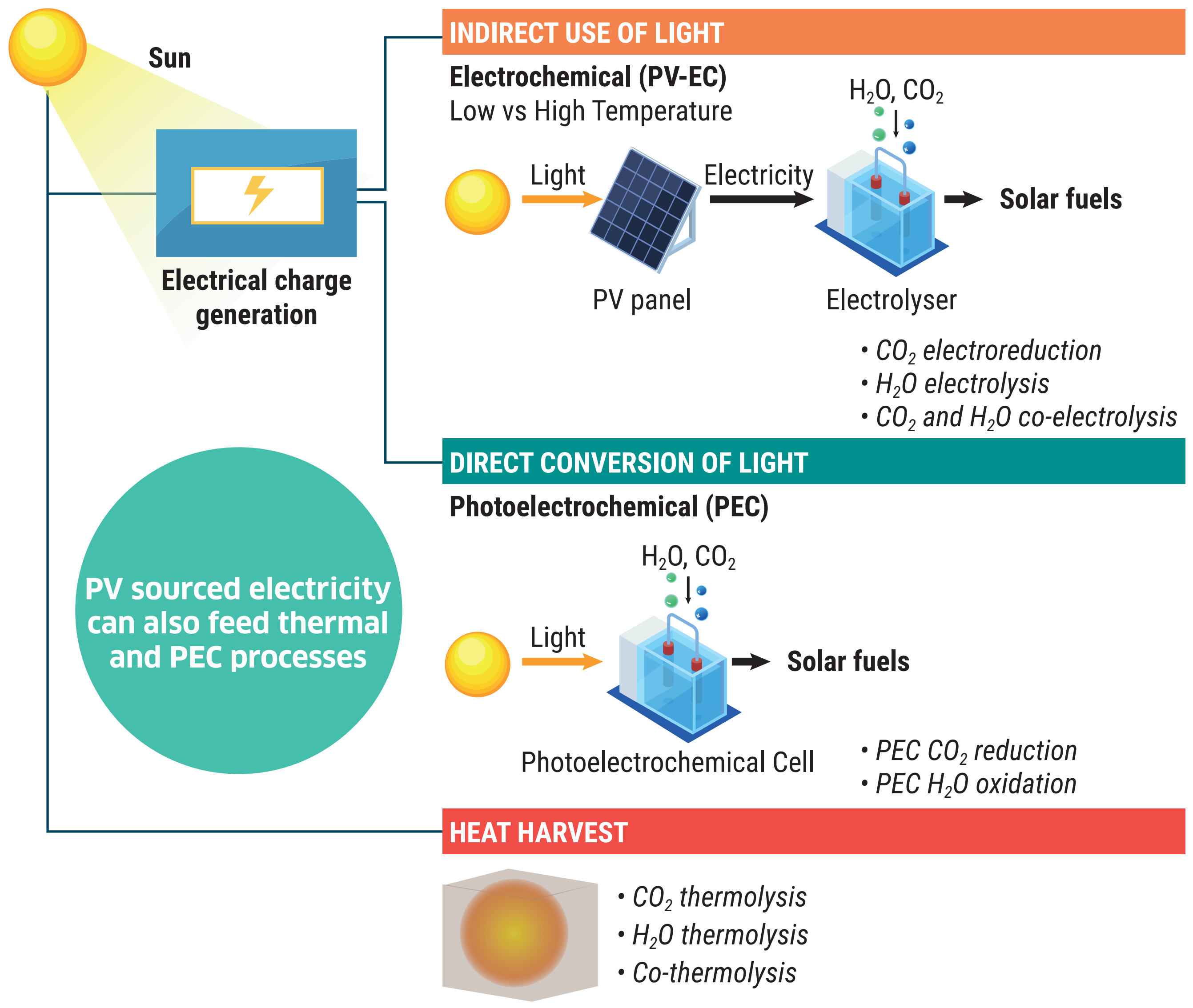


Source [1]

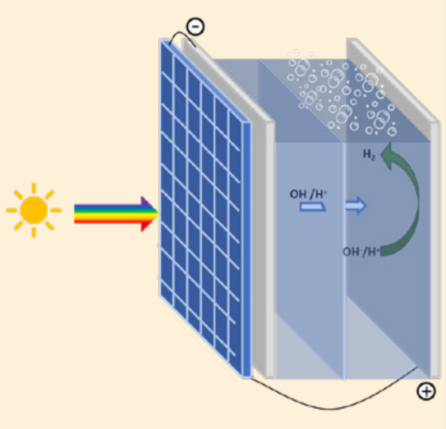
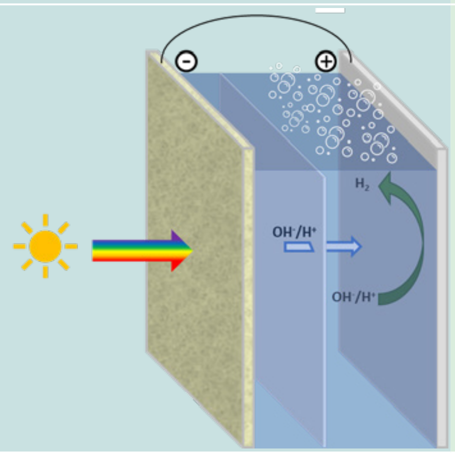
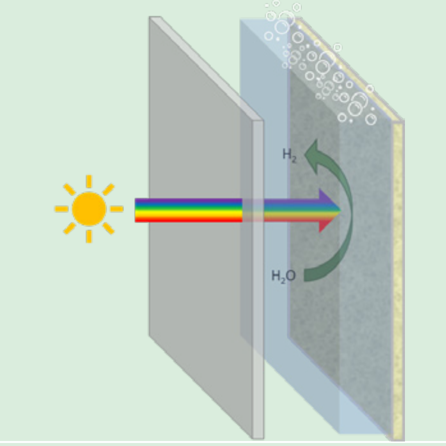
# What does it mean?

> “Solar fuels are fuels made from common substances like water and carbon dioxide using the energy of sunlight. Solar energy can be used through heat harvesting or electrical charge generation.” [2]

**Solar fuels =**
- **Hydrogen from $H_2O$**
- **Syngas,methane/methanol, formic acid, $C_2$+ liquid fuels...** from $CO_2$ / $CO_2 + H_2O$



# 3 main solar splitting processes to produce $H_2$.

| **Photovoltaic-electrochemical (PV-EC) system** | **Photoelectrochemical (PEC) system** | **Photocatalytic (PC) particulate system** |
|---|---|---|
| Mature technology | In development | Innovation |
|  |  |  |
| PV apparatus absorbs photons and generates power, which is transmitted to the EC cell, where electrodes perform redox reaction | Contains one or two photoelectrodes. Hence the light absorption and the redox reactions take place at the same location. | High specific surface photocatalyst |
| 👍 PV device is a relatively mature technology<br>👍 Light absorber can be outside of the aqueous solution, so no photo-corrosion issues<br>👍 2-compartement cell: easy chemical separation<br>👍 PV and EC systems can be freely modulated<br>👎 Two-step process: larger footprint, more raw material needed | 👍 Integrated one-step process: lighter footprint/ lower raw material needs<br>👍 2-compartement cell: easy chemical separation<br>👍 PV and EC systems can be freely modulated<br>👎 Light absorber in contact with solution: photocorrosion issues | 👍 Simplest system: no electrical circuit involved, no electrolyte needed<br>👍 Both reduction and oxidation reactions take place at the surface of particles, so the distance between the two sites is very limited, which favors efficiency and allows functioning without additional electrolyte<br>👎 Chemical separator is needed ($H_2$ and $O_2$ recombination is explosive!) |

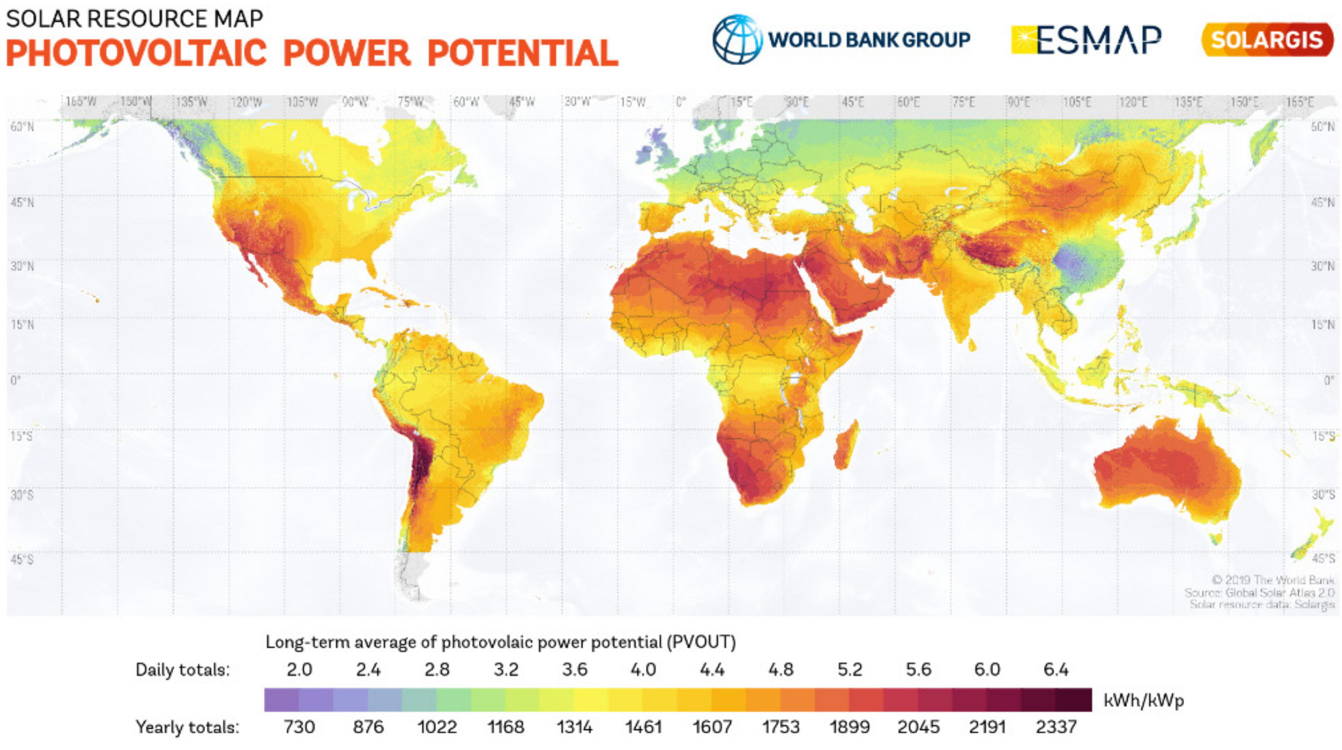
© ENGIE

Source [3]

# Long-term storage and long-distance transport of intermittent solar energy.

**Even if large scale electrification is part of most decarbonisation roadmaps, deployment of solar fuels technologies will still be needed for long-term storage and long-distance transport of intermittent solar energy into molecules.**

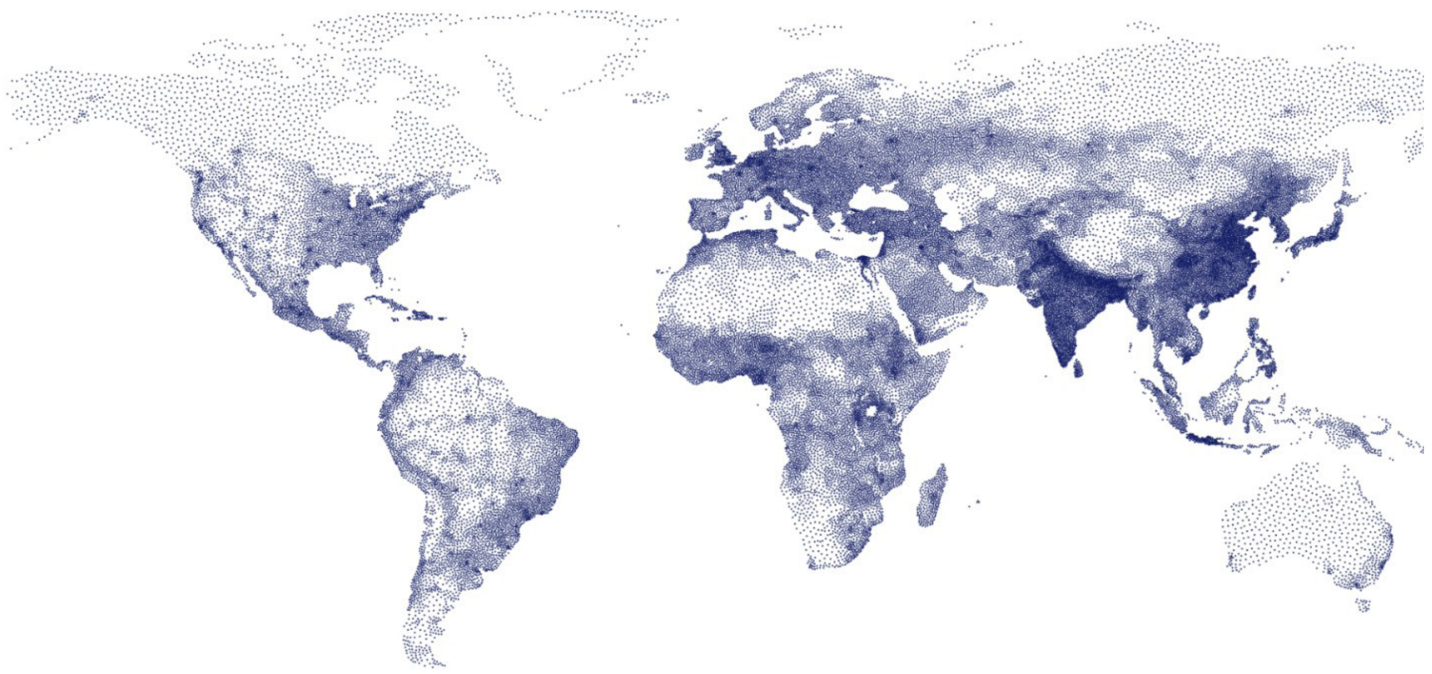
Indeed, world distribution of solar radiation does not match the population density distribution. Fuels become necessary for storage and long-distance transport of the harvested energy.



**Solar resource map: photovoltaïc power potential.**

*© 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.*

Taking advantage of unlimited and free solar energy is one of the primary goals of solar fuels.



**Population density map.** [4]

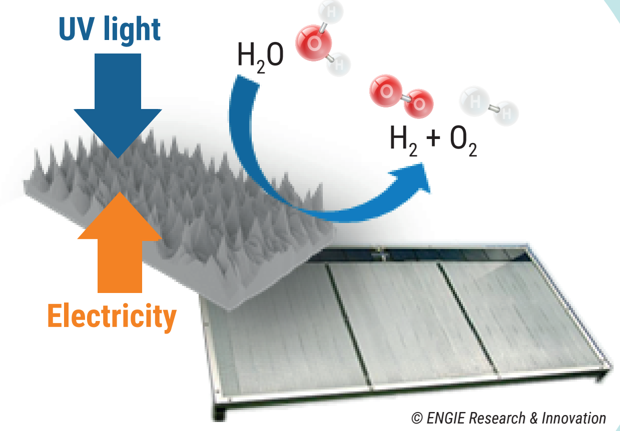
Areas receiving the greatest solar illumination are often not the most densely populated ones. Therefore, harvesting solar energy through solar fuels becomes essential.

Electrochemical $CO_2$ reduction technologies are not yet available on the market: while few large technology providers dominate the market on high-temperature electrolysis, **a surge of start-ups and R&D centers are positioning themselves on low-temperature electrolysis**.

With a much lower TRL, **$CO_2$-based PEC solar fuels are today mainly developed at prototype scale** by academics even if growing interest is observed from some industrial players, already positioned in $H_2$ production by PE.

## NanoH$_2$

ENGIE Research & Innovation works on solar-assisted electrolysis of hydrogen technology that allows the reduction of electrical cost of hydrogen by direct use of sunlight.



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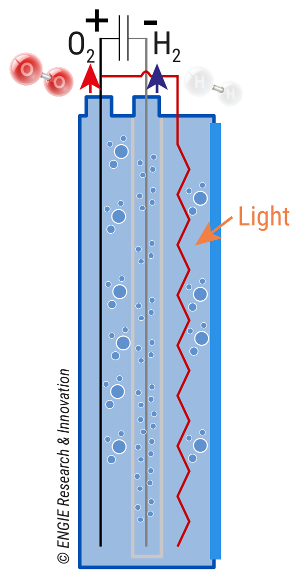


© ENGIE Research & Innovation

### Technological disruptions:

- **High scalability:**
  Panel design allows to precisely scale production capacity to customer needs.
- **High modularity:**
  Adding and removing panels to adjust the production capacity to customer needs.
- **Ease production of green hydrogen:**
  Green hydrogen production does not rely only on electrical mix.
- **Steppingstone:**
  Engineering solutions developed can be applied to fully photocatalytic systems once their durability and efficiency reaches industrial standards.

© AdobeStock

# Today, solar fuels solution are trusted by a European consortium while an increasing number of industrial players launch PEC $H_2$ production.

- **SUNER-C** an EU project for the coordination and the support action to accelerate the transition of technologies for the generation of solar fuels and chemicals [5]
- Members of the **SUNERGY** Community

**EUROPEAN COMMUNITY**

Horizon Europe CSA 'Innovation community for solar fuels and chemicals'

**2 CONSORTIUMS IN EUROPE H2020 PROJECTS**

**CO2NDOR**

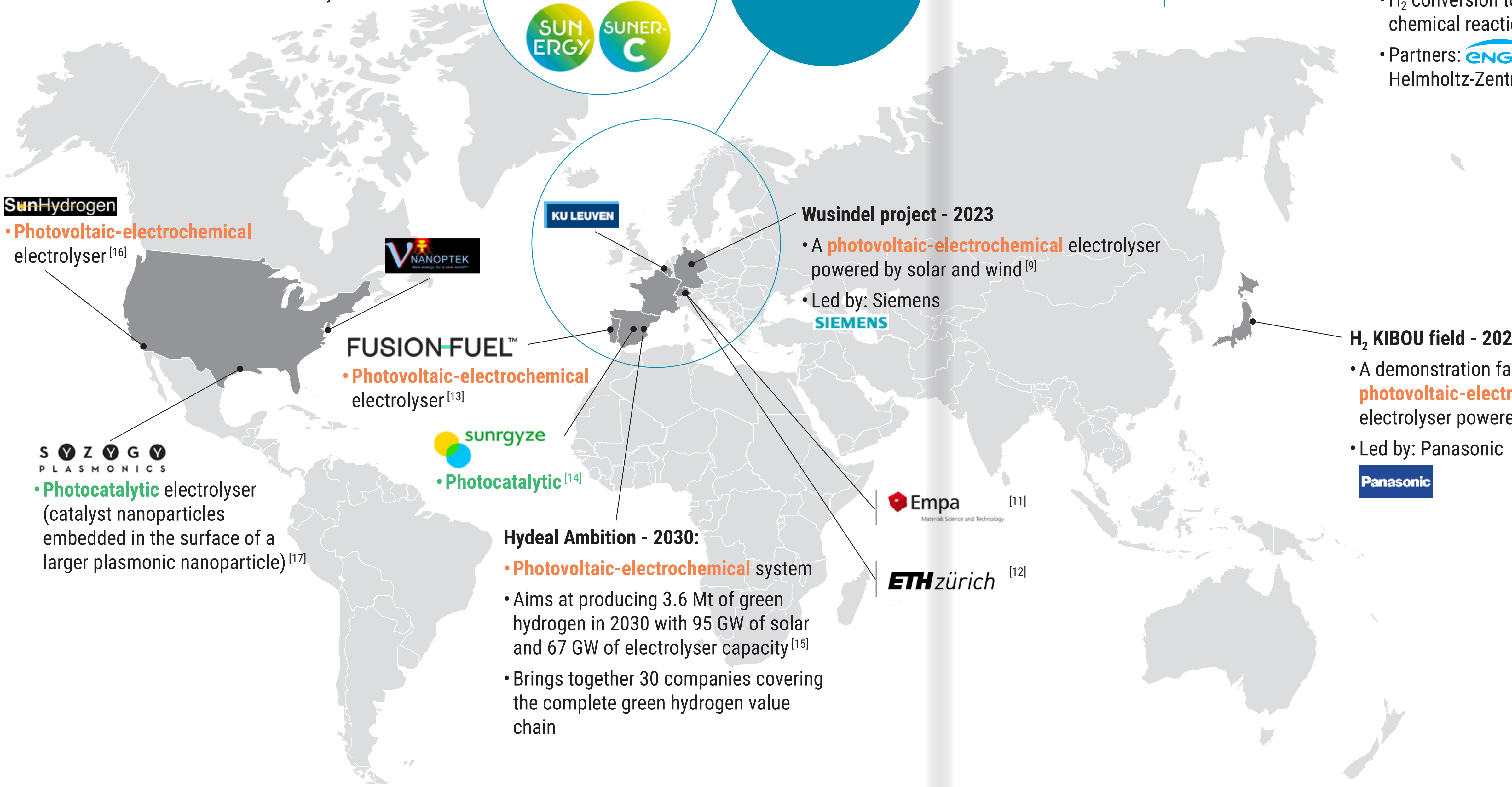
**Technology:**

- Flow photoelectrochemical cell for the production of $H_2$ and CO (syngas) and biomass valorisation
- **Photocatalytic** reactor for the conversion of syngas (produced in compartment 1) into fuel ($CH_3OH$ or DME) [6]
- Partners: ENGIE, University of Bologne, Catalan inst. for chemical research, national research council of Italy, Utrecht University, University of Ferrara, Hygear, Amires, The University of Carolina at Chapel Hill

**SUNtoX** Solar Energy for Carbon-Free Liquid Fuel

**Technology:**

- **Photoelectrochemical** process to produce $H_2$
- $H_2$ conversion to Hydrosil (liquid fuel) through chemical reaction [7]
- Partners: ENGIE, CEA, Differ, EPFL, Hysilabs, Helmholtz-Zentrum Berlin, Light Fuel, LGI Consulting



**SunHydrogen**

- **Photovoltaic-electrochemical** electrolyser [16]

**NANOPTEK**

**KU LEUVEN**

**Wusindel project - 2023**

- A **photovoltaic-electrochemical** electrolyser powered by solar and wind [9]
- Led by: Siemens

**FUSION FUEL**

- **Photovoltaic-electrochemical** electrolyser [13]

**SYZYGY PLASMONICS**

- **Photocatalytic** electrolyser (catalyst nanoparticles embedded in the surface of a larger plasmonic nanoparticle) [17]

**sunrgyze**

- **Photocatalytic** [14]

**Hydeal Ambition - 2030:**

- **Photovoltaic-electrochemical** system
- Aims at producing 3.6 Mt of green hydrogen in 2030 with 95 GW of solar and 67 GW of electrolyser capacity [15]
- Brings together 30 companies covering the complete green hydrogen value chain

**Empa** [11]

**ETH zürich** [12]

**$H_2$ KIBOU field - 2022:**

- A demonstration facility with a **photovoltaic-electrochemical** electrolyser powered by solar panels [8]
- Led by: Panasonic

# BIBLIOGRAPHY

## INTRODUCTION

[1] Drechsler C and Agar D W (2020) Intensified integrated direct air capture - power-to-gas process based on $H_2O$ and $CO_2$ from ambient air. *Applied Energy*, 273, 1150763. DOI: 10.1016/j.apenergy.2020.115076

[2] Wurzbacher J A, Gebald C , Piatkowski N and Steinfeld A. (2012) Concurrent Separation of $CO_2$ and $H_2O$ from Air by a Temperature-Vacuum Swing Adsorption/Desorption Cycle. *Environ. Sci. Technol.*46, 9191–9198. DOI: 10.1021/es301953k

[3] Elving J and Sainio T (2021) Kinetic approach to modelling $CO_2$ adsorption from humid air using amine-functionalized resin: Equilibrium isotherms and column dynamics. *Chemical Engineering Science*, 246, 116885. DOI: 10.1016/j.ces.2021.116885

## CRITICAL MATERIAL CHALLENGE: EXAMPLES OF TERAWATT SCALE PV AND BATTERIES

[1] Futuretimeline (2022) Solar power reaches 1 TW milestone. Available at: https://www.futuretimeline.net/blog/2022/03/24-solar-power-future-timeline.htm

[2] Kim T. Y. and al. (2022) The role of Criticla Minerals in Clean Energy Transitions. IEA. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary

[3] Bett A. and al. (2022) Photovoltaic report. Fraunhofer Institute for Solar Energy Systems with support of PSE Projects. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[4] Mikeska K. R., Lu M. and Liao W. (2019) Tellurium-based screen-printable conductor metallizations for crystalline silicon solar cells. Prog Photovolt Res Appl. 27: 1071– 1080. DOI: 10.1002/pip.3185

[5] Solar choice. How are Solar Panels made? What are they made of? List of Solar Panel components. Solar Choice. Available at: https://www.solarchoice.net.au/solar-power/how-are-solar-panels-made/

[6] Abdelilah Y., Bahar H. and Briens F. (2022) Solar PV Global Supply Chains – An IEA Special Report. IEA. Available at: https://www.iea.org/reports/solar-pv-global-supply-chains

[7] Frischknecht R. and Krebs L. (2021) Environmental life cycle assessment of electricity from PV systems. IEA. Available at: https://iea-pvps.org/wp-content/uploads/2021/11/IEA-PVPS-Task12-LCA-PV-electricity-_-Fact-Sheet.pdf

[8] IEA (2022) Global Supply Chains of EV Batteries. IEA. Available at: https://www.iea.org/reports/global-supply-chains-of-ev-batteries

[9] Guevara Opinska L. and al. (2021) Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis: final report. Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2833/946002

[10] Systematiq (2022) Critical raw materials for the energy transition in the EU: How circular economy approaches can increase supply security for critical raw materials. Systematiq. Available at: https://www.systemiq.earth/raw-materials-europe/

[11] Fischer M. and al. (2022) International Technology Roadmap for Photovoltaic (ITRPV) 2021 Results. Avaliable at: https://www.vdma.org/international-technology-roadmap-photovoltaic

[12] Goldschmidt J.C. and al. (2021) Technological learning for resource efficient terawatt scale photovoltaics. Energy Environ. Sci. 5147-5160. DOI: 10.1039/D1EE02497C

[13] Apollon star website. Avaliable at: https://en.apollonsolar.com/home

[14] Macé P., Bosch E. and Aleman M. (2021) Terawatt Scale PV by 2050 and Competition for Minerals: The Case of Silver and Copper. 38th European Photovoltaic Solar Energy Conference and Exhibition Brussels. Belgium. September 2021. pp 683-689. DOI:10.4229/EUPVSEC20212021-4CO.4.6

[15] Lee S. H. and al. (2017) Review of Conductive Copper Paste for c-Si Solar Cells. Korean J. Met. Mater. Vol. 55. No. 9. pp. 637-644. DOI:10.3365/KJMM.2017.55.9.637

[16] Heliateck. Heliasol(R) The innovative solar film. Heliateck. Available at: https://www.heliatek.com/en/technology/

[17] Jin C. et al (2021) Biomass-based materials for green lithium secondary batteries. Energy Environ. Sci.14 1326. DOI: 10.1039/D0EE02848G

[18] Majani d'Inguimbert C. and Clément B. (2018) World premiere in recycling photovoltaic panels. Veolia Group. Avaliable at: https://youtu.be/PaUlSZ2biI8

[19] Harper G. et al. (2019) Recycling lithium-ion batteries from electric vehicles. Nature. pp. 75–86 DOI: 10.1038/s41586-019-1682-5

[20] Searcey D., Forsythe M. and Lipton E. (2021) A Power Struggle Over Cobalt Rattles the Clean Energy Revolution. The New York Times. Avaliable at: https://www.nytimes.com/2021/11/20/world/china-congo-cobalt.html

## GEOENGINEERING

[1] Lawrence M. G. and al. (2018) Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. Nat Commun. DOI: 10.1038/s41467-018-05938-3

[2] Vaughan N. E. and Lenton T. M. (2011) A review of climate geoengineering proposals. Climatic change. DOI: 10.1007/s10584-011-0027-7

[3] Pavel I. (2022) Géo-ingénierie – Perspectives, limites et risques. Annales des Mines - Responsabilité et environnement. DOI: 10.3917/re1.105.0083

[4] Edenhofer O. and Madruga R. P. (2012) IPCC Expert Meeting on Geoengineering: Lima. Peru. 20-22 June 2011: Meeting Report. IPCC Working Group III Technical Support Unit. Available at: https://archive.ipcc.ch/pdf/supporting-material/EM_GeoE_Meeting_Report_final.pdf

[5] Lenton T. M. and Vaughan N. E. (2009) The radiative forcing potential of different climate geoengineering options. Atmos Chem Phys. DOI:10.5194/acp-9-5539-2009

[6] Leeds University (2014) Geoengineering our climate is not a 'quick fix'. Leeds University. Available at: https://www.leeds.ac.uk/news-environment/news/article/3631/geoengineering-our-climate-is-not-a-quick-fix

[7] IPCC. FAQ Chapter 4. IPCC. Available at: https://www.ipcc.ch/sr15/faq/faq-chapter-4/

[8] Denchak M. (2019) Greenhouse Effect 101. NRDC. Available at: https://www.nrdc.org/stories/greenhouse-effect-101

[9] Geoengineering.global. Advancing the mitigation of Climate Change and Global Warming through Geoengineering education and research. Geoengineering.global. Available at: https://geoengineering.global/solar-radiation-management/

[10] National Research Council (2015) Climate intervention: carbon dioxide removal and reliable sequestration. National Academies Press. DOI: 10.17226/18805.

[11] Burns L. and al. (2019) Technology Factsheet Series: Solar Geoengineering. Belfer Center for Science and International Affairs. Harvard Kennedy School. Available at: https://www.belfercenter.org/publication/technology-factsheet-solar-geoengineering

[12] Shukla P. R. and al. (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. DOI: 10.1017/9781009157926.001.

[13] Markusson N., Shackley S. and Evar B. (2012) The Social Dynamics of Carbon Capture and Storage: Understanding CCS Representations, Governance and Innovation. Routledge. ISBN 9781849713153

[14] Robock A. (2020) Benefits and risks of stratospheric solar radiation management for climate intervention (geoengineering). Bridge. Available at: https://www.nae.edu/19579/19582/21020/228883/228936/Benefits-and-Risks-of-Stratospheric-Solar-Radiation-Management-for-Climate-Intervention-Geoengineering

[15] Irvine P. J., Keith D. W. and Moore J. (2018) Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts. The Cryosphere. DOI: 10.5194/tc-12-2501-2018

[16] Sovacool B. K. (2021) Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering. Energy Strategy Reviews. DOI: 10.1016/j.esr.2021.100656

[17] Low S and al. (2013) Geoengineering policy and governance issues. In Geoengineering responses to climate change. pp. 169-191. Springer. DOI: 10.1007/978-1-4614-5770-1_8

[18] WWF. Solar geoengineering non-use agreement. WWF's Endorsement. Available at: https://www.solargeoeng.org/endorsements/wwf-france/

[19] Rochon E., Bjureby E., Johnston P. and. al. (2008). False Hope Why Carbon Capture and Storage Won't save the Climate. Green Peace. Available at: https://www.greenpeace.org/usa/wp-content/uploads/legacy/Global/usa/report/2008/5/false-hope-why-carbon-capture.pdf

[20] Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. pp. 442 Cambridge University Press, Cambridge. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

[21] Bastin J. F. and al. (2019) The global tree restoration potential. Science. 365(6448). pp. 76-79. DOI: 10.1126/science.aax0848

[22] Santos F. M. and al (2019) Bioenergy with Carbon Capture and Storage: Using Natural Resources for Sustainable Development. Elsevier. DOI:10.1016/C2017-0-04413-0

[23] Boyd P. and Vivian C. (2019) Should we fertilize oceans or seed clouds? No one knows. Nature. Available at: https://www.nature.com/articles/d41586-019-01790-7

[24] Vesta website. Avaliable at: https://www.vesta.earth/

[25] Chow C. (2020) Enhanced Weathering for Carbon Capture. Earth Org. Available at: https://earth.org/enhanced-weathering-for-carbon-capture/

[26] Energy capital the magazine (2021) Orca, biggest $CO_2$ Direct Air Capture plant starts operations in Iceland. Energy capital the magazine. Available at: https://energycapitalmedia.com/2021/09/08/orca-biggest-co$_2$-direct-air-capture-plant-starts-operations-in-iceland/

[27] Drax Power Station. Drax website. Available at: https://www.drax.com/about-us/our-sites-and-businesses/drax-power-station/

[28] SCoPEx: Stratospheric Controlled Perturbation Experiment. Keutschgroup at Harvard. Available at: https://www.keutschgroup.com/scopex

[29] Dongying, China: Growing Forests in Saline Soil (2017) The world bank. Available at: https://www.worldbank.org/en/news/video/2017/07/26/dongying-china-growing-forests-in-saline-soil

[30] Tollefson J. (2021) Can artificially altered clouds save the Great Barrier Reef?. Nature. DOI: 10.1038/d41586-021-02290-3

[31] Total (2021) Total and Forêt Ressources Management to Plant a 40,000-Hectare Forest in the Republic of the Congo. Total. Available at: https://totalenergies.com/media/news/press-releases/total-and-frm-to-plant-forest-in-congo

## NATURAL-BASED SOLUTIONS

[1] Fuss S. and al. (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. DOI: 10.1088/1748-9326/aabf9f

[2] Shukla P. R. and al. (2022) Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment. Report of the Intergovernmental Panel on Climate Change. IPCC. DOI: 10.1017/9781009157926.001.

[3] Lenton T. M. and Vaughan N. E. (2009) The radiative forcing potential of different climate geoengineering options. Atmos Chem Phys. DOI:10.5194/acp-9-5539-2009

[4] Leeds University (2014) Geoengineering our climate is not a 'quick fix'. Leeds University. Available at: https://www.leeds.ac.uk/news-environment/news/article/3631/geoengineering-our-climate-is-not-a-quick-fix

[5] Climate science (2022) Afforestation vs reforestation. Climate science. Available at: https://climatescience.org/advanced-reforestation-afforestation-tree-planting

[6] Kippar K. (2022) Reforestation lending a helping hand to our planet. Make it neutral. Available at: https://makeitneutral.com/reforestation/

[7] Lewis S. et al. (2019) Regenerate natural forests is the best way to remove atmospheric carbon. Nature. Available at: https://www.nature.com/articles/d41586-019-01026-8

[8] ENGIE (2022) AXA IM Alts, ENGIE and The Shared Wood Company join forces to develop nature-based solutions projects at scale. ENGIE. Available at: https://gems.engie.com/business-news/axa-im-alts-engie-and-the-shared-wood-company-join-forces-to-develop-nature-based-solutions-projects-at-scale/

[9] TotalEnergies (2022) Gabon: TotalEnergies and Compagnie des Bois du Gabon Join Forces to Develop a New Forest Management Model Combining Wood Production and Carbon Sink. TotalEnergies. Available at: https://totalenergies.com/media/news/press-releases/gabon-totalenergies-and-compagnie-des-bois-du-gabon-join-forces-develop

[10] Net Zero (2021) Whole Life Carbon Roadmap: A Pathway for the UK Built Environment. UK Green Building Council. Available at: https://ukgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2021/11/28194152/UKGBC-Whole-Life-Carbon-Roadmap-A-Pathway-to-Net-Zero.pdf

[11] de Coninck H. (2022) Global Warming of 1.5°C. Strengthening and Implementing the Global Response. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press. pp. 313-444. DOI: 10.1017/9781009157940.006

[12] Raynal J. (2022) Le biochar, ce nouvel or noir pour le climat qui fait rêver les industriels de la décarbonation. La tribune. Available at: https://www.latribune.fr/

[13] Pyreg website. Available at: https://pyreg.com/our-technology/

[14] IEA (2022) Bioenergy with Carbon Capture and Storage. IEA. Available at: https://www.iea.org/reports/bioenergy-with-carbon-capture-and-storage

[15] Budinis S. (2020) Going carbon negative: What are the technology options?. IEA. Available at: https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options

[16] Sutton-Grier A. E. and al. (2014) Incorporating ecosystem services into the implementation of existing U.S. natural resource management regulations: Operationalizing carbon sequestration and storage. Marine Policy. pp. 246-253. DOI: 10.1016/j.marpol.2013.06.003

[17] Bertram C. and al. (2021) The blue carbon wealth of nations. Nat. Clim. Chang. pp. 704–709. DOI: 10.1038/s41558-021-01089-4

[18] The Nature Conservancy (2016) Mapping ocean wealth. The Nature Conservancy. Available at: https://oceanwealth.org/wp-content/uploads/2016/06/BlueCarbon_InfoGraph.png

[20] Naylor D., Sadler D. and Bhattacharjee A. (2020) Soil Microbiomes Under Climate Change and Implications for Carbon Cycling. Annual Review of Environment and Resources. DOI: 10.1146/annurev-environ-012320-082720

[21] Griscom B. W. and al. (2017) Natural climate solutions. Proceedings of the National Academy of Sciences. Vol. 114. No. 44. DOI: 10.1073/pnas.1710465114

[22] Griscom B. W. and al. (2019) We need both natural and energy solutions to stabilize our climate. Glob Change Biol. pp. 1889-1890. DOI: 10.1111/gcb.14612

## SOLAR SPACE POWER

[1] Frazer Nash (2021) Report Space Based Solar Power – De-risking the pathway to Net Zero. Frazer-Nash Consultancy. Avaliable at: https://www.fnc.co.uk/media/e15ing0q/frazer-nash-sbsp-executive-summary-final.pdf

[2] Solteau M (2021) Space Solar Power – the UK Study and the Space Energy Initiative. ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[3] Mankins J C (2021) SPS-ALPHA and the Economics of Space Solar Power, Initiative. ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[4] Baycan S (2021) Space Solar Power - The Australian Context, International workshop on Space-Based Solar Power for Net-Zero, ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[5] Ian Cash M (2021) CASSIOPEIA SPS, Space Based Solar Power for Net Zero, ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[6] HOU X and Li M (2021) Activities of SPS Development in China, ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[7] Tanaka K (2021) Efforts to develop solar power satellite in Japan over the past 10 years. ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[8] ChoiJ M (2021) Net Zero Scenario and Status of Space Based Solar Power, Research in Korea. ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

[9] Greenmatch (2020) Space-Based Solar Power: The Future Source of Energy?. 12 July 2022. Available at: https://www.greenmatch.co.uk/blog/2020/02/space-based-solar-power

[10] Radulovic J (2022) A solar power station in space? Here's how it would work – and the benefits it could bring. The conversation. Available at: https://theconversation.com/a-solar-power-station-in-space-heres-how-it-would-work-and-the-benefits-it-could-bring-179344

[11] Makaya A (2021) Clean Energy - New Ideas for Solar Power from Space, Summary of ESA OSIP Campaign, ESA Space Based Solar Power for Net Zero 2050 Workshop 2021. Webex. 9-10 December 2021. ESA ESTEC. Available at: https://indico.esa.int/event/399/

## PYROLYSIS FOR TURQUOISE HYDROGEN?

[1] Diab J. et al. (2022) Why turquoise hydrogen will Be a game changer for the energy transition. International Journal of Hydrogen Energ. DOI: 10.1016/j.ijhydene.2022.05.299

[2] Internal source / Baraton L. (2021) TPP Hydrogen Production. ENGIE. Available at: https://engie.sharepoint.com/sites/ExpertCentre/TPP/SiteAssets/TPP $H_2$ Production 2021-12-24 Final version.pdf

[3] Mann D. (2022) Methane pyrolysis: An alternative route to low-carbon hydrogen production. IHS Markit. Available at: https://connect.ihsmarkit.com/document/show/phoenix/4475642?connectPath=Search&searchSessionId=d70ca5e0-6c2f-4304-9435-16f42cb27817

[4] Monolith brochure (2021) Monolith Materials inc. Avaliable at: https://monolith-corp.com/storage/documents/Corporate-Brochure-LoRes.pdf

[5] McFarland E. and al. (2019) $H_2$ Focus Programs OF C-Zero. Methane Pyrolysis Cohort. 10 December 2019. Houston. Texas. Available at: https://arpa-e.energy.gov/sites/default/files/9%2010%20H2%20Performers%20C-Zero_Comprssed.pdf

[6] Daloz W. and al. (2019) The quest for $CO_2$ -free hydrogen – methane pyrolysis at scale Methane Pyrolysis Cohort. 10 December 2019. Houston. Texas. Available at: https://arpa-e.energy.gov/sites/default/files/1%20Scale%20up%20BASF.pdf

[7] Lentech. Activated Carbon. Lentech. Available at: https://www.lenntech.com/products/activated-carbon.html

[8] Von Keitz M. (2019) ARPA-E/DOE Methane Pyrolysis Cohort Kickoff. Methane Pyrolysis Cohort. 9 December 2019. Houston. Texas. Available at: https://arpa-e.energy.gov/sites/default/files/1%20Marc%20Von%20Keitz..pdf

[9] Fulccheri L. (2022) Turquoise hydrogen takes a step towards the next level. Polytechnic insights. Available at: https://www.polytechnique-insights.com/en/columns/energy/turquoise-hydrogen-takes-a-step-towards-the-next-level/

[10] Mesrobian C. (2019) Taking Methane Pyrolysis from Concept to Industrial Plant. Methane Pyrolysis Cohort. 9 December 2019. Houston. Texas. Available at: https://arpa-e.energy.gov/sites/default/files/2021-01/08%20OK%20-Monolith_ARPAE_MethanePyrolysis2021_v3.pdf

[11] Saadi F. (2022) Methane pyrolysis: producing hydrogen without carbon emissions, $H_2$ Focus Programs OF CZero. Methane Pyrolysis Cohort. Webex. 12 January 2022. https://arpa-e.energy.gov/sites/default/files/2022-01/7x%20-%20CZero%20ARPA-E%20Annual%20Meeting%202022.pdf

[12] C-Zero (2019) C-Zero Announces Project with SoCalGas and PG&E. C-Zero. Available at: https://www.czero.energy/post/c-zero-announces-project-with-socalgas-and-pg-e

[13] Materia Nova website. Available at: https://www.materianova.be/fr/

[14] Hiiroc website. Available at: https://hiiroc.com/

[15] Université Paris Saclay (2021) SPARK: Réduire les émissions de $CO_2$ et décentraliser la production. Université Paris Saclay. Available at: https://www.universite-paris-saclay.fr/actualites/spark-reduire-les-emissions-de-co$_2$-et-decentraliser-la-production-dhydrogene

[16] Plenesys website. Available at: https://plenesys.com/fr/

[17] Sakowin website. Available at: https://sakowin.com/

[18] TNO website. Available at: https://www.tno.nl/en/

[19] Hazer group website. Available at: https://hazergroup.com

[20] Zohaib A. (2022) Burrard Hazer hydrogen project secures funding. $H_2$ Bulletin. Available at: https://www.h2bulletin.com/burrard-hazer-hydrogen-project-secures-funding/

[21] Petersen J. B. (2022) New project will design first Danish reactor for carbon negative hydrogen production from biogas. Aarhus university. Available at: https://bce.au.dk/en/currently/news/show/artikel/ny-teknologi-giver-co$_2$-negativ-brintproduktion-fra-biogas

[22] BASF (2022) BASF, SABIC and Linde start construction of the world's first demonstration plant for large-scale electrically heated steam cracker furnaces. BASF. Available at: https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2022/basf-sabic-and-linde-start-construction-of-the-worlds-first-demonstration-plant-for-large-scale-electrically-heated-steam-cracker-furnaces.html

## LIGHT-DRIVEN CHEMISTRY TO SOLAR FUELS PRODUCTION

[1] Jensen K., Jensen P.E. and Moller B.L. (2012) Light-driven chemical synthesis. Trends in plant science. pp. 60-63. DOI: 10.1016/j.tplants.2011.12.008

[2] Office of Science. DOE Explains...Solar Fuels. Office of science. Available at: https://www.energy.gov/science/doe-explainssolar-fuels

[3] Internal source / Baraton L. (2021) TPP Hydrogen Production. ENGIE. Available at: https://engie.sharepoint.com/sites/ExpertCentre/TPP/SiteAssets/TPP $H_2$ Production 2021-12-24 Final version.pdf

[4] Which global cities have the highest population densities? (2019) enterprise the state of the nation. Available at: https://enterprise.press/stories/2019/03/20/which-global-cities-have-the-highest-population-densities/

[5] Sunergy website. Available at: https://sunergy-initiative.eu/

[6] Condor website. Available at: https://condor-h2020.eu/

[7] Sun to X website. Available at: https://sun-to-x.eu/project-partners/

[8] Panasonic Corporation (2022) Panasonic to Begin Operating $H_2$ KIBOU FIELD Demonstration Facility Utilizing Pure Hydrogen Fuel Cell Generators. Panasonic Corporation. Available at: https://news.panasonic.com/global/press/en220427-1

[9] Siemens (2022) Siemens commissions one of Germany's largest green hydrogen generation. Siemens AG. Available at: https://press.siemens.com/global/en/pressrelease/siemens-commissions-one-germanys-largest-green-hydrogen-generation-plants

[10] KU Leven (2019) KU Leuven scientists crack the code for affordable, eco-friendly hydrogen gas. KU Leven. Available at: https://nieuws.kuleuven.be/en/content/2019/belgian-scientists-crack-the-code-for-affordable-eco-friendly-hydrogen-gas

[11] Empa website. Available at: https://www.empa.ch

[12] ETH Zurih. Electrochemistry Homepage. ETH Zurich. Available at: https://electrochemistry.ethz.ch/

[13] Fusion fuel website. Available at: https://www.fusion-fuel.eu/

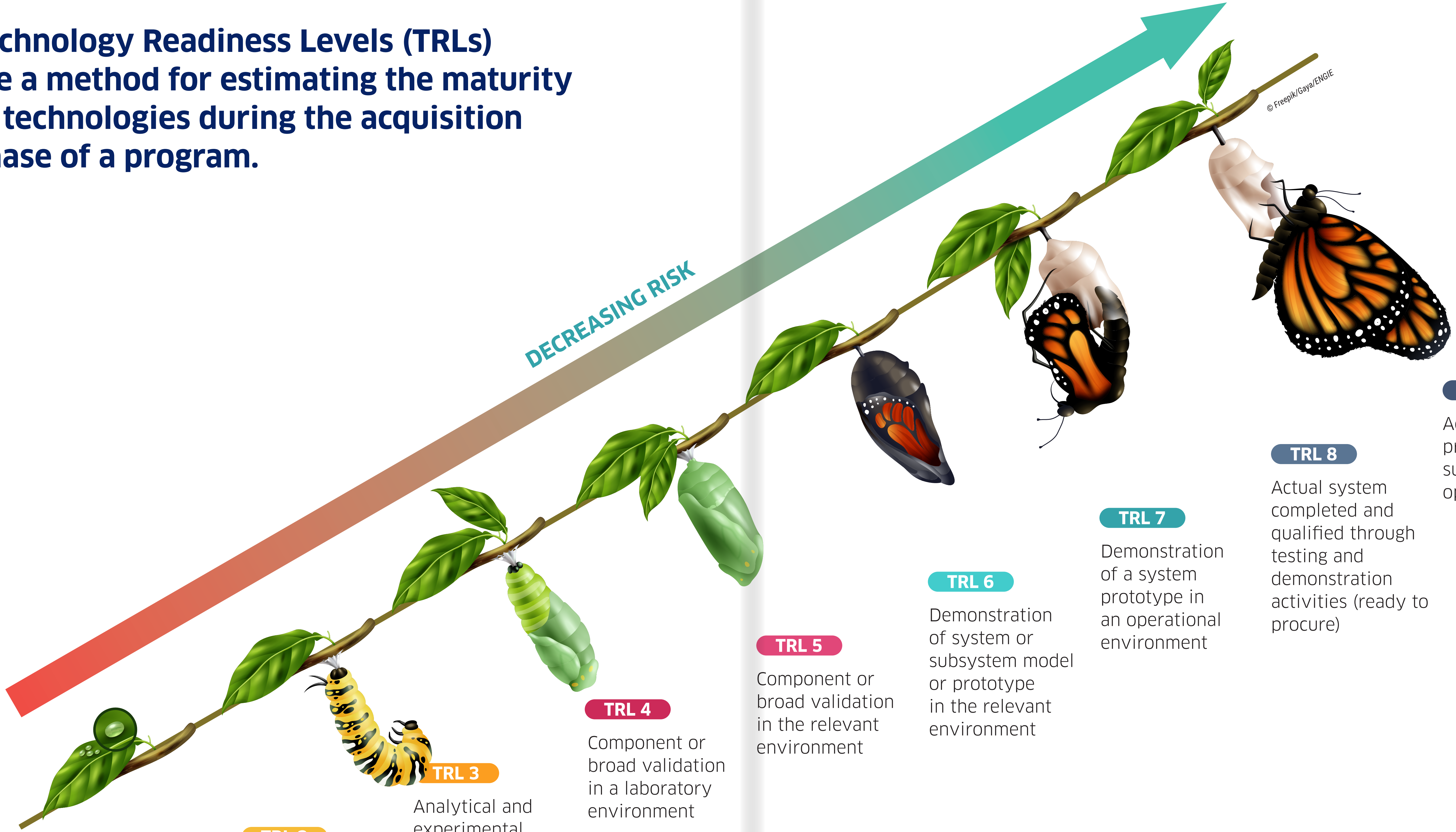
[14] Sunergyse website. Available at: https://sunrgyze.com/en/

[15] Hydeal Ambition website. Available at: https://www.hydeal.com

[16] Sunhydrogen website. Available at: https://www.sunhydrogen.com/technology

[17] Syzygy website. Available at: https://plasmonics.tech/photoreactor-technology

# Technology Readiness Levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program.



**TRL 1**

Basic principles observed and reported

**TRL 2**

Technology concepts or applications (or both) formulated

**TRL 3**

Analytical and experimental critical function or characteristic proof of concept (or both)

**TRL 4**

Component or broad validation in a laboratory environment

**TRL 5**

Component or broad validation in the relevant environment

**TRL 6**

Demonstration of system or subsystem model or prototype in the relevant environment

**TRL 7**

Demonstration of a system prototype in an operational environment

**TRL 8**

Actual system completed and qualified through testing and demonstration activities (ready to procure)

**TRL 9**

Actual system proven through successful operations (O&M)

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