ENGIE Research

Emerging Sustainable Technologies

2021 Edition

External version

Emerging Sustainable Technologies

Edition 2021

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Editorial

How were the technologies selected?

Current efforts to limit global warming to 2 degrees above pre-industrial levels, as agreed in 2015 at the COP 21 in Paris, are insufficient.

The IPCC 2021 report — like all other forecasting efforts — makes no mention of possible breakthrough technologies which could emerge and speed up our pathway to carbon neutrality. One could consider this a conservative approach, justified by the huge difficulty of predicting the next technology breakthroughs and their potential.

In this Emerging Sustainable Technologies 2021 document we present topical areas we think will offer non-trivial benefits for this transition. ENGIE does not only keep a close eye on their development but also has the ambition to help bring some of these technologies to the market at an increased pace through piloting and demonstrating.

How did we select these technologies? We have tried several methods to pick them in an ‘objective’ manner using quantitative indicators such as the number of publications and of patents, mentions in other reports and in press releases. However, we have not found any one quantitative method that was satisfying on its own.

In fact, using ‘objective’ quantitative measures results in mostly digital solutions dominating the selection due to the enormous work being carried out worldwide on our digital transformation. If ENGIE adopted the same approach we would, in effect, all be reporting the same and add little value.

Instead, we decided to trust the insights of our ENGIE experts in a wide variety of domains to compile this selection. This approach implies a degree of subjectivity, reflecting our unique ENGIE expertise in game-changing scientific and technological trends in energy-related activities.

Editorial

What happened to the technologies featured in previous reports?

For the first time this year, we look back at technologies we highlighted in previous editions of this report.

A qualitative evaluation is given based on our experts' insights into the technologies that are constantly evolving. In this second part of the report, we illustrate how many of these technologies have rapidly gained in maturity, enhancing their potential to speed up our pathway to carbon neutrality and prove the roadmaps wrong.

Others, meanwhile, either mature at a slower speed or fail to live up to the expectations they raised at the time — a reminder how notoriously difficult it is to accurately evaluate the potential of new technologies. It also means we have to be ready to change direction if early hopes are not fulfilled.

No technology has the potential to rise to this challenge on its own. It is therefore essential to explore a variety of solutions relating to energy production, transport, storage and use.

The challenge is also too vast for a single person/company/sector to handle on their own — working together is key.

The main purpose of this document is to help inspire a new sense of collaboration between all the players in this hugely important endeavour.

Dr. Jan Mertens,
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Disclaimer: please note that the incorporation of a certain technology does not imply that it is part of ENGIE's strategy towards carbon neutrality.

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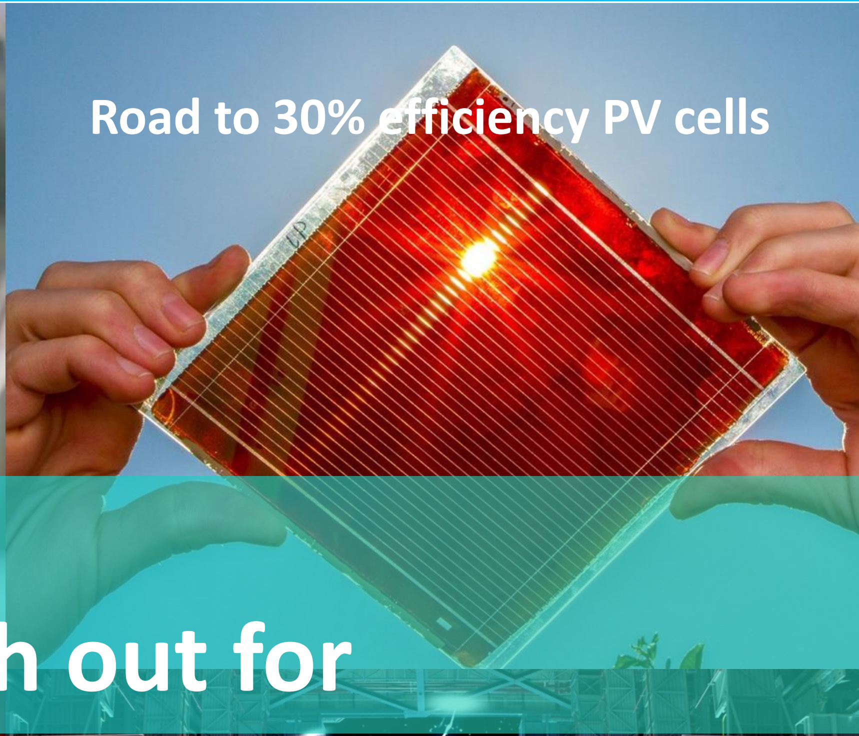
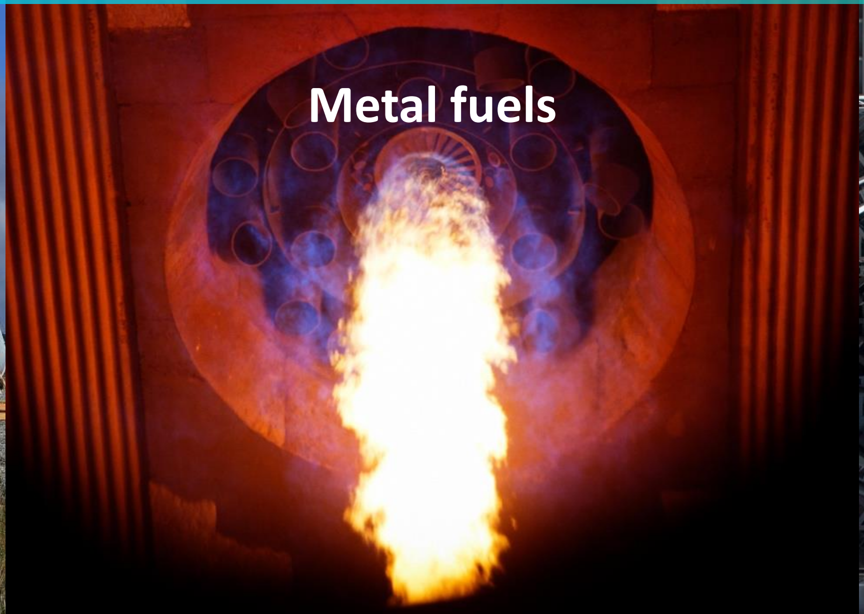
PART 1
New emerging technologies to watch out for



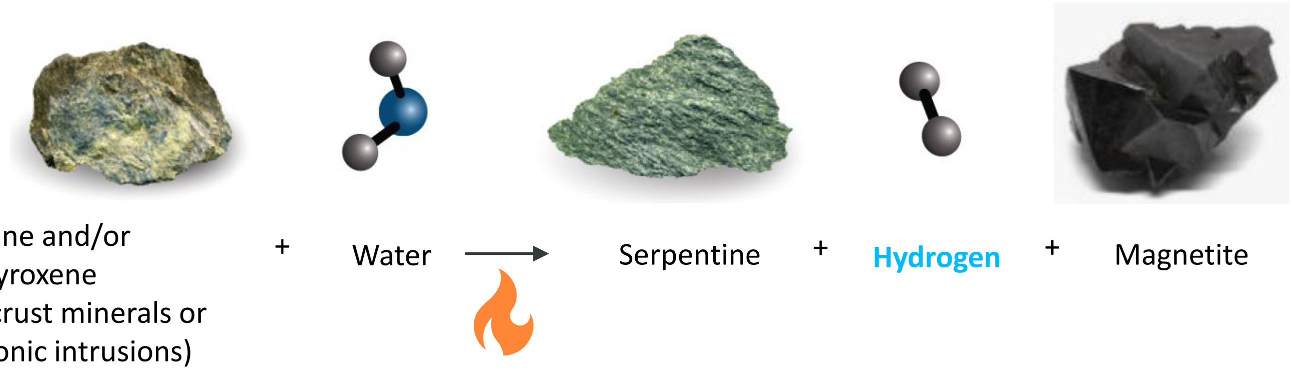


Natural hydrogen

Natural hydrogen is generated by natural geochemical processes inside the Earth's crust

Water plays a key role in the natural hydrogen cycle

A REDOX REACTION BETWEEN MINERALS AND WATER CAN PRODUCE H_2



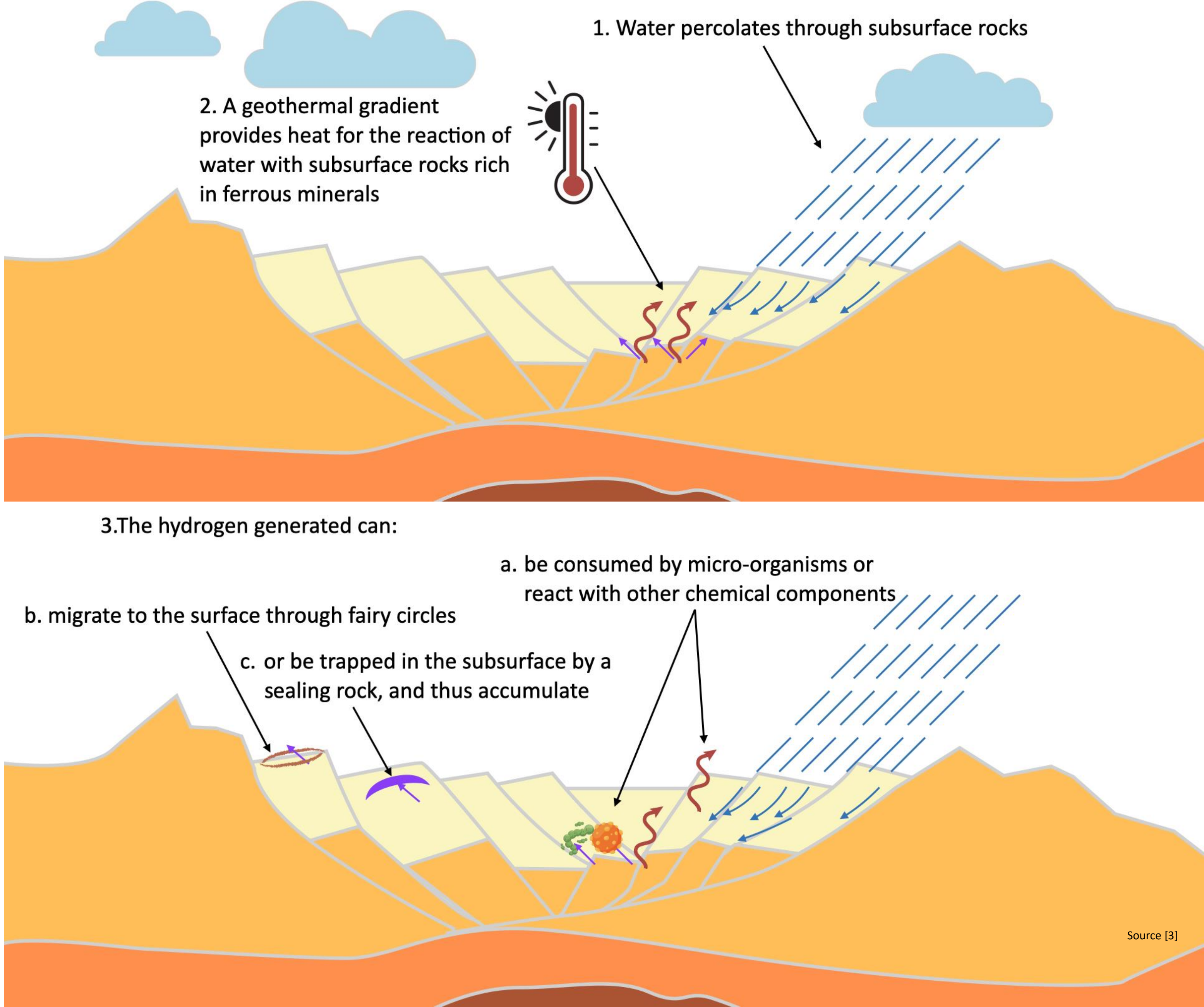
Olivine and/or Pyroxene (Oceanic crust minerals or intracratonic intrusions) + Water → Serpentine + **Hydrogen** + Magnetite

Heat from geothermal gradient

- The Earth is at the heart of iron oxide redox reactions between ferrous minerals and water percolating in the subsurface to generate H_2 via serpentinization reactions.
- Natural hydrogen leakages are estimated by extrapolation at several Mt/y (same order of magnitude as current annual hydrogen consumption ~70 Mt/y).

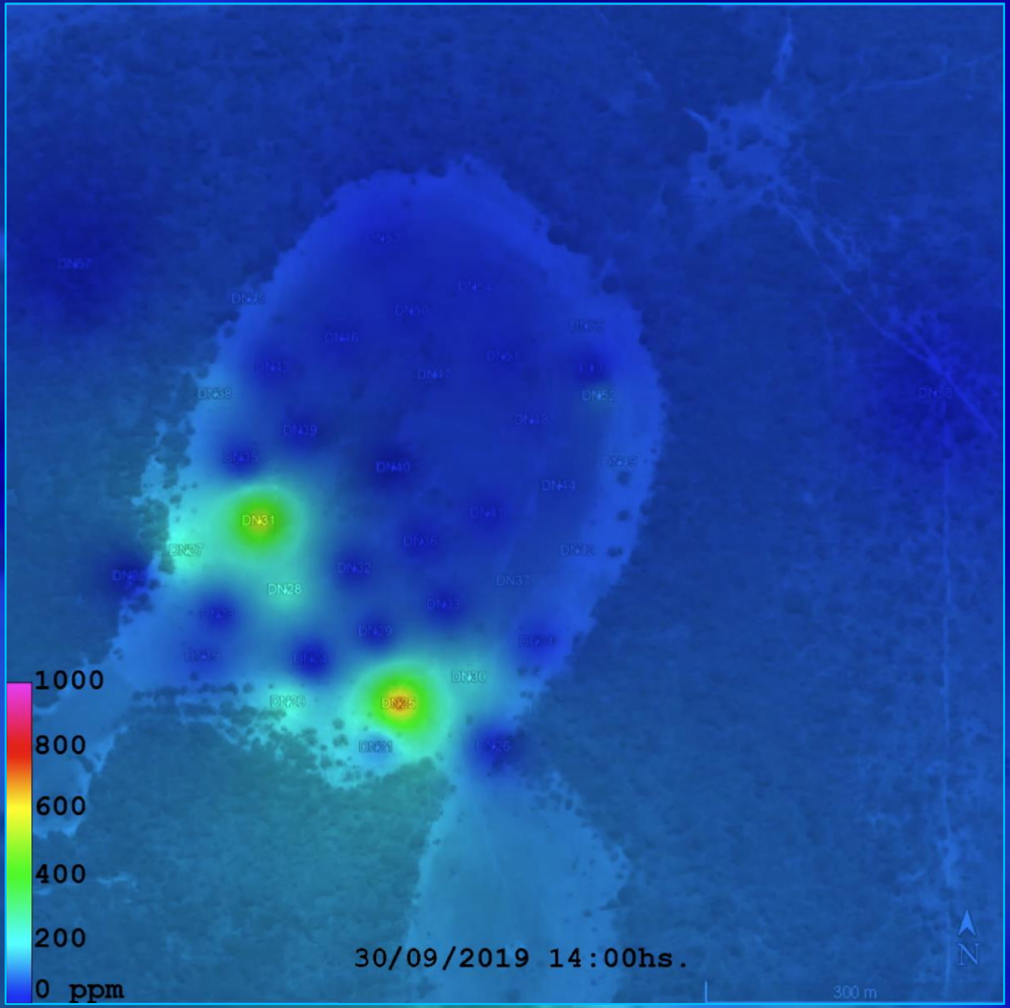
Hydrogen emissions from rocks containing ferrous minerals in an onshore bassin [1] (see above) or along medio-oceanic ridges [2] (see below).

The hydrogen system: generation, migration, accumulation and emissions from the surface



Source [3]

Long-term monitoring of natural H_2 superficial emissions in Brazil

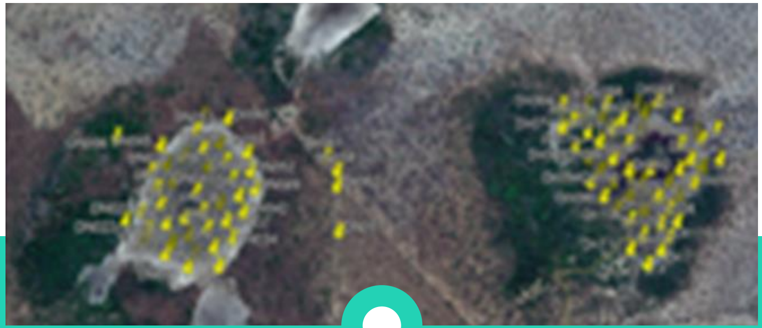


Monitoring allows a more precise evaluation of the quantity of H_2 released at surface level by structures known as fairy circles. Quantity is estimated at several hundred of kilos per day confirming the high H_2 potential of the São Francisco basin [4]. Researchers are still working to understand this phenomenon [5].

Why produce natural hydrogen when there are already a multitude of ways to produce it?

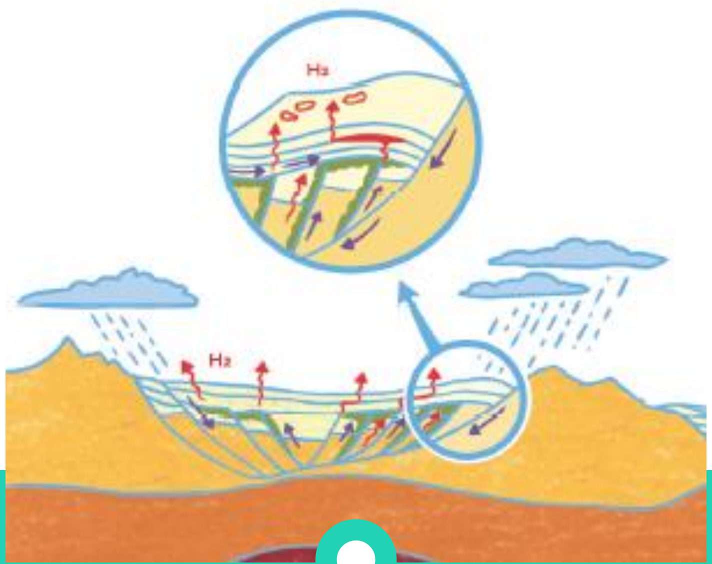
Advantages

- Continuous production: hydrogen could be produced continuously with large volumes permanently replenished.
- Dedicated sensors have been developped to identify prospective areas (TRL 7-8). Existing geophysical data is often used to make the link with the subsurface (TRL 9).
- Exploration & Production tools and technologies can be reused (TRL 9).
- Low cost onshore and low carbon production.
- Low footprint on the ground.



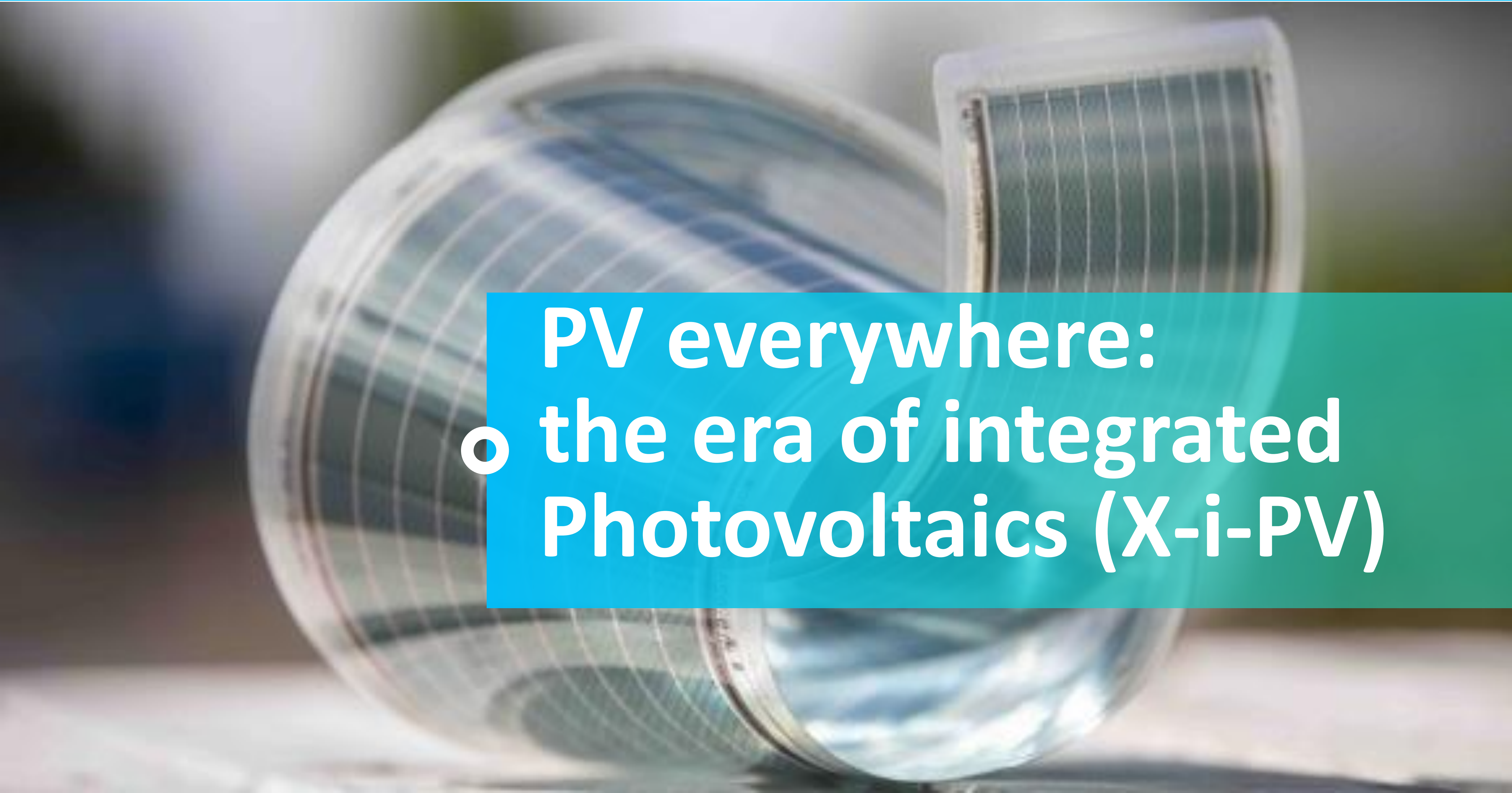
Challenges

- Hydrogen generation and potential trapping needs to be better understood (TRL 3-4).
- The hydrogen system still needs to be proven by drilling wells.
- Rates and volumes may not be economical (TRL 3-4).



Challenges to overcome through:

- Research programs are necessary in order to better understand mechanisms and model each brick.
- Need to participate in practical projects to demonstrate potential and get a global vision of accumulation mechanisms.

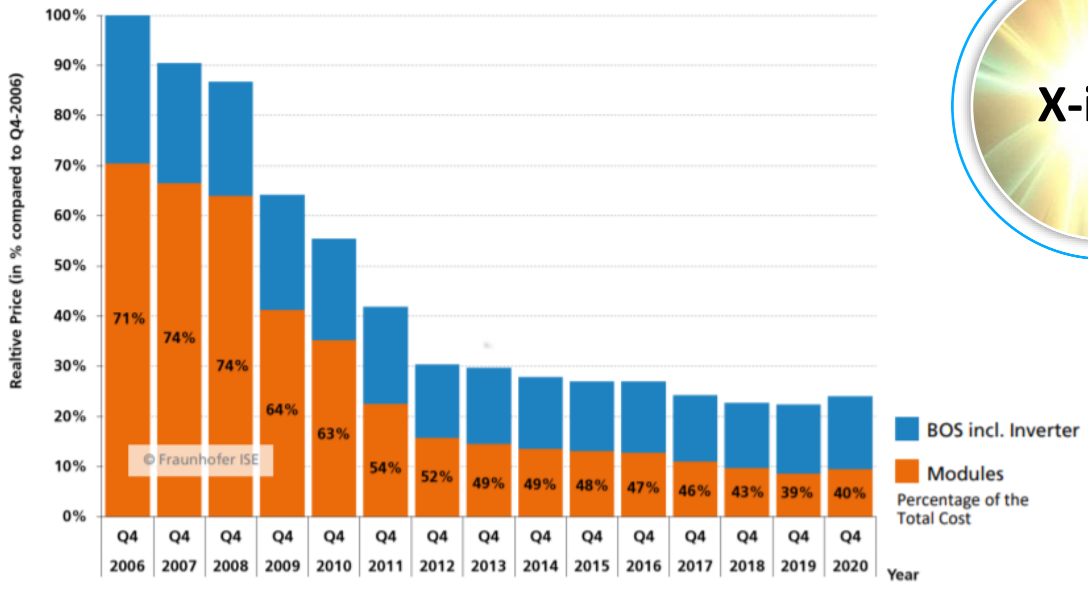


PV everywhere: the era of integrated Photovoltaics (X-i-PV)

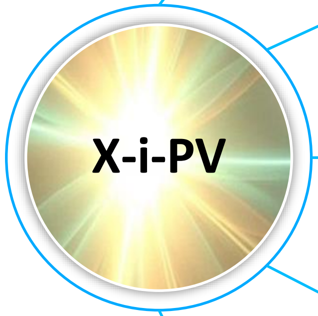
The significant and continuing fall in PV prices is facilitating the development of a multitude of new applications

PRICES DIVIDED BY ALMOST 5 IN THE LAST 10 YEARS

- When solar PV modules are installed on windows, walls, agriculture, light-roof structures etc. requirements other than efficiency need to be taken into account: weight, flexibility, color, transparency…



Price development for PV Rooftop Systems in Germany (10kWp – 100kWp) [6]



Floating PV

- A photovoltaic installation mounted on a floating structure

Vehicle integrated PV (VIPV)

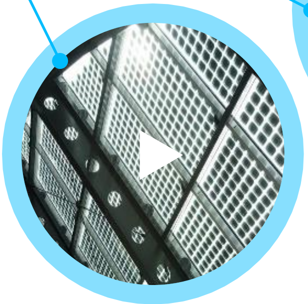
- A PV installation integrated into the vehicle, connected to electric loads or batteries in electric vehicles

Agri PV

- PV combined with standard structures (e.g. greenhouses)
- Intensify the land use (crops harvesting and energy generation)

Infrastructure integrated PV (IIPV)

- Refers to embedding solar power in infrastructures such as: noise barriers, carports, streetlights etc.



Building integrated PV (BIPV)

- PV used to replace conventional building materials in parts of the building envelope such as the roof, skylights, windows or facades

Sources [7], [8], [9], [10], [11]

Despite their common goal of optimising land use to produce energy, X-i-PV encompasses very different realities



	AGRI PV	FLOATING	BIPV
ADVANTAGES	• Lessen the competition for land use between growing food and generating energy in densely populated areas [12] • Create favorable environments for crops (shade, temperature, humidity conditions) [12] • Bring additional revenues to farmers at marginal cost either thanks to electricity generation (self consumption), crops (quality/quantity), land lease or free / less costly equipment [12]	• New opportunities to produce solar energy in countries with a high population density and where competition uses for land is rife [13] • Attractive in combination with hydropower assets as both technologies can benefit from each other: grid connection already in place, reduction of evaporation, complementary production profile…[13] • Synergies between fresh water and PV: the cooling effect of water can boost the energy yield, reduction or elimination of panel shading, elimination of the need for major site preparation (leveling, foundations etc.) [13] [14]	• Thanks to advantageous regulations, the BIPV market is expected to grow by an average of 2.7% per year [15] • Numerous aesthetically appealing products have been launched (semi transparent, colored PV, flexible etc.**)** [16] • Mitigation of the timing imbalance between supply and demand of electricity thanks to BIPV façade oriented towards east or west [17] • Bring additional revenues at marginal cost thanks to integration on existing envelope functionalities.
CHALLENGES	• Major module manufacturers do not yet market modules of a suitable size and efficiency for Agri PV systems [12] • Possible higher price due to its innovative nature; specific regulatory frameworks are needed to support its development [12] • Soiling from products, components, and fertilizers used in agricultural activities could impact the durability and power production [12]	• Need for specific floating PV test for drinking-water compatibility, wind resistance of platforms etc. International certifications are lacking [13] • O&M more complex compared to conventional PV (electrical circuit, cleaning due to possible soiling caused by birds) [13] • Difficulty of implementation in the sea where water surface conditions are much rougher [13]	• Today, BIPV is a niche market [18] • PV modules lose efficiency as temperature increases, special care should therefore be taken regarding façade ventilation [19] • BIPV projects require advanced collaboration between building stakeholders: PV, architects, construction and real estate sectors [15]

New business models and opportunities, with ambitious roadmaps unveiled by countries with land availability issues

Flagship commercial projects*

ENGIE BIPV demonstrators
- Linkebeek in 2017, 2.37 kWp, first integration of OPV into glass [20]
- Zwijndrecht in 2018, 40m² of organic façade BIPV [21]

Largest floating PV in Belgium developed by ENGIE
Sibelco: 7MWp 17256 modules, construction completed in 2019 [22]

Largest bifacial noise barrier
Along the A50 in the Nederlands, 400m long [23]

First commercial floating PV
Completed in 2008,
175 kWp in the Far Niente Winery [13]

Biggest Agri-PV plant
640 MW solar park in the Binhe New District, combined with goji berry production [25]

Fisker Karma
2011, first mass production of a car with a 120W solar roof [27]

World largest floating plant
Hangzhou Fengling solar floating farm. Completed in 2020, 320 MW [26]

Largest BIPV façade
Mumbai, Ctrls Data Center, 800 kWp completed in 2019 [24]

Carport by ENGIE
Completed in 2016,
13,5 MWp in Rivesaltes [28]

** This is a non-exhaustive selection of examples of recent technology developments and achievments.*

A global acceleration of X-i-PV deployment

Countries with significant X-i-PV projects

		Floating PV	Agri PV	BIPV	IIPV	VIPV
Europe	Austria			◉		
	France	◉	◉	◉	◉	
	Germany		◉		◉	◉
	Italy	◉	◉	◉		
	The Netherlands	◉	◉	◉	◉	◉
	Norway	◉				
	Portugal	◉				
	Spain	◉	◉	◉		
	Scandinavia		◉	◉		
	Sweden	◉				
	Switzerland	◉	◉	◉	◉	
	Turkey	◉				
	United Kingdom	◉				
North America	Canada	◉		◉		
	United States	◉	◉	◉		◉

		Floating PV	Agri PV	BIPV	IIPV	VIPV
Asia	Australia	◉				
	China	◉	◉	◉		
	India	◉	◉	◉		
	Indonesia	◉				
	Israel	◉				
	Japan	◉		◉		◉
	Malaysia	◉				
	Maldives	◉				
	Republic of Korea	◉				◉
	Singapore	◉				
	Sri Lanka	◉				
	Taiwan	◉				
	Thailand	◉				
	Vietnam	◉				
Latin America	Brazil	◉				
	Panama	◉				
Africa	Tunisia	◉				

Road to 30% efficiency PV cells

Silicon solar modules represent over 95% of global installed PV capacity with one challenger, Perovskite solar cells

SILICON SOLAR CELLS ARE LEADING THE MARKET

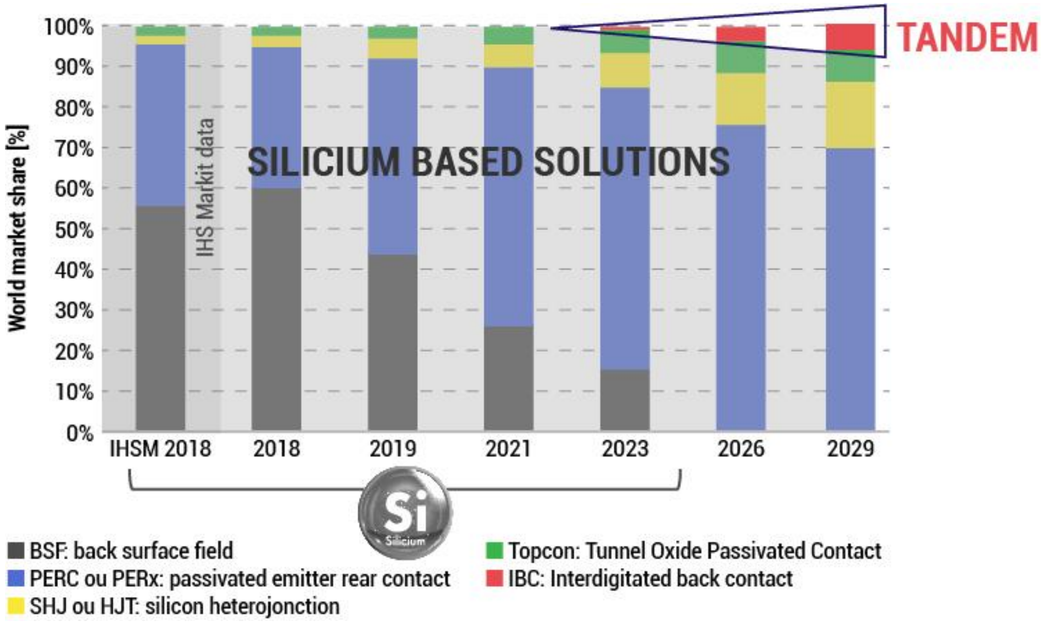
The rapid increase in overall photovoltaic electricity production has been facilitated by the declining cost of silicon-based solar cells [29].

COMPETITIVE MARKET FOR NEWCOMERS

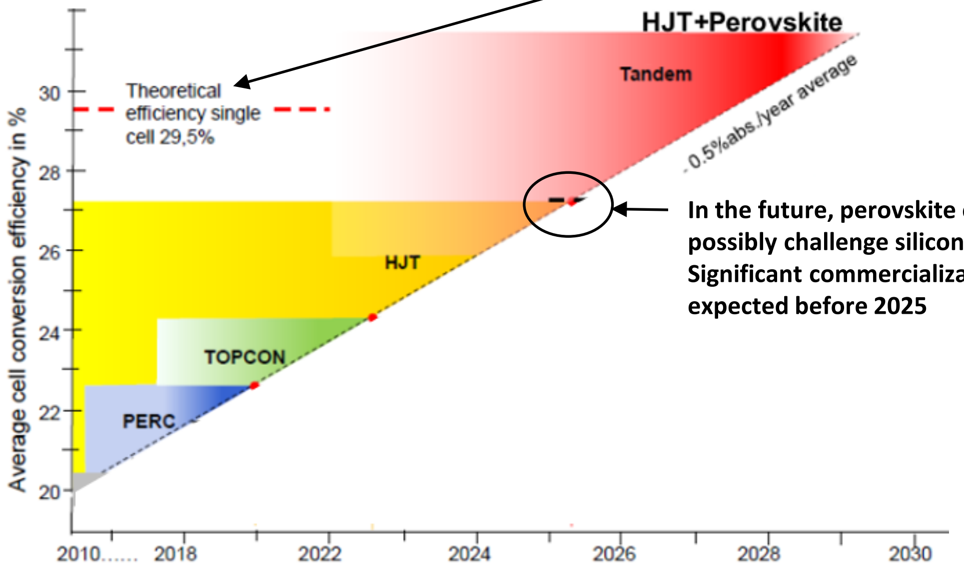
Due to its technological maturity, its prominence in the microelectronics industry and its cheap cost, Silicon based technology is a difficult supply chain to challenge.

SIGNIFICANT IMPROVEMENT OF THE EFFICIENCY

During the last decade, solar PV has seen a substantial improvement in efficiency: from 16% in 2010 to 22% in 2021. The efficiency value of silicon solar cell is moving towards the **maximum achievable limit of 29.2%** [29]



Trend: share of cell technologies [30] [31]



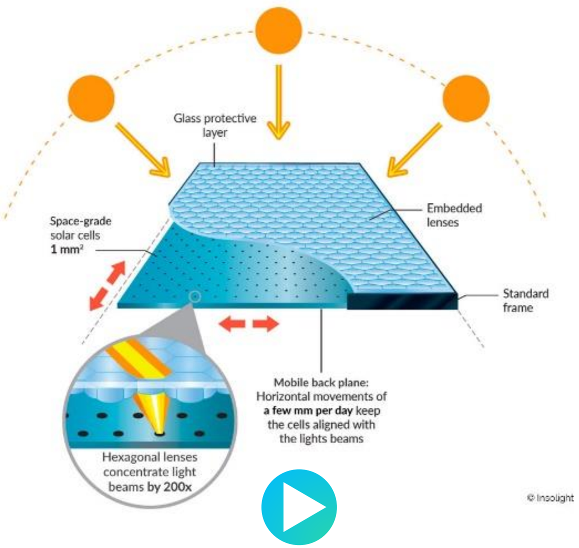
In the future, perovskite cells will possibly challenge silicon solar cells. Significant commercialization is not expected before 2025

Cell Efficiency Trend in Mass Production, current and roadmap [29] [31]

New concepts are being developed to overcome the physical limitations of silicon cells (efficiency, weight and intermittency)

CONCENTRATED PV

- Integration of tiny, highly efficient, multi-junction cells on top of standard silicon panels.
- Use of micro-lenses and micro-trackers to track the sun's position.
- Measured efficiency of 29%. [32] [33] [34]



TANDEM PEROVSKITE SOLAR CELLS

- Layer of perovskites absorb only the high-energy blue end of the spectrum that silicon cells are unable to capture [29].

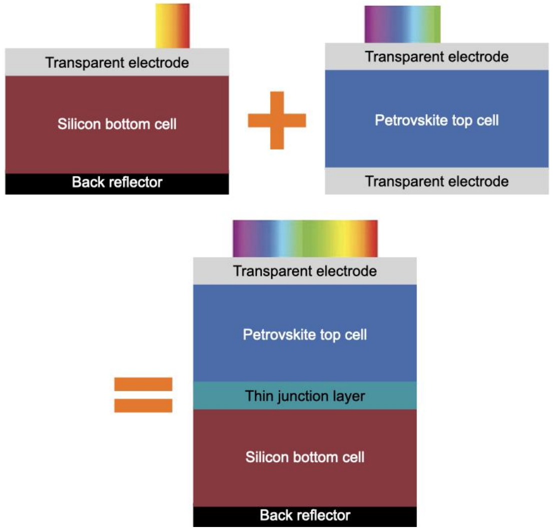


Illustration of the concept of a tandem perovskite-on-silicon cell

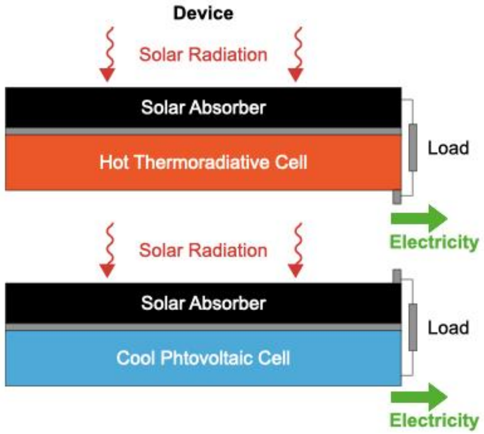
LIGHTWEIGHT PV

- Weight: 1-10 kg/m^2 as opposed to 12- 15kg/m^2 for standard PV.
- Encompasses several technologies: organic PV, Silicon, CiGS etc.
- Different approaches exist such as replacing the glass with lightweight polymers. [16]

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

THERMORADIATIVE PHOTOVOLTAICS

- [35] proposes a "night time photovoltaic cell" that uses the earth as a heat source and the night sky as a heat sink.
- [36] demonstrated a similar device that can produce 25mW/m^2 (for 150 W/m^2 for silicon) at night using a thermoelectric module that radiates heat towards the extreme cold of space.

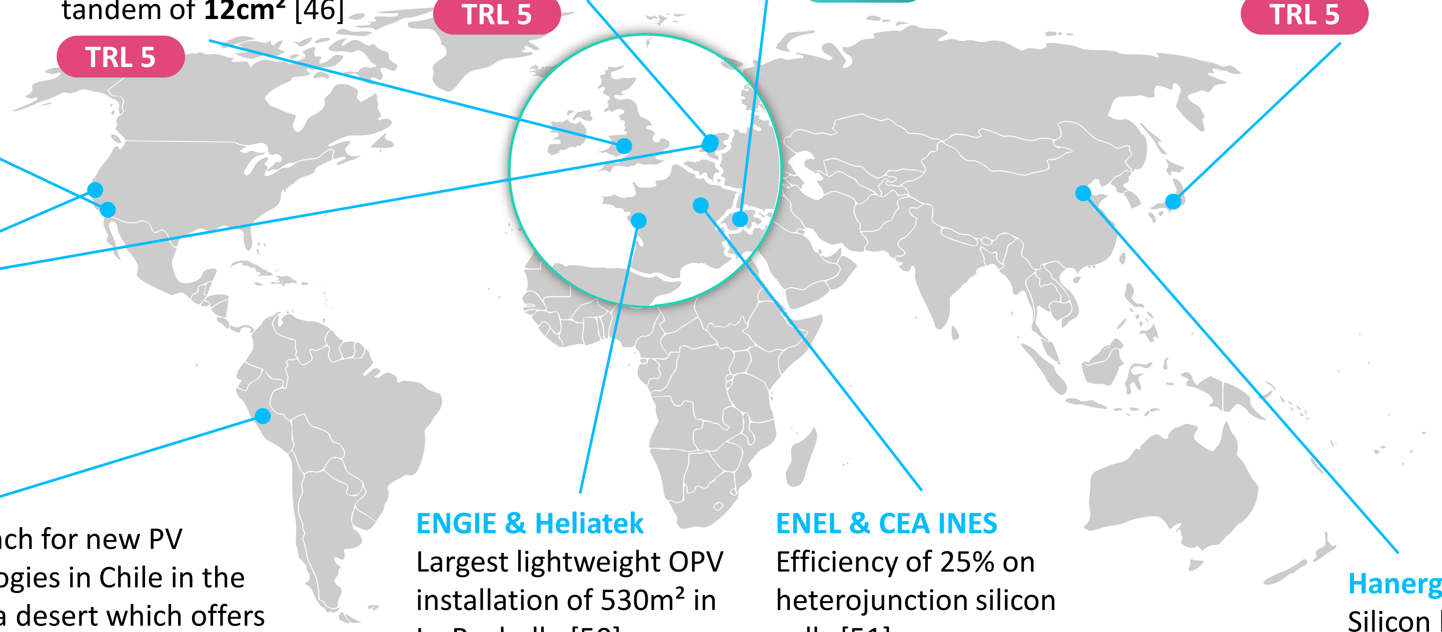


Description of the concept [37]

Comparison of new concepts and materials

	CONCENTRATED PV	TANDEM PEROVSKITE SOLAR CELLS	LIGHTWEIGHT PV	THERMORADIATIVE PV
ADVANTAGES	• Assembly of technological mature bricks in an innovative module giving concentrated PV a higher module efficiency than tandem perovskite/silicon modules [34] • Increasing efficiency decreases the environmental footprint of PV • Micro-tracking allows for a flattened production curve [34]	• High efficiency allowing the efficiency limit of silicon to be exceeded [40] • High and tunable spectral performances [41] • Intensive R&D activity which accelerates the development [43]	• Possible implementation of PV on unused areas/surfaces that require lightweight or flexible PV [16] • Already commercially available [16] • High-cost reduction potential due to innovative manufacturing such as roll-to-roll [16]	• Possible production of electricity during nighttime [35] [36] • PV cells could be combined with thermoradiative cells [35]
CHALLENGES	• Complex technology inducing an overpricing and possible reliability issues [34] • Gallium Arsenide (GaAs) offers high efficiency, but competitive prices must be maintained on an industrial scale [34][38] • Gallium is listed as a critical raw material by the European Commission [39]	• Maturity not yet reached, problems with stability over the lifetime of the modules (degradation can be caused by environmental conditions) [40] [43] • Retaining high efficiencies on an industrial scale and module size with competitive prices [40[43][42] • Presence of lead in the best-performing perovskite cells might require a specific recycling process [40] [44]	• Efficiency is currently lower than conventional PV modules. • Adapting the best existing efficiencies to lightweight manufacturing processes [45] • €/Wp costs are still higher than standard PV [16]	• New technology still in early research phase with a low TRL (1-3) • Due to a lack of maturity, several different concepts currently exist [35][36] • The demonstrated power production remains low (25mW/m²) [36]

Several companies and research labs are aiming to develop the future PV technology*



Stanford or UC Davis
Thermoraditative photovoltaics concepts [35] [36]
TRL 1-3

Oxford PV
Record efficiency of 29.52% efficiencies for perovskite/silicon tandem of **$12cm^2$** [46]
TRL 5

Solliance
Perovskite/silicon tandem of $9mm^2$. Efficiency: 28.7% [47]
TRL 5

Insolight
Hiperion
Efficiency: 29% [32]
TRL 6-7

Panasonic
Perovskite
Efficiency:16% for **full** modules of 30cmx30cm [53]
TRL 5

Miasolé & Solliance
Perovskite/CiGS Efficiency: 26.5% efficiency [48]
TRL 5-6

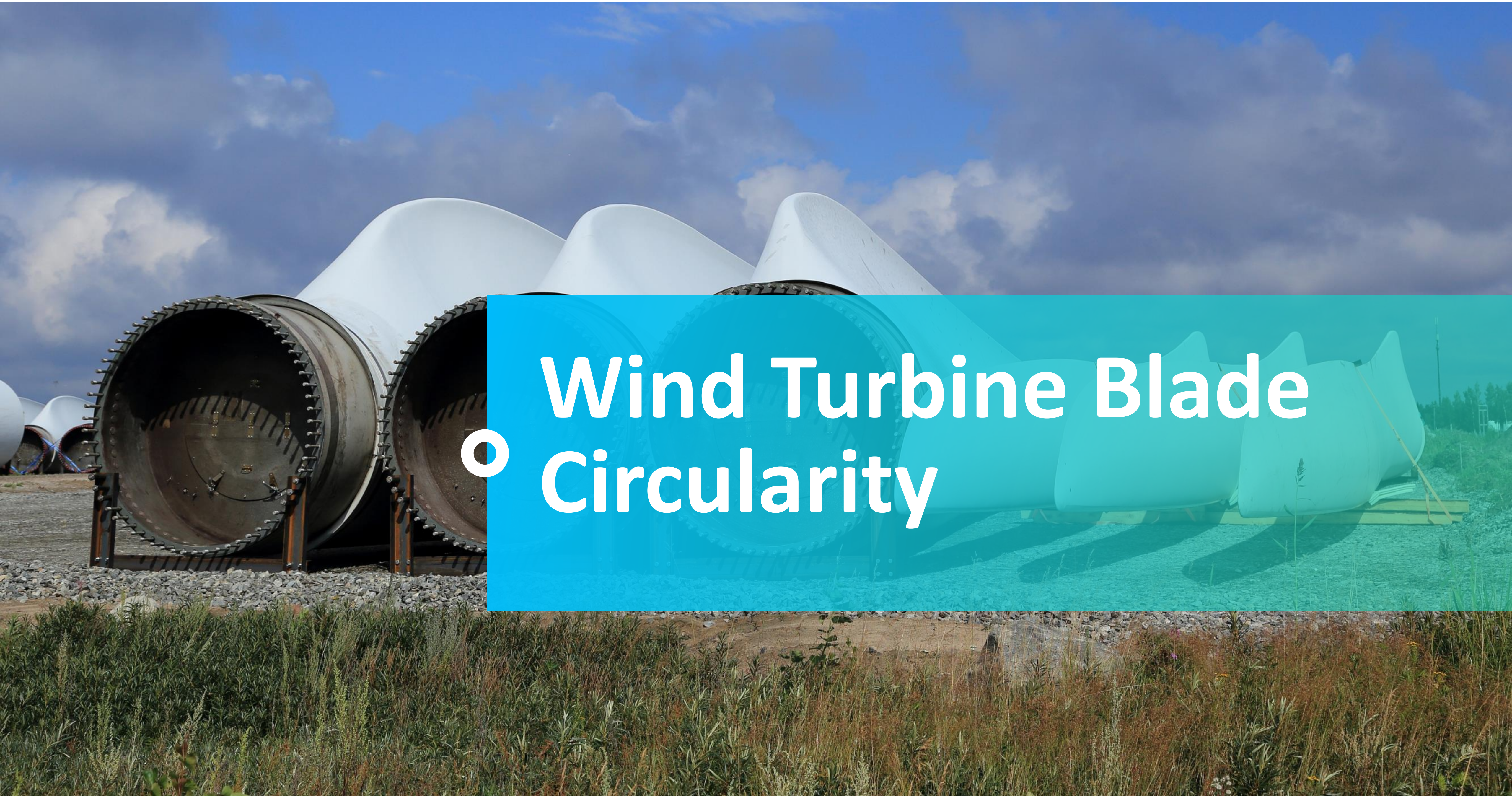
ENGIE
Test bench for new PV technologies in Chile in the Atacama desert which offers among the highest surface irradiance on earth [49]
TRL 7-9

ENGIE & Heliatek
Largest lightweight OPV installation of $530m^2$ in La Rochelle [50]
TRL 8-9

ENEL & CEA INES
Efficiency of 25% on heterojunction silicon cells [51]
TRL 5-6

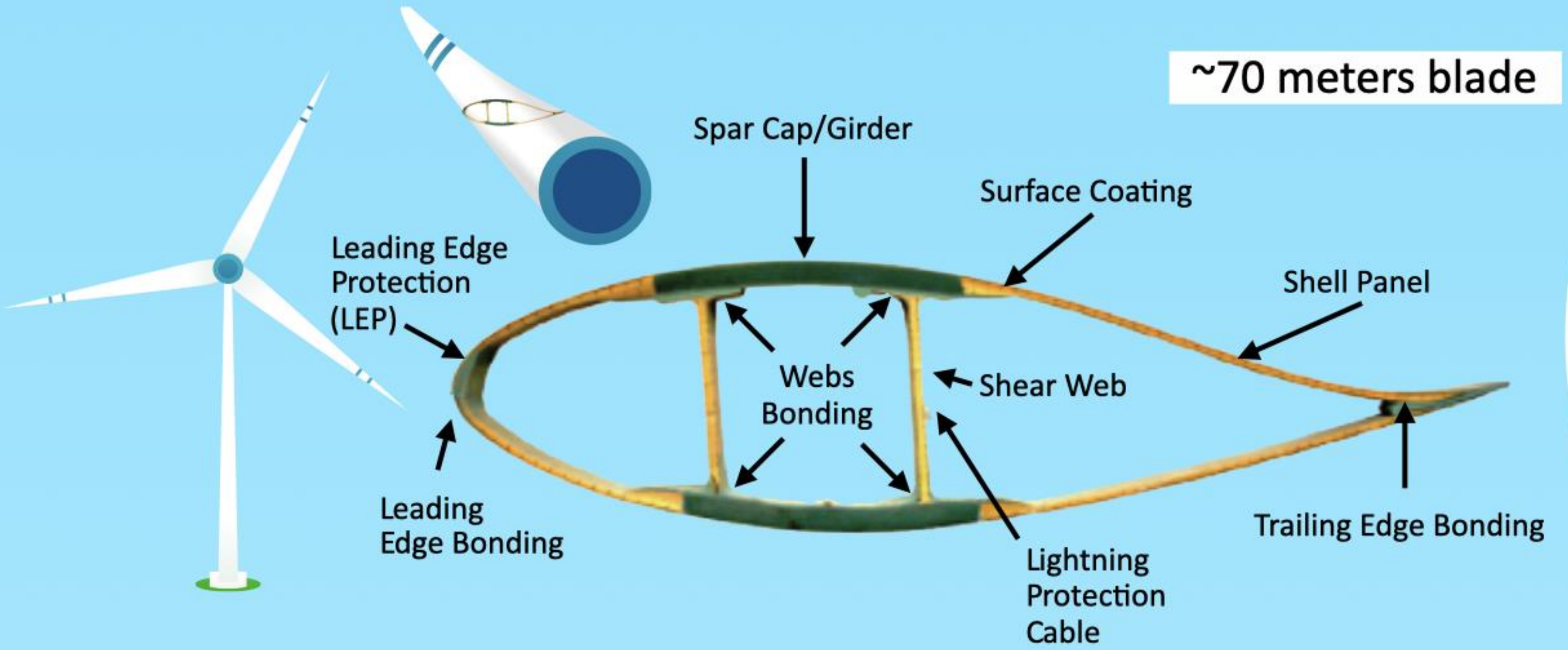
Hanergy
Silicon heterojunction modules of 2mx1m Efficiency of 25.11% [52]
TRL 6-7

These are a non exhaustive selection of examples of recent technology development and achievments



Wind Turbine Blade Circularity

Wind Blade Waste is composed of valuable resources that should be recycled to make the supply chain even more sustainable



Spar Caps/Girders: Glass/Carbon fiber-Thermoset composites (epoxy or polyester)

Webs and Shells: Sandwich Panels with foam core (synthetic or Balsa) and Glass Fiber Composite Skins

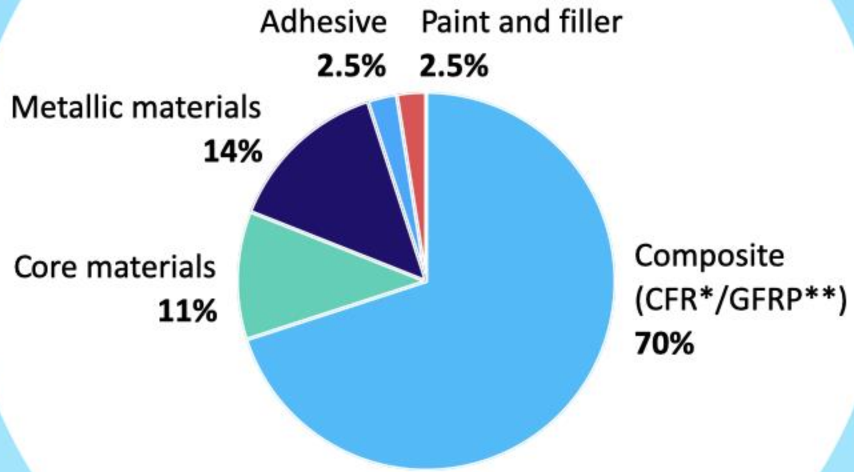
Bonding lines: Epoxy or Polyurethane Structural Adhesives

Lightning Protection Cable: Aluminum or Copper

Surface coating and LEP: Polyurethane based paints or tapes

Source [55]

BLADE COMPOSITION

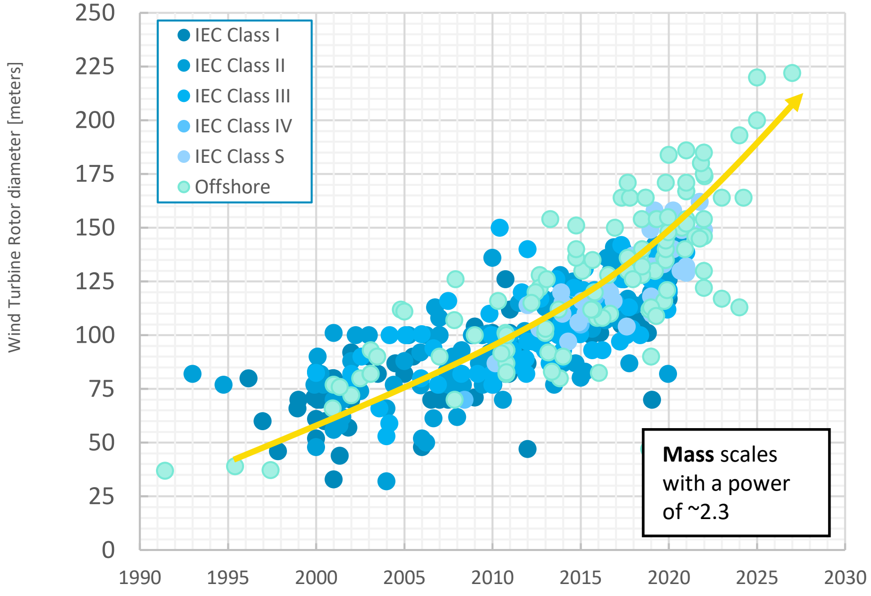


** CFR: Carbon Fiber Reinforced*
*** GFRP: Glass Fiber Reinforced Polymer*

Sources [56][57]

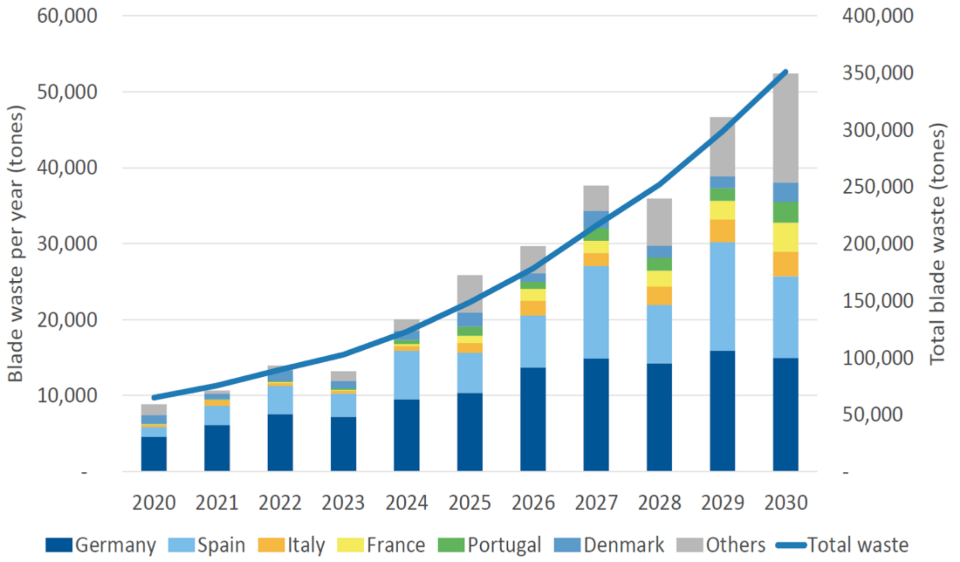
End-of-life management is challenging but crucial in order to meet the wind industry sustainability goals

BLADE DIMENSIONS INCREASING



Source [57]

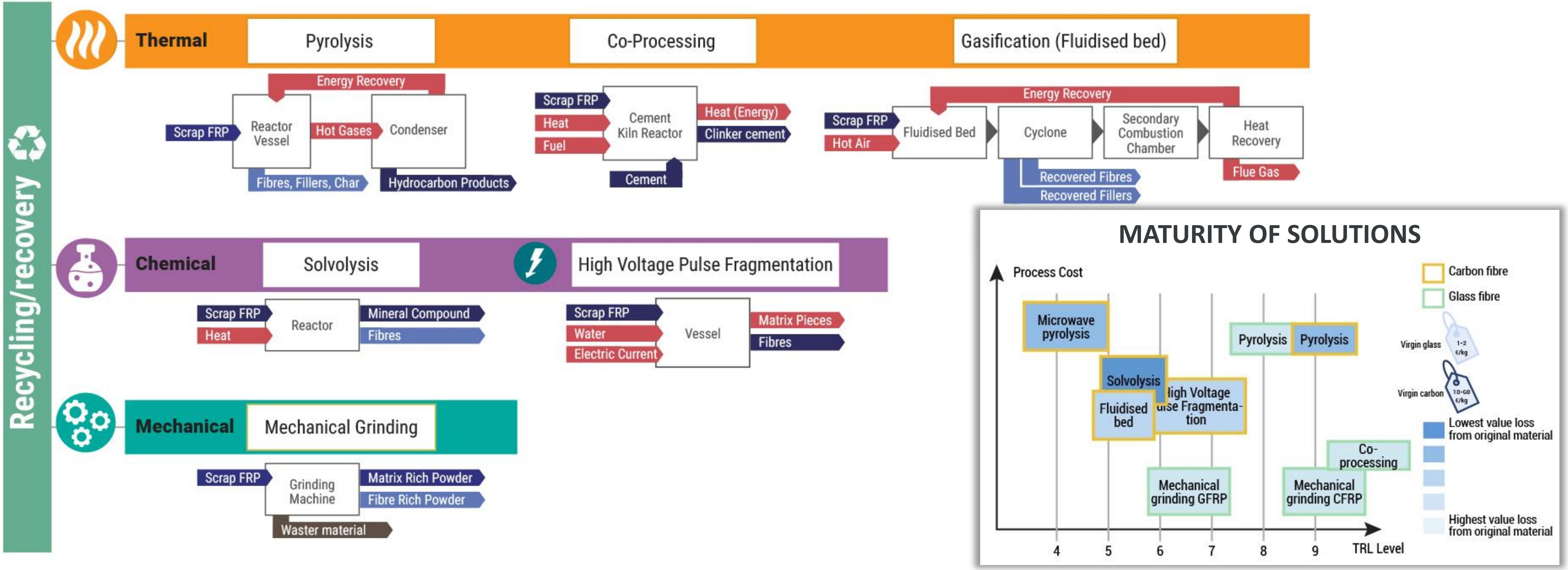
BLADE DECOMMISSIONING KICKING IN



Source [58]

- In five to ten years time, the number of decommissioned blades will be so high that it will be crucial to adapt the current waste processing system.
- The wind energy industry believes an EU landfill ban will accelerate the scaling up of recycling technologies, which in turn, will see the demand for recycled materials rise.

Several technologies could be scaled up to process the enormous volume of wind blades. Applications shredded composite material still need to be developed.



Source [58]

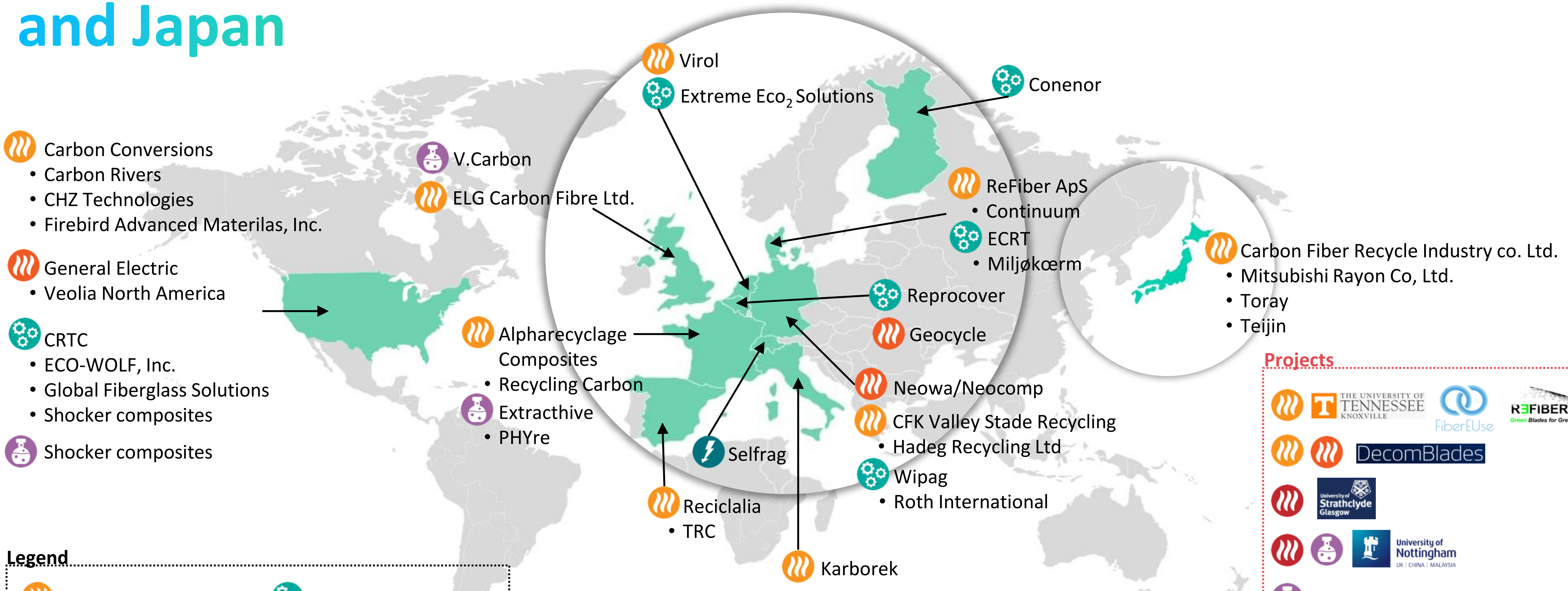
FRP: Fibre-Reinforced Plastic

This broad range of new technologies need to be scaled up drastically to absorb high volumes of materials

		STRENGTHS	CHALLENGES
Thermal	**PYROLYSIS**	• Pyrolysis gas/oil can be used as an energy source in processes or in chemicals production; • Easily scaled up; • Microwave Pyrolysis: easier to control. Less damage to the fiber.	• Fiber product may retain oxidation residue or char (combine with gasification) • Potential gas leakage from waste treatment chambers
	CO-PROCESSING	• Highly efficient, fast and scalable; • Large quantities can be processed; • No ash left over.	• Loss of original material form; • Additional energy needed to reach high processing temperatures • Emissions of pollutants and particulate matter
	GASIFICATION (Fluidized bed)	• Recovery of energy and potential precursor chemicals; • High efficiency of heat transfer.	• Recovery of low-quality material; • Economically viable at > 10,000 t/year; • Process-related emissions
Chemical	**SOLVOLYSIS**	• Recovery of full length clean fibers; • Recovery of resin which can be re-used.	• Low efficiency; • High energy consumption due to the high temperature and pressure • Large amounts of solvents required, ecotoxicity from gas emissions
	HIGH VOLTAGE PULSE FRAGMENTATION	• Scalable to treat large amounts of waste; • Low investments required to reach the next TRL.	• Only laboratory- and pilot-scale machinery is available; • Heavily decreased modulus of glass fiber.
Mechanical	**MECHANICAL GRINDING**	• Efficient and high throughput rates.	• Cost efficiency; • Low quality of output. High content of other materials; • Requires space and facilities to treat materials.

Source [59]

Companies and recent projects involved in the recycling or recovery of composites are based in North America, Europe and Japan



Legend

- Pyrolysis
- Co-Processing
- Gasification (Fluidized Bed)
- Mechanical Grinding
- Solvolysis
- HV Pulse Fragmentation

Projects

- The University of Tennessee Knoxville; FiberEUse; REFIBER Green Blades for Green Energy; Decom Tools
- DecomBlades
- University of Strathclyde Glasgow
- University of Nottingham UK | China | Malaysia
- RECY-COMPOSITE; RELICARIO
- BRIO – Green – Tech Fibre Insulation
- ? SusWIND

The industry’s ambition is to achieve full circularity with respect to blades

Today’s Focus is on recycling but the major manufacturers are now working on future eco-designed blades

PORT-LA-NOUVELLE WIND FARM IN FRANCE

Reciclalia · ENGIE Green

TRL 9

Source [60]

The ZEBRA project goal is to demonstrate on a full scale the technical, economic and environmental relevance of thermoplastic wind turbine blades, with an eco-design approach to get a 100 % recyclable wind turbine blade. The project has been launched in 2020 for a period of 42 months with a budget of €18.5 million.

The shredded material can be used to make solid recovered fuel (SRF). Gasification of this SRF is planned on the GAYA platform of ENGIE.

GAYA

gaya

TRL 4

ZEBRA

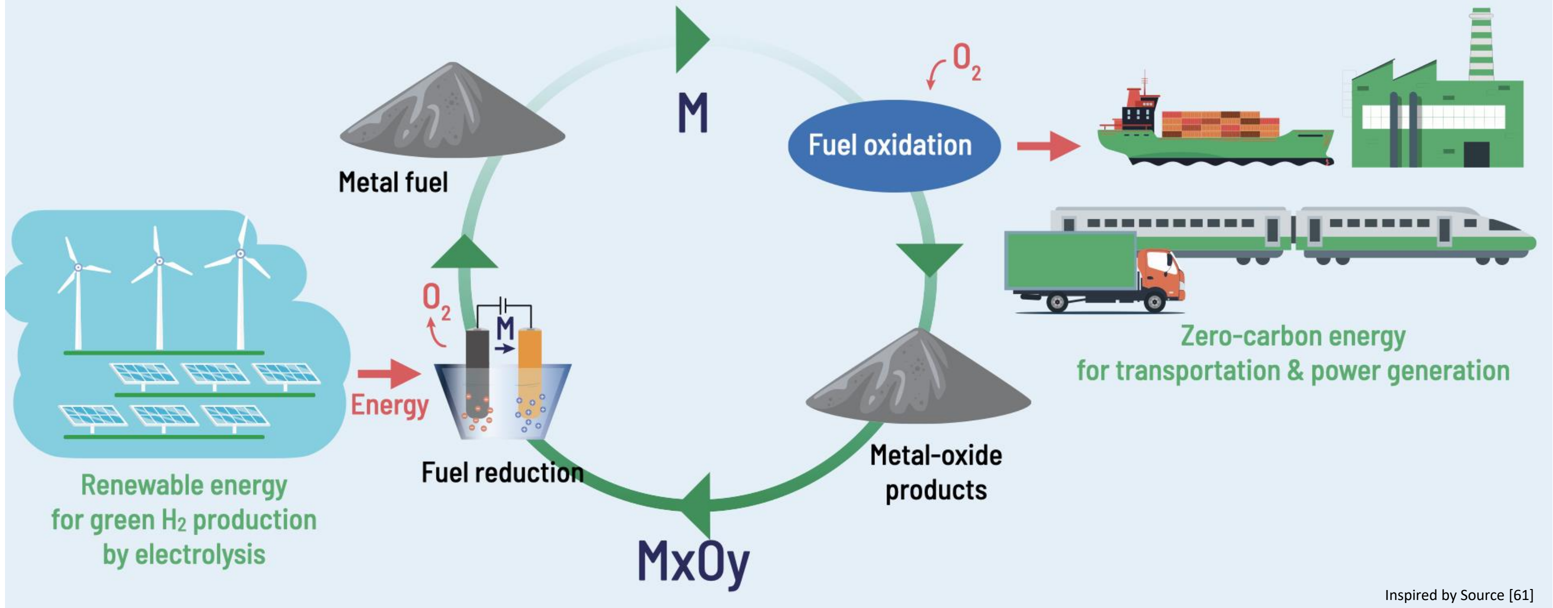
suez · LM Wind Power (a GE Renewable Energy business) · ARKEMA · ZEBRA Zero wastE Blades ReseArch Project · IRT Jules Verne · Owens Corning · ENGIE

TRL 5-6

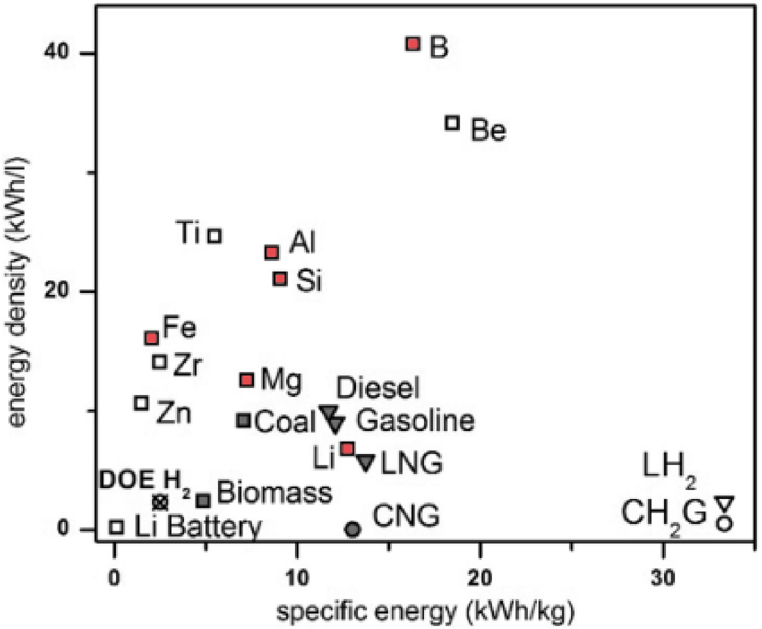
Metal fuels

Metals as recyclable carbon neutral fuels are promising alternatives to fossil fuels

Metals have high energy densities and serve as fuels in many batteries, energy materials, and propellants. Metal fuels can be burned with air or made to react with water to release their chemical energy in a range of power-generation scales. Metal-oxide combustion products are solids that can be recycled, enabling metals to be used as recyclable carbon neutral solar fuels or electro-fuels.



Inspired by Source [61]



Potential metal fuel candidates. The element must be oxidized by O_2 from air, with high specific energy, be cheap and non-toxic [62]

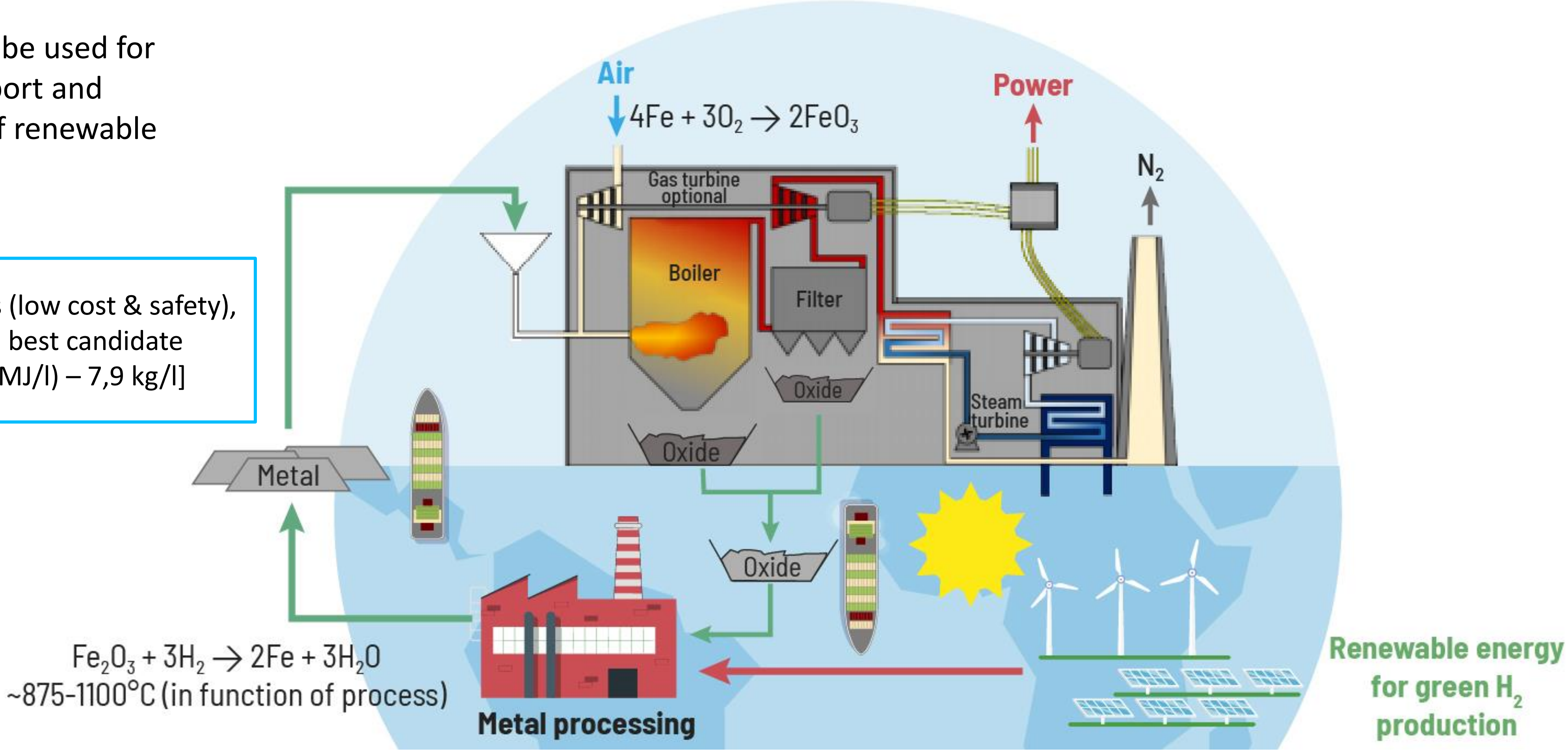
? Electro-fuels are primarily produced from electricity, during the reduction process to convert spent combustion/oxidation products back into reactive fuel.

The oxidation and reduction of metal fuels can be decoupled in terms of time and location…

…so metal fuels can be used for long-distance transport and long-term storage of renewable energy

!

For practical reasons (low cost & safety), Iron seems to be the best candidate
[Fe= 15,8 kWh/l (57 MJ/l) – 7,9 kg/l]

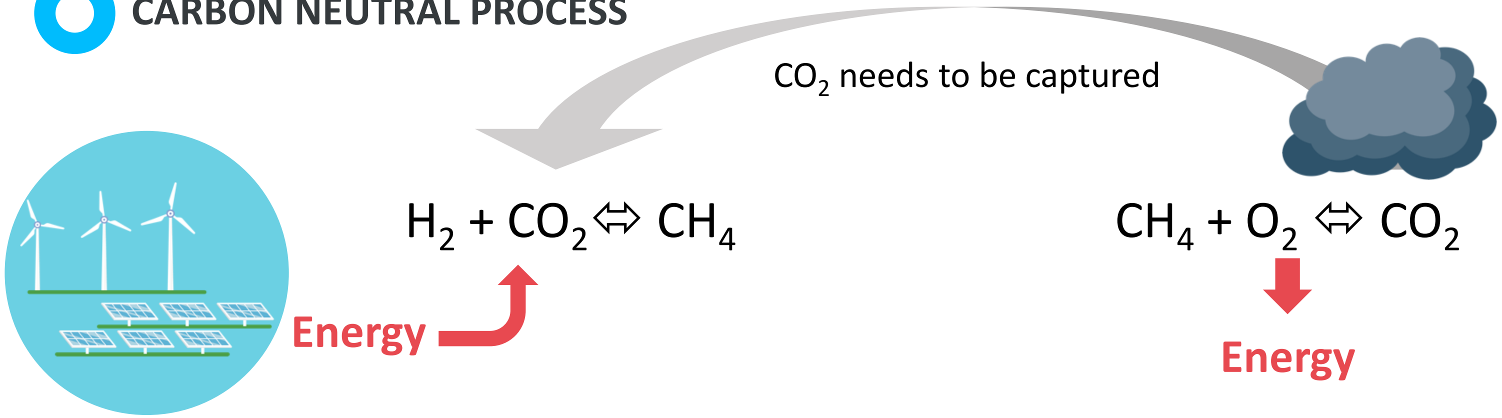


Inspired by Source [63]

Advantages: using a solid fuel facilitates the CO_2 free closed loop owing to green H_2 reduction

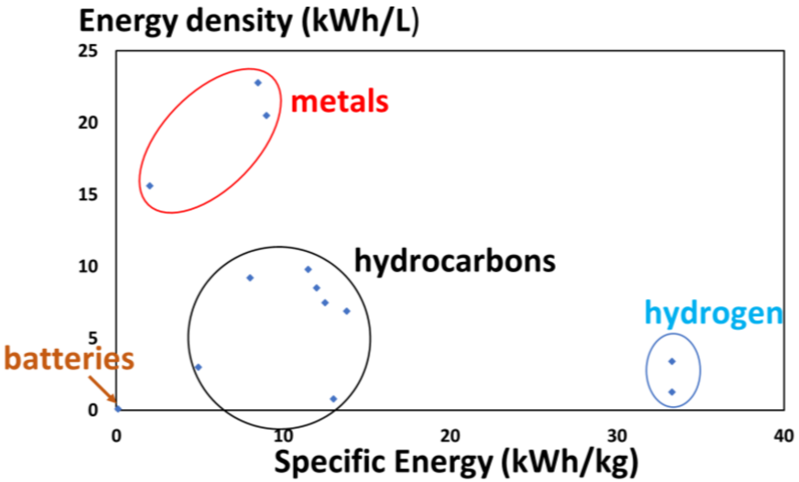
METAL FUEL PROCESS

CARBON NEUTRAL PROCESS



Advantages

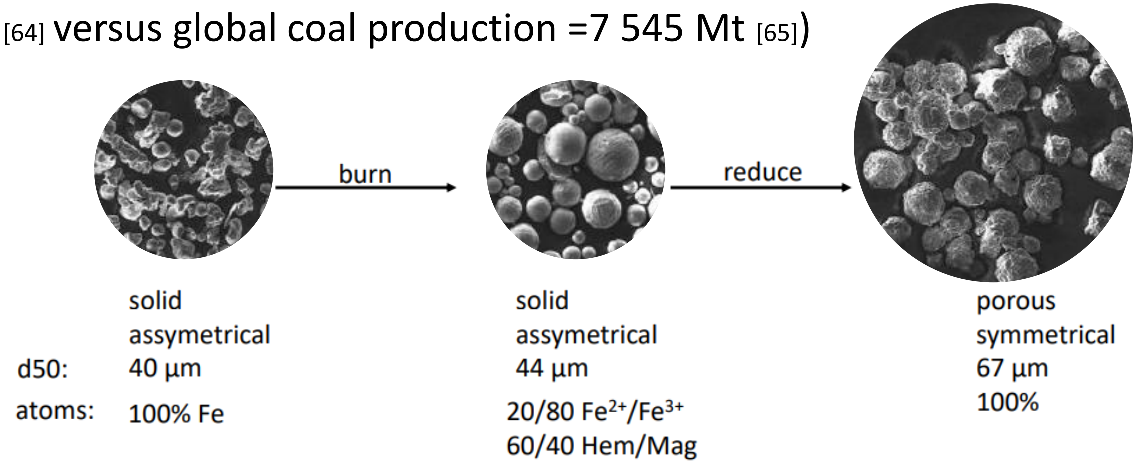
- Iron easy to transport
- CO_2/NOx/SOx free cycle
- Iron oxide easy to collect
- Metal fuels present higher energy density and specific energy than liquid fuels when oxidized



Adapted from source [61]

Challenges: a new energy generation system with a low maturity level TRL 3-5 and a few technical hurdles

- Particle emissions
- Safety during handling
- Availability of the powder:
  → 100 kW burns 50 kg/h Fe. So 1 GW during 8000 h would require 4 millions tons Fe but iron would be recycled!(global iron powder production in 2017=1,4 Mt [64] versus global coal production =7 545 Mt [65])
- Metal regeneration and overall efficiency
  → What about powder cycling/lifespan?



Diameter change during process [66]

Maturity and market players

Metal powder

- Pometon powder (IT)
- Laiwu (CN)
- JFE Steel Corp (JP)
- Hoganas (SE)
- Wuhan iron & steel (CN)
- Rio Tinto (US)
- MA Steel (CN)
- Kobelco (JP)
- CNPC powder (CN)
- Hangzhou Ytong New Material (CN)
- Anshan Iron & steel (CN)

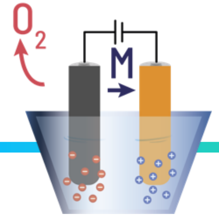
Oxidation TRL 5

- TUEindhoven
- Shell
- Uniper
- EMGroup
- Romico Hold
- Airbus
- McGill
- Ruhr Universität Bochum
- + all other players using metal powders as propellants

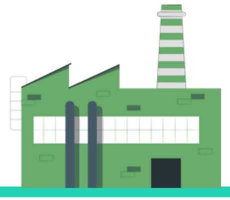
Fuel oxidation

Reduction TRL 3

- Doosan
- Vattenfal
- Swedish steel

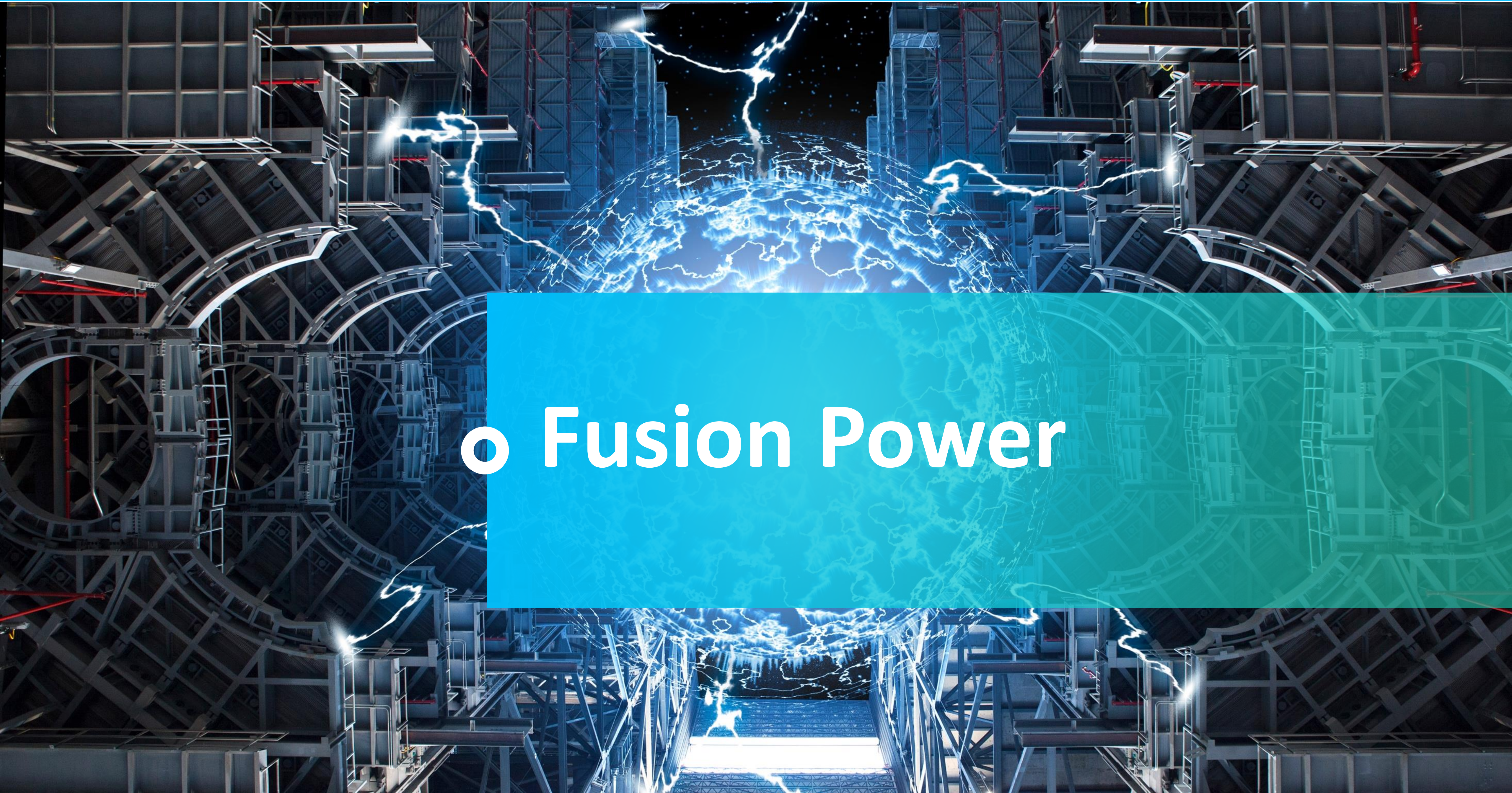


Power plant project examples



uniper
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

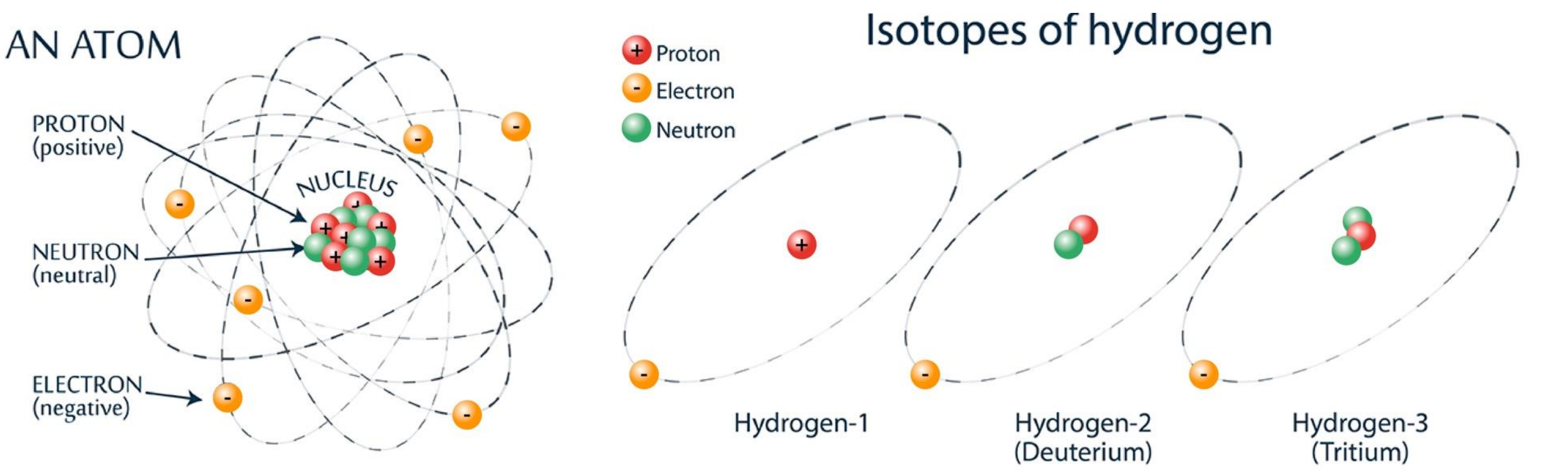
2019-2020	2024	2030?
Lighthouse burner	WSG Rotterdam	MPP3 Maasvlakte
100 kW	**5 MW**	**30x74 MW**



Fusion Power

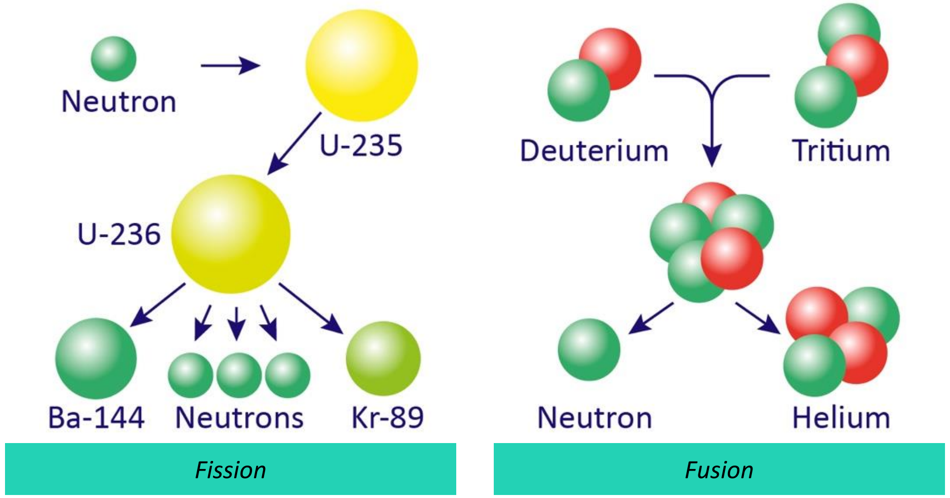
Fission is a nuclear technology based on splitting one large atom into two smaller atoms whilst Fusion is the fusing of two light atoms into a larger one.

REMINDER



Fission is a nuclear technology based on splitting one large atom into two smaller atoms whilst Fusion is the fusing of two light atoms into a larger one.

- Fusion occurs in high-temperature confined plasma, an ionized gas, composed of ions and free electrons.
- The « easiest » fusion reaction for power production is Deuterium - Tritium (D-T)
  - Fission of ^{235}U versus Fusion deuterium - tritium

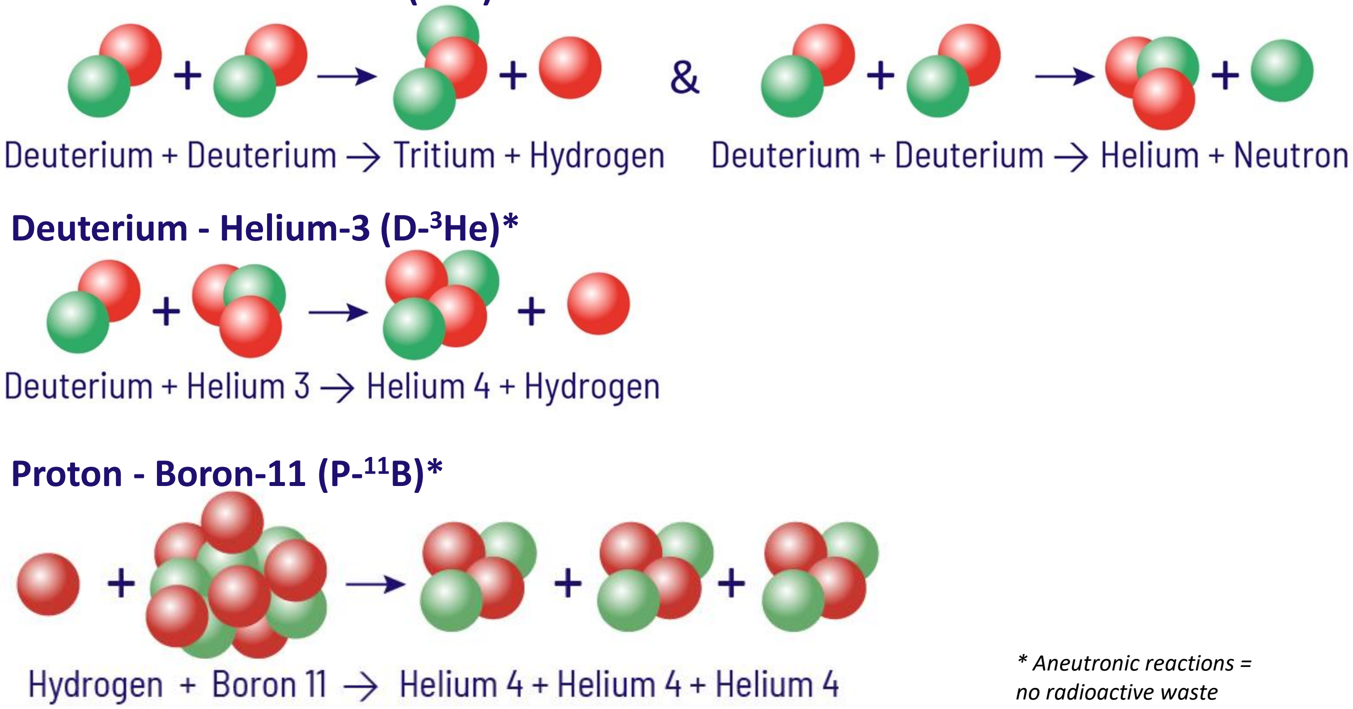


But other reactions are possible (at higher temperature)

Deuterium - Deuterium (D-D)

Deuterium - Helium-3 (D-^{3}He)*

Proton - Boron-11 (P-^{11}B)*



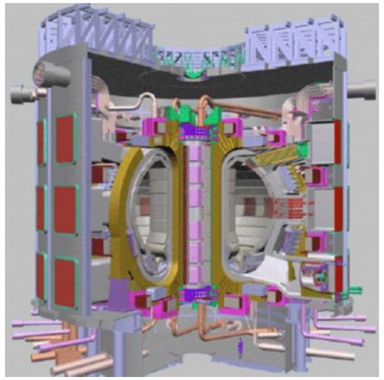
** Aneutronic reactions = no radioactive waste*

Three different technologies can be used

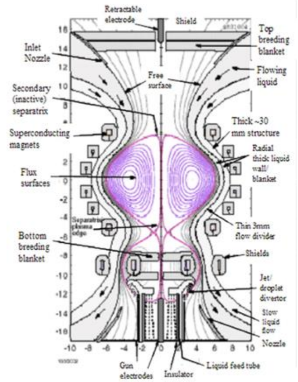
ALL CONFINEMENT — ALL COMPRESSION — COMBINATION

1. Magnetic confinement fusion (MCF): the plasma is confined thanks to magnetic fields using superconductors.

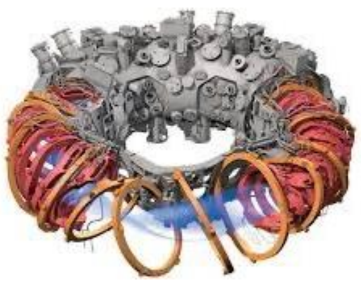
- Tokamak: best developed approach, driving hot plasma around in a magnetically confined torus, with an internal current (e.g., ITER)
- Spheromak: an arrangement of plasma formed into a toroidal shape similar to a smoke ring, using external magnets (e.g. Sustained Spheromak Physics Experiment)
- Stellarator: twisted rings of hot plasma, attempting to create a natural twisted plasma path, using external magnets (e.g. Wendelstein 7-X, in Germany)



Iter design [67]

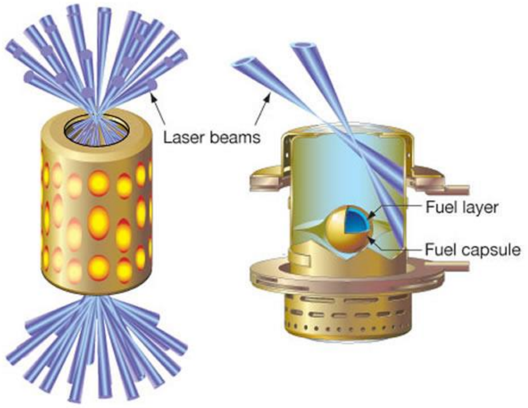


Liquid wall spheromak reactor [68]



Wendelstein 7-X [69]

2. Inertial Confinement Fusion (ICF): using lasers, ion beams or projectiles to heat and compress the fuel inserted into a target



Inertial Confinement Fusion [70]

3. Other technologies: magnetized target fusion (MTF), magnetic or electric pinches, inertial electrostatic confinement,…

Magnetized target fusion [71]

Fusion Power: Advantages and Challenges

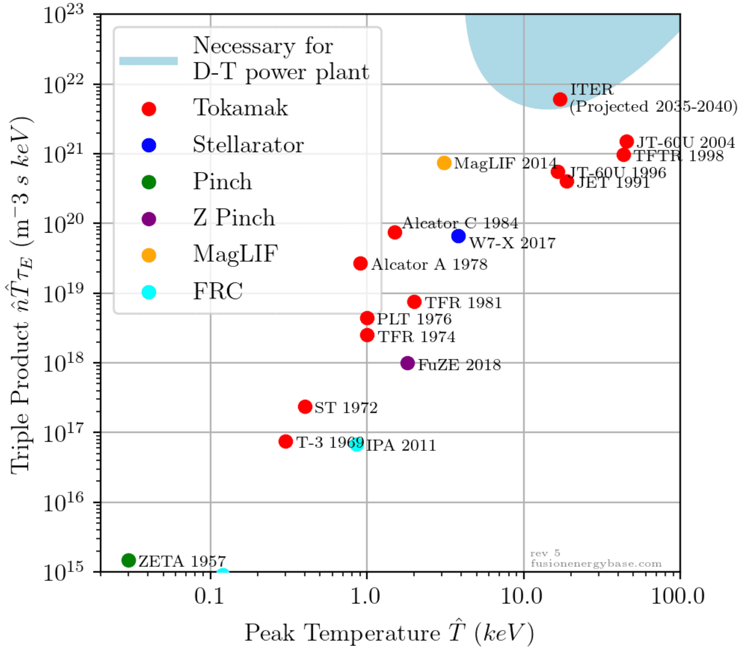
Advantages

- Exceptionally high-density energy
- Process intrinsically safe: no uncontrolled fission reactions, no risk of fuel meltdown or large radioactive releases
- No production of high-level radioactive wastes; Neutrons involved in the D-D and D-T reactions will create low-level radioactive waste
- Virtually limitless energy supply:
  - *Hydrogen, deuterium and boron are abundant on earth*
  - *Tritium can be produced (using lithium)*
  - *Helium-3 can be found on the moon (or produced)*

Challenges

- Achieve the triple product for the reaction:
  - T°C: very high temperature (~100k°K) to heat plasma
  - ρ: sufficient plasma particle density
  - t: sufficient confinement time (minutes for magnetic confinement, microseconds for inertial confinement)
- In parallel maintain low-temperature (<30°K) superconductors for magnetic confinement
  - *New types of superconductors, including high-temperature (70-100°K) superconductors are being developped*
- Find resistant material able to sustain high temperature + radiations + neutron embrittlement
- Reach energy gain* by managing the triple product: never been reached experimentally so far.

** Energy output should be higher than energy input*



Triple Product vs Peak Temperature Achieved [72]

At a global level, many publicly-funded R&D projects are linked to ITER and focus on the triple product, superconductors and the plasma heating…

Project	Organisation	Country	Confinement	Status
ITER	ITER Org	International	Magnetic	Construction
WEST	CEA	France	Magnetic	Operational
Laser Megajoule	CEA	France	Inertial	Operational
Divertor Tokamak Test Project	DTT Consortio	Italy	Magnetic	Construction
Neutral Beam Test Facility	Consortio NFX	Italy	Neutral beam injection testing (heating the plasma)	Construction
Wendelstein 7-X	Max Planck Institute	Germany	Magnetic	Operational
International Fusion Materials Irradiation Facility	IFMIF/DONES	Spain, Croatia	Only material testing	Operational
Hiper	EU (10 countries)	EU	Inertial	Conception
MAST upgrade	UKAEA	UK	Magnetic	Operational
Jet	Joint European Torus	UK, EU	Magnetic	Operational
ShenGuang-III	Laser fusion research center	China	Inertial	Operational
EAST	Institute of Plasma Physics, Academy of Sciences	China	Magnetic	Operational

Project	Organisation	Country	Confinement	Status
HL-2A	SOUTHWESTERN INSTITUTE OF PHYSICS	China	Magnetic	Operational
HL-2M	SOUTHWESTERN INSTITUTE OF PHYSICS	China	Magnetic	Operational
J-TEXT	Hubai University	China	Magnetic	Operational
KTX	Hefei University	China	Magnetic	Operational
JT-60	Japanese Atomic Energy Agency	Japan	Magnetic	Shut down
JT-60SA	Japanese Atomic Energy Agency	Japan	Magnetic	Commissioning
Aditya	Institute for plasma research	India	Magnetic	Operational
SST-1	Institute for plasma research	India	Magnetic	Operational
T-15MD	Kurchatov Institute	Russia	Magnetic	Operational
National Ignition Facility	Lawrence Livermore National Laboratory	USA	Inertial	Operational
DIII-D	General Electric (DOE)	USA	Magnetic	Operational
NSTX-U	Princeton Plasma Physics Laboratory	USA	Magnetic	Operational
KSTAR	Korean Institute for Fusion	South Korea	Magnetic	Operational

Conception
Construction
Commissioning
Operational
Shut down

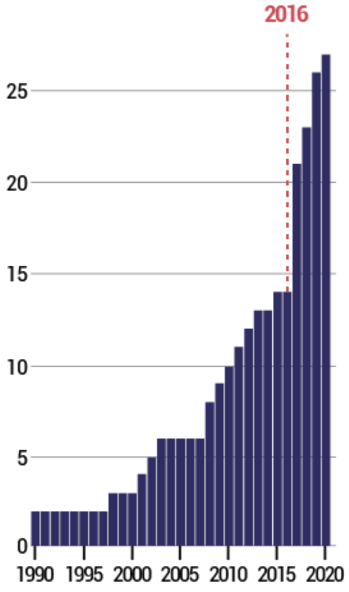
The challenge of the climate change is inciting private equity funds to invest in demonstrators construction all over the world which is new. The race is on for 2030!

Organisation	Country	Confinement	Fusion reaction
Lockheed Martin		Magnetic	D-T
Institute of Plasma Physics, Academy of Sciences		Magnetic	D-T
Commonwealth Fusion System		Magnetic	D-T
General Fusion		Magnetic+Inertial	D-T
Tokamak Energy		Magnetic	D-T
TAE Technologies		Magnetic	$P-^{11}B$
Helion Energy		Magnetic+Inertial	$D-^{3}He$
LPP Fusion		Electric pinch	$P-^{11}B$
Hyperjet Fusion		Inertial	D-T
Magneto-Inertial Fusion Technologies		Magnetic+Inertial	D-T

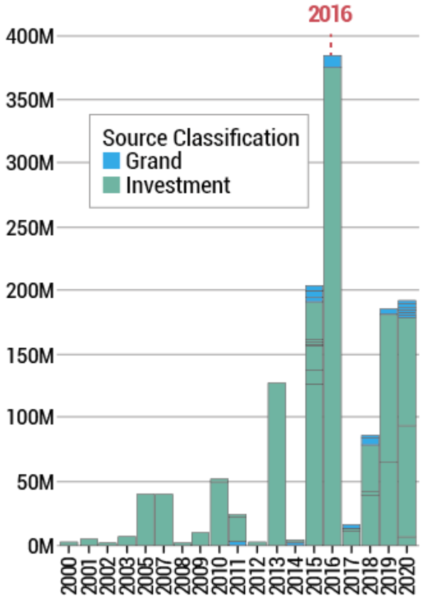
Organisation	Country	Confinement	Fusion reaction
First Light Fusion		Inertial	D-T
CTFusion		Magnetic	D-T
Compact Fusion Systems		Magnetic	D-T
EMC2		Inertial electrostatic	D-T
UKAEA		Magnetic	D-T
HB11 energy		Inertial	$P-^{11}B$
Marvel Fusion		Inertial	$P-^{11}B$
Type One Energy		Magnetic	D-D
Renaissance Fusion		Magnetic	D-T
Zap Energy		Electric pinch	D-T

In blue: significant announcement observed in 2021

More than 25 fusion start-ups planning to produce a demonstrator by 2030s using approaches different from ITER (compact and simple reactors, different technologies,…). Will they reach commercial viability?



Number of Companies Pursuing Fusion Energy [73]



Funding to Fusion Energy Companies by year (USD) [74]

The challenge of the climate change is inciting private equity funds to invest in demonstrators construction all over the world which is new. The race is on for 2030!

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A message from Benjamin P. Youman, BlackStarTech Strategic Implementation Director

Nuclear Station Beyond-Design-Basis Electrical Power Supply Coping System

It's Hydrogen Day—and yes, that has a lot to do with nuclear
Fri, Oct 8, 2021, 7:01PM

Palo Verde gets $20 million to make hydrogen while the sun shines
Fri, Oct 8, 2021, 4:30PM

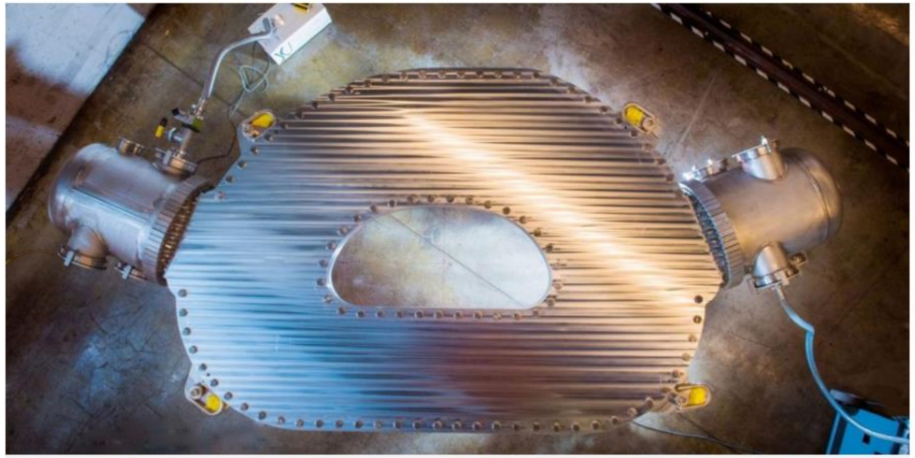
Framatome signs MOU to advance nuclear technology in Hungary
Fri, Oct 8, 2021, 2:00PM

Washington, Oregon receive over $33 million in Hanford assistance grants

RESEARCH & APPLICATIONS

MIT ramps 10-ton magnet up to 20 tesla in proof of concept for commercial fusion

Fri, Sep 10, 2021, 6:59PM | Nuclear News



This large-bore, full-scale high-temperature superconducting magnet designed and built by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center is the strongest fusion magnet in the world. (Photo: Gretchen Ertl, CFS/MIT-PSFC)

CFS and MIT hope to produce net energy in a compact tokamak device known as SPARC by 2025, on track for commercial fusion energy in the early 2030s.

Source [75]

NUCLEAR ENGINEERING INTERNATIONAL

Targeting a Fusion Demonstration Plant

8 November 2021

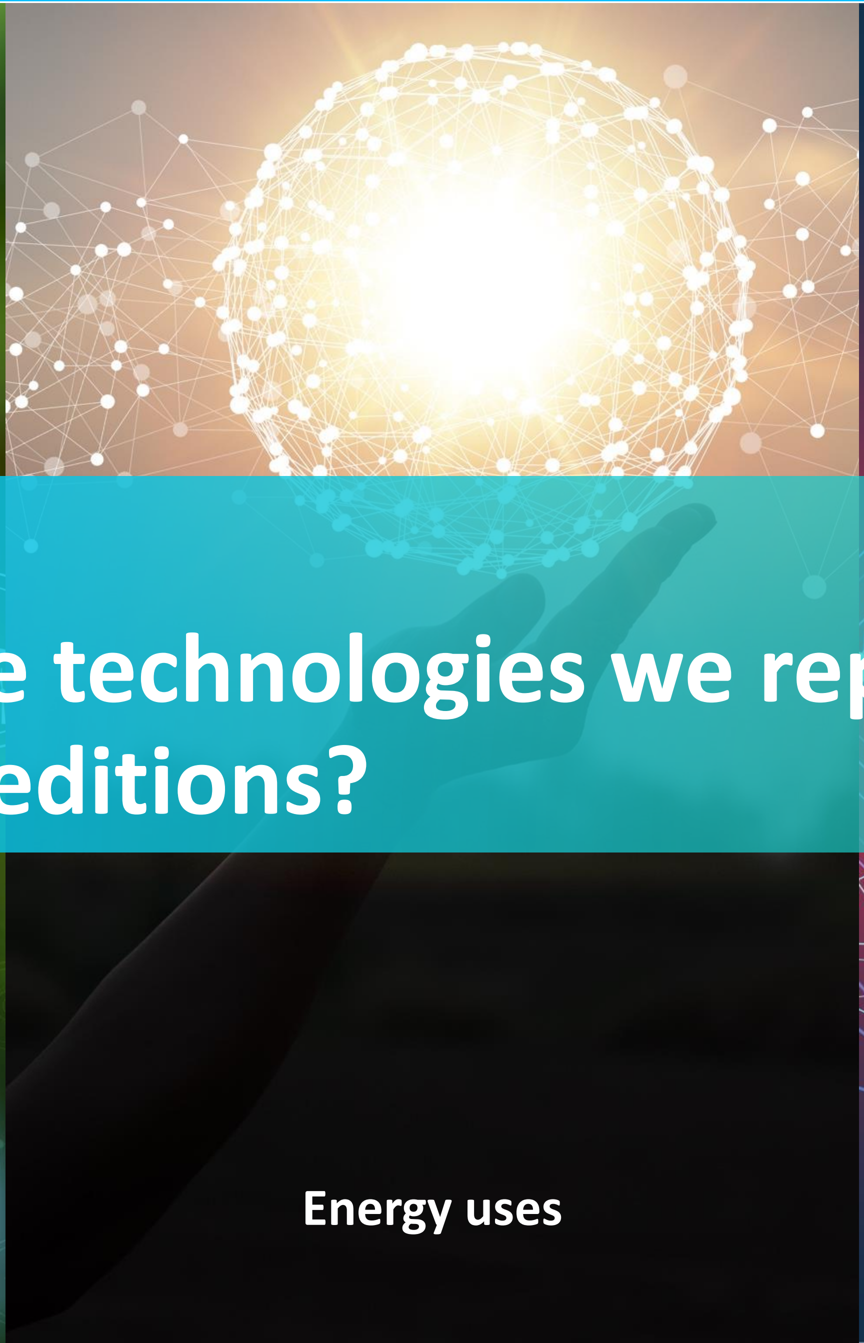
Canada-based General Fusion is aiming to transform the way the world is energised with its Magnetized Target Fusion (MTF) technology

The race to commercialise clean fusion energy reached a milestone this year when General Fusion announced it will build a demonstration plant for its magnetized target fusion (MTF) technology. The plant will be used to verify that General Fusion's MTF technology can create fusion conditions in a practical and cost-effective manner at power plant relevant scales. Construction is anticipated to begin in 2022, with operations beginning approximately three years later.

Source [76]

PART 2
What about the technologies we reported on in previous editions?

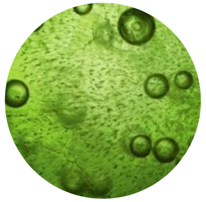

Sustainable energies

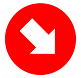

Energy uses


Enabling technologies

Sustainable energies

- Strong R&D activity and business increasing
- Active research and first emerging business
- Work in progress
- Decreasing R&D activity

	Technologies	Description	What has happened?	Trend
	**Generating power from electricity in the air**	Energy harvesting technologies use energy from the ambient environment as a primary energy source and convert it into electricity. Power can be taken from the air via various radiation conversions: e.g., ultrasonic sounds, infrared beams, magnetic radiation for induction, radio frequency signals, Wi-Fi,...	The number of start-up companies in the field of electro-magnetic wave energy harvesting and energy transport through the air increased significantly few years ago. However, ultrasonic and radiofrequency still present low performance and have not experienced any significant development. Conversely inductive and infrared technologies are doing well with applications currently dedicated to the military sector (charging of submarine batteries, PV panel in space to charge devices in desert locations...). Source [80]	
	**Hydrothermal gasification of biomass & waste**	Conversion of liquid organic waste into Synthetic Gas (methane, hydrogen) under supercritical conditions.	We continue to observe technological divergence in Europe with high activity in The Netherlands, whilst Switzerland is favouring more mature technology. New concepts are continuing to emerge (low TRL) in France. A couple of pilot projects are under discussion for the future.	
	**Pyrogasification of waste (Solid Recovered Fuel)**	Conversion of dry waste (as opposed to biomass) into energy carriers at high temperature (~1000°C) in a low-oxygen environment.	Pyrogasification is now a mature technology now with commercial projects ongoing all over the world (SWINDON, Cameleon...). In Europe, the challenge is to produce synthetic gas from Solid Recovered Waste. This trend is driven by the European legislation to greatly reduce landfilling (no more than 10% landfilling by 2035). The ENGIE GAYA platform was producing biomethane from waste (SRF) at the end of 2020 - a world first on a semi-industrial scale. Source [81]	
	**Biotechnology for energy**	Biotechnology utilizes biological systems, living organisms or parts of them to develop or create different products. Emerging biotechnology enables next-generation "advanced" hydrocarbon fuels to be obtained from industrial gas recycling.	Biotechnology for energy production is experiencing strong growth with a large amount of pilot units having been established since 2019. LanzaTech, a Chicago-based company launched in 2005, takes carbon-rich gases from industry to make ethanol, which can then be used for a range of low carbon products, including jet fuel. The company is involved in a couple of sustainable aviation fuels projects. In parallel, Electrochaea's two-step biomethanation process starts with the production of hydrogen by electrolysis using renewable power. The renewable hydrogen is combined with carbon dioxide and fed into the reactor which houses a methanogenic archaea to produce methane. Sources [82], [83]	

	Technologies	Description	What has happened?	Trend
	**Photovoltaics (PV)**	PV gets its name from the process of converting light (photons) to electricity (voltage), which is known as the photovoltaic effect.	Today, electricity from solar cells has become cost competitive in many regions and photovoltaic systems are being deployed on a wide scale to help power the electric grid. The vast majority of today's solar cells are made from silicon and offer both reasonable prices and good efficiency. These cells are usually assembled into larger modules that can be installed on the roofs of residential or commercial buildings or deployed on ground-mounted racks to create huge, utility-scale systems.	
	**Artificial photosynthesis**	Artificial photosynthesis refers to processes that convert direct solar light into sustainable fuels. These processes imitate natural photosynthesis, the process by which plants produce biomass from water and carbon dioxide. In artificial photosynthesis, water is split into hydrogen and oxygen and combined with CO_2 to produce hydrocarbons.	It comprises 3 approaches: electrochemical conversion with solar power, direct conversion via photo(electro)chemical systems and direct conversion via biological and biohybrid systems (i.e., living photosynthetic cell factories). Around 100 research groups worldwide are working on understanding basic relationships and developing prototypes. Most of the available systems show low solar-to-chemicals conversion efficiencies and need significant improvements in order to serve as industrial-scale production platforms. The goal in the near future is to increase performance to 10% solar-to-hydrogen efficiency. Efforts are aimed at increasing the efficiency to 30% by 2050. Furthermore, artificial photosynthesis could benefit from progress in the field of CO_2 capture and from the development of photovoltaic components. Source [84]	
	**Solar Energy storage in organic molecules** (Photon Energy Storage Materials –PESM)	PESM are able to capture and store solar energy using thermal 'switchable' molecules. During charging, the sunlight is absorbed by the molecule which either modifies its bond or switches its atoms to another position. During discharge, the molecule releases energy using a catalyst, a low level of sunlight energy or a low heat input.	The smart utilization of photons is attracting attention at a global level with respect to renewable energy and information technology. However, it is still impossible to store photons as batteries as condensers do for electrons. Present technologies utilize the energy of photons in situ, such as solar panels, or in spontaneous relaxation processes, such as photoluminescence. Experiments are still at the laboratory stage, but they are in competition with thermal storage and phase change materials. Stability of the molecule remains a main issue. Source [85]	

	Technologies	Description	What has happened?	Trend
	**Floating offshore wind (FOW)**	FOW are wind turbines mounted on floating structures rather than fixed structures that allows the turbine to generate electricity in water depths where fixed-foundation turbines are not feasible.	Following the first successful prototypes and demonstration projects, floating offshore wind is now taking its first steps towards commercialization. European companies are the pioneers with three quarters of the 50+ FOW projects at different stages of development worldwide followed by the USA and Japan. There is still a need to minimize the risk to increase confidence in projects. Source [86]	
	**The ocean as a primary renewable energy source**	It includes energy from currents (tidal stream), energy from differences in sea level between high and low tide (tidal range) and energy from wave movement.	In the case of tidal energy, the main challenge is to succeed in operating in very harsh conditions although the potential remains very high. Technologies are now tested on a large scale in real sea conditions with a convergence for high current areas (e.g., MeyGen, ENGIE). For waves, the industry took a step back a few years ago in order to focus on components (e.g., Drivetrain), and is now moving back towards testing full devices. For combined tidal and wave energies, developments and tests are increasing namely outside of Europe (Japan, Faroe Islands, China, Chile, etc.).	
		Ocean Thermal Energy Conversion (OTEC) is a process where energy is generated thanks to the difference in temperature between deep cold water and warm surface water. It includes Sea Water Air Conditioning (SWAC). Salinity Gradient Energy is generated thanks to the difference in salt content between freshwater and saltwater.	Ocean geothermal energy is still a non-mature technology. However, the first French demonstrator Thassalia is now finished. Installed at the *Grand Port Maritime* de Marseille in 2016, this plant is the first of its kind to use marine thermal energy both in France and in Europe. It supplies heating and cooling to all of the buildings connected to it via a 3 km network, which will eventually cover 500,000 m² in an eco-district which represents 70% fewer greenhouse gas emissions. Regarding salinity gradient energy, major operational issues related to the membrane persist. Source [87]	
	**Airborne high altitude wind energy**	Airborne Wind Energy Converters (AWEC) consist in tethered aircrafts that extract high density wind energy at high altitudes (200-600m) with 90% material savings compared to horizontal axis wind turbines (HAWT).	Airborne wind demonstrators are emerging alongside new pilots. We continue to observe a multitude of new concept whilst market players are faced with unknown, external challenges. Technological convergence has not yet happened. Source [88]	

Example: Small Modular Nuclear for decentralized zero carbon electricity production

Where are we in 2021? Trend

DESCRIPTION

SMR are nuclear fission reactors of up to 300MWe equivalent, designed with modular factory fabrication (current nuclear power stations are larger than 1,000 MWe in current net capacity).

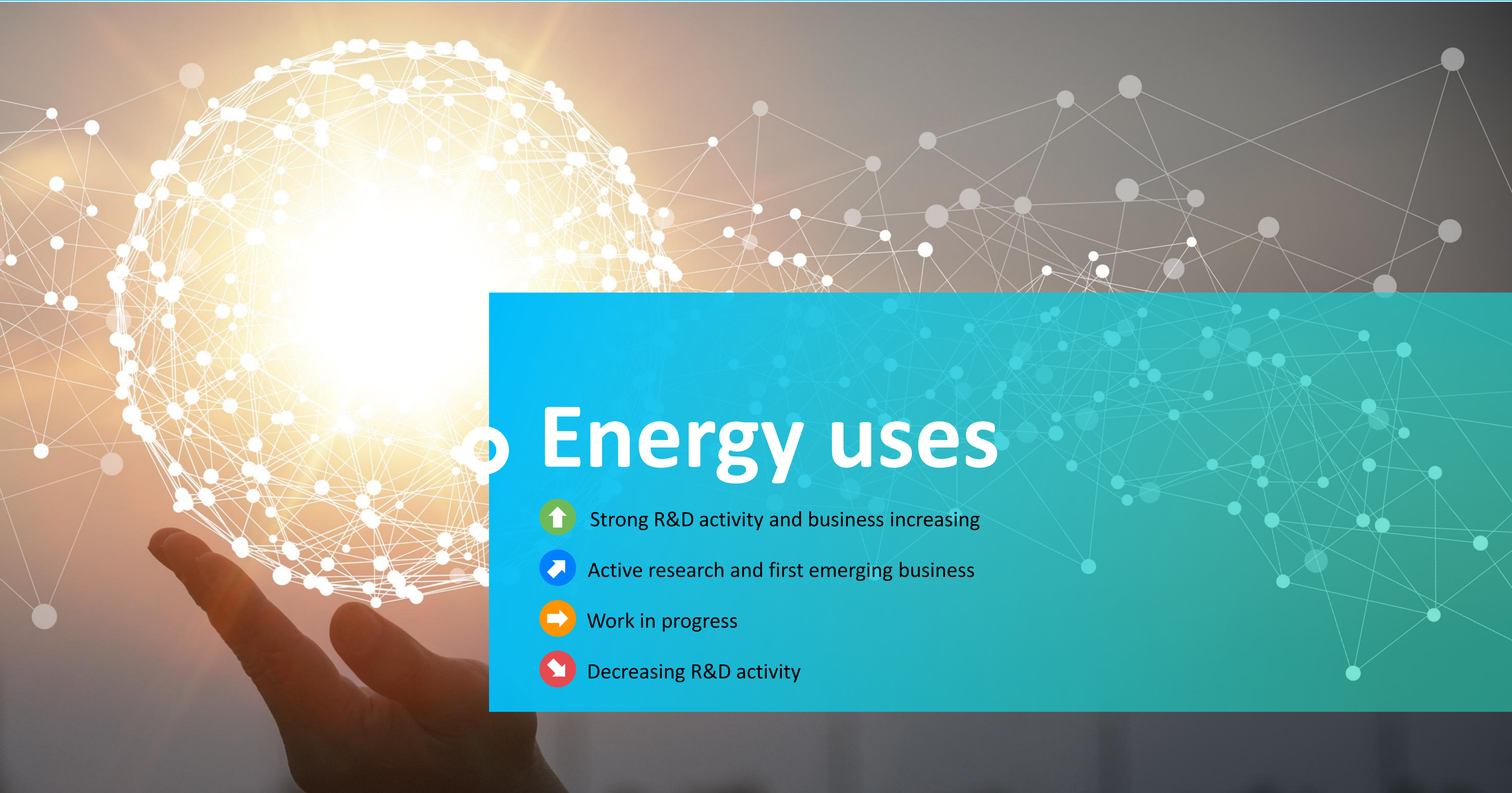
WHAT HAS HAPPENED?

The commercial phase has begun: Canada is very active in SMR development and has made its commitment official. Ontario Power Generation has chosen the BWRX 300 designed by GE-Hitachi for its Darlington project. In July, China began building the first commercial SMR onshore nuclear project using its own "Linglong One" SMR design with a 125 MW capacity. Finally, in October, French President Macron announced a €1 billion investment in the building of SMR as part of the "France 2030" five-year investment plan to drive industrial development.

In April, Terrestrial Energy contracted with ENGIE Laborelec for technical services relating to its nuclear fuel salt qualification program for the IMSR (Integral Molten Salt Reactor).

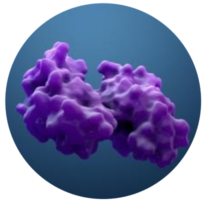
Construction of the first commercial nuclear SMR project 'Linglong One' in China in July 2021 [77]

Sources [78], [79]



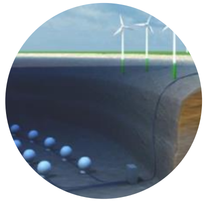
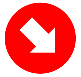
Energy uses

- Strong R&D activity and business increasing
- Active research and first emerging business
- Work in progress
- Decreasing R&D activity

	Technologies	Description	What has happened?	Trend
	**Power-to proteins**	Production of a protein thanks to bacterial and electrolytic H_2 as an energy source.	Creation of proteins, lipids, and functional ingredients for meat, egg, and dairy alternatives is one of the newest and most promising applications for fermentation. Non-conventional stakeholders are beginning to get involved in this domain (e.g., Total invests in Deep Branch, March ‘21), whilst for several oil & gas companies (Chevron & Shell) and energy utilities (Uniper & Drax) this field is already chartered territory. Despite the high activity level, the alternative protein industry is immature and needs to be tested thanks to demonstrators. Source [90]	
	**Pumped Hydro Compressed Air**	Hybridization of a mechanical solution (CAES) with a thermo-dynamic cycle (PHCA) for energy storage.	In 2020, this technology has been selected by ENGIE as one of most promising technologies to tackle the storage issue in developing of deep-water wind farms. However, this technology is not mature enough for large investment. A PHCA pilot, developed by PackGy, is closely followed by ENGIE and the company Triballat is interested in testing it. Source [91]	
	**Multi-purpose offshore platforms**	Constellation and synergies of various (far-)offshore economic activities, such as renewable energy generation (wind, solar, wave,...), energy storage, aquaculture, desalination, marine research, security, etc.	Today, multi-purpose offshore platforms do not yet exist. Only a few calls for tenders have been launched in Europe, e.g. Marseille harbour for offshore bunkering. Bunkering is the supplying of fuel for use by ships and includes the shipboard logistics of loading fuel and distributing it among available bunker tanks. The consortium C-NERGY conducted a feasibility study with a view to creating offshore islands on the Belgian coast. Source [92]	
	**Green ammonia and green fertilizer**	Production of sustainable ammonia and nitrogen based fertilizers by integrating renewable feedstock into the conventional process.	The current focus is on green ammonia production as energy vector by making it with green electricity and no longer from gas. The production is now driven by the potential demand of maritime transport. For green fertilizer, the main challenge is the down scaling in order to decentralize the production at an affordable price. Indeed, the production of a few thousand tons per day isn't adapted to a renewable electricity production at a local level. Research is active in this sector.	

	Technologies	Description	What has happened?	Trend
	**CO_2 cycle**	CO_2 cycle replaces the classical water steam cycle. The Allam cycle technology burns natural gas with pure oxygen. The resulting CO_2 is recycled through the combustor, turbine, heat exchanger, and compressor, creating lower-cost power with zero emissions. The main advantage is the 'Free' CO_2 capture which is ready for use as a resource rather than a waste.	NET Power has constructed a 50 MW demonstrator plant in Texas that is up and running, with plans to bring a full-scale 300 MW plant into service in 2025. The success of its zero-emissions natural-gas power plant has opened the way for NET Power to plan the construction of similar plants around the world. Few additional players are involved in this field. Toshiba, Parametric solutions, SwRI (South West Research Institute), the Gas Turbine Institute and GE are working together to design of a CO_2 turbine. Lastly, the potential for captured CO_2 in industry is growing: companies are pioneering new ways to use CO_2 in concrete and cement production, fertilizer production, e-methanol, e-jetfuel, e-methane... Sources [93], [94]	
	**Electrochemical storage: what's new in batteries**	A lithium-ion battery is a type of rechargeable battery in which lithium ions move from the negative electrode through an electrolyte to the positive electrode during discharge, and than back again when charging.	Batteries are still widely studied with multitudes of publications every week relating to the increasing charge rate for electrical vehicles and increasing energy density suppressing cobalt (using graphene, silicon,..). As regards, lithium-ion batteries, Europe is moving to establish a lithium-ion battery (LIB) industry with European and Asian players, facing competition from the US and Asia. Silicon doped anodes are gradually appearing on the battery cell market, offering an energy density of 330 Wh/kg. In parallel, some producers are broadening their technological portfolio to focus on Na-ion batteries. We continue to observe that technology evolution is driven by safety aspects and critical materials (e.g., Tesla has decided to move towards lithium-iron-phosphate-based battery).	
		Towards more sustainable and safer battery chemistry: Redox Flow Batteries and Solid-state batteries	Redox-Flow: this technology is still slow to penetrate the market although a big project has recently been announced (100-500 MWh in China). Solid State Lithium Batteries: car manufacturers are still believing in solid state battery development- cells should be ready to be validated by labs in 2022. Sources [95], [96], [97], [98]	

	Technologies	Description	What has happened?	Trend
	**Green mobility: what' new? Hyperloop**	Hyperloop is described as a sealed tube or system of tubes with low air pressure through which a pod may travel substantially free of air resistance or friction.	Hyperloop is now a mature technology. The Virgin Hyperloop tested human travel in a hyperloop pod for the first-time in November 2020. The high-speed transport system will become a reality in many parts of the world by the end of this decade according to the CEO of DP World. Initial projects will be probably be freight-related. Sources [99], [100]	
	Sustainable Aviation Fuel (SAF)	Hydrogen in aviation: a hydrogen-powered aircraft is an airplane that uses hydrogen fuel as a power source. Hydrogen can either be burned in a jet engine or can be used to power a fuel cell in order to generate electricity to power a propeller.	Research has intensified over recent years. But the road to hydrogen-powered aircraft still requires significant efforts on the part of the aviation industry and beyond. From hydrogen storage, cost and infrastructure to public perceptions on safety, the aviation sector is working to mature this technology whilst tackling major challenges. However, only one aircraft manufacturing company Airbus has promised hydrogen airplanes for 2035 for short haul and limited passengers transport (e.g., ZEROe project). Source [101]	
		Bio-jet-fuel in aviation: biomass-derived synthesized paraffinic kerosene (SPK) that is blended into conventionally petroleum-derived jet fuel to power aircraft.	Due to the limited options for carbon reduction and the significant capital cost of fleet replacement, "drop-in" alternatives with bio-jet-fuel is key for greenhouse gas emissions mitigation strategies in the aviation sector. This is reinforced by European ambition which will be gradually ramped up to 2% of SAF by 2025 and to 5% by 2030 as part of the European Green Deal. In the US, the Energy department is empowering energy companies and aviation stakeholders to launch a bio-jet-fuel demonstration plant while used cooking oil is already being blended with kerosene. Sources [102], [103]	
	**Direct Current (DC) grids**	DC distinguishes itself from Alternating Current owing to the electric charge flowing in a constant direction. Direct Current is native to solar PV electricity generation, battery storage, low-power domestic and commercial applications.	Currently known as nanogrids, the number of projects implemented is very low. Returns on investment seem too low in developed countries: gains in terms of energy efficiency are too low compared to the classical AC solution, voltage quality issues may arise, there are significant losses in wiring. However, the benefits also depend on the penetration rate of IoT, battery, PV panels, EV, smart power systems etc, in domestic settings. Nanogrids are solutions that are definitely being considered in emerging countries due to their ability to be off-grid.	

	Technologies	Description	What has happened?	Trend
	**Electricity storage in the sea**	To store excess wind energy, this technology makes use of a pump which empties the water contained in an underwater concrete sphere; electricity is released by a turbine which refills the sphere with ocean water.	This technology, among others, will be evaluated in the European project FORWARD2030. Development of new bio concrete and 3D concrete printers in collaboration with Holcim could increase the interest in this technology. For now, there isn't enough deep offshore wind farms to create a significant breakthrough. Source [104]	
	**Electricity storage inside wind turbine tower**	Pumped Storage Hydro is integrated into wind turbines in order to store excess electricity in turbine towers.	The GE and Max Bögl wind-hydro hybrid project for the world's tallest wind turbine in Gaildorf (DE) hasn't been developed. However, recent publications by GE and Holcim on the development of a 178m high wind turbine support using concrete 3D printers could point to a simple delay in the project as opposed to its standby.	
	**(Ambient) CO_2 to fuels using Hydrogen**	E-fuels are synthetic fuels, resulting from the combination of 'green or e-hydrogen' produced by the electrolysis of water with renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuels also called PtX, include a broad range of molecules: e-methane, e-methanol, formic acid, e-jet fuel…	In Europe, more than 220 e-fuels research and demonstrator projects have either been developed, completed, or are currently being planned with a peak reached in 2018. Installed electrolyzer capacities are getting higher and higher, indicating that consolidation is taking place, as fewer projects are closer to commercialization. Projects involve a large amount of partners in order to meet significant investment costs to develop these industries. Technical demonstrators and systems integration are of major importance for integrating PtX into energy systems and qualifying the business model: processes are highly dependant on the costs of electricity for electrolysis and of CO_2. • E-methanol: the e-CO_2Met project at the Hydrogen Lab Leuna, North-C-Methanol… • E-methane: still at demonstrator phase with several megawatt scale pilots mainly based in Europe with Jupiter 1000, Methycentre, GRHYD, ZSW, Store & Go, Audi & Mann… • Formic Acid: BASF (TRL 2) • E-jetfuel: Westküste 1000, Air to fuels^{TM}, Haru Oni (Siemens Energy) • DME: C2FUEL, ALIGN-CCUS, CO2FOKUS, TNO, GTI (membrane-based reactor)… Sources [105], [106], [107], [108], [109], [110]	

Example: Direct Air Capture for CO_2 removal from ambient air using chemical processes

Where are we in 2021? Trend ↑

DESCRIPTION

- Carbon dioxide can be removed from ambient air via chemical processes using acid base reactions at high or low temperature. Direct Air Capture (DAC) is comparable to the human respiratory system or the photosynthesis where the process releases captured gases from the material.
- CO_2 can be permanently stored in deep geological formations or used to produce fuels, chemicals, building materials or other products containing CO_2. When CO_2 is geologically stored, it is permanently removed from the atmosphere, resulting in negative emissions.

WHAT HAS HAPPENED?

- Significant acceleration after the last IPCC report release in August 2021. DAC will be part of Carbon Dioxide Removal technologies for carbon sequestration.
- A first commercial unit, the Orca unit belonging to Climeworks has been set up in Iceland; certificates trading is in the development stage
- The project currently requires several more large-scale demonstrations to be developed in order to fine-tune the technology and reduce capture costs.

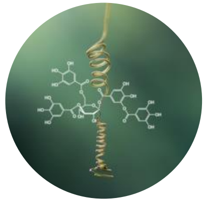
The world's largest climate-positive direct air capture plant: Orca!, 4kt/y with sequestration [89]

Enabling technologies

- Strong R&D activity and business increasing
- Active research and first emerging business
- Work in progress
- Decreasing R&D activity

	Technologies	Description	What has happened?	Trend
	**Biomimicry for Cybersecurity**	Cybersecurity refers to hardware and software components that protect computer devices from unauthorised access, but also to non-technical measures such as legislation and user training. The challenge is to keep systems cyber secure by using bio-inspired techniques.	A couple of trials are in place which make use of biomimicry in response to cybersecurity challenges. Cybersecurity includes a multitude of different aspects such as defense layers, counter attack, misleading attackers, protection strategies and also human error, which is often referred to as the weakest link. This domain is still at the research project stage. At this moment in time, no breakthroughs relating to biomimicry have been observed.	
	**Sustainable catalysts as energy transition enablers**	Catalysts increase the reaction rate without being consumed in order to achieve the chemical equilibrium at a suitable temperature. A catalyst is specific to each final product, reaction conditions and type of process.	Platinum group metal (PGM) catalysts dominate today's applications with the vast development of electrochemical processes, that build a bridge between the molecule-based economy and green electricity production. Alternative catalysts to replace iron, nickel and copper also exist, but they are rare and costly. As such, a significant scientific effort is being devoted to the development of low-PGM and PGM-free catalysts. Research is currently focusing on these sustainable catalysts with non-transition metals.	
	**Water harvesting from the air based on the atmospheric water generator (AWG)**	AWG is a device that extracts water from humid ambient air. Dew water collection systems are divided into three categories: i) dew water harvesting using the radiative cooling surface, ii) the solar-regenerated desiccant system and iii) active condensation technology.	Atmospheric water harvesting (AWH) is emerging as a promising means of overcoming the water scarcity in arid regions, particularly for inland areas lacking liquid water sources. These technologies haven't increased as such but now offer new possibilities thanks to their combination with Direct Air Capture research programs. Some challenges remain in order to optimize efficiency and ensure the delivery of good quality water at an affordable cost.	

	Technologies	Description	What has happened?	Trend
	**Artificial Intelligence: dueling neural networks or Generative Adversarial Networks GANs**	The generator takes simple random variables as inputs and generates new data. The discriminator takes "true" and "generated" data and tries to discriminate them, building a classifier. The goal of the generator is to fool the discriminator (increase the classification error by mixing up generated data with true data as much as possible) and the goal of the discriminator is to distinguish between true and generated data.	GAN is an already mature & usable technology, but more progress is expected in the coming years. The main uses are: fake data generation (images, text, video,...), fake data detection, automatic data classification. This technology could have an important impact on society, being used to generate "deep fakes" for example. It can either be used as a "base brick" in classification solutions (e.g., detect asset defects from photos) or to generate dummy data to avoid transferring "real data" protected by GDPR for example. Ethical and policy issues still need to be resolved.	
	**Quantum computing**	Quantum computing harnesses the phenomena of quantum mechanics to provide a huge leap forward in computation in order to resolve certain problems. It uses qubits (quantum bits) which are associated with the quantum state of a physical component (e.g., spin of an electron, polarization of an ion). Calculations are made using laws of quantum mechanics.	Quantum computing will open door to more efficient algorithms, but it remains an immature and very complex technology which, for now, cannot be used in an industrial setting, although progress is constant. In coming years, hardware development will focus on increasing the number of quantum bits and in particular on further reducing, and ideally completely correcting errors that can occur in calculations. In terms of applications, intensive efforts are being made to develop algorithms to resolve optimization problems in the chemical, financial, pharmaceutical, logistics, transport and other industries. The challenges are so complex that the next steps in the development of quantum computing will most likely be led by large research collaborations and industrial research centers.	

	Technologies	Description	What has happened?	Trend
	**3D metal printing**	New concepts & applications combining design freedom and tailor-made materials.	The 3D Printing of metallic materials is now reaching its maturity for critical and high-end applications. For example, Ariane Group is currently integrating qualified 3D printed metallic components in Ariane 6 launchers. Different 3D printing technologies for ceramics (zirconia, alumina...) have shown significant progress during recent years with the production of small-size demonstrators with complex structures. Significant improvement is still required to ensure stable fabrication and increase the targeted build volume.	
	**3D to 4D printing**	4D printing uses the same techniques as 3D printing. However, the resulting 3D shape is able to morph into different forms in response to environmental stimulus, with the 4th dimension being the time-dependent shape change after the printing.	This technology is also known as 4D bioprinting, active origami, or shape-morphing systems. Although a variety of stimuli-responsive microstructures have been reported, 4D printing technology still requires a significant amount of effort at the level of the development and improvement of new materials and printing methods, as the majority of current demonstrators still remain at lab scale. Source [80]	
	**Self-healing materials**	Material with the ability to automatically heal (recover/repair) damages without any external (human) intervention.	Self-healing materials cover a wide range of materials (polymers, composites, concretes…) and healing mechanisms. A series of products are already commercially available on the market but feedback from the field is still required (bio-concretes, polymers with intrinsic healing) whilst self-healing composites are still in the research phase and require upscaling efforts at the level of the production process.	
	**Internet of Things (IoT)**	The IoT describes physical objects that are embedded with sensors, software and other technologies, and that connect and exchange data with other devices and systems over the Internet or via other communications networks. The result is the merging of the physical and digital worlds with the possibility of creating new products and services (e.g., smart mobility).	Numerous IoT applications have already existed for several years. Nevertheless, manufacturing companies are finding it difficult to tap the potential of the IoT. The “digitalization paradox” describes the worldwide phenomenon according to which the high investments made in connectivity do not generate the expected revenues. However, be it for highly automated vehicles, smart houses, medical fitness trackers or connected production systems, the disruptive power of the IoT will fundamentally change the business logic of many sectors.	

Example: Radiative cooling for a “cool island” to combat urban heat

Where are we in 2021? Trend

DESCRIPTION

- Radiative cooling is based on the radiative emission of heat energy, leading to the spontaneous cooling of any body.
- The system rejects heat from earth systems, sending it into space, using it as an infinite cold radiator or reservoir at -270°C. Through selected infrared radiations, it acts like a greenhouse effect in reverse.

WHAT HAS HAPPENED?

- Radiative cooling panels can provide cooling for industrial or tertiary installation, help fight urban heat islands and be coupled with photovoltaics panels.
- Deployments have occurred on the retail market in the US and in South East Asia on skid or airport roofs and in Europe with the “cool island“ system.
- Good medium-term prospects for air conditioning, sub-cooler refrigeration, small network district cooling but also data centers, PV trigeneration (heating, cooling and electricity), clean rooms and industrial cooling.

Cool island installed by ENGIE at La Defense business district in France

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Research

Discussion / Questions

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