ENGIE

Research

Emerging Sustainable Technologies

2019 version of ENGIE's technology watch

Edito

Join us in our journey to a zero-carbon energy transition. The transition remains challenging, but we are convinced, as ENGIE Research, that technological advances will be part of the solution. It is extremely hard to predict next technology breakthroughs but, in this document, we present topical areas that we think will offer non-trivial benefits and impacts on this transition. Therefore ENGIE is working on these topics and keeping a close eye on their trends.

Investment in the development of these new ‘sustainable’ technologies is required and collaboration between public organizations and private organizations required. Apart from the environment and economics, the support of the citizens is crucial. The social acceptance and consequent adoption of new technologies will (co-)determine whether a technology will breakthrough.

The energy transition will therefore be an ‘AND’ story along two axes: (i) we will need many emerging ‘sustainable’ technologies; there is not one that has the potential to overcome the challenge alone and (ii) the challenge is too large to overcome alone as a person/company/sector, we must collaborate. The document has little pretention apart from inspiring its readers and it is in the context of this spirit of collaboration that this document is written and published.

Dr. Jan Mertens, Chief Science Officer @ ENGIE, Visiting Professor @Ugent
Dr. Elodie Le Cadre, Lead Science Advisor @ENGIE

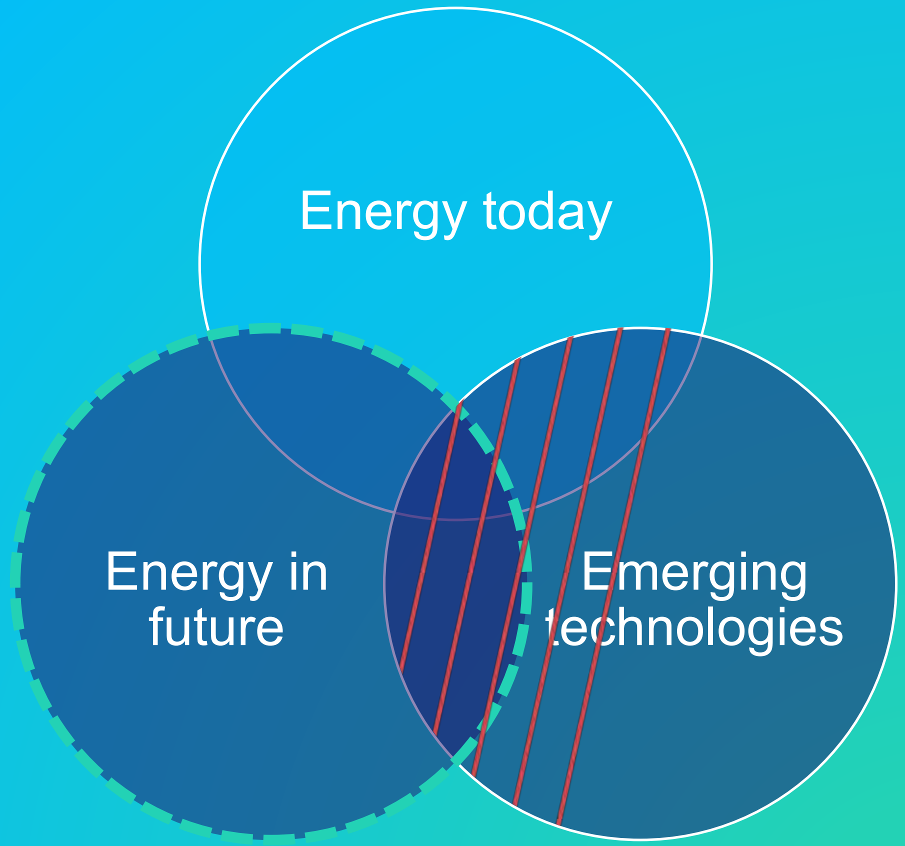
Just before the start…

Objective of this document

Present emerging technologies that:

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

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



Introduction

Renewable is not always sustainable

Environment is not CO_2

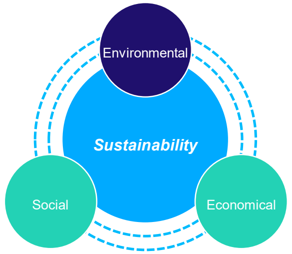
Sustainable includes social aspects

Renewable versus sustainable energy

Renewable energy

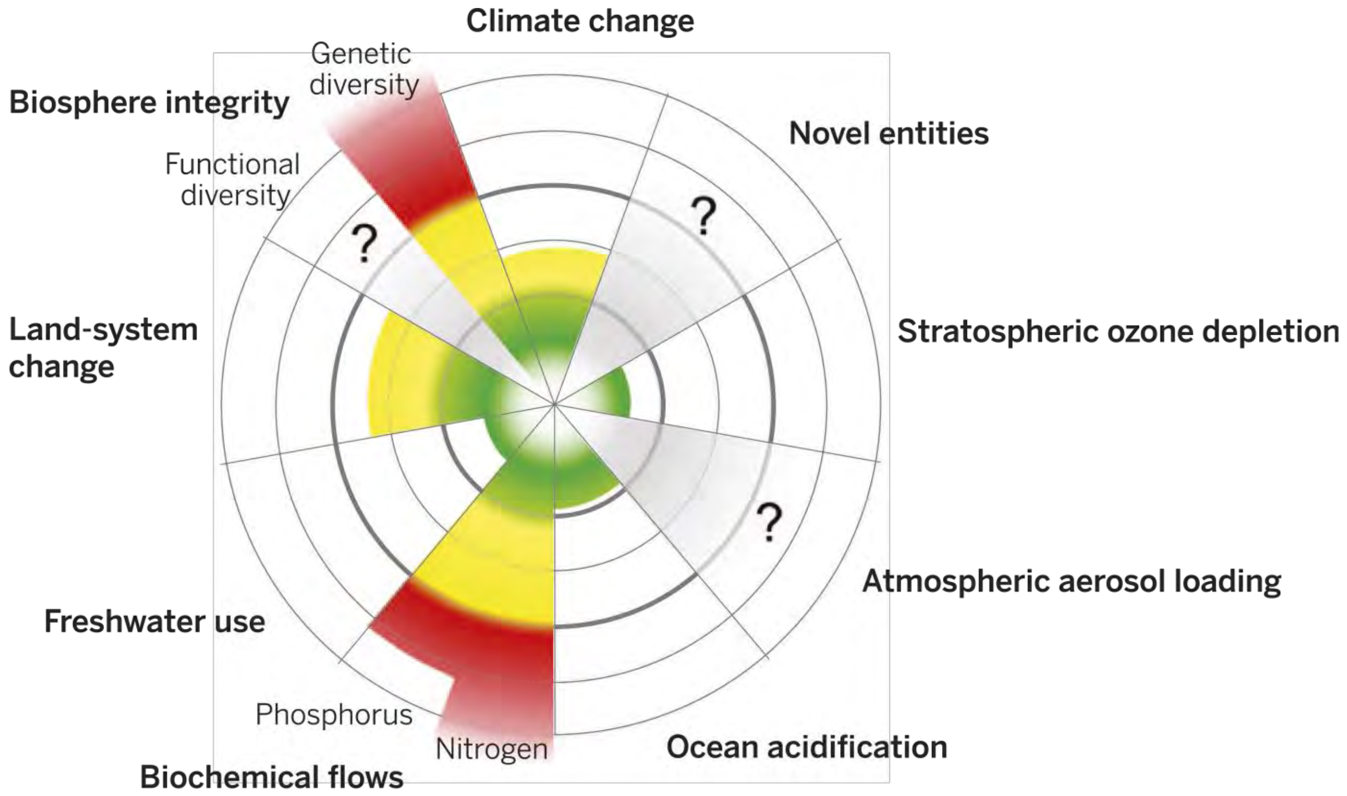
Sources that are naturally replenished on a human timescale

Sustainable energy



The planetary boundary concept defines the limits within which humanity can safely operate

Current status of the control variables for seven of the planetary boundaries



Beyond zone of uncertainty (high risk)
In zone of uncertainty (increasing risk)
Below boundary (safe)
Boundary not yet quantified

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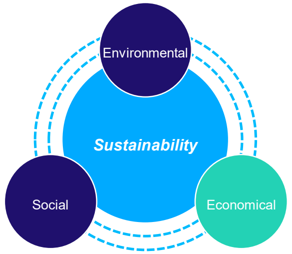
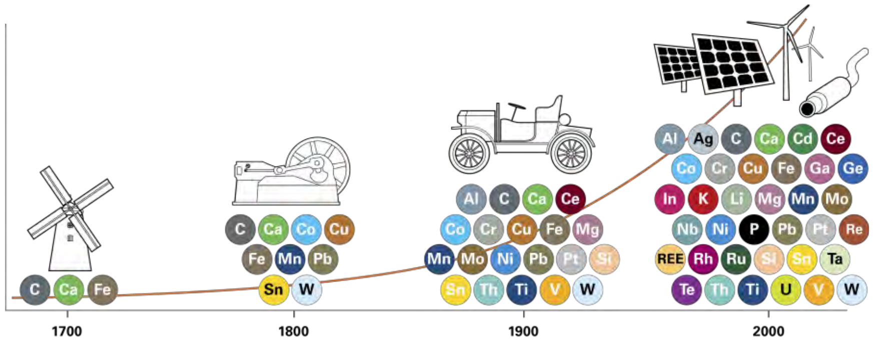


Materials for renewable energy: environmental, social and ethical challenges

- Scarcity as such may not be the largest challenge; however possible issue of new mines not opening fast enough…
- Recycling and search for earth abundant alternatives is on-going
- **Main issues related to the sustainable mining: both from an environmental as well as social (ethical) aspect**

Materials widely used in energy technologies



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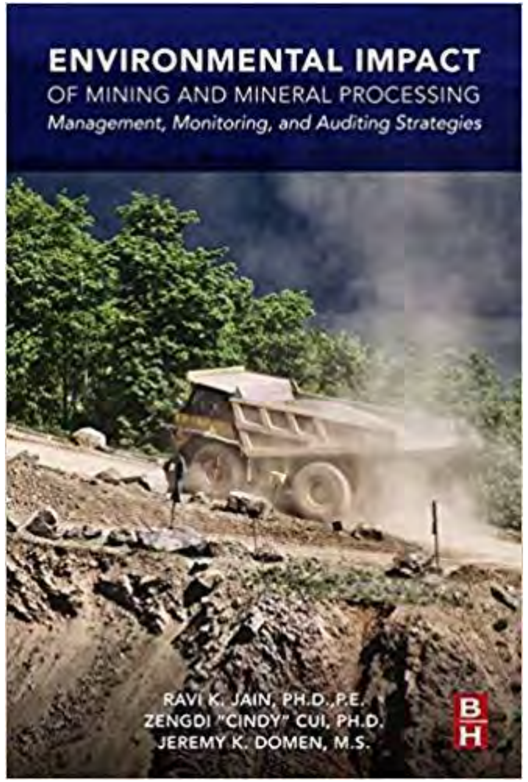

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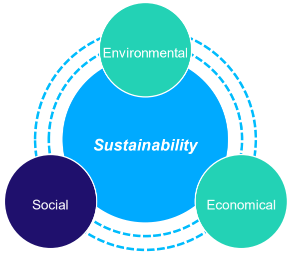
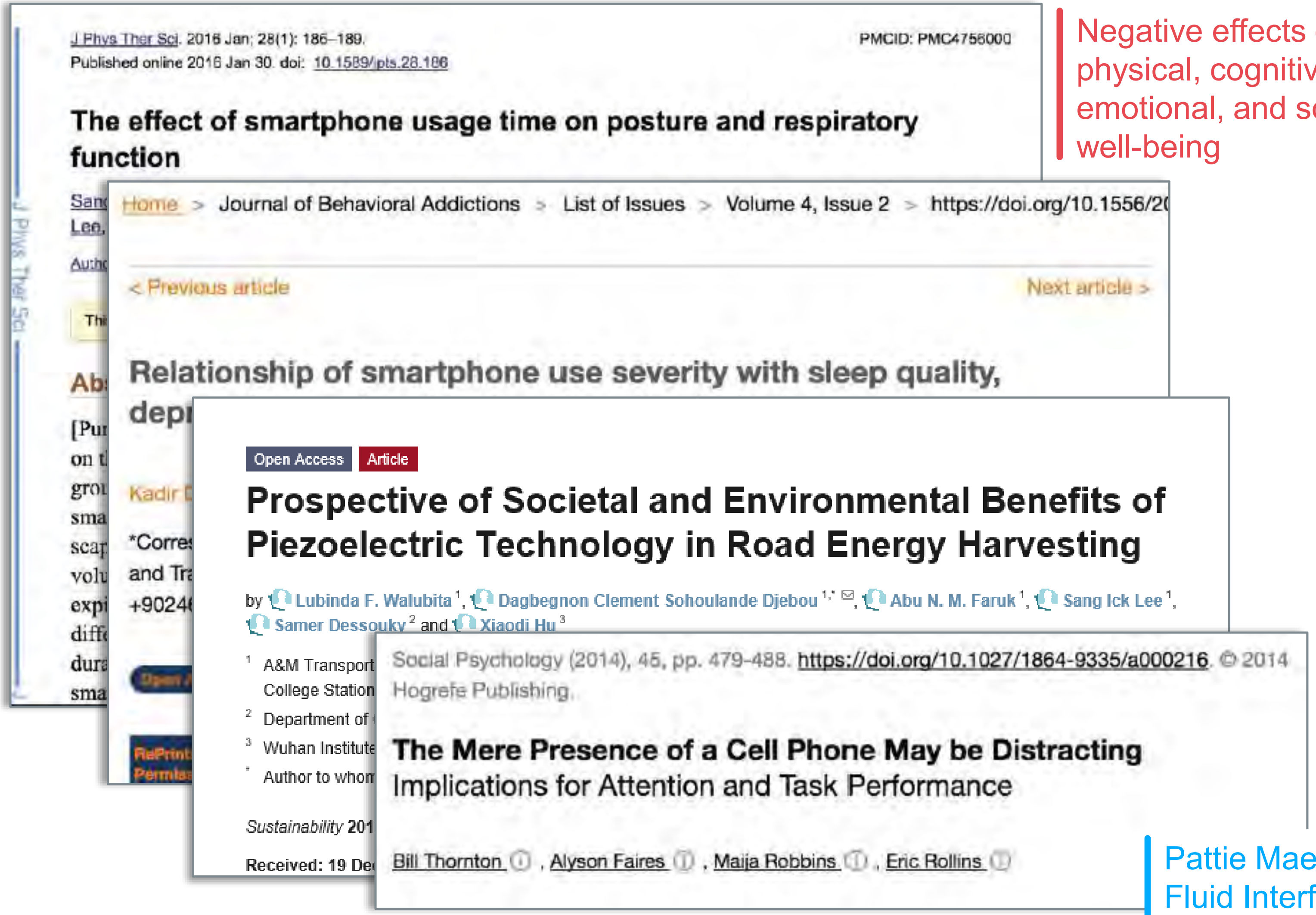


Sustainable and social: social well being of technologies?



J Phys Ther Sci. 2016 Jan; 28(1): 186–189.
Published online 2016 Jan 30. doi: 10.1589/jpts.28.186
PMCID: PMC4756000

The effect of smartphone usage time on posture and respiratory function

Home > Journal of Behavioral Addictions > List of Issues > Volume 4, Issue 2 > https://doi.org/10.1556/2

< Previous article
Next article >

Relationship of smartphone use severity with sleep quality,

Open Access
Article

Prospective of Societal and Environmental Benefits of Piezoelectric Technology in Road Energy Harvesting

by Lubinda F. Walubita[1], Dagbegnon Clement Sohoulande Djebou[1,*], Abu N. M. Faruk[1], Sang Ick Lee[1], Samer Dessouky[2] and Xiaodi Hu[3]

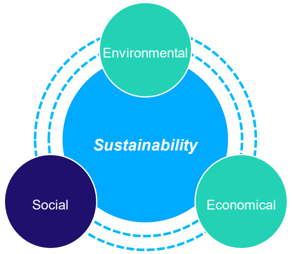
Social Psychology (2014), 45, pp. 479-488. https://doi.org/10.1027/1864-9335/a000216. © 2014 Hogrefe Publishing.

The Mere Presence of a Cell Phone May be Distracting
Implications for Attention and Task Performance

Bill Thornton, Alyson Faires, Maija Robbins, Eric Rollins

Negative effects on physical, cognitive, emotional, and social well-being

Pattie Maes
Fluid Interfaces Group



Challenges are not only technical but…

Even more great challenges:

- Safety
- Security
- Privacy
- Ethics

« A robot may not injure a human being or, through inaction, allow a human being to come to harm.

A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.

A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws. »

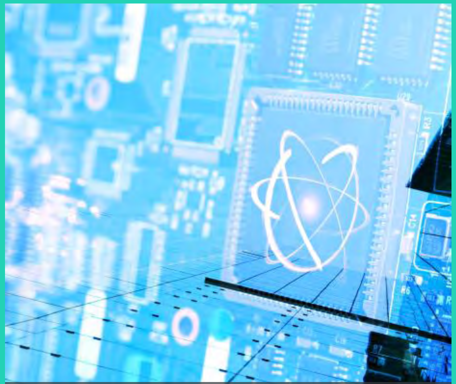
Isaac Asimov, *3 Laws of Robots* (1942)

Emerging Sustainable Technologies

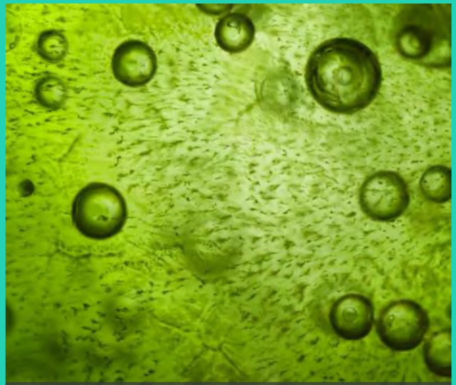
Electrochemical storage

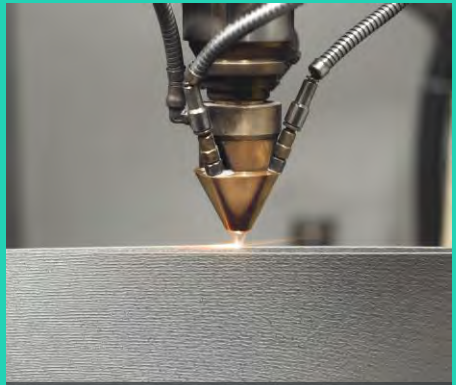

Radiative cooling


Artificial Intelligence

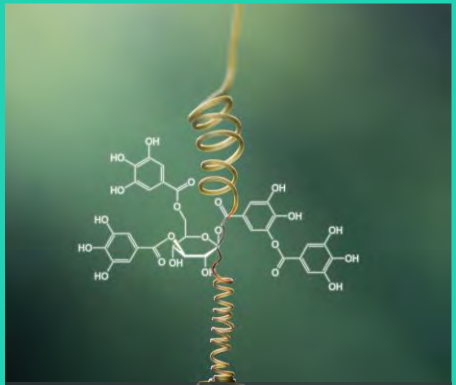

Quantum computing


CO_2 cycle


Biotech


3D metal printing


Green mobility


Self-healing materials

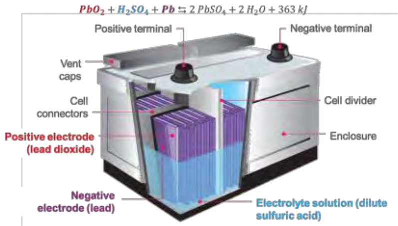
1

Electrochemical storage: what is new in batteries?

Drive not only towards cheaper but more sustainable and safer battery chemistries

Lead acid: mature technology

2019



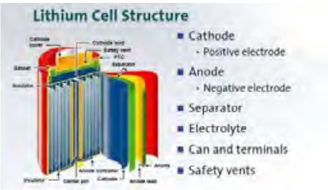
Source [5]

Li Ni Mn Co Al
Si Fe
F Pb C
Sb S Water

Main Advantages
- Cost (150-300 €/kWh)
- Recyclability
- Mature
- Robust

Main Drawbacks
- Danger (overheating, …)
- Low energy density (50-100 Wh/L)
- Low cycle life (500-2000)
- Toxic components

Conventional Lithium ion: performances



Source [6]

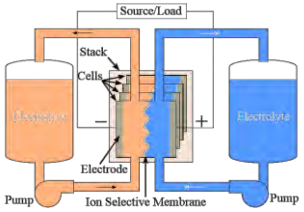
Li Ni Mn Co Al
Si Fe P Ti Cu
F C
Water

Main Advantages
- Energy density (200-350 Wh/L)
- Long cycle life (1000-10000 cycles)
- High roundtrip efficiency

Main Drawbacks
- Safety (thermal runaway)
- Cost
- Sophisticated BMS required
- Lifetime (less than 10 years)
- Temperature (irreversible thermal degradation when > 70°C)

Redox Flow batteries: more sustainable?

2025-2035?



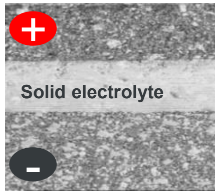
Source [7]

Al
Fe P Ti
Zn Br F Pb C
V Pt Water

Main Advantages
- Less sensitive to T°C
- Energy and power scalable independently
- High cycle (20000) and calendar life expectancy for Vanadium Redox Flow
- R&D for organic flow batteries

Main Drawbacks
- Risk of leakage, Requires pumps, valves, sensors maintenance
- Higher CAPEX
- Low energy density (10-50 Wh/kg)

Solid state batteries: safer?

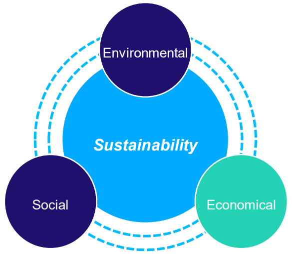


Source [8]

Li Ni Mn Co Al
Si Fe P Ti Cu
F C
Pt Y Water
Zr

Main Advantages
- Safe
- Theoretical more energy dense

Main Drawbacks
- Few commercial products not fully stabilized
- Need to heat the system
- R&D stages



Redox Flow Batteries (RFB): technology description

- Two electrolytes (external tanks), acting as liquid energy carriers, are pumped simultaneously through the two half-cells of the reaction cell separated by a membrane
- The RFB technology combines electrochemistry and mechanics (fluid pumping, fluid distribution,…)
- RFB operate by changing the metal ion valence

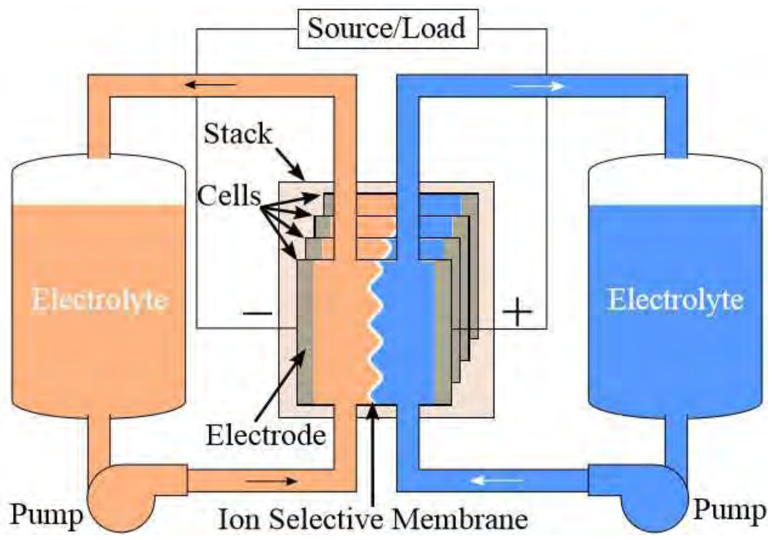
ADVANTAGES:

- Less sensitive to T°C
- Power and energy are independent and can be scaled separately:
  - Add Power = increase electrode surface
  - Add Energy = increase tank size
- Long term energy storage solution (typical > 3 to 8h)

CHALLENGES

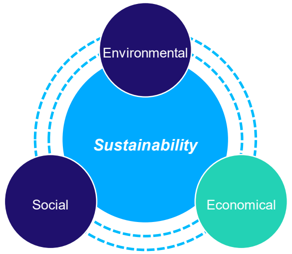
- Capex Cost
- Risk of leakage

Redox Flow Battery System



Negative electrode:	Positive electrode:
Discharge $V^{2+} \rightleftarrows V^{3+} + e^-$ Charge	Discharge $VO_2^+ + 2H^+ + e^- \rightleftarrows VO^{2+} + H_2O$ Charge

Source [7]



Solid State Batteries:
technology description

Similar to a Li-ion battery but with a polymer or ceramic (solid state) electrolyte instead of liquid electrolyte

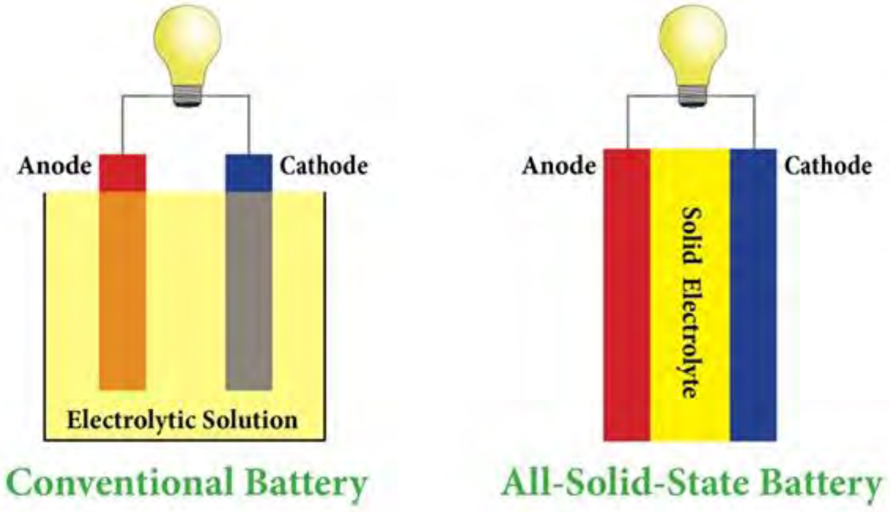
ADVANTAGES:

- Safer than Li-ion batteries. Internal short-circuits are avoided (Lithium dendrites growth is limited as electrolyte is solid)
- Solid system allows various sizes and shapes for cells
- Theoretic potential of higher energy densities

CHALLENGES:

- Low temperature operation can be a challenge
- R&D development of electrolytes with sufficient ionic conductivity
- High self-discharge (some sub-families)

Description of Solid State Batteries



Source [9]

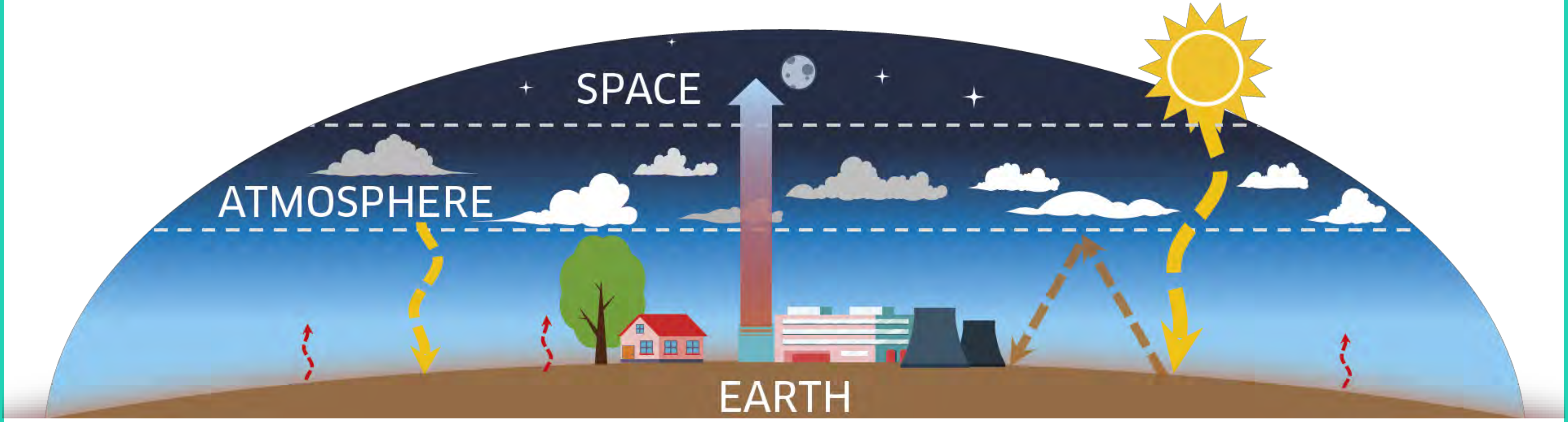
2

Radiative cooling

What is Skycooling?

Trade our heat with the infinite cold space

- Skycooling is based on **radiative emission of heat energy**, leading to a spontaneous cooling of any body.
- **Reject heat from earth systems into space**, using it as an infinite cold radiator or reservoir at -270°C.
- Through selected infrared radiations, it acts like a **reversed green-house effect**



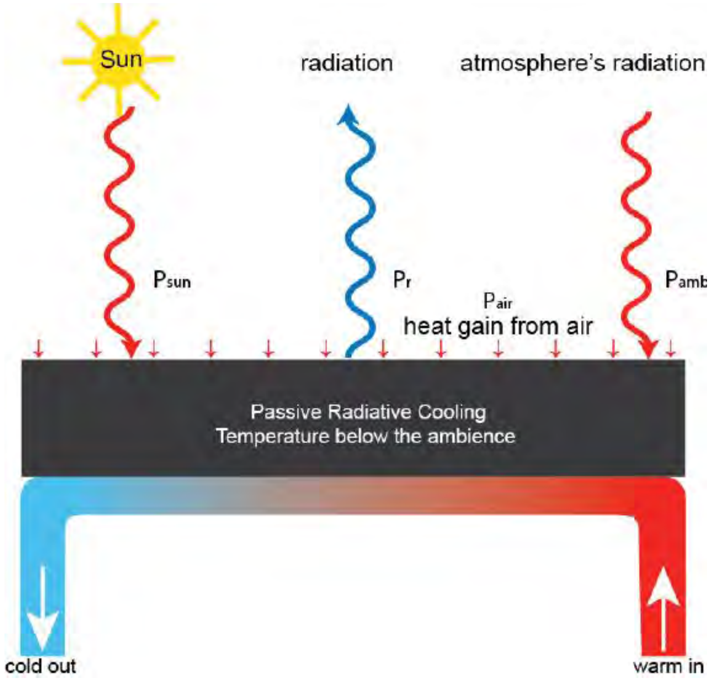
How does it work?

Selectively emits energy through atmosphere

Principle: nanocoatings can limit incoming heat and enhance outgoing radiation

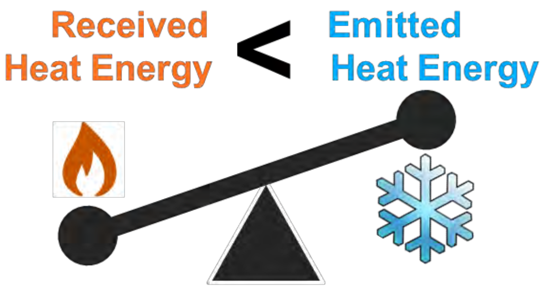
- Advanced nanocoatings can now effectively reflect solar radiation, while emiting desired infrared wavelengths capable of travelling through “atmospheric transparent windows” (8-13μm)
- Radiations in this range will be far less absorbed by our atmospher, allowing exchange with the space

Nanocoating principle

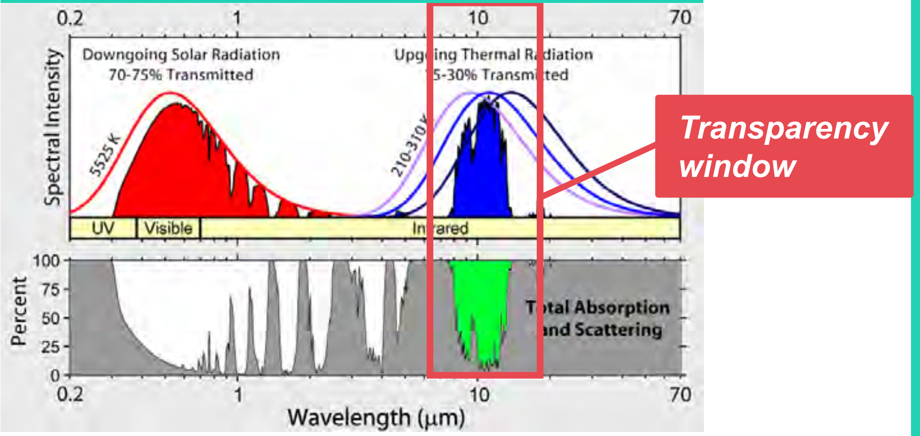


Source [10]

Thermal balance of cooling



Radiation Transmitted by the Atmosphere



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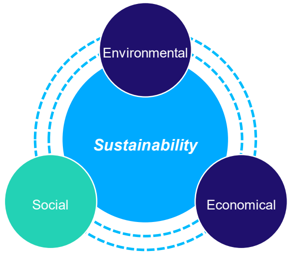


Radiative cooling:
large market closed to maturity !

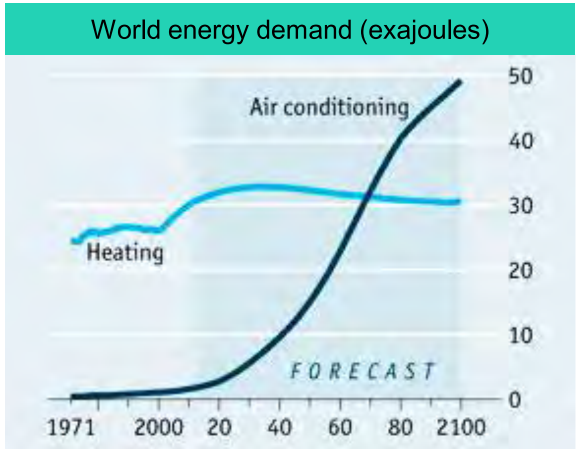
ADVANTAGES:

New nano-structured materials offers affordable and flexible solutions (coatings, films)

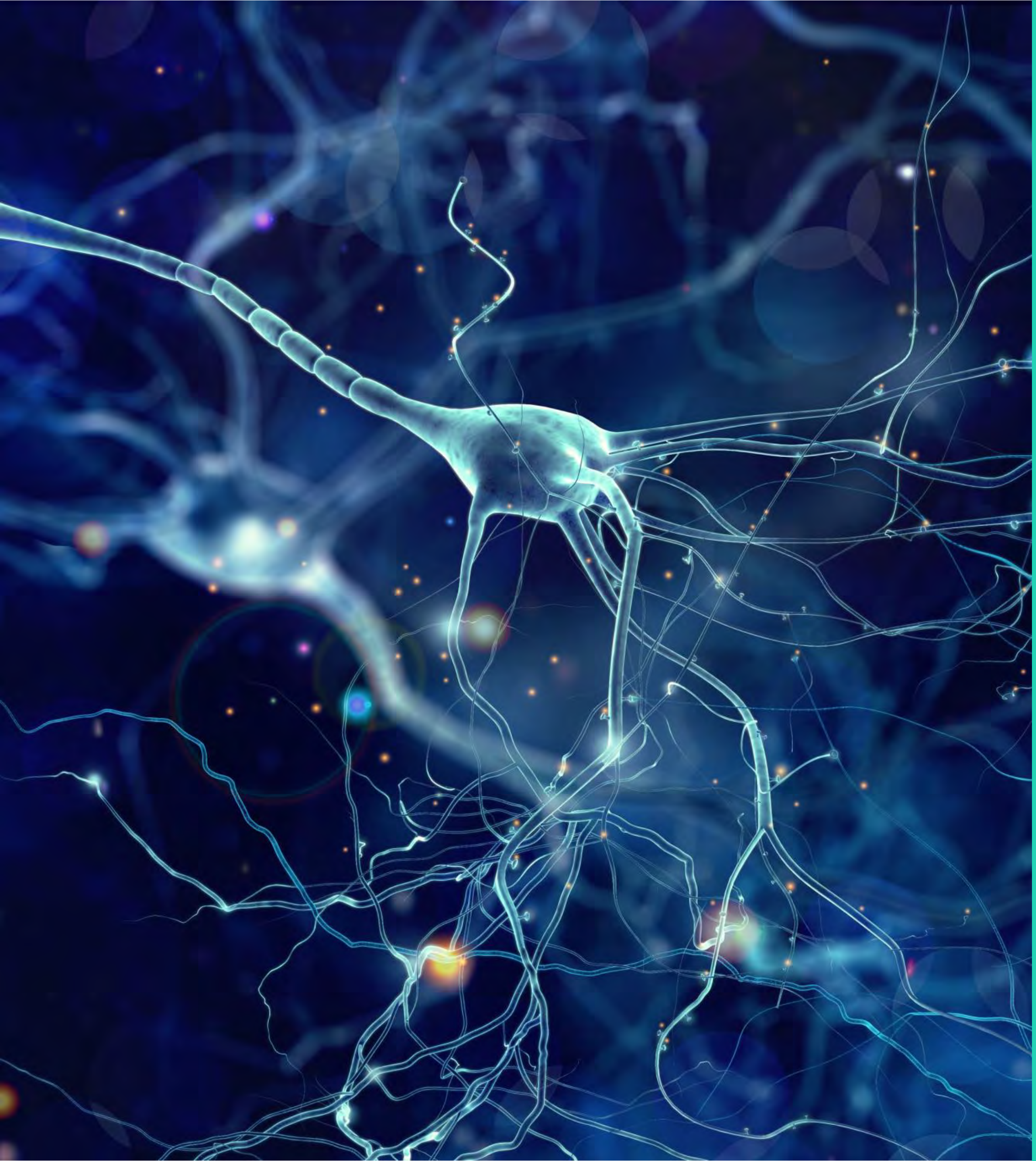
- Products already available for building heat shielding (TRL9)
- Emerging products for cold water production (TRL4-5)
- Reduce use of high GWP coolants (CFC, HFC)
- Fight Global Warming using chemical-free, low temperature, passive phenomenon
- Save water and energy using infinite cold reservoir
- Contribute to global cooling through “Reversed” green-house effect

CHALLENGES:

- Sensitive to climatic conditions
- Low energy density
- Dazzling reflections in urban area



Source [12]



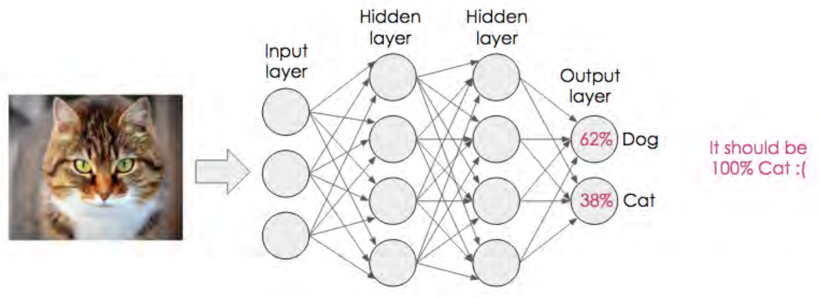
3

Artificial Intelligence: the concept of duelling neural networks

Duelling neural networks or Generative adversarial networks (GANs)

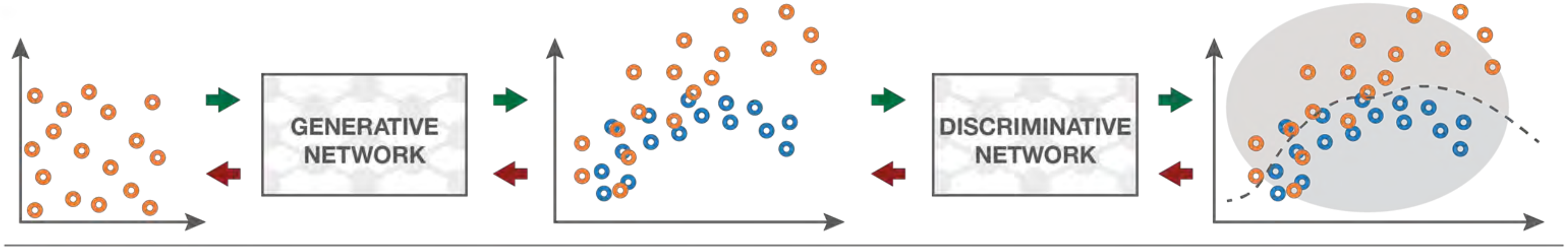
‘Normal’ Neural network:

input data → predicts the output



Duelling neural networks or Generative adversarial networks (GANs):

The generator takes simple random variables as inputs and generate new data. The discriminator takes “true” and “generated” data and try to discriminate them, building a classifier. The goal of the generator is to fool the discriminator (increase the classification error by mixing up as much as possible generated data with true data) and the goal of the discriminator is to distinguish between true and generated data.



Forward propagation (generation and classification)

Backward propagation (adversarial training)

Input random variables

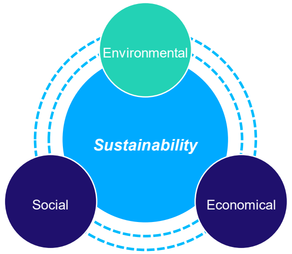
The generative network is trained to **maximise** the final classification error

The **generated distribution** and the **true distribution** are not compared directly

The discriminative network is trained to **minimise** the final classification error

The classification error is the basis metric for the training of the both networks

Source [13]



Applications of GANs vary widely:
from medicine to graphical and text applications

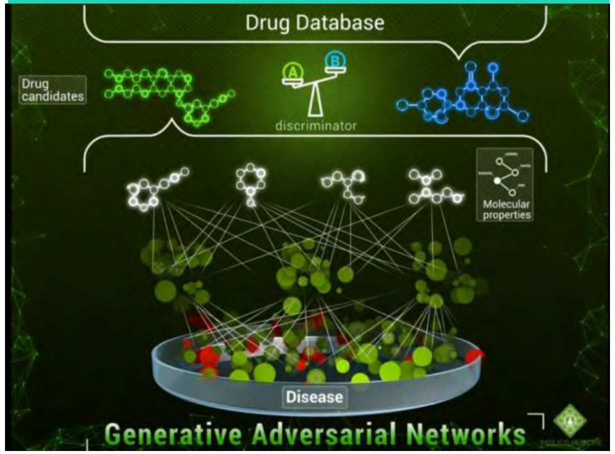
Example in medicine

An original application of GANs was proposed by Insilico Medicine.
They use it for **an artificially intelligent drug discovery**.

To train the Generator to sample drug candidates for a given disease as precisely as possible to existing drugs from a Drug Database.

Then generate a drug for a previously incurable disease using the Generator, and using the Discriminator to determine whether the sampled drug actually cures the given disease.

Creating Molecules from scratch: Drug Discovery with Generative Adversarial Networks

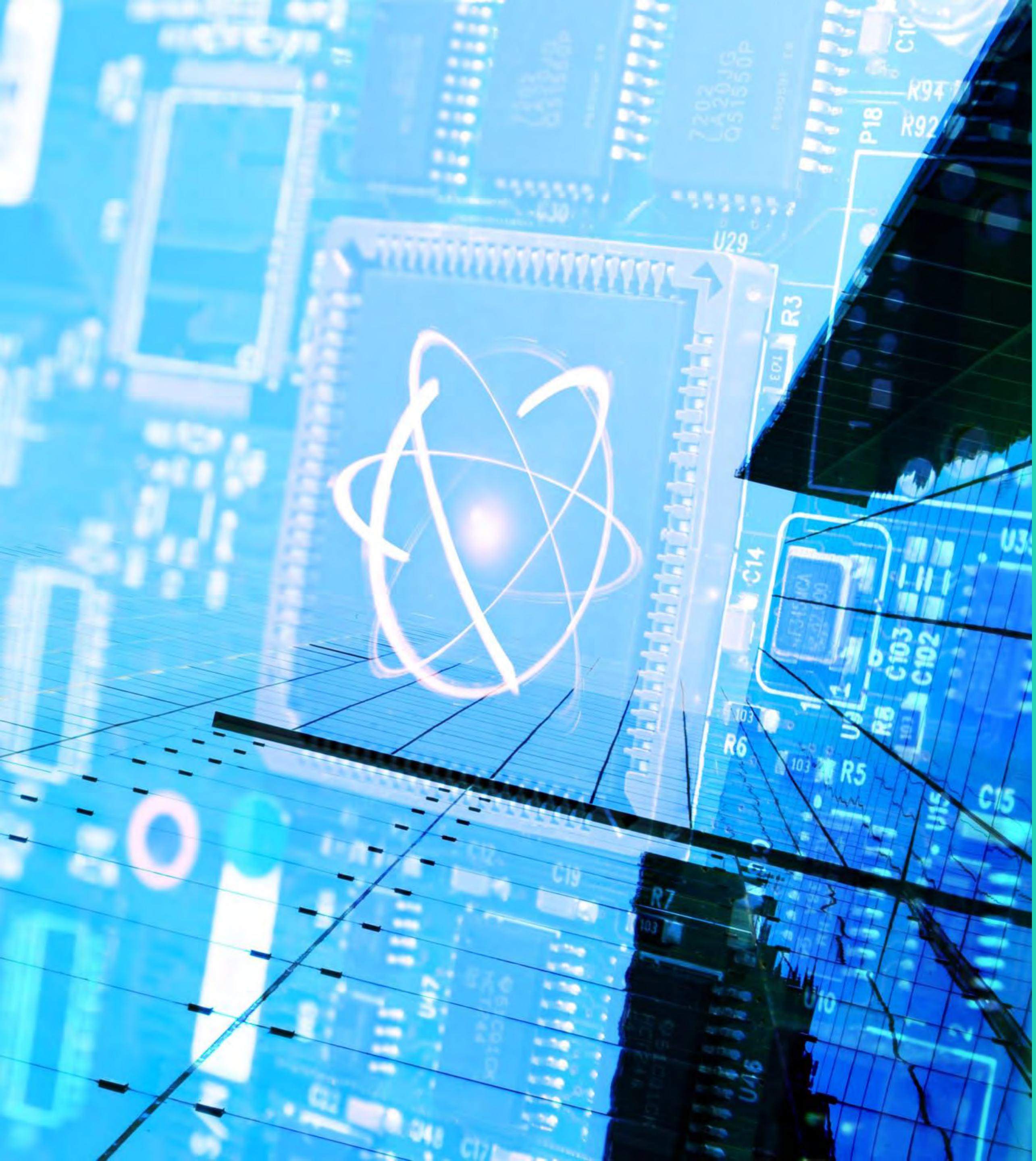


Source [14]

Example in text to image

Text to image is one of the earlier application of domain-transfer GAN. We input a sentence and generate multiple images fitting the description. “The bird has a yellow belly and tarsus, grey back, wings, and brown throat, nape with a black face”.

What is in for Energy?
Not sure for the moment



4

Quantum computing

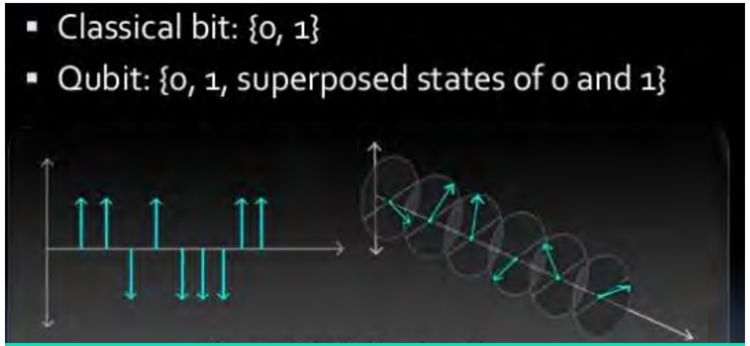
Differences between classical & quantum computing

Classical computing is using bits (binary digits)

- Bits have well-defined values: either 0 or 1
- Taking N times more bits allows to handle N times more information
- Calculations are done in essentially the same manner as by hand
- (plus, minus, if…then…else)

Quantum computing is using qubits (quantum bits)

- Qubits are associated to the quantum state of a physical component (e.g. spin of an electron, polarization of an ion)
- This quantum state is more similar to a probability distribution than a well-defined property (i.e. a single value)
- Taking N times more qubits allows to handle 2^N times more information
- Calculations are done using laws of quantum mechanics. Open door to more efficient algorithms



Classical bits vs Quantum bits

"I think I can safely say that nobody understands Quantum Mechanics"

Richard Feynman, 1967

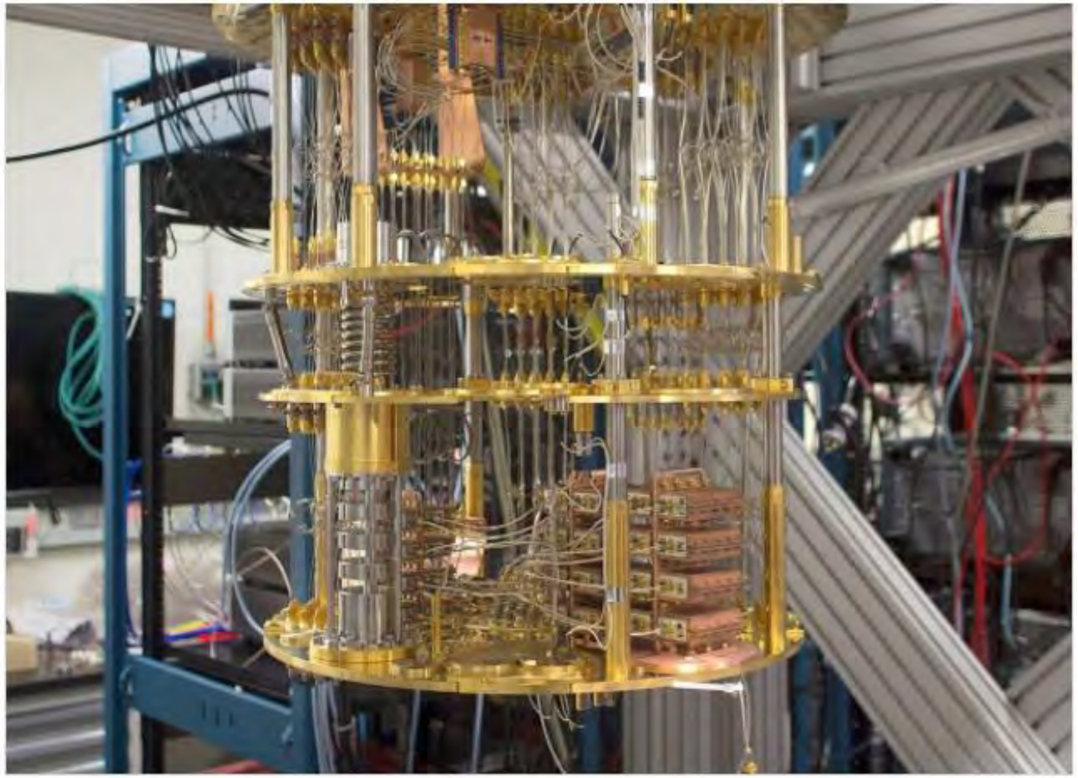
Advantages & challenges of quantum computing

ADVANTAGES:

- Possibility to compute on the 2^N information set simultaneously ≈ computing 2^N faster
- Open the door to actually intractable problems
  - Solving complex minimization problems: that could be applied to simulate protein folding

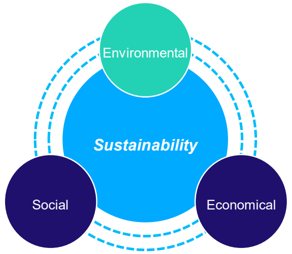
CHALLENGES:

- Classical algorithms cannot be used as-is in a quantum computer. It needs specific algorithms. There won't necessary exist quantum algorithm for all problems
  → not all problems will be solvable 2^N faster
- Quantum computers are much harder to build (transferring & storing qubits is already a challenge)



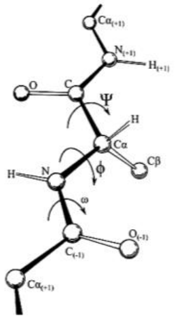
An IBM quantum computer. (IBM Research)

Progress in quantum computing is real, but still far from industrial applications



Quantum Computing applications:
not suited for word and mail…

- QC will make it possible to simulate the behavior of matter down to the atomic level → discovery of new chemicals, materials, drugs,…
  - Eg. for batteries: improvements in battery density have been running at just 5 to 8 percent annually—painfully slow compared to the familiar exponential Moore's Law pace… Could QC could speed that up?
  - Artificial photosynthesis
- Cryptography and security by cracking otherwise invincible codes
- Complex logistic scheduling
- Financial portfolio management
- …



https://en.wikipedia.org/wiki/File:Protein_backbone_PhiPsiOmega_drawing.svg

Molecular modelling

"Nature is quantum, goddam it! So if we want to simulate it, we need a quantum computer."

MIT Technology review, 2018

What is in for Energy? *Not sure yet.*
QC computer works under cryogenic conditions so QC computer will be developed in computing center, not at home. However, how to manage the energy of these centers ?

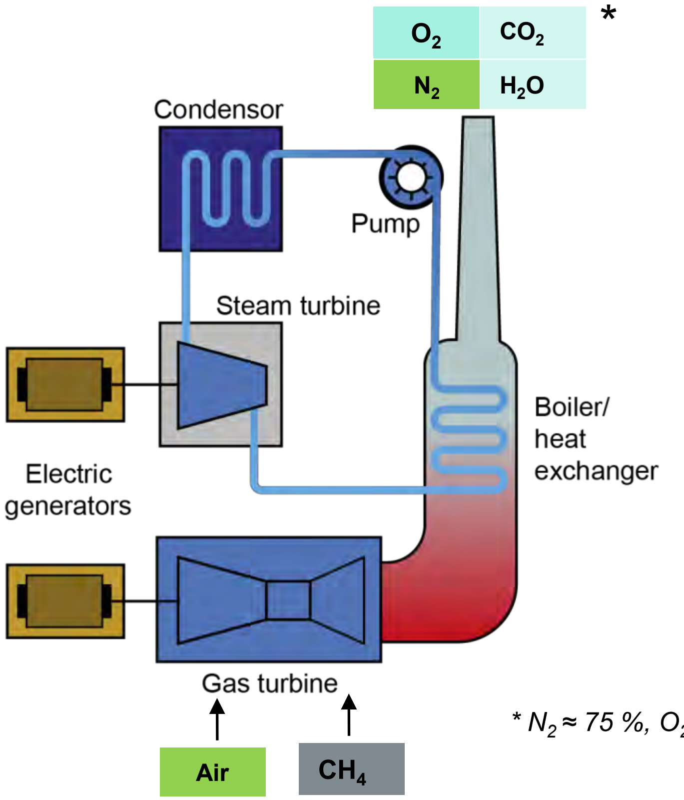
5

CO_2 cycle

CO_2 cycle replaces the classical water-steam cycle

Normal Gas fired Combined Cycle Gas Turbine

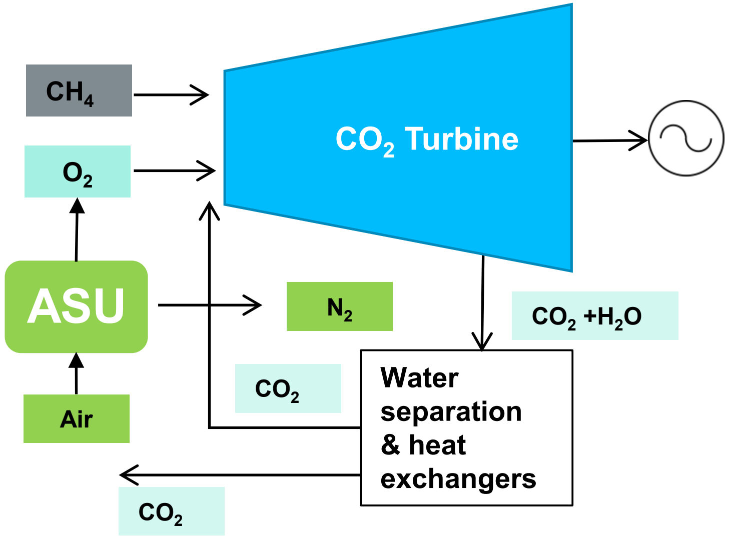
- CH_4 + AIR (80 % N_2 and 20 % O_2) → CO_2 + 2 H_2O + N_2



* N_2 ≈ 75 %, O_2 ≈ 15 %, CO_2 ≈ 4%, H_2O ≈6 %

CO_2 cycle with natural gas

- CH_4 + 2O_2 → CO_2 + 2 H_2O



With **NG, efficiency rate expected is 59%,** similar to CCGT plus exhaust flue gas with **90% CO_2** concentration.

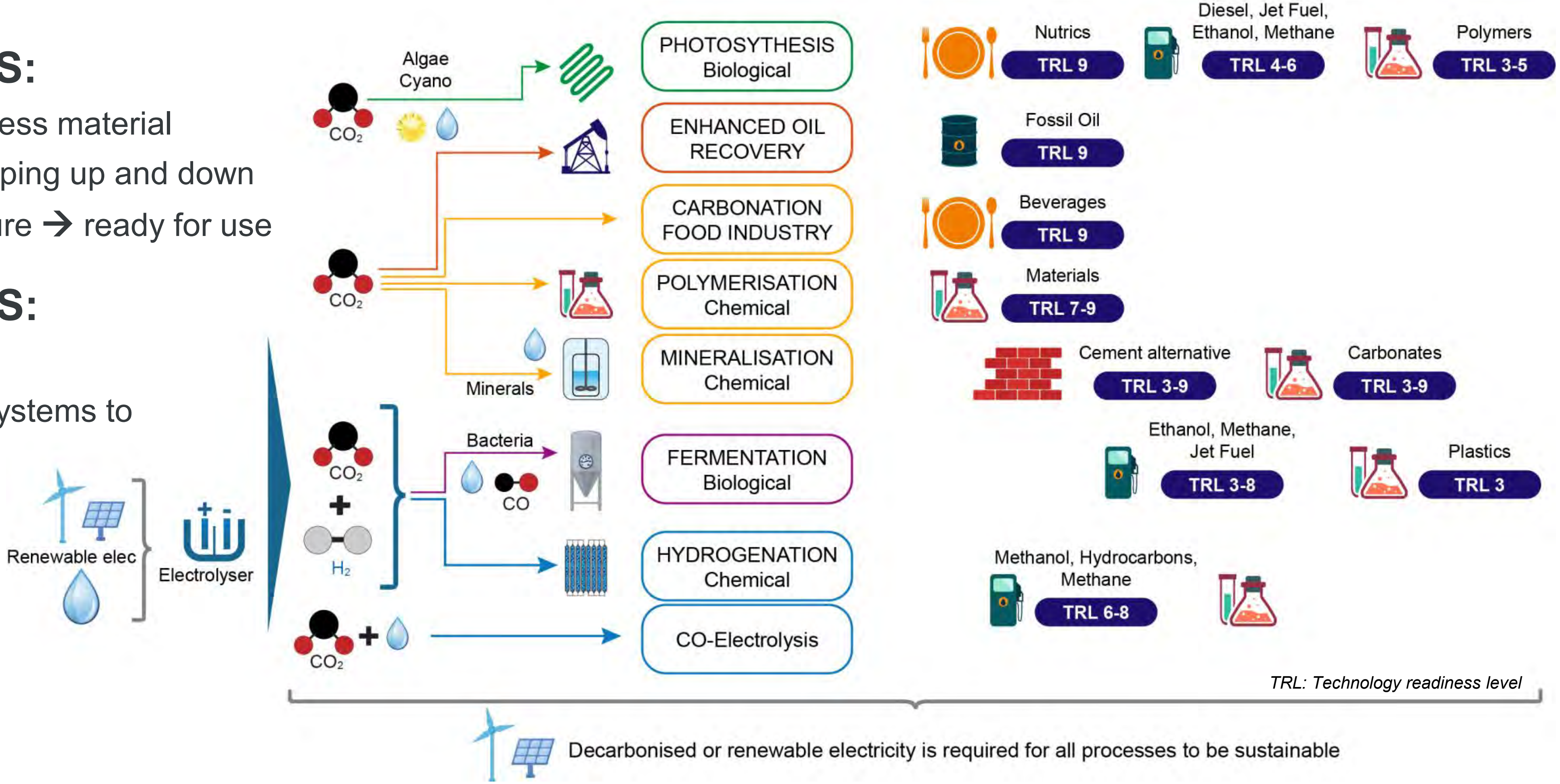
Main advantage 'Free' CO_2 capture:
ready for use as resource rather than a waste!

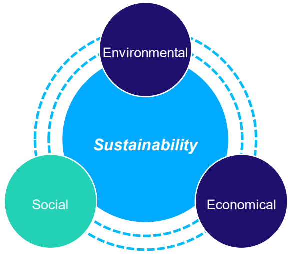
ADVANTAGES:

- Lower CAPEX; less material
- Much faster ramping up and down
- 'Free' CO_2 capture → ready for use

CHALLENGES:

- Competitivenes
- New industrial systems to implement





NETPOWER 50 MW demonstration on-going in Houston: full scale 300 MW planned as early as 2021

- **Net Power 50 MWth demonstration plant commissioned in May 2018**
- **Full Scale 300 MW planned as early as 2021**

NET Power Achieves Major Milestone for Carbon Capture with Demonstration Plant First Fire

The Company Is Now Operating Its Low-Cost, Emissions-Free Natural Gas Power System

NEWS PROVIDED BY
NET Power, LLC →
May 30, 2018, 09:00 ET

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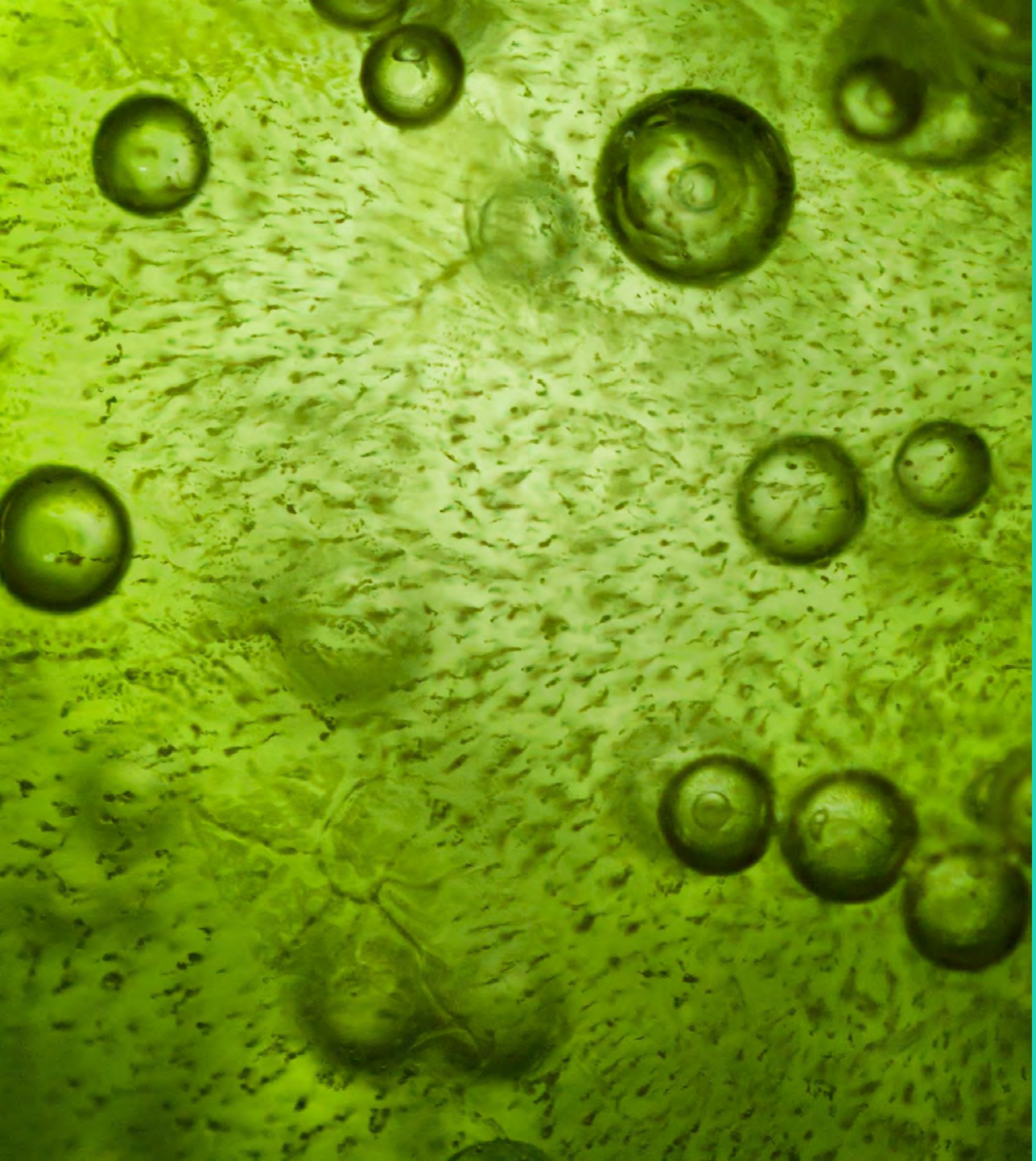
LA PORTE, Texas, May 30, 2018 /PRNewswire/ -- NET Power, LLC, today announced that it has successfully achieved first fire of its supercritical carbon dioxide (CO_2) demonstration power plant and test facility located in La Porte, TX, including the firing of the 50MWth Toshiba Energy Systems & Solutions Corporation ("Toshiba") commercial-scale combustor. Firing of the combustor involves the integrated operation of the full NET Power process. Following rigorous testing, the combustor will be integrated with the turbine and power will be generated. NET Power is targeting the global deployment of 300MWe-class commercial-scale plants beginning as early as 2021.

First fire is a critical milestone for the demonstration plant, as it validates the fundamental operability and technical foundation of NET Power's new power system, which is designed to produce low-cost electricity from natural gas while generating near-zero atmospheric emissions, including full CO_2 capture. The achievement also confirms the operation of Toshiba's combustor at commercial scale, as several 50MWth combustors will be utilized together in NET Power's 300MWe commercial facilities.

NET Power's 50 MWth Demonstration Plant in La Porte, Texas



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Biotechnology and Energy

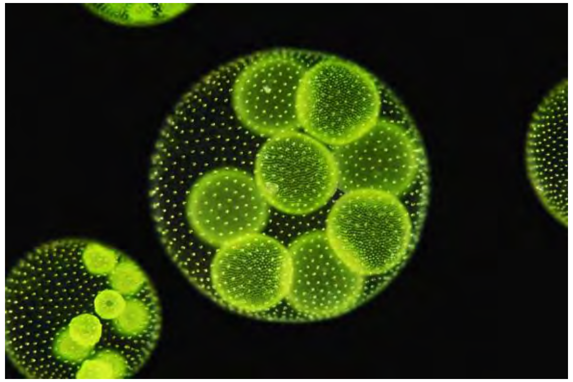
Biotechnology is not Bio-energy

DEFINITIONS:

- **Biotechnology** is the use of **living systems and organisms** to develop or make products, or "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" *(UN Convention on Biological Diversity, Art. 2)*
- **Bioenergy** (heat and cold, electricity) and **Biofuels** (liquid and gaseous) are renewable energies made available from materials derived from biological sources

So biomass combustion for electricity or biomass gasification to produce 2G Biogas is not biotechnology but bioenergy! However, anaerobic digestion (1G Biogas) or any fermentation process using living organisms (eg. yeast, bacteria, …) is biotechnology.

Not always straightforward: drying Algae for combustion to produce heat or electricity classifies as bio-energy whilst using Algae (or Cyano-bacteria) for the production of products (eg. oil, ethanol, sugars, proteins, …) would classify as biotechnology



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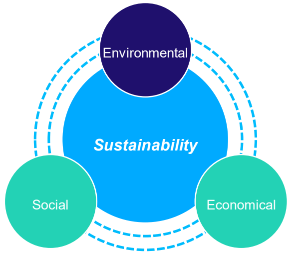
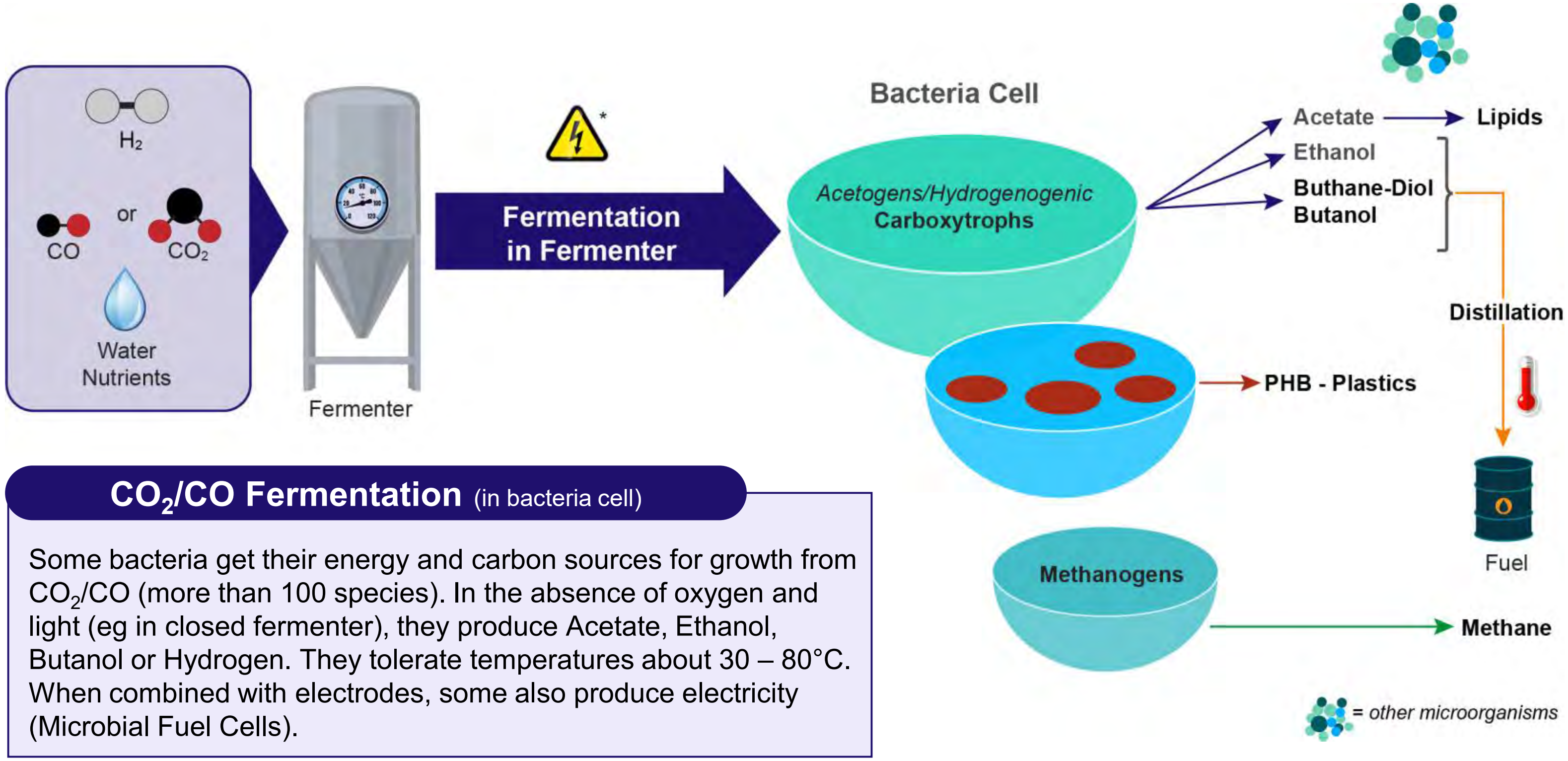


Emerging biotechnology for hydrocarbon fuel production **in the absence of light and oxygen**

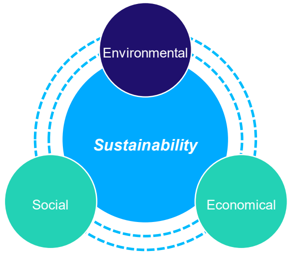
In the absence of light and oxygen, some bacteria can convert CO_2 and/or CO and hydrogen into biofuels and bioplastics precursors



CO_2/CO Fermentation (in bacteria cell)

Some bacteria get their energy and carbon sources for growth from CO_2/CO (more than 100 species). In the absence of oxygen and light (eg in closed fermenter), they produce Acetate, Ethanol, Butanol or Hydrogen. They tolerate temperatures about 30 – 80°C. When combined with electrodes, some also produce electricity (Microbial Fuel Cells).

* Electricity is required for operating the fermenter.
Some systems can also use direct power in the fermenter to produce hydrogen (no electrolysis required upfront).



Emerging biotechnology for hydrocarbon fuel production in the absence of light and oxygen

CO, CO_2 and Hydrogen fermentation to fuel and chemicals

vito

CO_2 + H2 to PHB (Polyhydroxybutyrate = precursors for plastics)

Electrochaea

CO_2 to Methane

LanzaTech

ArcelorMittal and Lanzatech break ground on €150million project to revolutionise blast furnace carbon emissions capture (June 2018)
Demo: Steelgas to Ethanol (378 m^3/yr)
Lab: CO_2 + H_2 to acetate (→ algae lipids)

KRAJETE

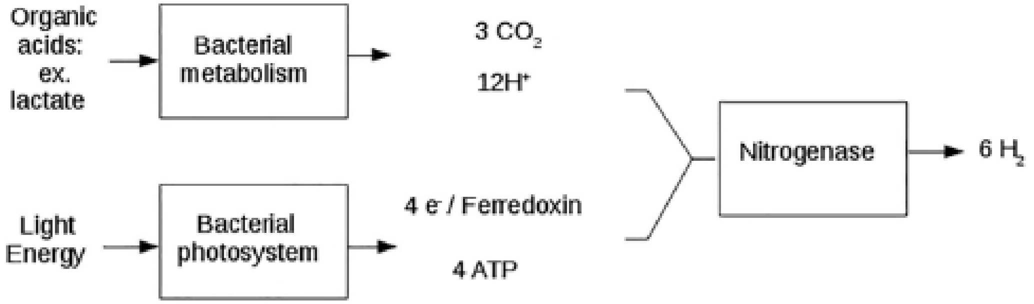
CO_2 to Methane

INEOS Bio

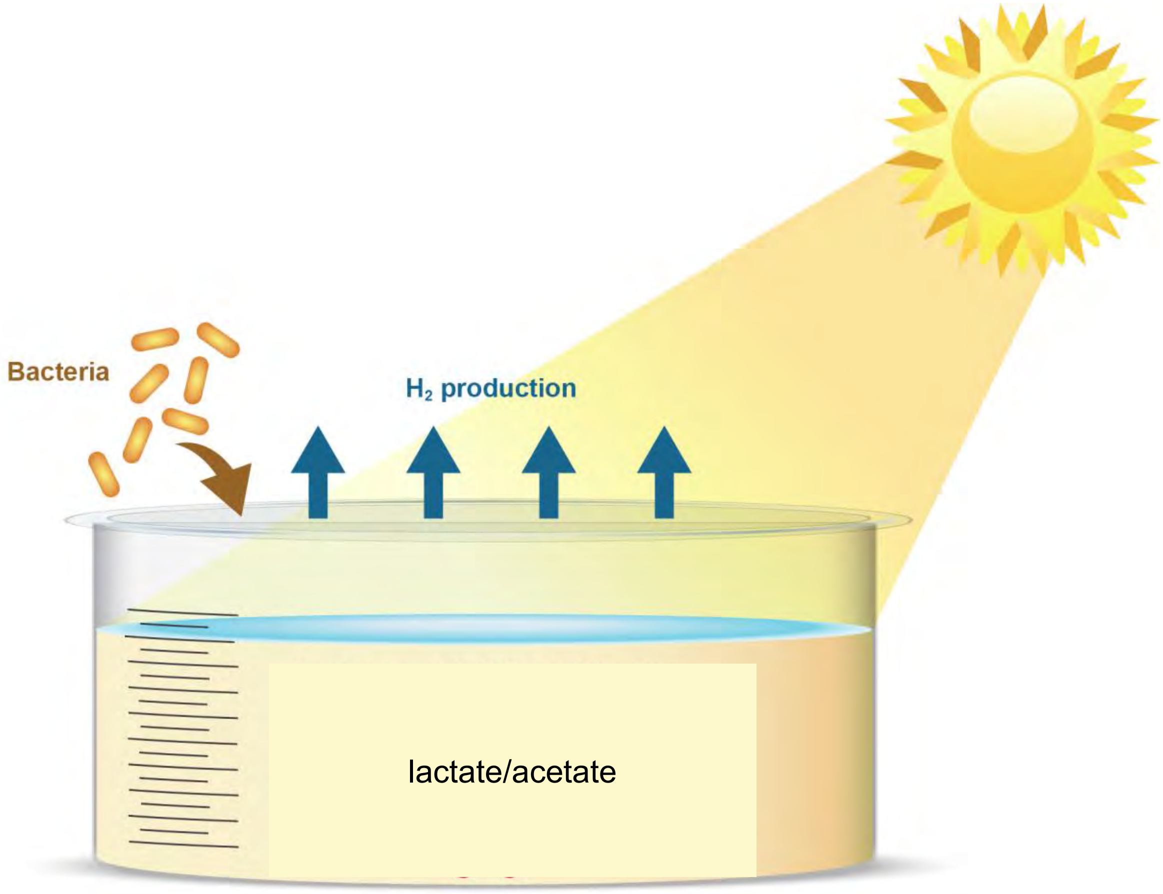
Biomass syngas to Ethanol (forecast): 3028 m^3/yr

Emerging biotechnology for hydrogen production in the presence of light and oxygen

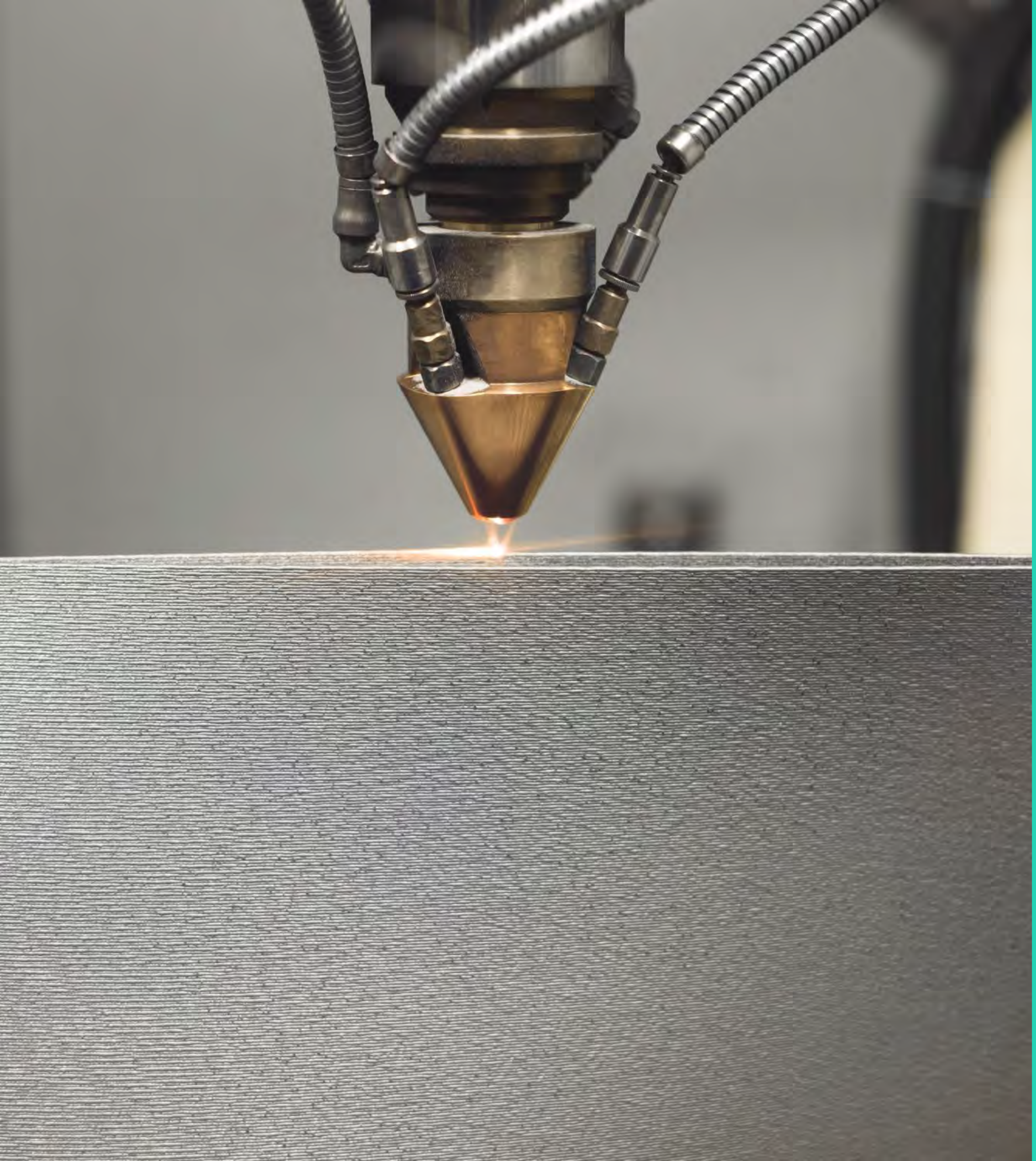
Rhodobacter capsulatus is a bacteria which produces H_2 from organic assets *eg*. lactate/acetate in a light-dependent process



Main pathways of hydrogen production by photofermentation of organic acids by using photosynthetic bacteria



Source [15]



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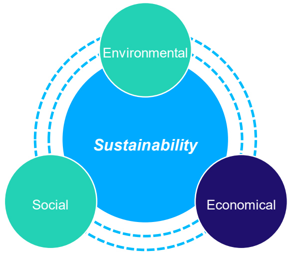
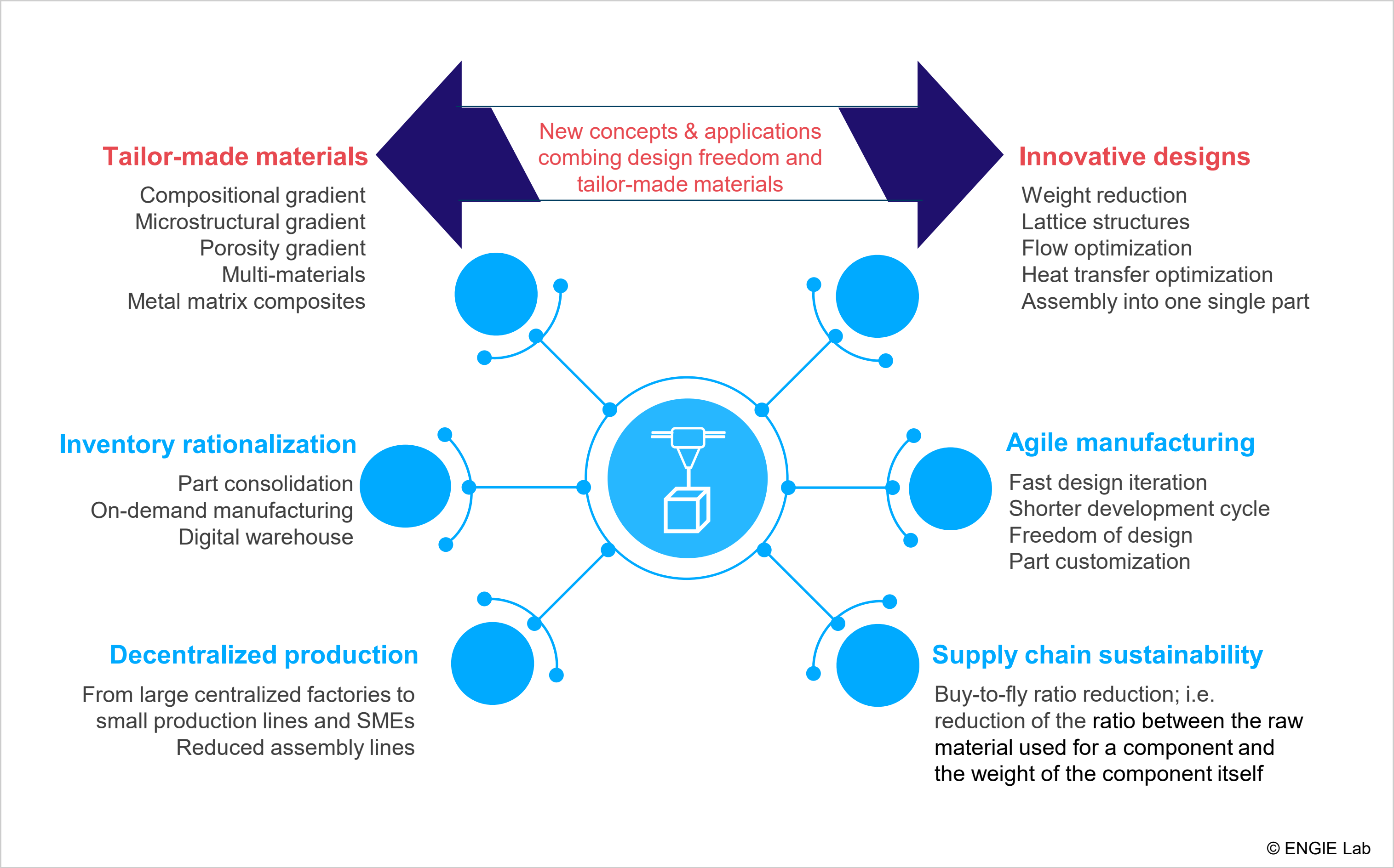
3D metal printing



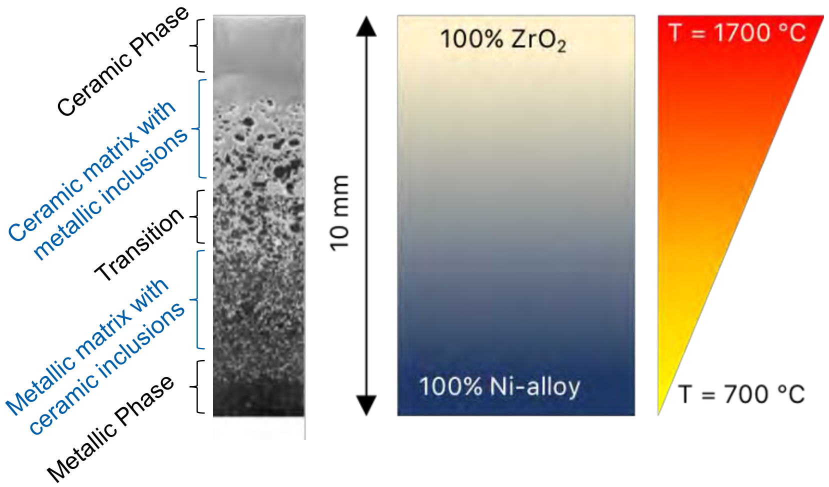
Additive Manufacturing Technologies

Additive Manufacturing Technologies are considerably modifying the way to design parts, develop industrial applications and organize production and maintenance activities



Additive Manufacturing Technologies:
Tailor-made material configurations for tailor-made functionalities

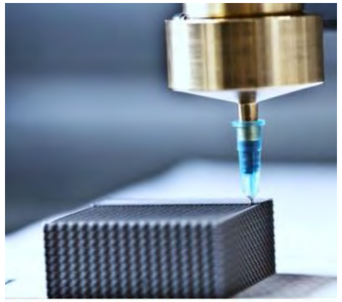
Heat exchanger concept in nickel-based material and stainless steel (NLR)
Source [16]



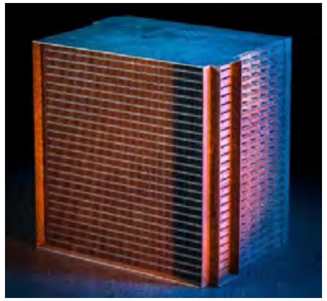
Metal-ceramic FGMs can withstand high heat gradients without cracking or plastic deformation
Source [17]

Aerosint's concept technology for selective deposition of powder on 3D printing machine build platform, showing co-pattern of titanium (grey powder) and polymer PA12 (white powder)
Source [18]

Additive Manufacturing Technologies:
Tailor-made structures & designs for tailor-made functionalities

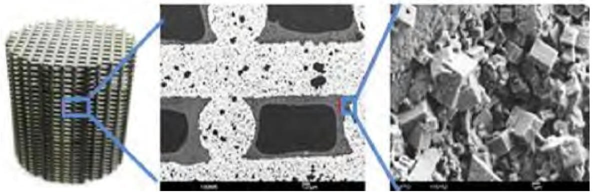


Production of 3D structured catalyst through micro-extrusion of a ceramic/metallic paste to built a porous material (VITO)
Source [19]



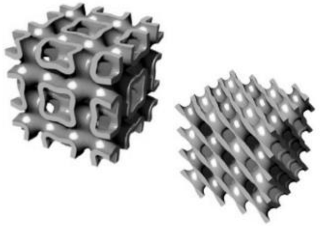
HIETA compact heat exchangers and recuperators
Source [20]

Michelin's Vision concept tire contains material composition, porosity, and colour gradients
Source [21]



Printing *+ Functionalisation (coating or impregnation)*

Optimizing of pore structure/sizes impacting mass transfer, heat transfer and pressure drop
Source [22]



Lattice cells
Source [23]

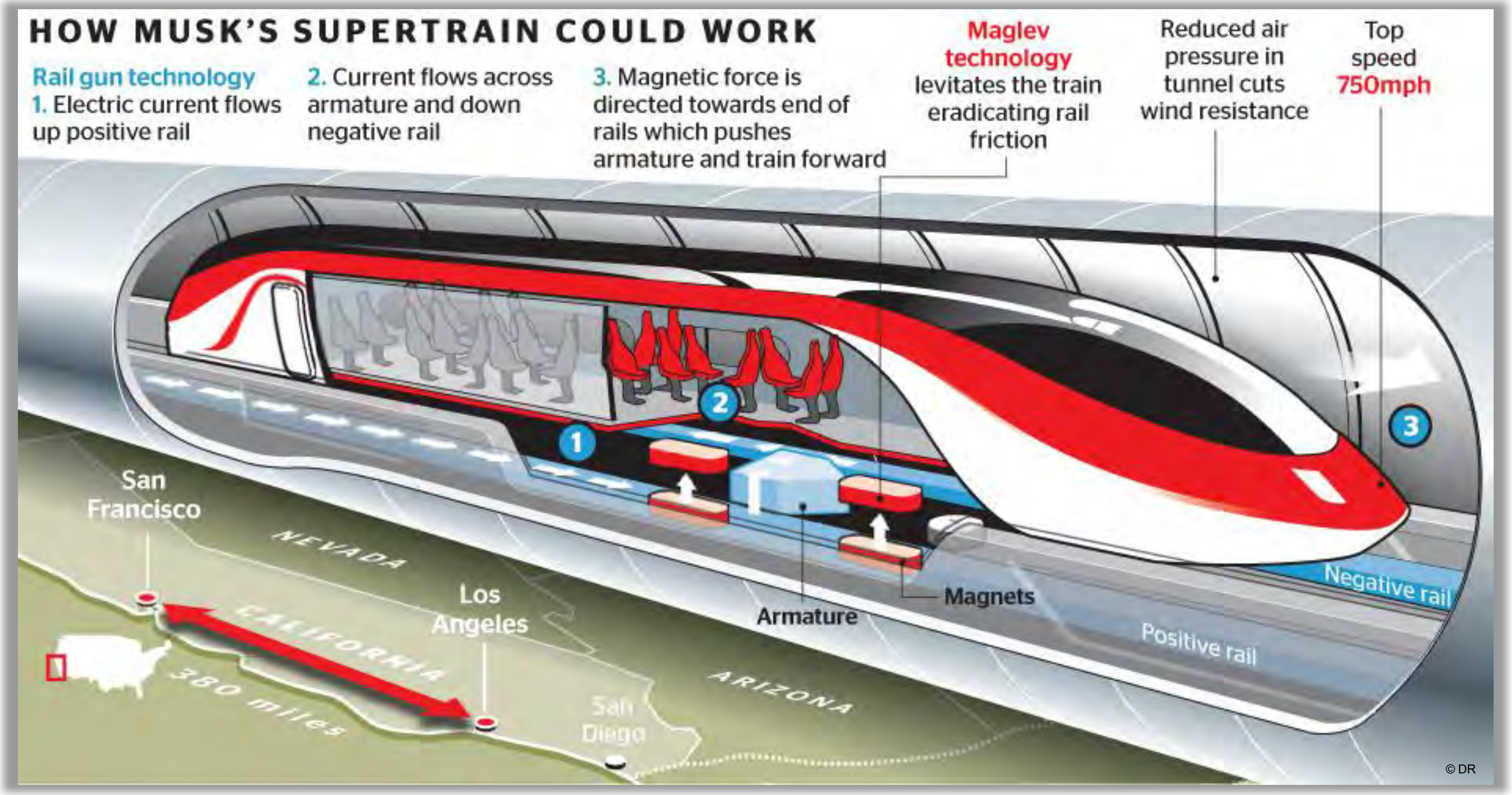
Lightweight metallic structures
Source [24]

8

Green Mobility: what is new?

Hyperloop: crazy (?) idea from Elon Musk

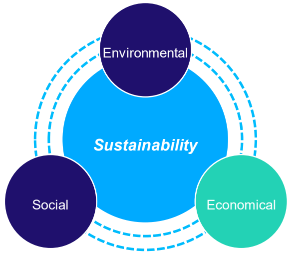
- In 2013, Elon Musk published white paper on Hyperloop: moving by levitating vehicles at high speeds through low-pressure tubes reaching a speed up to 1.200 km/h.
- This first design of concept was released as open source and should lead to safer, faster, lower cost, more convenient, immune to weather, sustainably self-powering, resistant to earthquakes and not disruptive for its environment (CO_2 free, no noise).



Hyperloop: from 'crazy' idea to reality?

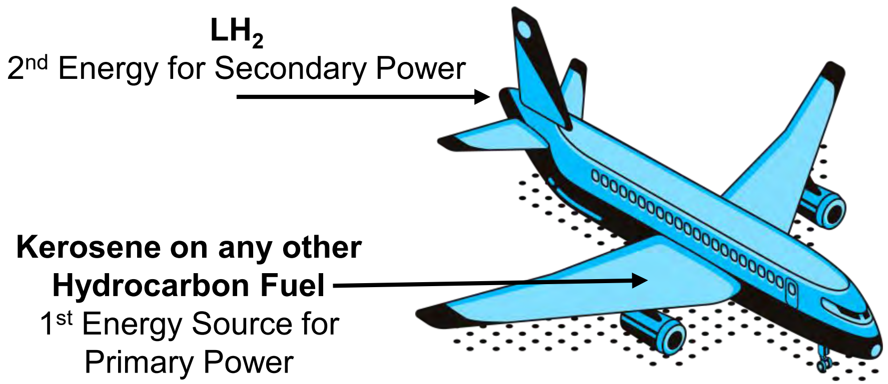
- After the publication of the white paper, it doesn't take long for new companies to start developing this.
- The first one **Hyperloop One**, later supported by Virgin and Richard Brandson.
- An important alternative is **Hyperloop Transportation Technologies**, a start-up regrouping more than 800 experts from all over the world.
- Others: Transpod, Hardt Hyperloop, …

	Develpment	Technology Based on a low pressure tube	Location
Virgin Hyperloop One	• Complete test track • Starting new operational track in India	• Active magnetic levitation • Linear induction motors	North America, United Arab Emirates, India
Hyperloop Transport Technologies	• Test track in progress at Toulouse • Will start soon a new operational track in United Arab Emirates	• Passive magnetic levitation • Linear induction motors • Smart material: Vibranium	United States, United Arab Emirates, India, Europe; South Korea, Brazil
Transpod	• Plans to build a test track in France around 2020	• Active magnetic levitation • Linear induction motors • Axial air compressor	Canada, France
Hardt Hyperloop	• Plans to build a 5km test track in Holland in the near future	• Magnetic levitation system by the top made of permanent magnet and electromagnet • Linear induction motors	The Netherlands

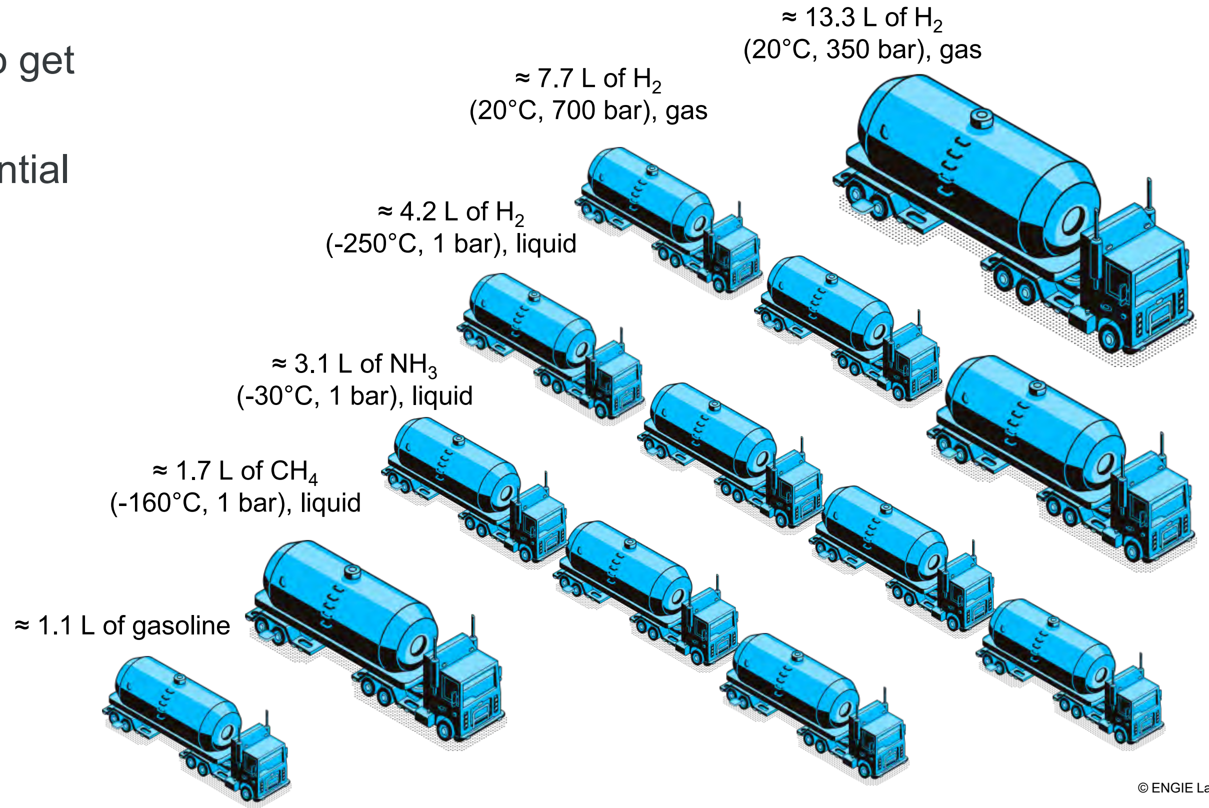


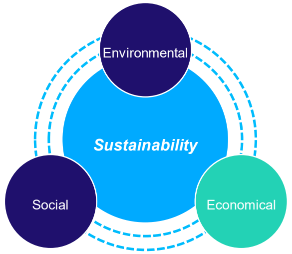
Real challenge for aviation is the ‘queste’ for ‘sustainable’ fuel… **Hydrogen?**

- AIRBUS looking at hydrogen; **not to power the jet engines, but to replace the Auxiliary Power Units (APUs)**
- Energy Density remains crucial for aviation; it is not likely to get (fully) out of hydrocarbon fuels any time soon.
  - Factor 4 larger tanks needed in case of LH_2 and the potential weight gain of hydrogen versus hydrocarbons remains uncertain due to high weight of the containment…



How to transport 10kWh of energy?

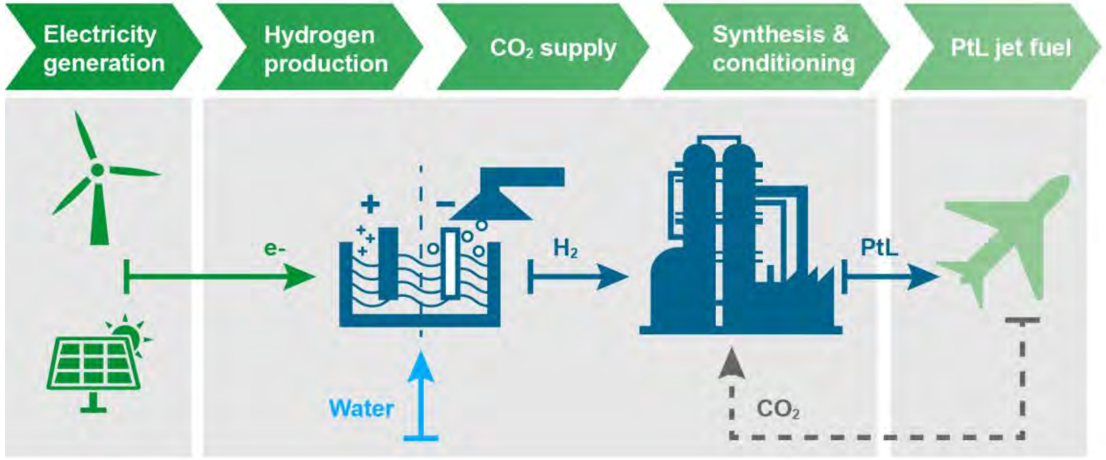




Real challenge for aviation is the 'queste' for 'sustainable' fuel… **Renewable hydrocarbon fuels?**

- Environmental and social impact better than most bio-fuels…
- Too expensive **today** but highly dependant on electricity price for electrolysis…

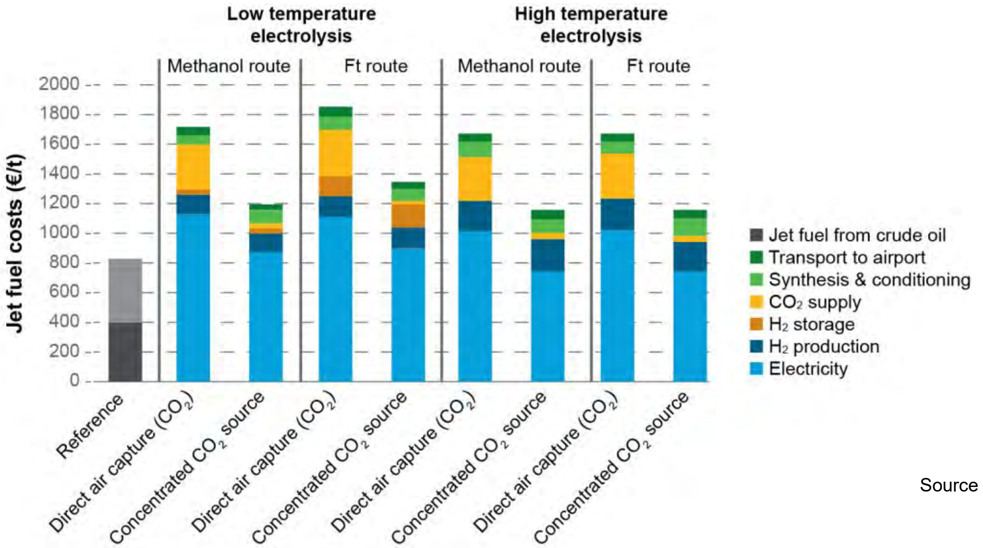
Power-to-liquids production (generic scheme)



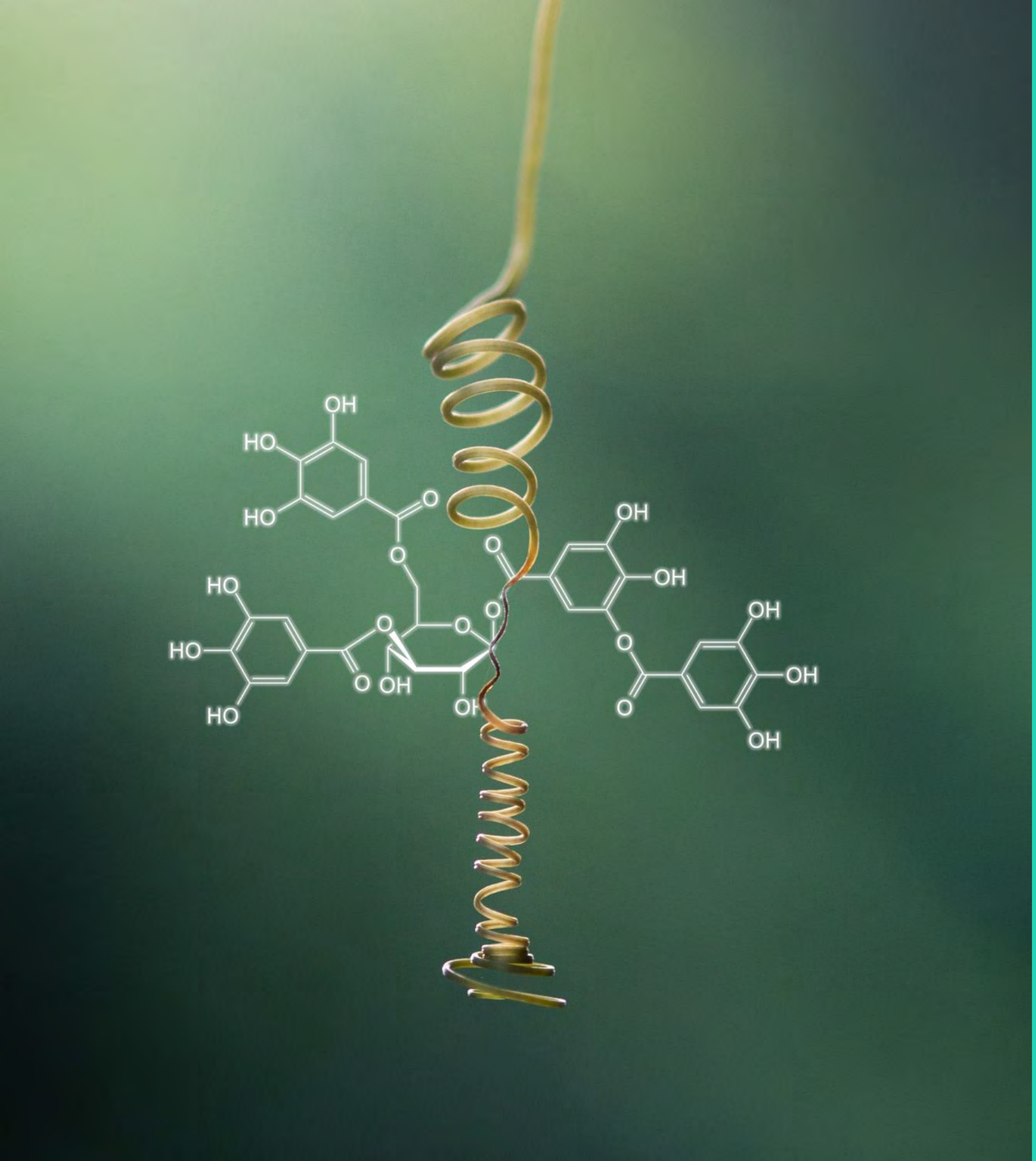
Source [25]

Jet fuel costs proected for future PtL plants in 2050

(jet fuel reference price: 42-95 US$/bbl; renewable electricity costs: 40€/MWh; equivalent full-load period: 3750h_{eq}/yr)



Source [26]



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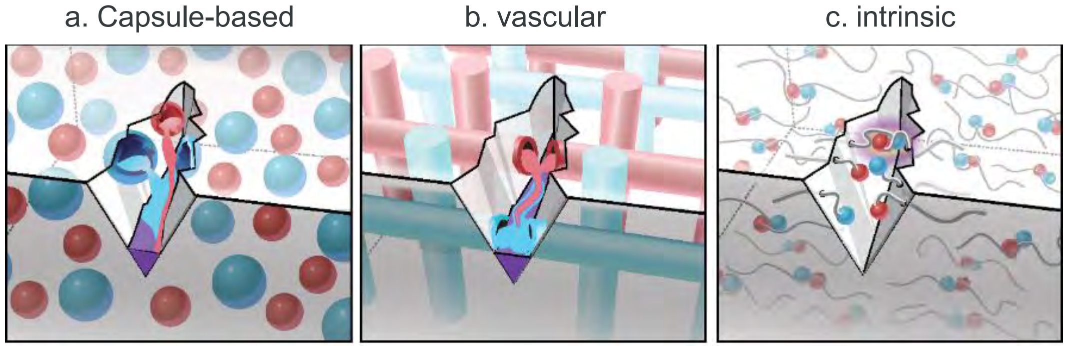
Self-healing materials

Self-healing materials (SHM)

- Material having the **ability to automatically heal (recover/repair) damages** without any external (human) intervention
- ‘Healing’ **extends the lifetime** of materials
- Two types of self-healing abilities:

Autonomic	Non-autonomic
No trigger needed	Needs external trigger (e.g. heat, UV, voltage…)
Direct healing: release of self-healing agent when damage occurs	Discontinuous (retarded) healing
Use of micro/nano-scale carrier containing self-healing agent	Use of intrinsic self-healing matrix or ‘self-healing’ carrier



Source [27]

- Key concepts (non-exhaustive):
  - Retention or recovery of mechanical strength through (micro-) crack healing
  - Elimination of superficial scratches by induced polymer flow (e.g. automotive)
  - Restoration of material properties (gloss, conductivity, acoustics…)
- Materials of interest: polymers, composites, paints, coatings, alloys, ceramics and concrete

Self-healing strategies

Self-healing Strategies

Established Technologies

TRL 4-8

Release of healing agents

- Liquid active agents (even bacteria) stored in microcapsules, hollow fibers, or microvascular networks that are embedded into systems during manufacturing stage.
- Release of active agent and local polymerisation/precipitation/ into cracks to ensure crack closure

Before healing

After healing

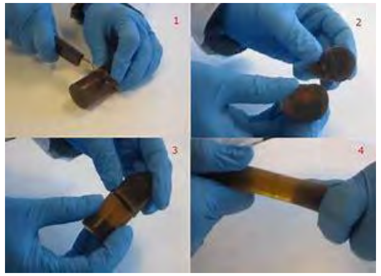
Source [28]

Microcapsule

Reversible cross-link

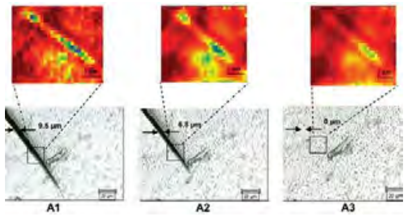
- Cross-link, i.e. bond that links one polymer chain to another, is generally irreversible and aims at achieving superior mechanical properties
- Reversible cross-link strategy requires external trigger such as thermal, photo, chemical or electrical activation and involves complex chemical reactions.

Bond recovery



Source [29]

Scratch healing



Source [30]

Emerging Technologies

TRL 1-4

- Electro-hydrodynamics
- Conductivity
- Shape Memory Effect
- Nanoparticle Migration
- Co-deposition

Maturity level is strongly dependent on applied concept; few commercial activities (e.g. Autonomic Materials)

Self-healing applications & potential

- Adhesives
- Concrete foundations & Structures
- Coatings and paint
- Underground and sub-sea cables
- Structural (reinforced) plastic components
- Micro-electronics

Autonomic Materials

Source [31]

- Waterways
- Offshore (wind)
- Harbour infrastructure

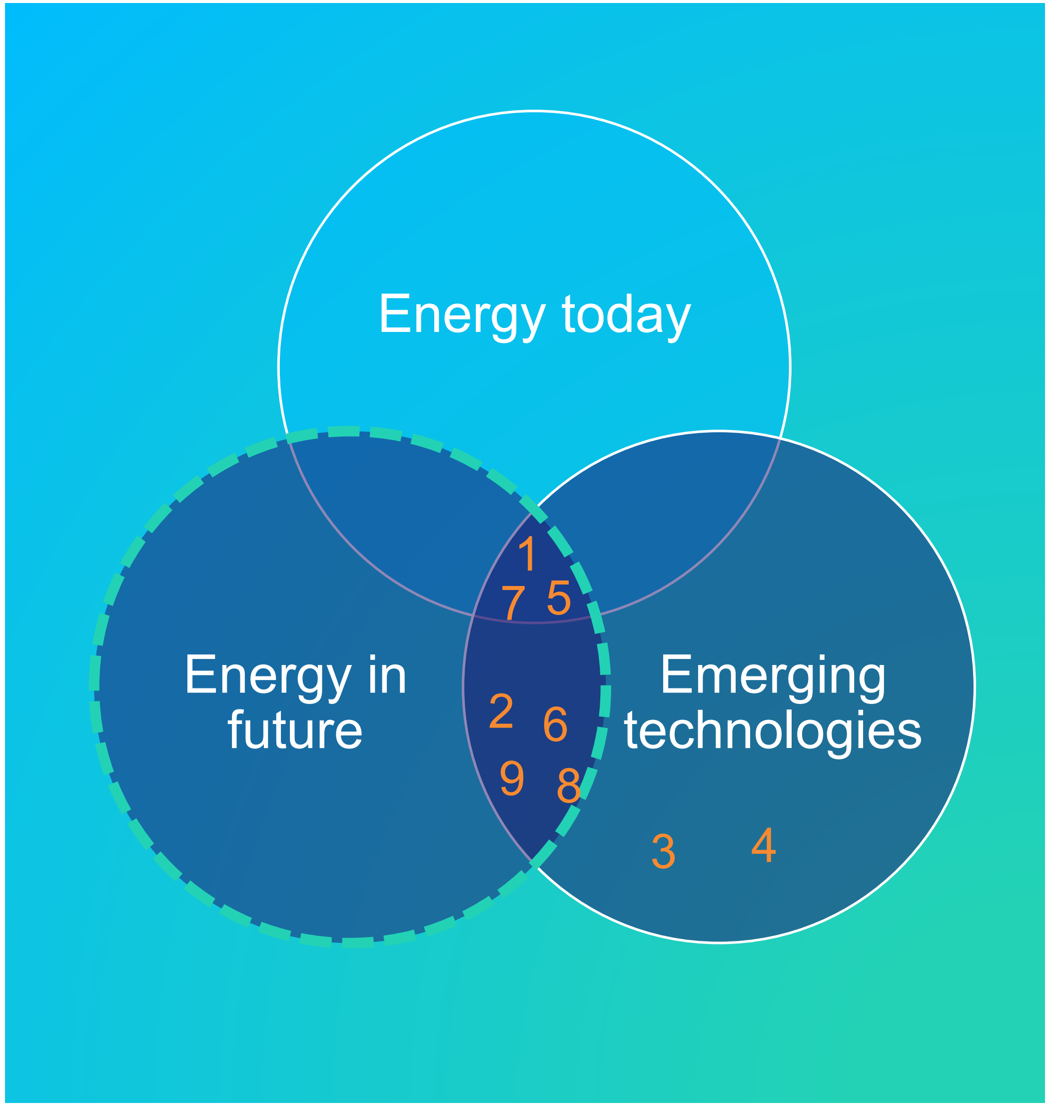
Ex: self-healing fluid-filled power cables (Northern Powergrid)

Source [32]

Conclusions

Emerging technologies and Energy: today and in future

1. Electrochemical storage: what is new in batteries?
2. Radiative cooling
3. Artificial Intelligence: the concept of duelling neural networks (GANs)
4. Quantum computing
5. CO_2 cycle
6. Biotech
7. 3D metal printing
8. Green mobility
9. Self-healing material



ENGIE Research

Discussion / Questions

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