

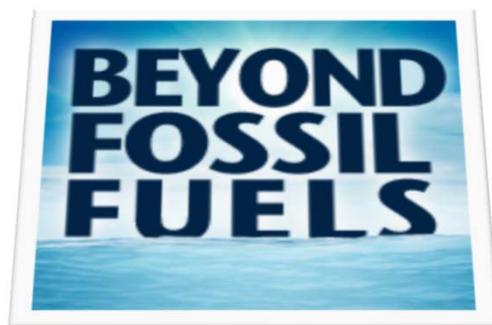
PILLAR 1 – NANO for ENERGY (PARALLEL SESSION 1.1)
Nanotechnologies and Advanced Materials for a Carbon-neutral Society by 2050

Bucharest (Romania), June 12th, 2019

Possible scientific/ technological solutions

Challenges in energy nanomaterials to
substitute the use of fossil fuels

→ *the crucial factor: solar fuels and chemicals*



Gabriele CENTI



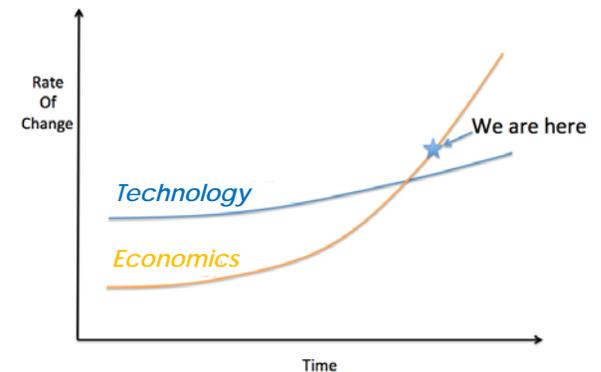
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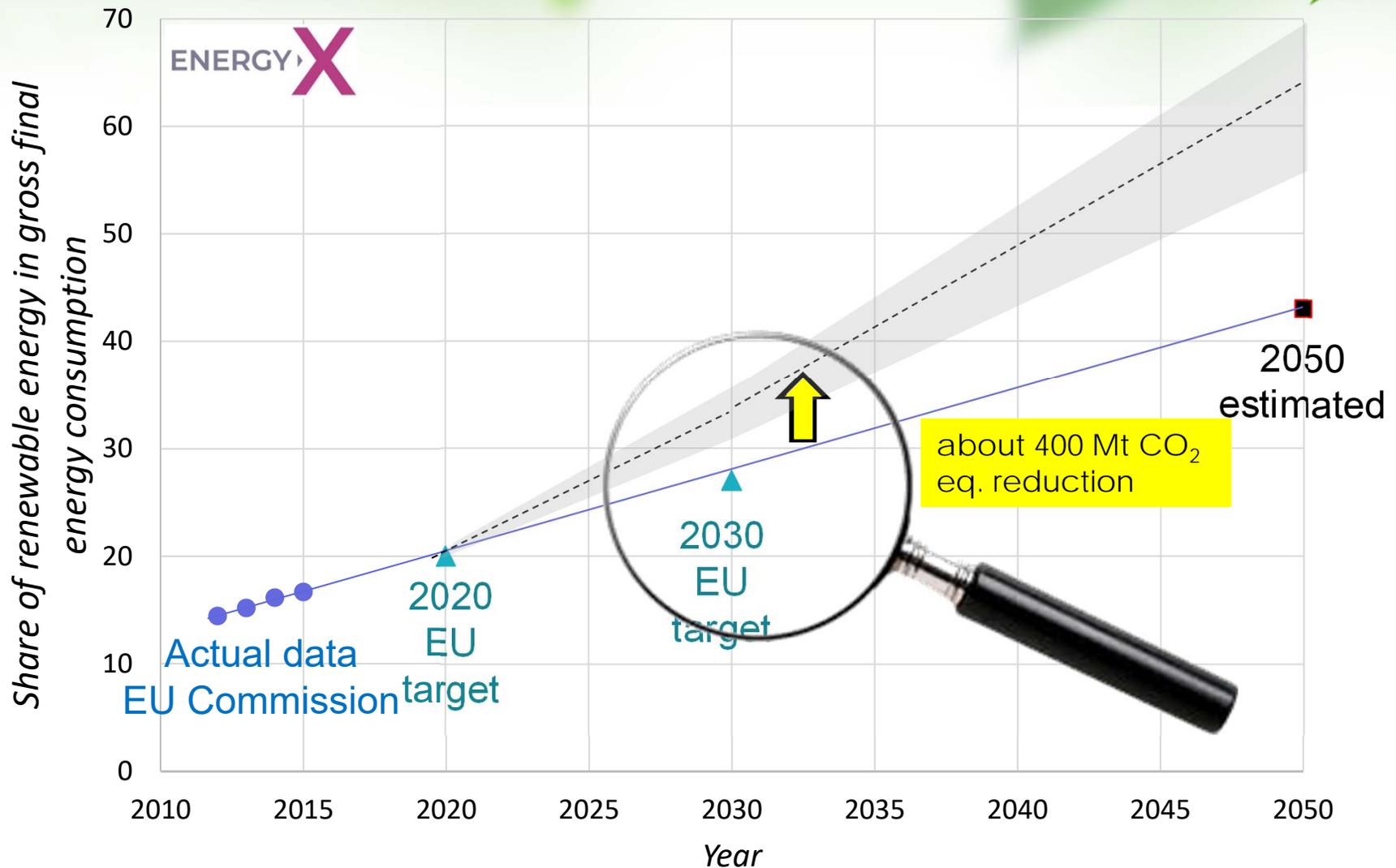
Why solar fuels and chemicals

- Materials & technologies for **solar fuels and chemicals** are the *missing & limiting* factor to accelerate the **rate of introduction** of renewable energy in the EU energy mix, the **necessary factor** to meet climate change targets AND realize an innovative competitiveness & sustainable growth
 - Already today there are the economic bases for this transition, but the **limiting factor** is the still **too slow** progress in the development of the related technologies and energy materials.
 - There is the need to **accelerate** the scientific and technological progress in this area by developing the necessary **large initiative**, to realize an integrated and coherent wide TRL approach on short-, medium/long term perspective
 - *Catalyze synergies and critical mass, not only identify priorities*



How to meet GHG targets in EU

AND industrial competitiveness, EU innovation, energy security, etc.



The limiting (missing) factors

To increase the rate of RE introduction in the energy mix

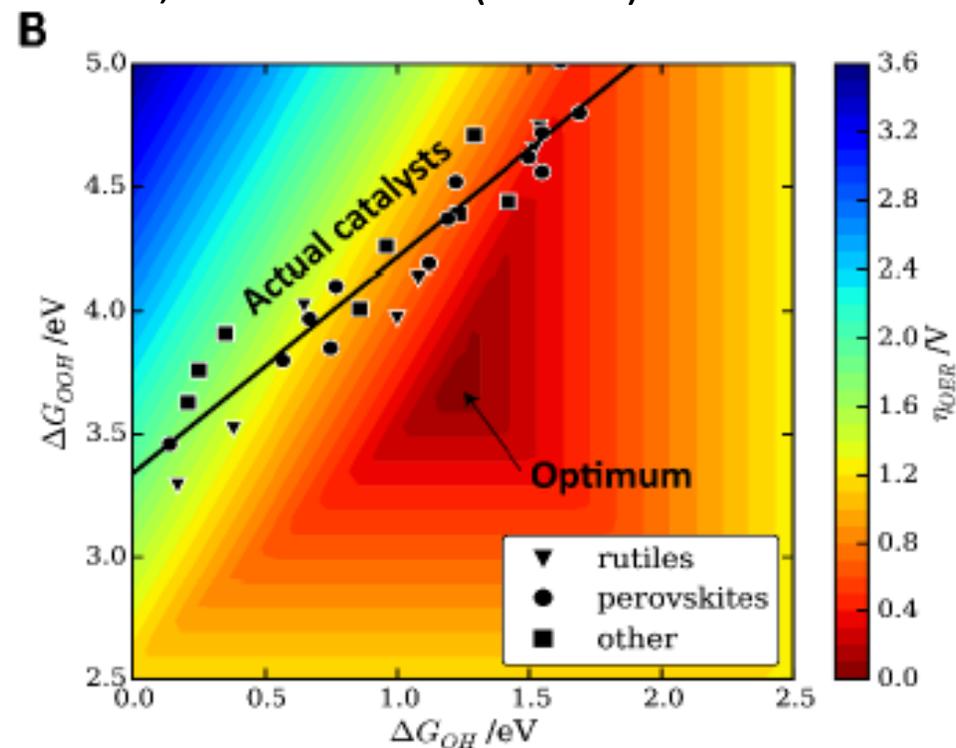
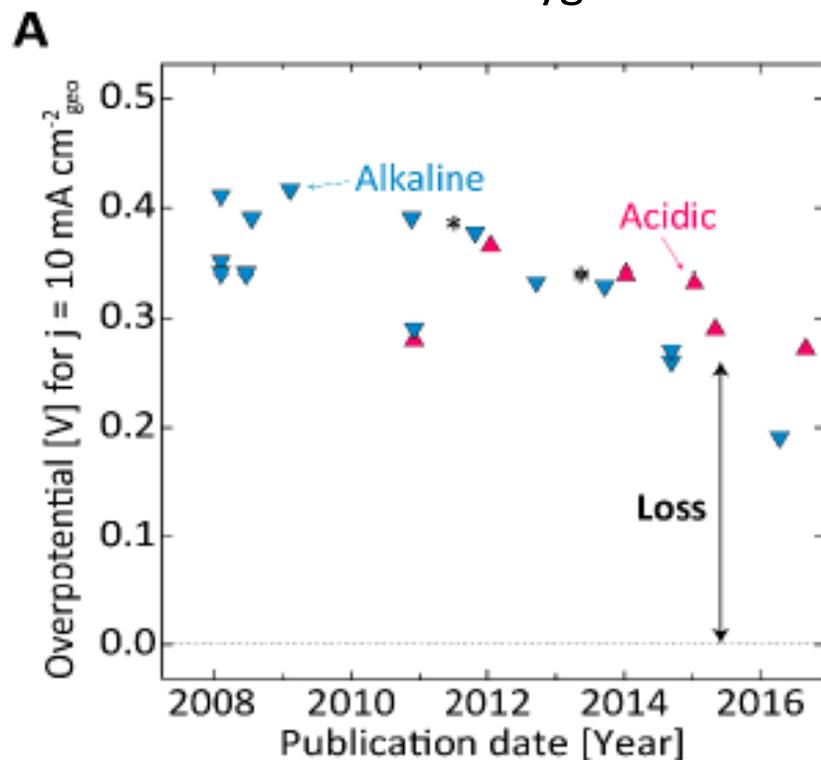
- **Import** RE from remote area
 - develop effective chemical energy vectors (e.g. **solar fuels**) which are the equivalent to actual fossil-based vectors AND which can be introduced in the actual energy infrastructure without major (costly) changes; they should be *easily stored and transported*
- **Stabilize** grid (from fluctuations) and exploit “excess” (not used) RE sources
 - seasonal / yearly storage (→ chemical energy vectors)
- **Defossilization** (rather than decarbonization) of the chemical production
 - nexus between chemistry and energy, bases for manufacture
 - electrify production, use alternative C-sources to fossil fuels
 - change in the model of production (distributed)

RE are already the more economic (in prospect) source of energy



BUT a science & technology gap

scientific challenge associated with finding good catalyst materials for the oxygen evolution reaction, $\text{H}_2\text{O} \rightarrow \text{O}_2 + 4 (\text{H}^+ + \text{e}^-)$.



In spite of a decade of intensive research, only a small decrease in the overpotential, a measure of the energy loss in the process, has been obtained

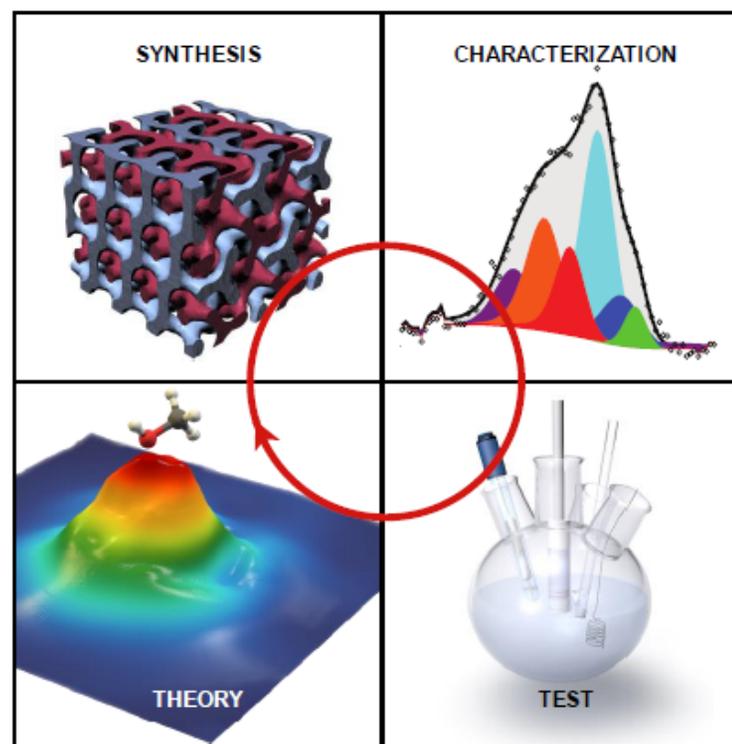
Most materials have properties that are well off the optimum value where the overpotential is lowest. We need to discover new classes of materials with completely new surface chemical properties.

A change in the scientific approach is needed

New scientific developments

New paradigm in materials discovery

- New synthesis with molecular scale precision
- New advanced characterization methods
- Theoretical/computational materials design
- Data-driven methods and machine learning



BUT science development should be linked to technology development & to **demo units**

In these critical areas still underdeveloped

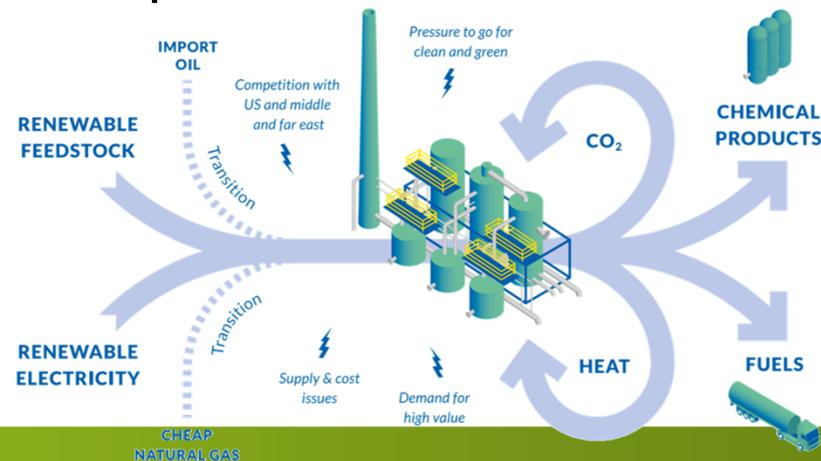
- **Transport fuels**

- complementary to the electrification, offering **solutions** where batteries are generally less effective, like e.g. for ***long-distance transport*** or for ***freight transport***, energy transmission and grid stabilization services.

- **Chemicals and decentralised production**

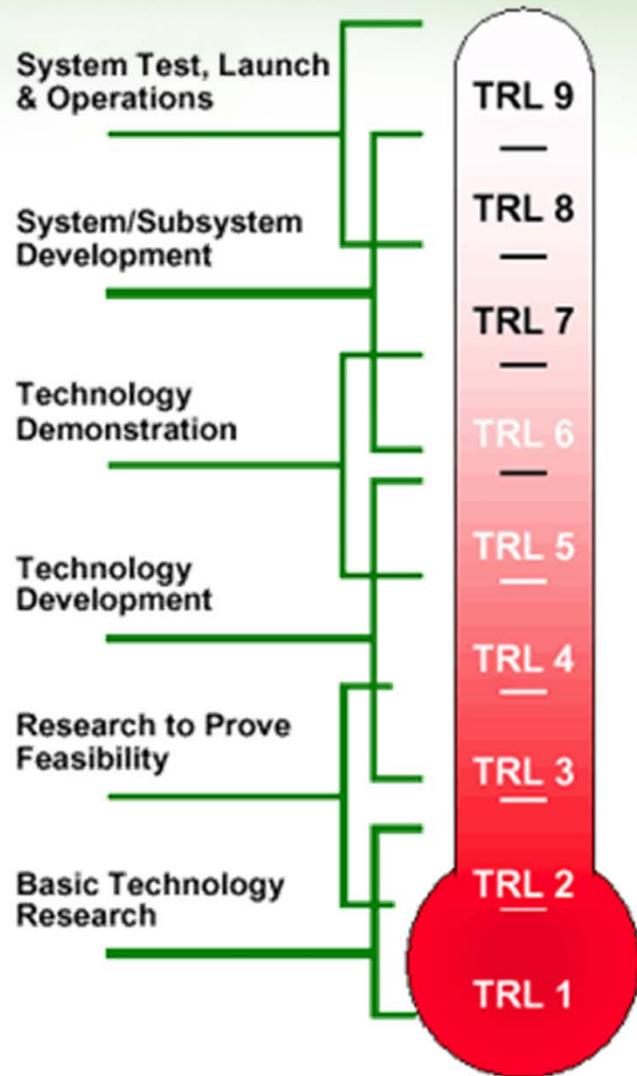
- production of chemicals by applying renewable electricity, **decentralized** production

A sustainable, circular chemical industry



Bridging a wide TRL gap

Solar fuels and chemicals



Application gap

Technology gap

Science gap

Need of a single coherent approach to catalyse the transformation

An integrated multi-TRL development of nanomaterials, technologies and demo



A timeline of energy nanomaterials

1/2



Solar fuels and chemicals

- **On short term**

- *Increase rate of RE share in energy mix:*
 - Nanomaterials and technologies for **chemical energy storage**, to transport RE from long distance (& seasonal/yearly RE storage)
 - **Green H₂** (higher performance, noble-metal free, nanostructured electrodes, scale-up electrodes) and **CO₂-energy vectors** as CH₃OH (higher productive cat., less sensible to deactivation, integration with electrolyzers)
- *Defossilize chemical production:*
 - Develop novel **waste to chemicals** technologies (with RE integration)
 - **Power-to-X** materials & technologies, to reuse CO₂ industrial emissions (with novel materials to recover CO₂)
 - Energy valorisation of *low temperature streams*
- *Develop the background **knowledge** for more efficient energy nanomat.*
 - Comprehensive theoretical modelling of reaction systems, prediction of materials and processes, synthesis, kinetics, functional analysis
 - Understanding electro- and photo-catalysts & plasma-catalysis interaction



A timeline of energy nanomaterials

2/2



Solar fuels and chemicals

- **From short to medium term**
 - Develop **pilot technologies** to use science developments in electro- and photo-catalytic as well as plasma-catalytic processes
 - Low P (& T) ammonia synthesis (and materials for the *direct* electrocatalytic production of fertilizers)
 - Materials/processes for e-(bio)refineries
 - Advanced design of electrode (selectivity, high productivity) and novel methodologies for their (low cost, scalable) preparation
 - Use of non-critical raw materials in electrodes (and energy nanomat.)
 - Technologies & processes to produce novel **low-carbon fuels and chemicals** (using **energy vectors**)
 - CO₂ (from biogas) and RE to biofuels (jet fuels, heavy trucks and ships)
 - Base raw materials for chemical production (olefins, aromatics) from energy vectors (as methanol)
 - Novel **PEC** approaches (& related materials)
 - Effective photo/electro integration, robust design, scalable and industrially exploitable, higher T/P operations (for intensification)



BACKUP SLIDES



How integrate RE in chemical production

- Plasma (@catalysis)
- Microwave
- Photocatalysis
- Electrocatalysis (and photo-electro catalysis)

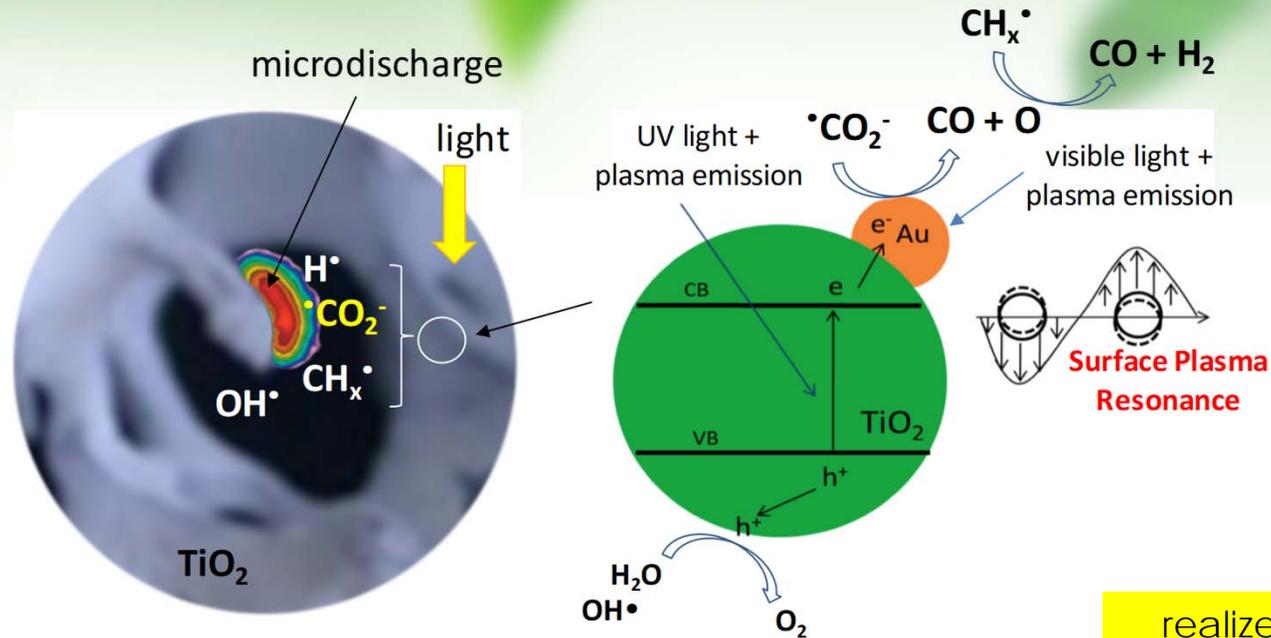
All these technologies are particularly suited for small-size (distributed) devices, i.e. systems which can be used up to a regional or district level, and for a circular economy

All above options are relevant to develop novel routes for a solar-driven chemistry, **electro-catalysis** is perhaps the **most advanced** presently for industrial implementations.

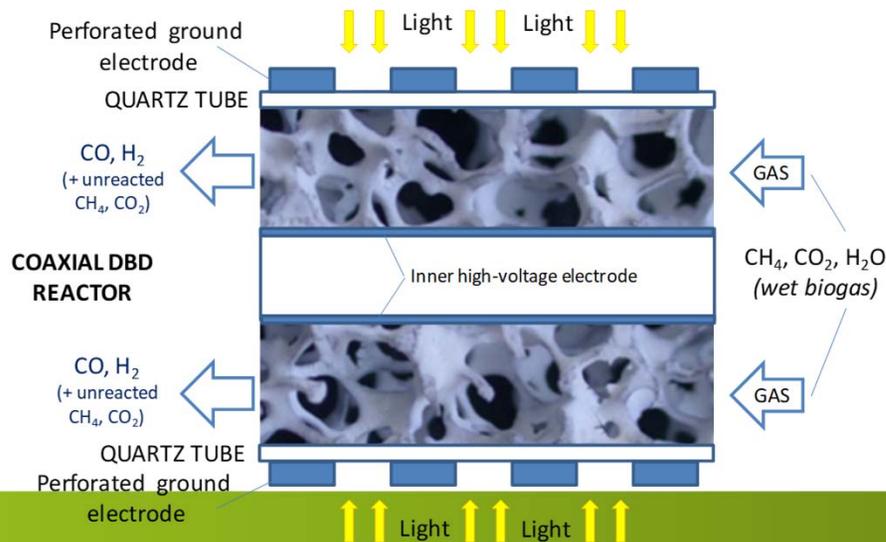
More advanced on crucial aspects such scalability to larger-size devices, which is actually the major limit of the other technologies.



Catalytic plasma-plasmonic synergy



realize a synergy between plasma and catalysis



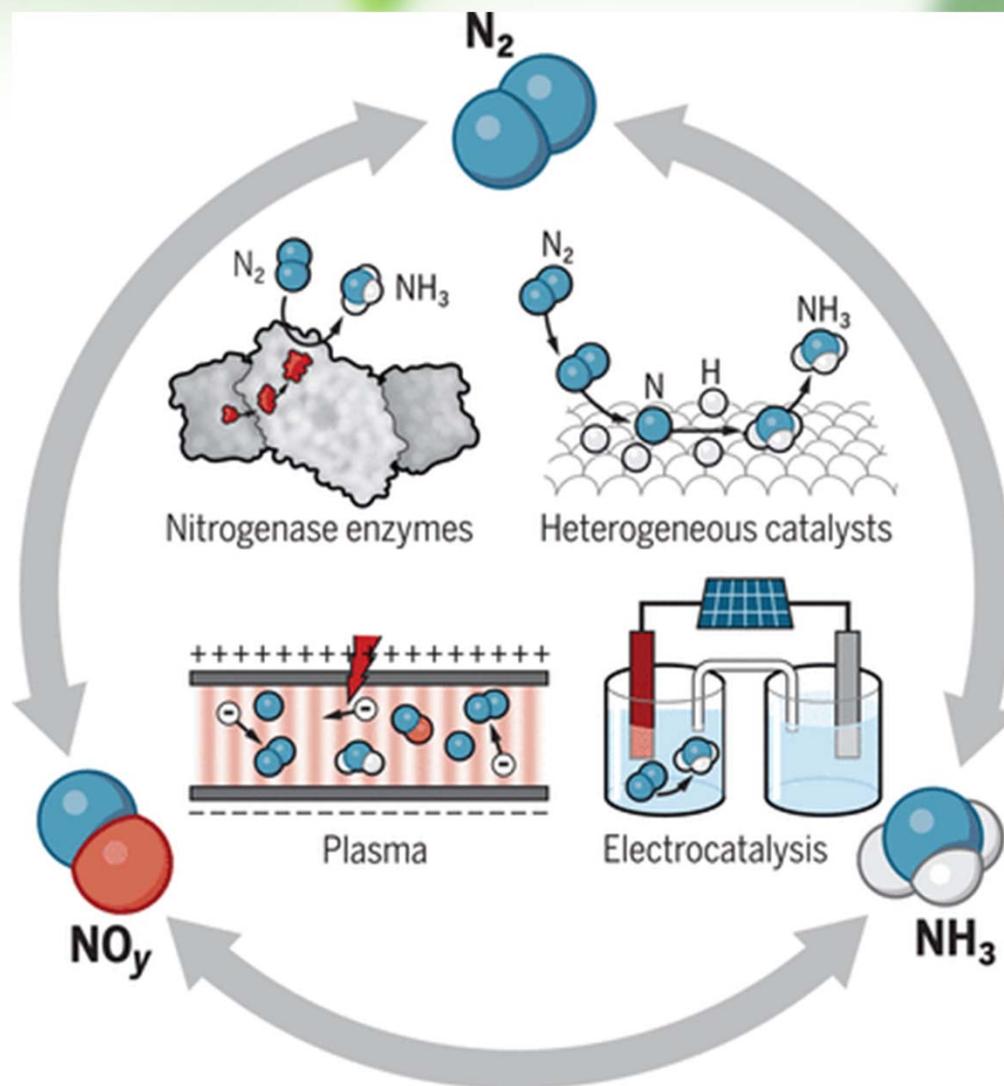
Challenges and opportunities

for electrocatalysis

- Identify **disruptive** processes for the new solar-driven chemistry scenario
- Creating an **innovative** landscape
- Pushing development of **ground-breaking** catalysts and catalysis **concepts**
- Process **Intensification** by electrocatalysis
- Opening of **new value chains**
- **New reaction paths** for the electrocatalytic conversion
- The role of **surface confinement** in the electrocatalytic conversion



Beyond fossil fuel-driven N transformations



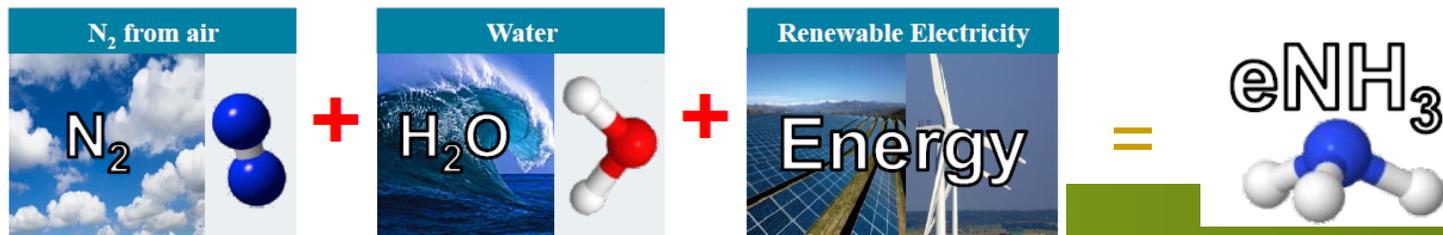
Science 25 May 2018:

Chen et al., Vol. 360, Issue 6391, eaar6611 DOI: 10.1126/science.aar6611

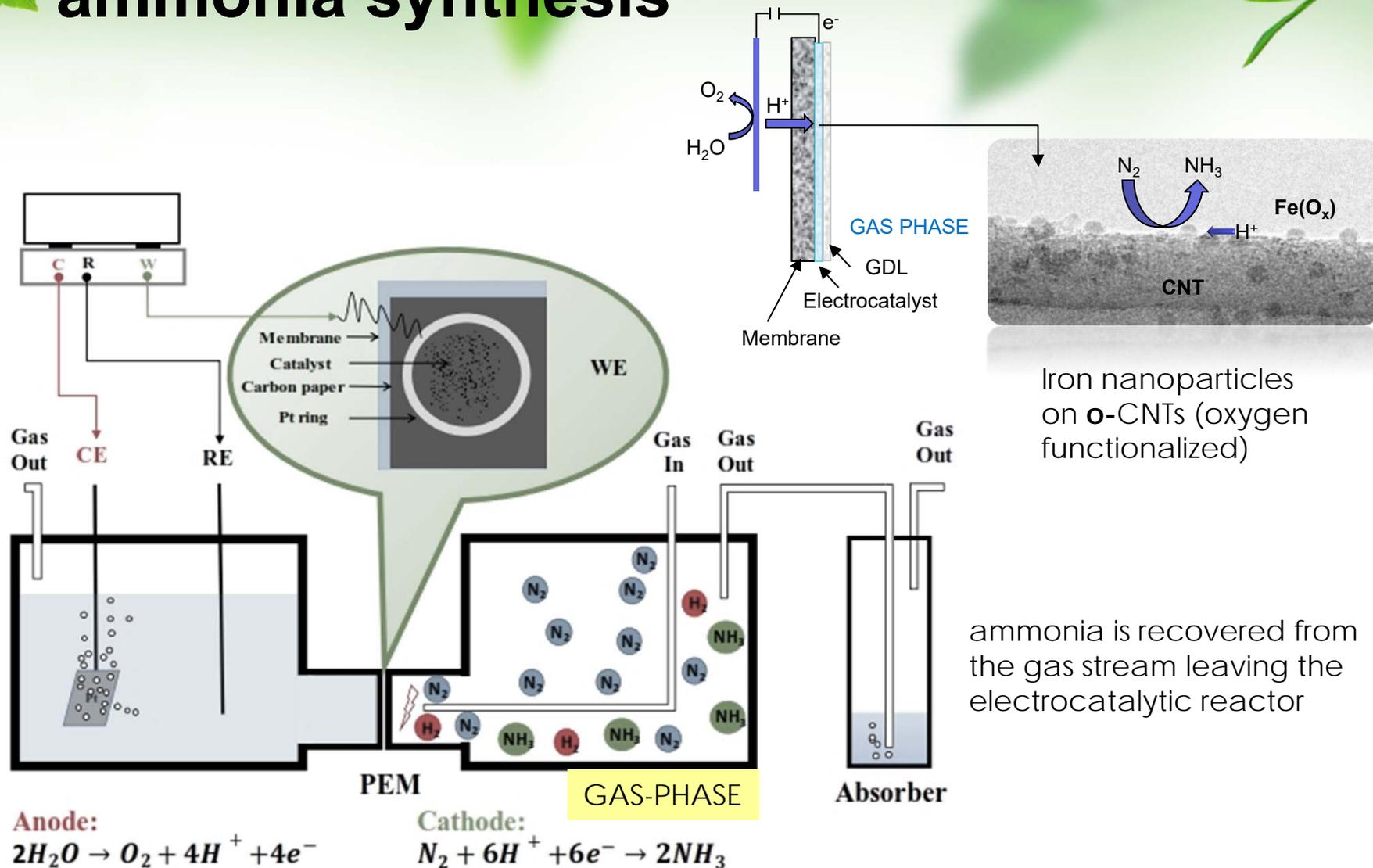
The case of ammonia synthesis

The direct electrocatalytic ammonia (NH_3) synthesis **decreases by 93% the carbon footprint** (e.g. CO_2 emissions) from $1.83 \text{ t}_{\text{CO}_2}/\text{t}_{\text{NH}_3}$ in the actual ammonia production scheme to $0.12 \text{ t}_{\text{CO}_2\text{eq}}/\text{t}_{\text{NH}_3}$ in the direct synthesis, besides the *advantages* in terms of

- large reduction in the process steps,
- milder operations,
- elimination of the use of fossil fuels,
- suitability for distributed production (avoiding impact of large-scale processes and relevant local impact, cost and impact of transporting ammonia),
- use for the chemical storage of excess renewable energy



Electrocatalytic flow reactor for ammonia synthesis

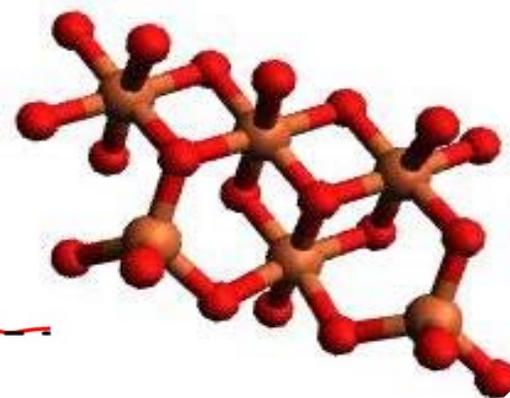
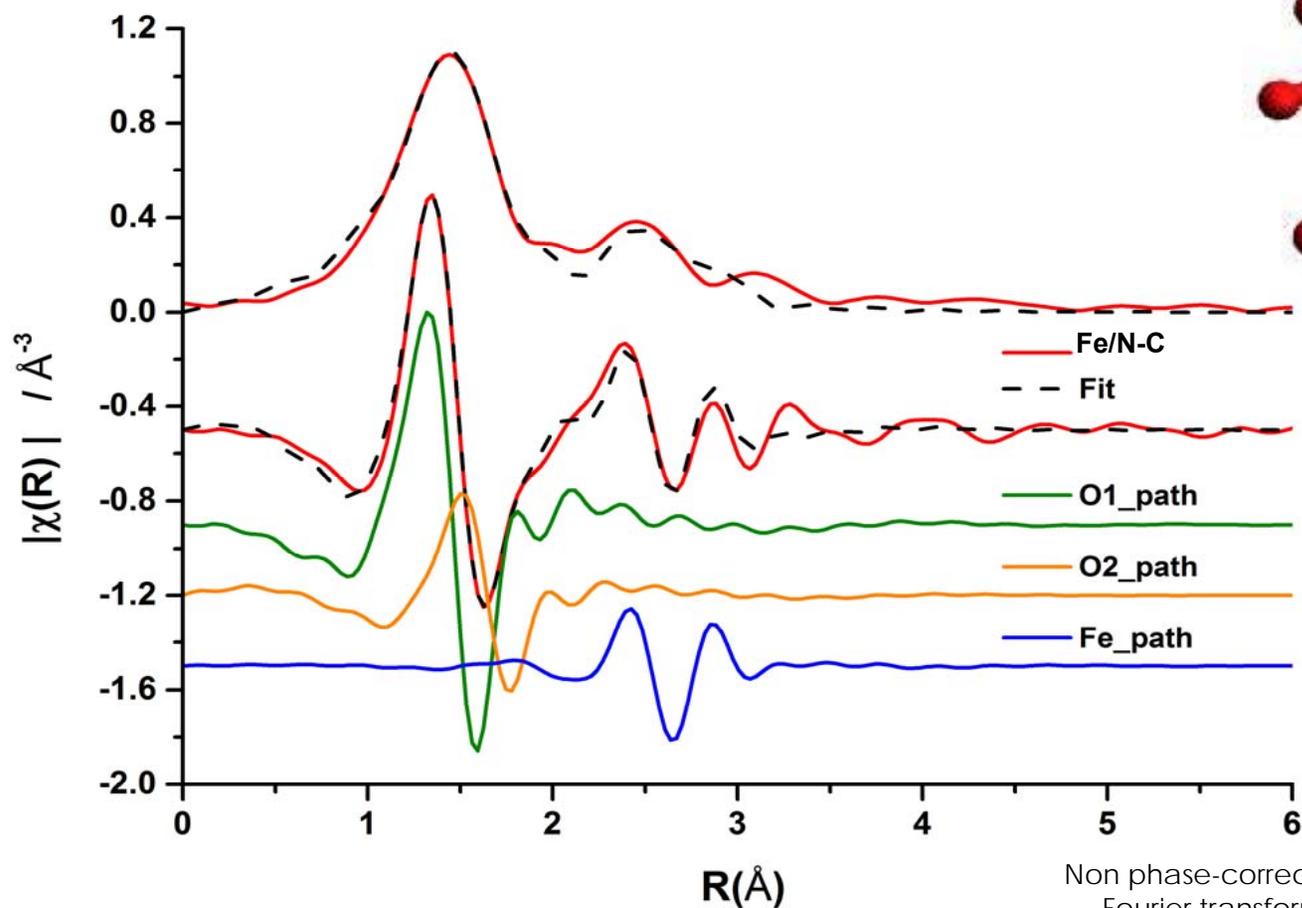


Iron nanoparticles on o-CNTs (oxygen functionalized)

ammonia is recovered from the gas stream leaving the electrocatalytic reactor

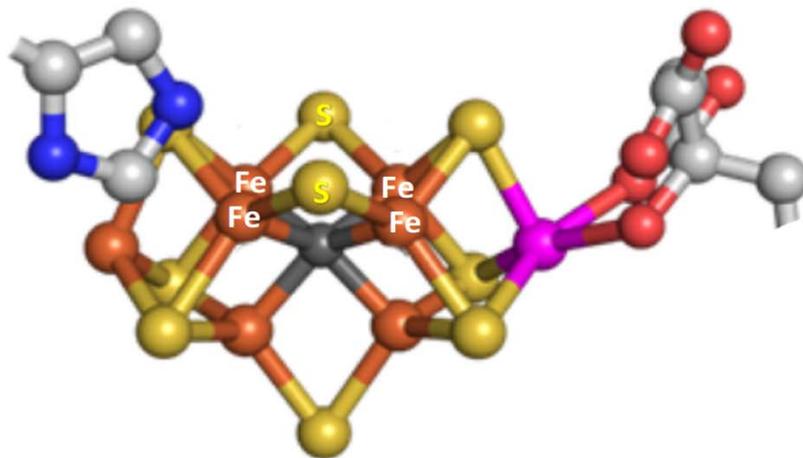
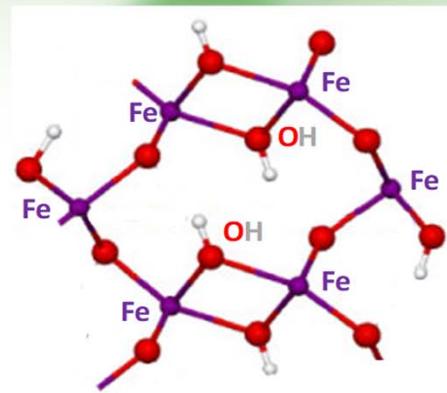
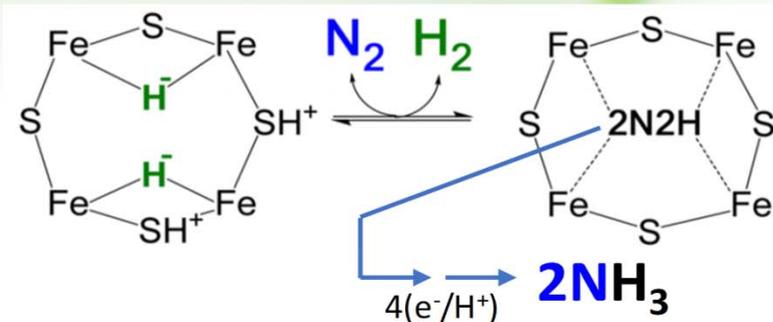
Nature of iron species (Operando EXAFS)

A ferrihydrate (FeOOH) is present rather than a Fe_2O_3 phase under working conditions, with the ferrihydrate nanoparticles located predominantly at the carbon defect sites.

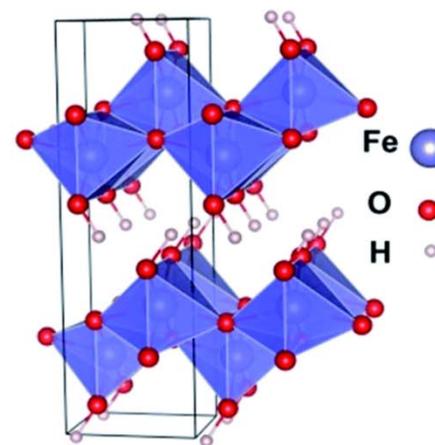


Non phase-corrected k^2 weighted
Fourier transform EXAFS data

Analogies with *Nitrogenase* FeMo-cofactor



Nitrogenase FeMo-cofactor



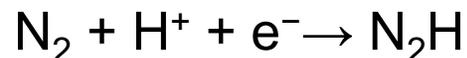
FeOOH

- **strained-FeOOH** nanorods exhibited enhanced catalytic water oxidation and FeOOH shows high electrocatalytic oxygen reduction activity. (Park et al., *Nanoscale*, 9 (2017) 4751; Luo et al., *J Mater Chem A*, 5 (2017) 2021)
- In both cases, the behavior was associated to the specific surface configuration, able to give **multielectron transfer** in water oxidation and oxygen electrocatalytic reduction.

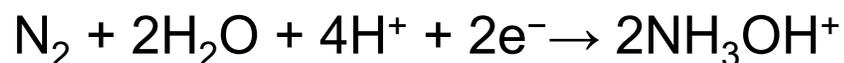


A multielectron transfer

- To develop low temperature (and pressure) active electrocatalysts for direct NH_3 synthesis the **direct hydrogenation of N_2** rather than first dissociation is a preferable route, because N_2 dissociation would be hardly realized under mild conditions where the catalytic chemistry is dominated from the **strongly bounded species**.
- However, the direct hydrogenation of N_2 would generate high-energy intermediate (N_2H , N_2H_2). The reduction potential of



is -3.2 V vs. NHE, while -1.83 V vs. NHE in the 2-e reduction process



For **multi-electron reduction** process, for example



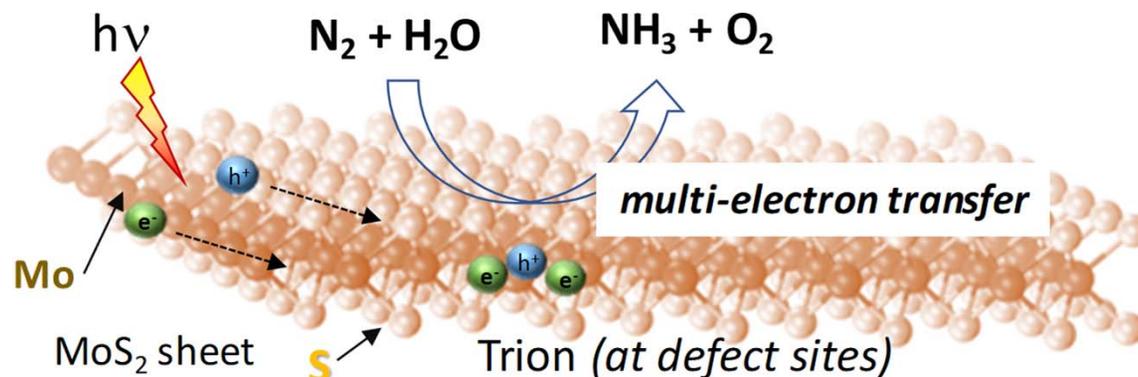
the reduction potential becomes -0.23 V and 0.274 V vs. NHE, respectively

How realize a multi e^-/H^+ transfer

- *Common approach*: realize biomimetic analogous (of nitrogenase Fe-Mo) metal complexes \Rightarrow how synchronize the simultaneous transfer
 - LIMITS: stability and productivity (per electrode area), loading on the electrode, ...
- *Alternative possibility*:
 - localized electrons in oxygen vacancies are active to adsorb N_2 by electron donation
 - tightly bound excitons can capture additional electrons to form charged excitons (such as trions, i.e. $e^-h^+e^-$)
 - These charged excitons with two or more electrons in one bound state, may act as electron-rich species to facilitate a multi-electron reduction process of molecular N_2 .

- Photo(electro)catalytic N_2 reduction to ammonia is possible on ultrathin MoS_2 with a mechanism likely involving the formation of trions

Sun et al APPCAT-B, 200 (2017) 323

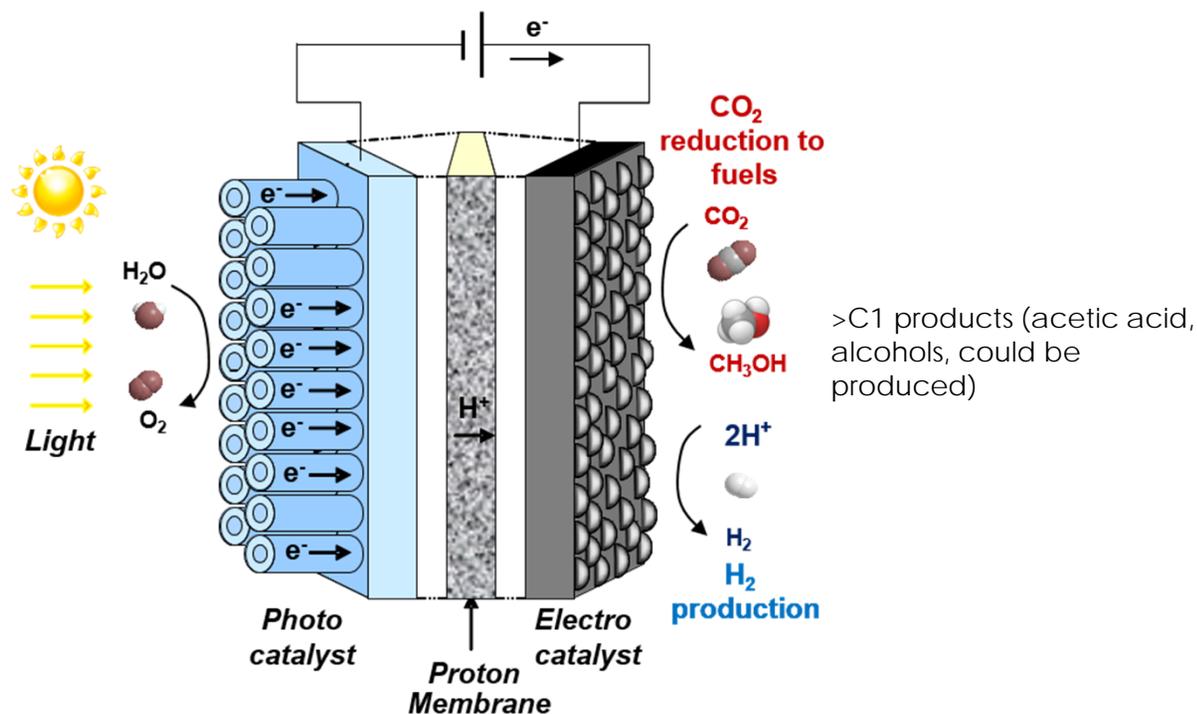


LONG-TERM: artificial leaves

Combine H^+/e^- solar production with direct use to produce fuels/chemicals

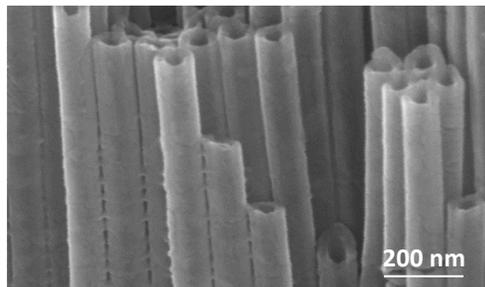
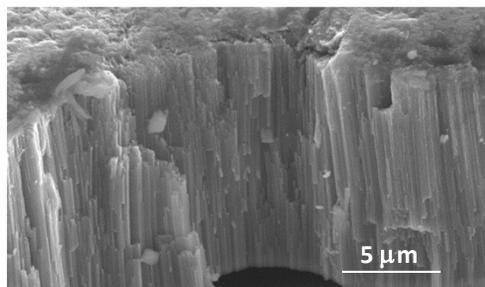
EL-PEC solar cells

Importance of non-energy intensive recovery of the reaction products and cell design easy for scale-up

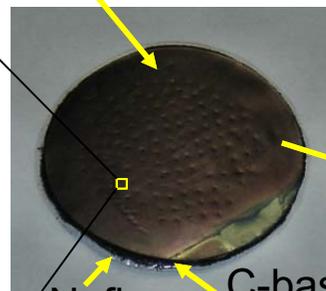




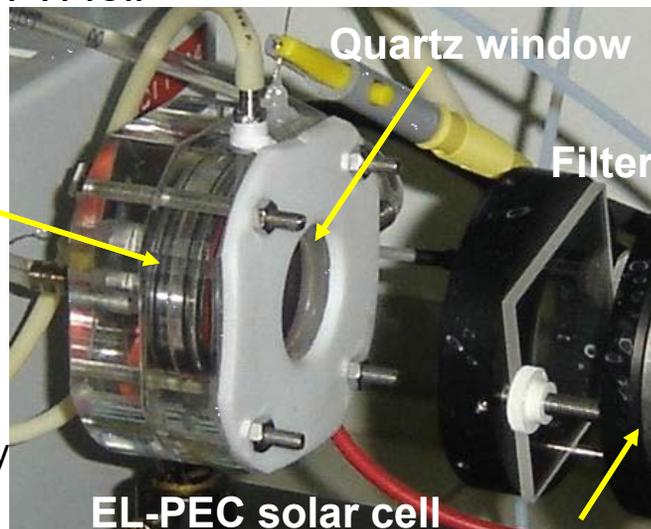
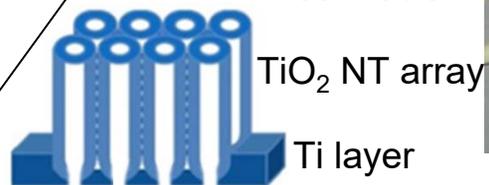
EL-PEC solar cell



photoanode: NT film on Ti foil



Nafion C-based cathode

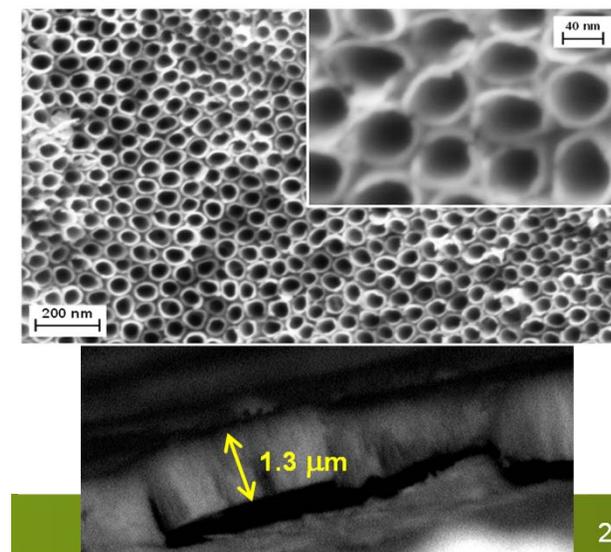
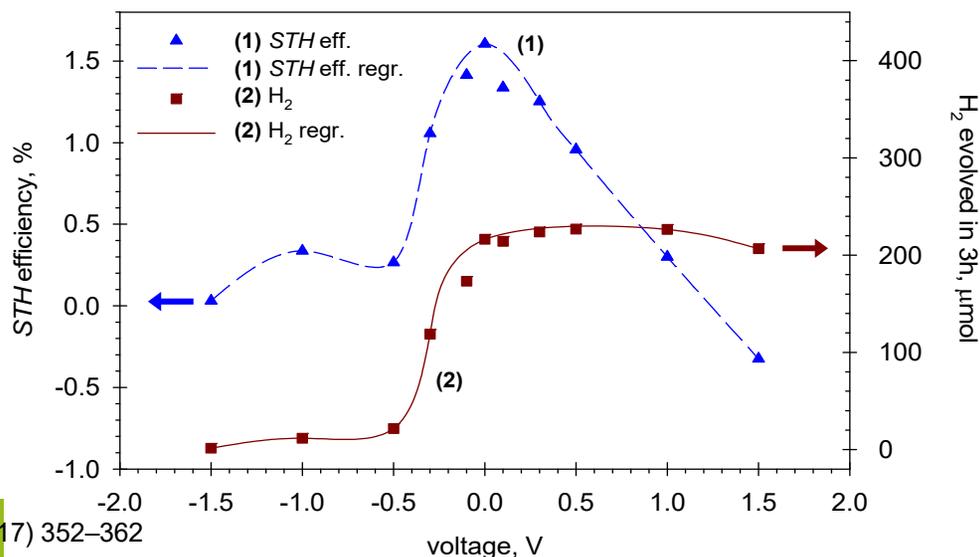


Solar simulator

Engineering of the photoanodes based on ordered TiO₂-nanotube (TNT) array

as a function of $NtTiO_2$ thickness and characteristics

- The best tested photo-catalyst was the one-hour TNT
 - 1.60 % *STH* efficiency (solar-to-hydrogen efficiency)
 - 99.2 % Faradaic efficiency
 - 65 % IPCE ($\lambda=330$ nm): incident photon to current conversion efficiency
- *Between the best reported for PECa cells using undoped TiO₂ photoanodes & absence of external bias or sacrificial agents.*



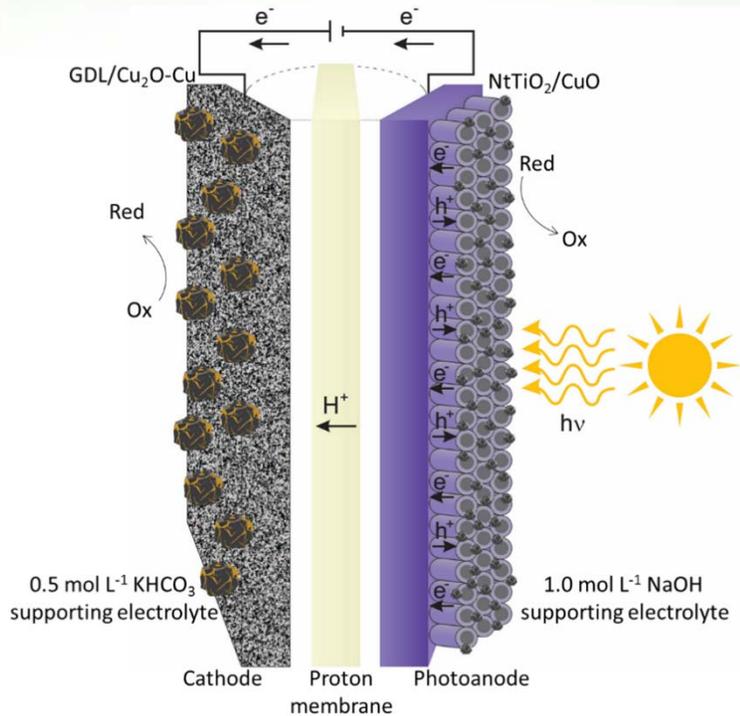
Solar-to-hydrogen efficiency (STH)

Photoanode	Incident light	H ₂ production rate (mmol h ⁻¹)	STH efficiency (%)
TNT	Open spectrum	85.5	1.68
TNT	Solar (AM 1.5G)	7.8	0.24
CuO-TNT	Open spectrum	104.3	2.04
CuO-TNT	Solar (AM 1.5G)	17.4	0.53

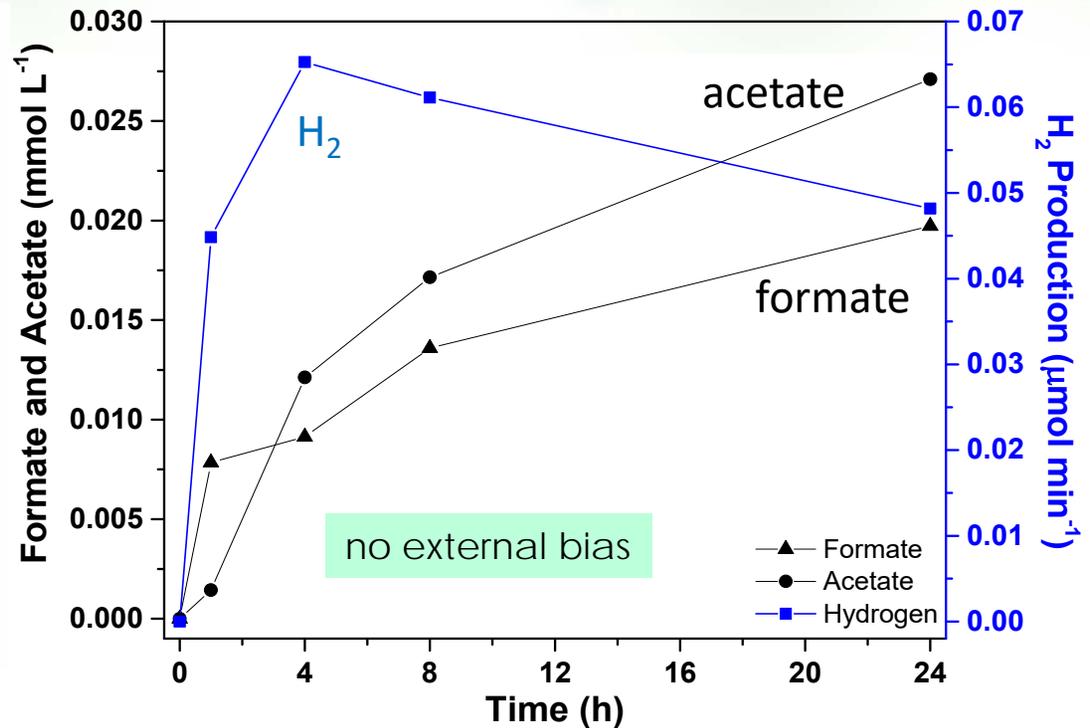
CO₂ reduction in a PEC full cell

current generated during this experiment → 0.2 mA

GDL/Cu₂O-Cu as cathode and NtTiO₂/CuO as photoanode



no sacrificial agents



- formate in this case is not the preferential product formed
- after 24 h the concentration of acetate and formate are similar, reaching 0.027 and 0.020 mmol L⁻¹, respectively

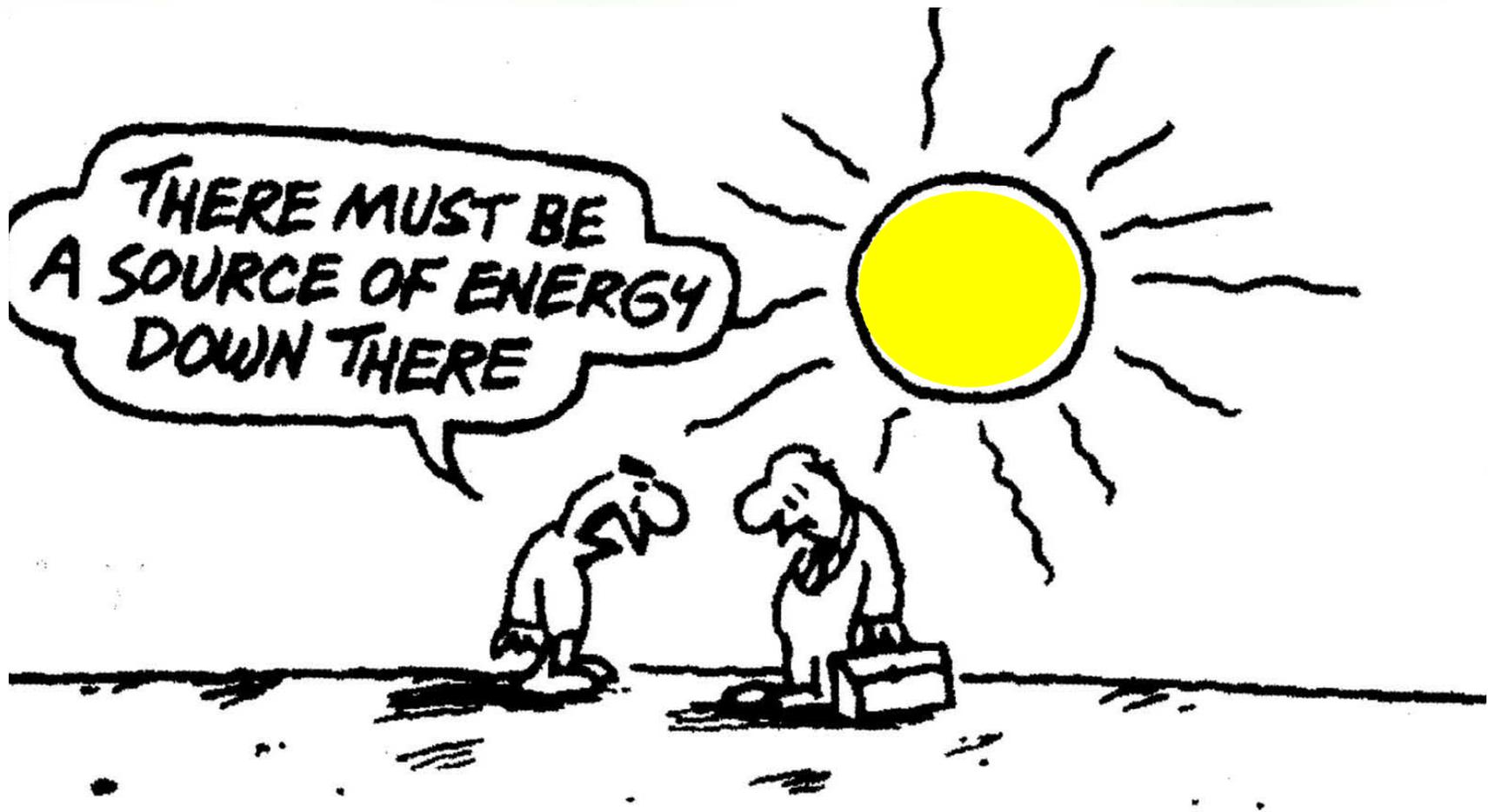
Conclusions

- We are moving to a **new scenario** for chem. and energy production, which requires to develop new route and technologies
 - Solar-driven chemistry and energy represents the vision of the future
 - smaller, cleaner, safer and more energy efficient technologies: the next revolution of the chemical industry to **significant increase the resource and energy efficiency.**
 - there is the need to develop the **catalysts**, technologies, processes able to use directly photons, electronics, etc. for chemical synthesis or energy storage
 - **we need to develop the knowledge to make possible this change which drivers, however, are external**



Conclusion







Outline

- **Why beyond fossil fuels**

- The new scenario for energy and chemistry
- Motivations and outlooks

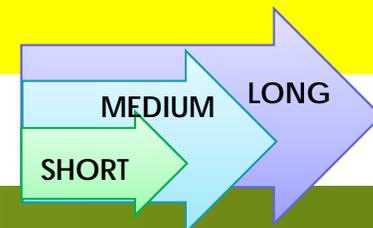
- **The use of alternatives feedstocks**

- *short-term*: MSW to urea and methanol (motivations, economics)
- *medium-term*: CO₂ as C-source and energy-vector (to enhance RE use)
- *long-term*: artificial-leaf



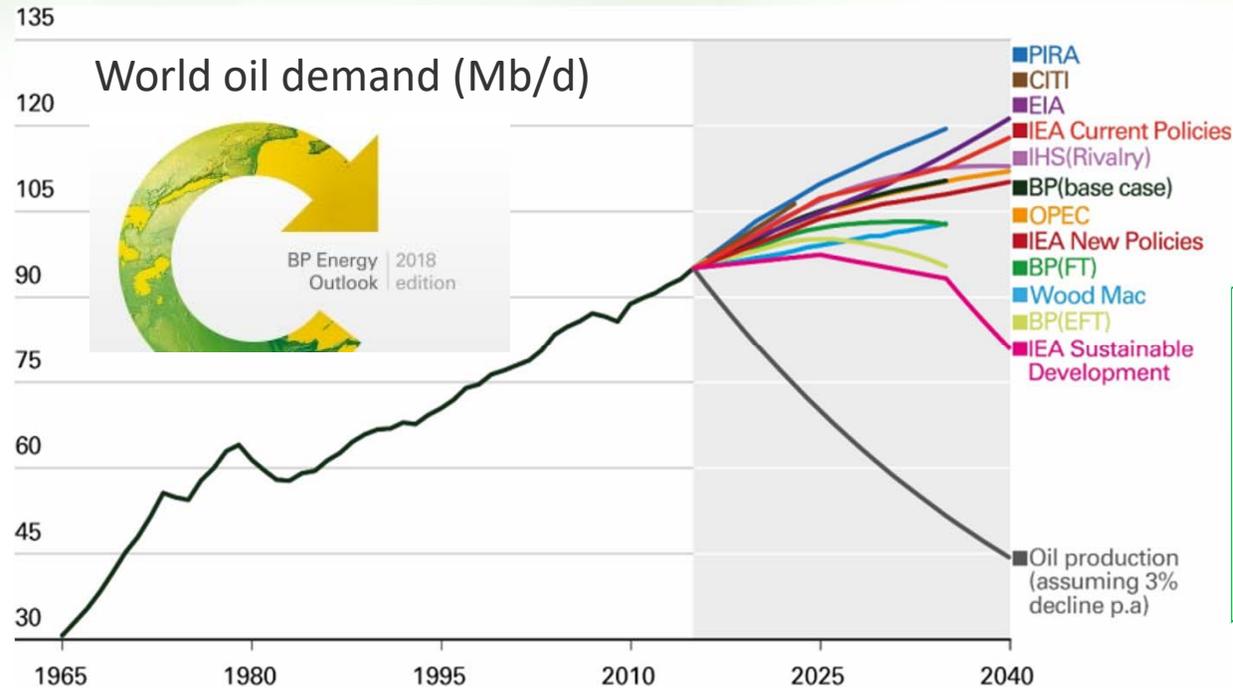
- **Conclusions**

While different technologies will be necessary in a longer term (electro-, photo- ...), there is the need of also short-term technologies to start transition



Oil peak and energy transition

forecast for oil demand over the next 25-30 years from a variety of public and private sector organizations



BP Energy Outlook 2018

- **wide range** of estimates of the point at which oil demand is likely to peak
- "there is **little reason** to believe that once it does peak, that **oil demand will fall sharply**. The world is likely to **demand large quantities of oil for many decades to come.**"

BUT

- these predictions catch the real trend in a complex economy with an on-going transition ?
- it is the correct way to analyse timing for the transition, and to prepare the related technologies?

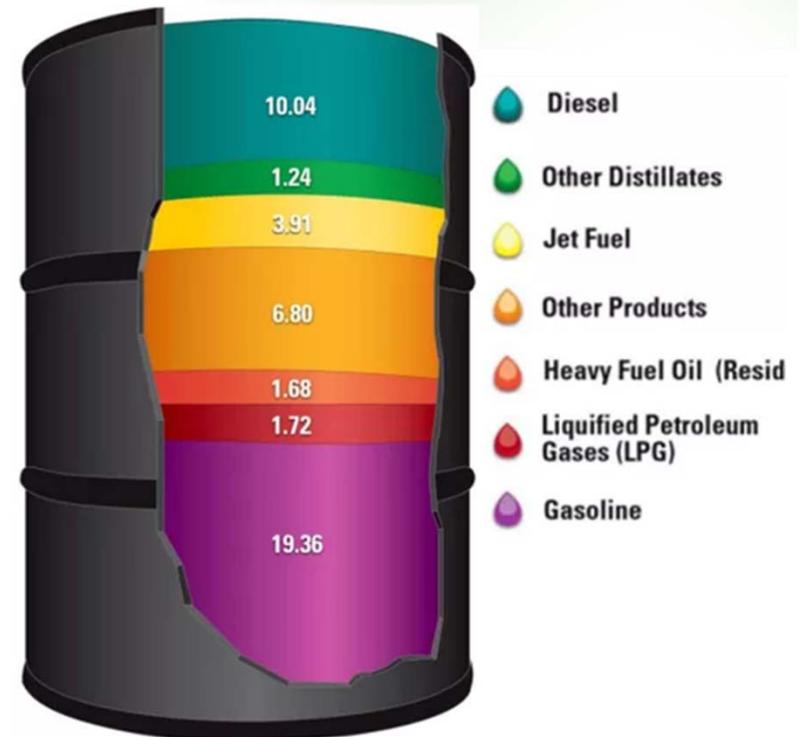
What is the cost of oil barrel



70-80 US\$

cost associated to sustain the economies of the extracting countries

cost of production



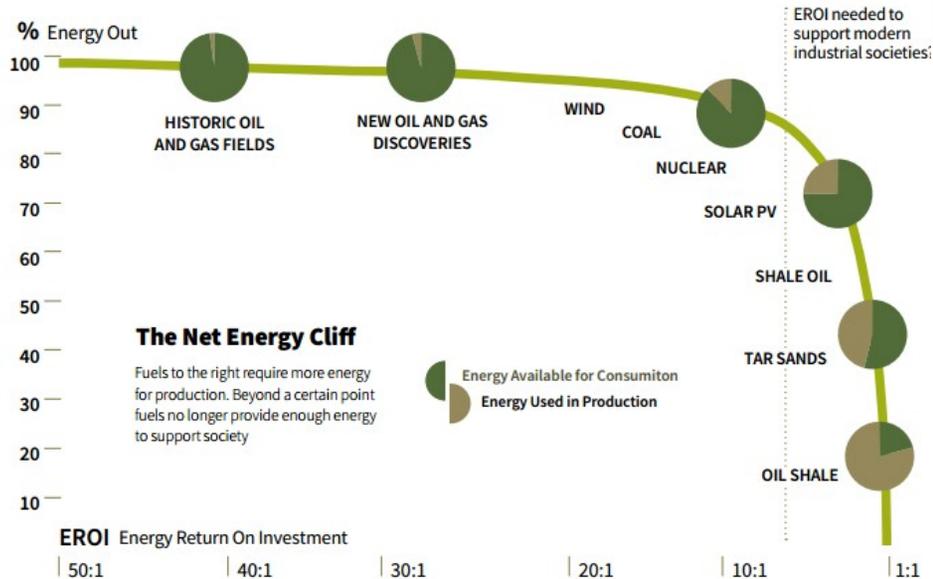
even considering market expansion, there is a decrease in request for mobility and residential / industrial due to progress in renewable energies

an increasing cost

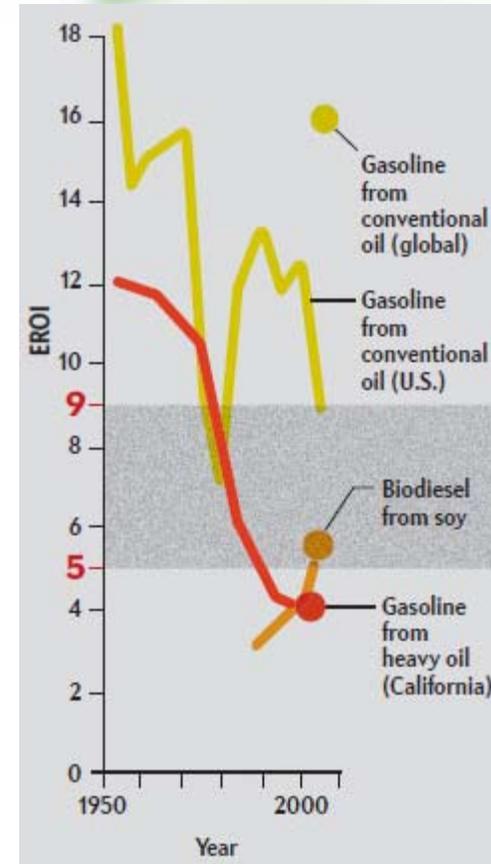
Energy Return On Investment (EROI)

ratio of energy delivered to energy costs

Original concept, Hall et al. Science, 211 (1981) 5769



Oil's Advantage Drops



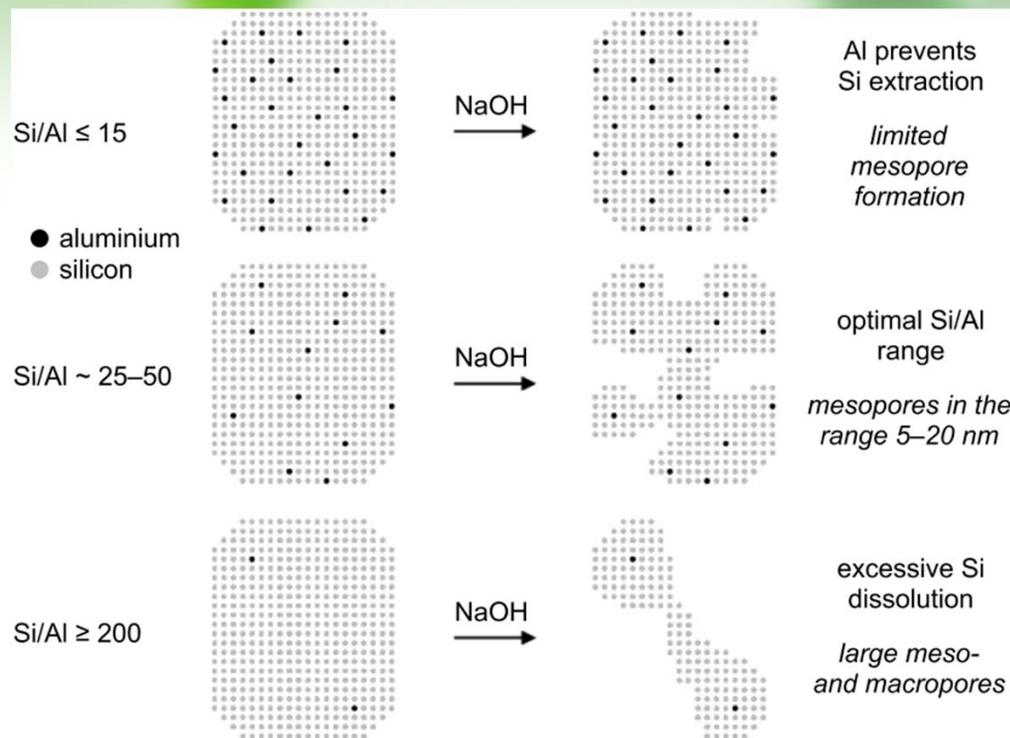
Solar PV EROI	2013	2018	2025
Increase effic.	6	12-15	> 20-25

Coal EROI	2013	2018	2025
incl. env. costs	8.7	~5	< 2

EROI will be soon not longer advantageous for fossil resources

Zeolite desilication

Need of alternative desilicating route, valid for any Si/Al, faster, and with less impact on acidity.



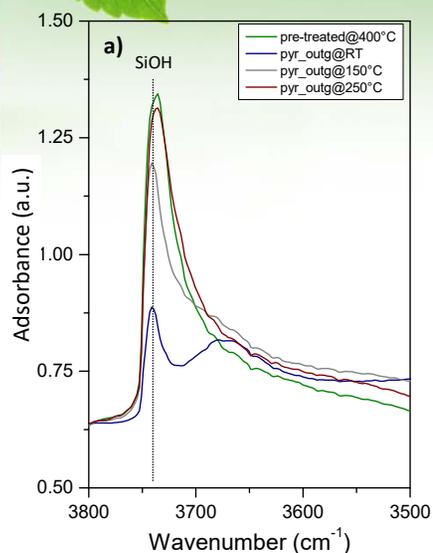
J.Phys.Chem.B
2004, 108, 13062.

- *Bottom-up method*: modification of synthesis
- *Top-down method*: post-synthesis treatment (demetallation, delamination)

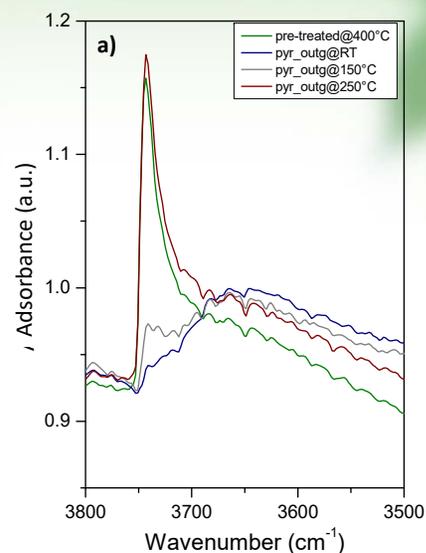
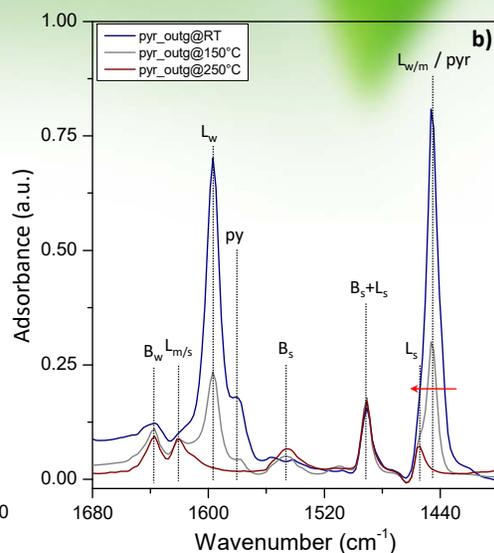
Drawbacks

- Acidity loss
- Defects insertion
- Valid for an optimal Si/Al range (in other cases, need to add pore directing agents)
- Time consuming/larger volumes

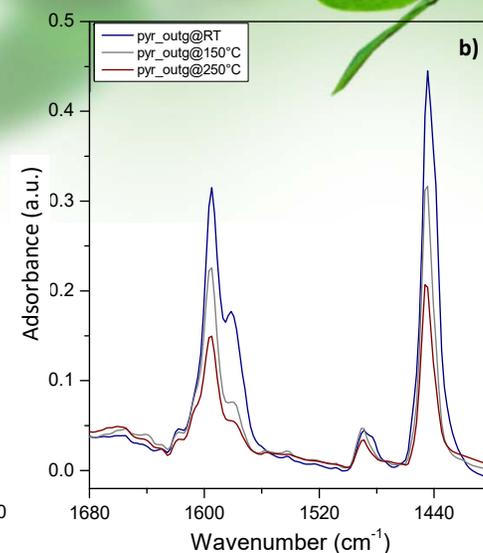
FTIR pyridine



Ni/Beta-75 before and after pyridine adsorption



Ni/Beta-75 Des before and after pyridine adsorption



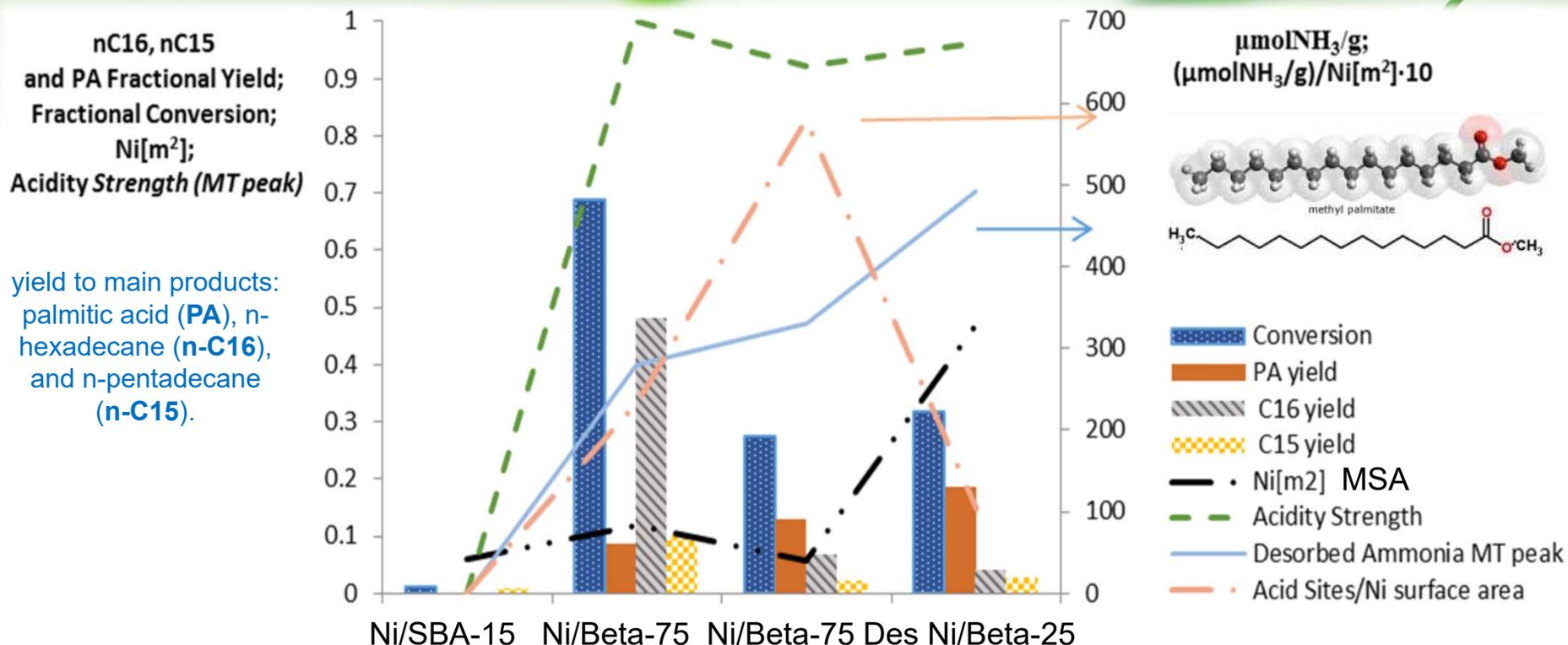
quantification of Brønsted and Lewis acid sites

Sample	Brønsted sites [$\mu\text{mol/g}$]	Lewis sites [$\mu\text{mol/g}$]
ASA	19.5	257.6
H-MFI	162.8	17.8
H-Beta	153.5	49.1
Des H-Beta	145.7	83.1

Amorphous silica-alumina, presents the highest acidity with a major contribution of the Lewis sites and a very low Brønsted acidity ($19.5 \mu\text{mol/g}$), while for the other supports Brønsted acidity drastically increase. FT-IR data confirm that the **desilication** treatment leads to a slight increase of the total acidity, introducing **prevalently Lewis acidic** sites.

Role of the acidity

selective hydrocracking of methyl palmitate



- Strong influence of the acidity and apparently no correlation with MSA;
- The conversion of MP shows a max for an intermediate number of acidic sites;
- The low conversion with the Ni/SBA-15 confirms that the prevailing mechanism for production of n-C15 and n-C16, in presence of acidic sites, goes through PA as intermediate (the HDO reaction thus requires an acid function together with the hydrogenation one).

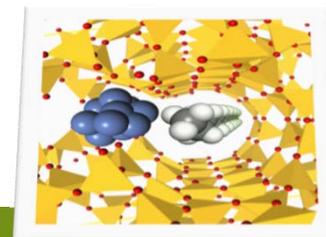
Conclusions (zeolies for algal oil)

➤ HDO and selective hydrocracking of methyl palmitate

- the localization of Ni particles, when located inside the zeolite channels show lower performances;
- the acidity of the zeolite (Brønsted acidity is necessary together with the hydrogenation function related to Ni);
- the presence of mesoporosity is necessary to provide a mechanism of selective cracking, via likely a pore mouth reaction mechanism.

➤ Hydroisomerization/hydrocracking of n-hexadecane

- the introduction of controlled mesoporosity increases the activity and the selectivity to most valuable cut (C11-C15) and leads to the formation of carbon species easily oxidable.





Hydroisomerization/hydrocracking of n-hexadecane



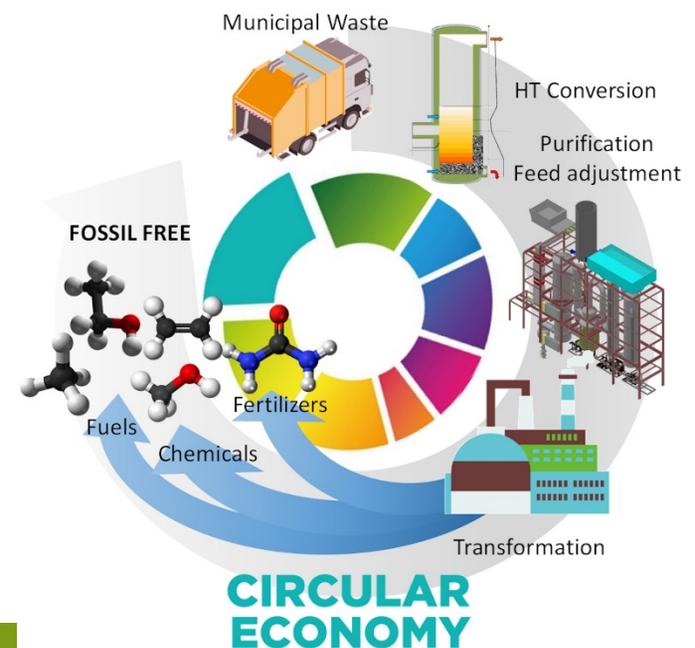
- The results, although limited to n-hexadecane, indicate that **Ni/Des H-Beta** has good characteristics for the **combined production of green jet fuels and diesel**.
- The use of Beta rather than MFI (ZSM-5) **reduces** significantly the **rate of coke formation**, which is further decreased by the **introduction of mesoporosity** (desilication). In addition, the latter treatment **reduces the hardness of carbon** and thus facilitates its removal by oxygen treatment.
- The acidity of the catalyst has a major effect on hydro-reactions.
 - The deposition of Ni on ASA (higher number of total acid sites, with negligible Brönsted and high Lewis acidity), leads to a catalyst with much lower activity than its **zeolitic** counterparts.
 - The better catalytic performance are obtained with **H-MFI**, which exhibits mainly Brönsted acidity, but with an unacceptable gas formation and very low hydroisomerization activity
 - A high catalytic activity is also observed **for H-Beta** which possess a concentration of Brönsted sites similar to H-MFI. The performance of Beta catalysts is enhanced after *desilication*, although Brönsted acidity is only slightly modified.
 - The introduction of **mesoporosity** by desilication enhances the activity, while still maintaining an acceptable gas formation and good hydroisomerization properties.

behaviour is likely related to both acid strength and proximity between acid sites and hydrogenation functions within the zeolite crystals; reducibility of Ni seems not a critical parameter

SHORT-TERM: THE VALORIZATION OF WASTE RESOURCES

WASTE TO CHEMICALS

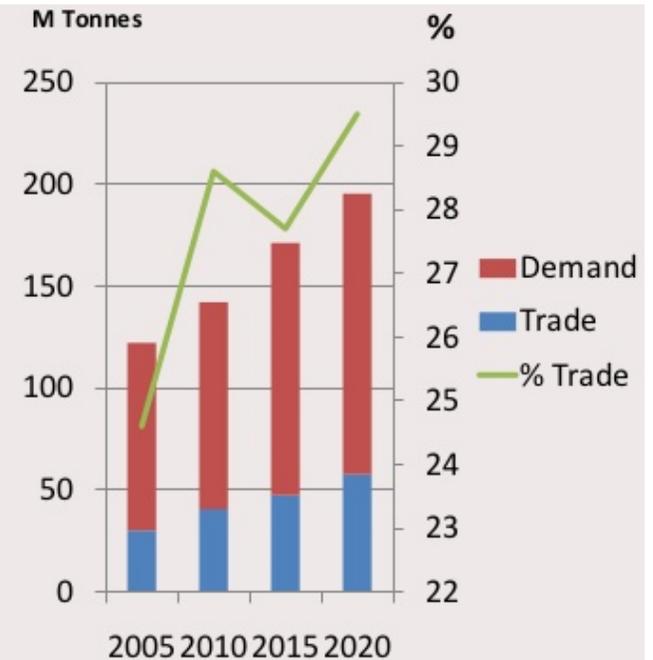
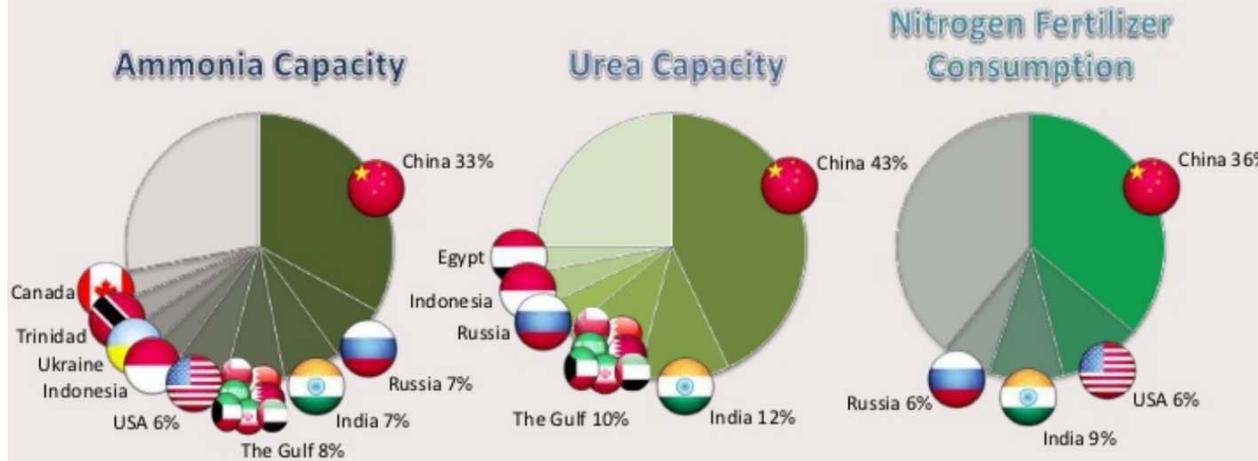
It is techno-economic
and environmental
feasible?



Waste-to-chemicals for a circular economy \Rightarrow *waste-to-urea*

Urea: Nitrogen product of choice representing 60% of total N fertilizer use

• Nutrient content is defined in terms of elemental N



• Natural Gas is the primary feedstock typically representing 70-80% of ammonia production cost – 80% of N capacity uses natural gas as feedstock

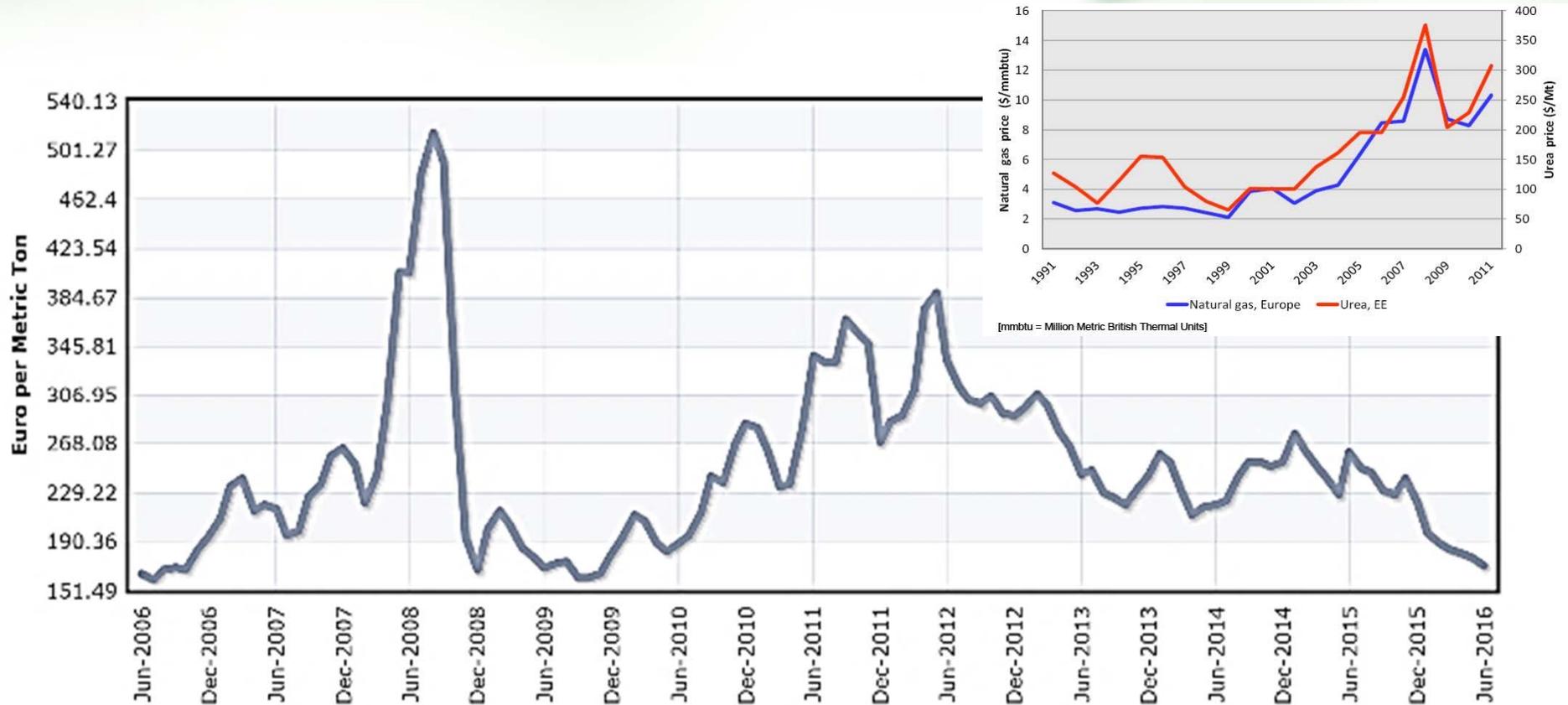




Urea production cost



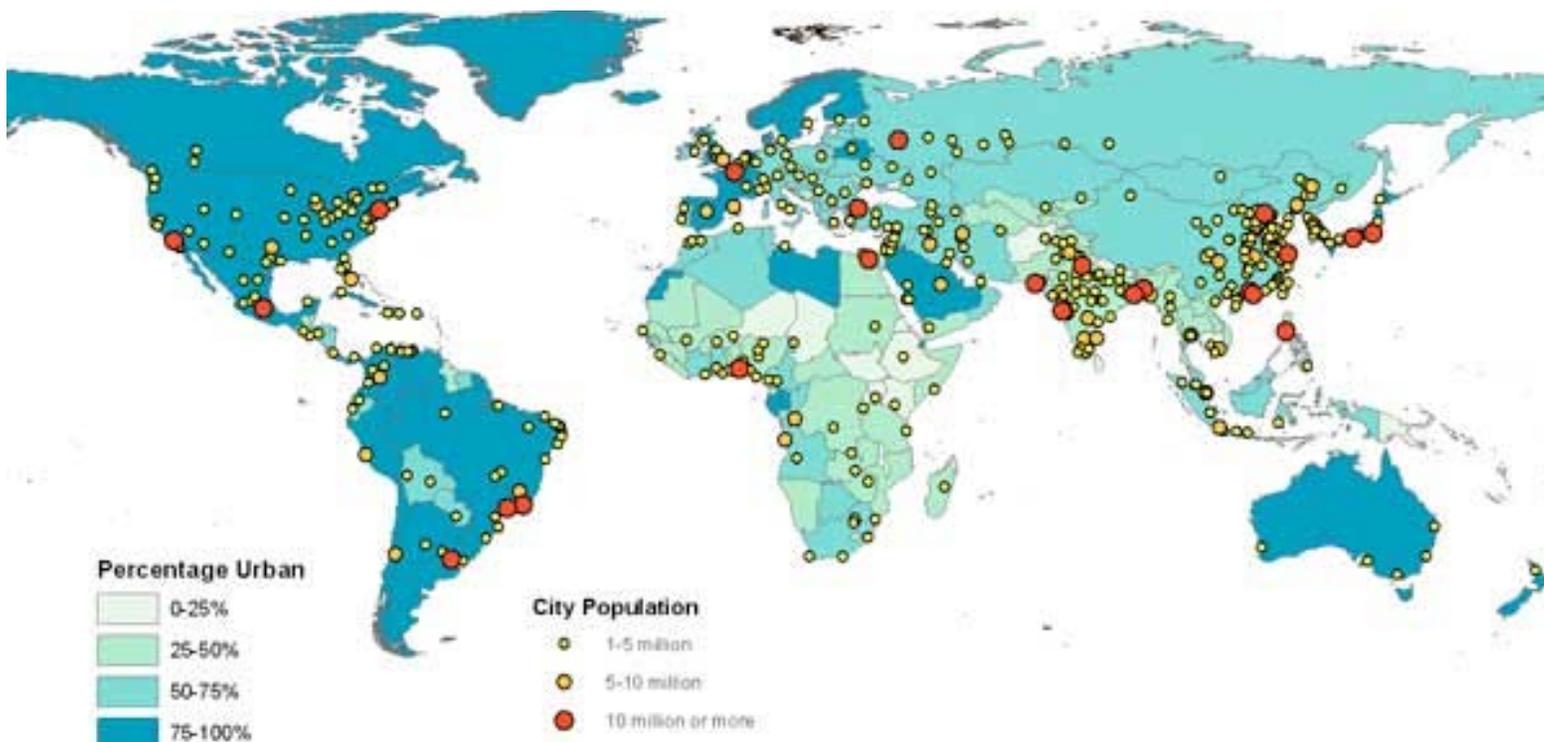
Urea price variation in the last ten years



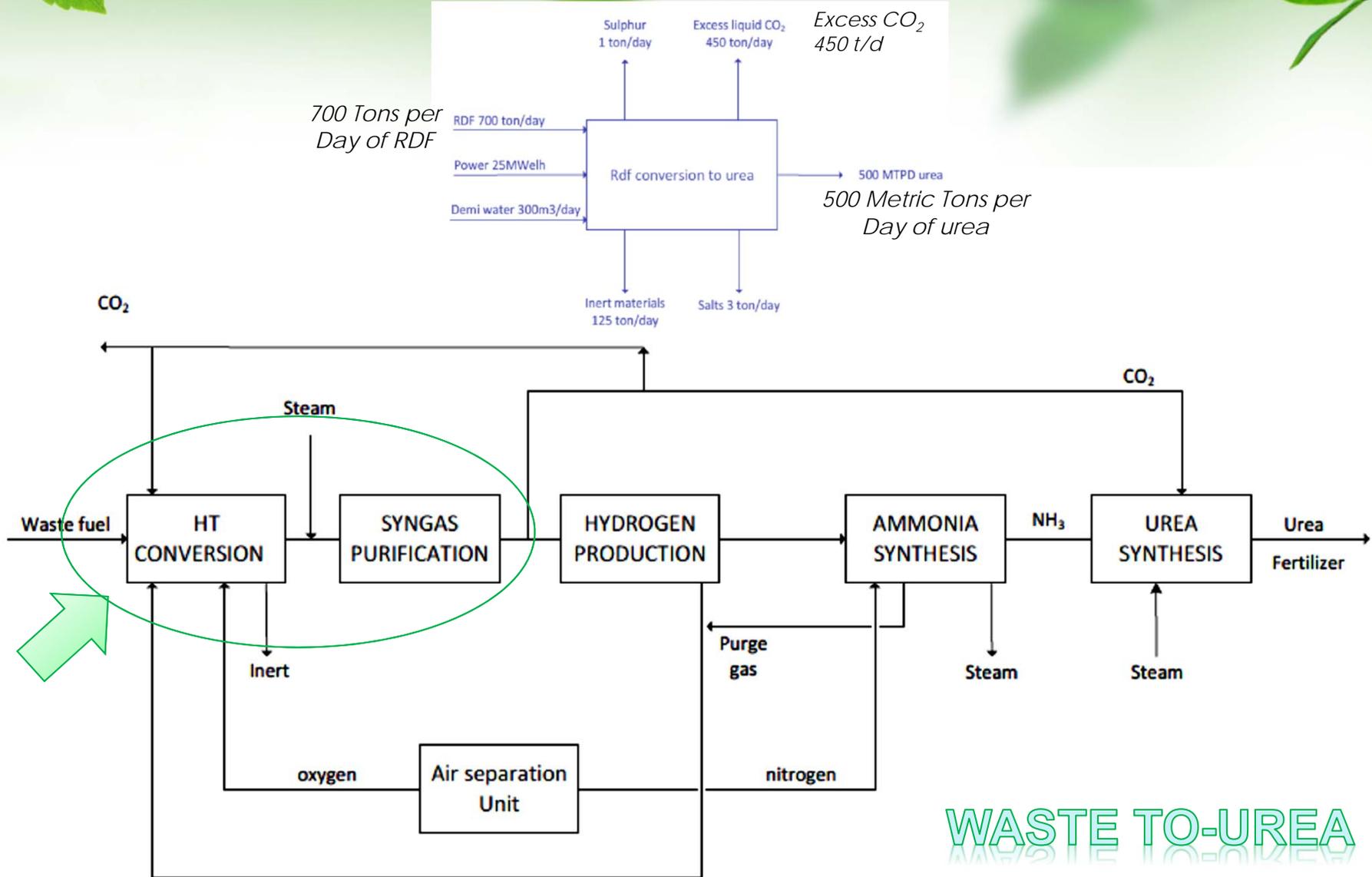
*To great variability and dependence on NG costs,
Price advantage of countries with NG reserve*

Municipal Solid Waste (MSW): *a diffused, underused, C source*

Rapid urban population growth has resulted in a number of challenges, including municipal solid-waste management. National and municipal governments often have insufficient capacity or funding to meet the growing demand for solid-waste management services. Solid-waste management is the single largest budget item for many cities



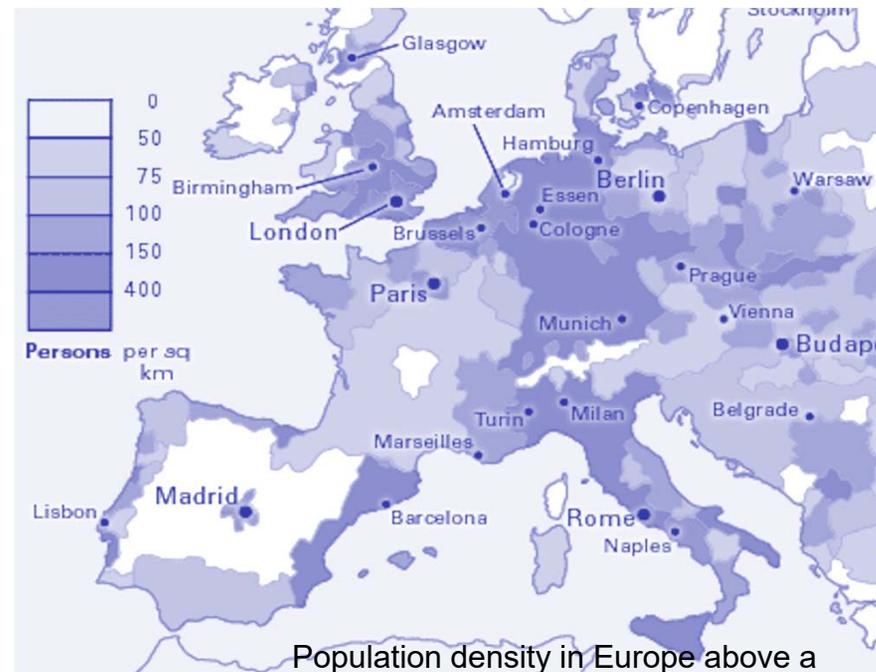
Block diagram for waste-to-urea process



Population density to feed the plant

- **RdF feed of 700 ton/d**

- average MSW annual production per habitant (475 kg) \Rightarrow 40% of RdF production from MSW \Rightarrow about 1.1 Million persons would be necessary to produce a RdF feed of 700 ton/d.
- considering that transport of RdF should be limited ≤ 100 km \Rightarrow **population density of about 35 persons/km²**



Population density in Europe above a threshold of 50 persons·km²

Economics assessment

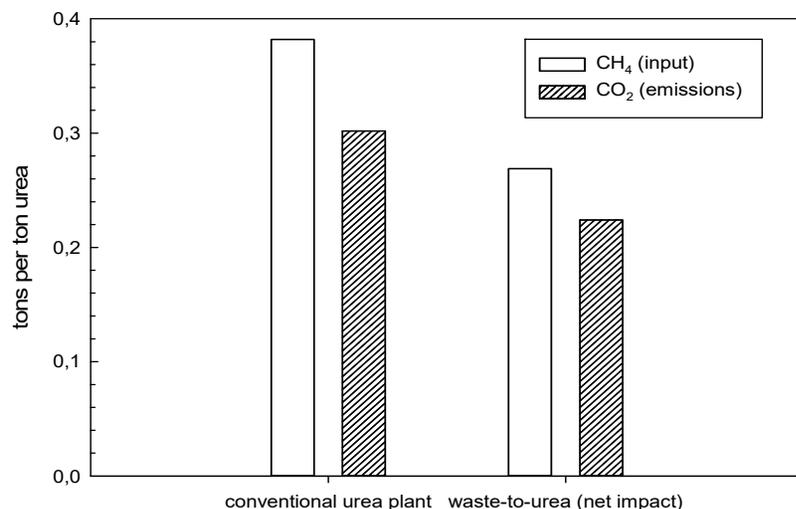
Cost of production and income per ton of urea, estimated cost (**COP**) for the production of urea from waste in a 500 MTPD plant starting from RdF

Category	M€ per year	
COSTS		
Power	9,7	<i>The estimated profit per ton of urea is in the range of 90€; IRR (Internal rate of return) of the project is in the range of 11-12%, which indicates the good profitability of the waste-to-urea approach.</i>
Slag disposal	0,9	
Maintenance	7,0	
Depreciation	30,4	
Other costs (well demiwater)	2,0	
Labor	4,0	
TOTAL COSTS	54,0	
INCOMES		
RdF (avoided disposal)	24,5	
CO ₂ avoided	1,95	15€ per ton of CO ₂
Excess CO ₂ for Bio-CSS	3,85	25€ per ton of CO ₂
TOTAL INCOMES	30,3 M€ per year	
Yearly urea production	175000 MTPY	
COP	135 € per ton of urea	

The largest part of the cost of production in the waste-to-urea technology is associated to the depreciation + maintenance term, constituting almost 70% of the overall costs

Environmental impact analysis

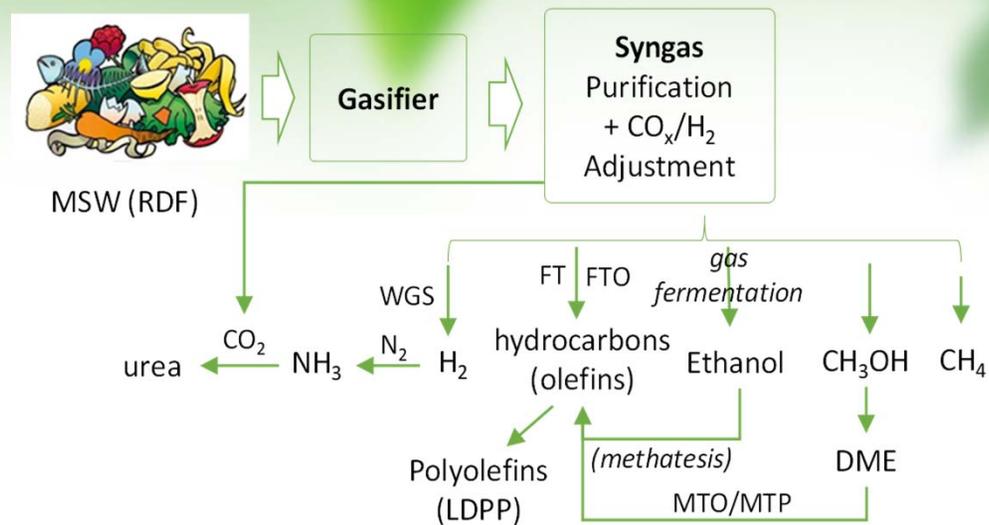
- **comparison of the conventional vs. waste-to-urea – WtU**
 - CO₂ is produced in an amount about three times higher in the WtU technology with respect to the conventional, but in a form easy usable for other applications (in liquid form), while is present diluted in the flue gases (together with other pollutants as NO_x) in the conventional technology.
 - Around 190 MTPD of methane should be fed in the conventional process instead of about 700 MTPD of RdF in the WtU approach
 - RdF is a waste produced anyway which should be thus disposed ⇒ WtE (waste to energy) ⇒ net effect is thus conventional + WtE – WtU



a saving of about 0,113 tons CH₄ and about 0,78 tons CO₂ per ton urea produced



Waste to Chemicals for a Circular Economy

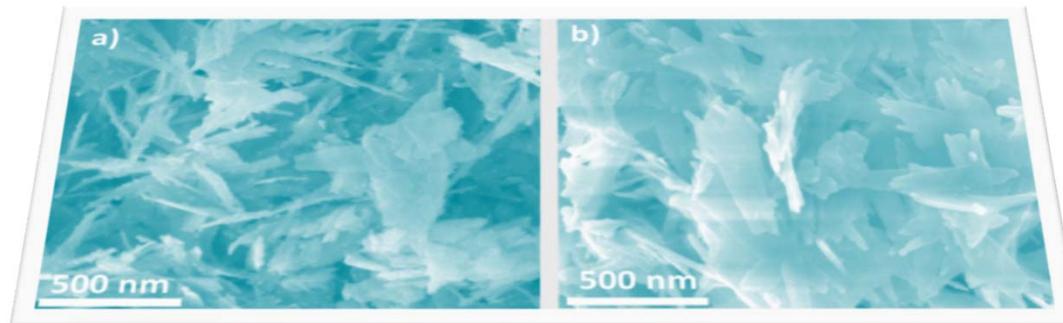


Cost of production of various chemicals via the waste-to-chemical concept

Chemical	Cost of production, €	Average product value, €
Urea, €/t	135	225
Methanol, €/t	150	325
Low density polypropylene, €/t	550	1000
H ₂ , €/Nm ³	0,07	0,12
CH ₄ , €/Nm ³	0,16	0,25

CO₂ as a waste resource

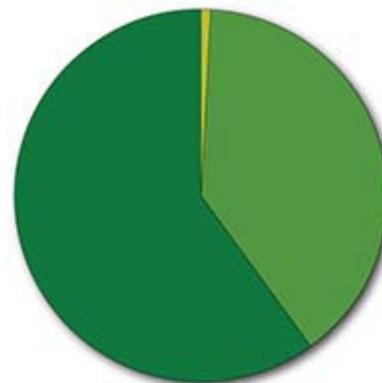
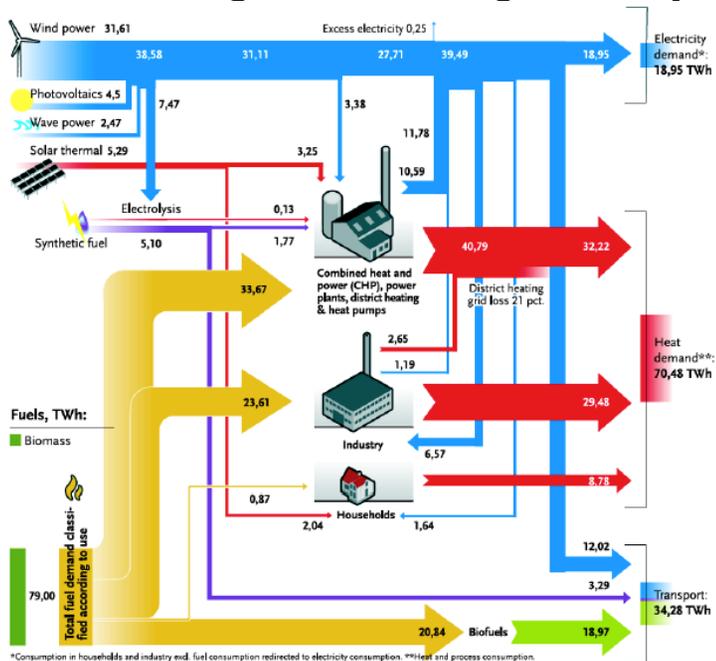
CO₂ to SNG (catalysis)



100% fossil-free Denmark

100% Renewable Power and Heat by 2035,
100% Renewable Energy in All Sectors by 2050

- Danish Energy Agency report: *Energy Scenarios for 2020, 2035 and 2050*
 - Different scenarios, but the most likely will be a mix of about 50% from wind and 50% of SNG from biogas
 - *Nov. 2017*: signed an agreement that 100% of the gas in the gas grid will be green by 2035.



Reduce GHG, increase productivity, store RE



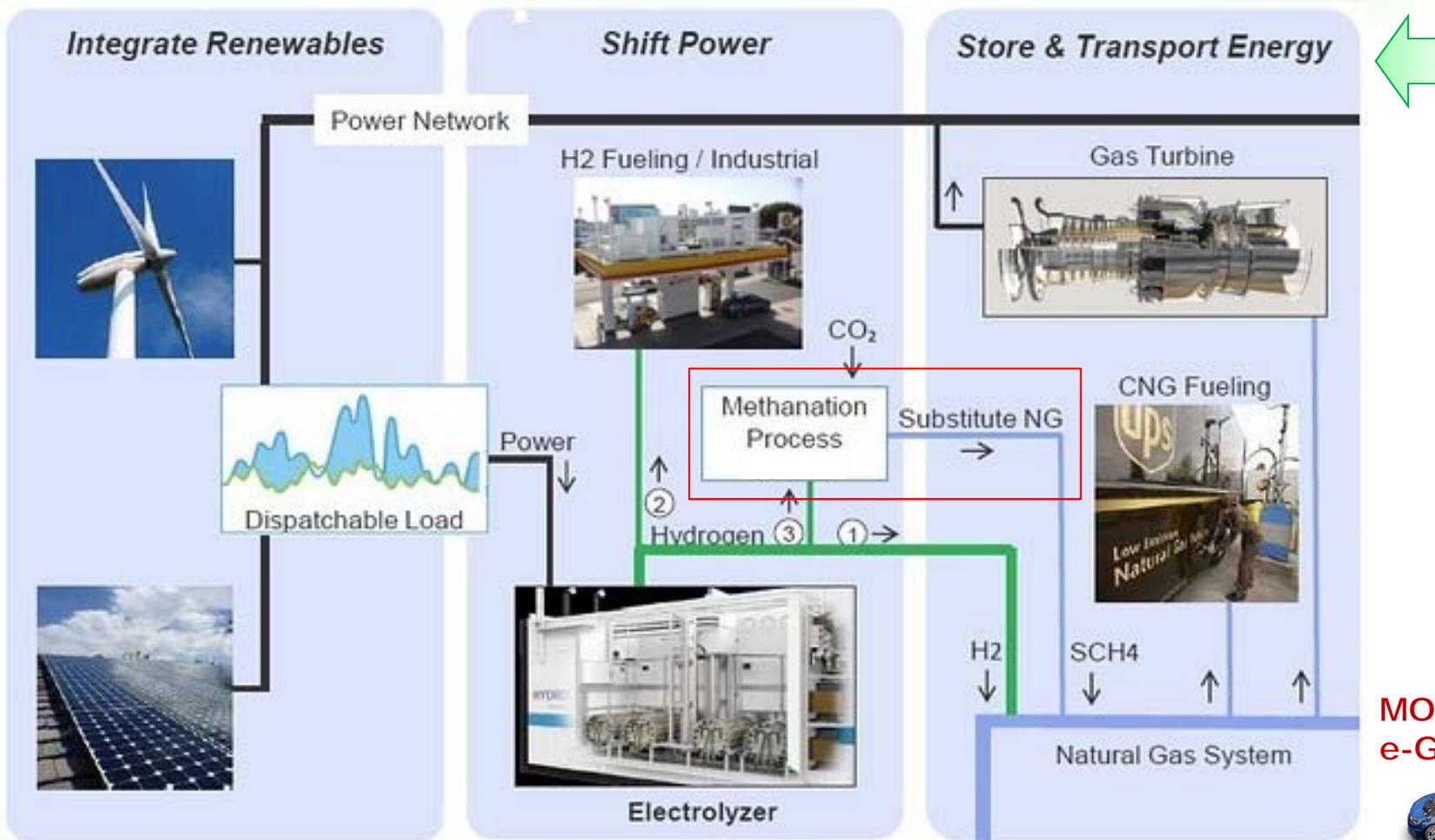


CO₂ (+H₂ *ren*) to SNG

CO₂ catalytic methanation

Local storage of excess ee (*grid stabiliz.*)

Power to gas technology (P2G)



MOBILITY
e-GAS (Audi)



High CO₂ gas fields offshore

- Exploitation of **high CO₂ – NG fields** is one of the new challenges for E&P companies worldwide
 - *High CO₂ content gas reservoirs make most of the gas field development uneconomical and it has remained undeveloped.*
- Methanation of CO₂ offers new possibilities to increase economics of these high CO₂ fields and at the same time to meet the increasing gas demand.

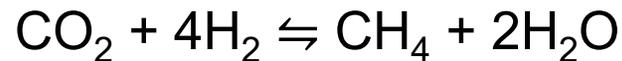




CO₂ catalytic methanation

THE SCIENTIFIC CHALLENGE

- The Sabatier reaction known from a century
- A reversible exothermic reaction



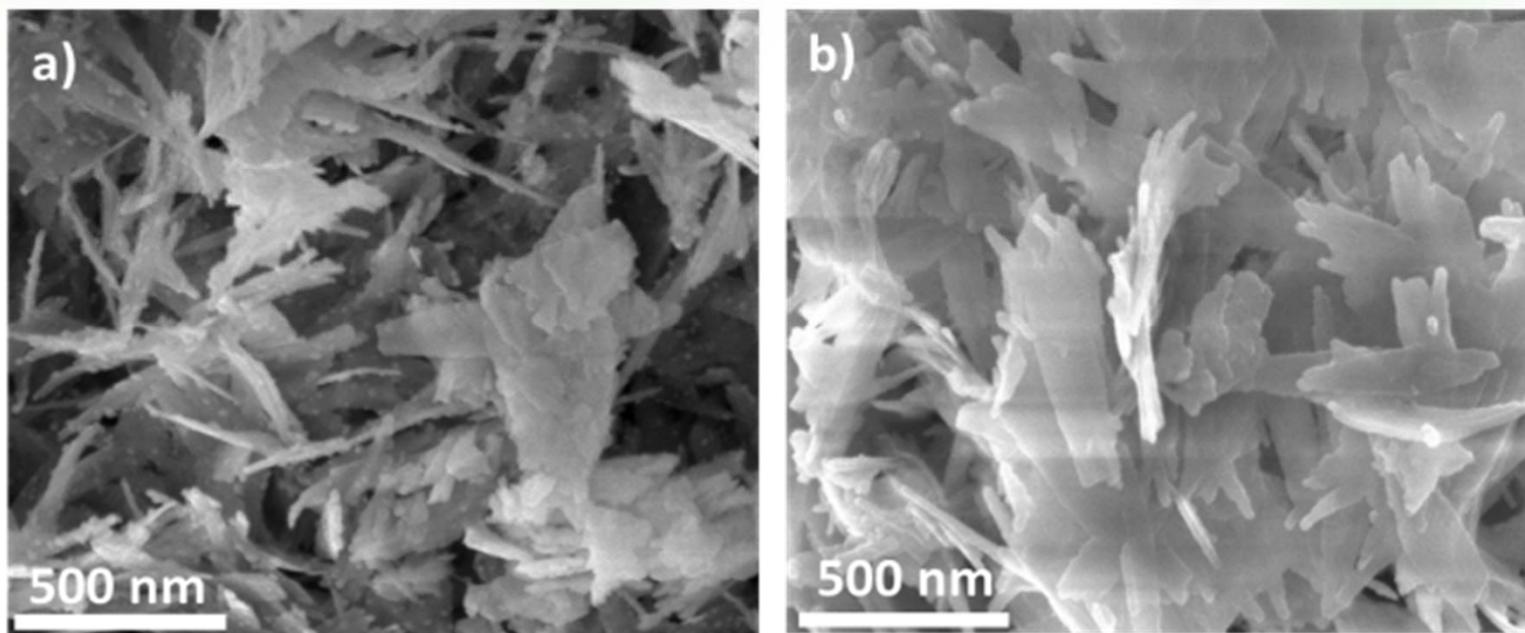
- **The scientific issue:**

- To meet in one-pass through reactor the **SNG specifications** (for grid injection) H₂ (residual) < 5%, CO₂ < 3%,), taking into account that it is a **reversible exothermic** reaction, it is necessary to operate at a maximum temperature (reactor outlet) of about 320°C
 - MOST of the literature data are at HIGHER temperatures
- These low-temperature of operation induce also problems of **long-term stability**, because due to high chemisorption of CO₂ & H₂O at these temperatures, *reconstruction* of the catalyst may occurs
- “Commercial” catalysts, derives from syngas methanation catalysts, contain **very high** (up to 70-80%) **amounts of Ni** (potential critical raw material, due to high economic importance)

Still need of improved catalysts

Ni-based nanosheet-type catalysts

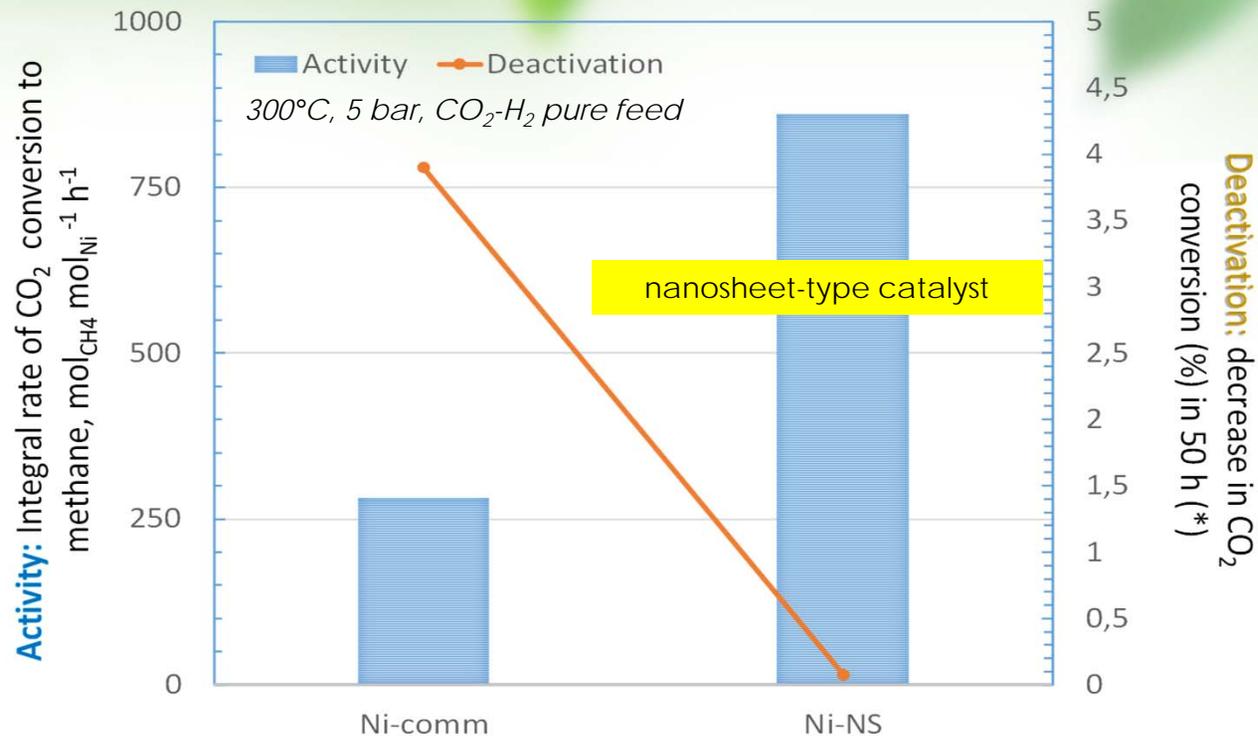
Ni nanoparticles (11-12 nm) on Fe-doped MgAlO_x nanosheets



SEM images of (a) 25%Ni- Al_2O_3 -NS and (b) 25%Ni-2.5%Fe- Al_2O_3 -NS.

nanosheet-type catalyst

CO₂ methanation catalysts: *stability at low temperature*



- *stabilization of small Ni nanoparticles on a highly accessible surface, associated to the nanosheet structure, leads to higher specific activity per Ni amount;*
- *enhanced stability associated to the fact that at these low temperatures, due to the water formed during methanation, Ni particles tend to form **Ni-hydroxide**, reducing thus availability of metallic Ni for the methanation reaction.*



How integrate RE in chemical production

- Plasma (@catalysis)
- Microwave
- Photocatalysis
- Electrocatalysis (and photo-electro catalysis)

All these technologies are particularly suited for small-size (distributed) devices, i.e. systems which can be used up to a regional or district level, and for a circular economy

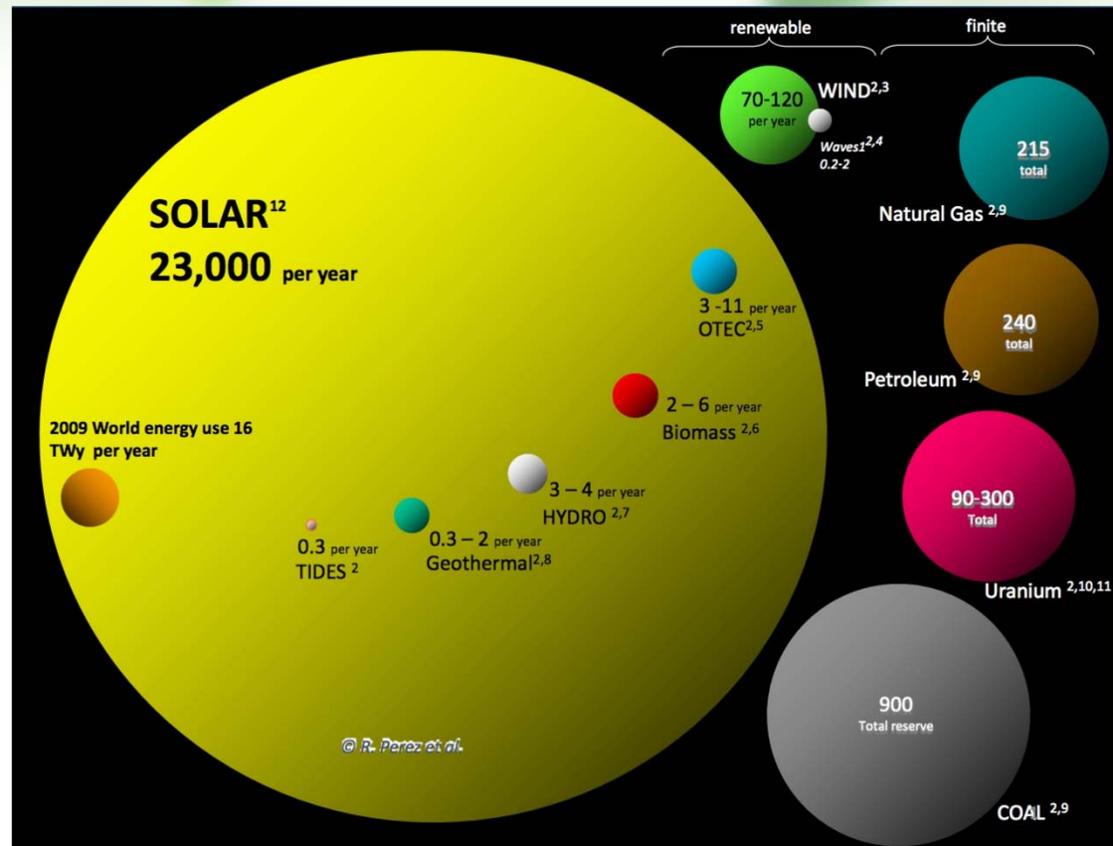
All above options are relevant to develop novel routes for a solar-driven chemistry, **electro-catalysis** is perhaps the **most advanced** presently for industrial implementations.

More advanced on crucial aspects such scalability to larger-size devices, which is actually the major limit of the other technologies.



Solar fuels and chemicals

Solar is the most abundant (and environmental clean) energy source



Solar fuels (& chemicals) represent the **bridging element** to connect solar (& related) energy to the products (and current infrastructure) at the basis of our life



Transformative chemistry and energy



- **Main impact on economy: *a sustainable model***

- *change the production model*: from fossil fuels as and energy-source to the use of *alternative C-sources* in strong **sybiosis** with the use of *renewable energy*

⇒ FOSTER INNOVATION:

- current production model (*low rate of new processes*), because based on the economy of scale → large plant sites (environ. & societal issues) → need of heat integration

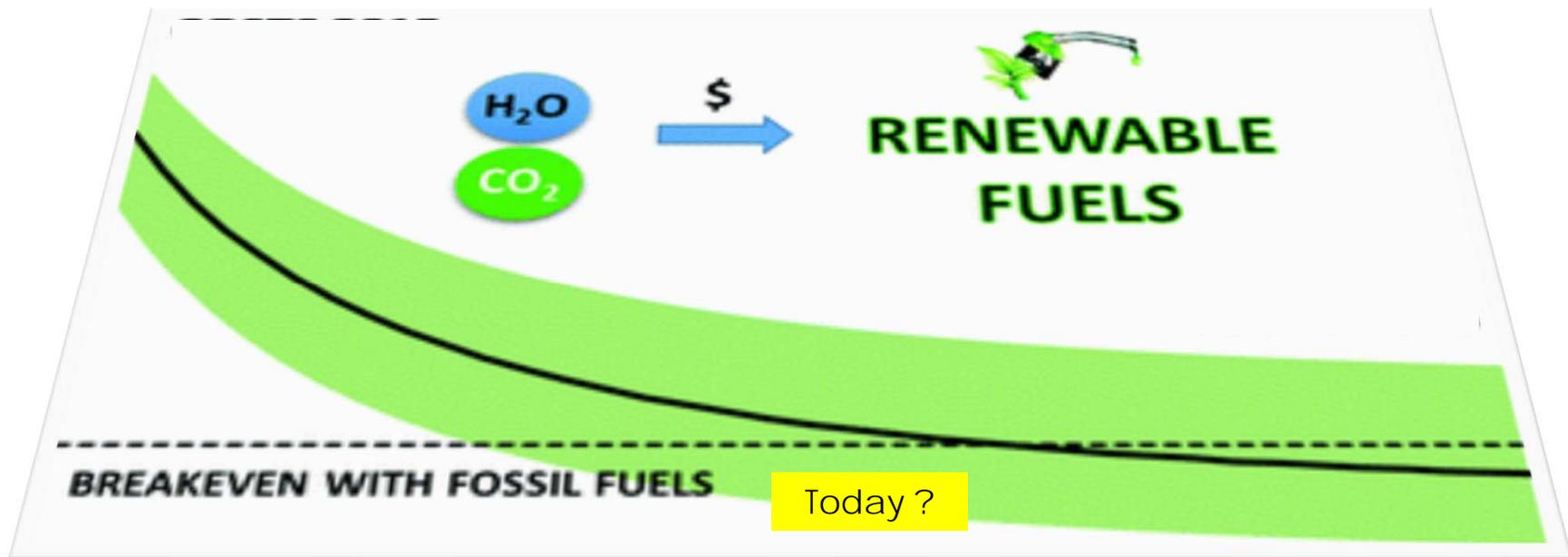
⇒ INDUSTRIAL IMPACT:

- to a **distributed** model, with easy scalable (parallelized approach), faster time to marked and high flexible processes
- a distributed model will favor new investors and create a positive impact on innovation → *new economic model*



Beyond fossil fuels

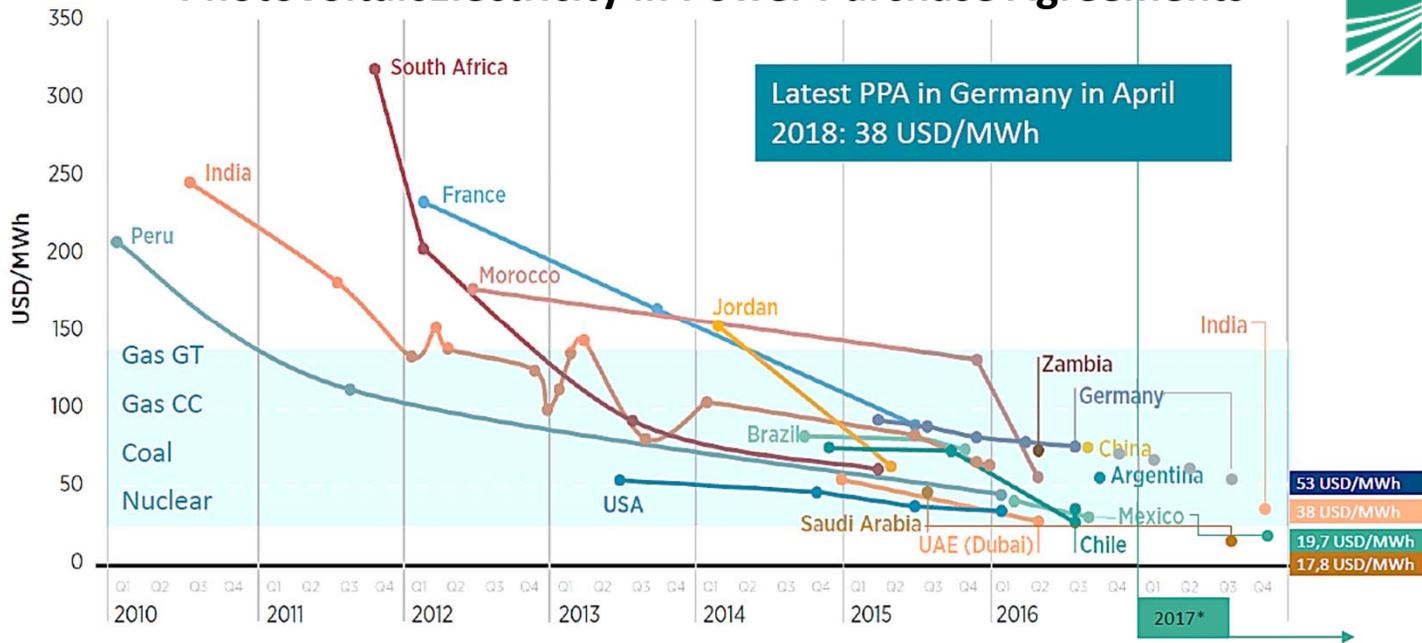
Solar Fuels and Chemicals



Economics evolve faster than predicted

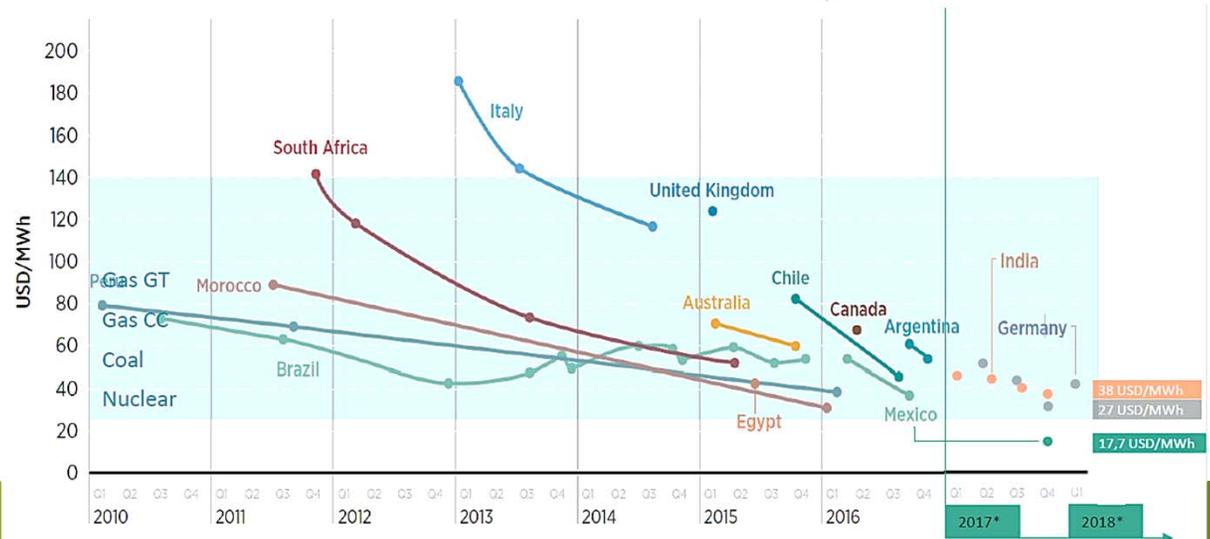
RE is becoming the more economic energy

Photovoltaic Electricity in Power Purchase Agreements



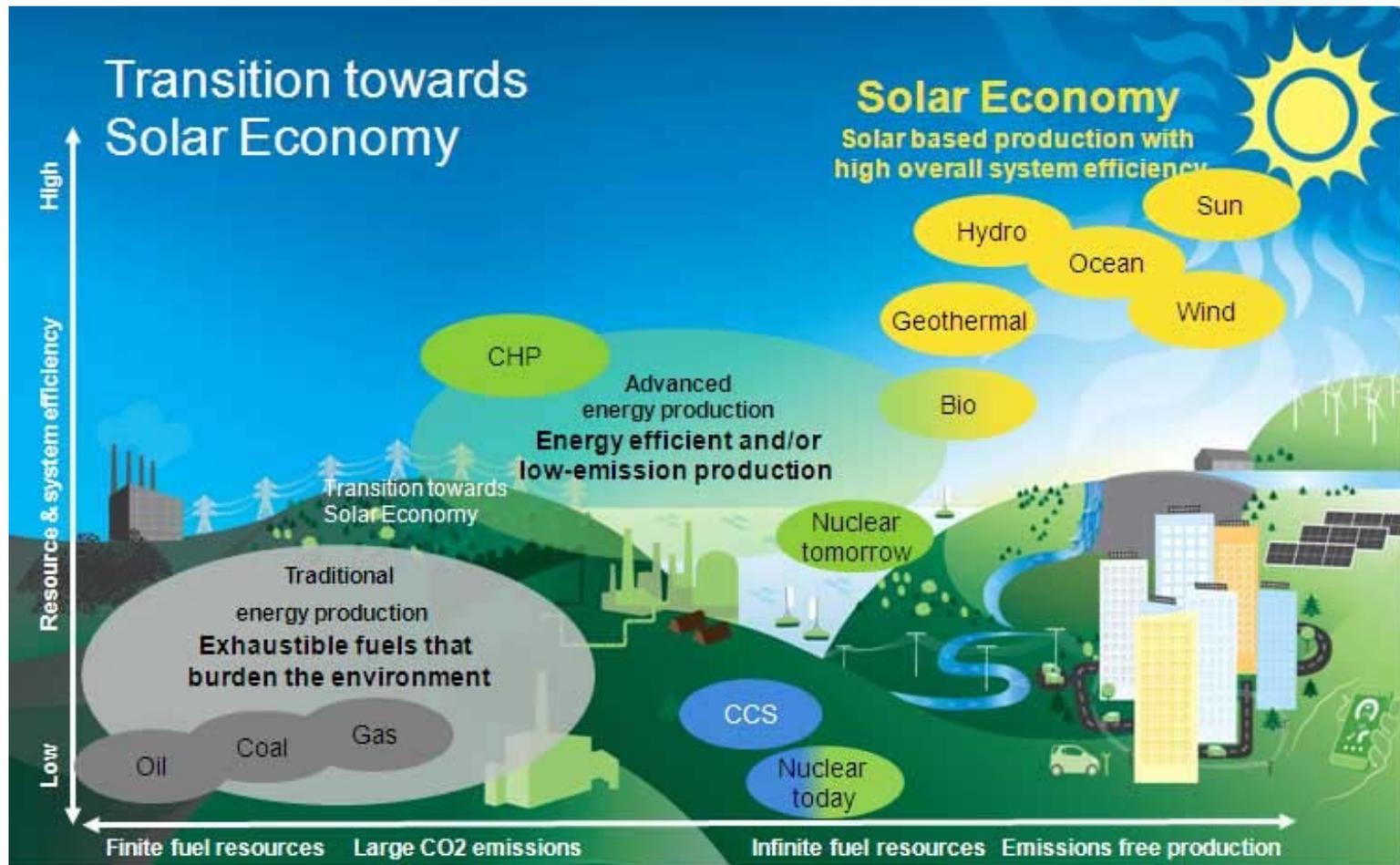
January 2010 –
December 2017

Onshore-Wind Electricity in Power Purchase Agreements



Solar fuels and chemicals

Bridging the transition to a new solar economy



Challenges and opportunities

for electrocatalysis

- Identify **disruptive** processes for the new solar-driven chemistry scenario
- Creating an **innovative** landscape
- Pushing development of **ground-breaking** catalysts and catalysis **concepts**
- Process **Intensification** by electrocatalysis
- Opening of **new value chains**
- **New reaction paths** for the electrocatalytic conversion
- The role of **surface confinement** in the electrocatalytic conversion

