DIFFER
Dutch Institute for
Fundamental Energy Research

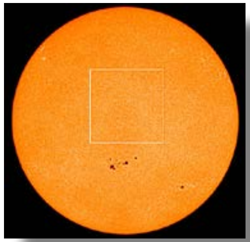
Solar PV 2050 Power Lab -1
Utrecht 17 maart 2014

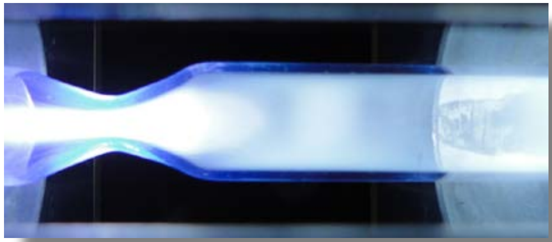
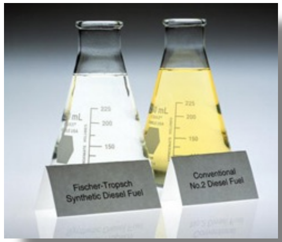
Energy storage in CO_2 neutral fuels:

a plasma perspective

Richard van de Sanden

Dutch Institute for Fundamental Energy Research &
Eindhoven University of Technology, Department of Applied Physics,
P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands



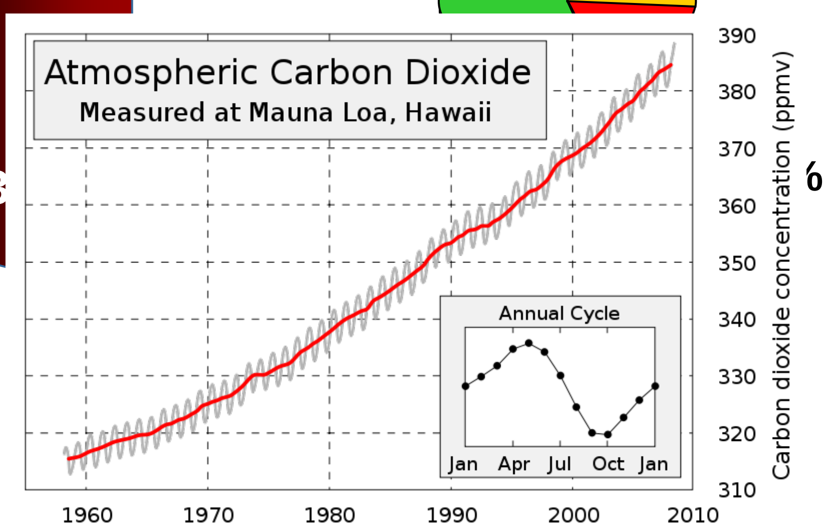




NWO FOM

Energy for the 21st century

- Increasing world population and higher standard of living
- In 2100: energy demand 4x higher
- **Strong increase of CO_2 levels**
- Small contribution renewable: >4%
- Strong increase sustainable necessary

hermal
0,11%

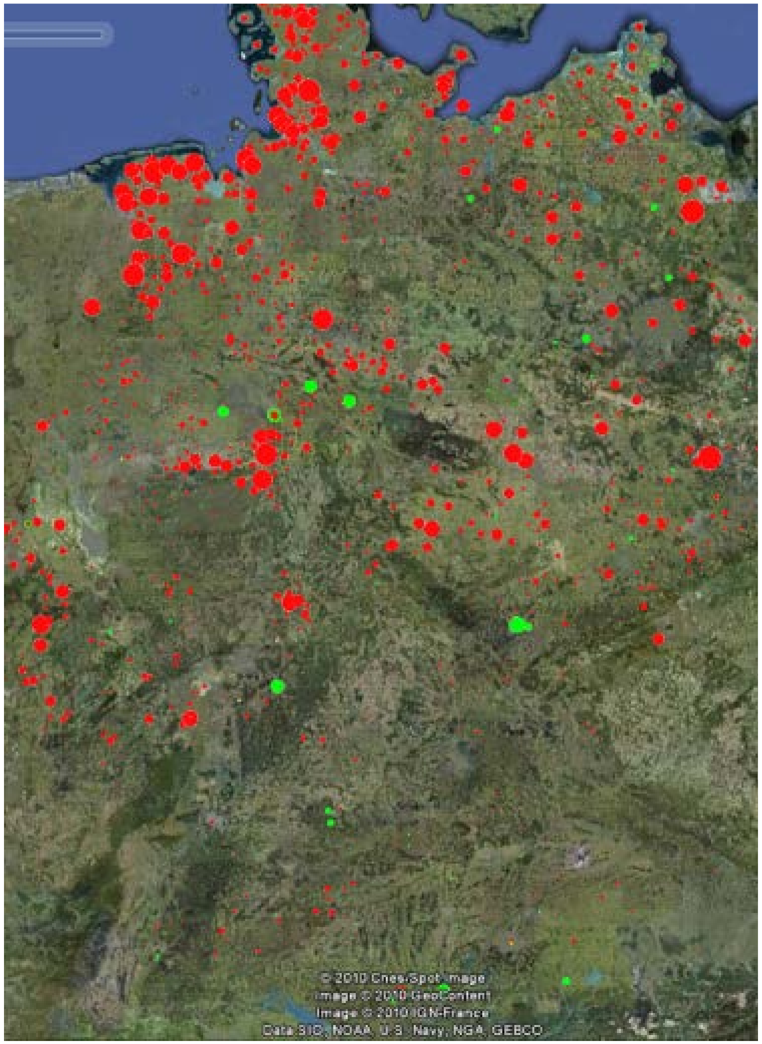


Urgency of a renewable energy infrastructure is climate change and CO_2 mitigation;

Not the availability of fossil fuels

IEA database 2008

Renewable energy in Germany



Total capacity of renewables
(End 2000)

~ 30,000 installations

Wind energy

PV

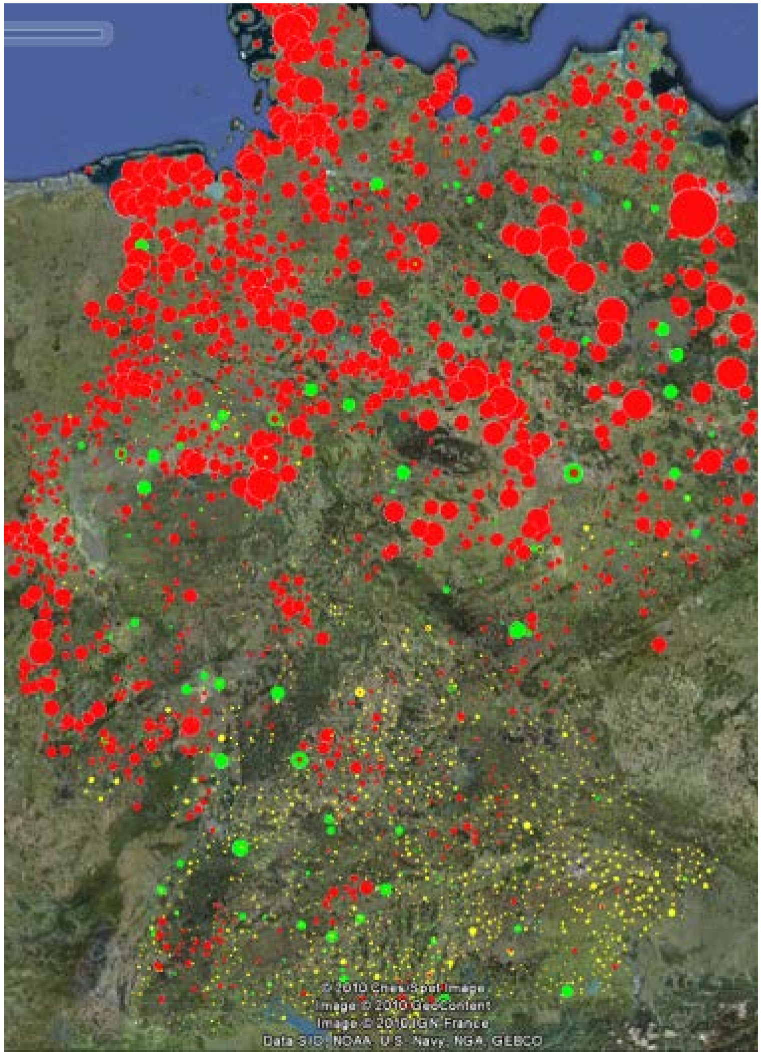
Biomass

The circle diameter is proportional to the electrical capacity

Sources: 50HertzT, TenneT, Amprion, TransnetBW, Elia group

Courtesy Daniel Dobbeni (Elia group)

Renewable energy in Germany



Total capacity of renewables
(End 2005)

~ 221,000 installations

Wind energy

PV

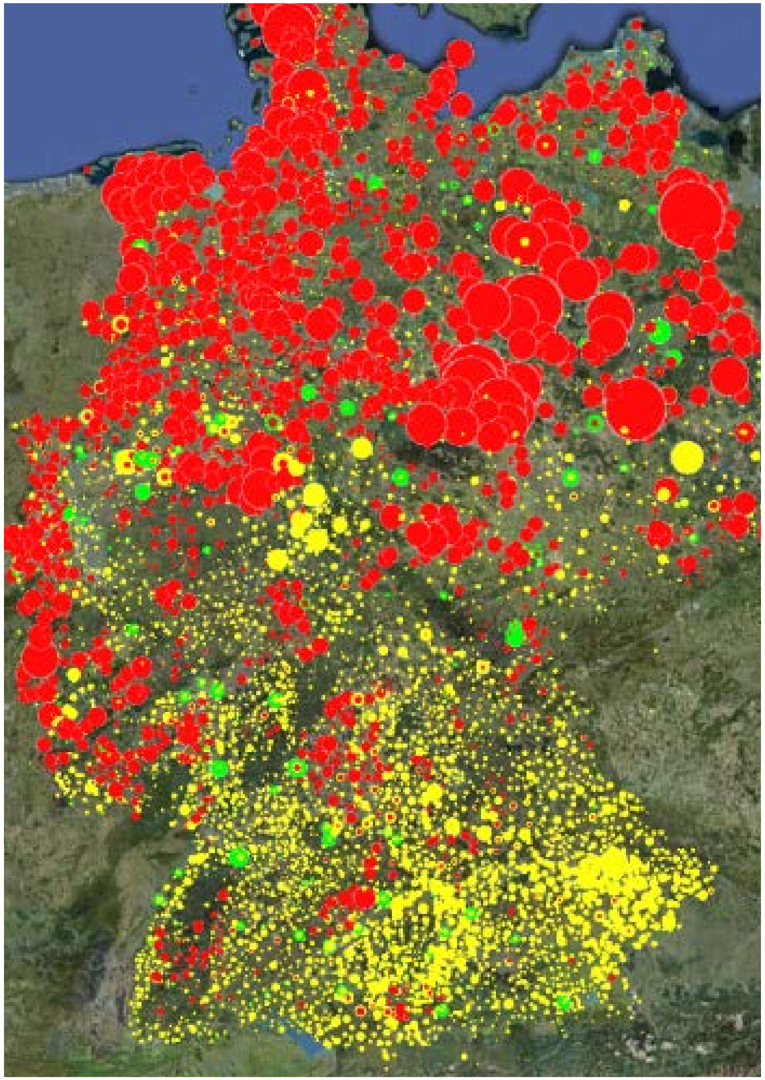
Biomass

The circle diameter is proportional to the electrical capacity

Sources: 50HertzT, TenneT, Amprion, TransnetBW, Elia group

Courtesy Daniel Dobbeni (Elia group)

Renewable energy in Germany



Total capacity of renewables
(End 2010)

~ 750,000 installations

Wind energy

PV

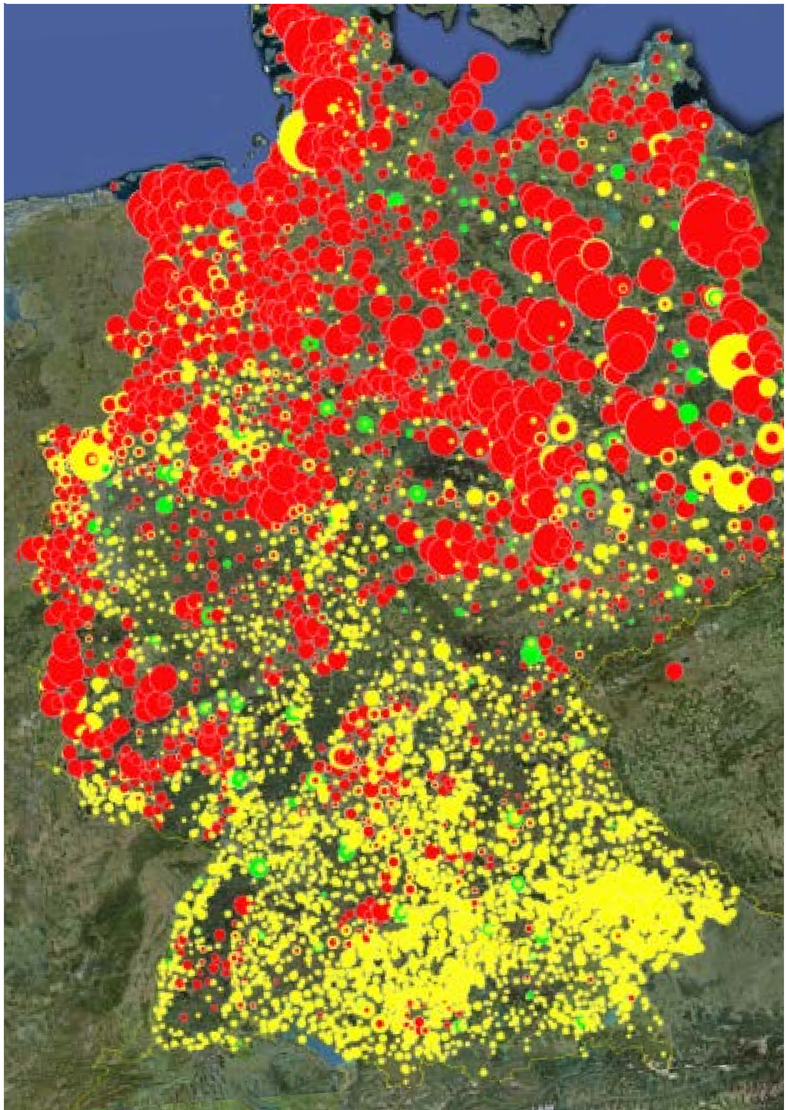
Biomass

The circle diameter is proportional to the electrical capacity

Sources: 50HertzT, TenneT, Amprion, TransnetBW, Elia group

Courtesy Daniel Dobbeni (Elia group)

Renewable energy in Germany



Total capacity of renewables
(End 2012)

~ 1,300,000 installations

Wind energy

PV

Biomass

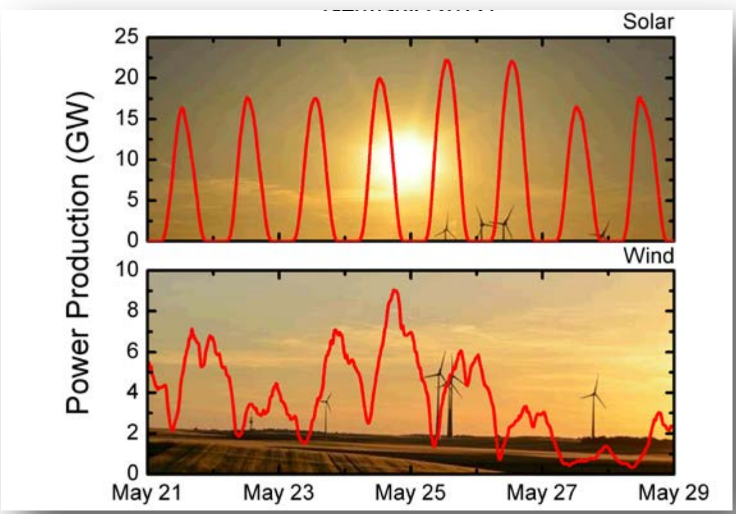
The circle diameter is proportional to the electrical capacity

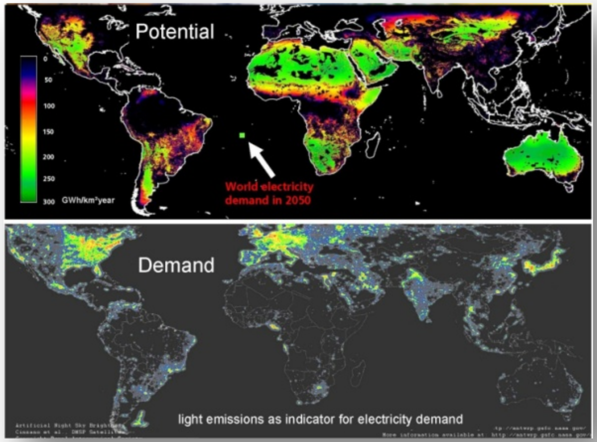
Sources: 50HertzT, TenneT, Amprion, TransnetBW, Elia group

Courtesy Daniel Dobbeni (Elia group)

However…….

German solar and wind energy





Sustainable power generation is booming but it is

inhomogeneous and intermittent

with time-scales ranging from minutes to months

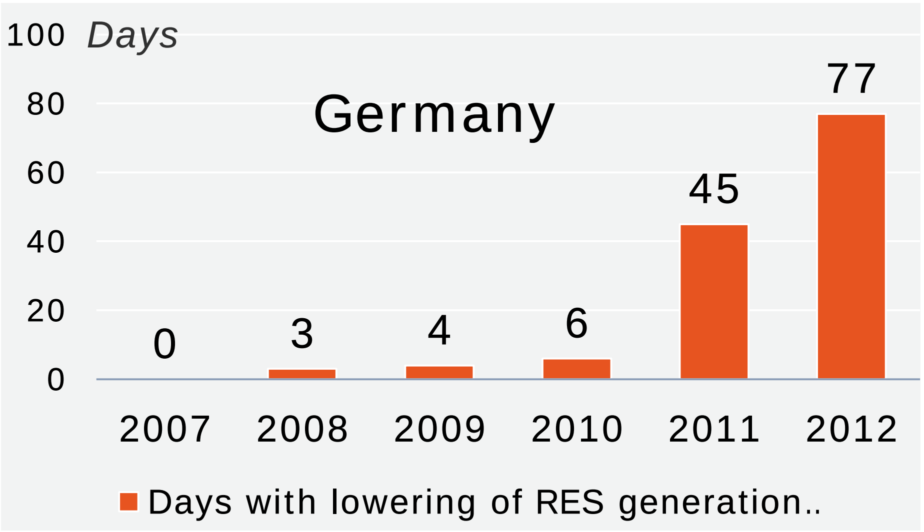
most renewables generate electricity

Transport fuels remain necessary

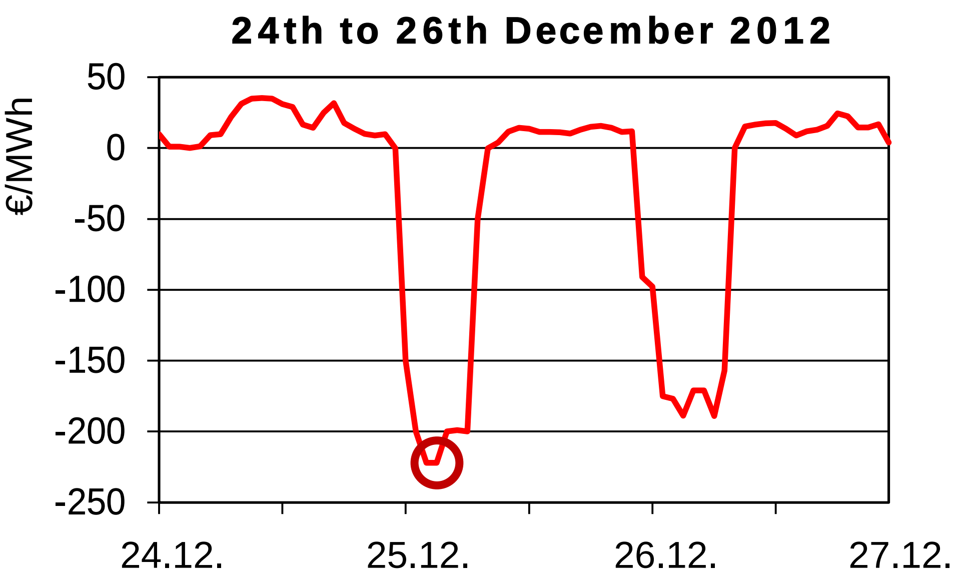
Mismatch between supply and demand

Lack of system approach

Large scale deployment of RES



Not only Germany: Spain lost 90 M€ due to wind power curtailment

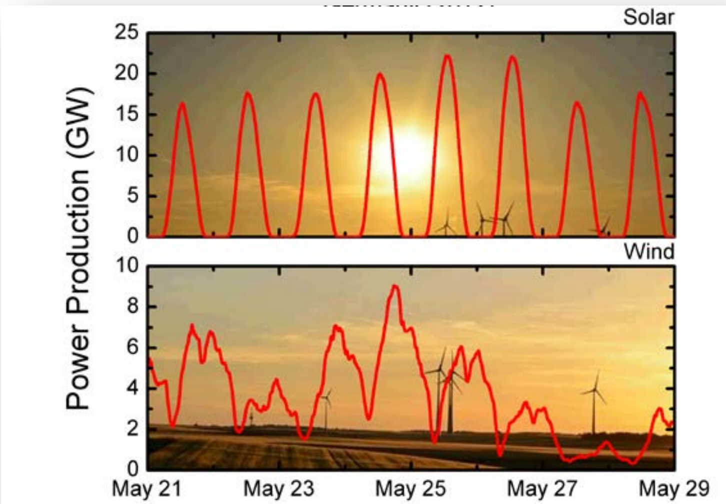


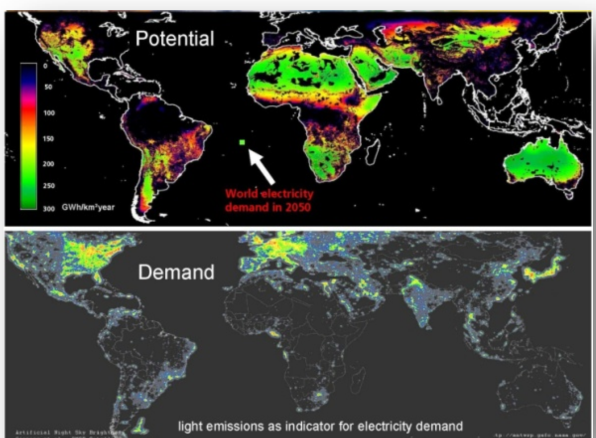
Min. market price: **- 221,99 € / MWh**

19 (out of 72) hrs with negative prices

However…….

German solar and wind energy





Sustainable power generation is booming but it is

inhomogeneous and intermittent

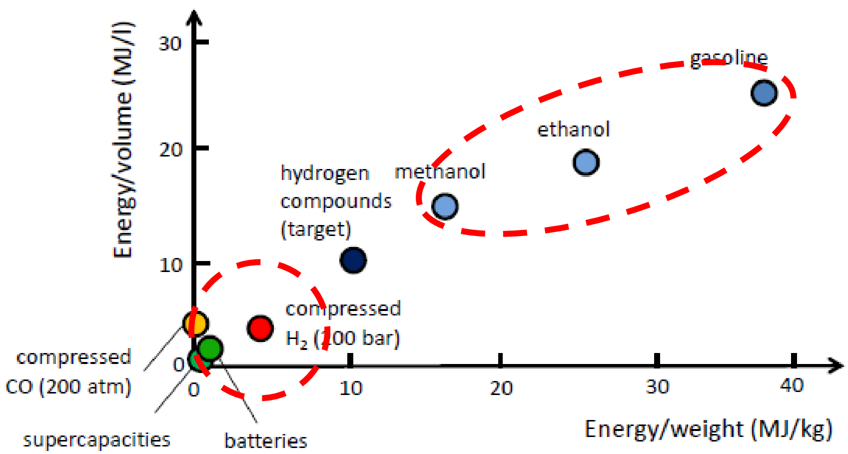
with time-scales ranging from minutes to months

most renewables generate electricity

Transport fuels remain necessary

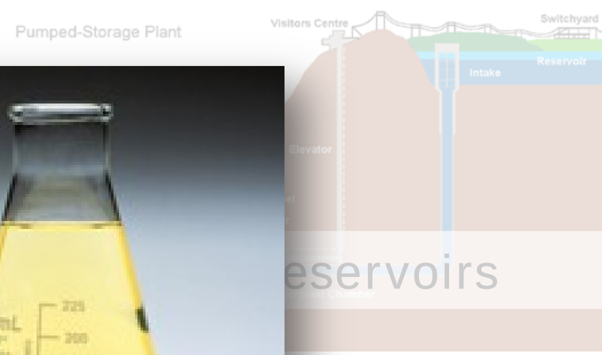
Solution:
Energy storage

RES infrastructure - storage needed

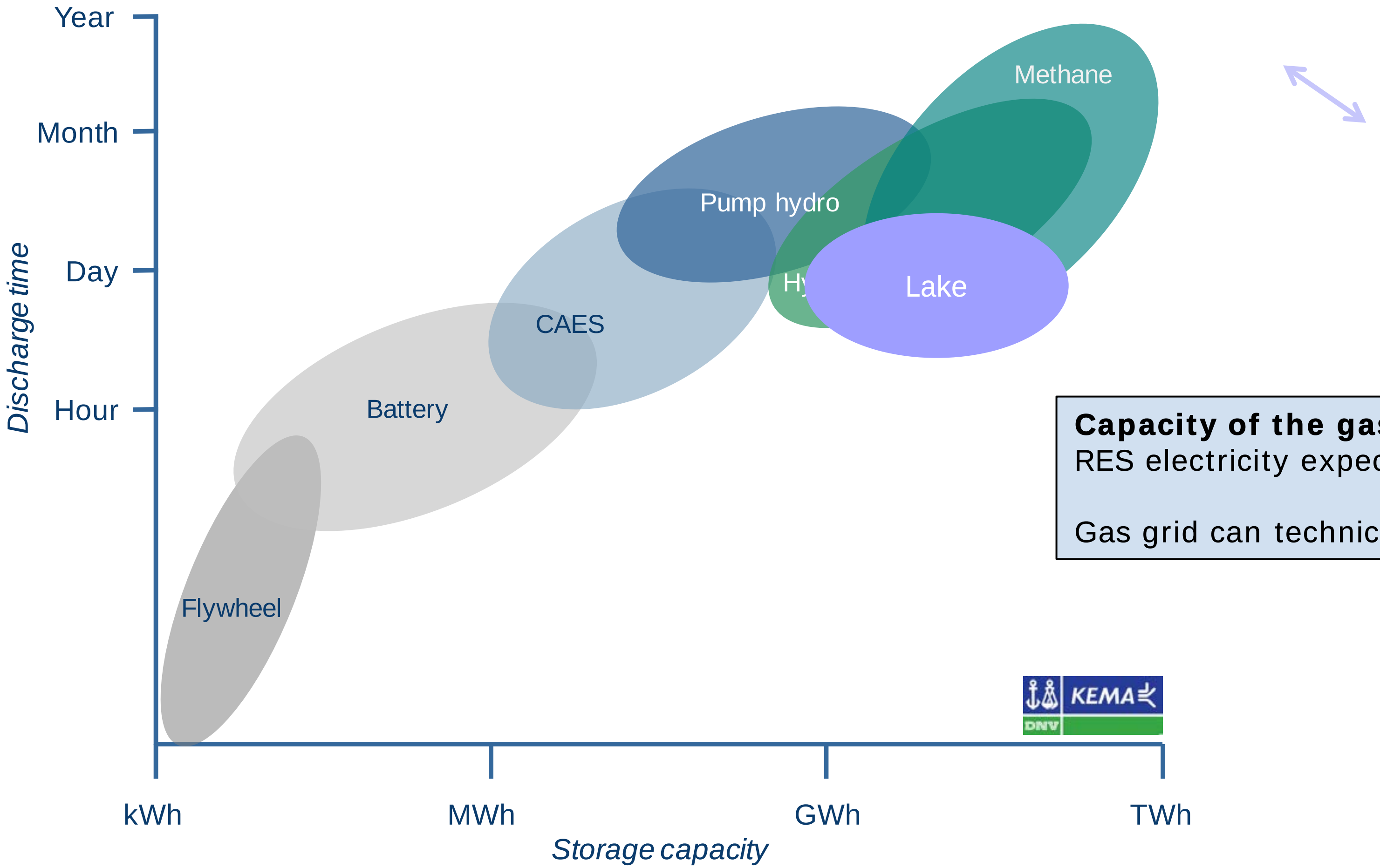


Storing energy:

- mechanical
- electrical
- electro-chemical
- chemical



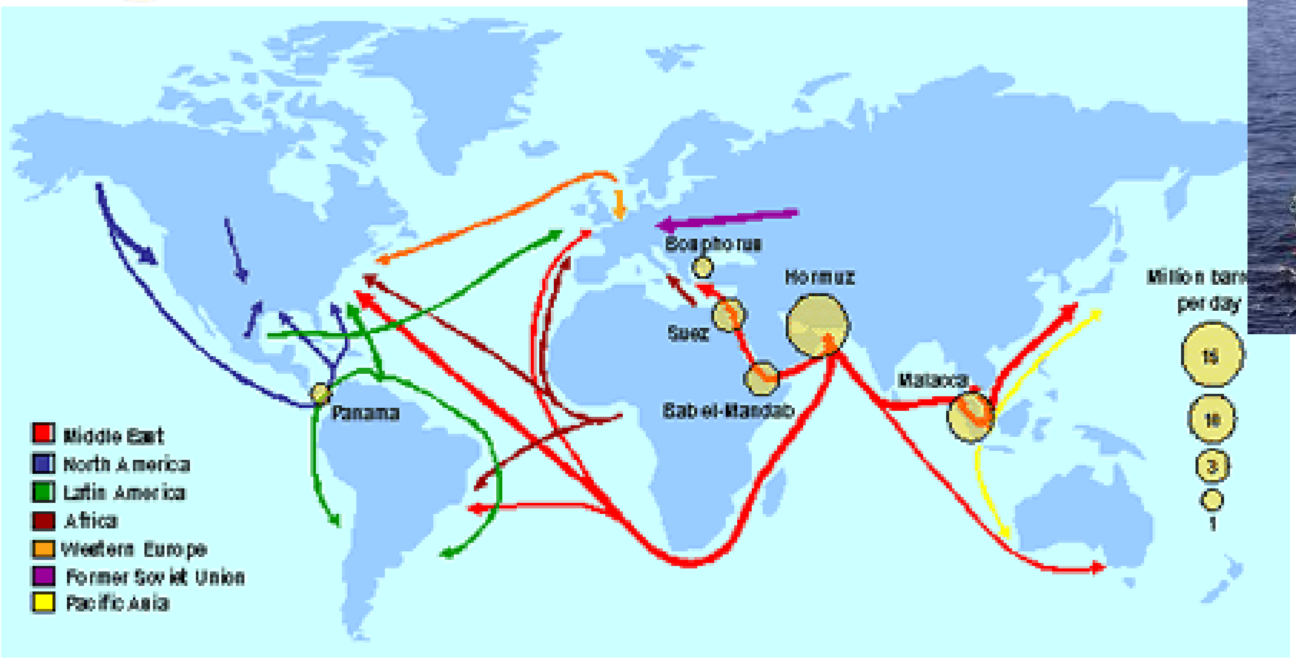
Options to store energy



Capacity of the gas grid
RES electricity expected: ca. 10TWh.

Gas grid can technically store 552 TWh

Storing and Transport of Energy



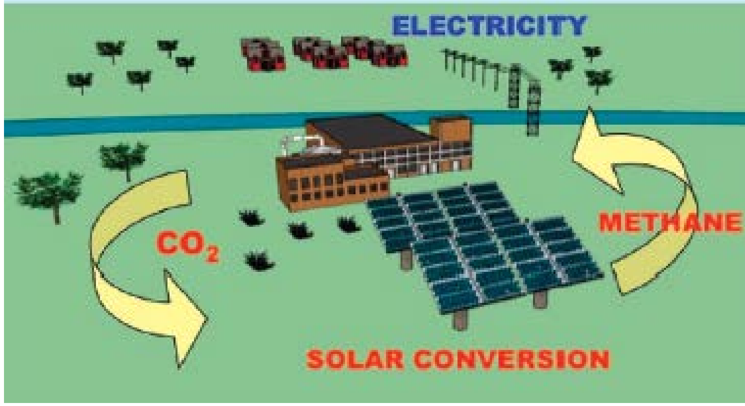
Presently: 85% of the global energy is transported by fuels*

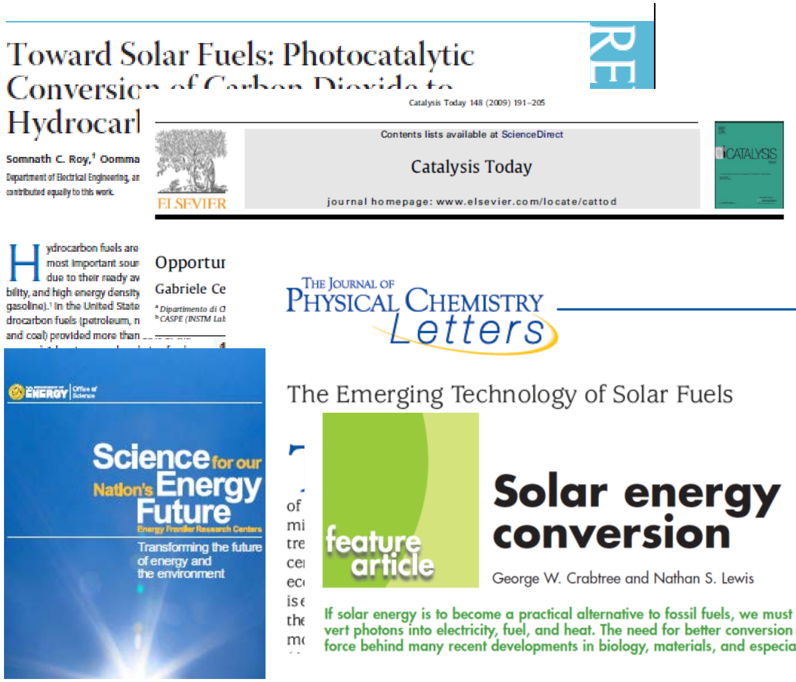
Global energy infrastructure is based up on transporting liquids

*Energy transport by gas is cheaper than by electricity per kWh (factor 2-20)

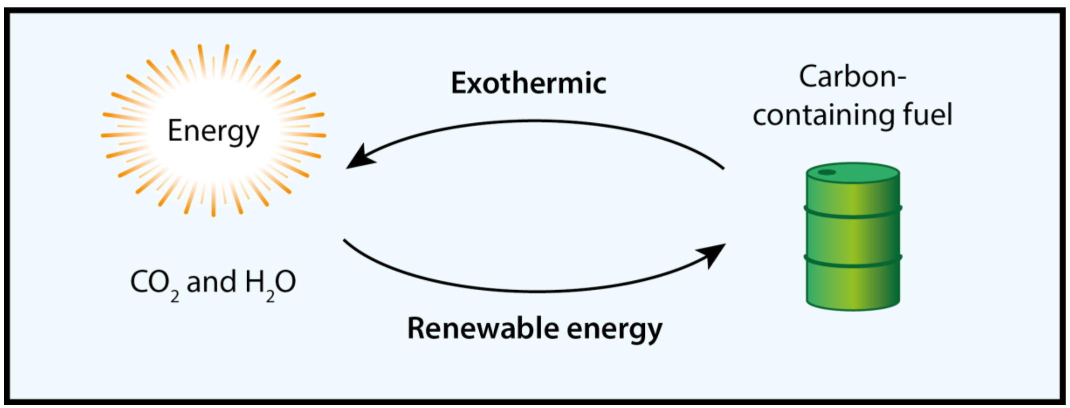
Vision: CO_2 neutral energy infrastructure

- Large potential to contribute to a CO_2 neutral energy infrastructure
- Storage and transport of sustainable energy in chemical bonds (hydrocarbons): solution close to present infrastructure; mobility and stationary
- Large efforts world wide on Solar Fuels:



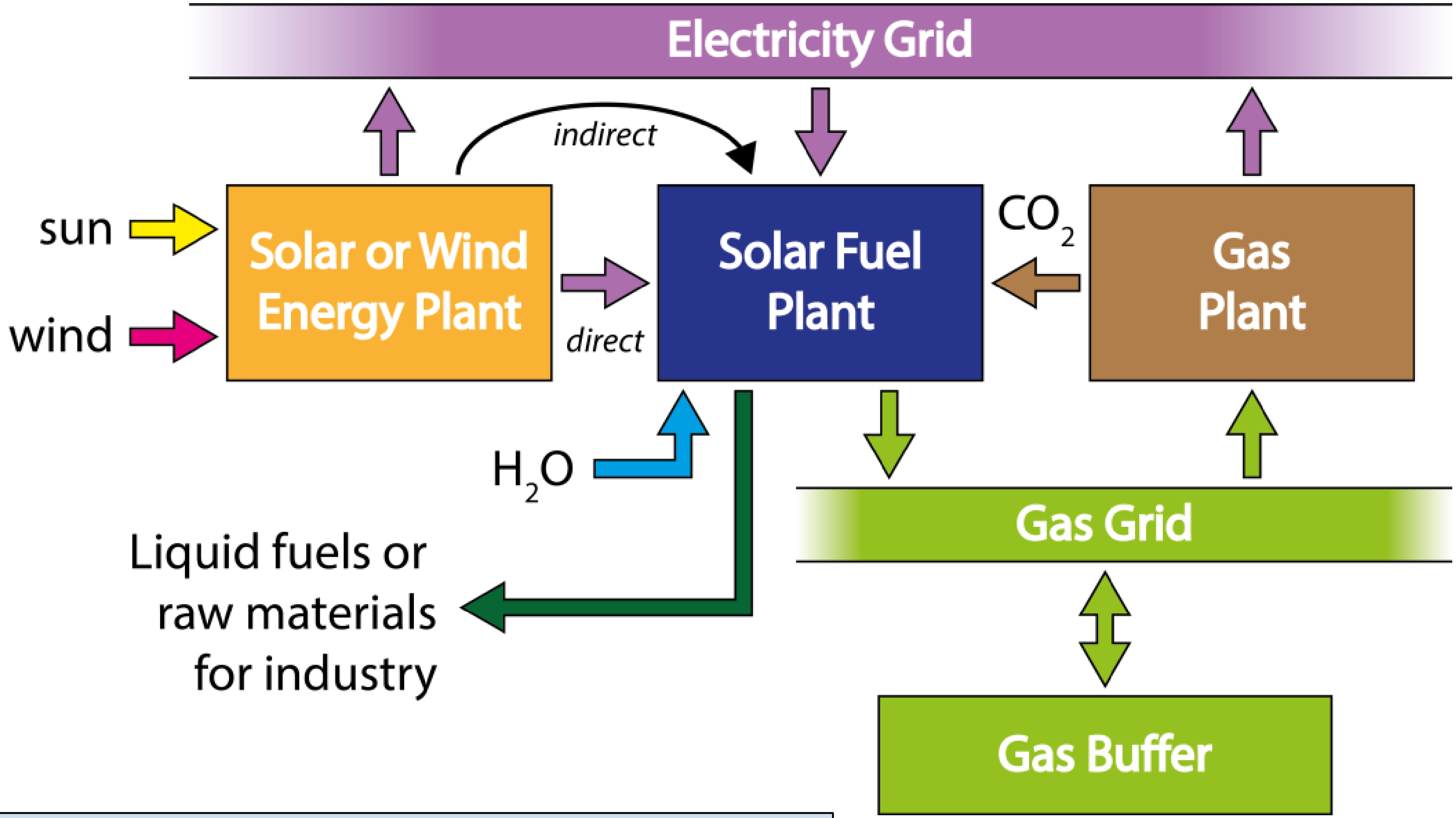


CO$_2$-neutral fuels



Pearson et al., Proc. IEEE **100**, 440 (2012)

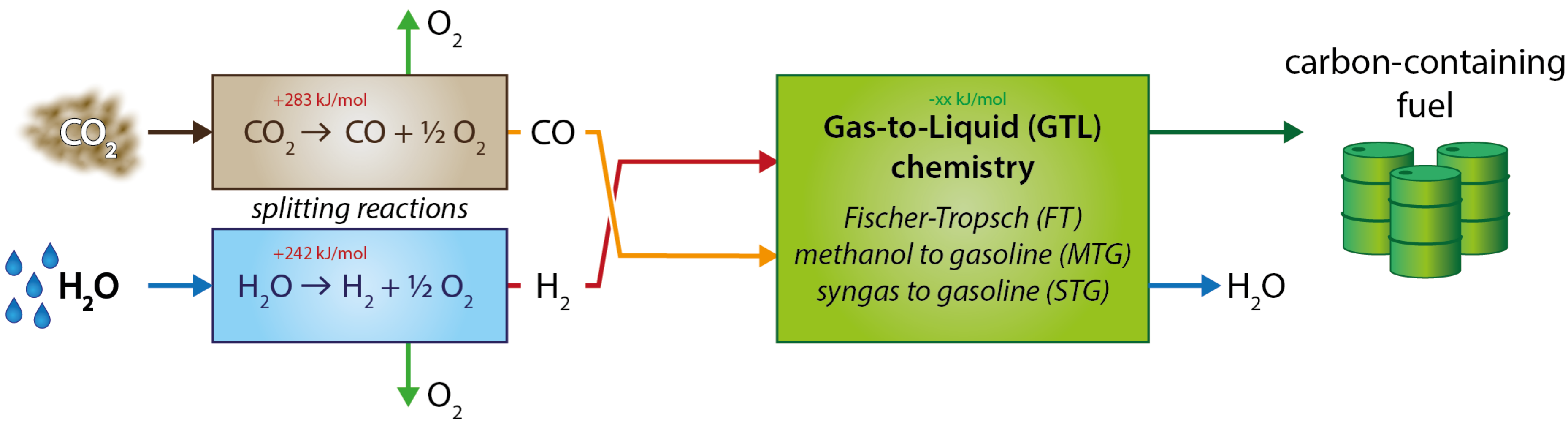
Vision: CO_2 neutral energy infrastructure



This vision includes CO_2 capture and re-use by means of direct air capture (DAC) or capture at point sources

Full chain of solar (=CO_2 neutral) fuels

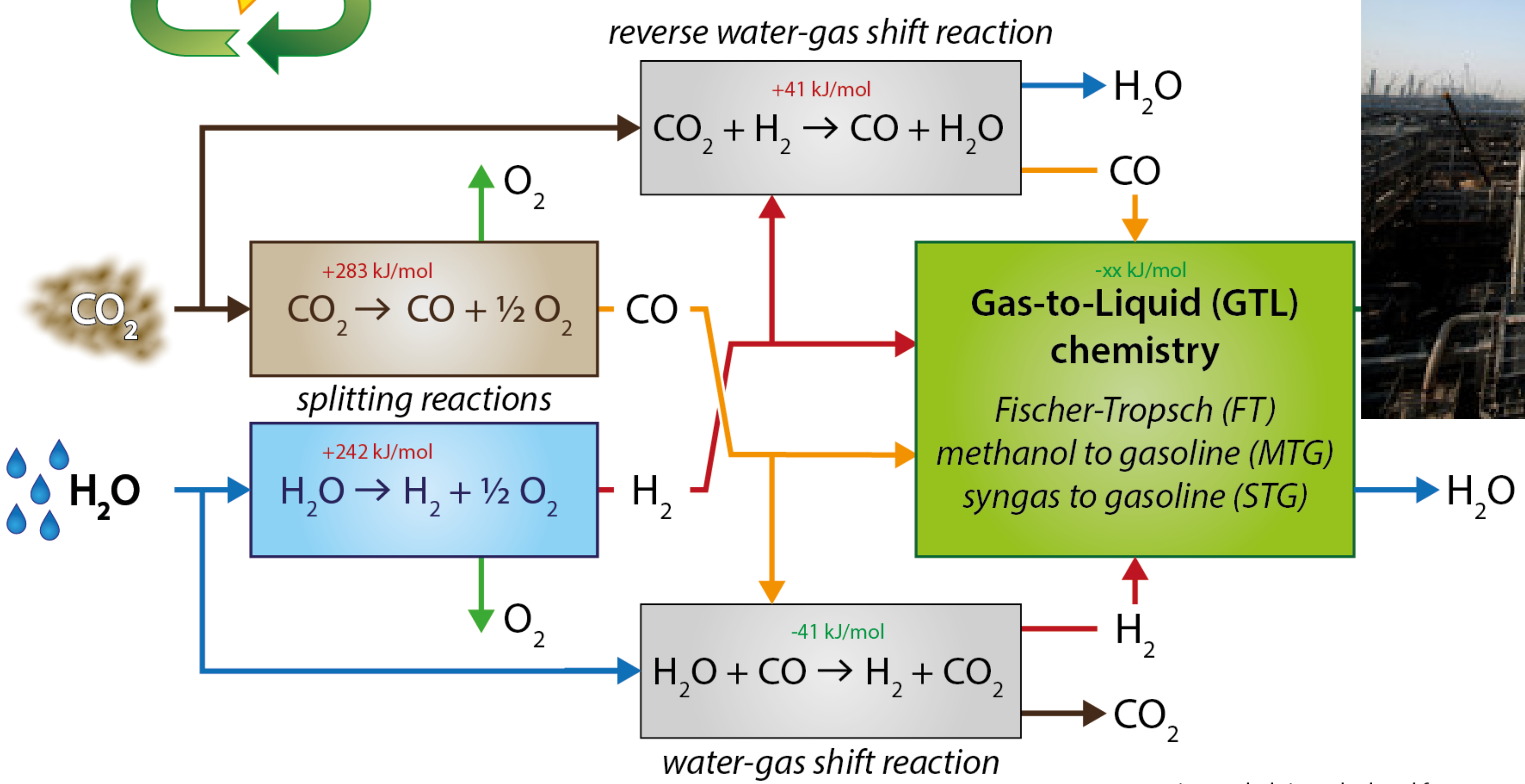
renewable energy



reaction enthalpies calculated for gaseous products at standard conditions

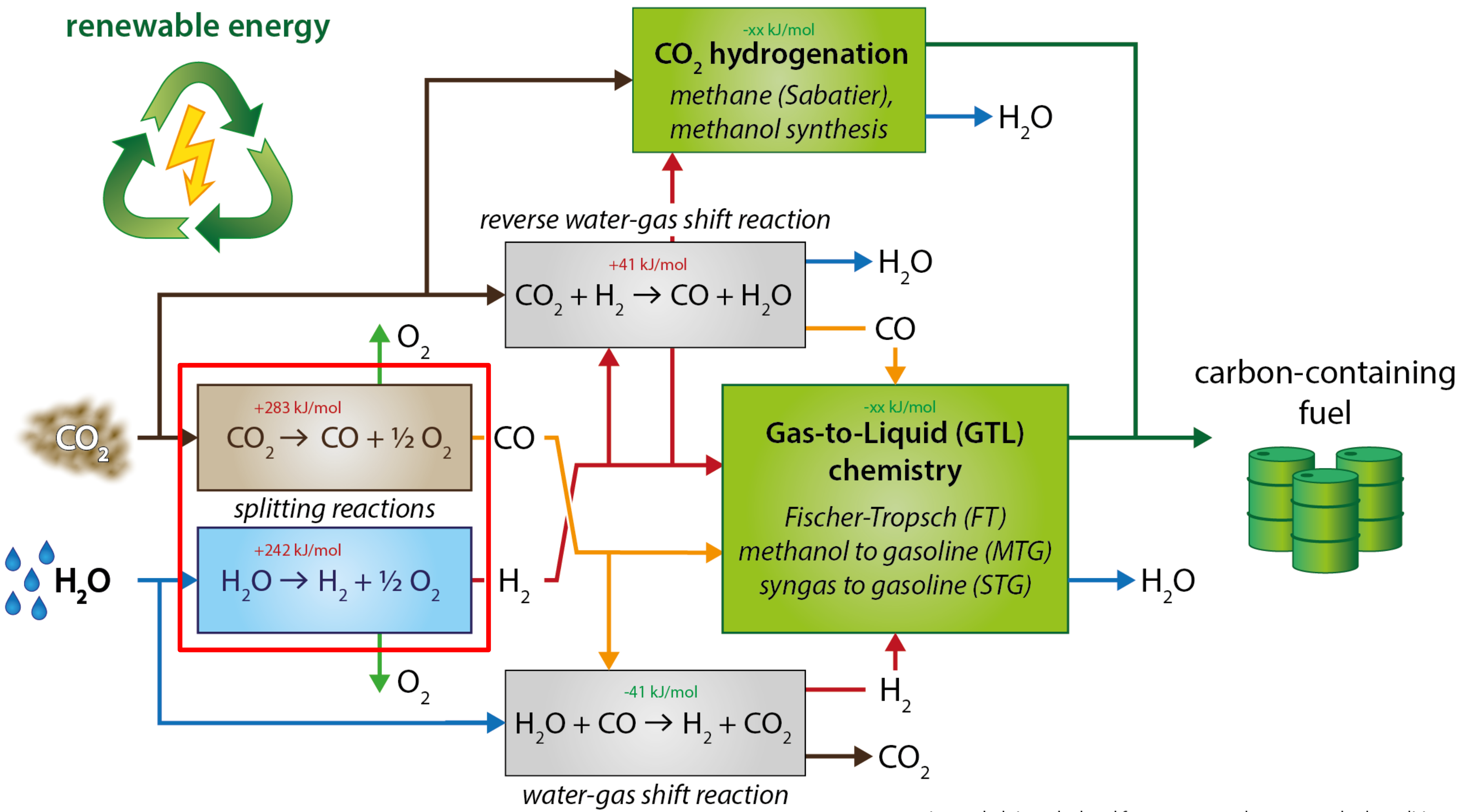
Full chain of solar (=CO_2 neutral) fuels

renewable energy



reaction enthalpies calculated for gaseous products at standard conditions

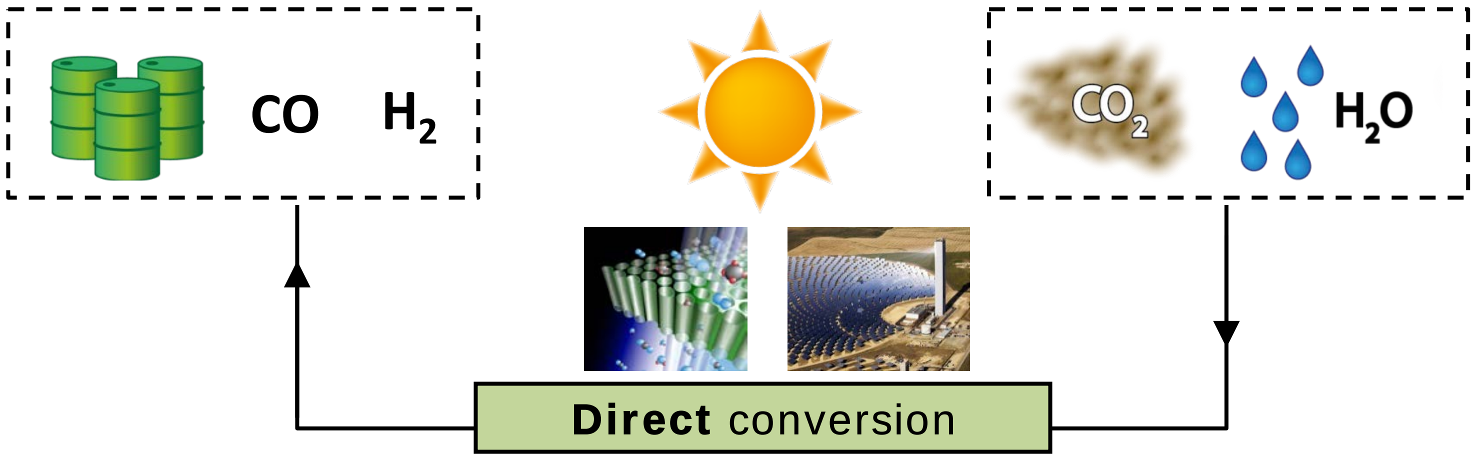
Full chain of solar (=CO_2 neutral) fuels



reaction enthalpies calculated for gaseous products at standard conditions

R&D mainly in energy and cost efficient splitting of CO_2 and H_2O

Concept of artificial chemical fuels



Photocatalytic: < 0.2-6 %

Solar thermal: 5–7 %

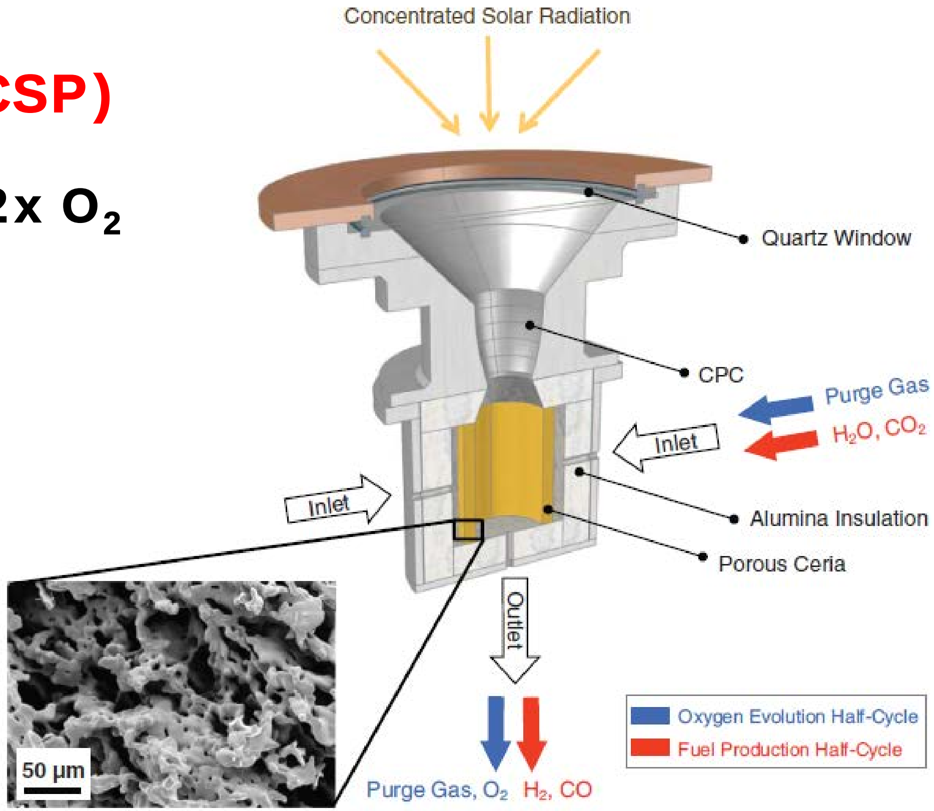
Thermochemical using CSP (direct)

Concentrated solar power (CSP)

CeO_2 + sunlight $\rightarrow$ CeO_{2-x} + 1/2x O_2

CO_2 + CeO_{2-x} $\rightarrow$ CO + CeO_2

Or based on ZnO, Fe_3O_4



Cyclic, solar to CO efficiency: 5-7 %

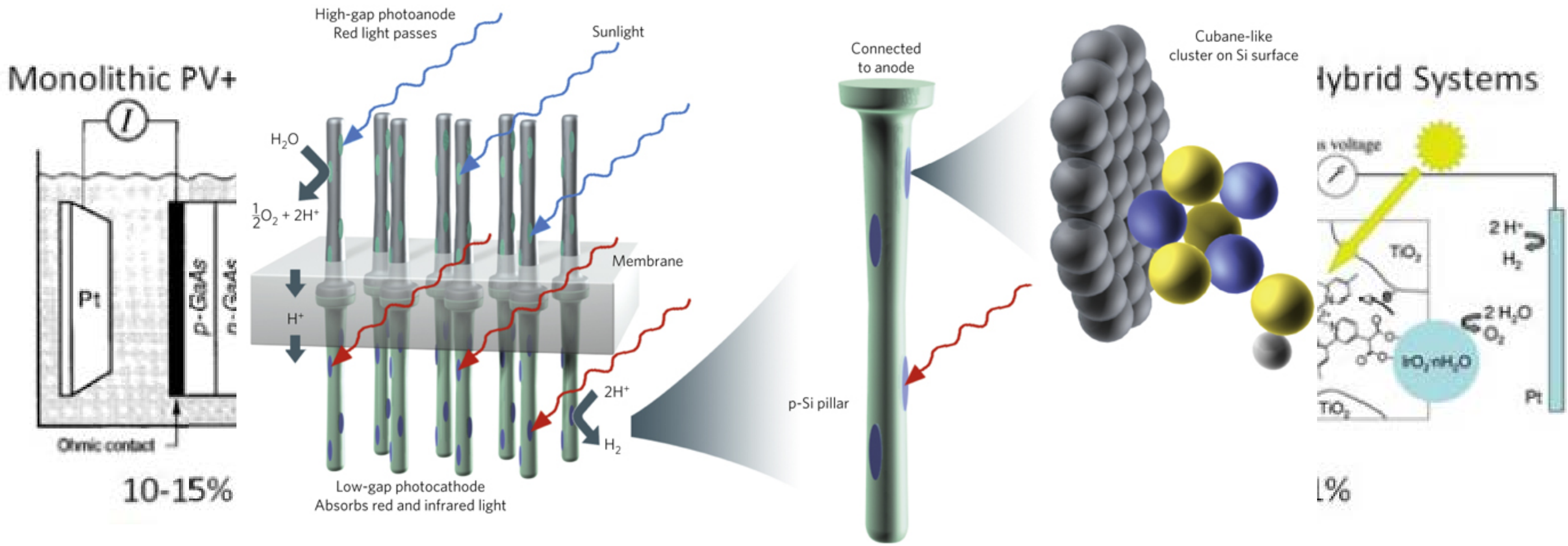
Nanostructuring of robuust materials + catalysis under harse conditions essential

Steinfeld group (ETH Zurich), Science **330** 1798 (2010)

Direct photocatalytic conversion of H_2O

The challenge

Which approach is most promising ?



Nano engineering/structuring of materials and catalysis essential

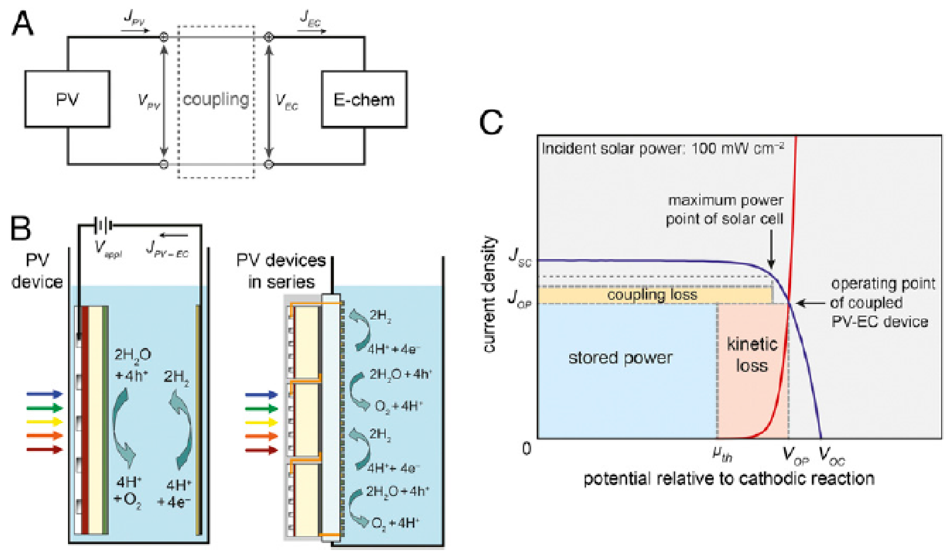
But also photon management: plasmonics, etc.

Lewis et al. DOE JCAP Collaboration

Direct photocatalytic conversion of H_2O

The challenge

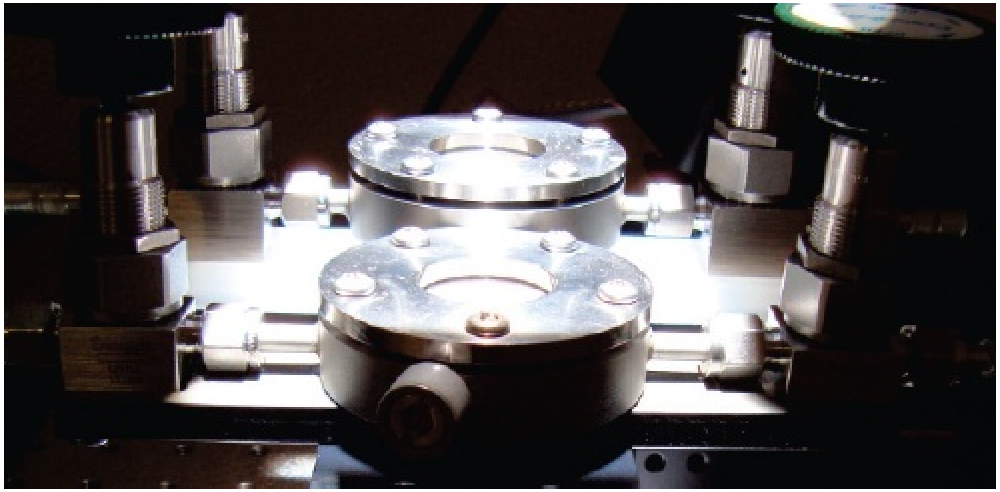
Which approach is most promising ?

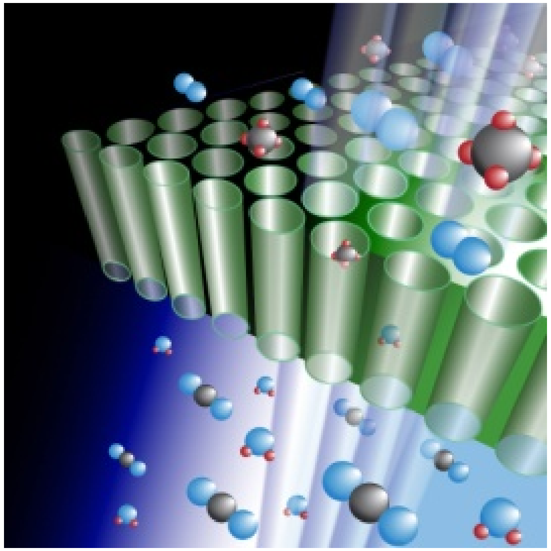


Basically a (tandem) solar cell with earth abundant catalyst

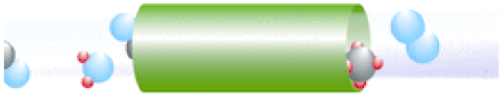
Nocera et al. Harvard University

What about the direct photocatalytic conversion of CO_2 ?





TiO tubes with Cu catalyst



The challenge

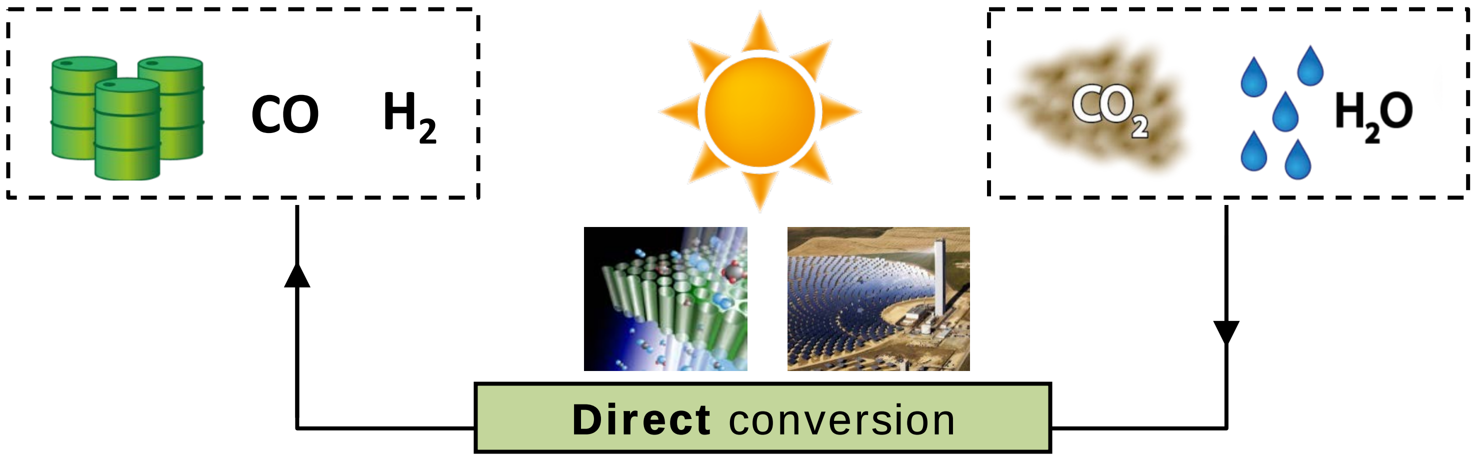
To tailor the catalyst to optimally use the solar spectrum for activating the catalyst

η = 0.0148 %

Nano engineering/structuring of abundant materials and discovery novel efficient catalysts essential (bio-inspired?)

Roy, Varghese, Paulose, Grimes, ACSNano **4**, 1260 (2010)

Concept of artificial chemical fuels



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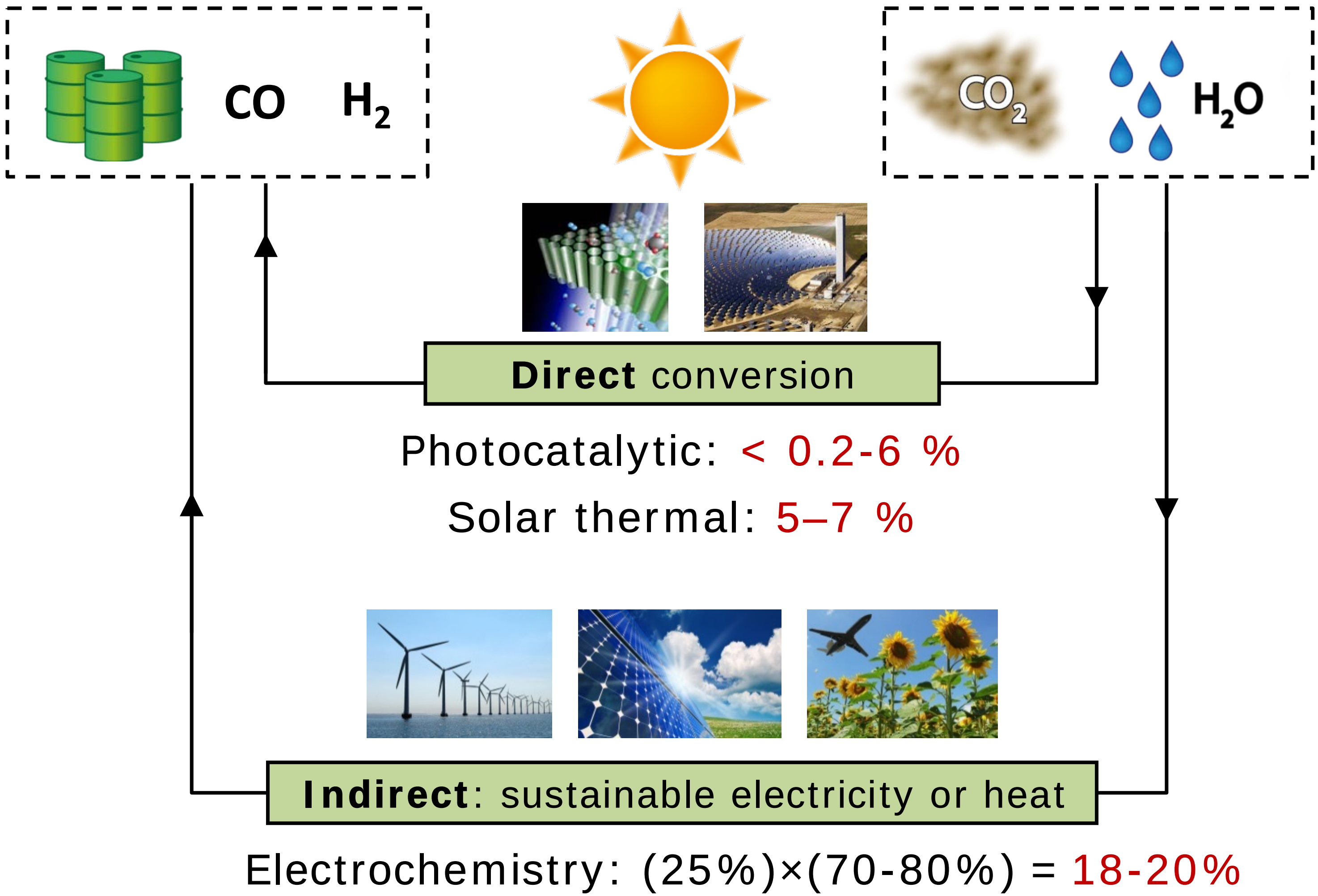
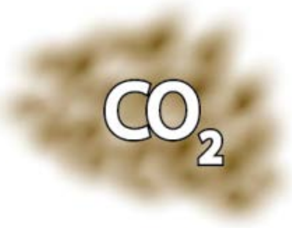
Concept of artificial chemical fuels



Benchmark for H_2 production

Steam reforming

+ Industrialized process: < 1 € / kg H_2
– Long term issue: **fossil fuel based**
– Prominent short term issue: **CO_2 footprint**
  - CO_2 emission price: 3-4 € / 1000 kg



steam reforming: $$CH_4 + H_2O \rightarrow CO + 3\,H_2$$

water-gas shift (WGS): $$CO + H_2O \rightarrow H_2 + CO_2$$

+

$$\boxed{CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2}$$

Intermezzo

H_2 production without CO_2 footprint

CO_2-neutral process (driven by sustainable energy)

→ **State-of-the-art water electrolysis**

$$2\,H_2O \rightarrow 2H_2 + O_2$$

6-10 € / kg H_2

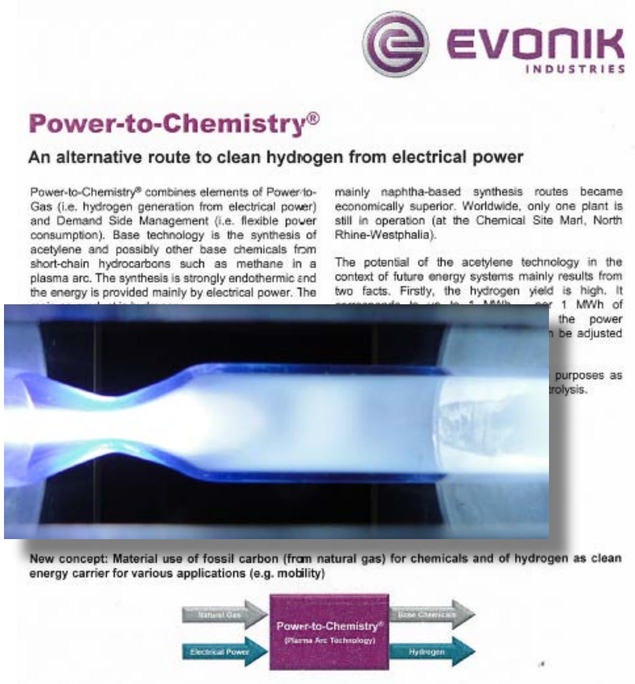
→ **Control chemistry: no CO_2 production** (Hüls arc process)

$$2\,CH_4 \rightarrow C_2H_2 + 3H_2$$

→ **CO activation and WGS**

$$\boxed{CO + H_2O \rightarrow H_2 + CO_2}$$

CO_2 activation



EVONIK INDUSTRIES

Power-to-Chemistry®

An alternative route to clean hydrogen from electrical power

Power-to-Chemistry® combines elements of Power-to-Gas (i.e. hydrogen generation from electrical power) and Demand Side Management (i.e. flexible power consumption). Base technology is the synthesis of acetylene and possibly other base chemicals from short-chain hydrocarbons such as methane in a plasma arc. The synthesis is strongly endothermic and the energy is provided mainly by electrical power. The

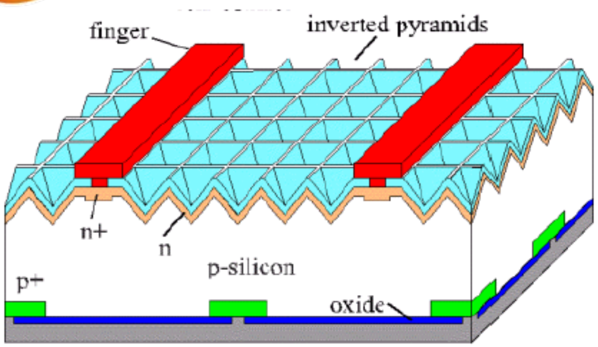
mainly naphtha-based synthesis routes became economically superior. Worldwide, only one plant is still in operation (at the Chemical Site Marl, North Rhine-Westphalia).

The potential of the acetylene technology in the context of future energy systems mainly results from two facts. Firstly, the hydrogen yield is high. It ... per 1 MWh of ... the power ... be adjusted ... purposes as ... trolysis.

New concept: Material use of fossil carbon (from natural gas) for chemicals and of hydrogen as clean energy carrier for various applications (e.g. mobility)

Intermezzo

Watersplitting using PV & electrolyser



Efficiency >> 20 %

> 6 € / kg*

sustainable energy

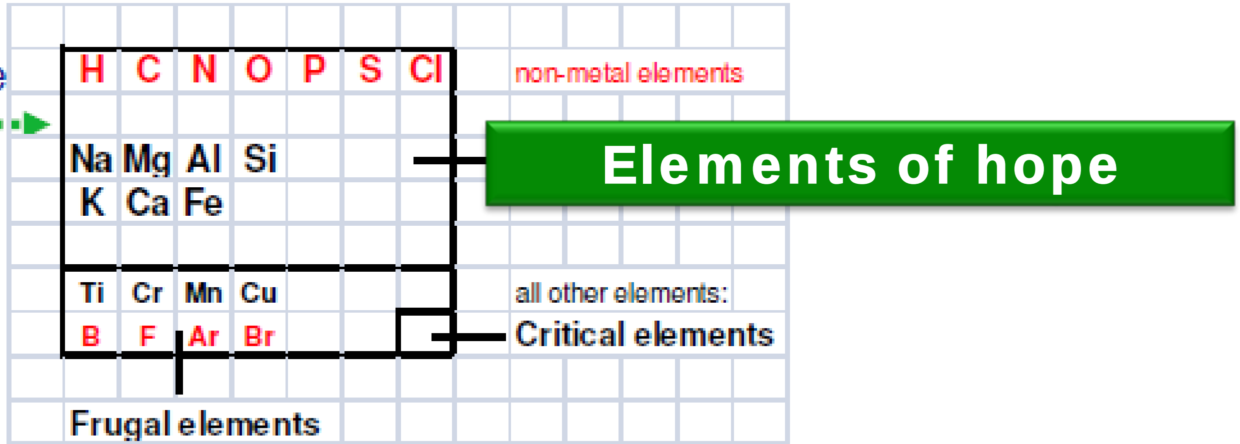
$$2H_2O \rightarrow 2H_2 + O_2$$

Advantage: separate optimization possible
Current bottleneck: use of scarce materials (a.o. Pt)

*H_2 generation from steam reformation <1€ / kg

However for all these approaches…….

1. Use less (*involves human behaviour and "managed austerity"*)
2. Longer life
3. Re-use and recycle
4. Substitute
5. Product and process (re)design
6. Buffers



Source: Global Resource Depletion, Managed Austerity and the Elements of Hope (2010), ISBN 9789059724259

1 A.M. Diederen, Materials scarcity Eindhoven, September 16, 2010

For large scale deployment essential use of earth abundant materials !

EASE / EERA report on Electrical Energy Storage

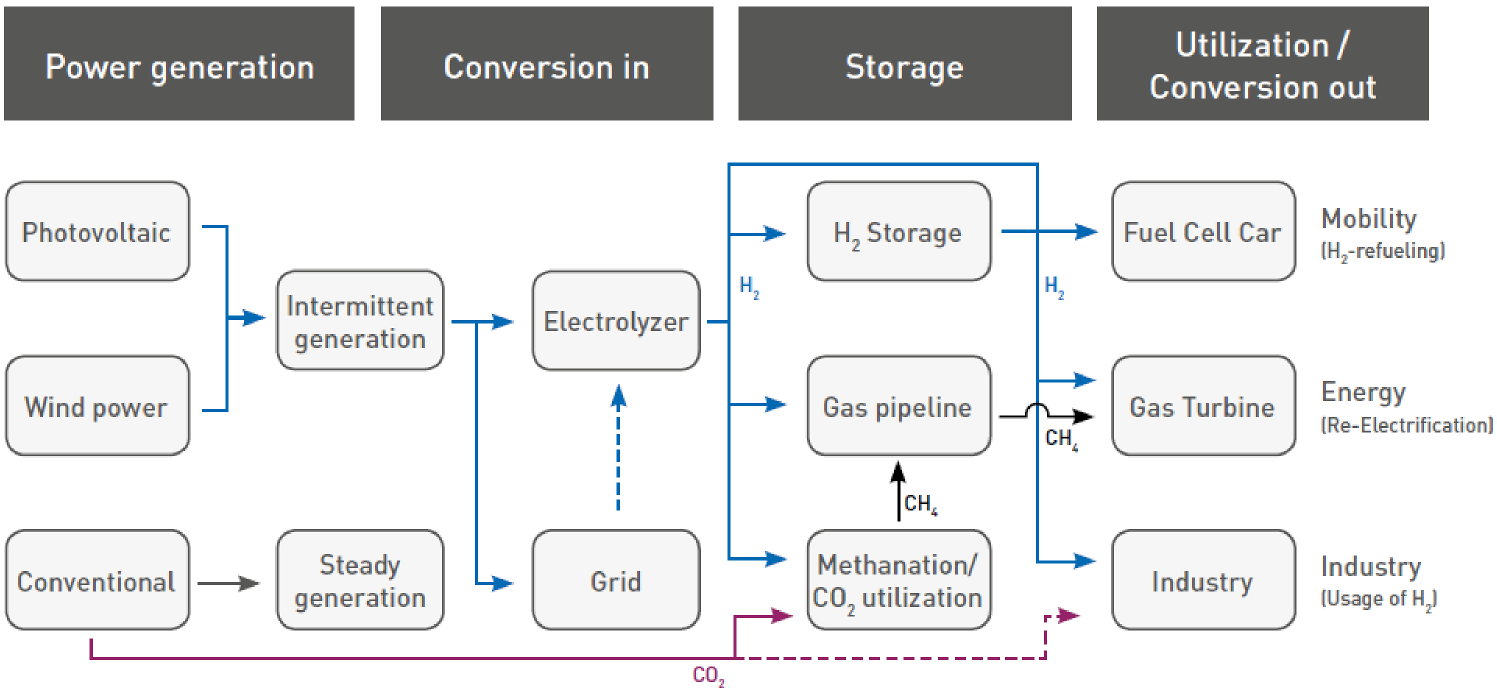


FIGURE 1 - Schematic of chemical storage pathways

For the chemical storage route: important role for H_2 and CH_4

Joint EASA/EERA recommendations for a joint European Energy Storage Technology Roadmap towards 2030

EASE / EERA report on Electrical Energy Storage

CO_2 capture
40 – 400 € / 1000 kg

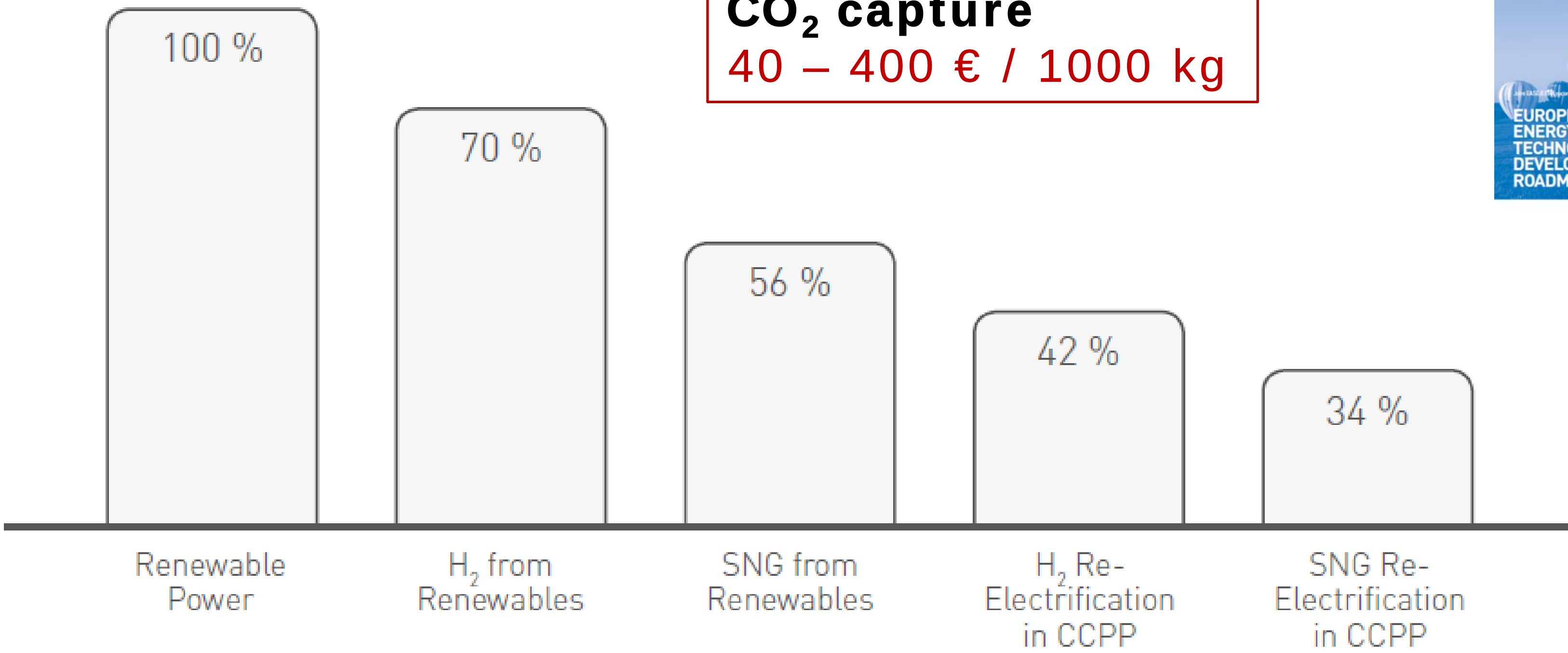
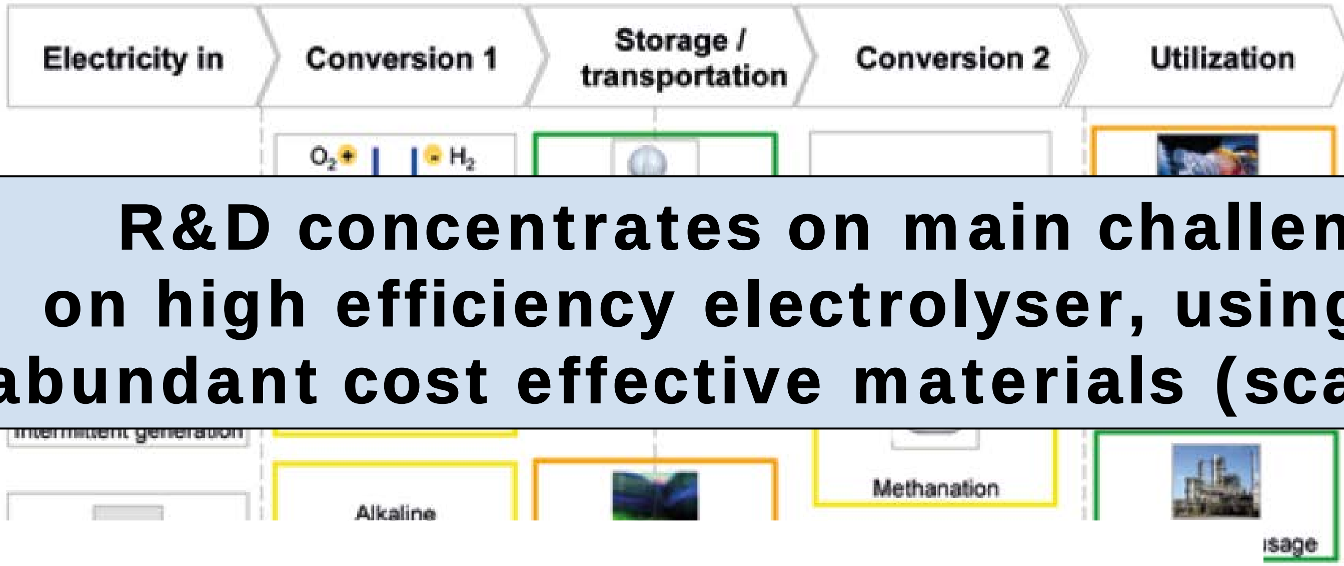


FIGURE 2 - Efficiency of hydrogen based chemical electricity

Note: most costly step is H_2 generation NOT CO_2 capture!

Joint EASA/EERA recommendations for a joint European Energy Storage Technology Roadmap towards 2030



R&D concentrates on main challenges: on high efficiency electrolyser, using earth abundant cost effective materials (scalability)

Environmental Science & Technology

VIEWPOINT

pubs.acs.org/

Efficient Production of Solar Fuel Using Existing Large Scale Production Technologies

Wim Haije[*,†,‡] and Hans Geerlings[†,§]

[†]Department of Chemical Engineering, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands
[‡]Energy research Centre of The Netherlands, PO BOX 1, 1755 ZG, Petten, The Netherlands
[§]Shell Global Solutions International B.V., Grasweg 31, 1031 HW Amsterdam, The Netherlands

Topsector Energy:

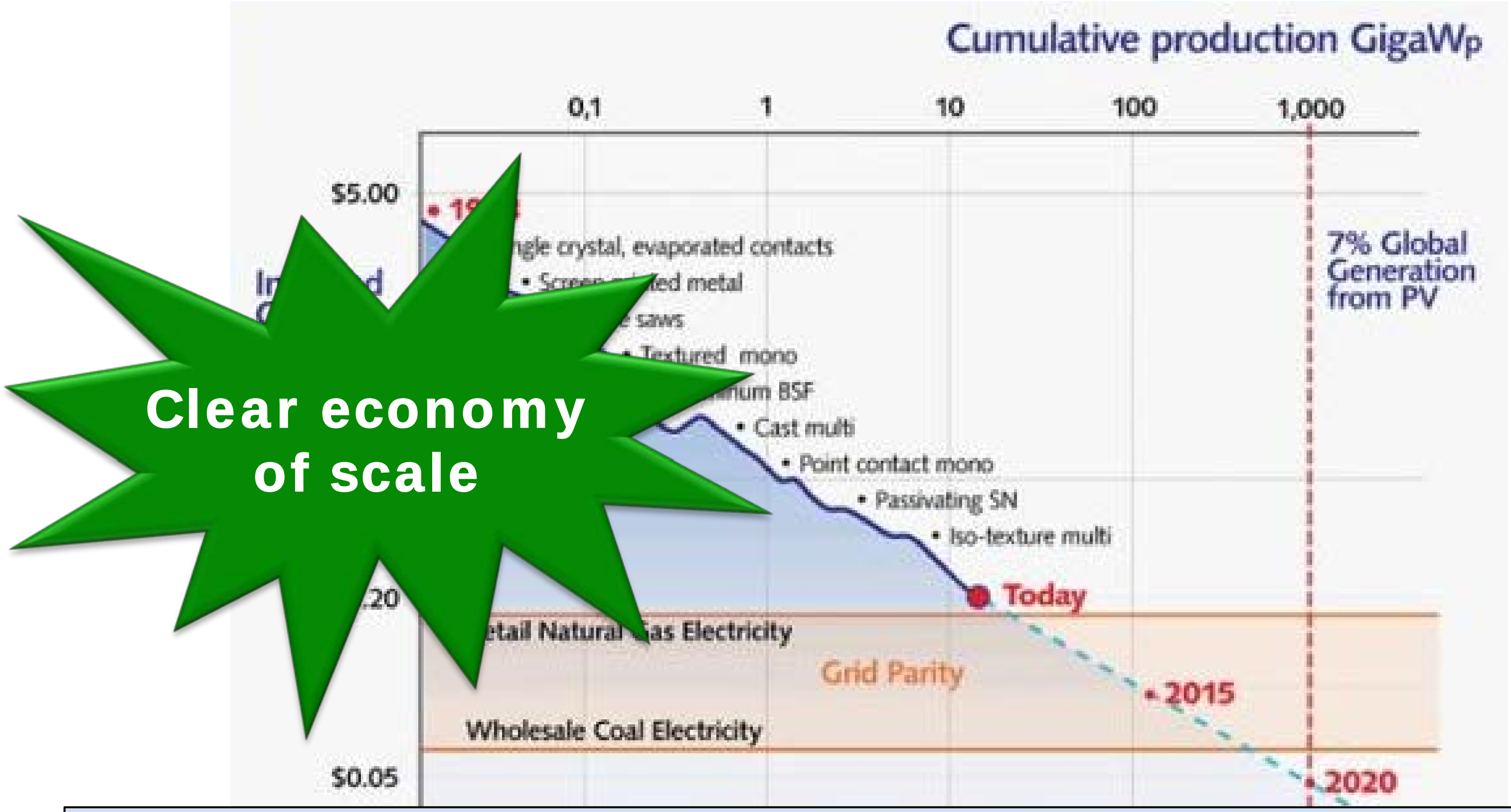
Power to gas (P2G) scheme

R&D needed!

Joint EASA/EERA recommendations for a joint European Energy Storage Technology Roadmap towards 2030

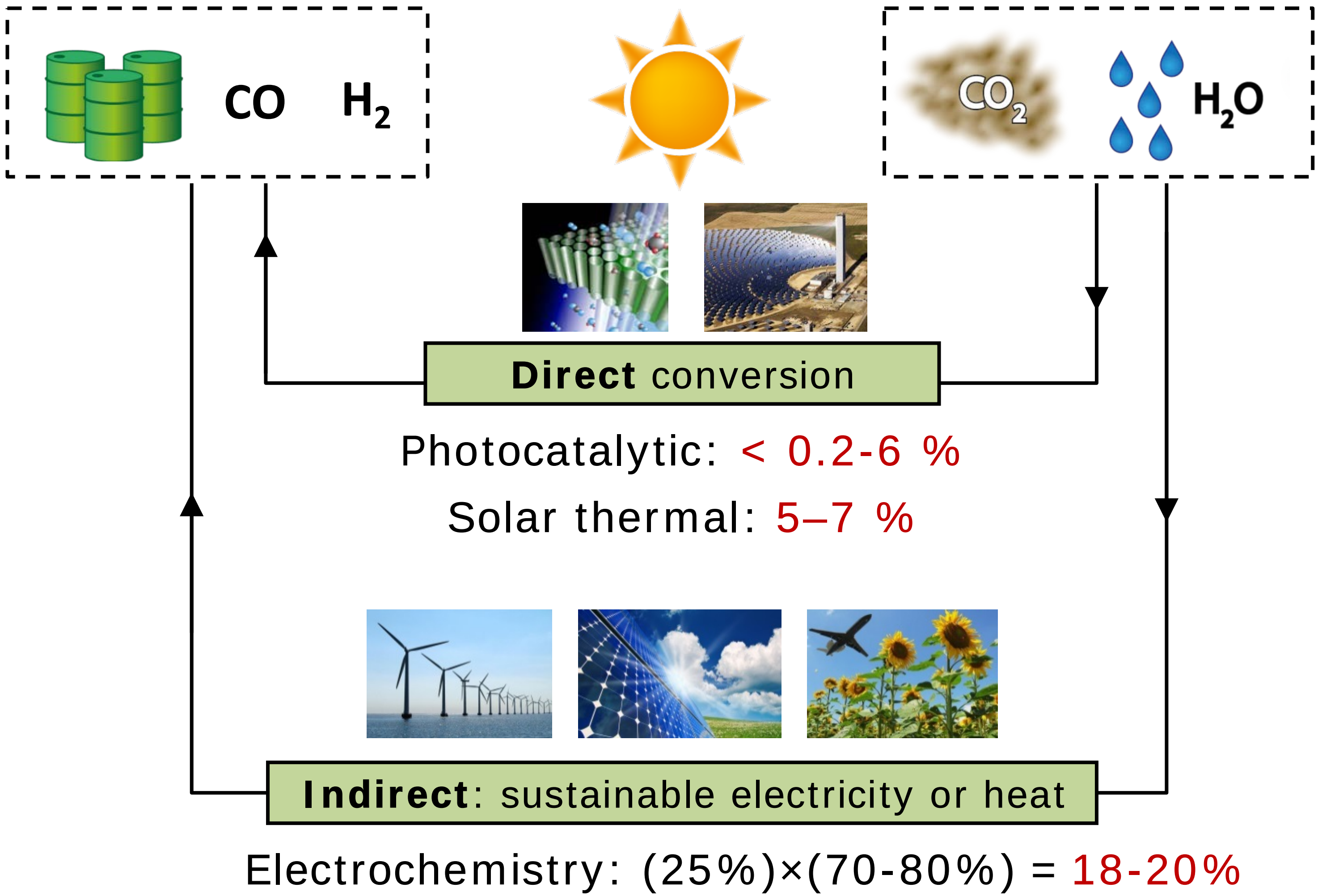
Solar power generation: Economy of scale

Price-experience curve of silicon PV modules
(combined effects of research innovation, experience and scale)



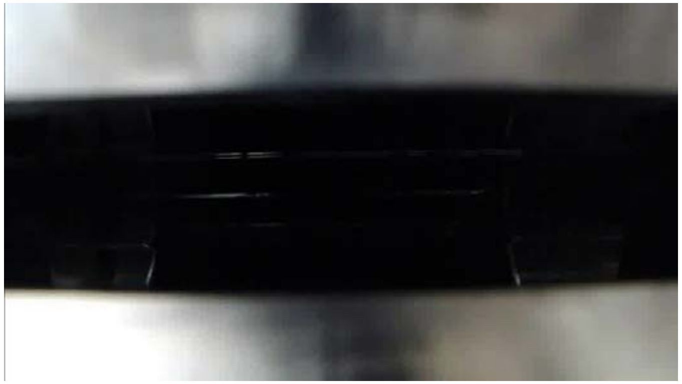
For electrolysers we need a > 10 cost reduction: research, innovation, experience and scale essential

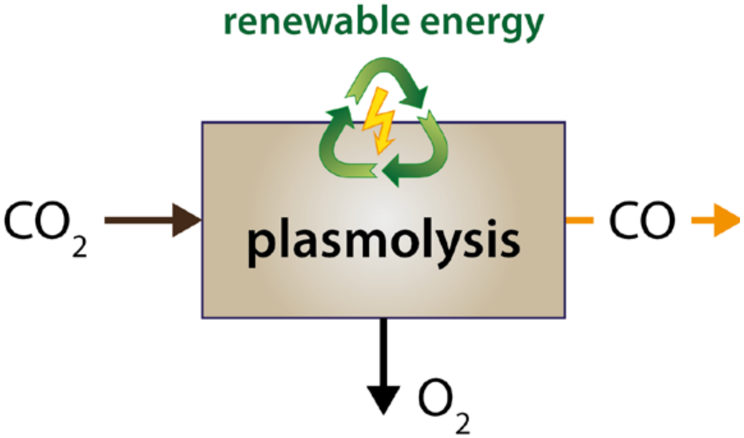
Concept of artificial chemical fuels



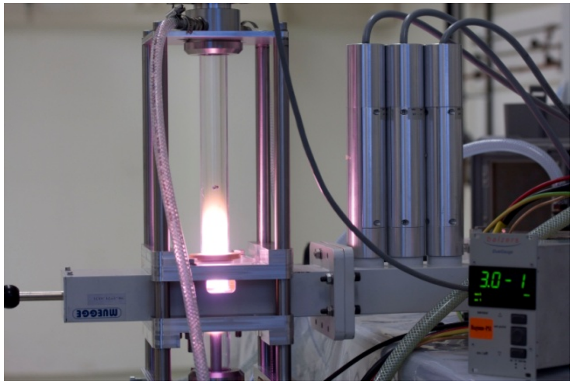
Activation of CO_2 difficult: plasma might provide pathway

Hydrogen generation using plasmolysis





- Generate a plasma in CO_2
- No use of scarce materials
- Higher power density, smaller footprint
- On demand capability
- H_2 generation using WGS reaction



CO_2 plasma set up @ DIFFER

HyPlasma project (TKI gas) Bongers et al. (2014)

CO_2 dissociation by plasma activation

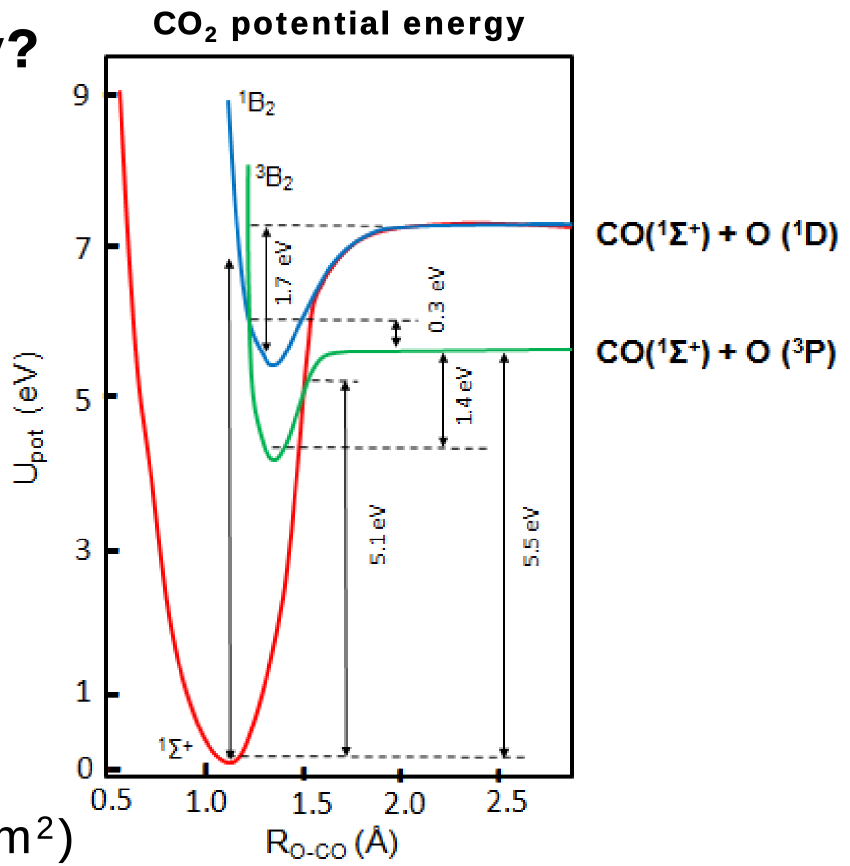
Can it be done energy efficiently?

Plasma processing energy expensive:

- Creating electron-ion pair > 30 eV
- Dissociation energy CO_2 > 5.5 eV

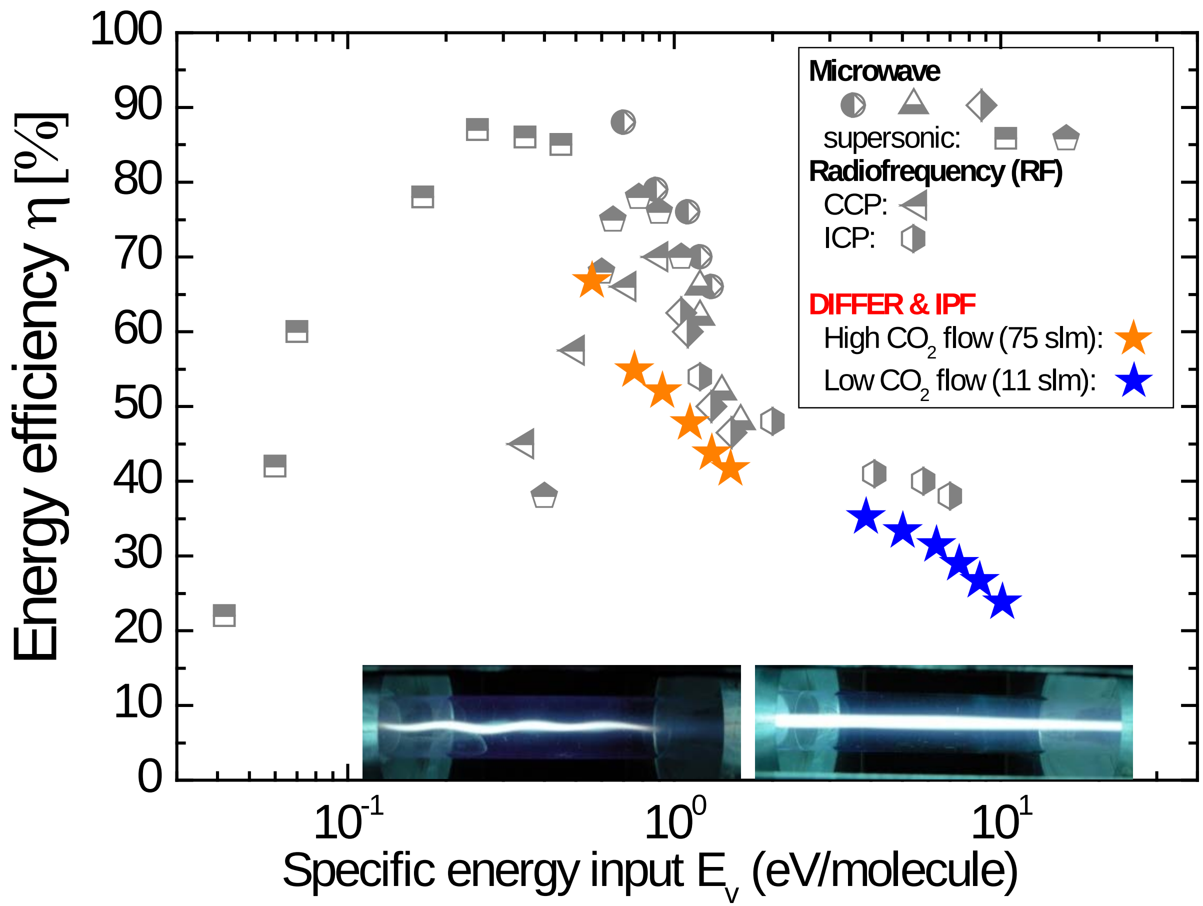
YES if:

- Vibrational excitation CO_2 by slow electrons (1 eV) creating out-of-equilibrium $T_{vib} > T_{gas}$
- Low degree of ionisation (10^{-5})
- Low reduced electric field (~10^{-16} Vcm^2)



energy efficient dissociation possible through **vibrational excitation CO_2** in asymmetric stretch mode

Reported results on energy efficiency



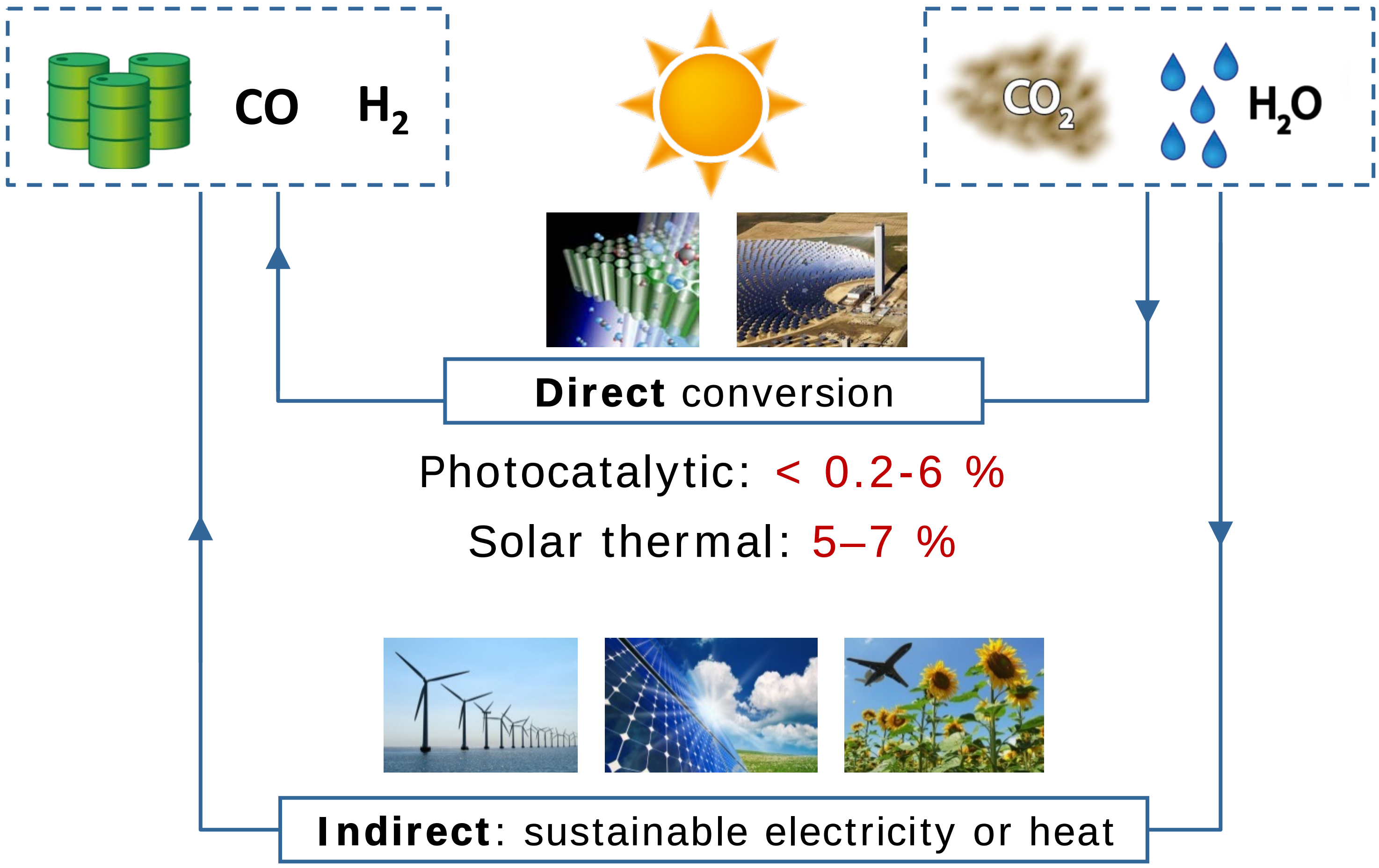
$\eta = \Delta H / E_{CO}$

Literature reports > 50% energy efficiency of CO_2 dissociation !

eV

From A. Fridman, “Plasma Chemistry” (Taylor&Francis 2009)

Concept of artificial chemical fuels



Electrochemistry: (25%)×(70-80%) = 18-20%

Plasmolysis: (25%)×(60-80%) = 15-20%

Conclusions

- Storage of sustainable energy in chemical fuels one of the approaches to provide a stable energy supply and liquid transport fuels: use of earth abundant materials essential because of the scale
- Especially power-to-gas is being deployed due to negative prices RES; more R&D is necessary to get cost and energy efficient P2G schemes; *there is not one solution, we need most probably a mix*
- *Innovations are necessary, new materials for membranes and catalysts, plasma might provide solutions if energy efficiency is proven*
- Several issues need to be addressed overall: CO_2 conversion efficiency, efficiency of the gas separation, supply of CO_2, *etc....*

TV uitzending Labyrint “CO_2”

http://www.uitzendinggemist.nl/afleveringen/1380791