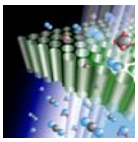
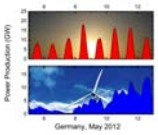
DIFFER

Introducing DIFFER: Mission and research program

Richard van de Sanden

DUTCH INSTITUTE FOR FUNDAMENTAL ENERGY RESEARCH, EINDHOVEN, THE NETHERLANDS

DIFFER is part of FOM and NWO

The TeraWatt Challenge

- Energy
- Water
- Food
- Environment
- Poverty
- War & Terrorism
- Disease
- Education
- Democracy
- Population

2004	6.5 billion humans
2050	9-10 billion humans

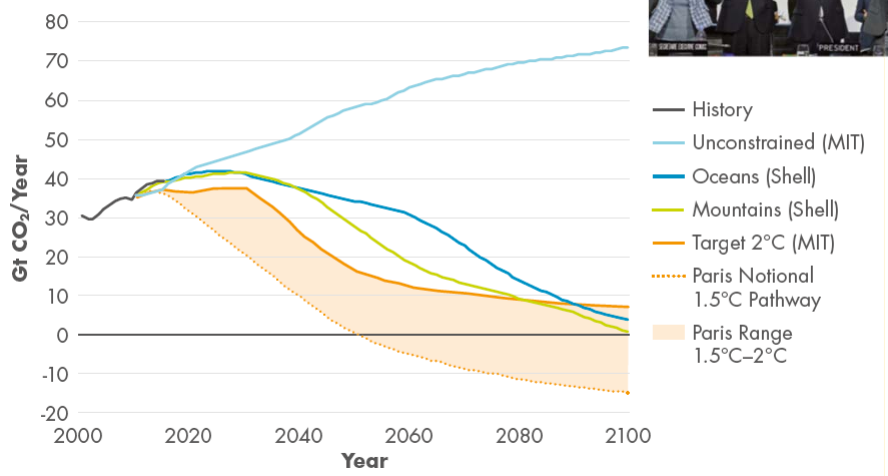
see also :

M.I. Hoffert et al. Nature **385,** 881 (1998)

R.E. Smalley, MRS Bulletin **30** 412 (2005)

CO_2 emissions

PATHWAYS FOR TOTAL CO_2



Shell report *A better life with a healthy planet (2016)*

The TeraWatt Challenge

- Energy
- Water
- Food
- Environment
- Poverty

Sustainable, CO_2 neutral, energy infrastructure essential to mitigate climate effects

- Education
- Democracy
- Population

2004	6.5 billion humans
2050	9-10 billion humans

see also :

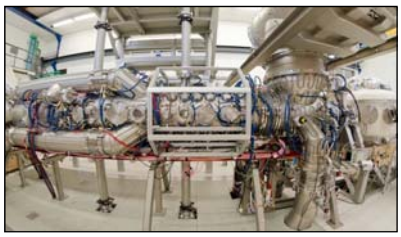
M.I. Hoffert et al. Nature **385,** 881 (1998)

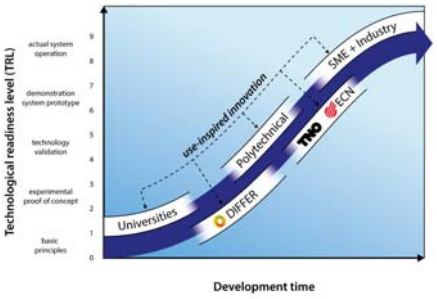
R.E. Smalley, MRS Bulletin **30** 412 (2005)

Mission of DIFFER

SCIENCE FOR FUTURE ENERGY

To perform leading fundamental **research**
in the scientific fields of **fusion energy** and **solar fuels**,
maintaining and exploiting a **high-quality technical infrastructure**,
in close **partnership** and **collaboration** with academia, institutes and industry.
And to build a **national community** on (multi-disciplinary) **energy research**.

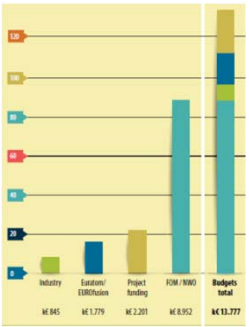


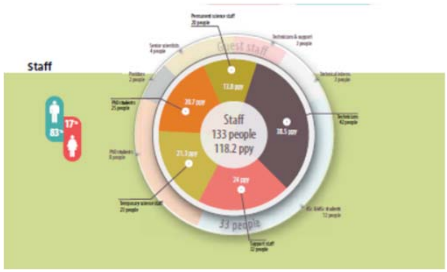


DIFFER in a nutshell

Staff 133 people
Total 166 people

Annual budget 13.8 M€





28 juni 2016

Motivation: the TeraWatt Challenge[1]

Energy mix required to meet rising global energy demand

Sustainable energy production to replace fossil fuels (CO_2 neutral !)

- Solar panels
- Wind turbines
- Bio-based processes and chemicals
- (Geo)thermal processes
- Hydro-energy
- …

[1] M.I. Hoffert et al. Nature **385,** 881 (1998)

Motivation: the TeraWatt Challenge[1]

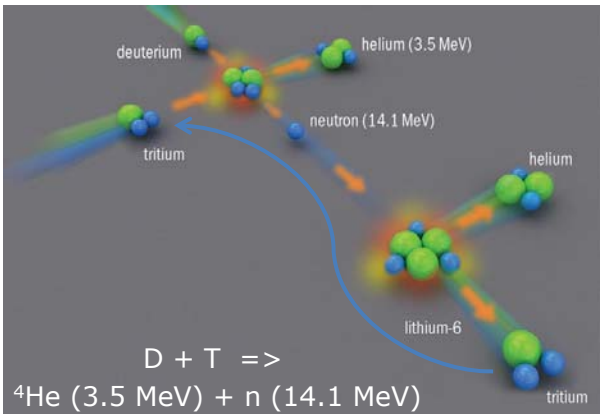
Energy mix required to meet rising global energy demand

Sustainable energy production to replace fossil fuels (CO_2 neutral !)

- Solar panels
- Wind turbines
- Bio-based processes and chemicals
- (Geo)thermal processes
- Hydro-energy
- …
- Nuclear fusion

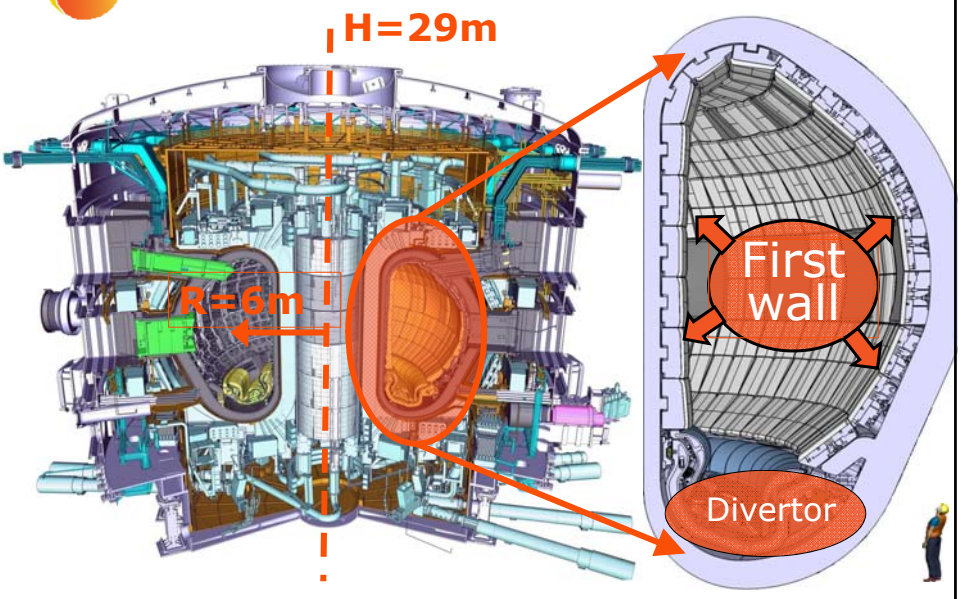
[1] M.I. Hoffert et al. Nature **385,** 881 (1998)

How does Fusion work?



- He (3.5 MeV) takes care of sustaining plasma heating
- Neutron (14.1) breeds T from ^{6}Li
- 30 million years of Lithium supply in seawater
- Billions of years of deuterium supply (1 in 6420 H_2O is a HDO)

The ITER tokamak



Heat loads: Extreme materials

HWR

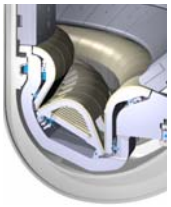
Re-entry vehicle

Ariane 5/Vulcain 2

~1 10 85 2000

Power load [MW/m^2]

Rolls Royce Trent 900



ITER steady-state

ITER transients

Motivation: the TeraWatt Challenge[1]

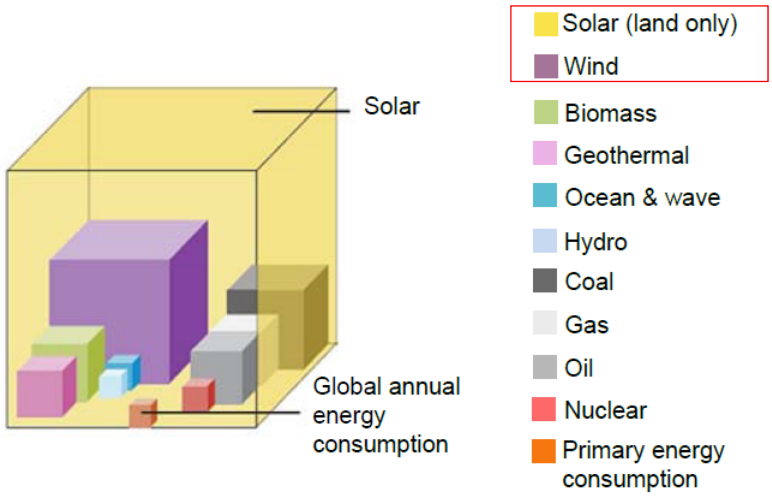
Energy mix required to meet rising global energy demand

Sustainable energy production to replace fossil fuels (CO_2 neutral !)

- Solar panels
- Wind turbines
- Bio-based processes and chemicals
- (Geo)thermal processes
- Hydro-energy
- …
- Nuclear fusion

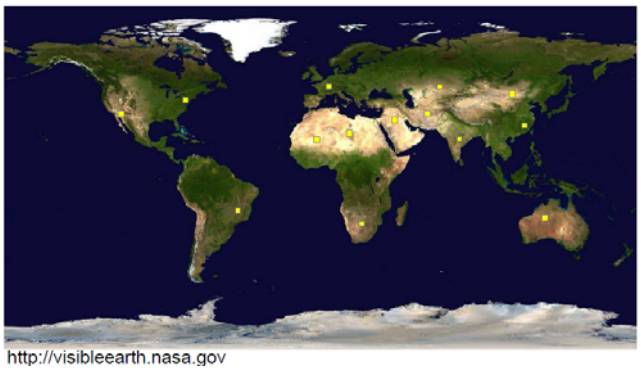
[1] M.I. Hoffert et al. Nature **385,** 881 (1998)

Theoretical potential energy sources



Source: European Photovoltaic Industry Association (EPIA), 2010

Solar power generation: large scale



http://visibleearth.nasa.gov

Solar resources (by far largest renewable > 10^5 TW)

At 10% overall efficiency (generation, transport and storage):

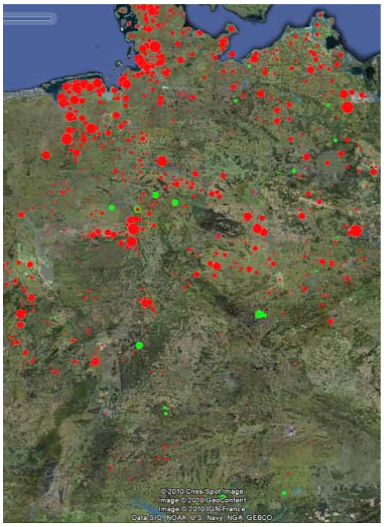
need 1200x1200 km² to cover estimated 2050 energy needs (1000 EJ)

Cost target € 0.20/Wp or € 0.03-0.04/kWh; equivalent to € 33/m² @ 15%

Courtesy Sinke et al.

Costs go down to level of fossil based electricity generation

Renewable energy in Germany



Total capacity of renewables
(End 2000)

~ 30,000 installations

Wind energy

PV

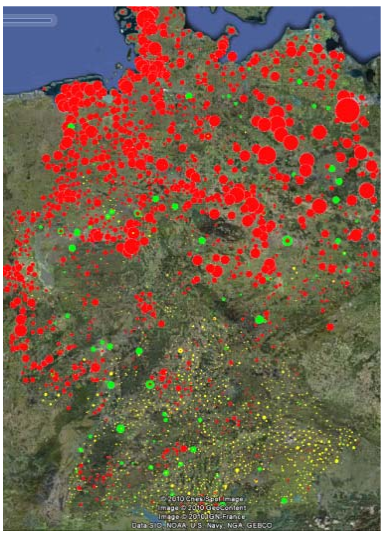
Biomass

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

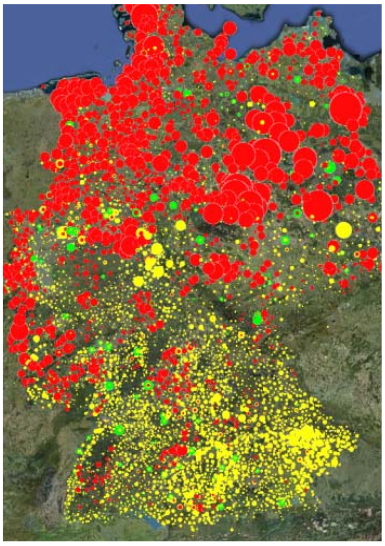
Biomass

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

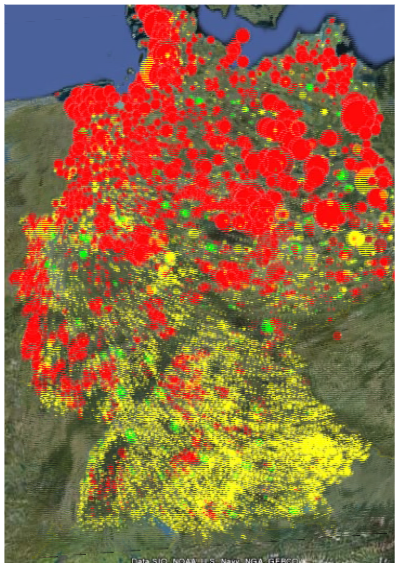
Biomass

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

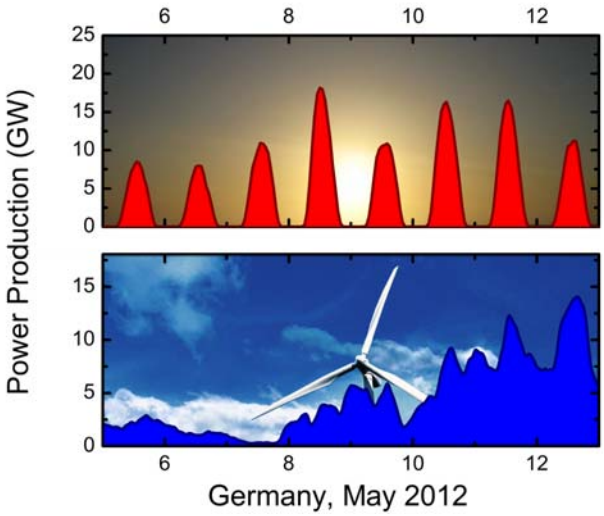
Biomass

The circle diameter is proportional to the electrical capacity

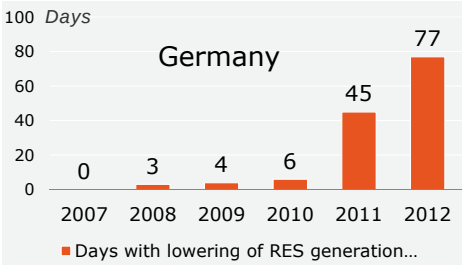
Sources: 50HertzT, TenneT, Amprion, TransnetBW, Elia group

Courtesy Daniel Dobbeni (Elia group)

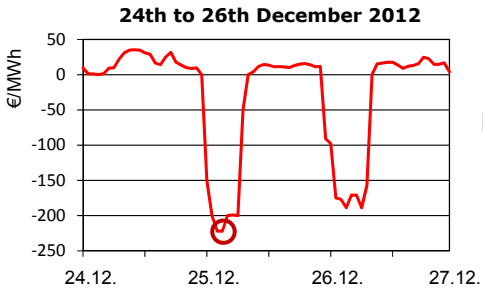
Renewable energy in Germany (2012)



Challenges of renewable electricity



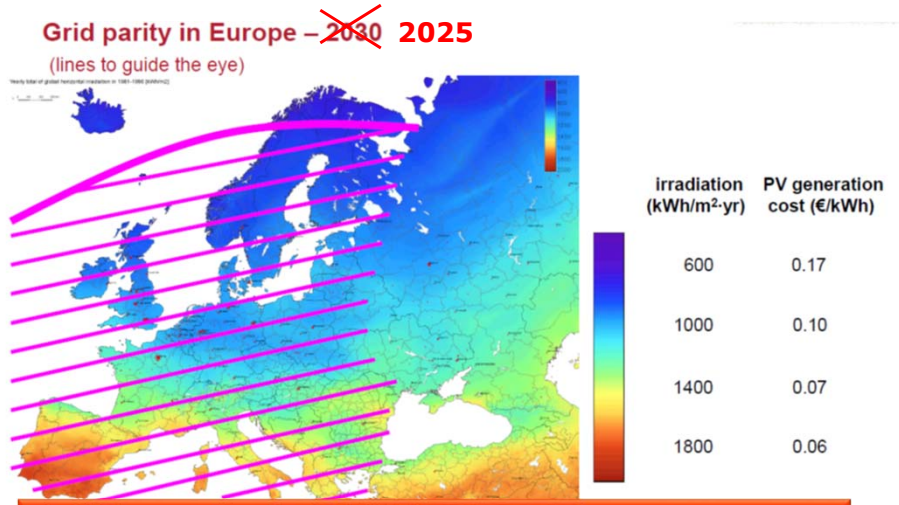
Not only Germany: Spain lost 90 M€ due to wind power curtailment



Min. market price: **- 221,99 €/MWh**

19 (out of 72) hrs with negative prices

Grid parity Solar PV Europe



From 2020 a significant fraction is renewable

Motivation: the TeraWatt Challenge[1]

Energy mix required to meet rising global energy demand

Sustainable energy production to replace fossil fuels (CO_2 neutral !)

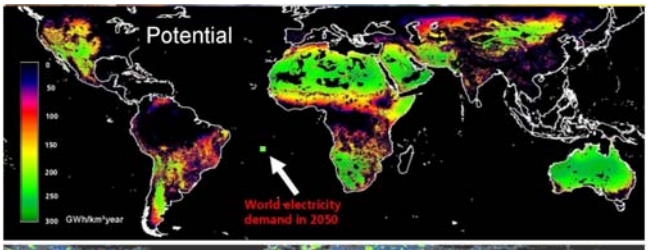
- Solar panels
- Wind turbines
- Bio-based processes and chemicals
- (Geo)thermal processes
- Hydro-energy
- …
- Nuclear fusion

All renewables produce (intermittent) electricity !!!

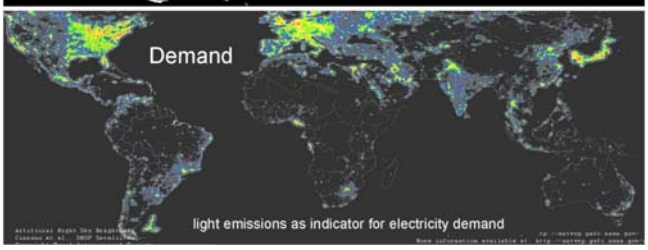
[1] M.I. Hoffert et al. Nature **385,** 881 (1998)

Transport of energy

solar generation

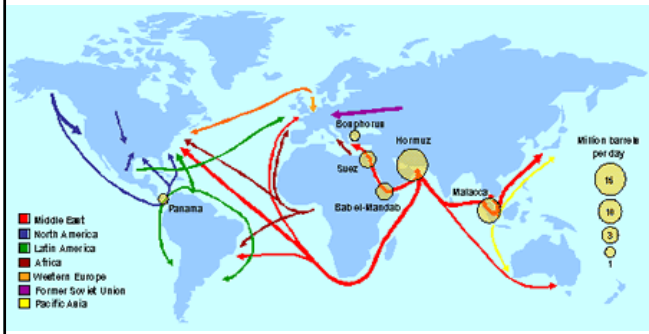


…energy demand



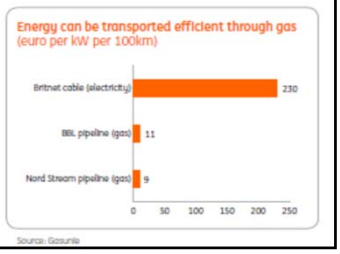
Storage and transport is part of the challenge!

Transport of energy

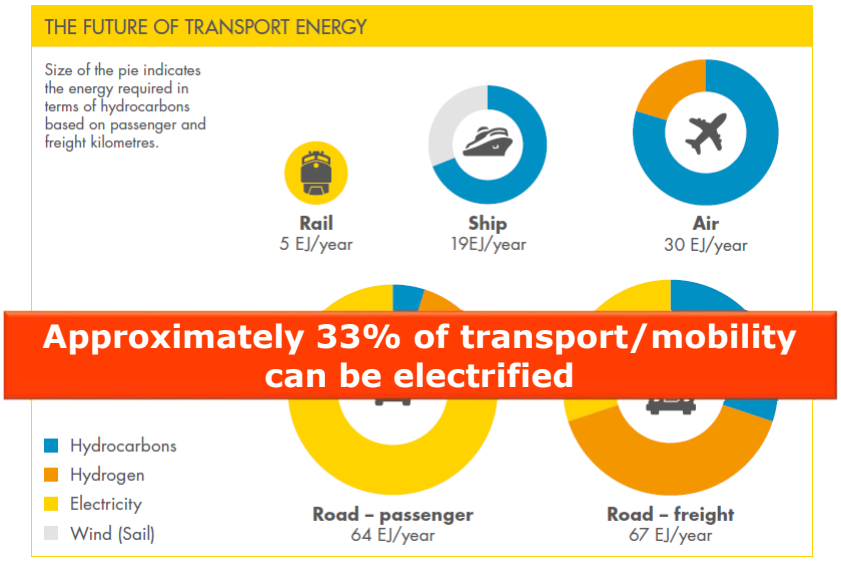


85% of the global energy is transported by fuels

Transport by electricity about 20 times more expensive



Future of transport/mobility

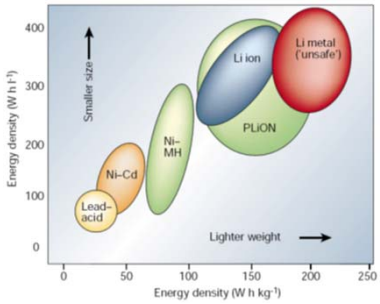


Approximately 33% of transport/mobility can be electrified

Shell report *A better life with a healthy planet (2016)*

Energy storage

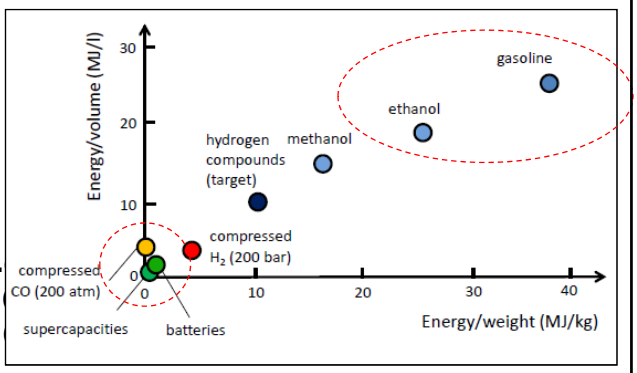
- **Electrical**
  - **Batteries**
  - **Super capacitors**



- **Heat Storage**
  - **Latent heat (e.g. aquifiers)**
  - **Sensible heat (e.g. phase change materials)**
  - **Chemical heat (e.g. salts)**

Energy storage

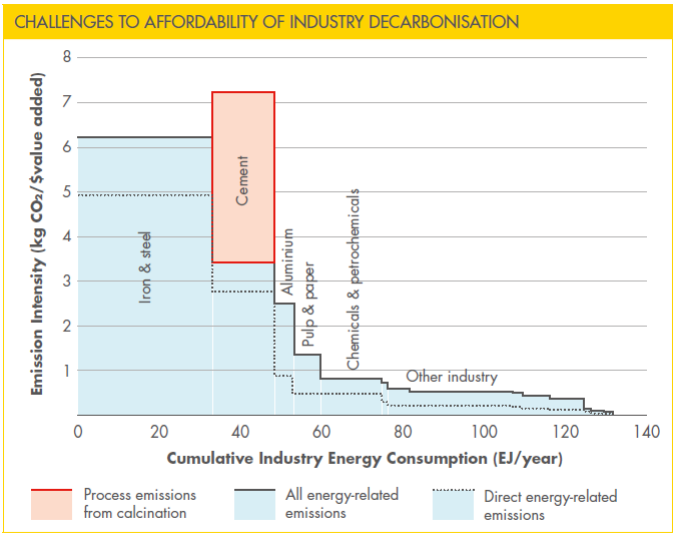
- **Electrical**
  - **Batteries**
  - **Super capacitors**



- **Heat Storage**
  - **Latent heat (e.**
  - **Sensible heat**
  - **Chemical heat**

- **Chemical storage**
  - **H_2**
  - **Fuels (>10 more energy density)**

Yet another aspect: greening the industry



Source: Shell analysis based on data from IEA and Oxford Economics.

Shell report *A better life with a healthy planet (2016)*

Motivation: the TeraWatt Challenge[1]

Energy mix required to meet rising global energy demand

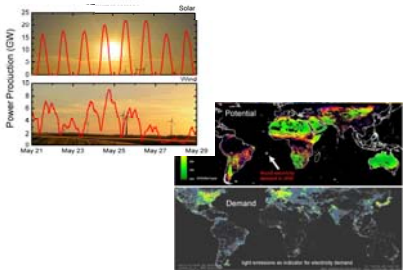
Sustainable energy production to replace fossil fuels (CO_2 neutral !)

- Solar panels
- Wind turbines
- Bio-based processes and chemicals
- (Geo)thermal processes
- Hydro-energy
- …
- Nuclear fusion

Match supply and demand

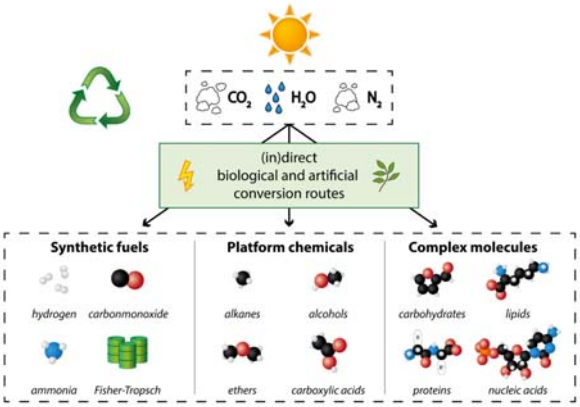
Inhomogenous and intermittent character of sustainable sources

- Smart grids
- Electrical energy storage
- (Geo-)thermal/geostatic storage
- Chemical fuels (CO_2-neutral!)
- …



[1] M.I. Hoffert et al. Nature **385,** 881 (1998)

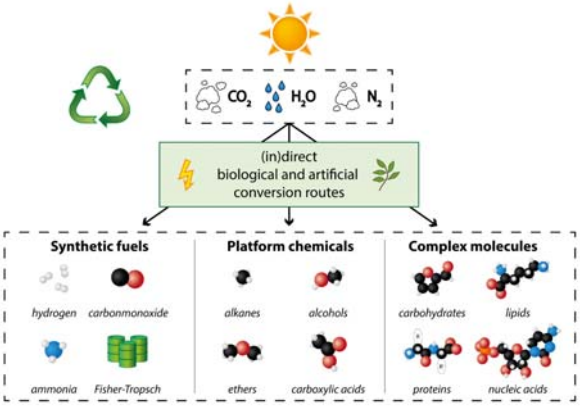
Motivation: CO_2 neutral (= Solar) fuels



- Excellent potential to harness solar energy
- Enables storage of sustainable energy in CO_2-neutral chemical fuels
- Essential ingredient in the future sustainable energy infrastructure
- Essential to provide future carbon based chemical feedstock!

28 juni 2016

Motivation: Circular fuels



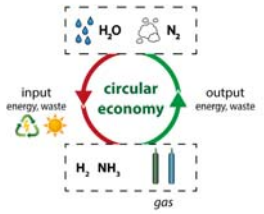
- Excellent potential to harness solar energy
- Enables storage of sustainable energy in CO_2-neutral chemical fuels
- Essential ingredient in the future sustainable energy infrastructure
- Essential to provide future carbon based chemical feedstock!

28 juni 2016

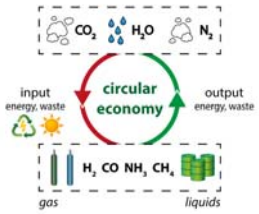
Sustainable CO_2-neutral processes

CO_2 - neutral fuels and chemicals

Carbon-free fuels



Hydrocarbons

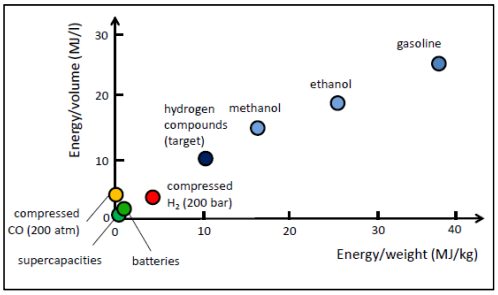


Fossil fuels + CCS
- Point source capture
- Permanent sequestration

P2G + CCU
- Point source and direct air capture
- Added-value fine chemicals

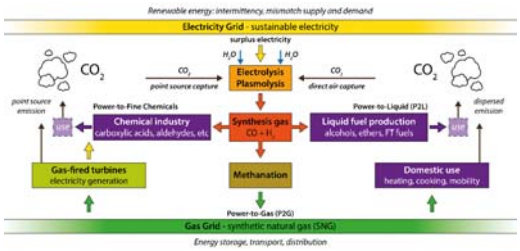
Challenges for research and innovation
- Improved materials for CCS/U and H_2O splitting and CO_2 activation
- Demonstration on system level (TRL 2 to TRL 5)
- Upscaling to MW level
- Economic feasibility (ETS policy, carbon tax)

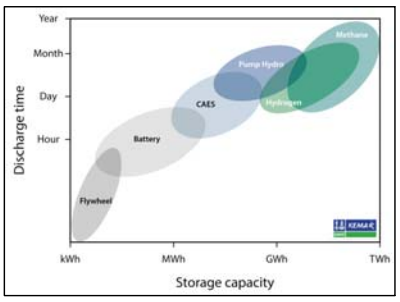
Motivation: Hydro-carbons?



- Ideal for energy storage
  - High energy density per volume and per mass
- Use of existing hydro-carbon infrastructure
  - Transport, distribution and use

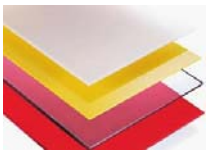
Motivation: Hydro-carbons?





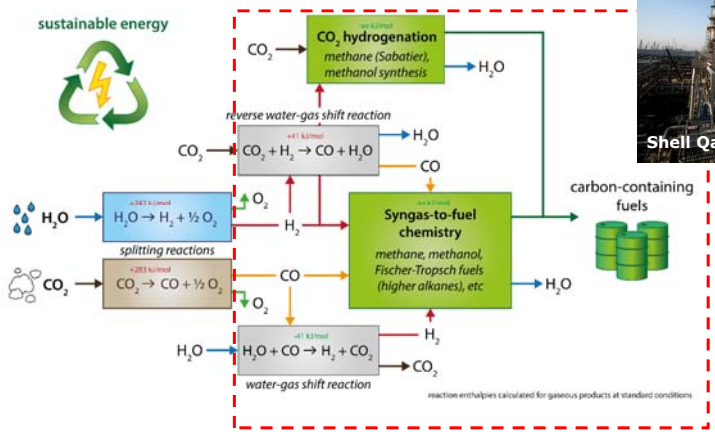
- Ideal for energy storage
  - High energy density per volume and per mass
- Use of existing hydro-carbon infrastructure
  - Transport, distribution and use
- Coupling electricity and gas system: Power-to-Gas (P2G)
  - Large storage capacity in gas grid (surplus RE electricity)
  - NL gas grid ~ 552 TWh (one day EU electrical power ~ 10 TWh)

Motivation: Hydro-carbons?



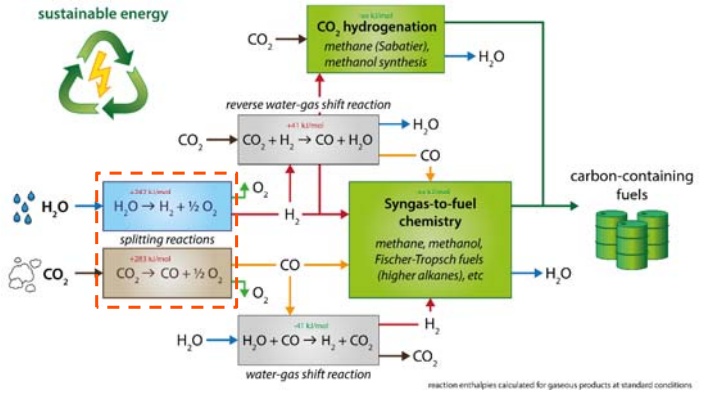
- Ideal for energy storage
  - High energy density per volume and per mass
- Use of existing hydro-carbon infrastructure
  - Transport, distribution and use
- Coupling electricity and gas system: Power-to-Gas (P2G)
  - Large storage capacity in gas grid (surplus RE electricity)
  - NL gas grid ~ 552 TWh (one day EU electrical power ~ 10 TWh)
- Feedstock for carbon-based materials

Challenge



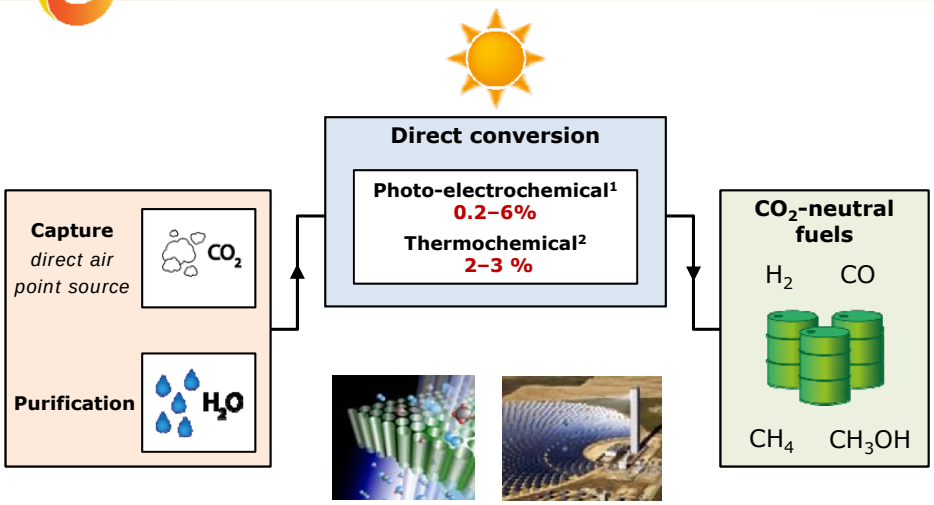
Carbon containing fuels from CO_2, H_2O and renewable energy

Challenge



- **Use-inspired research is focused on:**
  - *H_2 generation from H_2O*
  - *CO generation from CO_2*
- **The challenge:**
  - *To find a cost-effective and energy efficient conversion process using robust and scalable materials and processes*

Status & Potential



[1] See e.g Abdi et al. Nature Commun. **4 2195 (2013)**

[2] See e.g Steinfeld group (ETH Zurich), Science **330** 1798 (2010)

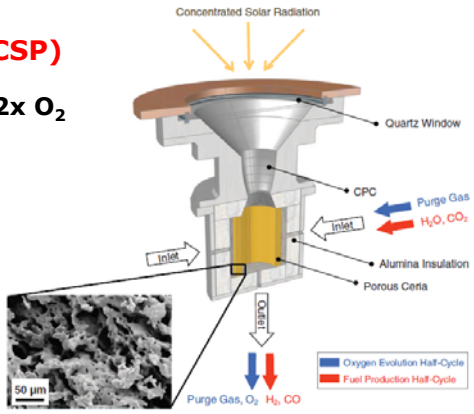
Thermochemical using CSP (direct)

Concentrated solar power (CSP)

CeO_2 + sunlight → CeO_{2-x} + 1/2x O_2

CO_2 + CeO_{2-x} → CO + CeO_2

Or based on ZnO, Fe_3O_4

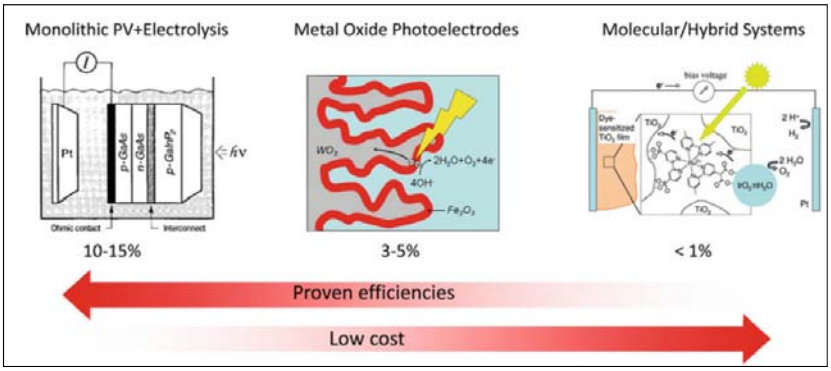


Cyclic, solar to CO/H_2 efficiency: 2-3%

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

Photo-electrochemical conversion

Three approaches with focus on H_2 generation:



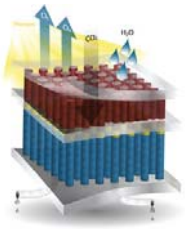
Van de Krol et al., J. Mater. Chem. **18** (2008) 2311.

Van de Krol et al., Photoelectrochemical Hydrogen Production, 2012.

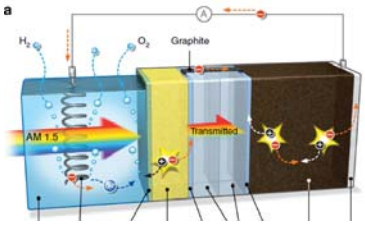
Photoelectrochemical Solar Fuel Conversion

Daniel Nocera Harvard/MIT

Rene Janssen TU/e-DIFFER

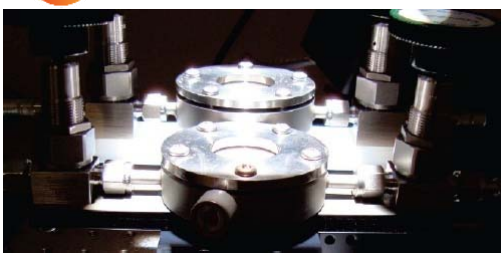


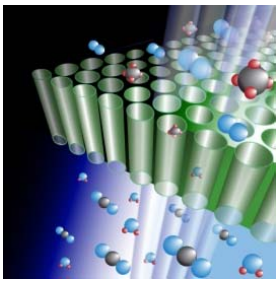
Nathan Lewis et al. JCAP



. Abdi et al. Nature Commun. **4** 2195 **(2013)**

Photo-electrochemical conversion of CO_2 ?





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

TiO_x tubes with Cu catalyst

$$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$$

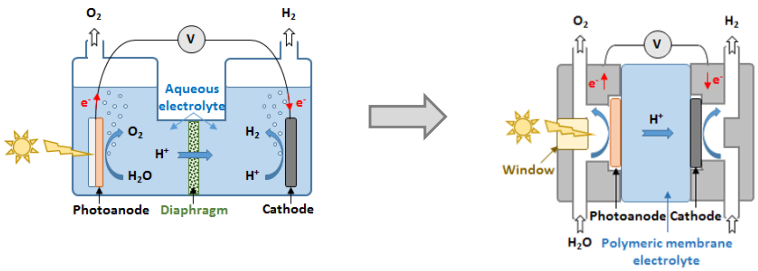
Solar to methane efficiency η = 0.0148%

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

DIFFER activities on direct conversion

Photo-electrochemical cells with polymeric electrolytes (inverse fuel cells + light)

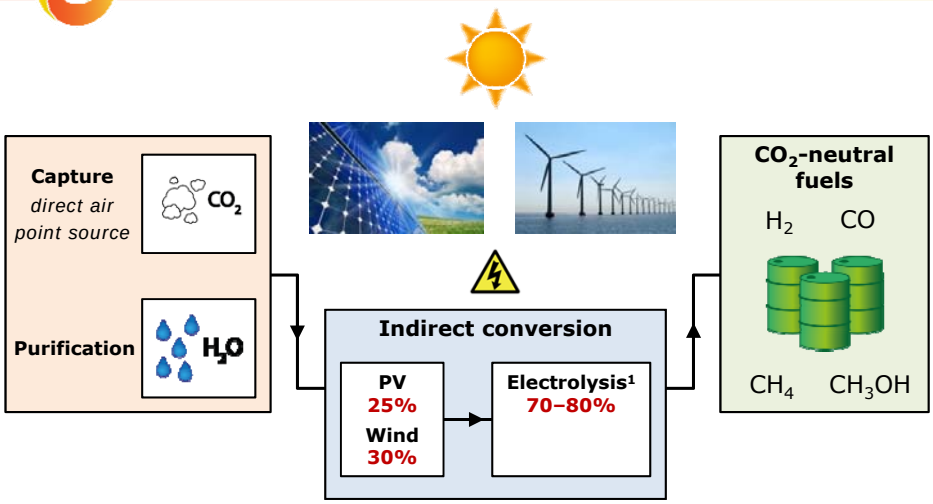
- Improve PEC efficiency; fundamental understanding for H_2O splitting and CO_2 activation



- Solid state electrodes: ceramic proton conducting membranes

Michail Tsampas

Status & Potential

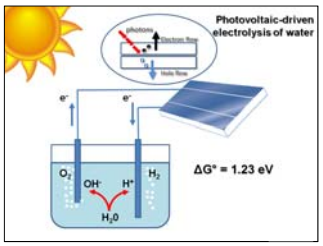


Overall energy efficiency: >18–20%

[1] See e.g. R. de Levie, J. Electroanalytical Chemistry **476** 92 (1999)

Challenges (indirect conversion)

Renewable electricity + Electrolysis



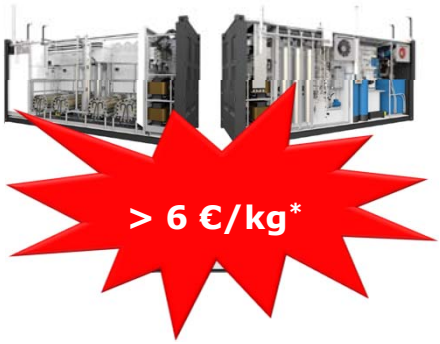
Indirect Solar-to-chemical energy conversion

- Alkaline Electrolysis
  - Liquid electrolyte, slow ramp up, robust, energy efficiency 67-82%
- Polymer Exchange Membrane Electrolysis
  - Inverse fuel cell, membranes are costly, energy efficiency 67-93%
- Solid Oxide Electrolysis
  - High temperature (700-1000 C), costly, energy efficiency 50-90%

Indirect Conversion of Solar Radiation

HYDROGENICS

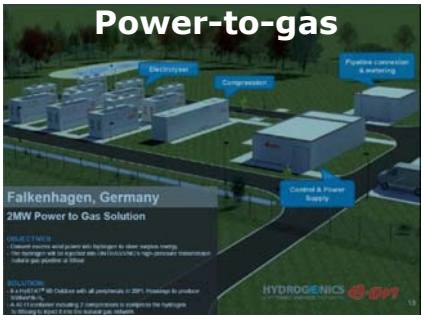
Hystat™ Water Electrolyzer



Large scale deployment ongoing a.o. in Germany !!

Costs determining factors

- Use of scarce materials
- Lifetime, durability
- Expensive (a.o. membranes)

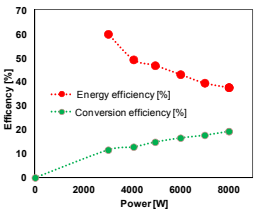


*H_2 generation from CH_4 steam reformation <1€/kg

Challenges (indirect conversion)

Renewable electricity + Plasmolysis

$CO_2 \rightarrow CO + ½O_2$

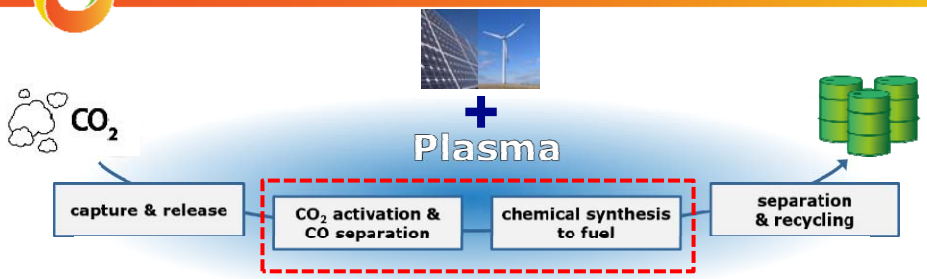


Bongers et al. (2013)

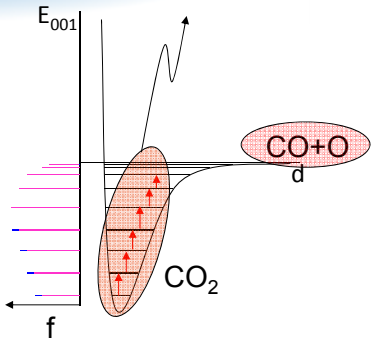
Indirect Solar-to-chemical energy conversion

- Improve flexibility ("cold start") and lifetime of electrodes
- Focused on cost efficient materials and materials synthesis
  - *e.g. polymer membranes for polymer membrane electrolysis*
- Novel innovative operational concepts
  - *e.g. heat integration and co-electrolysis for high pressure solid oxide electrolysis*
- To overcome these challenges for electrolysis:
  - *alternative indirect approach based on the generation of a non-equilibrium CO_2 plasma using renewable electric energy (DIFFER)*

Plasmolysis: our approach



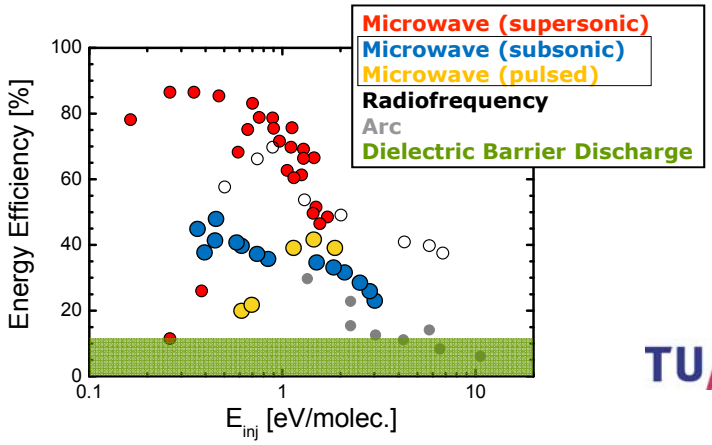
- Microwave plasma-assisted CO_2 conversion
- Vibrational excitation of gas phase & surface species



Gerard van Rooij, Waldo Bongers, Stefan Welzel, Paola Diomede

Plasmolysis of CO_2

Plasma-assisted CO_2 dissociation

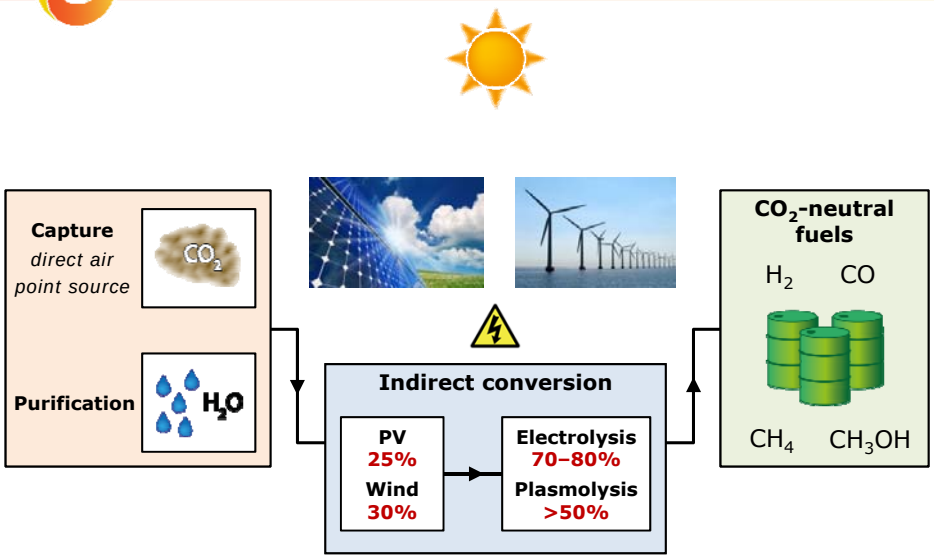


TU/e

A. Fridman, *Plasma Chemistry*
F. Brehmer et al. JAP **116** (2014) 123303
W. Bongers, S. Welzel et al. to be published

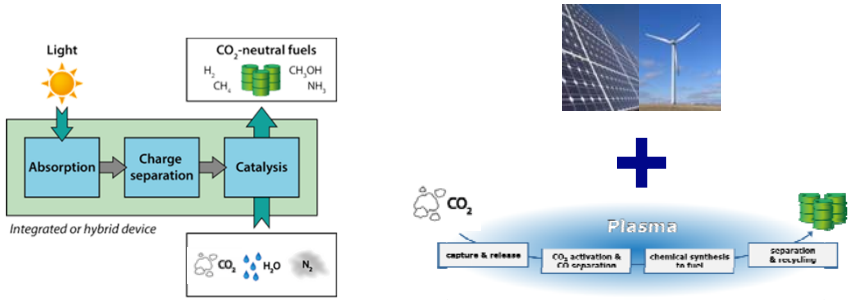
1 eV/molecule = 96.285 kJ/mol

Conversion of Renewable Energy into fuels



Overall energy efficiency: 18–20%

Strategy (DIFFER)



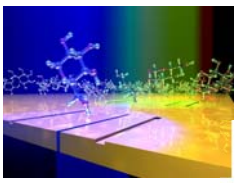
Artificial Leaf

Electro-chemistry/catalysis and plasma chemistry

DIFFER in its research strategy will focus on:

- *Direct conversion of solar energy by means of an **artificial leaf***
- *Indirect conversion of **renewable electricity** by means of **electro-chemistry/catalysis** or **plasma chemistry***

Overview of DIFFER Solar Fuels program



Presently 9 groups active:
total ~60 scientists and
research technicians

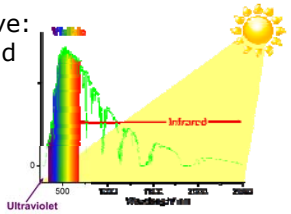
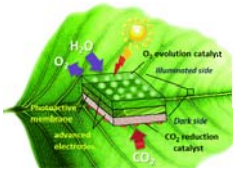
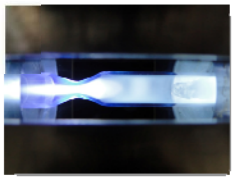
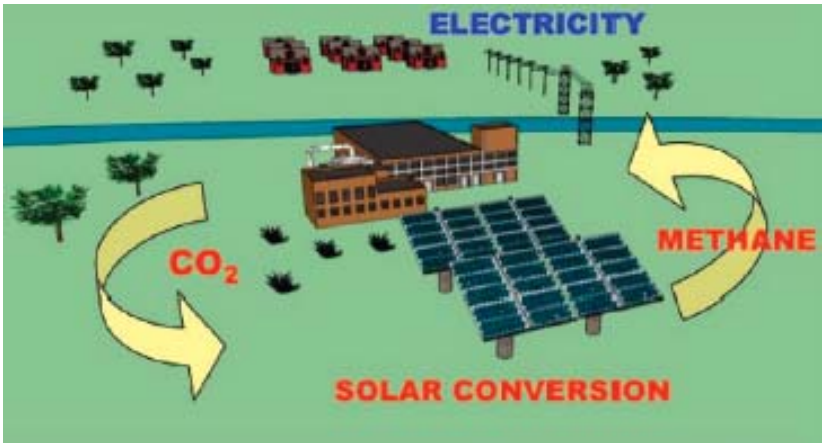


Photo)-Electrolysis
hoto-Electrocatalysis
rtificial Leaves

Solar Radiation
THz Radiation
μ-wave Radiation
Nanophotonics
Plasmonics



Plasma-Catalysis
Gas Separation Membranes



Circular approach for electricity generation