Renewable Energy

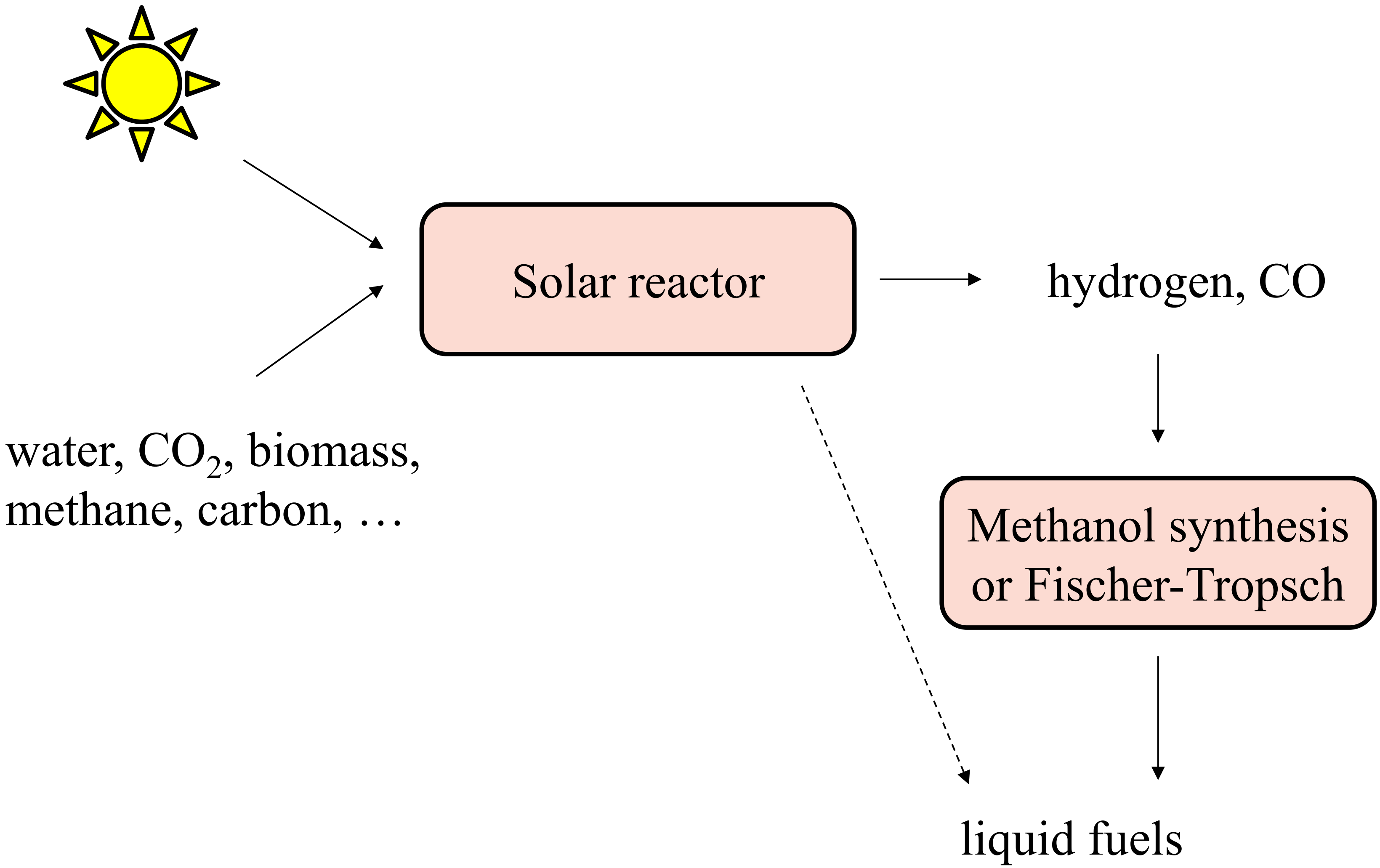
- Outline:
  - Conversion pathways solar-to-fuel
  - Hybrid pathways
  - Solar thermochemistry
  - Photochemistry

Learning outcomes of todays lecture

- Solar fuels:
  - How can solar energy be converted into fuels?
  - What is a hybrid pathway?
  - Why using fossil fuels together with solar energy?
  - What is solar thermochemistry and how can it be used for solar fuel processing?
  - Why is solar water-splitting via multi-step water splitting cycles preferred compared to direct thermolysis?
  - What is photoelectrochemistry and how can it be used for solar fuel processing?
  - What other chemical commodities or materials can be processed using solar energy?

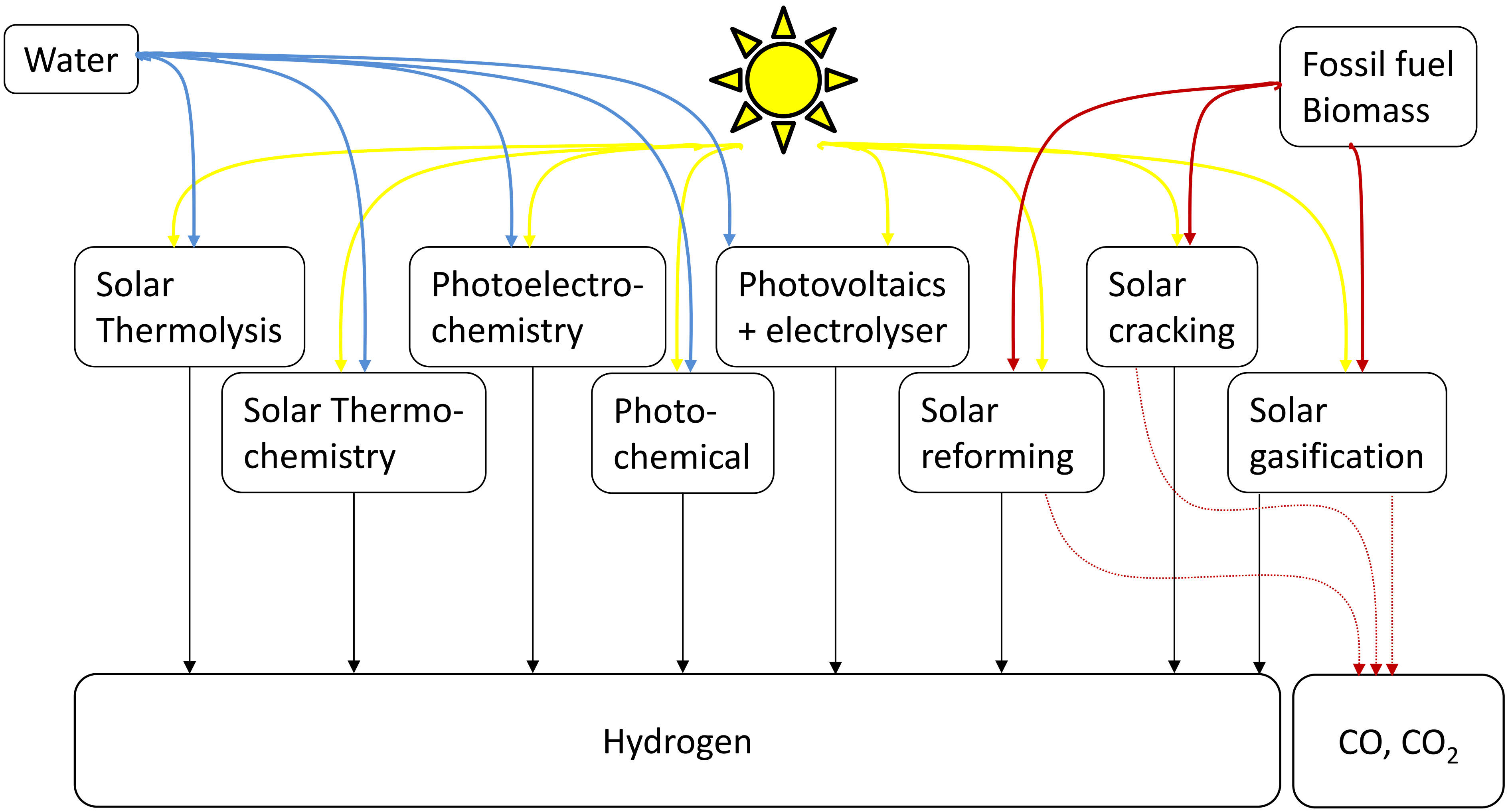
Conversion pathways

- Solar to fuels:



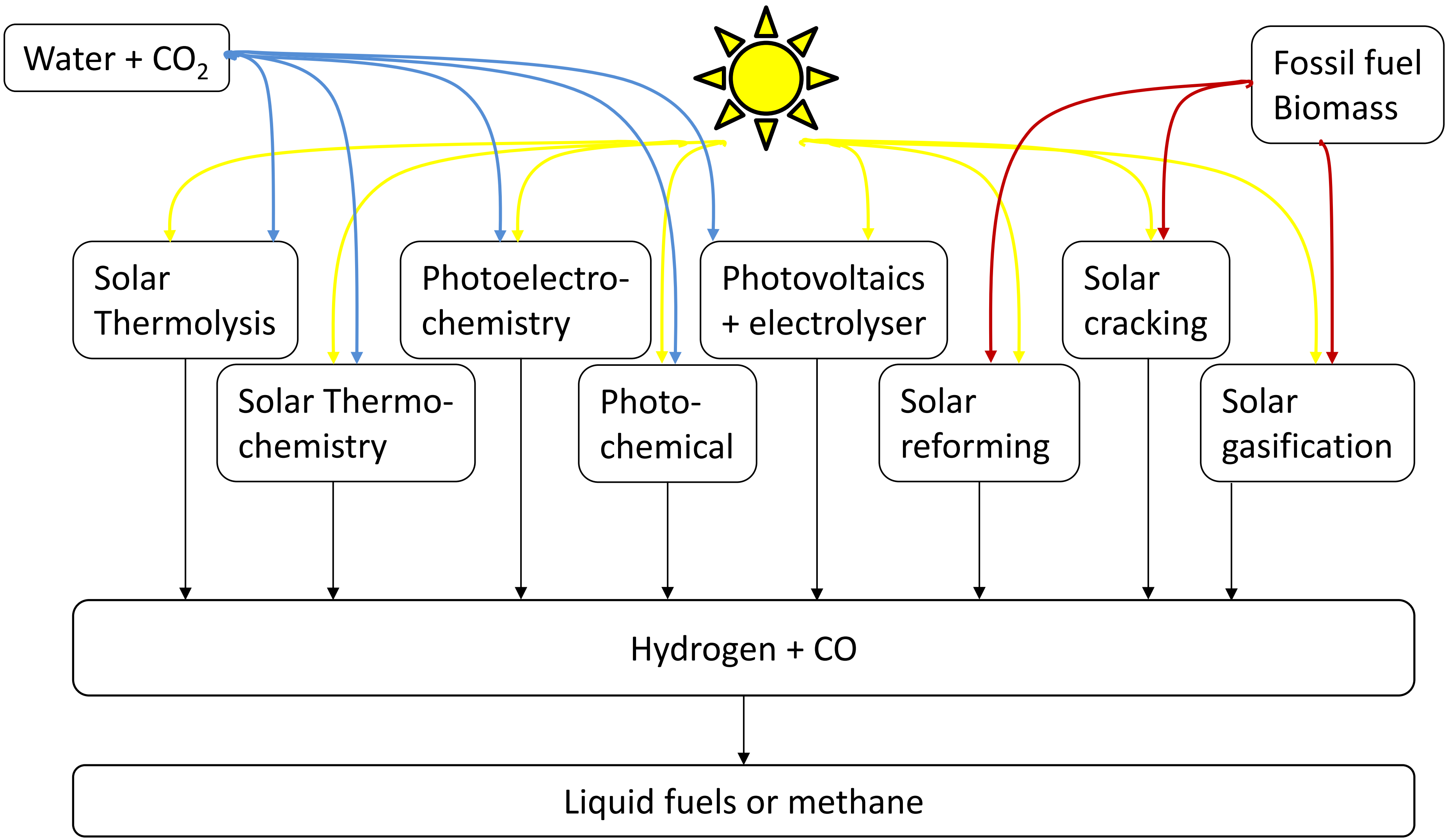
Conversion pathways

- Solar to hydrogen:



Conversion pathways

- Solar to synthesis gas (H_2+CO):

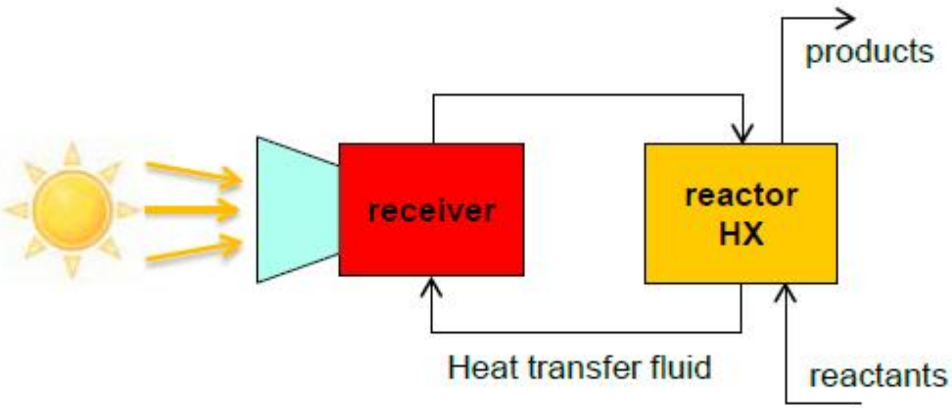


Conversion pathways

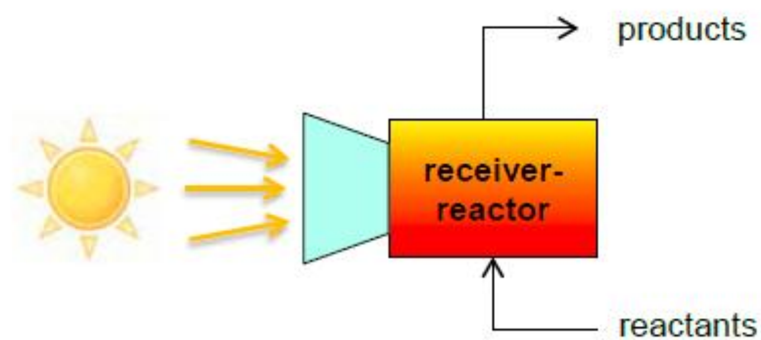
- General considerations:
  - What solar radiation concentration technology can be used (if needed)?
  - What solar reactor can be used and what are the requirements?
  - How can the sun be coupled into the process?
  - What can the reactor look like?

- Reactor concepts:

Decoupled receiver+reactor
Possibly with high-temperature storage



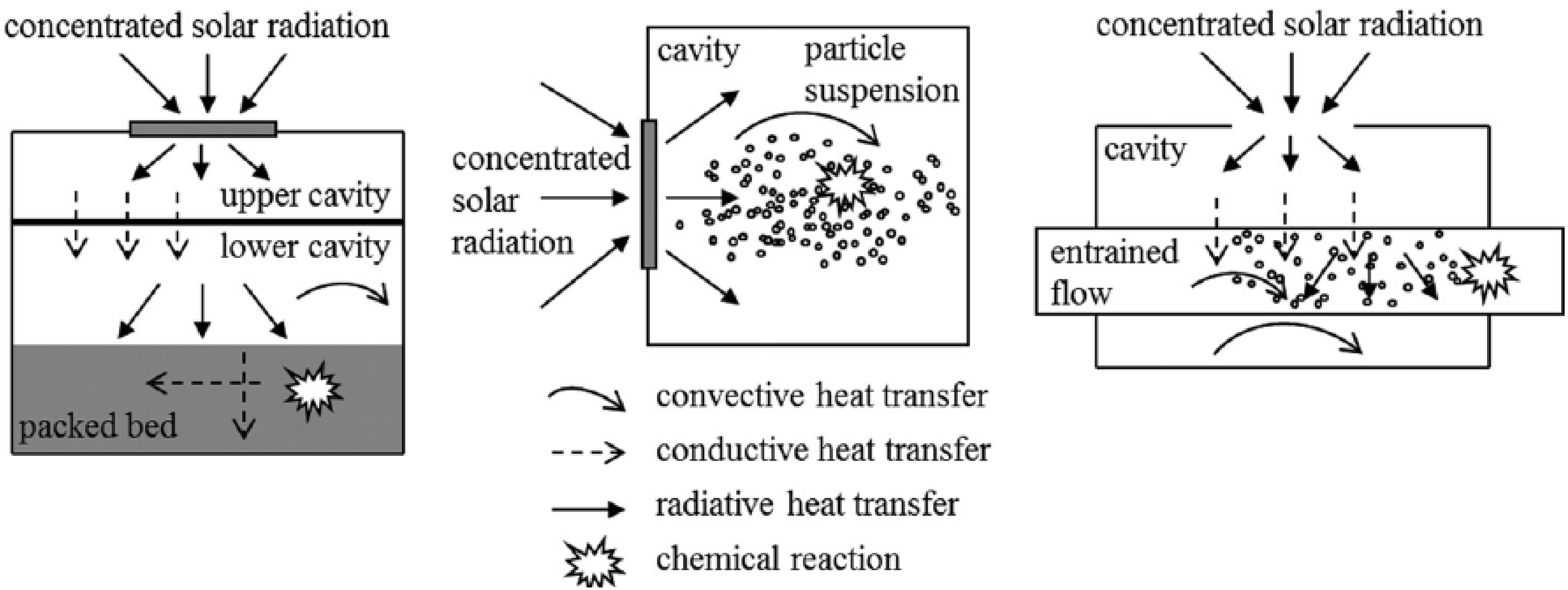
Coupled receiver-reactor



Conversion pathways

- Reactor concepts:

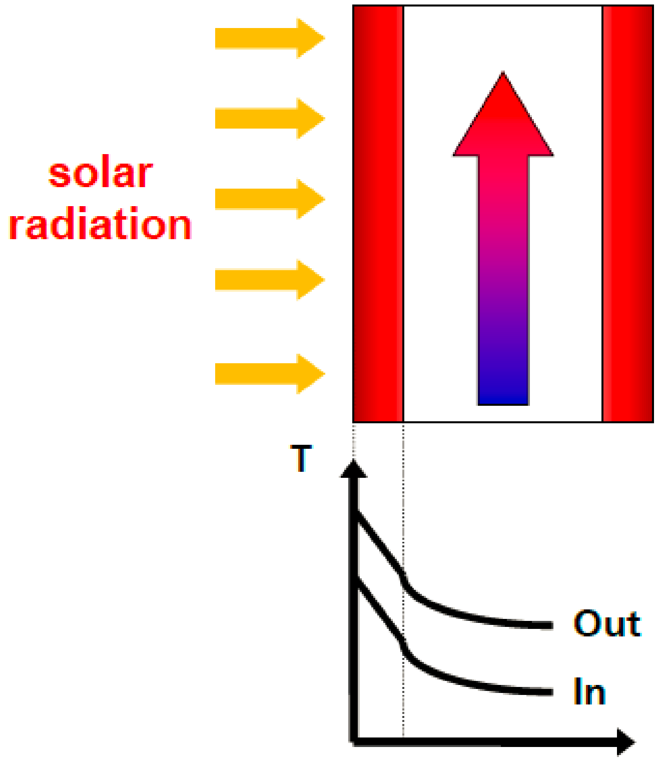
indirectly irradiated packed-bed | directly irradiated vortex-flow | indirectly irradiated entrained flow



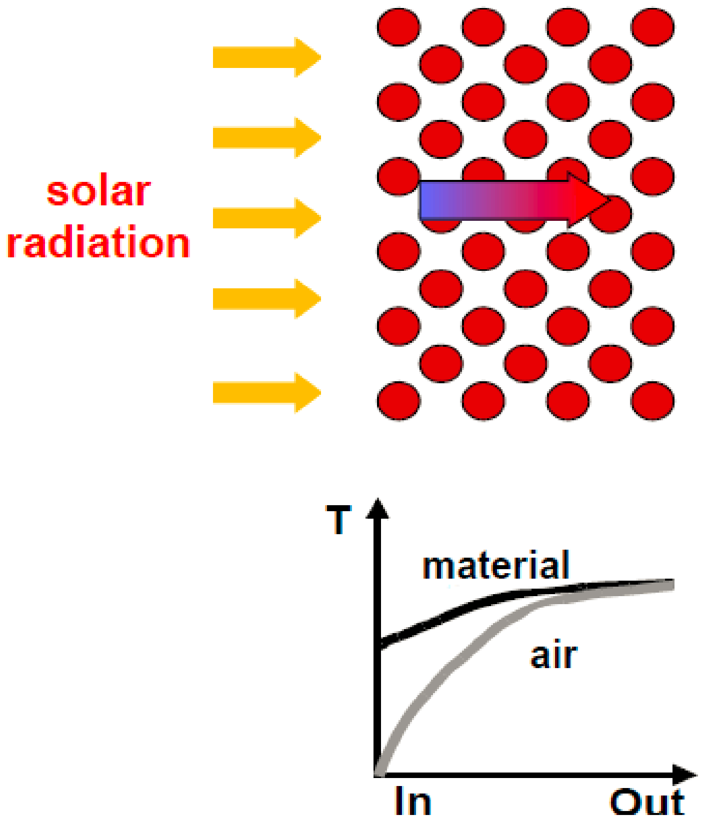
Conversion pathways

- Reactor concepts:

Tube receiver



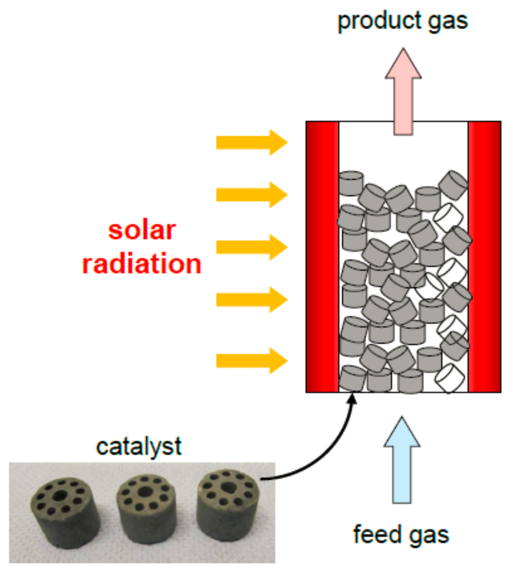
Volumetric receiver

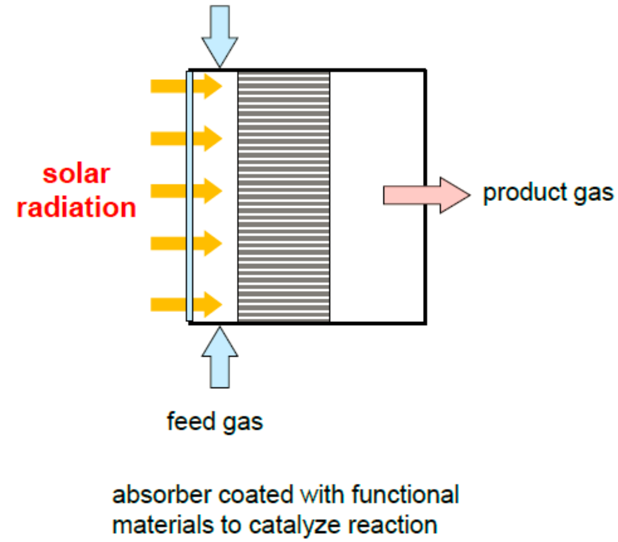


- Also: open versus closed systems

Conversion pathways

- Reactor concepts:
  - Stationary

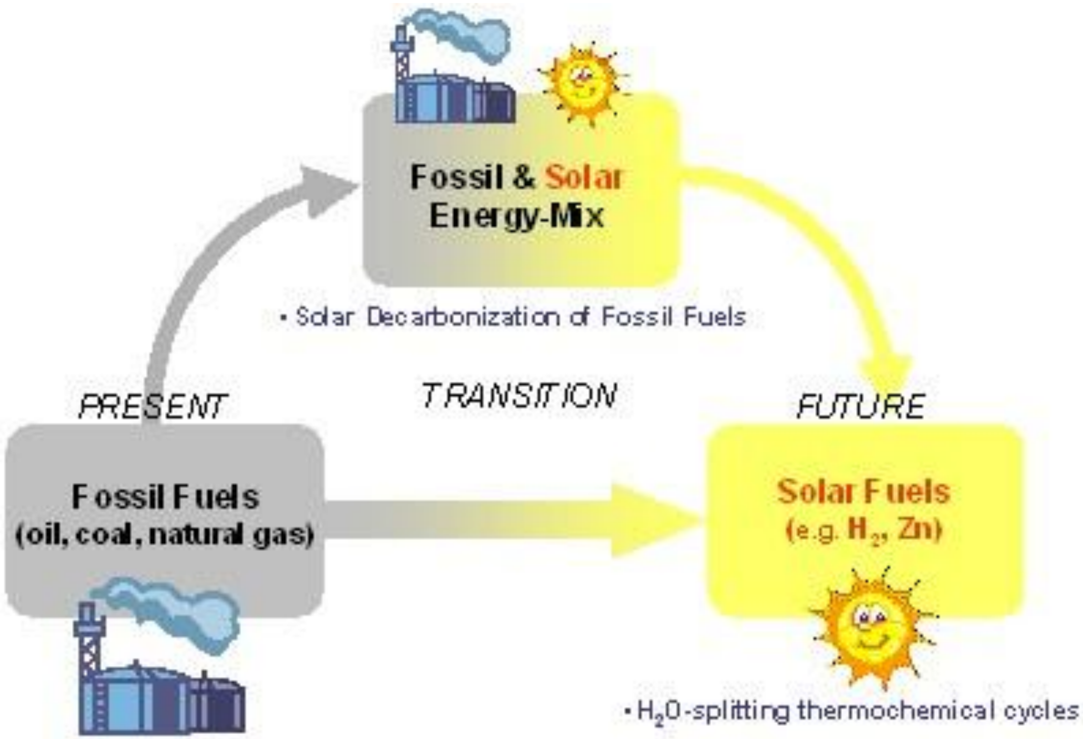




  - Moving:
    - Fluidized particle bed
    - Falling particle film
    - Rotating kiln
    - Moving particle bed

Hybrid solar conversion

- In the transition to a renewable future, hybrid pathways using fossil fuels exclusively as chemical source for the fuel production and solar energy as the process heat



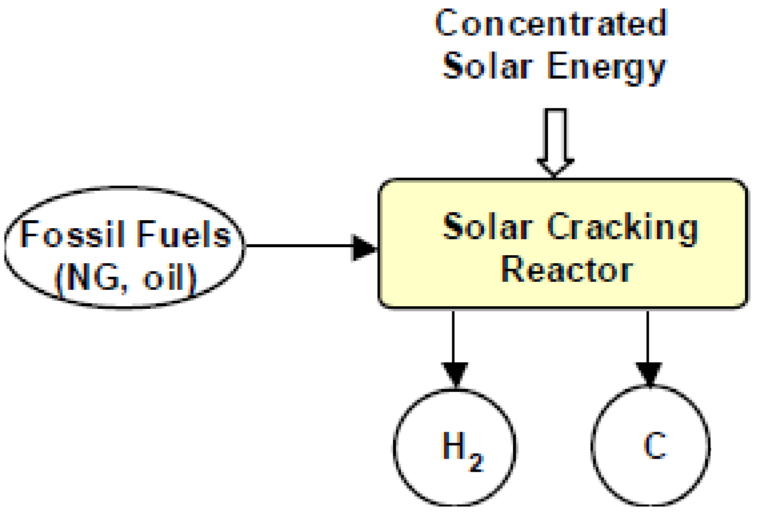
Hybrid solar conversion

- **Thermal cracking**: complex organic molecules such as heavy hydrocarbons are broken down into simpler molecules such as light hydrocarbons, by the breaking of carbon-carbon bonds in the precursors at high temperatures and by using catalysts

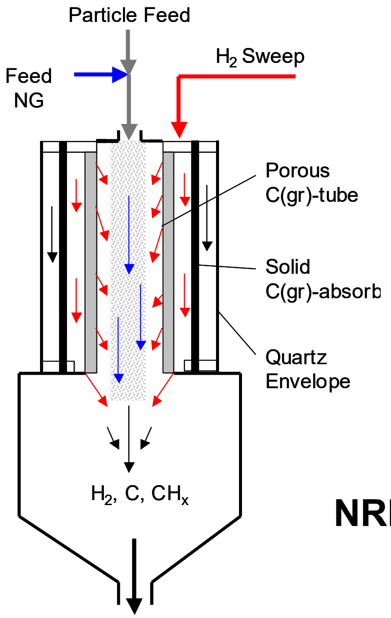
$$CH_4 \rightarrow C + 2H_2 \ (\Delta H = 74.85 \text{ kJ/mol})$$

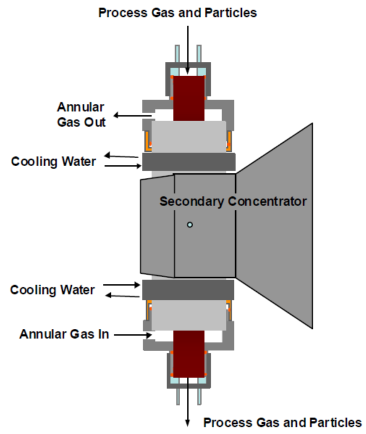
- General:

$$C_nH_m \rightarrow nC + (m/2)H_2$$

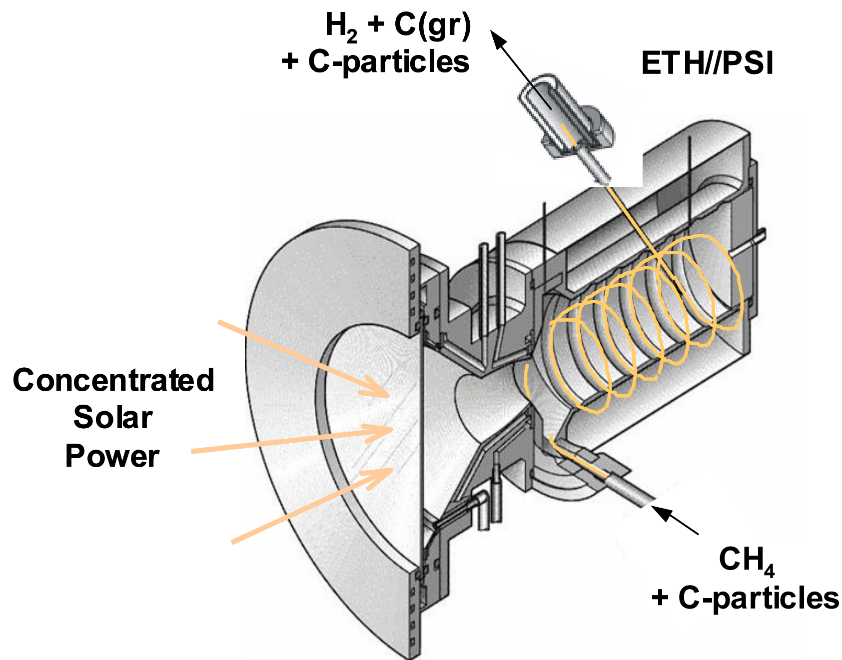


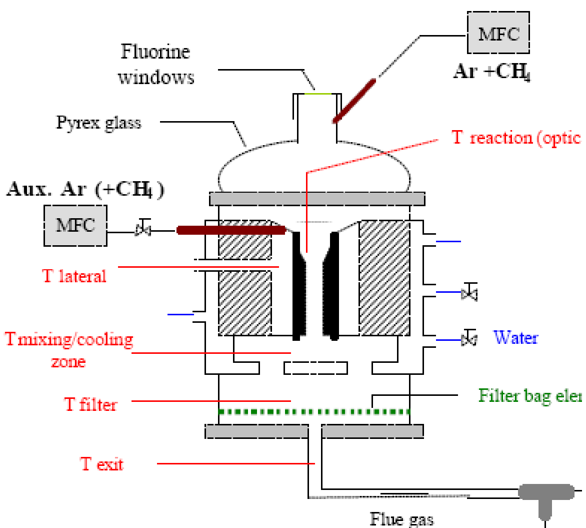
Solar Cracking of NG



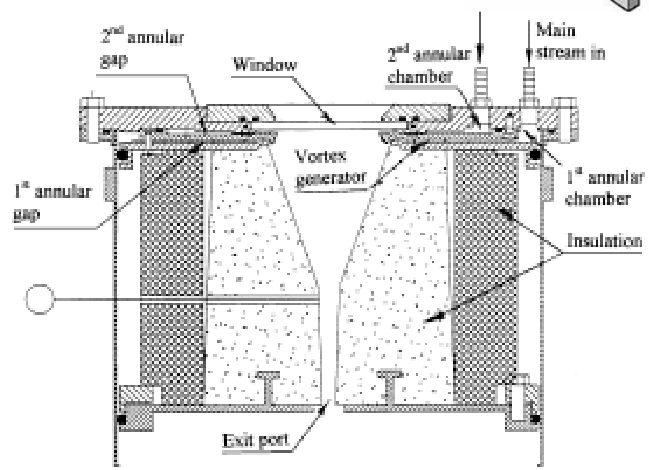


NREL/UC





CNRS



WIS

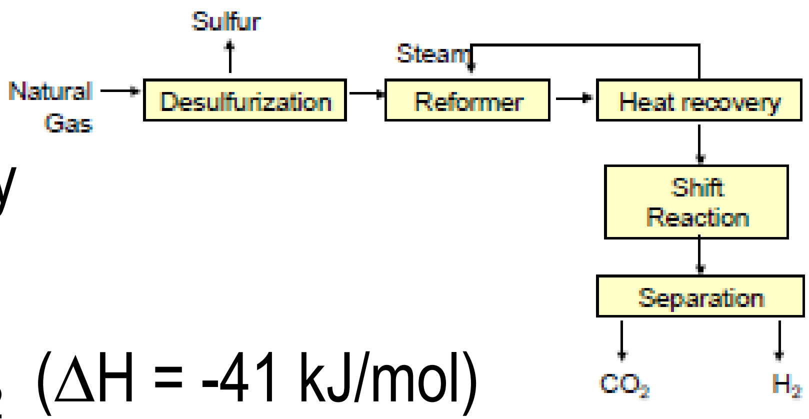
Int. J. Hydrogen Energy 34, 7676-7685, 2009.

Hybrid solar conversion

- **Steam reforming**: uses light hydrocarbon feedstock, usually methane, reacts it at elevated temperatures with steam and catalytically converts the feed into hydrogen

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \quad (\Delta H = 206 \text{ kJ/mol})$$

  - Operates around 700 – 925°C
  - Can achieve 65 – 75% efficiency



water gas shift: $CO + H_2O \rightarrow CO_2 + H_2 \quad (\Delta H = -41 \text{ kJ/mol})$

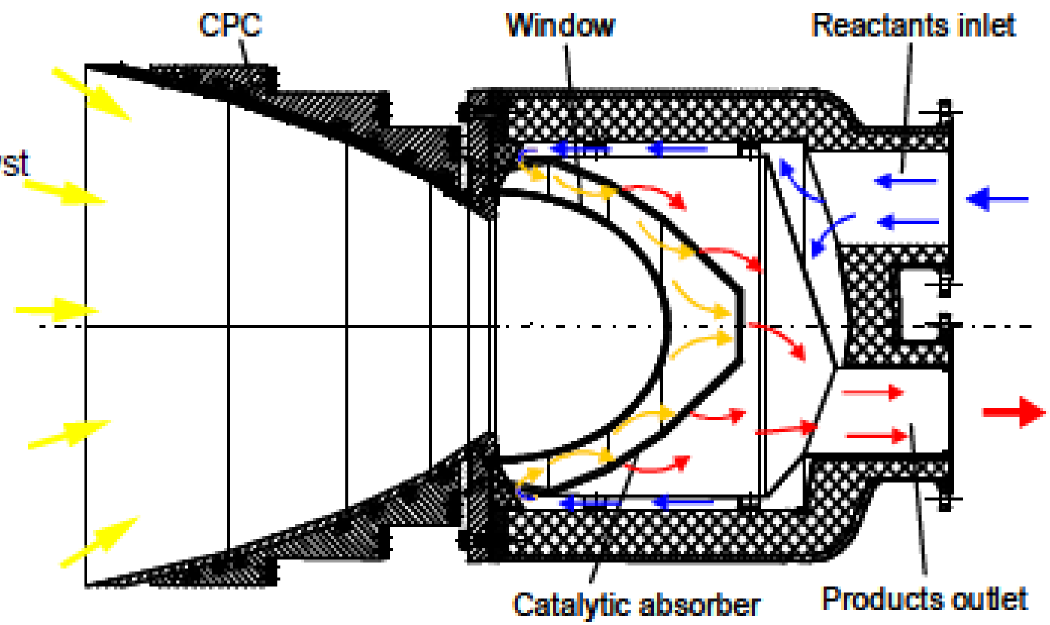
Hybrid solar conversion

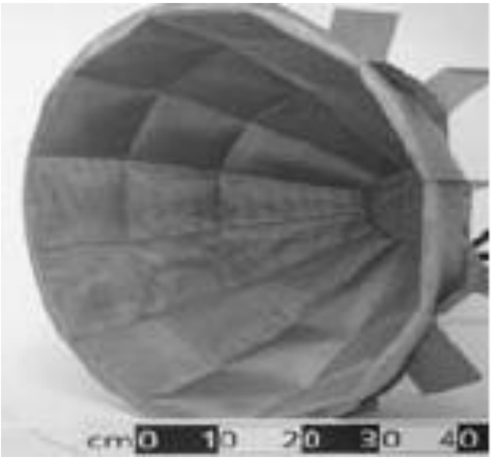
- Solar reactors developed for steam reforming

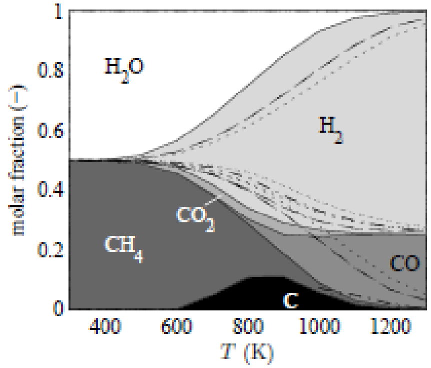
  Solar gasification of methane ($CH_4 + H_2O \rightarrow CO + 3H_2$), DLR

  SOLREF project

- 400 kW
- Rh catalyst
- 1100 K
- 10 bar







Hybrid solar conversion

- **Gasification**: uses carbonaceous materials, reacts it at high temperatures (>700 °C), without combustion, with a controlled amount of steam, oxygen, and/or CO_2. Results in CO, H_2, and CO_2.

- E.g. for coal, or C-sources

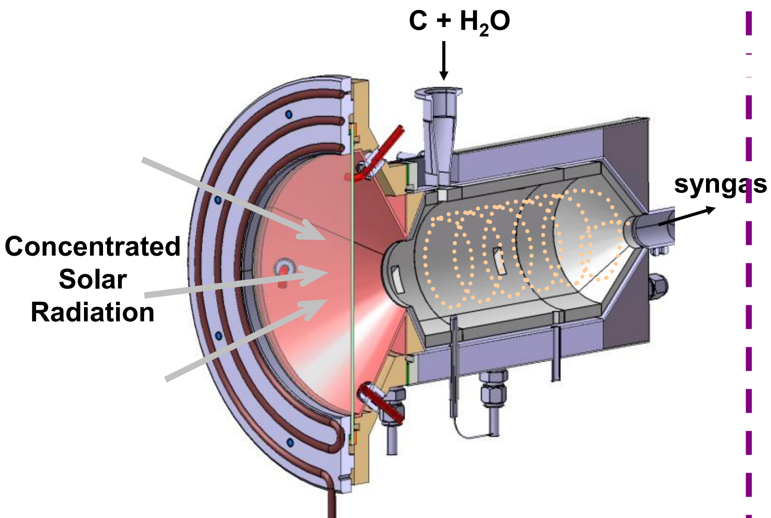
$$C + H_2O \rightarrow CO + H_2$$

- More realistic (especially for biomass, or C-waste):

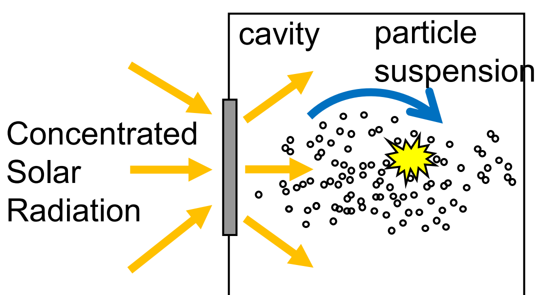
$$CH_xO_yS_zN_u + (1-y)H_2O = \frac{1}{2}(x + 2(1-y) - 2z)H_2 + CO + zH_2S + \frac{1}{2}uN_2$$

Solar Reactor Concepts

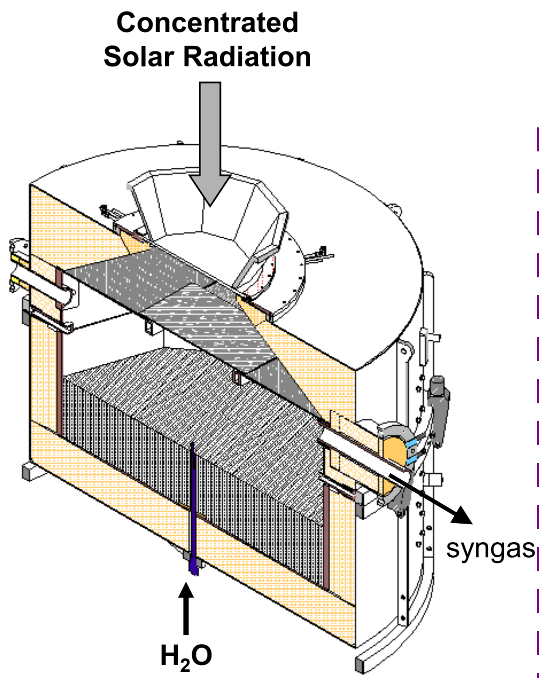
Direct-irradiation

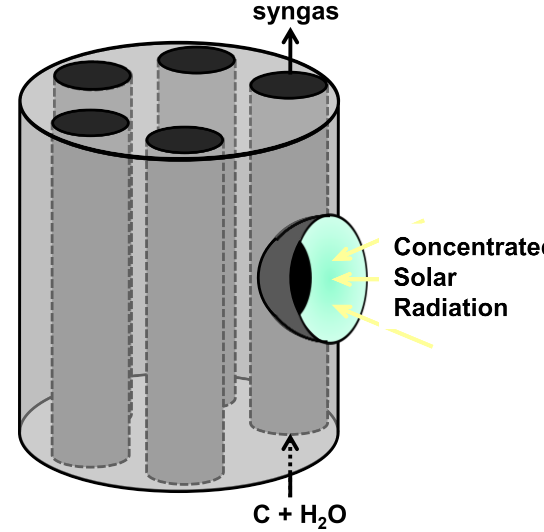


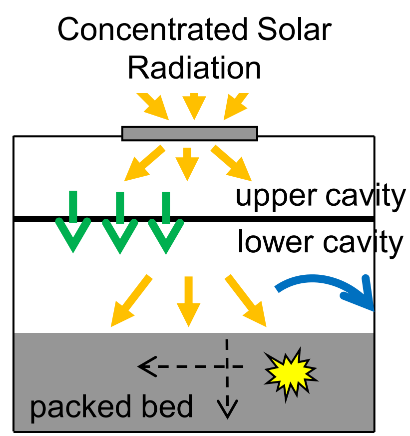
- convective heat transfer
- conductive heat transfer
- radiative heat transfer
- chemical reaction

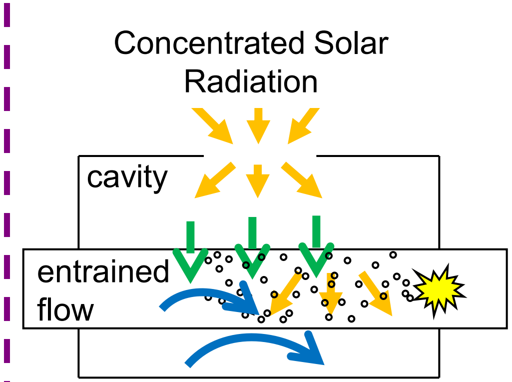


Indirect-irradiation









- *Energy & Env. Science* 4, 73-82, 2011

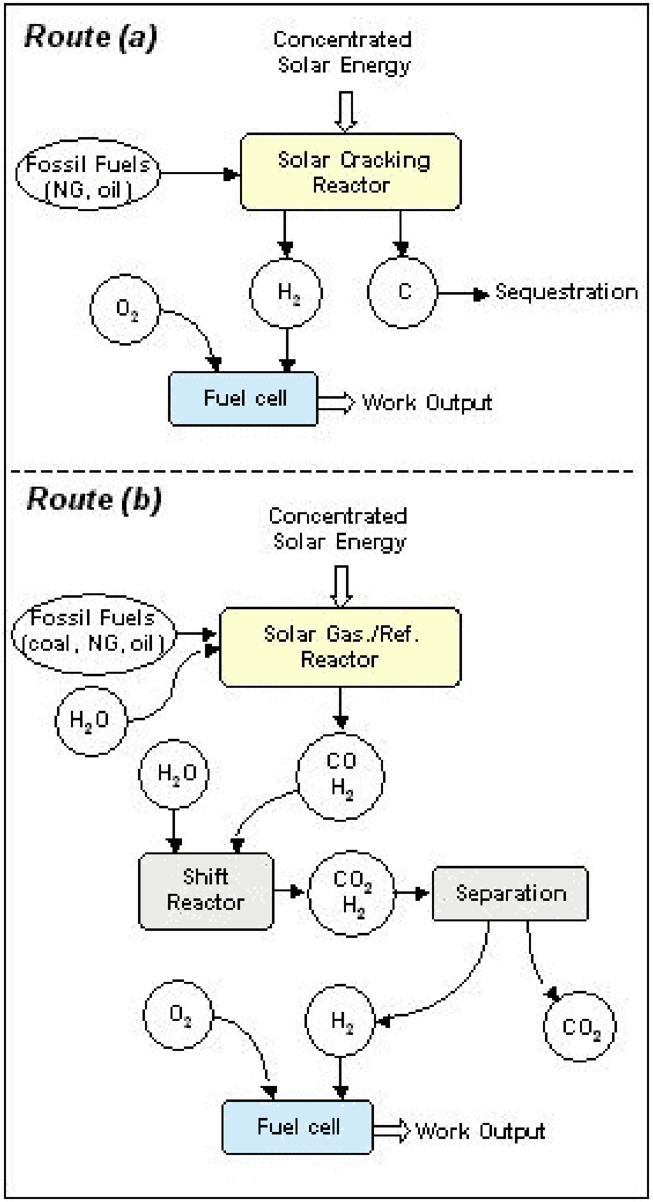
Hybrid solar conversion

- Hydrogen derived from fossil fuels has many impurities:
  - ~~From combustion: CO_2, CO, N_2~~
  - From the feedstock: sulfur

- Purification:
  - Desulfurization for gaseous feedstock: calcium-based slurries (SO_2 to sulfites and sulfates)
  - Desulfurization from solid/liquid feedstock: via catalysts into H_2S
  - ~~CO_2 removal:~~
    - temperature swing adsorption (solubility variation of CO_2 with temperature)
    - pressure swing adsorption (pressure dependent absorption of e.g. zeolites)
    - special membranes (cellulose)
  - CO removal from H_2 mixture: Hydrogen-permeable membranes made of metals (palladium)

Hybrid solar conversion

- Hybrid solar conversion
  - Advantage of hybrid process vs. conventional autothermal processes:
    - the gaseous products are not contaminated by combustion's by-products
    - the discharge of pollutants to the environment is reduced
    - the calorific value of the feedstock is upgraded
    - the fuel is decarbonized
    - there is no need for energy-intensive processing of pure oxygen



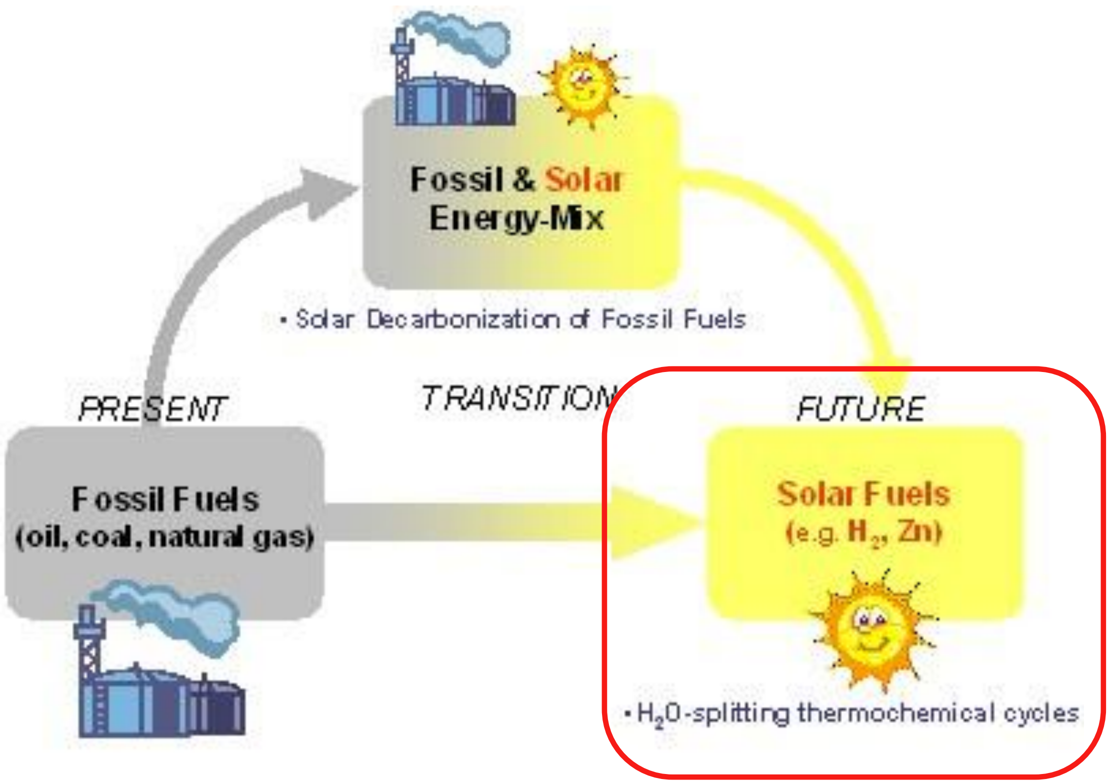
EPFL

Renewable Energy

- Outline:
  - Conversion pathways solar-to-fuel
  - Hybrid pathways
  - Solar thermochemistry
  - Photochemistry

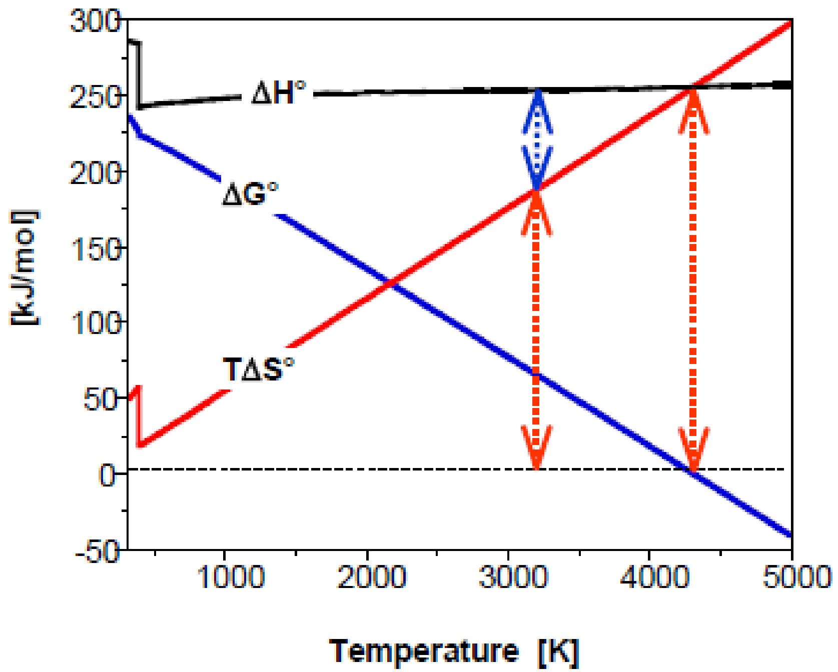
Solar thermolysis and thermochemistry

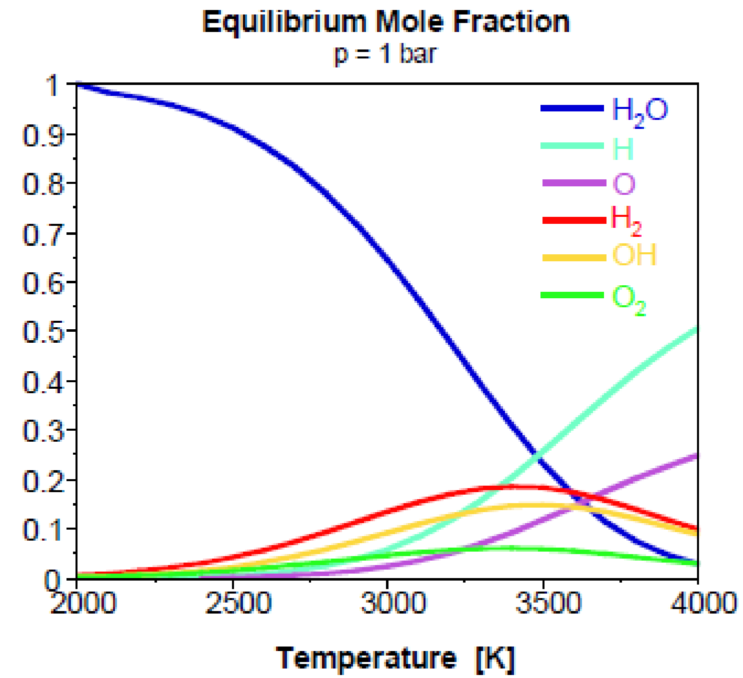
- In the transition to a renewable future, hybrid pathways using fossil fuels exclusively as chemical source for the fuel production and solar energy as the process heat



Solar thermolysis

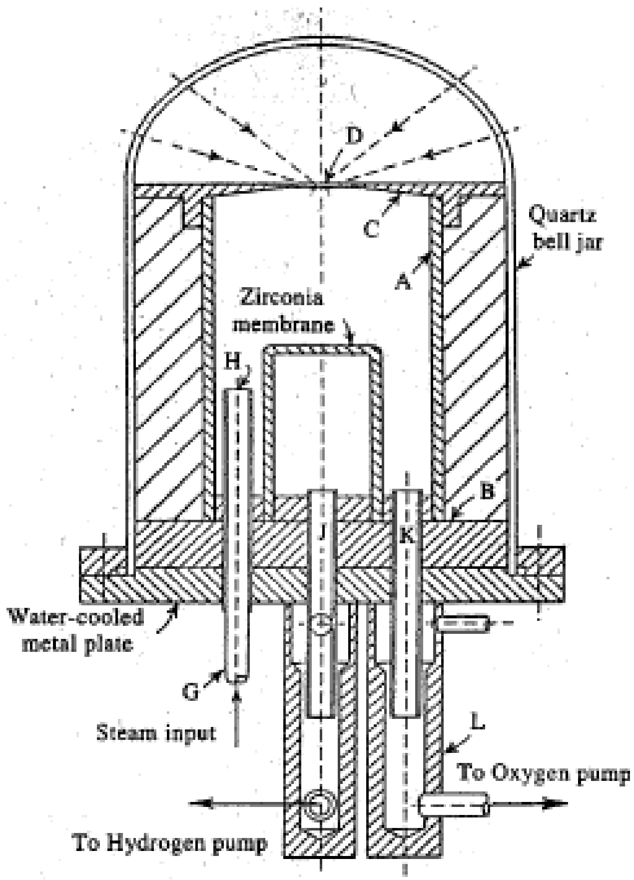
- Solar **thermolysis**
  - Solar energy is used as process heat of chemical reaction
  - Direct thermolysis of water: $H_2O \rightarrow 1/2O_2 + H_2$



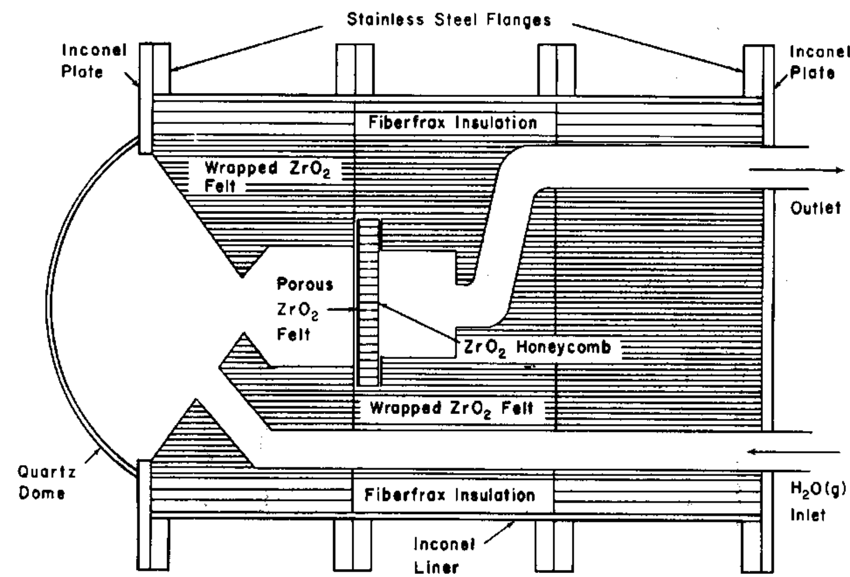


Solar thermolysis

- Reactor concept for solar thermolysis
  - Product separation by:
    - High temperature membranes
    - Rapid quenching of products

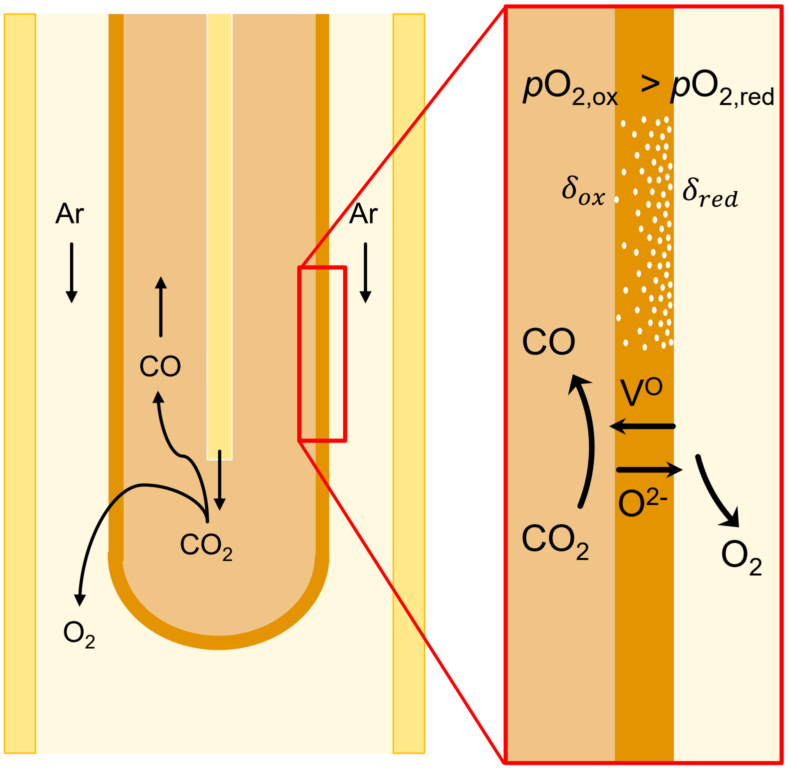


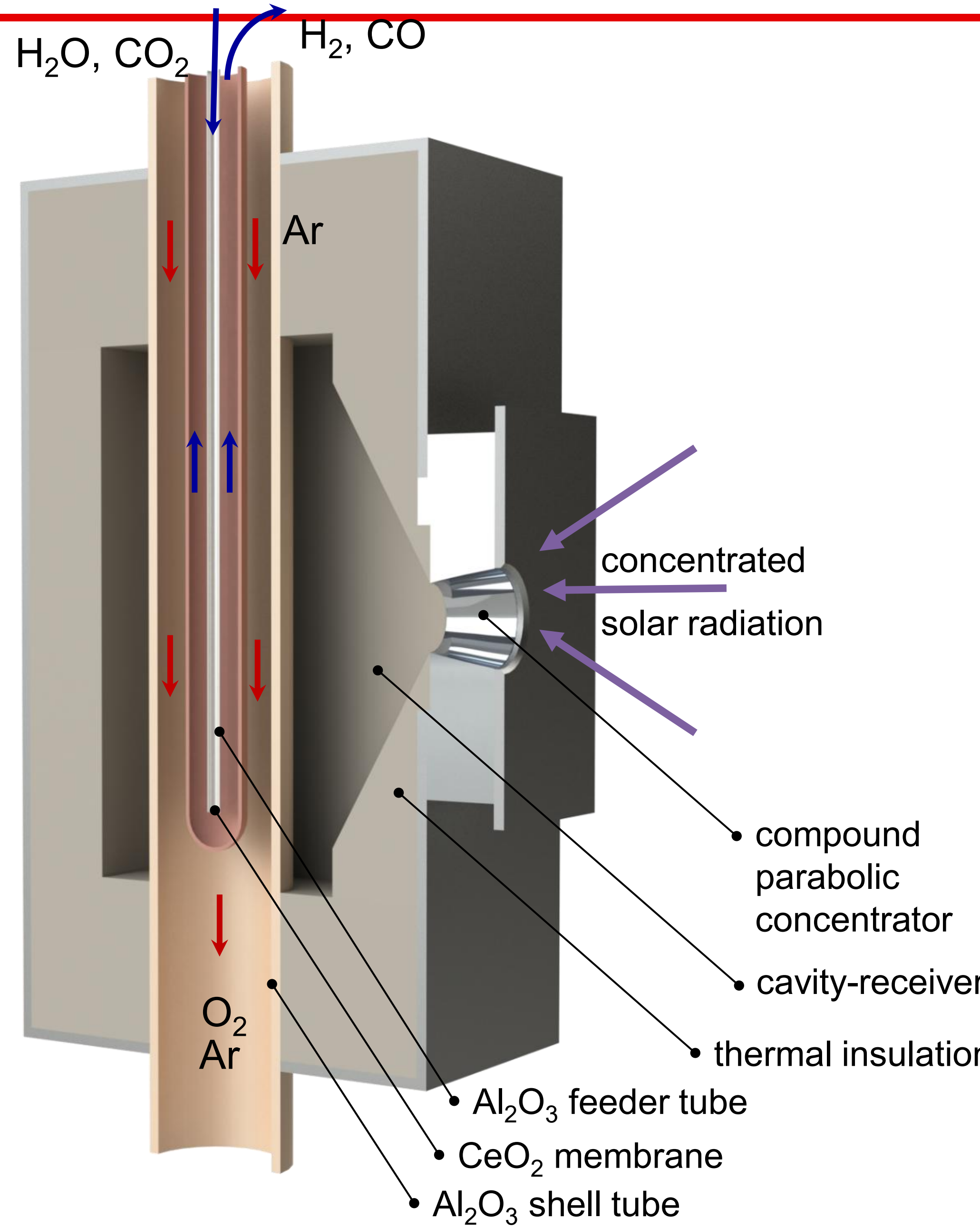
Kogan et al., *Int. J. Hydrogen Energy* **23**, 89-98, 1998.



Fletcher E., *J. Solar Energy Engineering* **123**, 63-74, 2001

Solar Thermolysis

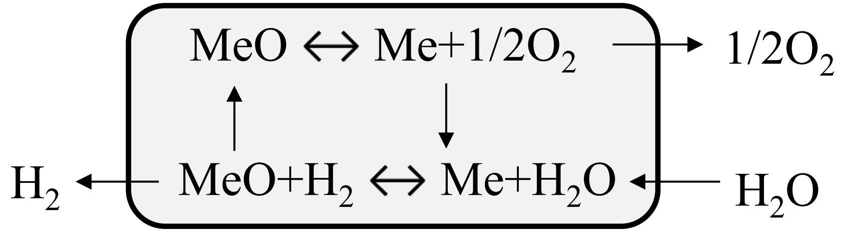




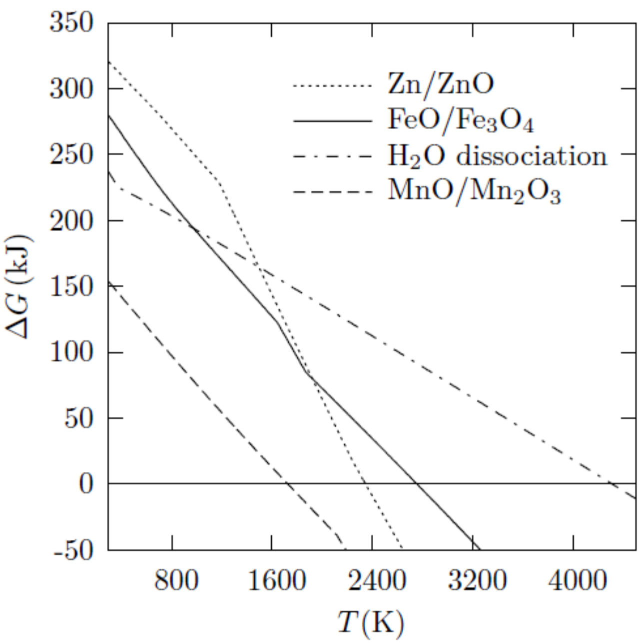
Joule, Vol. 1, pp. 146-154, 2017
Reaction Chemistry & Engineering, Vol. 4, pp. 1431–1438, 2019

Solar thermochemistry

- Solar **thermochemical** cycles
  - Solar energy is used as process heat of chemical reaction
  - Multi-step water-splitting reactions:



  - Omit explosive hydrogen and oxygen mixture since produced in separate steps
  - Requires lower temperatures
  - Possible redox pairs (Me/MeO):
    - Fe_2O_4/FeO
    - Ce_2O_3/CeO_2,
    - ZnO/Zn
    - SnO/SnO_2 …



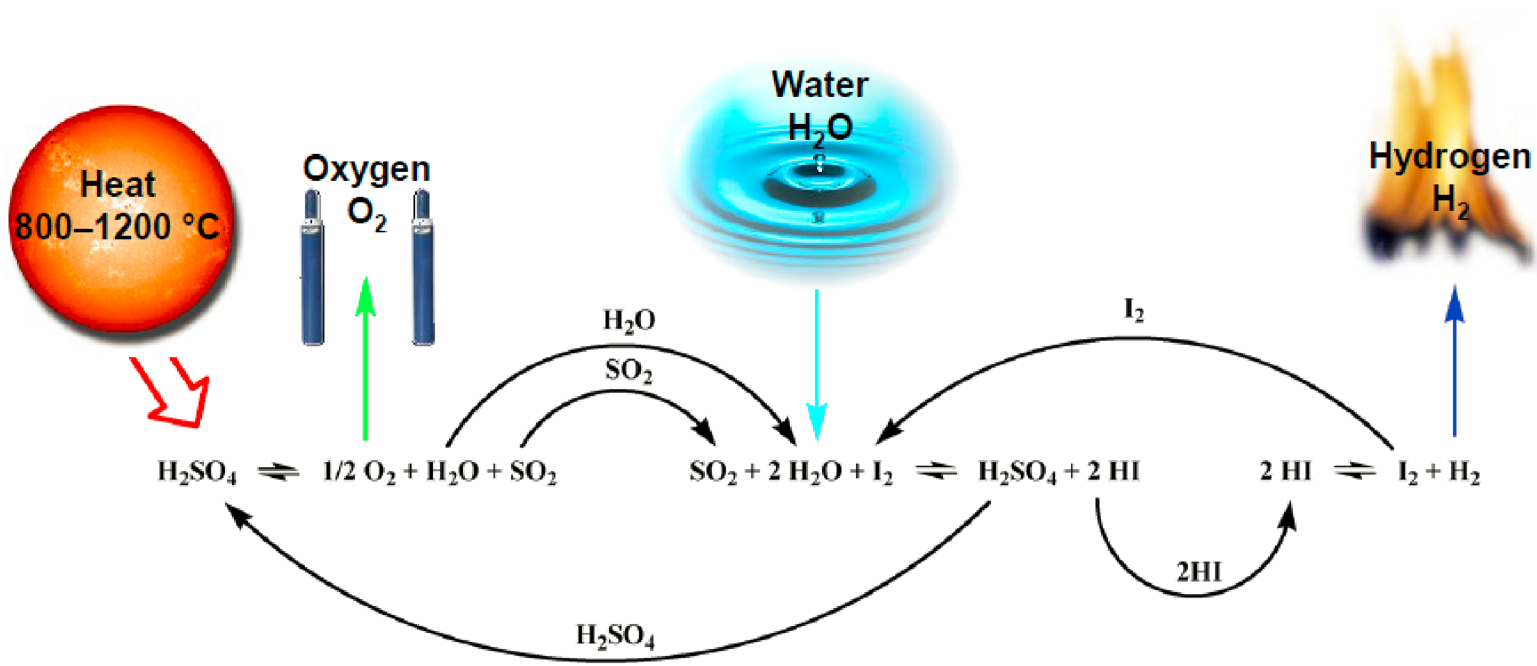
Solar thermochemistry

- Possible redox pairs for two-step cycles:

Cycle	Reactions	Cycle	Reactions
Zn/ZnO	$ZnO \rightarrow Zn + O_2$	SoO_2/SiO	$SiO_2 \rightarrow SiO + 1/2\ O_2$
	$Zn + H_2O \rightarrow ZnO + H_2$		$SiO + H_2O \rightarrow SiO_2 + H_2$
Fe_3O_4/FeO	$Fe_3O_4 \rightarrow 3\ FeO + ½\ O_2$	W/WO_3	$WO_3 \rightarrow W + 3/2\ O_2$
	$3\ FeO + H_2O \rightarrow Fe_3O_4 + H_2$		$W + 3H_2O \rightarrow WO_3 + 3H_2$
In_2O_3/In_2O	$In_2O_3 \rightarrow In_2O + 1/2\ O_2$	Hg/HgO	$Hg + H_2O \rightarrow HgO + H_2$
	$In_2O + 2H_2O \rightarrow In_2O_3 + 2H_2$		$HgO \rightarrow Hg + 1/2O_2$
SnO_2/Sn	$SnO_2 \rightarrow Sn + O_2$	Cd/CdO	$Cd + H_2O \rightarrow CdO + H_2$
	$Sn + 2H_2O \rightarrow SnO2 + 2H_2$		$CdO \rightarrow Cd + 1/2O_2$
$MnO/MnSO_4$	$MnSO_4 \rightarrow MnO + SO_2 + 1/2O_2$	CO/CO_2	$CO + H_2O \rightarrow CO_2 + H_2$
	$MnO + H_2O + SO_2 \rightarrow MnSO_4 + H_2$		$CO_2 \rightarrow CO + 1/2O_2$
$FeO/FeSo_4$	$FeSO_4 \rightarrow FeO + SO_2 + 1/2O_2$	Ce_2O_3/CeO_2	$CeO_2 \rightarrow Ce_2O_3$
	$FeO + H_2O + SO_2 \rightarrow FeSO_4 + H_2$		$Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2$
$CoO/CoSO_4$	$CoSO_4 \rightarrow CoO + SO_2 + 1/2O_2$	Mg/MgO	$MgO \rightarrow Mg + 1/2O_2$
	$CoO + H_2O + SO_2 \rightarrow CoSO_4 + H_2$		$Mg + H_2O \rightarrow MgO + H_2$
$Fe_3O_4/FeCl_2$	$Fe_3O_4 + 6HCl \rightarrow 3FeCl_2 + 3H_2O + 1/2O_2$	SnO/SnO2	$SnO_2 \rightarrow SnO + 1/2O_2$
	$3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2$		$SnO + H_2O \rightarrow SnO_2 + H_2$
Mo/Mo_2	$MoO_2 \rightarrow Mo + O_2$		
	$Mo + 2H_2O \rightarrow MoO_2 + 2H_2$		

Solar thermochemistry

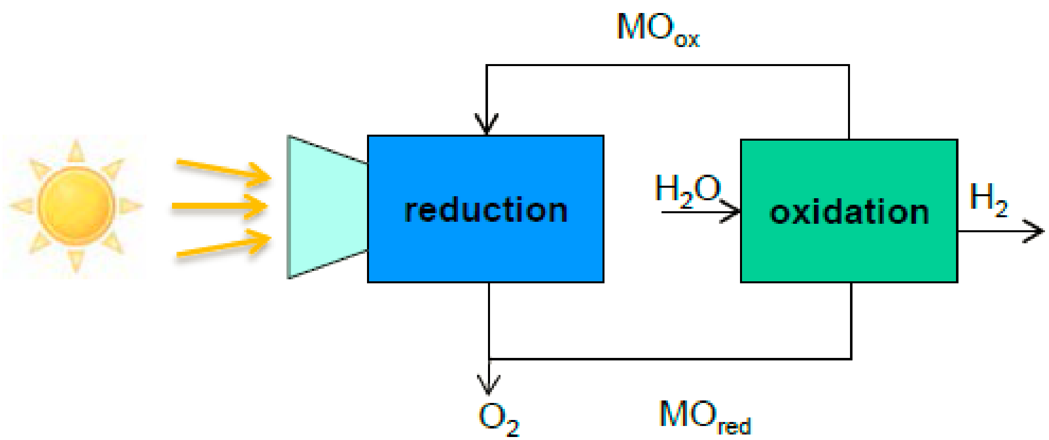
- Three-step water-splitting cycles, e.g. sulfur-iodine:
  - further lower temperatures
  - but run in corrosive environment



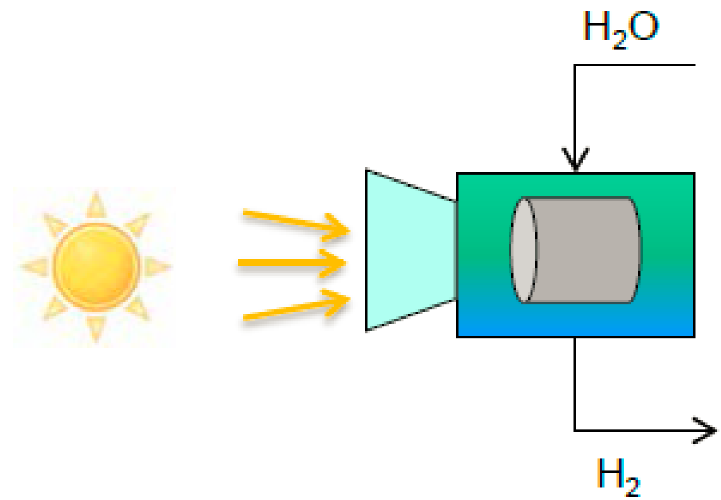
Solar thermochemistry

- Reactor concepts: two-step cycles

Moving material

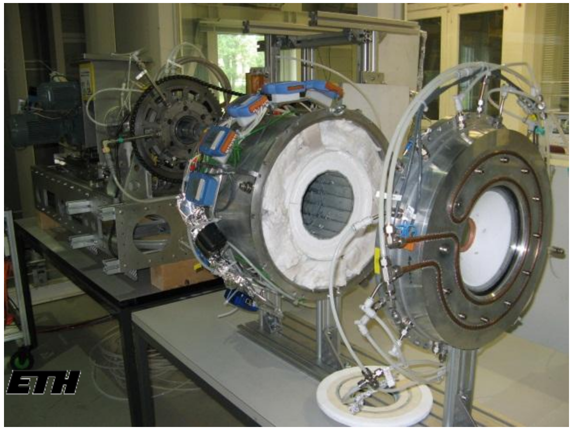


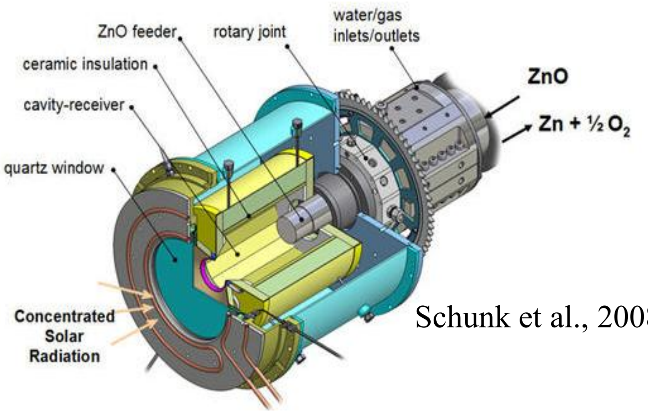
Stationary material



Solar thermochemistry

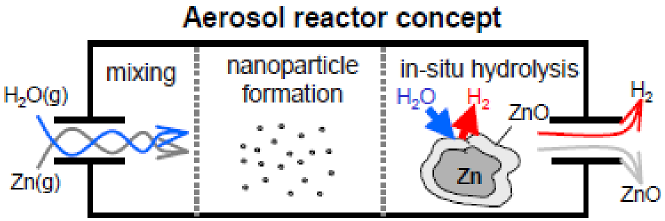
- Zn/ZnO-based proposed reactors, e.g. at ETH Zürich and PSI:
  - High-temperature reactor
    - – 10 kW reactor
    - – Reactor temperature: 2000 K
    - – Peak concentration: 5800 suns





Schunk et al., 2008.

  - Hydrolysis reactor:
    - – Reactor temperature: 1263 K

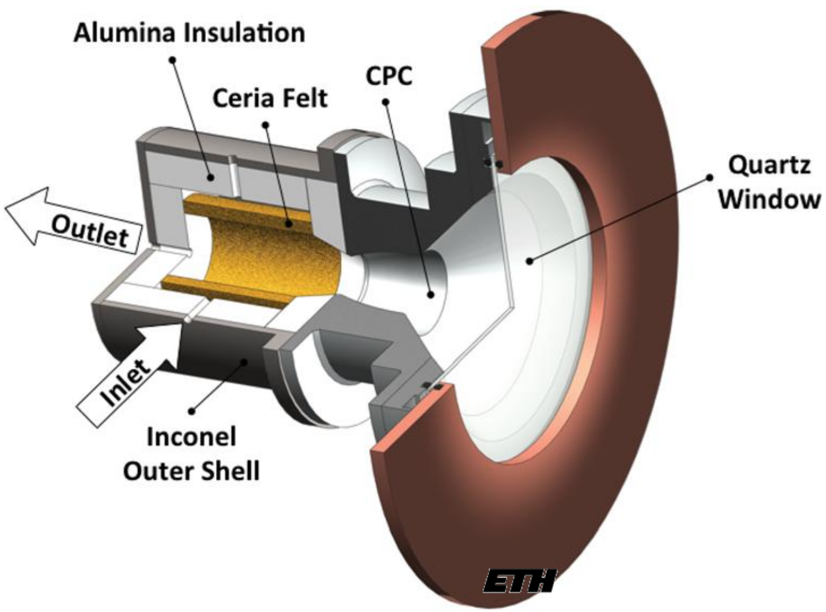


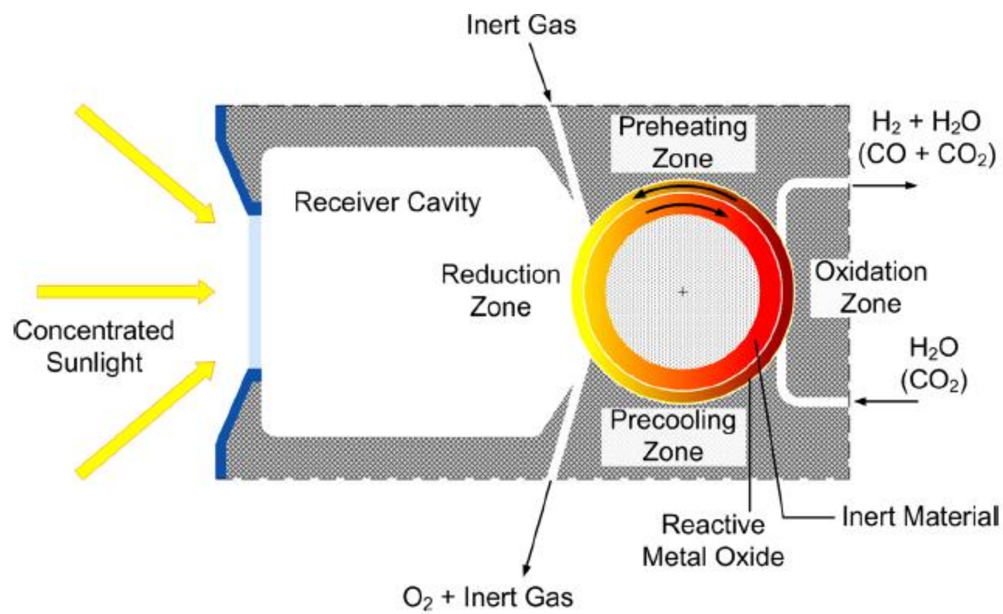
Melchior et al., 2009.

Solar thermochemistry

- Ceria-based proposed reactors, e.g.:

ETH Zürich | University of Minnesota



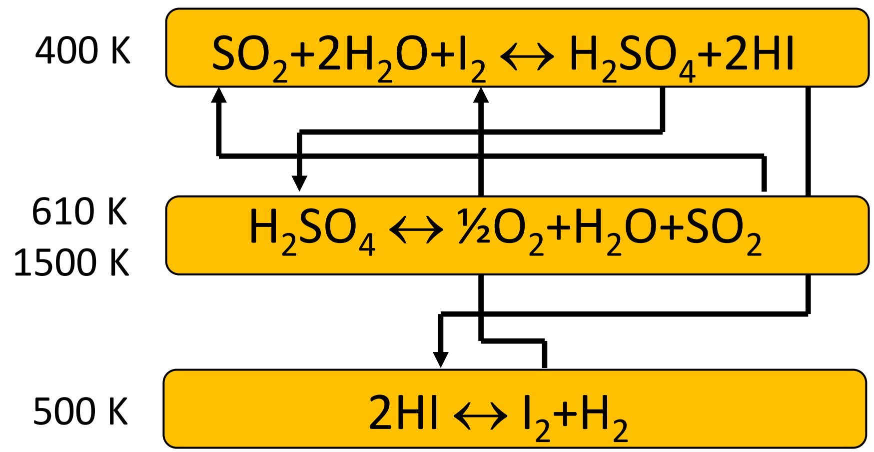


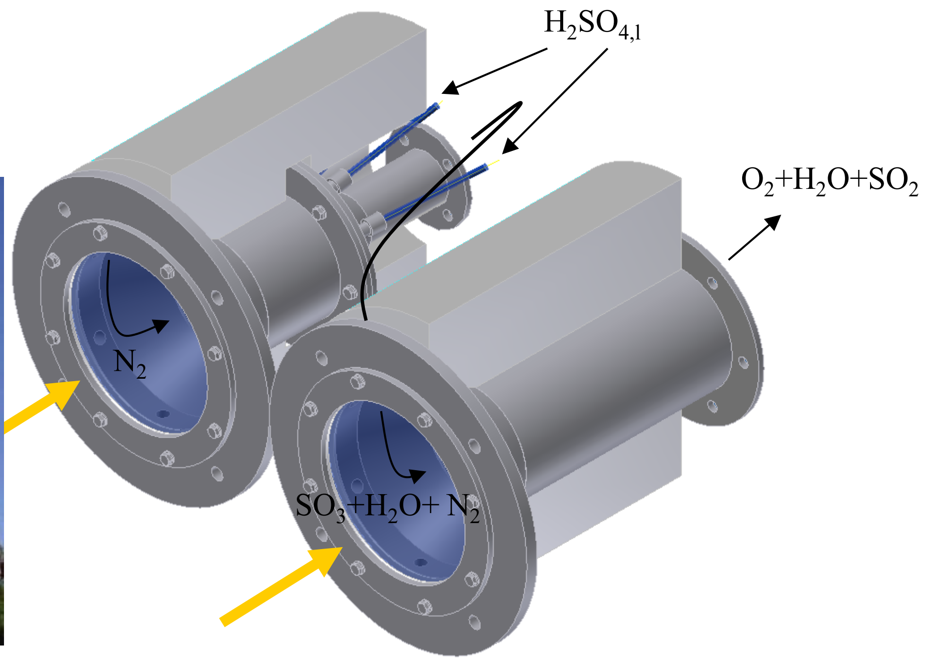
Temperature in reduction reaction: ~ 1800 K

Temperature in oxidation reaction: ~ 1200 K

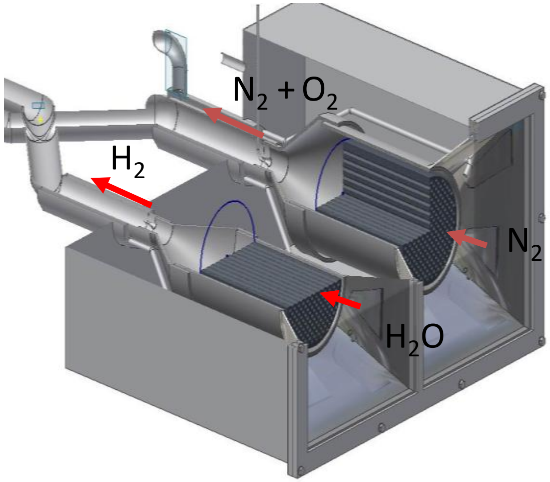
Solar thermochemistry

- SI-cycle, DLR Germany

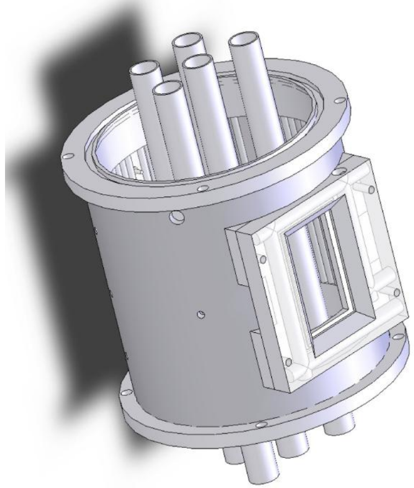




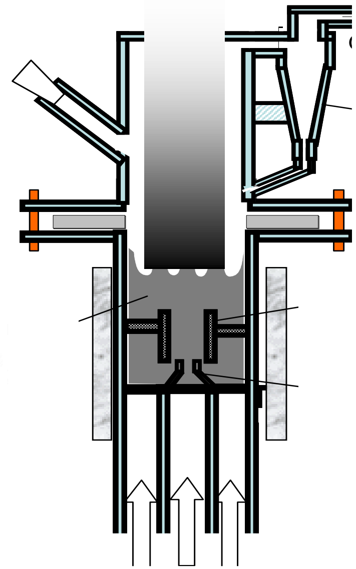
DLR, Germany
$ZnFe_2O_4$



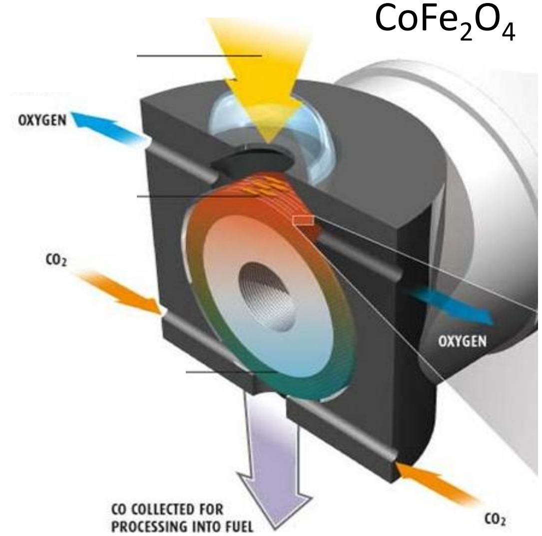
U. of CO, USA
$NiFe_2O_4$



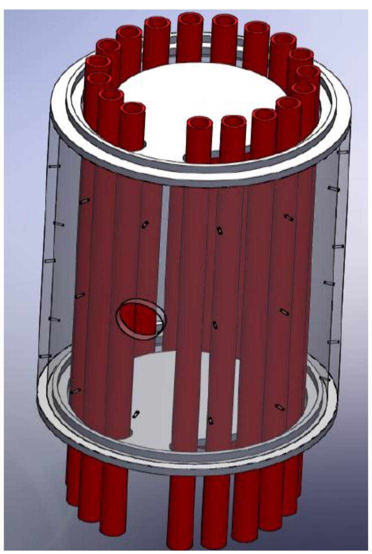
Niigata U., Japan
$NiFe_2O_4$



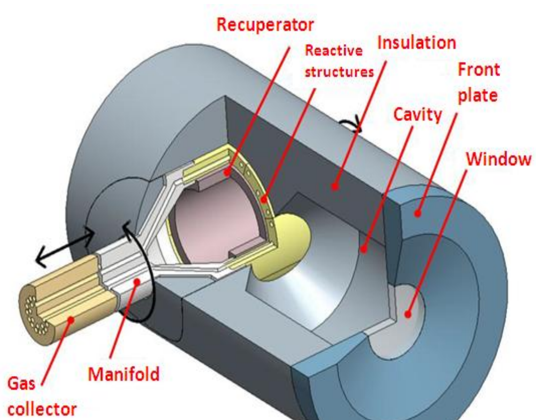
SNL, USA
$CoFe_2O_4$



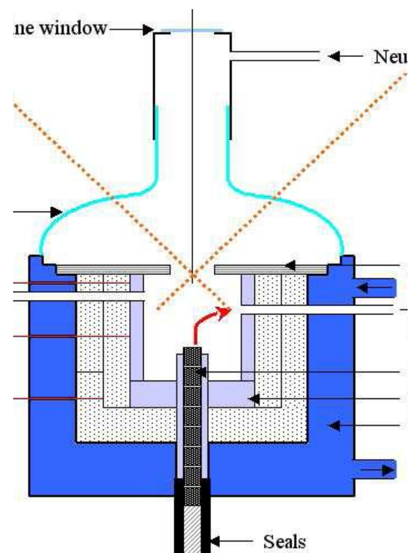
U. of FL, USA
$CoFe_2O_4$



U. of MN, USA
CeO_2



CNRS, France
ZnO, SnO_2



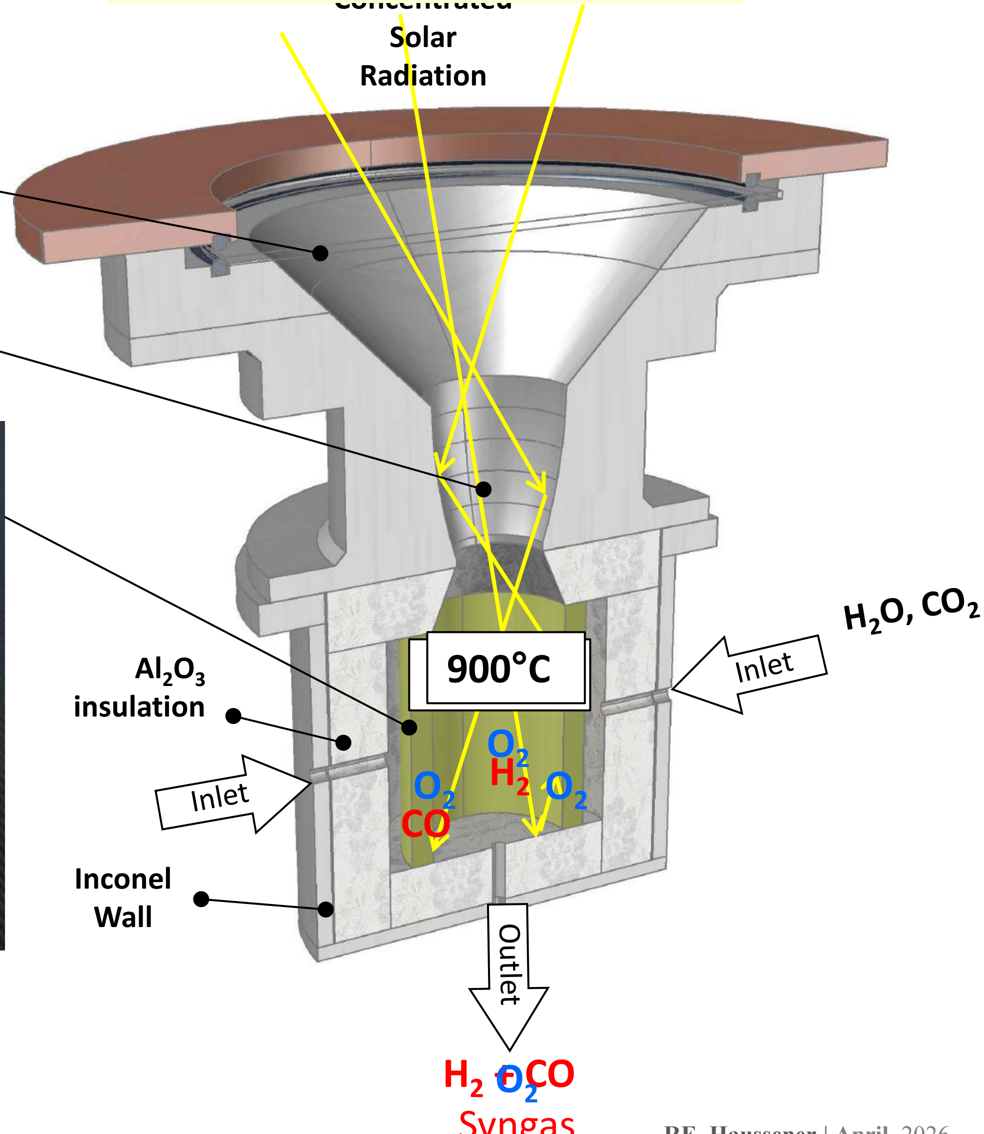
SNL, USA
CeO_2

Solar Reactor Technology

2nd step: Oxidation

$$CeO_{2-\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$
$$CeO_{2-\delta} + \delta CO_2 \rightarrow CeO_2 + \delta CO$$

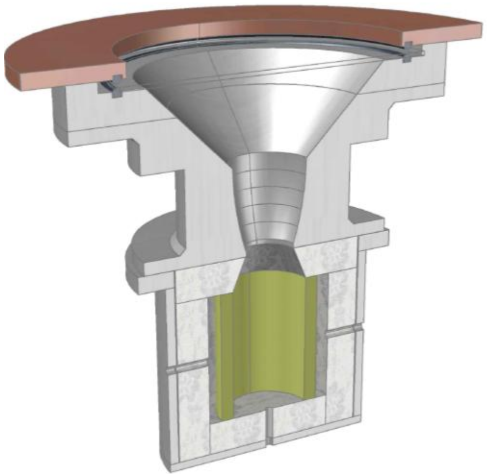
RPC



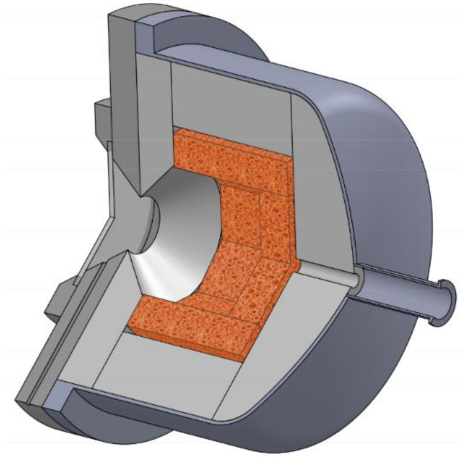
- Science 330, 1797-1801, 2010.
- *Energy & Env. Science* 5, 6098-6103, 2012.
- Energy & Fuels 26, 7051–7059, 2012.

Solar Reactor Technology

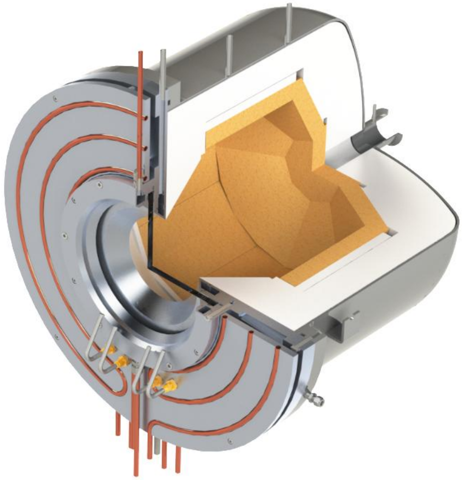
Generation 0
2 kW Lab-scale
Monoliths



Generation 1
4 kW Lab-scale
RPC



Generation 2
50 kW Pilot-scale
RPC

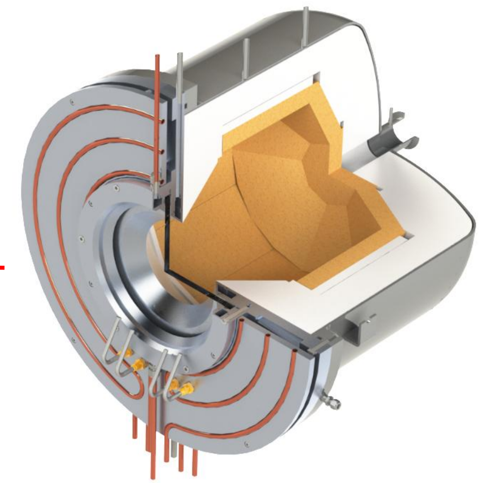


- Science 330, 1797-1801, 2010.
- Energy & Env. Science 10;1142-1149, 2017.

Solar Reactor Technology

EU Sun-to-Liquid Project

Generation 2
50 kW Pilot-scale
RPC



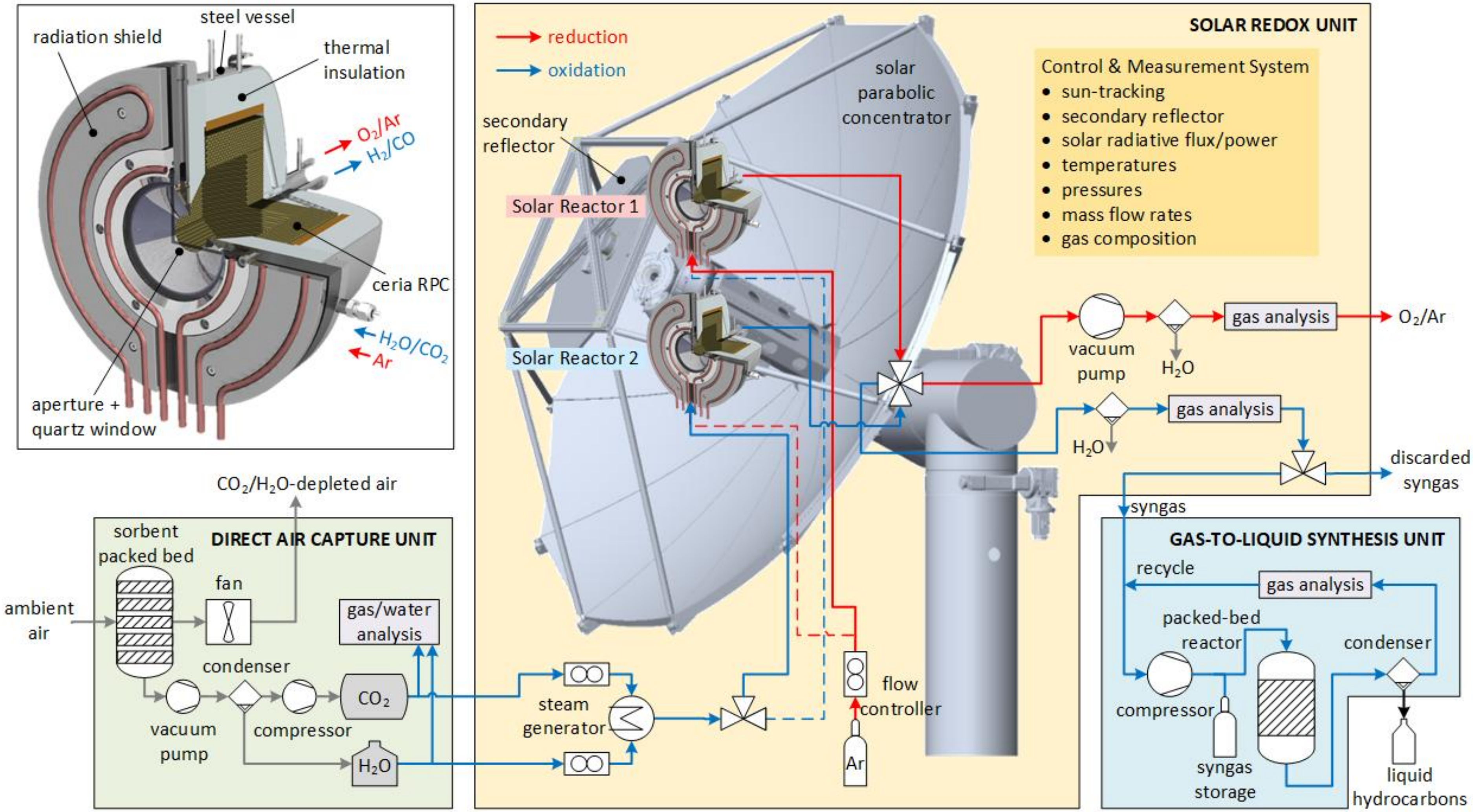
SUN to LIQUID
Fuels from concentrated sunlight

www.sun-to-liquid.eu

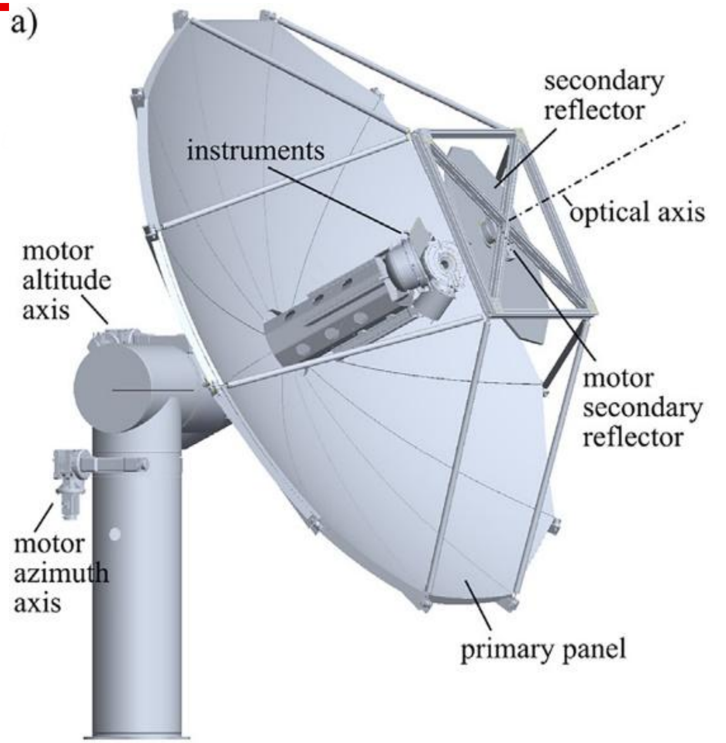
Fuels from Sunlight and Air

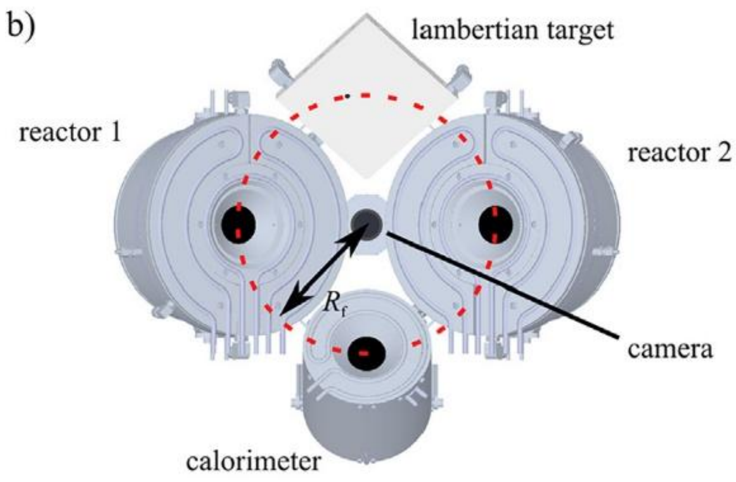
Fuels from Sunlight and Air

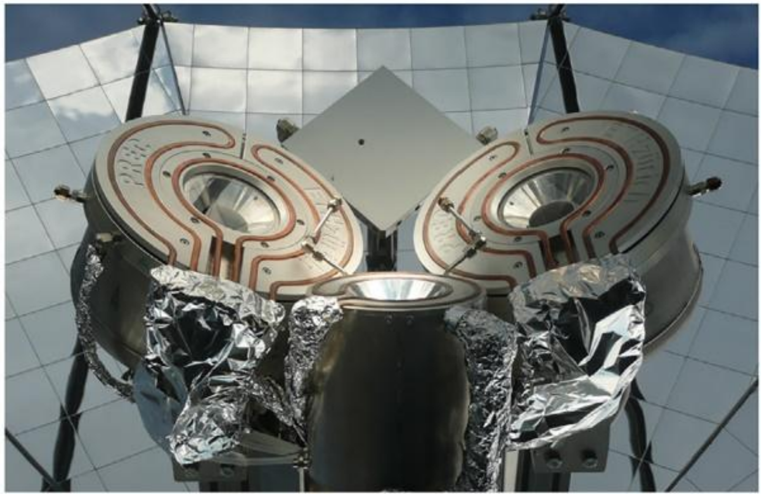
Solar Mini-Refinery @ ETH



Fuels from Sunlight and Air







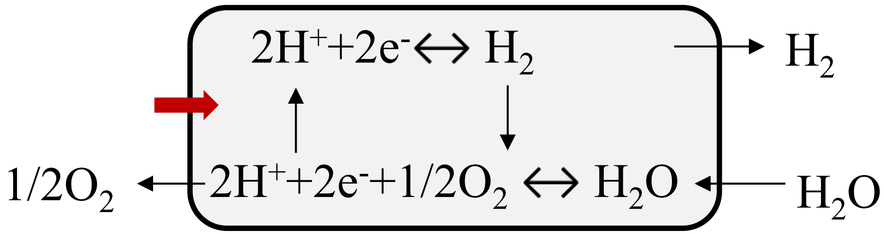
• Solar Energy 170, pp. 568-575, 2018.

Renewable Energy

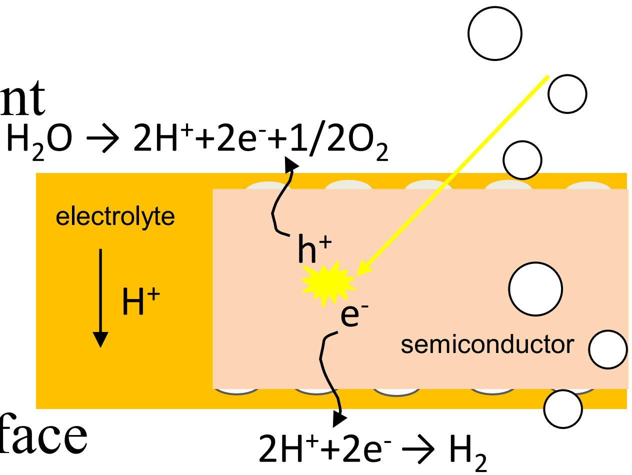
- Outline:
  - Conversion pathways solar-to-fuel
  - Hybrid pathways
  - Solar thermochemistry
  - Photochemistry

Photoelectrochemistry

- Photoelectrochemical processes
  - Solar energy is used as photon energy for the internal production of charge, which is separated at the solid-liquid junction
  - Multi-step water-splitting reactions (E_0=1.23 V):

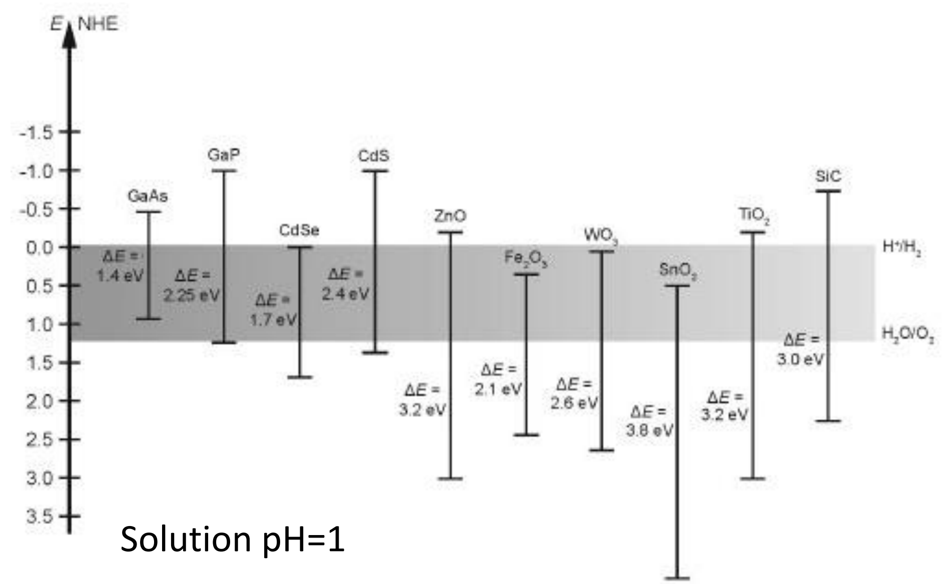


  - Works at room temperature
  - Spectral distribution of solar radiation important
  - Processes:
    - Solar absorption
    - Electron-hole generation
    - Use electron and holes at liquid-solid interface
    - Ionic transport



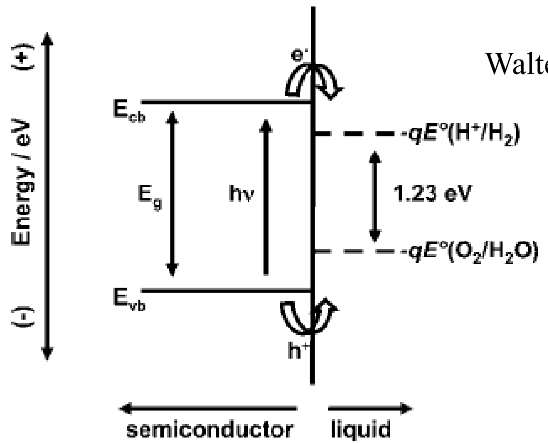
Photoelectrochemistry

- Stringent material requirements:
  - band gap size
  - suitable band edge position
  - high chemical stability in the dark and under illumination, as well as under highly acidic or base conditions
  - efficient charge transport in the semiconductor
  - selective and efficient electrochemical reactions
  - earth-abundance and low costs



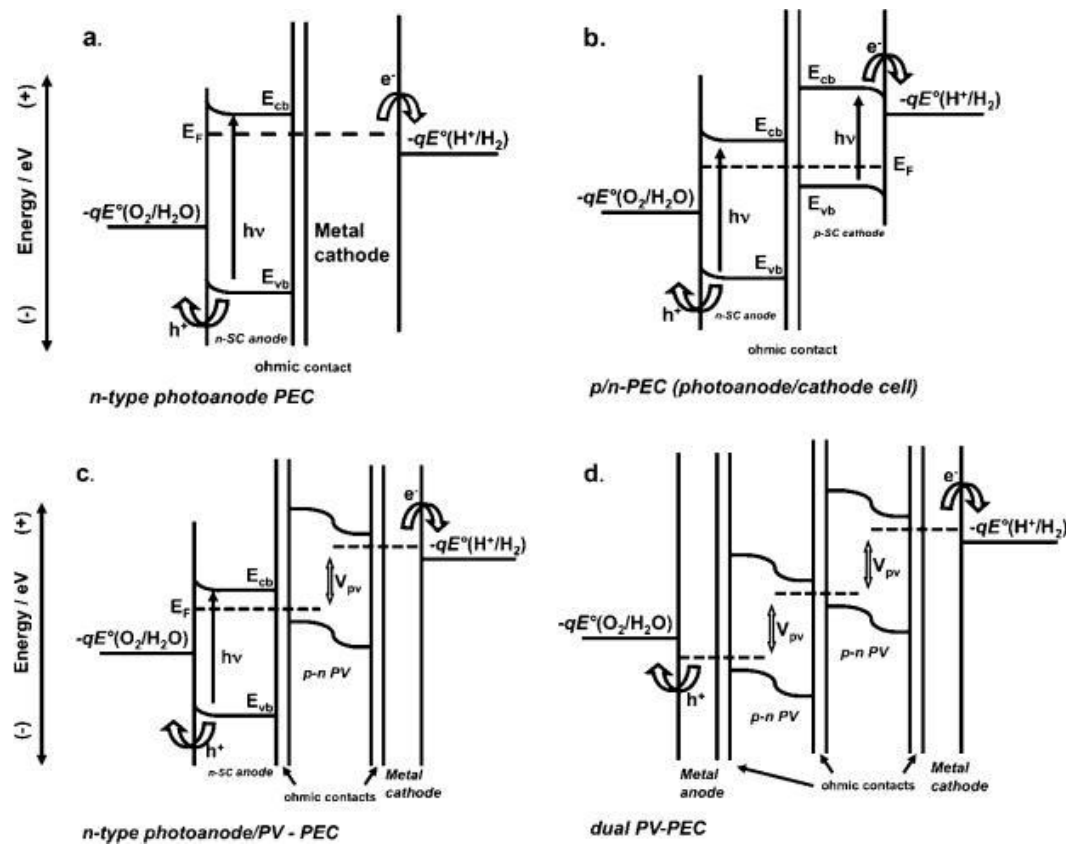
Photoelectrochemistry

- Band gap and band position of photoelectrode material must match reaction potentials:



Walter et al., 2006

- Various possible architectures:



Photoelectrochemistry

- Calculations:
  - Photoactive material(s) will show diode-like current-potential behavior:

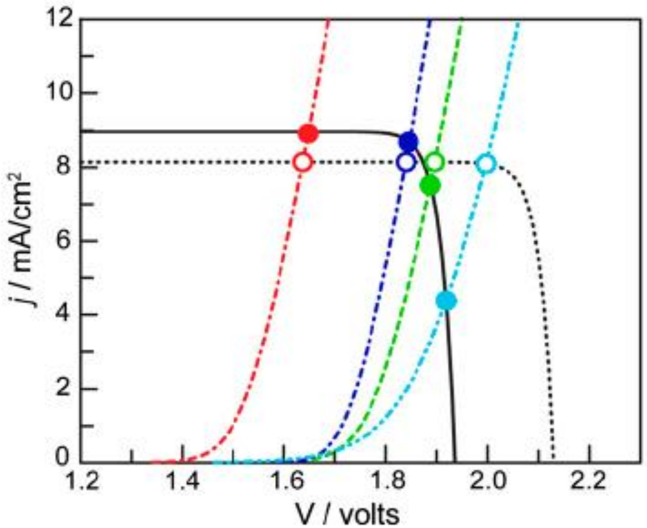
Elementary charge

$$i = i_L - i_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

  - Electrochemical system shows losses:
    - Reaction overpotentials
    - Ohmic losses
    - Concentration losses

$$E = E_0 + \eta_a + \eta_c + iR_{sol} + E_{mem} + E_{conc} > E_0$$

  - Electrochemical load curve will show electrolyzer like load curve
  - Intersection between both is operating point



Surendranath et al., 2012

Photoelectrochemistry

- Calculations:
  - Electrochemical system shows losses:
    - Reaction overpotentials
      - E.g. via Tafel equations:

Tafel slope

$$\eta_a = a_1 \log\left(\frac{i}{i_{0a}}\right) \qquad \eta_c = a_2 \log\left(\frac{i}{i_{0c}}\right)$$

      - Or Buttler-Volmer:

Exchange current density

Transfer coefficient

$$i_R = i_{0a/c}\left[\exp\left(\frac{\alpha_a F \eta_{a/c}}{RT}\right) - \exp\left(\frac{\alpha_c F \eta_{a/c}}{RT}\right)\right]$$

    - Ohmic losses account for resistances in electrolyte, membrane, and solid conductor:

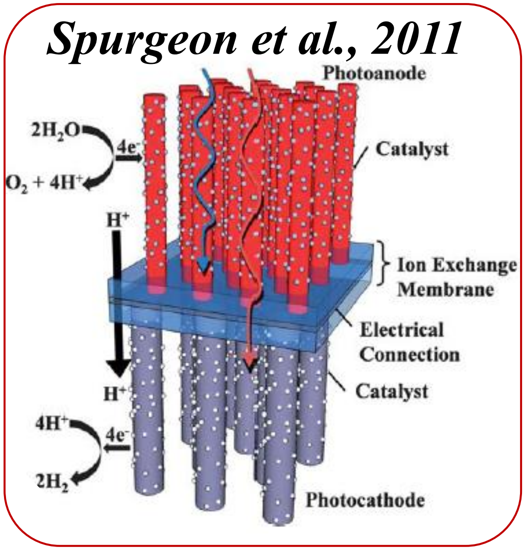
$$\Delta V_{ohm} = i \rho_{sol} l$$

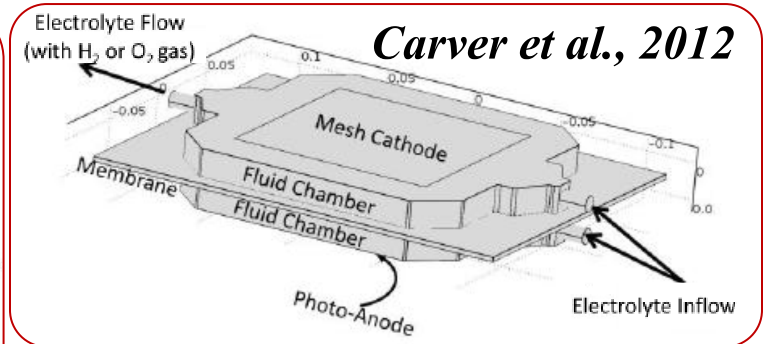
Characteristic ion and electron path length

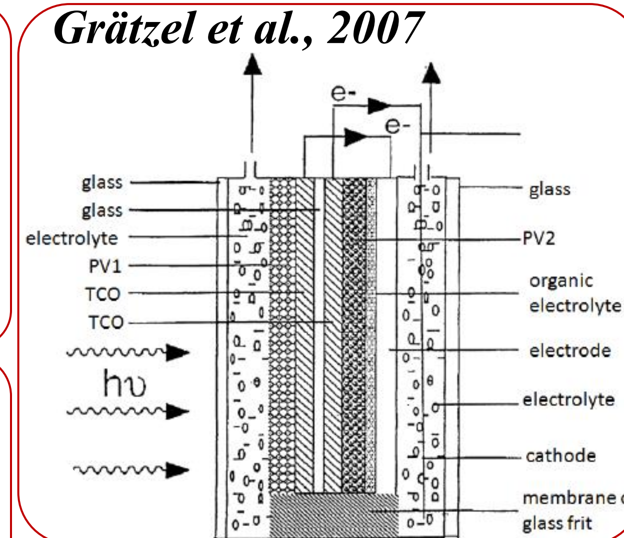
resistivity

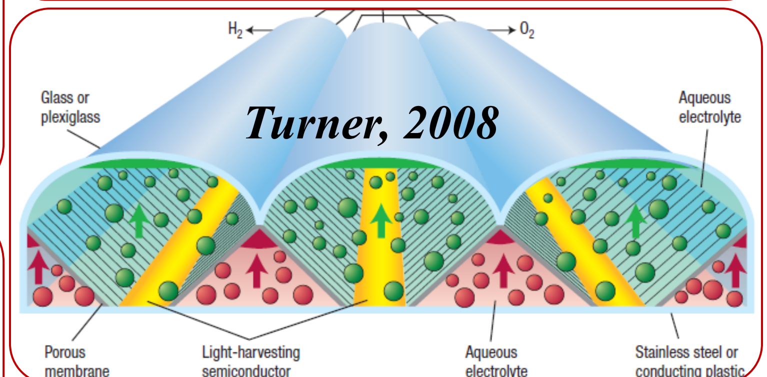
Photoelectrochemistry

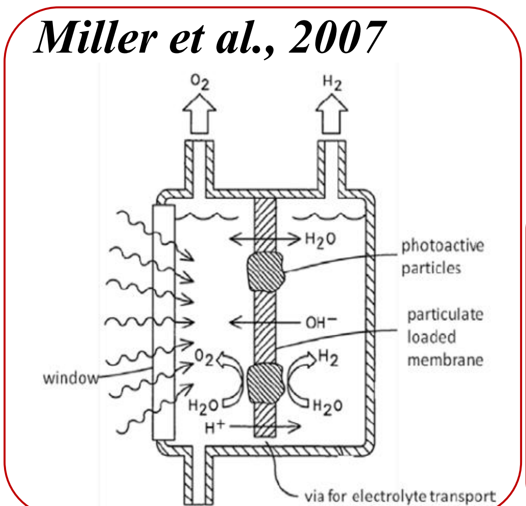
- Proposed devices

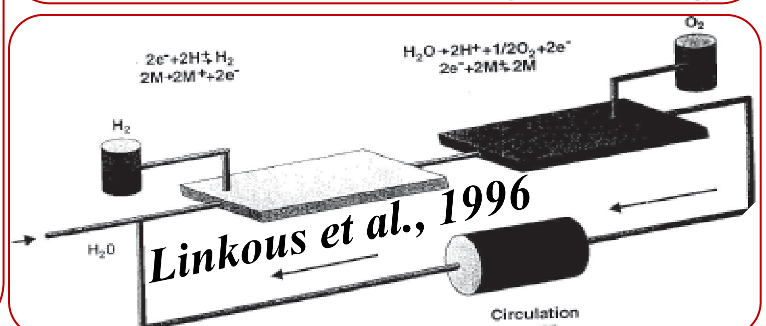


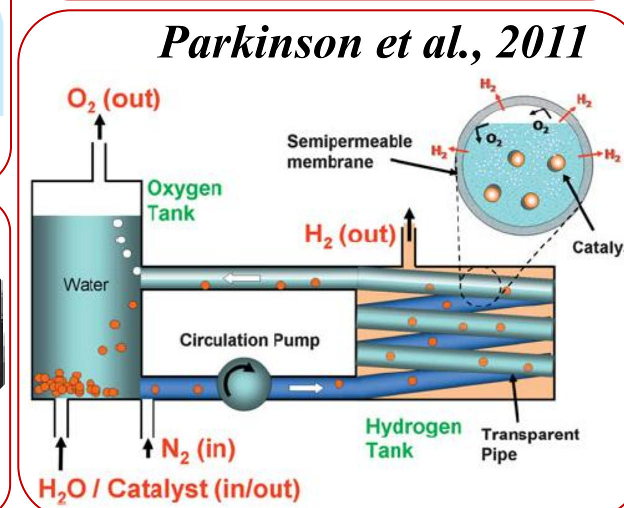






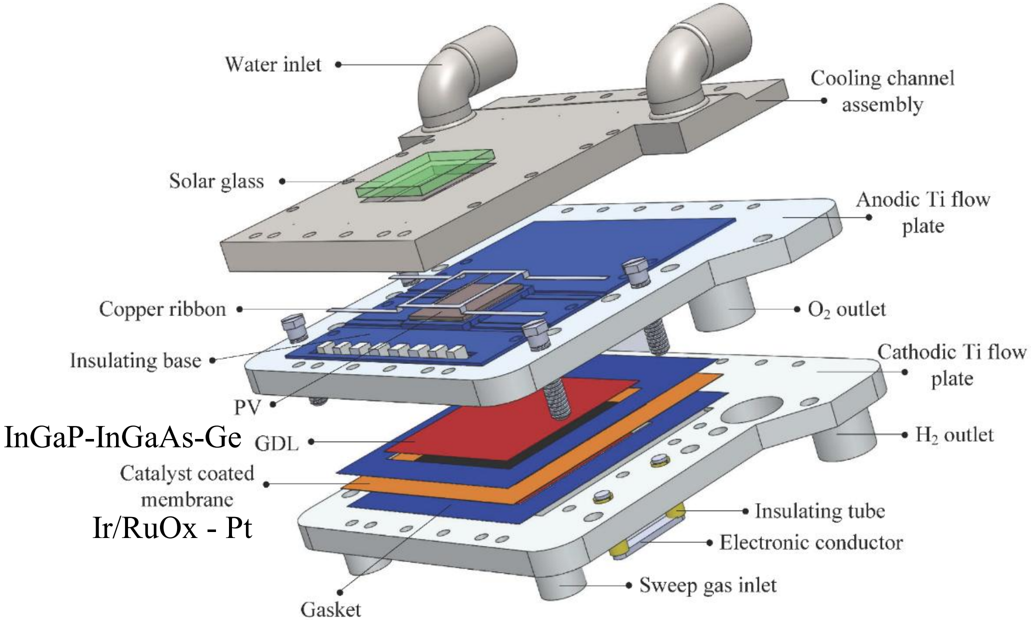


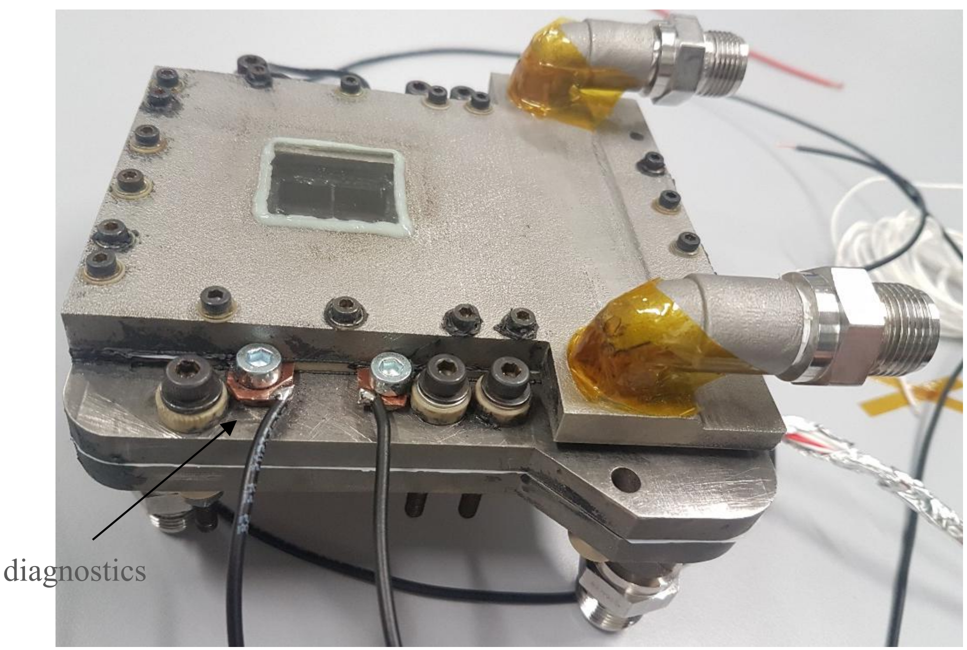


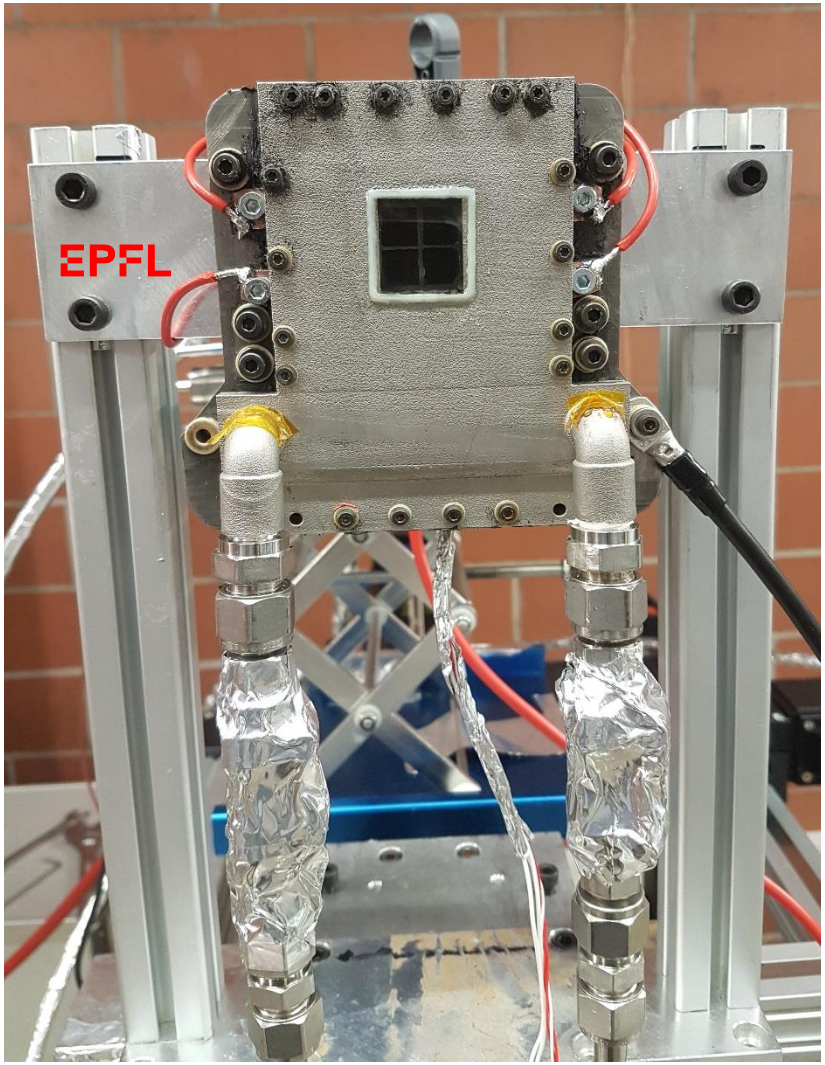


Photoelectrochemistry

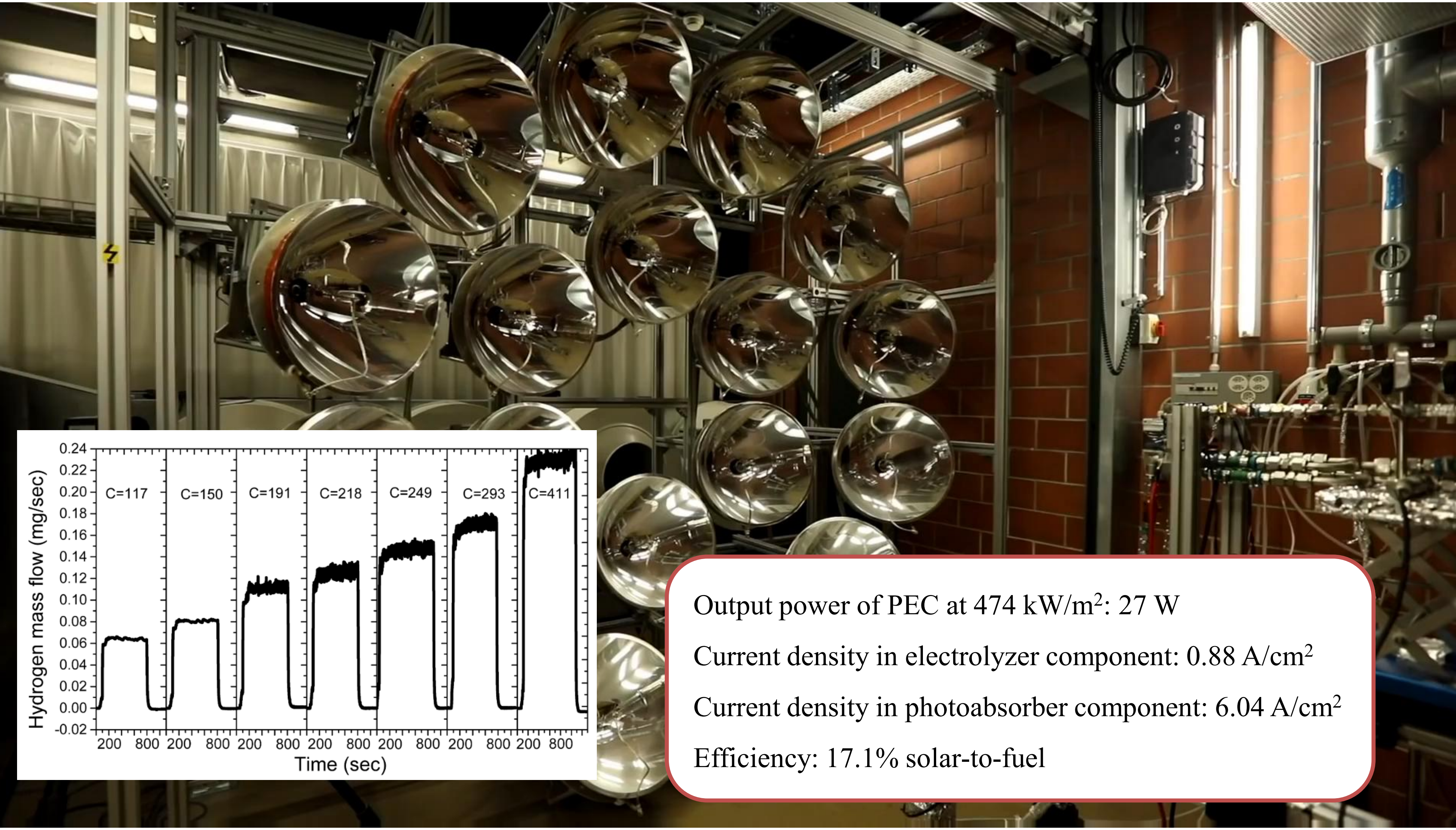
US Patent 62/376923
EP Patent 16020308.9







Experimental demonstration



Output power of PEC at 474 kW/m^2: 27 W

Current density in electrolyzer component: 0.88 A/cm^2

Current density in photoabsorber component: 6.04 A/cm^2

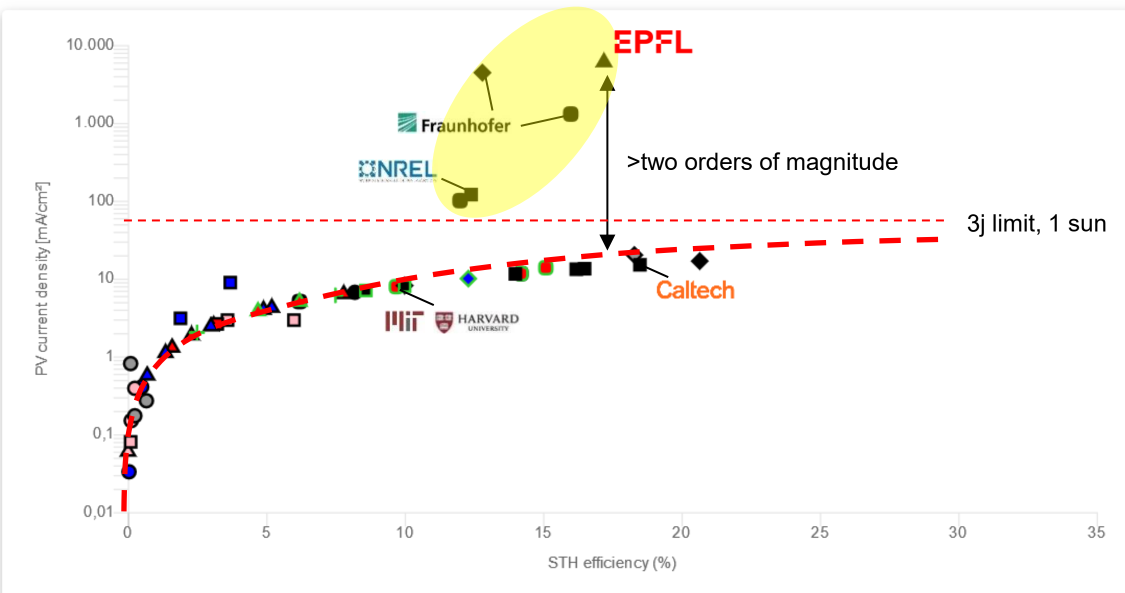
Efficiency: 17.1% solar-to-fuel

Tembhurne, Nandjou, Haussener, *Nature Energy*, doi: 10.1038/s41560-019-0373-7, 2019

Comparison

- Dynamic and online tool: – http://specdc.epfl.ch/ and http://solarfuelsdb.epfl.ch

SolarFuelsDB



Concentrated irradiation
AND
Thermal management

w/o multi-module demonstrations
w/o multiple electrolyzer demonstrations

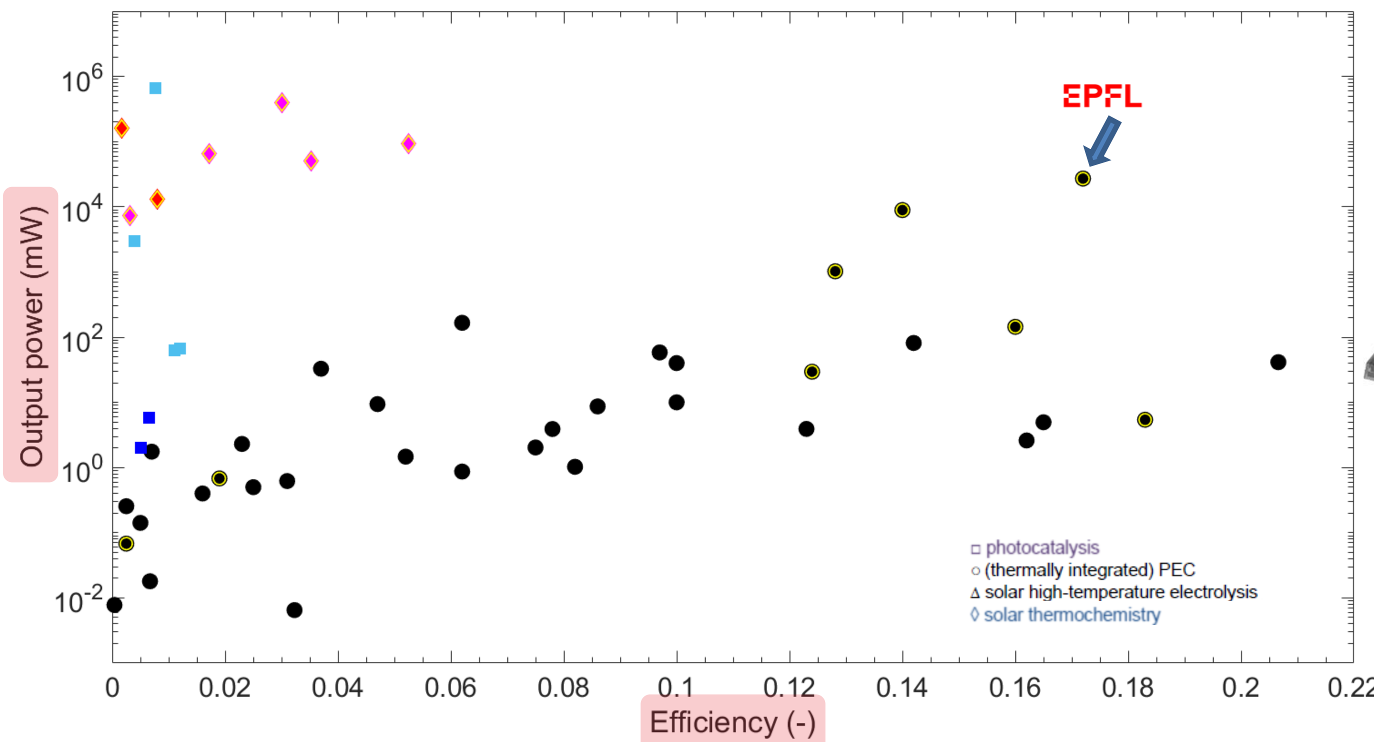
LEGEND

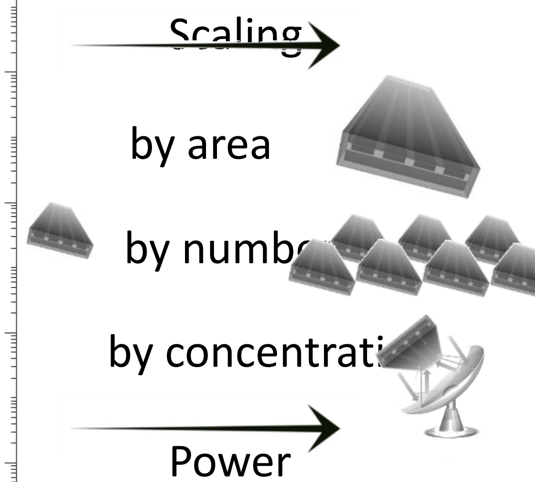
Fill color - PV / photoabsorber material	Boundary color - EC material	Symbol shape - PV / photoabsorber and EC configuration	
All III-V	**Rare metal-based (expensive)**	○ 2J, integrated PVs and catalyst	+ 3J, integrated PVs and catalyst
Partial III-V	Abundant (cheap)	□ 2J, integrated PVs, wired catalyst	△ 3J, integrated PVs, wired catalyst
All Si		◇ 2J, non-integrated PVs or catalyst	O 3J, non-integrated PVs or catalyst
Partial Si			
Oxides and others			

Tembhurne, Nandjou, Haussener, *Nature Energy*, doi: 10.1038/s41560-019-0373-7, 2019

Scaling?

SolarFuelsDB

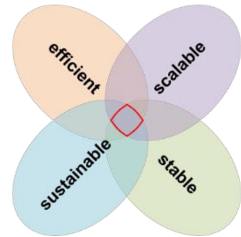


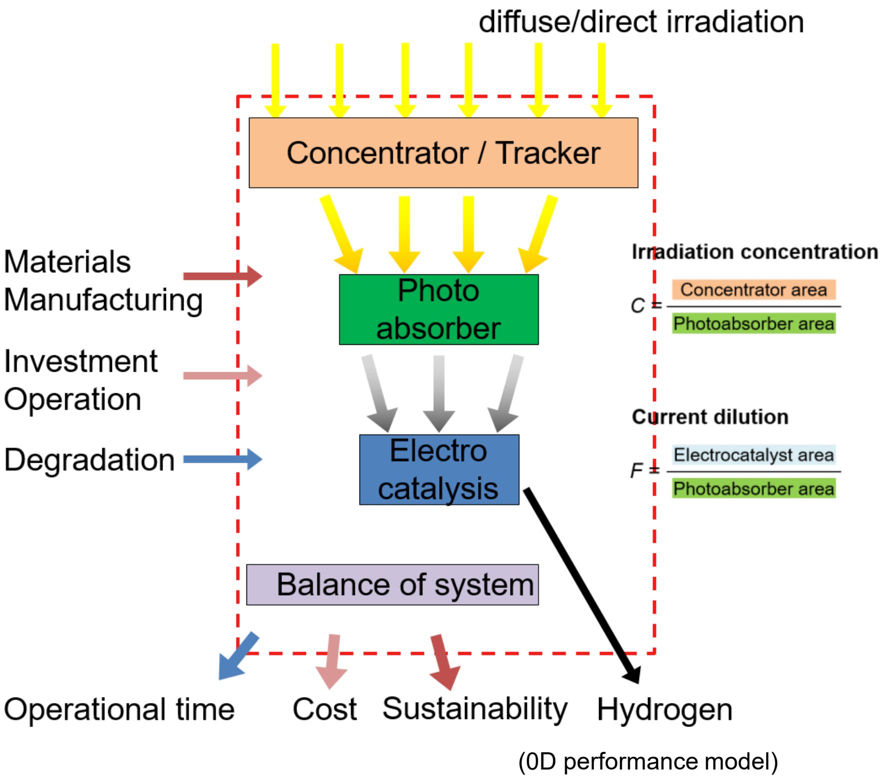


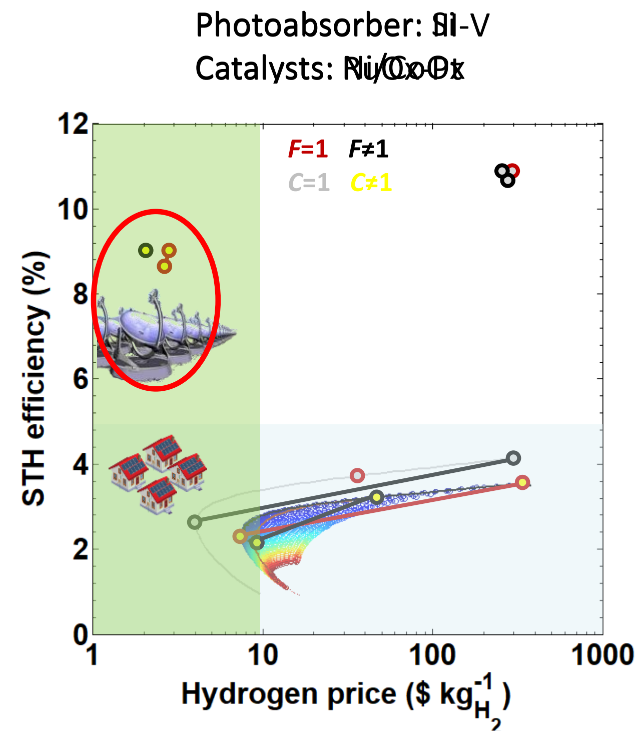
Tembhurne, Nandjou, Haussener, *Nature Energy*, doi: 10.1038/s41560-019-0373-7, 2019

Techno-Economics and LCA

- Promising device design groups





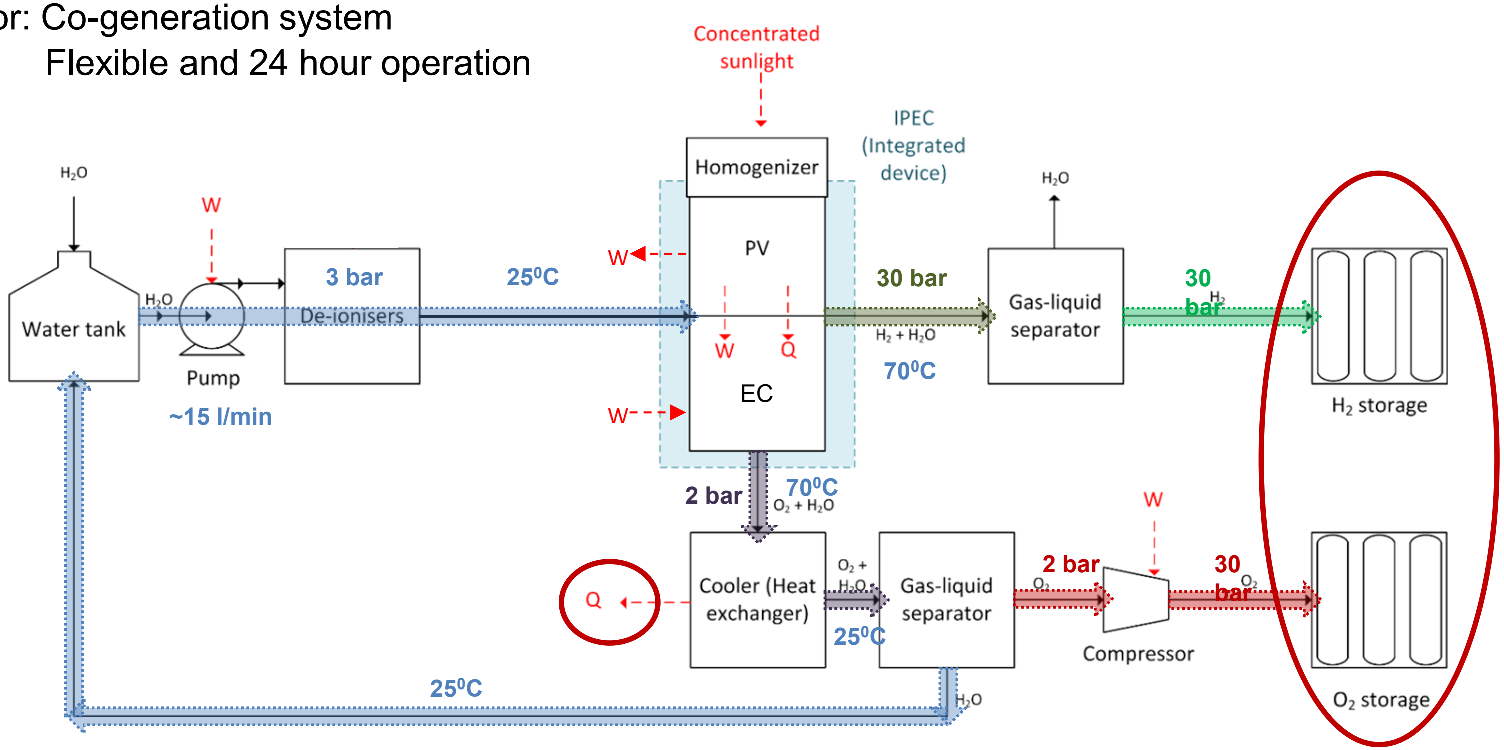


Dumortier, Tembhurne, Haussener, *Energy Environ Sci*, 8, 2015; http://specdo.epfl.ch


EPFL
~0.5kg H_2/day, kW-scale, long-term, on-sun demonstration

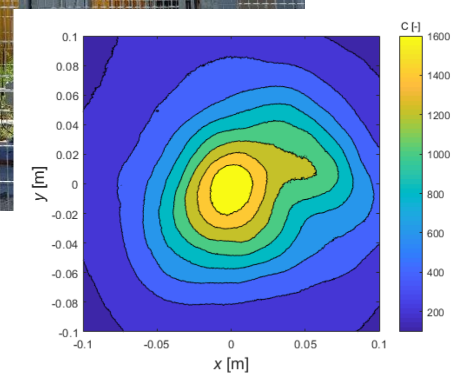
System Process Flow Diagram

Potential for: Co-generation system
Flexible and 24 hour operation



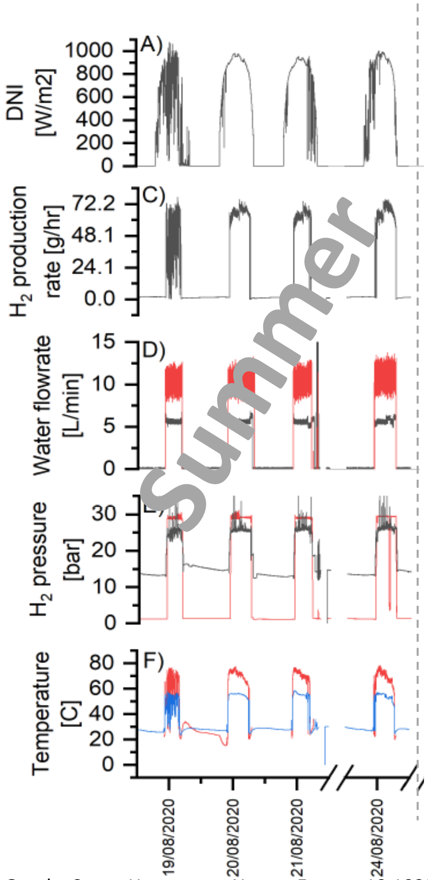
Tembhurne, Holmes-Gentle, Suter, Haussener, Nature Energy, 2023

Reactor and System in Operation



Operational Versatility

- Operation for multiple seasons:



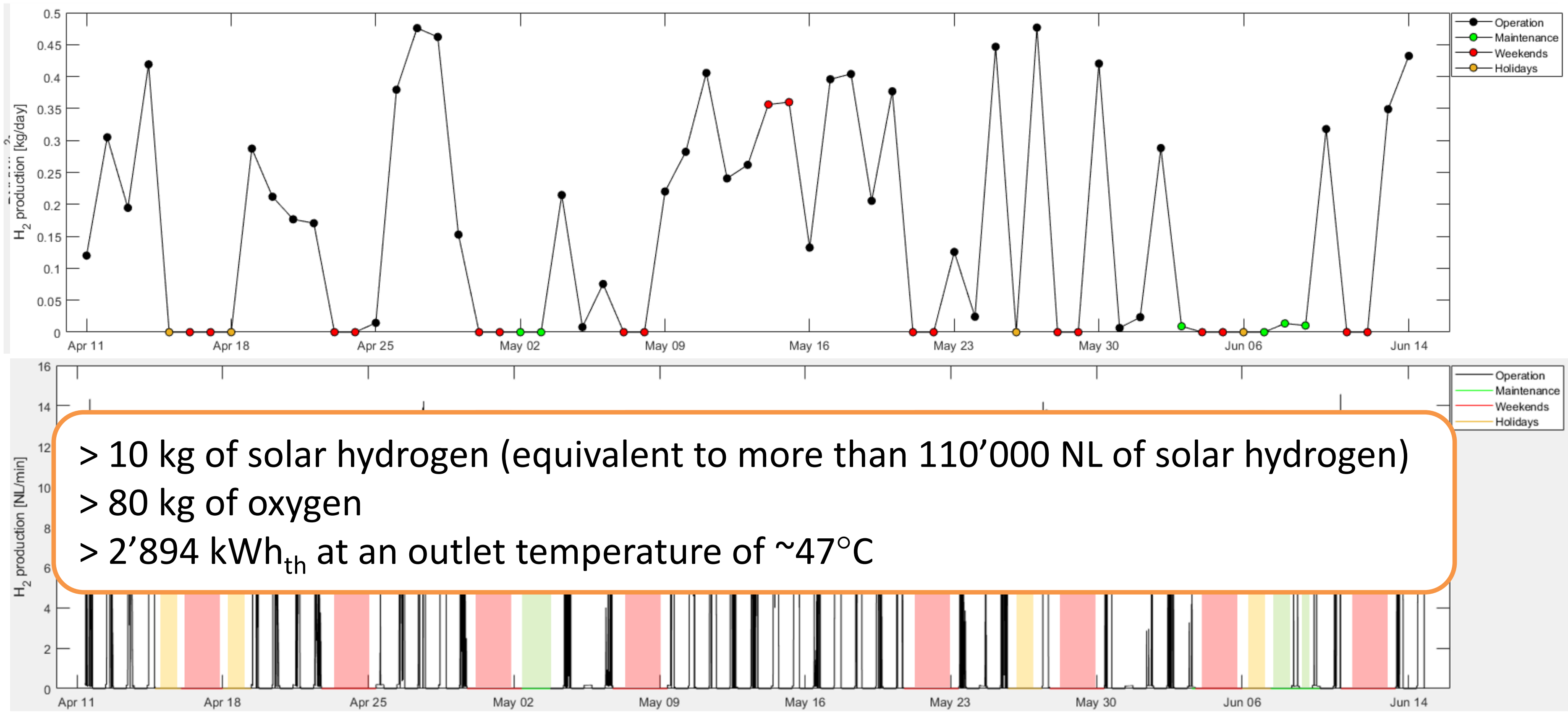
Tembhurne, Holmes-Gentle, Suter, Haussener, *Nature Energy*, 10.1038/s41560-023-01247-2, 2023

Operation is reproducible
Operation is consistent
Operation in winter possible
Device level STH efficiency 21%

EPFL

Durability

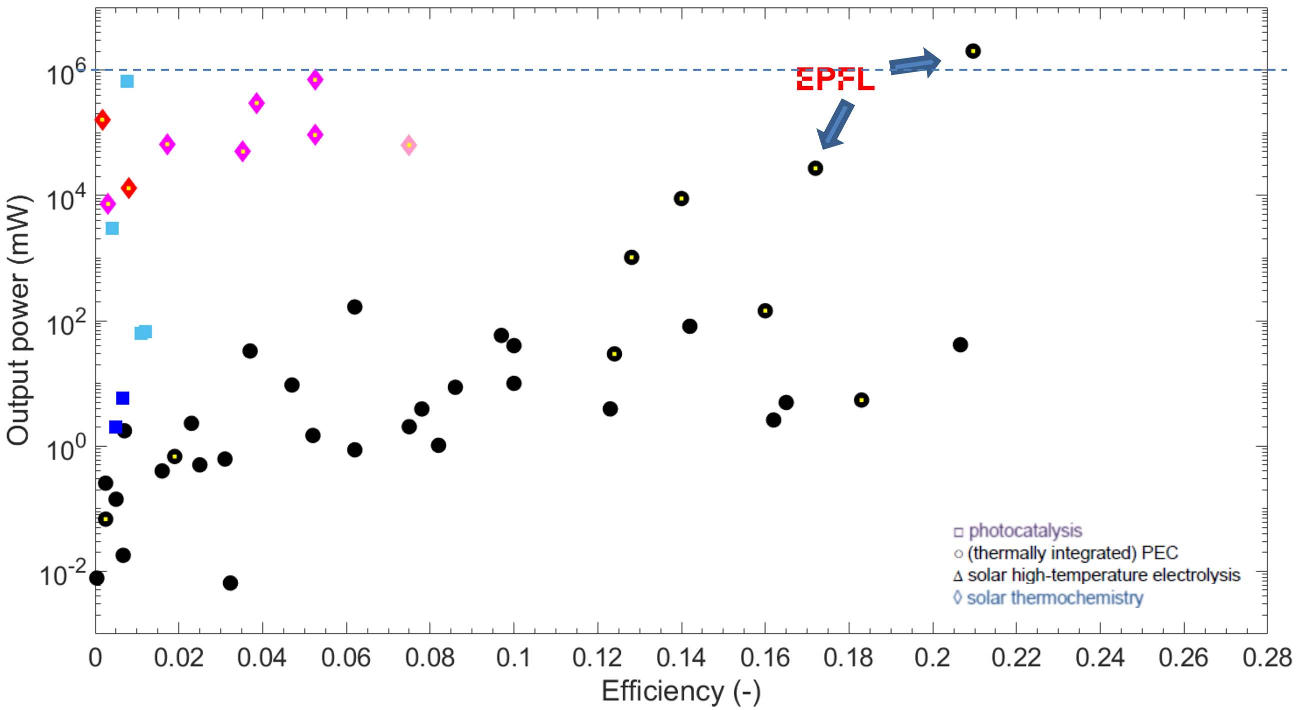
- Long term operation:

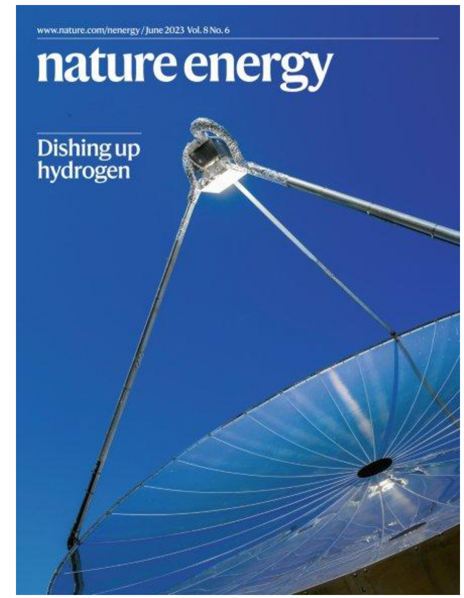


> 10 kg of solar hydrogen (equivalent to more than 110'000 NL of solar hydrogen)
> 80 kg of oxygen
> 2'894 kWh_{th} at an outlet temperature of ~47°C

Comparison

SolarFuelsDB





Tembhurne, Holmes-Gentle, Suter, Haussener, *Nature Energy*, 10.1038/s41560-023-01247-2, 2023

Scaling?

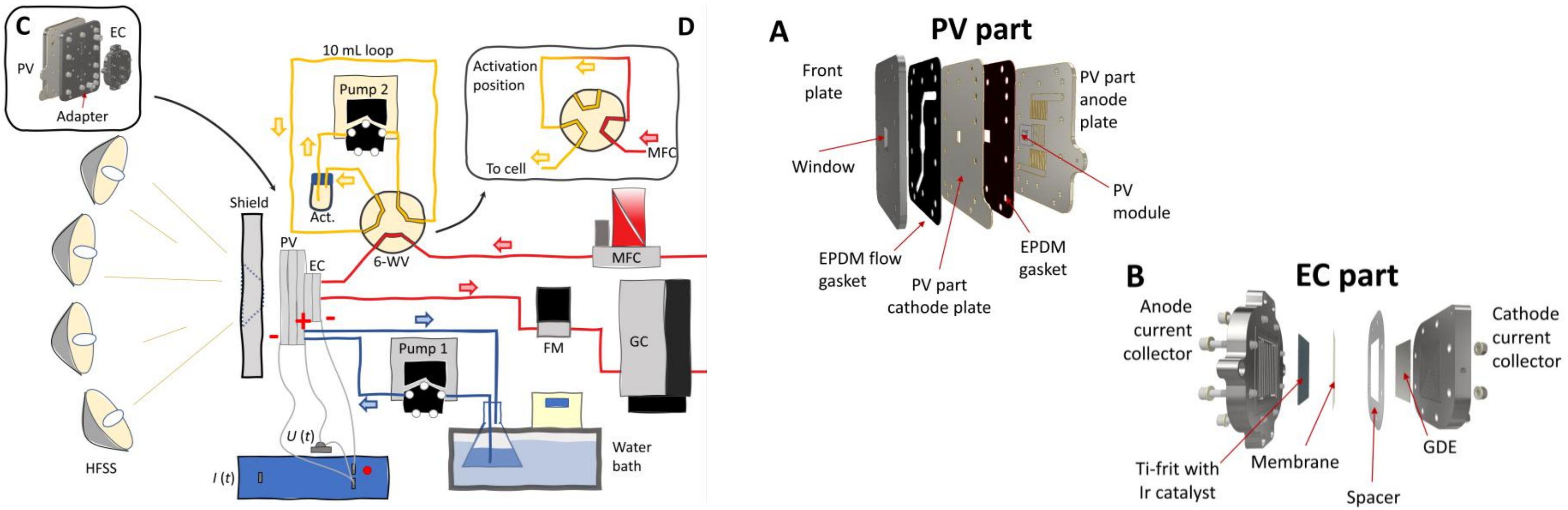
EPFL

SoHHytec
SOLAR FUEL, THE SMARTER WAY

http:\\www.sohhytec.com

Alternative Chemistry

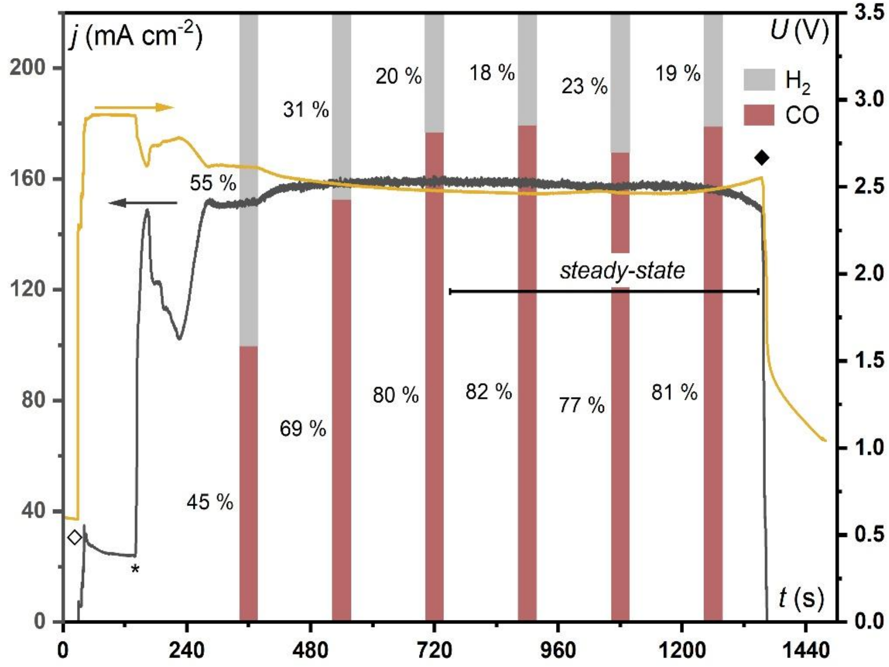
- Do design guidelines (thermal integration, concentrated radiation) also apply to CO_2 reduction?
- Confirmation of design approach with silver catalyst in zero-gap gas diffusion electrode (GDE) configuration



Boutin, Patel, Kecsenovity, Suter, Janaky, Haussener, *Advanced Energy Materials*. doi:: 10.1002/aenm.202200585, 2022

CO_2 Reduction with Concentrated Light

- Typical experimental run



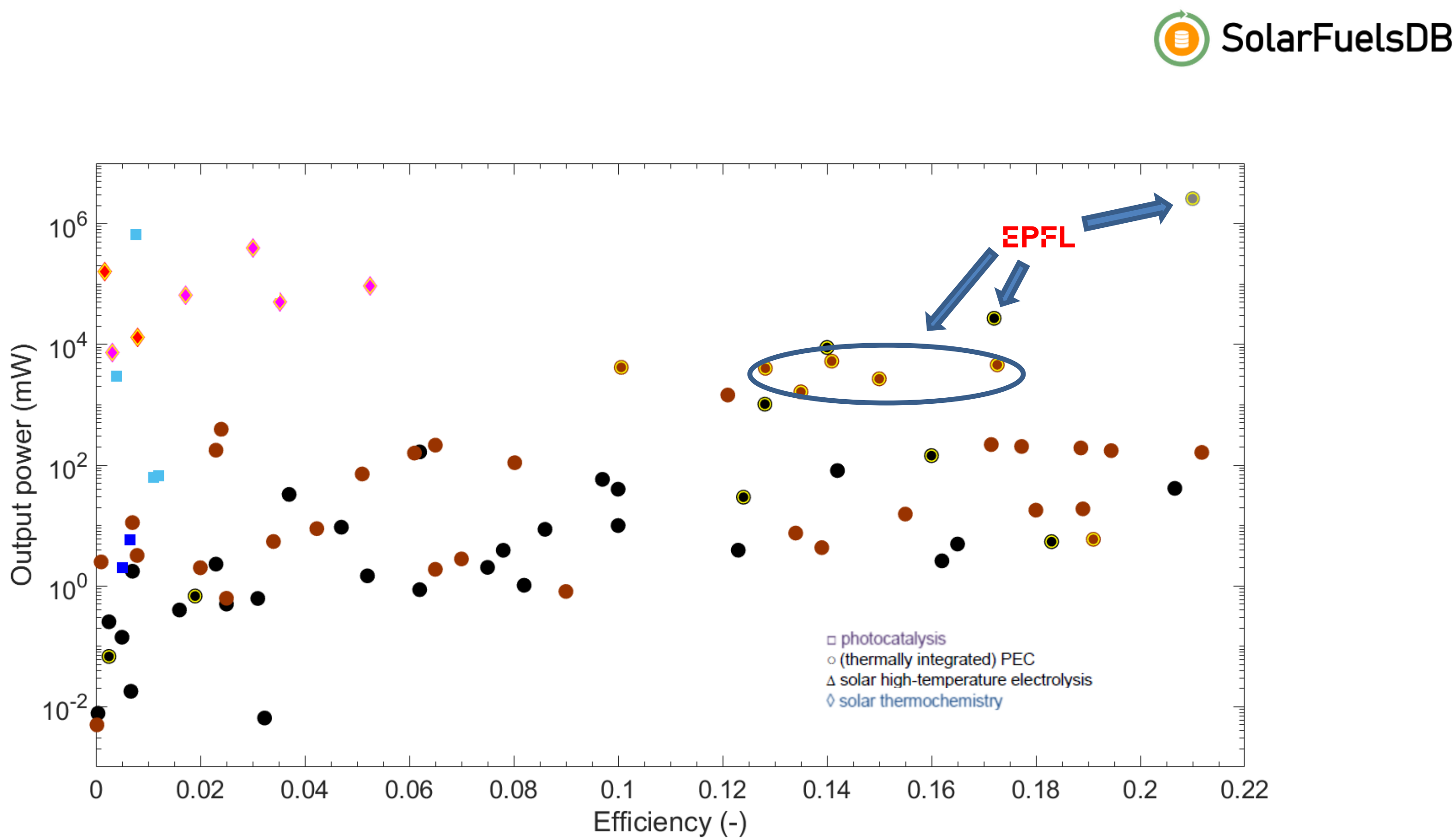
Typical 20 min experiment at 341 suns with the integrated PEC cell.

S_{CPV}: 0.92 cm^2.
Q_{CO2}: 312 sccm.
Averaged T_{water}: 55° C.

◇ : lamps switch on.
◆ : lamp switch off.
* : activation with 10 cm^3 of 1 M CsOH solution in 1:3 isopropanol/water mixture.

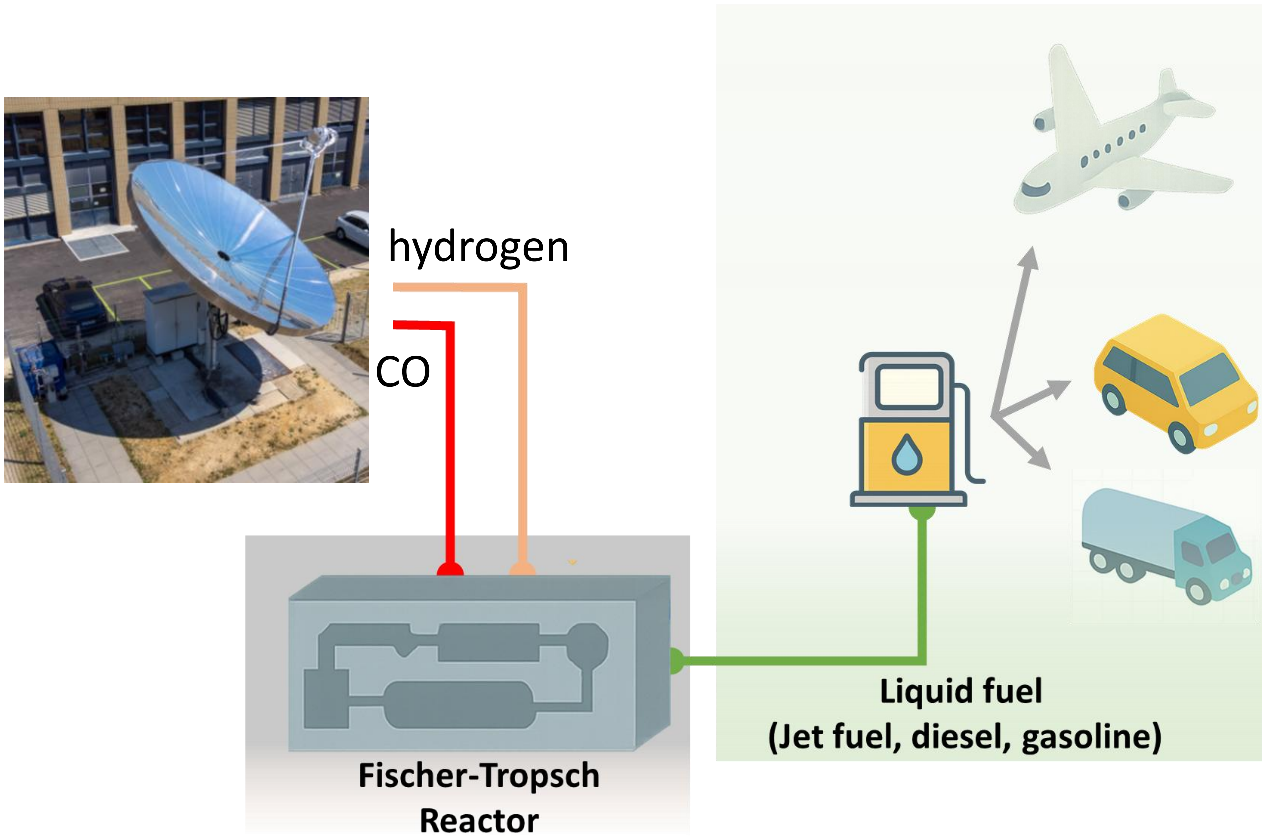
Boutin, Patel, Kecsenovity, Suter, Janaky, Haussener, *Advanced Energy Materials*. doi:: 10.1002/aenm.202200585, 2022

Comparison



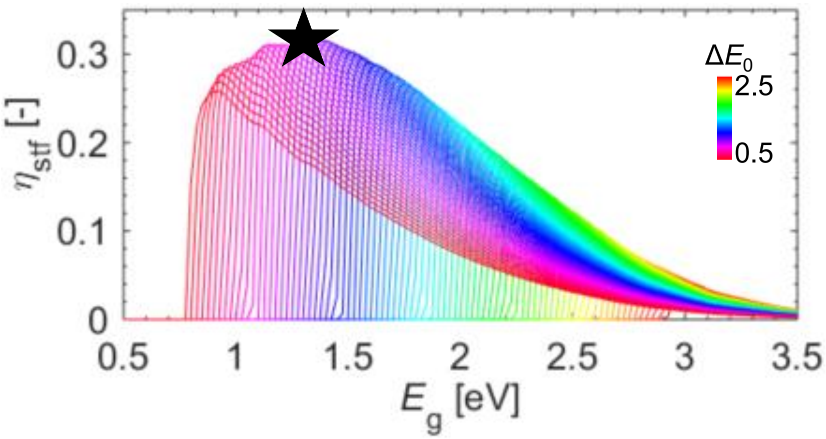
EPFL

From Hydrogen to Synthesis Gas and Beyond

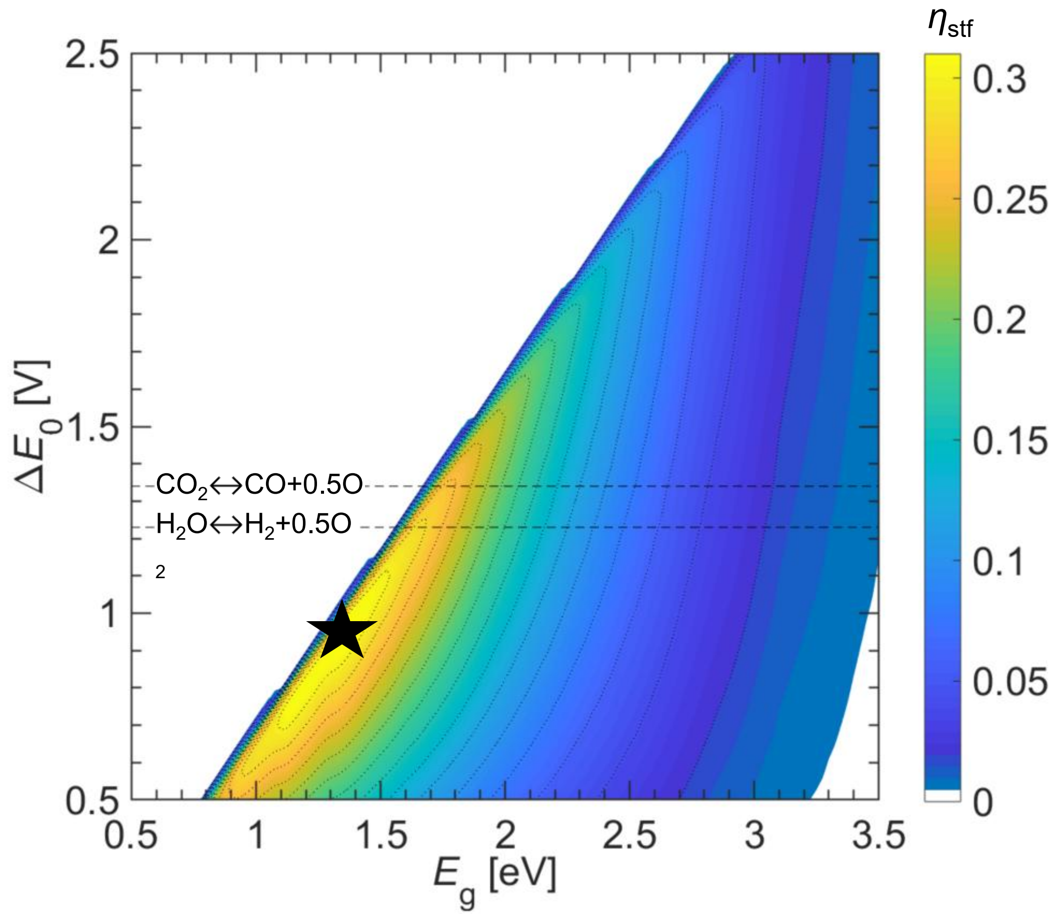


Beyond water splitting or CO_2 reduction

- Which reactions are interesting?
- Limiting efficiencies:



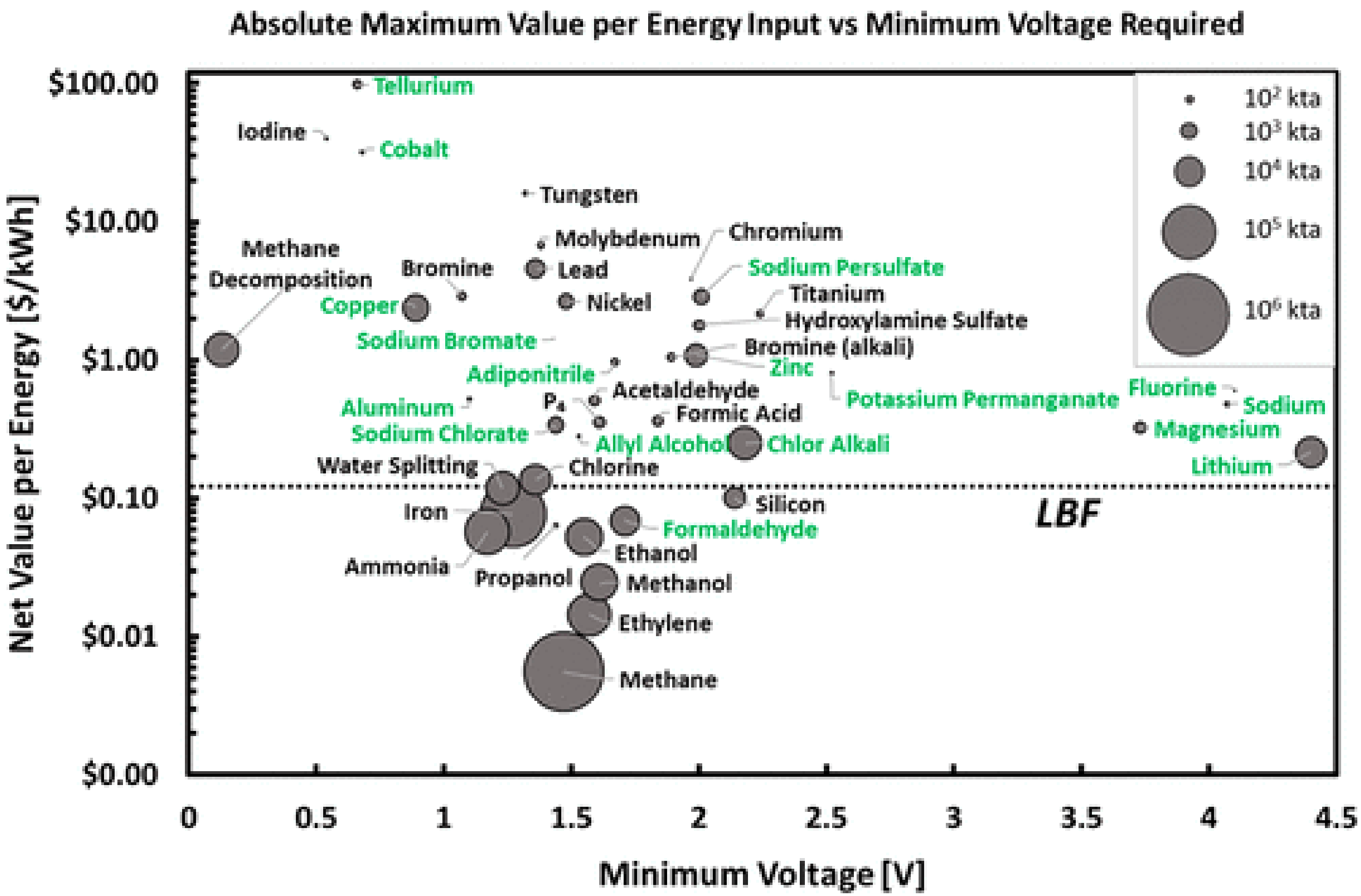
Global maxima:
η_{STF} = 32% at E_g=1.35eV and ΔE_0=0.96V



Haussener, Suter, Gutierrez Perez, Solar fuel devices: Multi-scale modeling and device design guidelines, Chapter, Springer, 2020

Solar materials

- (Photo)electrochemical:

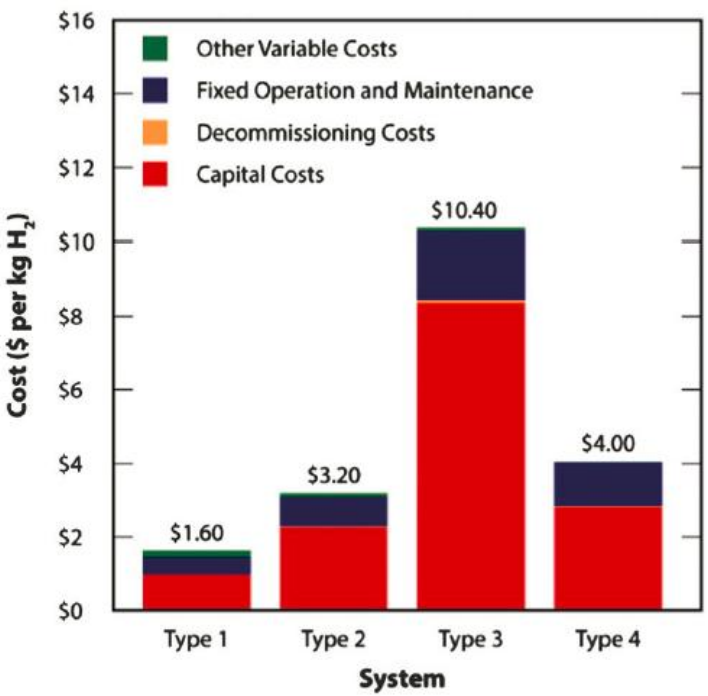


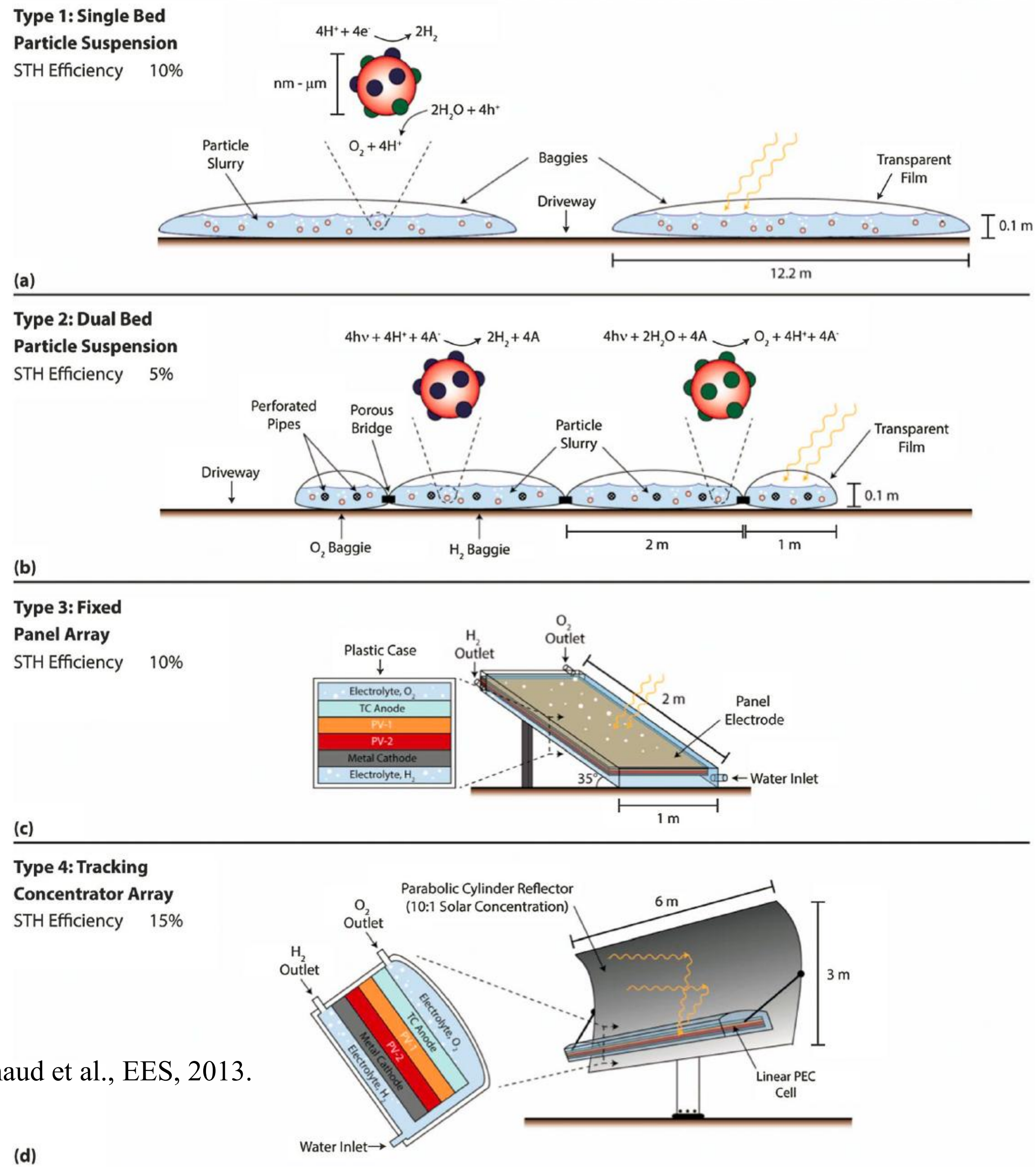
Maximum net value per energy input (log scale) plotted versus minimum voltage required for all electrochemical processes or electrochemical equivalents of thermochemical processes. For each point, the width of the circle corresponds to the relative market size. Processes highlighted in green are conducted electrochemically in industry, to any appreciable extent. The lower bound of feasibility (LBF) is plotted as the horizontal dashed line

Palmer et al., Technoeconomics of Commodity Chemical Production Using Sunlight, ACS Sustainable Chemistry & Engineering, 2018

Photoelectrochemistry

- Proposed devices

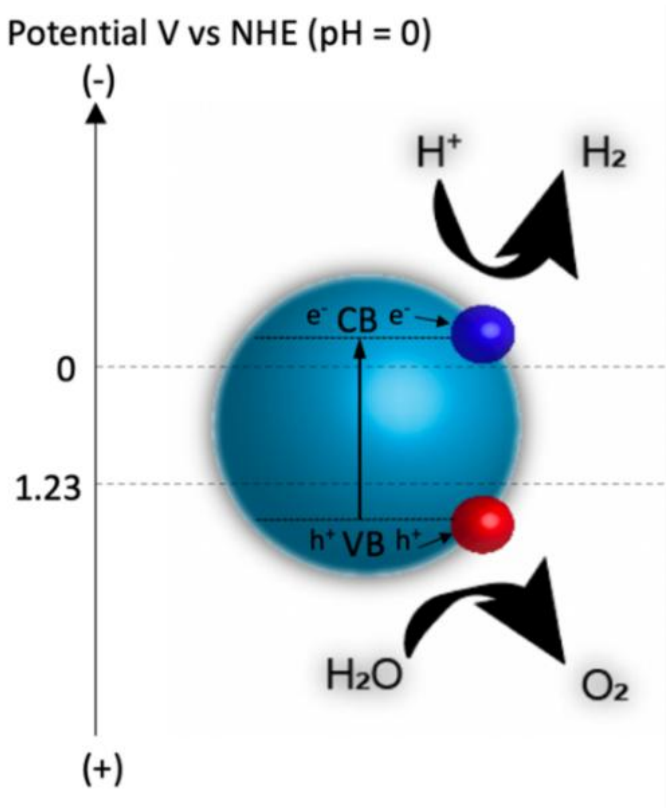


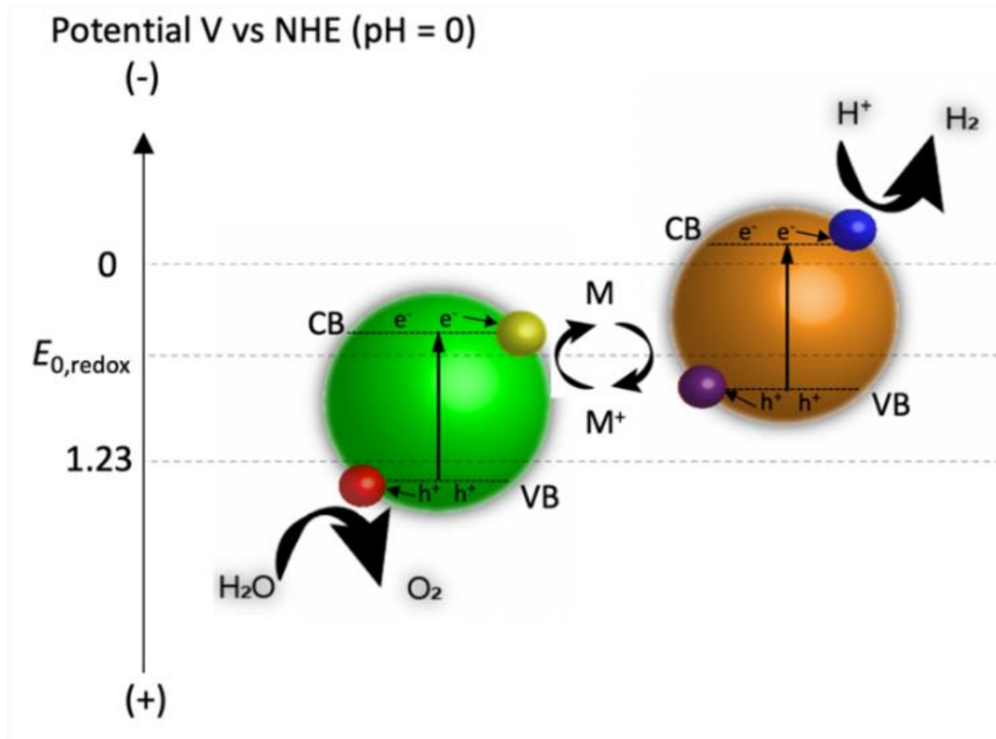


Pinaud et al., EES, 2013.

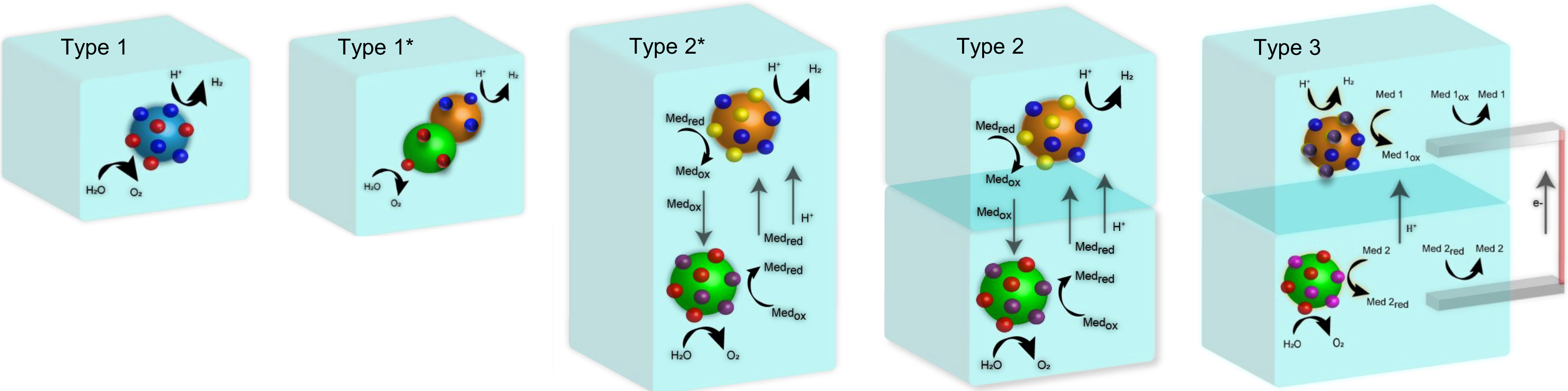
Photocatalysis

- Working principle

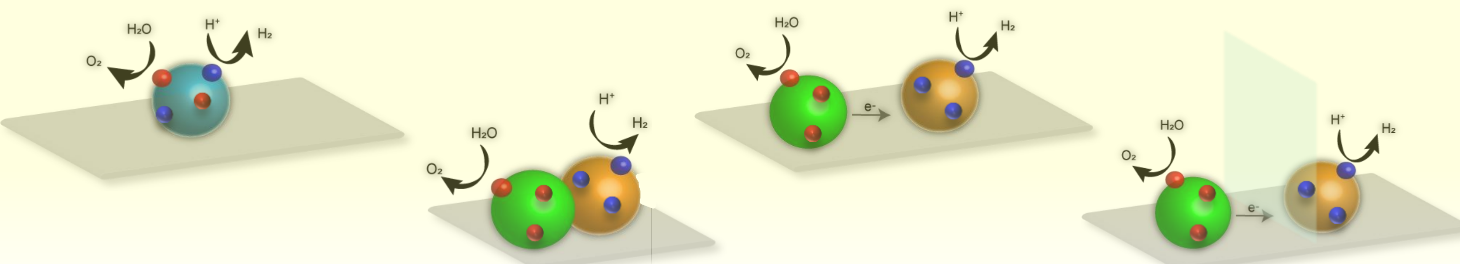




Potential Design Options

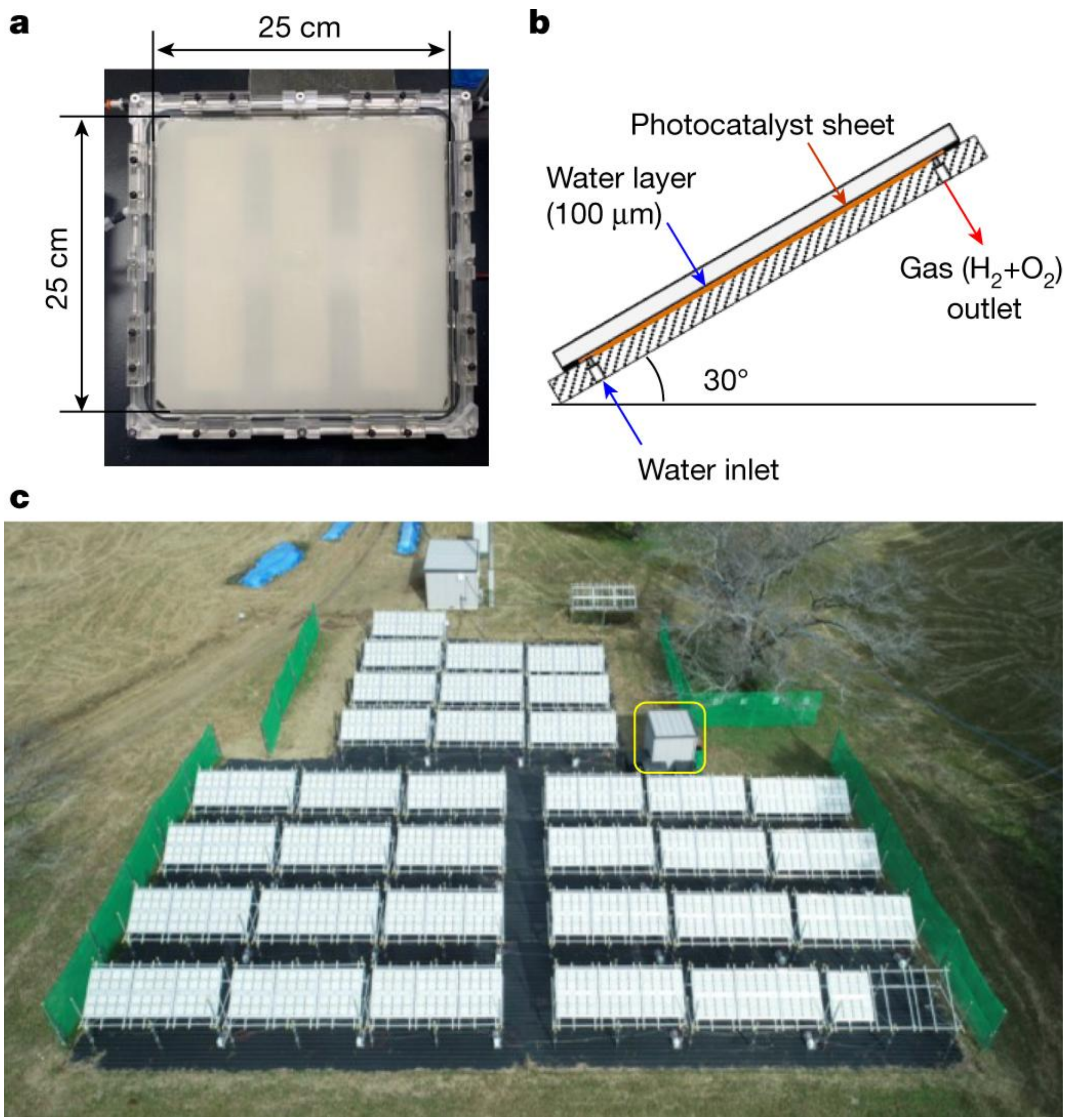


Catalyst sheets version



Savant et al., Chem. Sci., 10.1039/d1sc01504d, 2021

Large-scale Photocatalystic Hydrogen Demo



aluminium-doped strontium titanate particulate photocatalyst, with a maximum STH of 0.76%

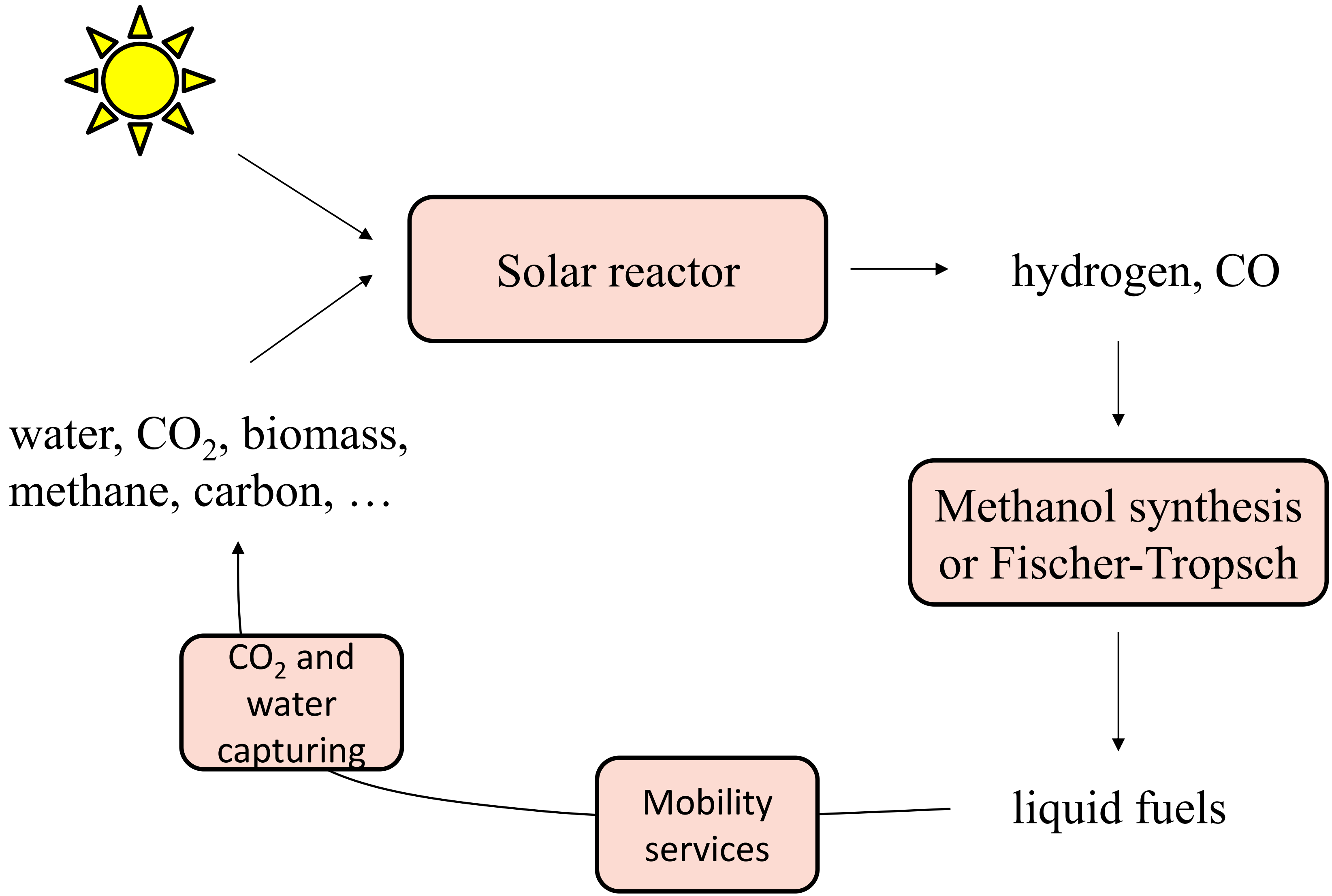
Nishiyama et al., Nature, 2021

Renewable Energy

- Outline:
  - Conversion pathways solar-to-fuel
  - Hybrid pathways
  - Solar thermochemistry
  - Photochemistry

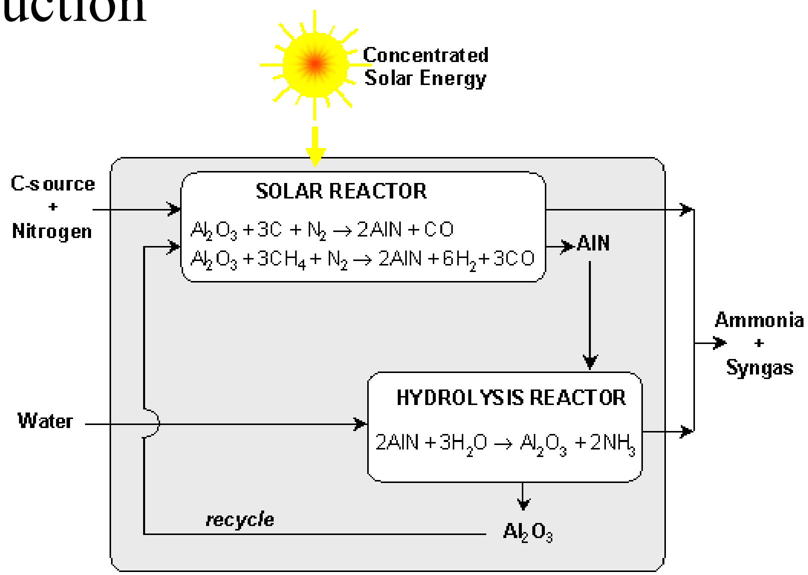
Sustainability issue

- Solar to fuels:



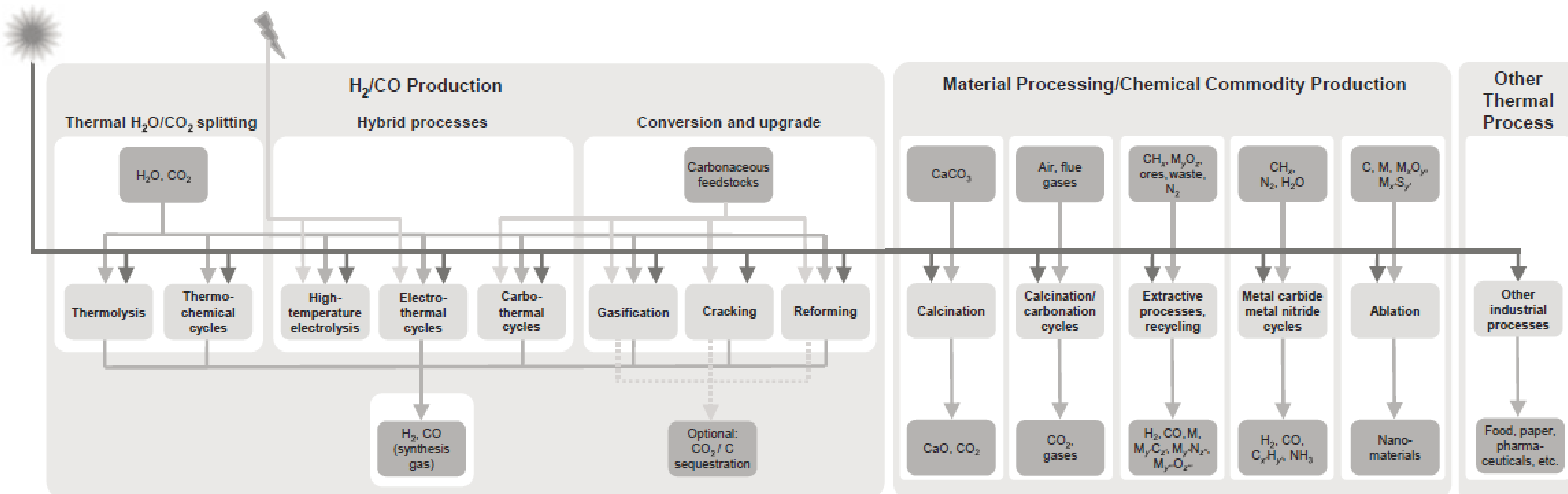
Solar materials

- Solar to materials:
  - In principle any other chemical reaction could be driven by solar thermochemistry or photoelectrochemistry if enthalpy of reaction matches solar irradiation, or equilibrium potential and band edge position matches solar irradiation and material combinations
  - E.g.:
    - Carbothermic reduction of alumina under near vacuum conditions
    - Ammonia production



Solar materials

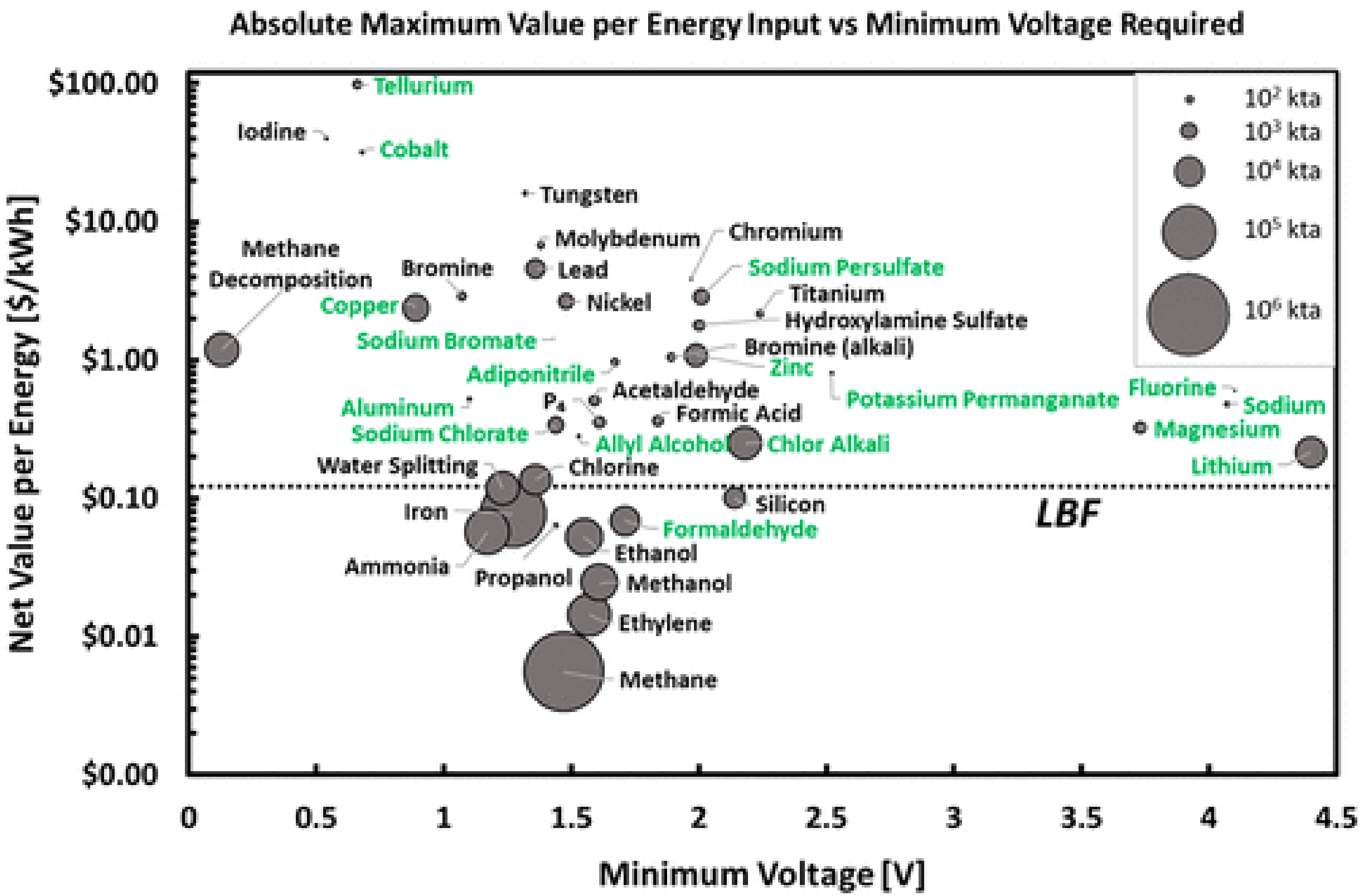
- Thermochemical:



Bader et al., 2016

Solar materials

- (Photo)electrochemical:



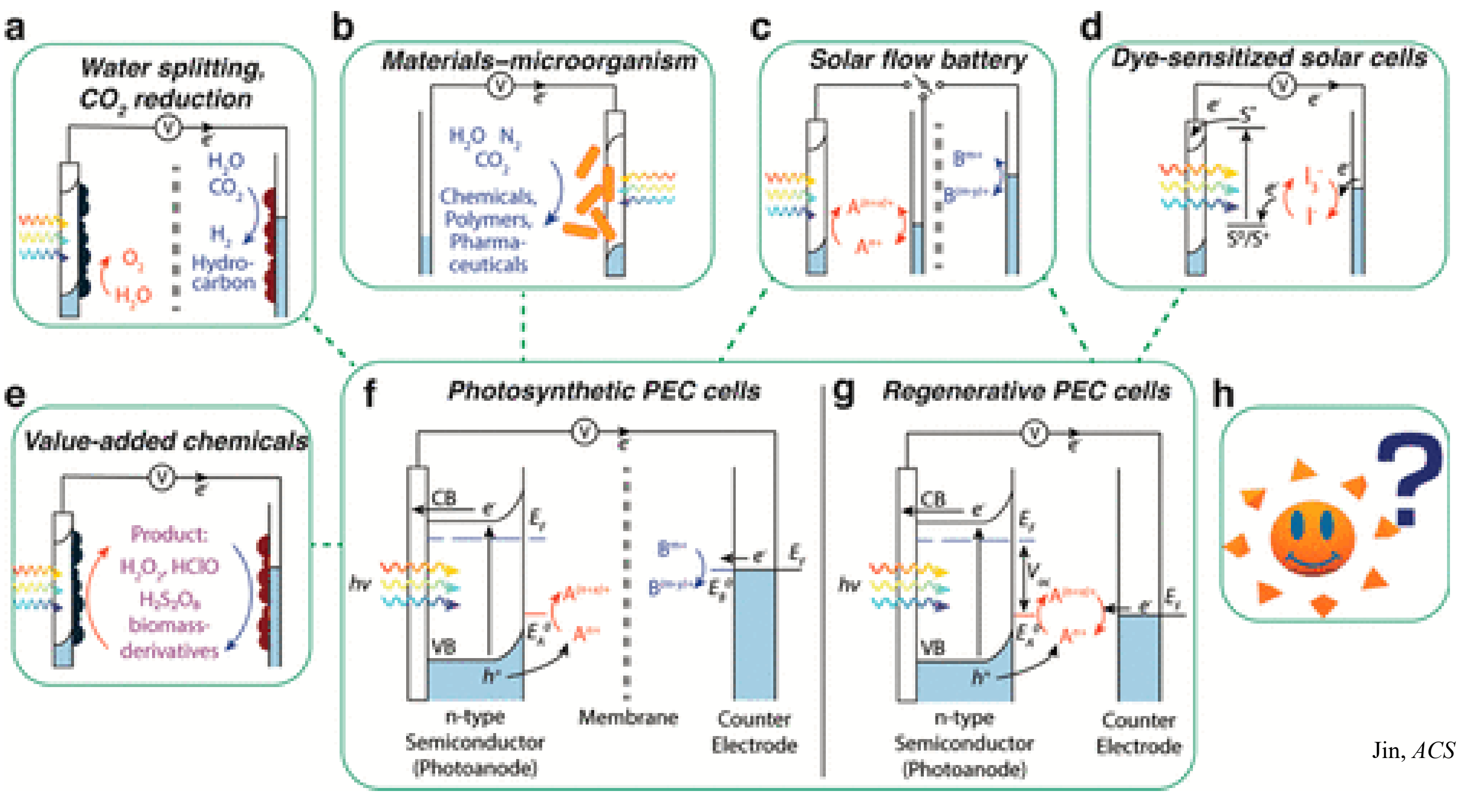
Maximum net value per energy input (log scale) plotted versus minimum voltage required for all electrochemical processes or electrochemical equivalents of thermochemical processes. For each point, the width of the circle corresponds to the relative market size. Processes highlighted in green are conducted electrochemically in industry, to any appreciable extent. The lower bound of feasibility (LBF) is plotted as the horizontal dashed line

Palmer et al., Technoeconomics of Commodity Chemical Production Using Sunlight, ACS Sustainable Chemistry & Engineering, 2018

Other photo-driven chemistry

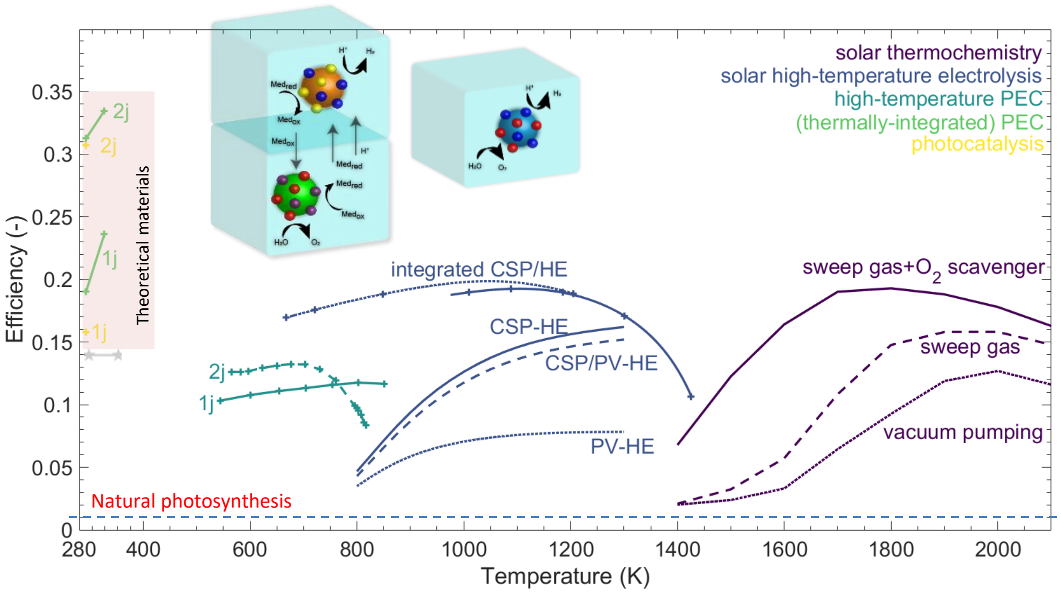
- Photo-electro-chemistry – more than fuels:
  - Oxidation of organic matter

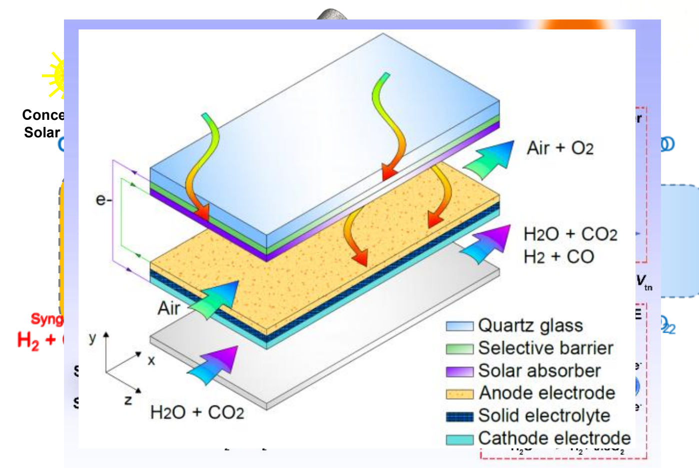
  (water treatment, air cleaning, medical disinfection, …)
  - Photo-electrochemical nitrogen reduction
  - Photo-driven flowbatteries (I_3^-/I^-, VO_2^+/VO^{2+}…)



Jin, *ACS Energy Letters*, 3, 2018

Efficiency limits – Comparing solar fuel approaches





Nandy et al., *Chem Sci*, 29, 2021

- Comparison:
  - Similar achievable STF efficiency for technical pathways
  - Lower temperature requirements for HTE
  - Less stringent requirement for heat recovery in HTE
  - No requirement for p_{o2} at OER (1 Pa for TCC, Air for HTE)
  - But significant, unsolved thermo-mechanical material challenges for HTE
  - For PEC: Comparable STF, low temperature, but corrosive environments

Learning outcomes of todays lecture

- Solar fuels:
  - How can solar energy be converted into fuels?
  - What is a hybrid pathway?
  - Why using fossil fuels together with solar energy?
  - What is solar thermochemistry and how can it be used for solar fuel processing?
  - Why is solar water-splitting via multi-step water splitting cycles preferred compared to direct thermolysis?
  - What is photoelectrochemistry and how can it be used for solar fuel processing?
  - What other chemical commodities or materials can be processed using solar energy?