ETH zürich

Solar Reactor Technology
for the production of
Sustainable Aviation Fuels

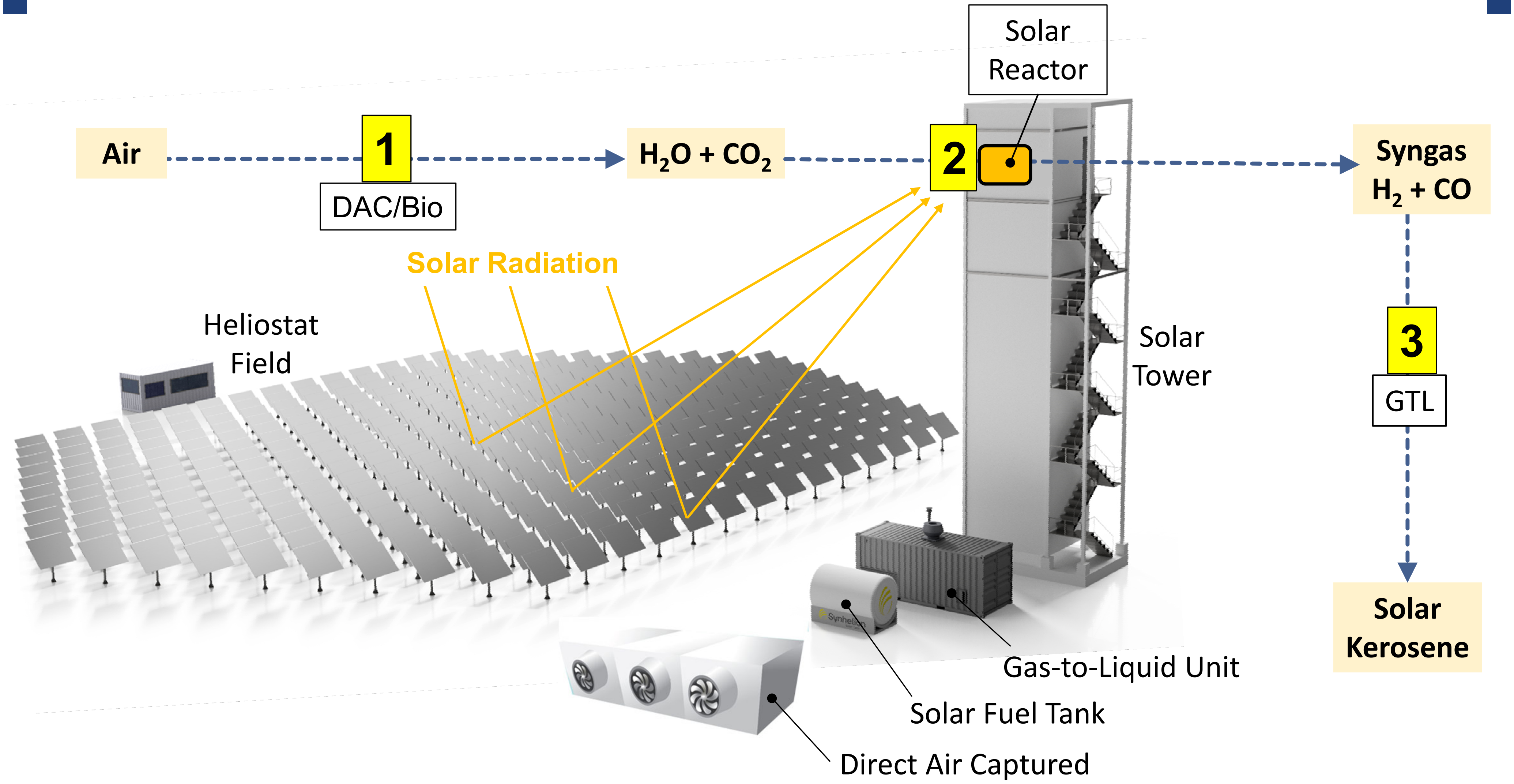
PREC
Professorship of Renewable Energy Carriers
www.prec.ethz.ch

AWST Benchmarking Workshop
ASU 20-09-2023

Aldo Steinfeld

Photo: IMDEA Solar Tower

The SUN-to-LIQUID pathway



Air

1

DAC/Bio

$H_2O + CO_2$

2

Solar Reactor

Syngas
$H_2 + CO$

3

GTL

Solar Kerosene

Solar Radiation

Heliostat Field

Solar Tower

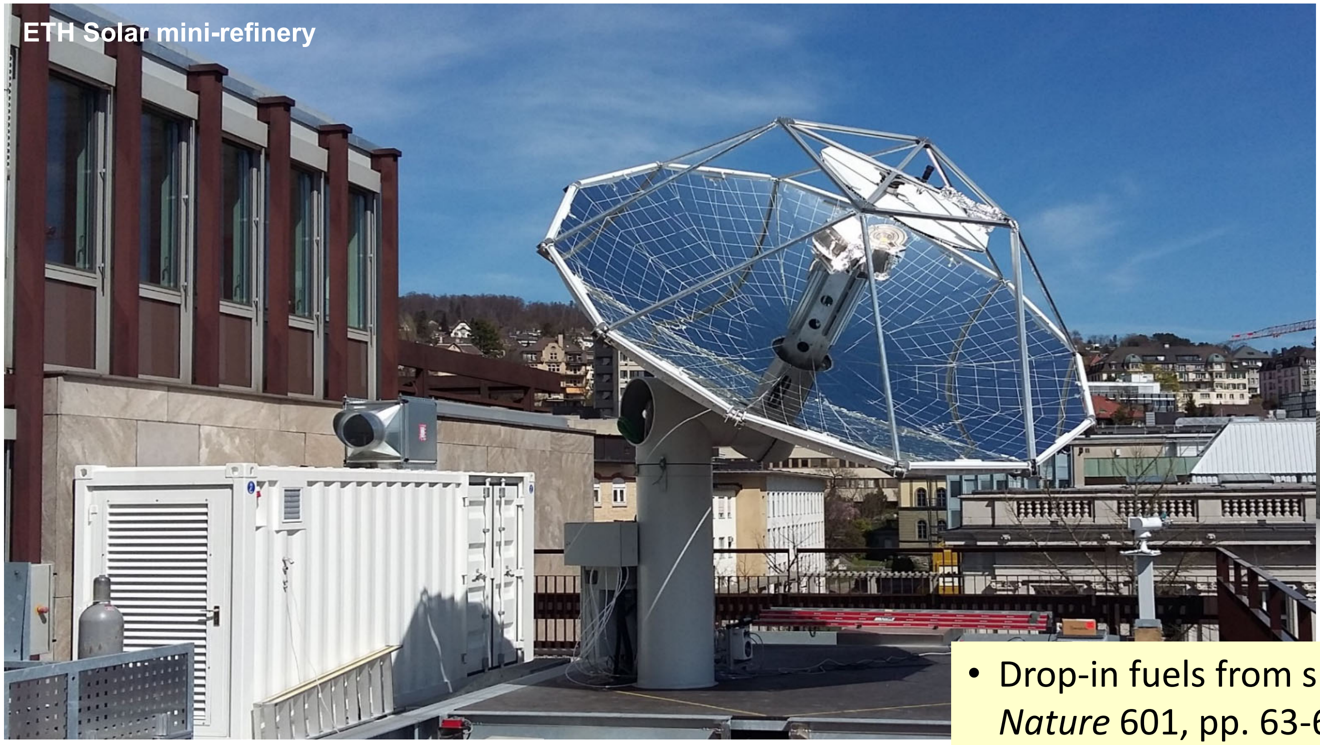
Gas-to-Liquid Unit

Solar Fuel Tank

Direct Air Captured

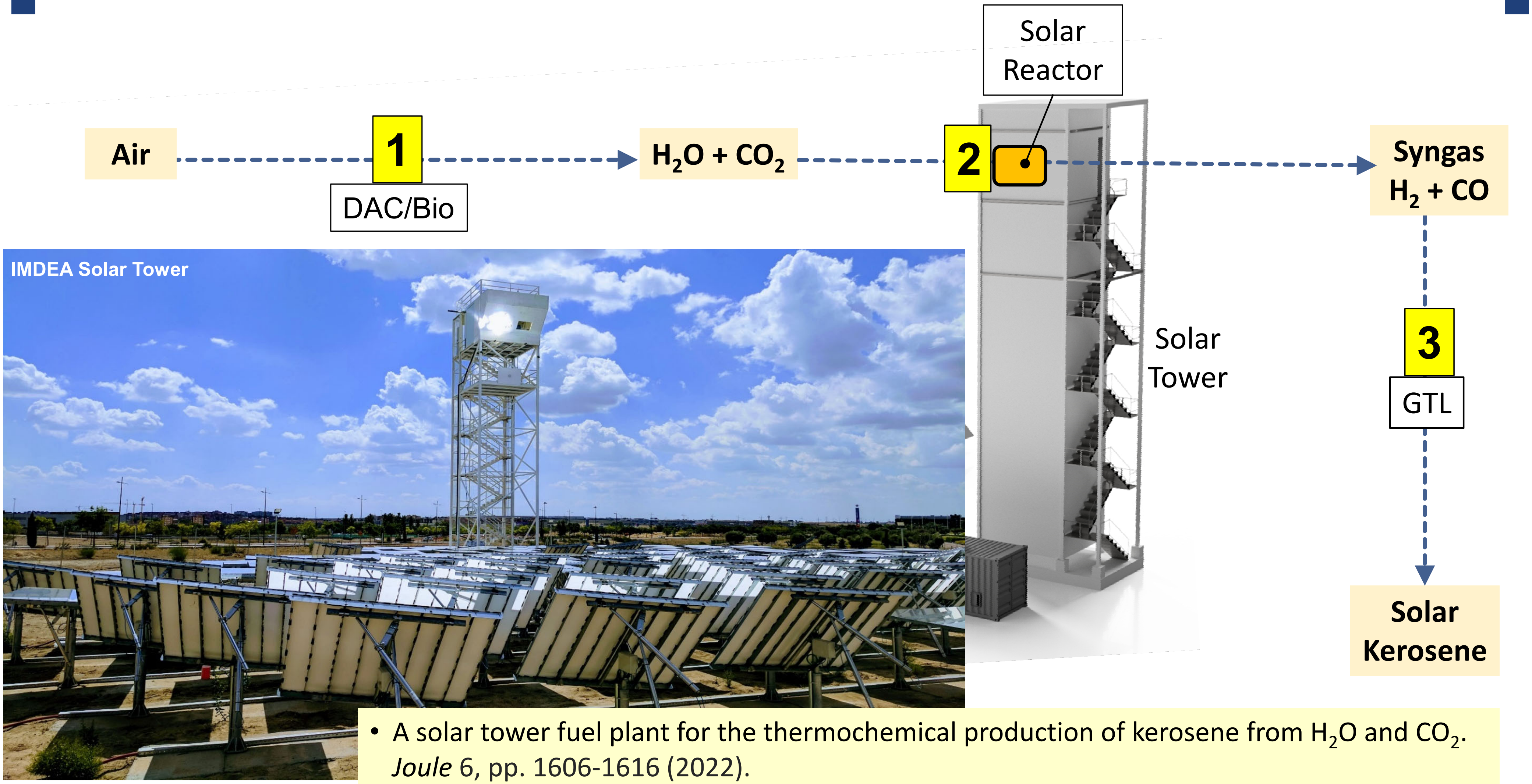
The SUN-to-LIQUID pathway

Air → **1** DAC/Bio → **$H_2O + CO_2$** → **2** Solar Reactor → **Syngas $H_2 + CO$** → **3** GTL → **Solar Kerosene**


ETH Solar mini-refinery

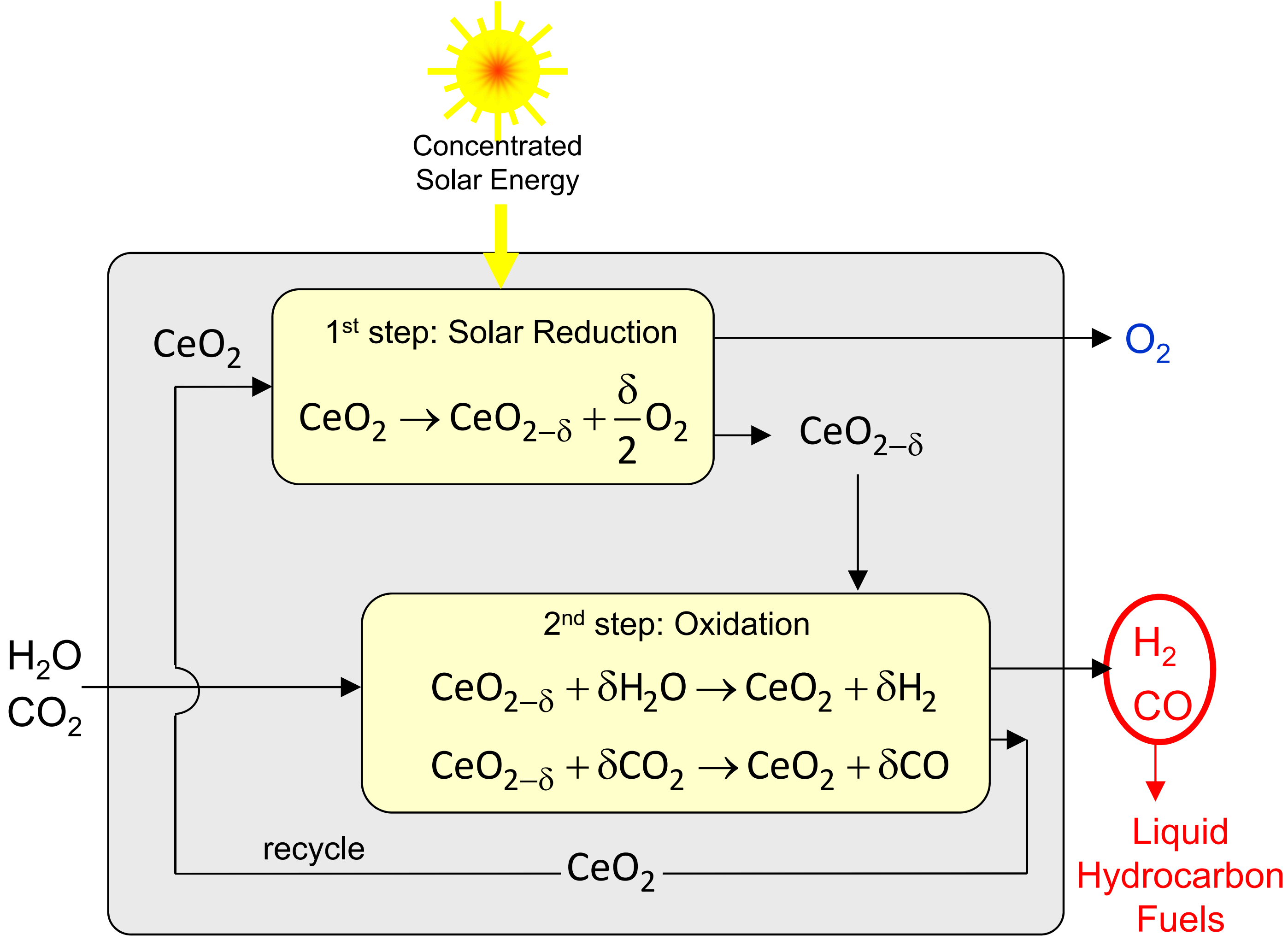
- Drop-in fuels from sunlight and air
  Nature 601, pp. 63-68 (2022)

The SUN-to-LIQUID pathway



- A solar tower fuel plant for the thermochemical production of kerosene from H_2O and CO_2. *Joule* 6, pp. 1606-1616 (2022).

Solar Thermochemical Redox Cycle



Concentrated Solar Energy

CeO_2

1st step: Solar Reduction

$$CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2} O_2$$

O_2

$CeO_{2-\delta}$

H_2O

CO_2

2nd step: Oxidation

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

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

H_2

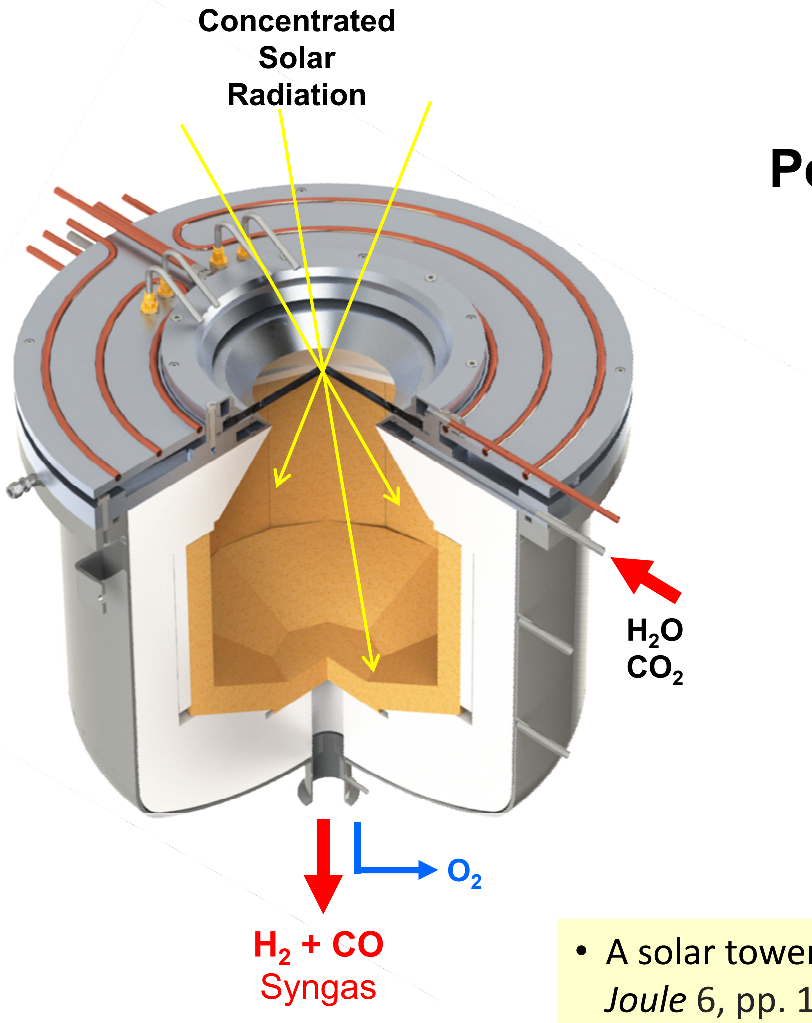
CO

Liquid Hydrocarbon Fuels

recycle

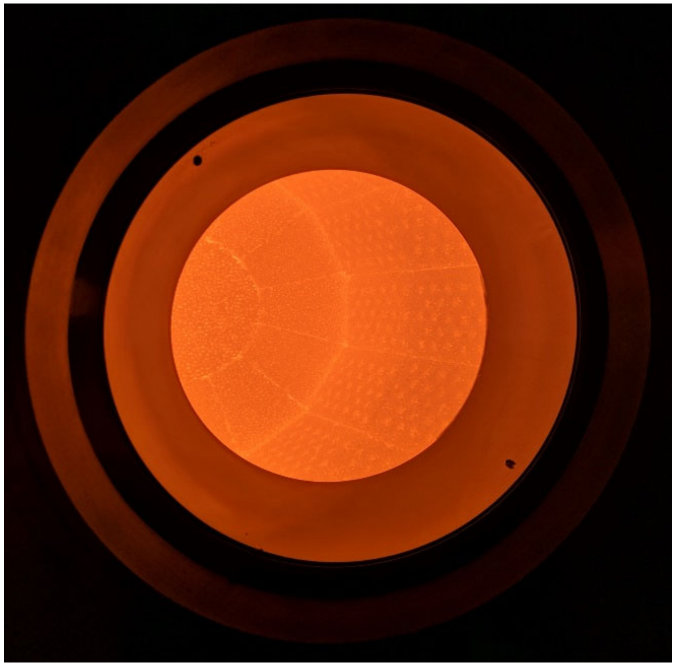
CeO_2

EU-project SUN-to-LIQUID



Performance Indicators

- Scalabilty ✓
- Selectivity ✓
- Conversion ✓
- Stability ✓
- Energy efficiency



- A solar tower fuel plant for the thermochemical production of kerosene from H_2O and CO_2. *Joule* 6, pp. 1606-1616 (2022).

Solar-to-Fuel Energy Efficiency

$$\eta_{\text{solar-to-fuel}} = \frac{\overbrace{HV_{\text{fuel}} \cdot \int r_{\text{fuel}}\,dt}^{\text{heating value of fuel produced}}}{\underbrace{\int P_{\text{solar}}\,dt}_{\text{solar energy input}} + \underbrace{E_{\text{parasitics}}}_{\substack{\text{vacuum pumping}\\ \text{or}\\ \text{inert gas recycling}}}} = \left\{ \begin{array}{ll} \mathbf{5.6\,\%} & \bullet \text{ pure } CO_2 \text{ splitting} \\ & \bullet \text{ without heat recovery} \\ & \\ \mathbf{4.1\,\%} & \bullet\ H_2O/CO_2 \text{ co-splitting} \\ & \bullet \text{ without heat recovery} \end{array} \right.$$

To boost the solar-to-fuel energy efficiency:

1) **Redox materials** → … with > δ than CeO_2 at same T,p
2) **Heat recovery** → … of heat rejected during redox cycles
3) **Porous structures** → … for improved radiative absorption

- *Joule* 6 (2022)

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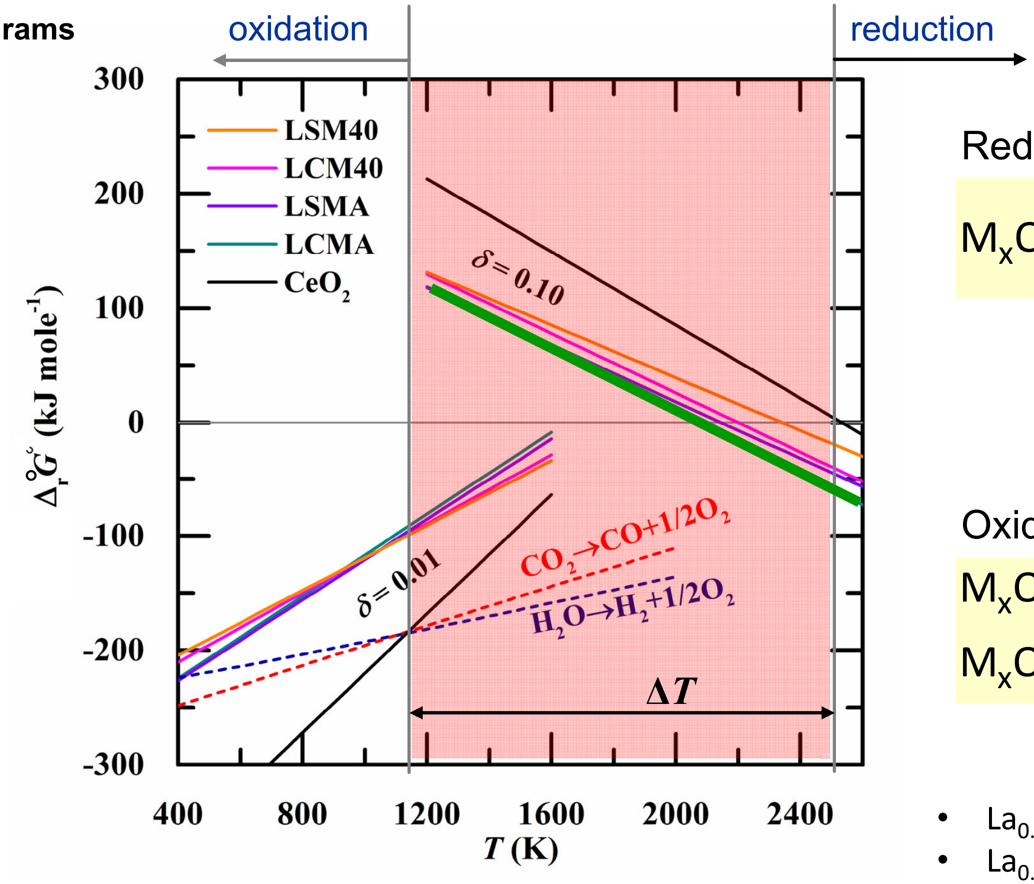
Redox Materials

PREC

- **Ellingham diagrams**



Reduction

$$M_xO_y \rightarrow M_xO_{y-\delta} + \frac{\delta}{2} O_2$$

Oxidation

$$M_xO_{y-\delta} + \delta H_2O \rightarrow M_xO_y + \delta H_2$$

$$M_xO_{y-\delta} + \delta CO_2 \rightarrow M_xO_y + \delta CO$$

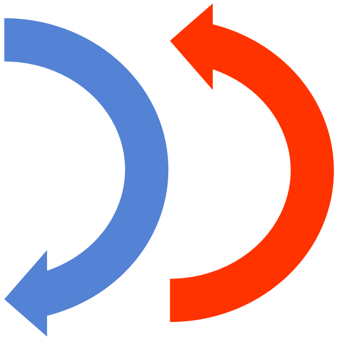
$La_{0.6}Sr_{0.4}Mn_{0.6}Al_{0.4}O_{3-\delta}$	(LSMA)
$La_{0.6}Sr_{0.4}MnO_{3-\delta}$	(LSM40)
$La_{0.6}Ca_{0.4}Mn_{0.6}Al_{0.4}O_{3-\delta}$	(LCMA)
$La_{0.6}Ca_{0.4}MnO_{3-\delta}$	(LCM40)

- *Acta Materialia* 103, pp. 700-710 (2016)
- *ChemSusChem* 10, 1517-1525 (2017)
- *J. Materials Chemistry* A 5, 4172-4182 (2017)

High-T Heat Recovery

1st step: Reduction @ $\boldsymbol{T}_{\mathbf{red}}$

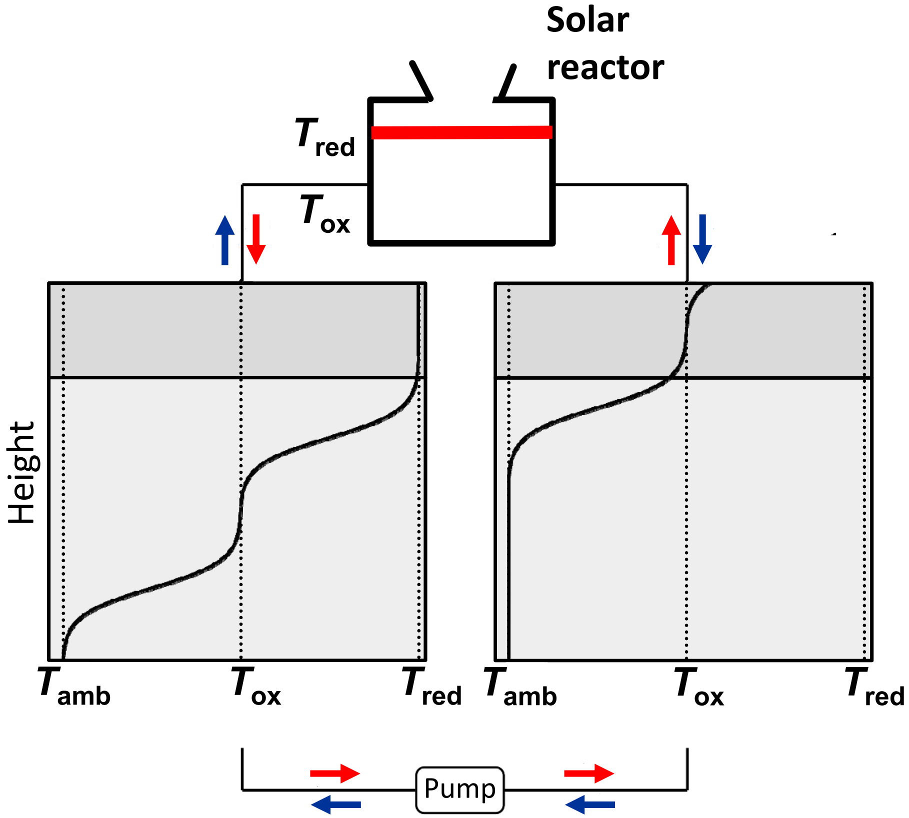
$$\mathrm{CeO_2} \rightarrow \mathrm{CeO_{2-\delta}} + \frac{\delta}{2}\mathrm{O_2}$$



2nd step: Oxidation @ $\boldsymbol{T}_{\mathbf{ox}}$

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

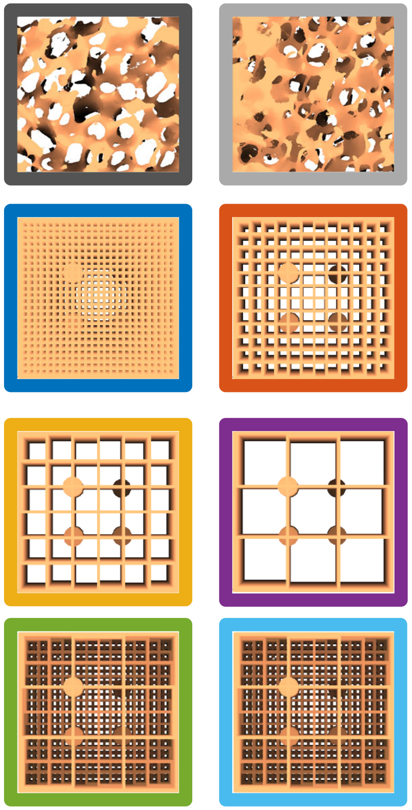
$$\mathrm{CeO_{2-\delta}} + \delta\mathrm{CO_2} \rightarrow \mathrm{CeO_2} + \delta\mathrm{CO}$$

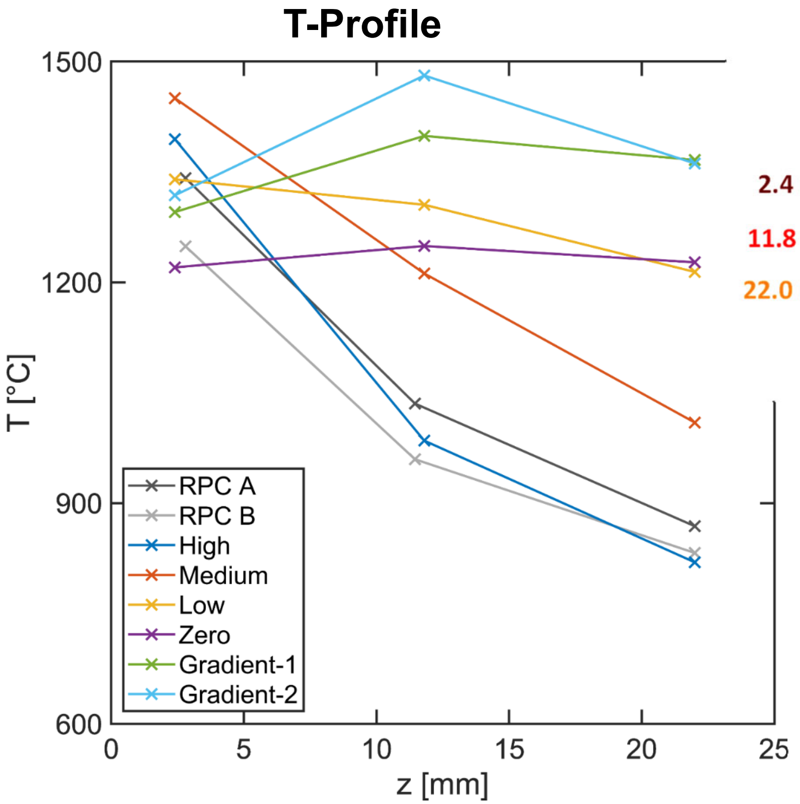


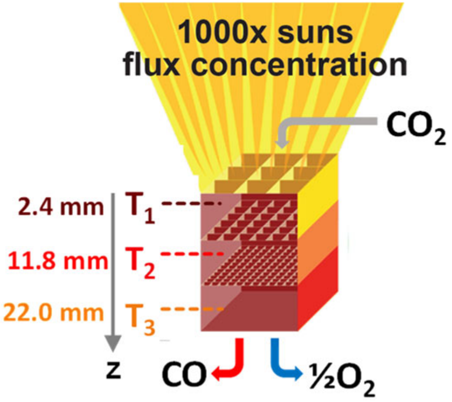
- High-temperature heat recovery from a solar reactor for the thermochemical redox splitting of H_2O and CO_2.
  Applied Energy 329, p. 120211 (2023)

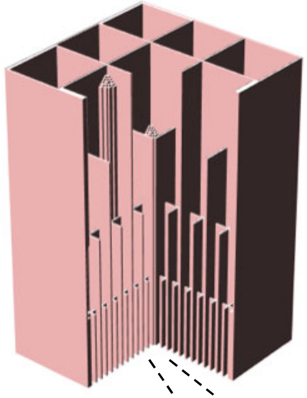
$$\eta_{\text{solar-to-fuel}} > 20\%$$

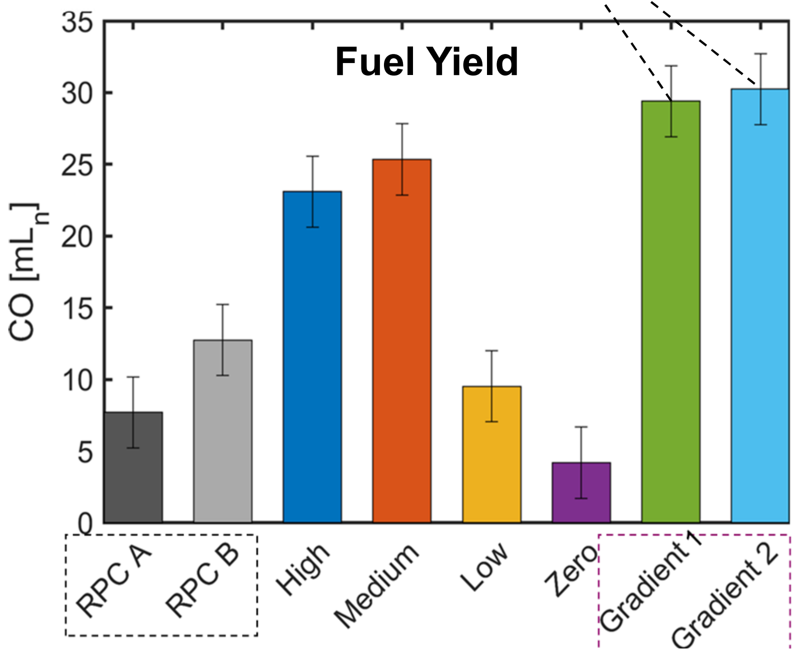
Hierarchically Channeled Structures







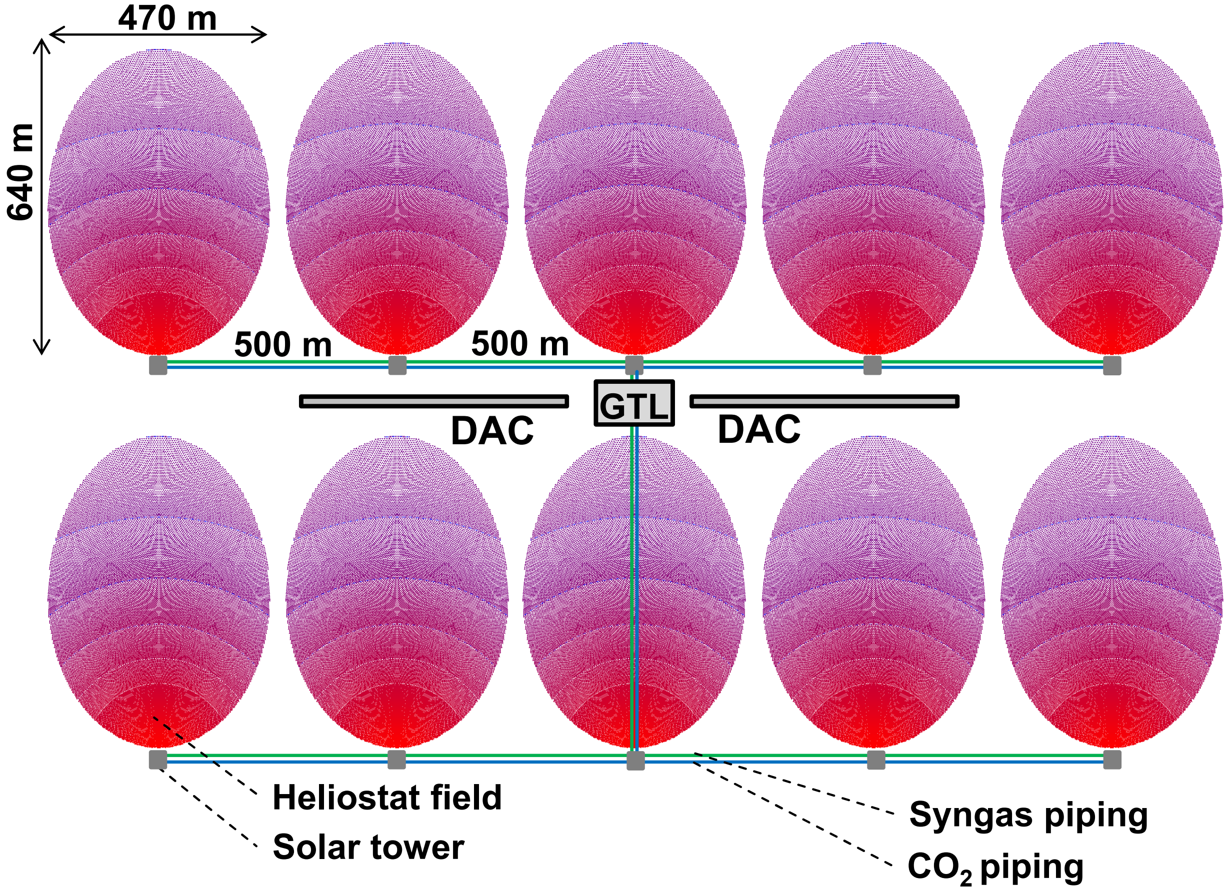




- Solar-driven redox splitting of CO_2 using 3D-printed hierarchically channeled ceria structures. *Advanced Materials Interfaces*, 2300452 (1 to11), 2023.

Solar Refinery of the Future

- Baseline design: 10 x 100 MW_{th} solar towers = 1 GW_{th} solar radiative input
- Overall energy efficiency = 10%
- Per year: 100,000 tons CO_2
- Per year: 34 million liters kerosene
- Per day: 95,000 liters kerosene
- Land footprint = 3.8 km^2
- DAC frontal area = 4500 m^2



- Drop-in fuels from sunlight and air
  Nature 601, pp. 63-68 (2022).

Relevant Publications 2022-2023

- Schäppi et al. Drop-in fuels from sunlight and air. *Nature* 601, pp. 63-68, 2022.
- Zoller et al. A solar tower fuel plant for the thermochemical production of kerosene from H_2O and CO_2. *Joule* 6, pp. 1606-1616, 2022.
- Lidor et al. High-temperature heat recovery from a solar reactor for the thermochemical redox splitting of H_2O and CO_2. *Applied Energy* 329, pp. 120211, 2023.
- Zuber et al. Methane dry reforming via a ceria-based redox cycle in a concentrating solar tower. *Sustainable Energy & Fuels* 7, pp. 1804–1817, 2023.
- Sas Brunser et al. Solar-driven redox splitting of CO_2 using 3D-printed hierarchically channeled ceria structures. *Advanced Materials Interfaces*, 2300452 (1 to11), 2023.
- Moretti et al. Technical, economic and environmental analysis of solar thermochemical production of drop-in fuels. *Science of the Total Environment* 901, pp. 166005 (1 to 16), 2023.
- Sas Brunser et al. Design and optimization of hierarchically ordered porous structures for solar thermochemical fuels production using a voxel-based Monte Carlo ray-tracing algorithm. *ACS Engineering Au*, in press.

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ROYAL SOCIETY
OF CHEMISTRY

PAPER
Aldo Steinfeld *et al.*
Methane dry reforming *via* a ceria-based redox cycle in a concentrating solar tower

Acknowledgments

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CLIMEWORKS

Synhelion
solar fuels