# "Tecnologías de captura, almacenamiento y usos del $CO_2$
# Soluciones para afrontar el cambio climático"

## Curso de verano 1 a 5 de julio 2019
## Campus de Móstoles. Aula CEI "Energía Inteligente" - URJC


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SUN to LIQUID
Fuels from concentrated sunlight

# Decarbonizing Transport: European Targets

- **Policy related frameworks** (Renewable Energy Directive, RED 2009)
  - **Binding renewable energy targets by 2020 (10% share in transport)***
  - **Binding climate relevant targets -20% emissions by 2020, -80% emissions by 2050**

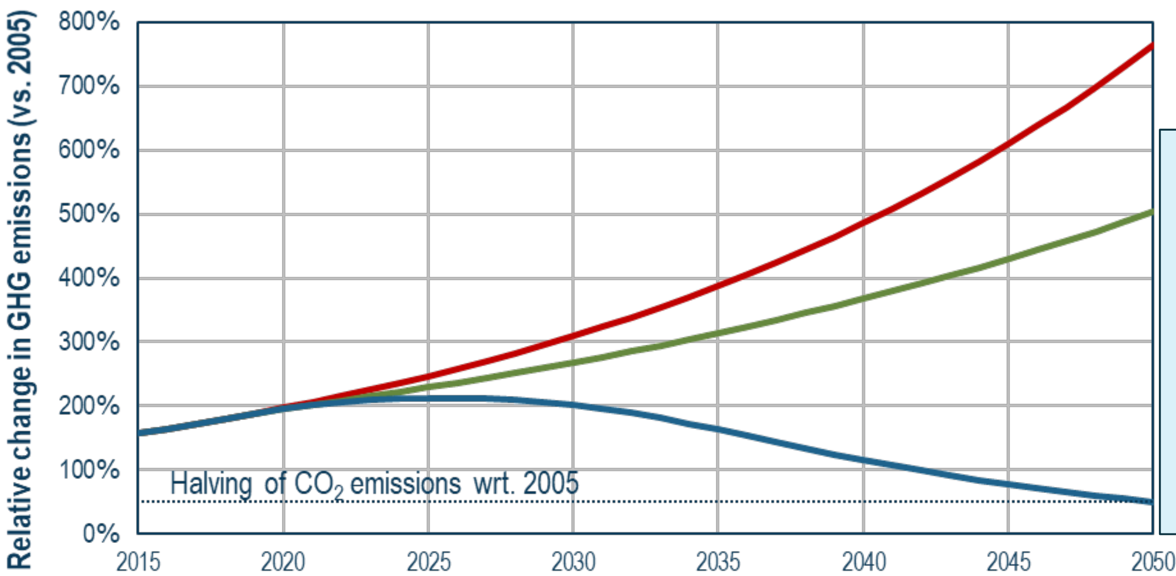
- **Industry related frameworks** (ACARE targets, ATAG targets)
  - **Advisory Council for Aviation Research & Innovation in Europe**
  - **ACARE Vision 2020 → SRA 2002-2020 (no sustainable fuel targets)**
  - **ACARE Flightpath 2050 → SRIA 2020-2050 (with sustainable fuel targets)**
    - Technologies and operations for **75%** $CO_2$ emission reduction (rel. to **2000, Aircraft**)
  - **Air Transport Action Grp. (ATAG) 50% $CO_2$ emission reduction (rel. to 2005, Global Fleet)**

- **Policy/industry joint initiatives**
  - **European Advanced Biofuels Flightpath → 2 Mio t sustainable biofuel p.a. by 2020**

* Fuel suppliers are also required to **reduce the greenhouse gas intensity of the EU fuel mix by 6% by 2020 in comparison to 2010. Increased renewable energy target for 2030 from 27% to 32%** (all forms of energy use including transport fuels)

# The Aviation Target:
# Reduce $CO_2$ by 50% by 2050 (rel. to 2005)

- Future GHG emissions are a function of three main factors: (3) zero carbon energy




100% substitution of fossil kerosene:

ATAG target requires
ca. 550 Mt/a
sustainable aviation fuel with
<10% carbon intensity
compared to conventional fuel by 2050

$$\dot{M}_{CO_2eq}(2050) = \dot{M}_{CO_2eq}(2005) \times \begin{bmatrix} \text{GROWTH} \\ \text{in} \\ \text{RPK} \end{bmatrix} \times \begin{bmatrix} \text{GAIN} \\ \text{in} \\ \text{EFFICIENCY} \end{bmatrix}^{-1} \times \left(1 - \begin{bmatrix} \text{FRACTION of 2050's} \\ \text{"ZERO-CARBON"} \\ \text{ENERGY} \end{bmatrix}\right)$$

# Key Technology: Ceria-based Redox Cycles

SUN to LIQUID
Fuels from concentrated sunlight

- State-of-art in laboratory: $\eta_{solar\text{-}to\text{-}CO}$ = 5.25% for thermochemical $CO_2$ splitting

**Endothermic reduction:**

$$(\sim 1500°C):\ CeO_2 \rightarrow CeO_{2\text{-}\delta} + \frac{\delta}{2} O_2$$

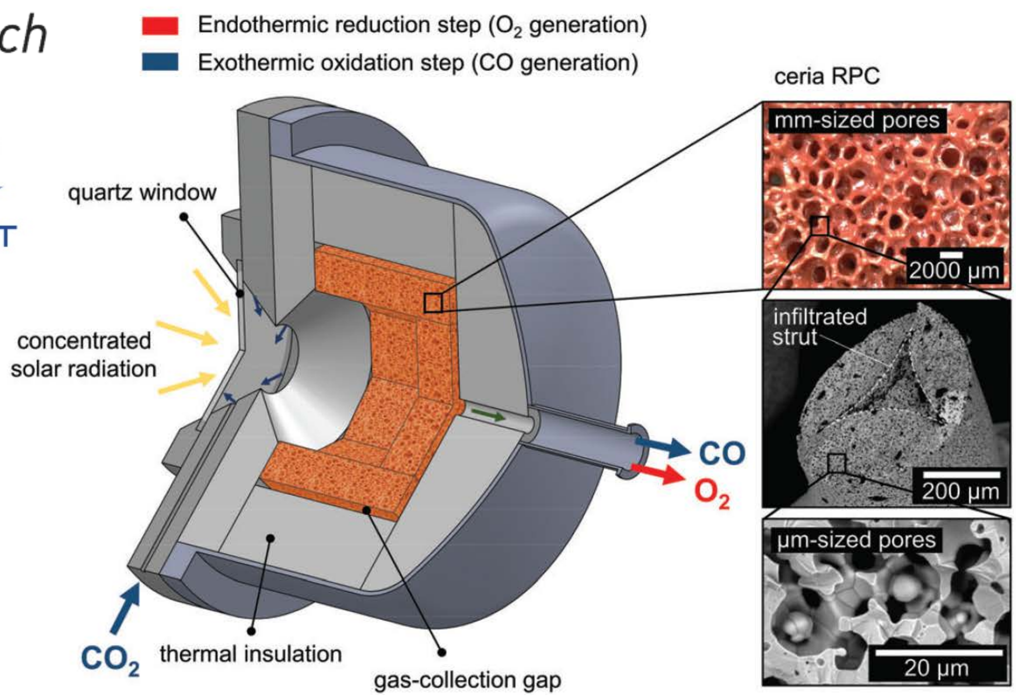
**Exothermic oxidation:**

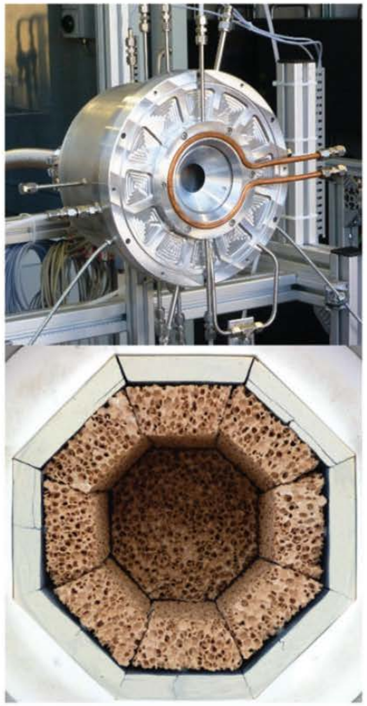
$$(\sim 1000°C):\ CeO_{2\text{-}\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$

$$(\sim 1000°C):\ CeO_{2\text{-}\delta} + \delta CO_2 \rightarrow CeO_2 + \delta CO$$

ETH zürich

SOLAR-JET

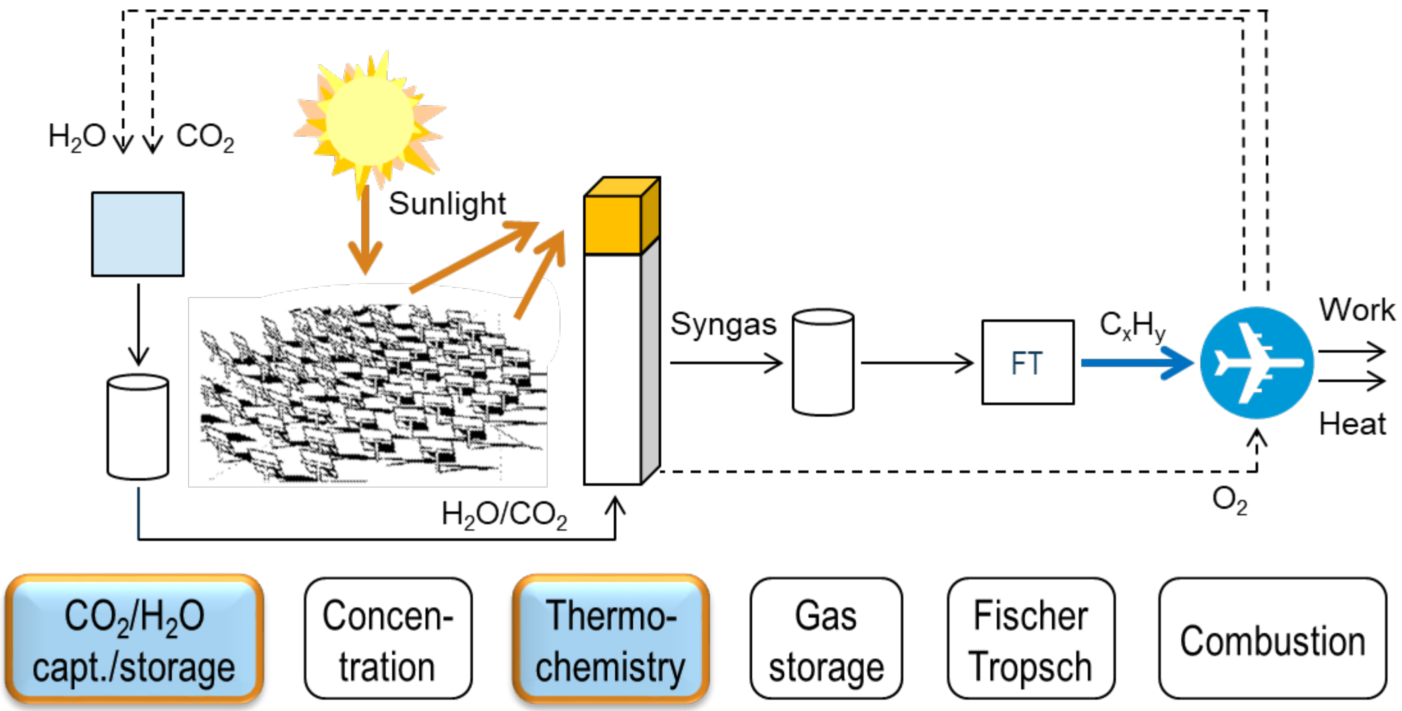


Source: Marxer et al, *Solar thermochemical splitting of $CO_2$ into separate streams of CO and $O_2$ with high selectivity, stability, conversion, and efficiency*, Energy Environ. Sci., 2017,10, 1142-1149; see also: http://www.solar-jet.aero/page/media-centre/scientific-publications.php

# SUN-to-LIQUID Approach to Solar Fuel

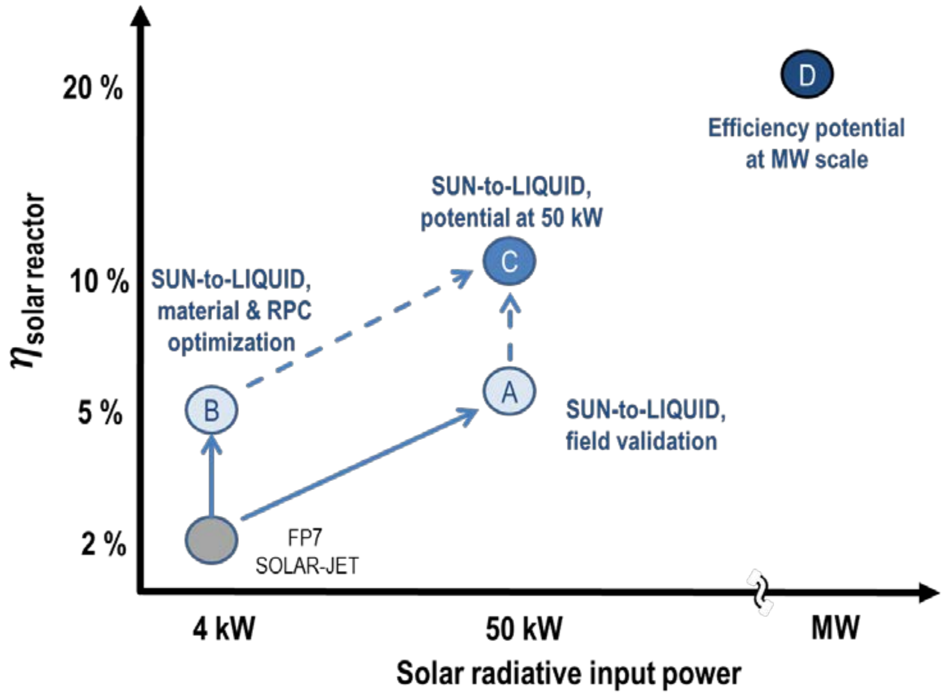
- Ambition: unlimited supply of renewable synthetic hydrocarbon fuels




- Some process steps already proven on an industrial scale
- Lowest technology readiness level for thermochemical conversion and $CO_2$ capture

# SUN-to-LIQUID Ambition

- Move from laboratory to field environment
- Demonstration of complete fuel production cycle in a relevant environment
- Increase TRL from 3 to 5
- Scale-up of thermal power input from 4 kW to 50 kW
- Optimization of reactor geometry and material structure to increase efficiency from 2% to 5-10%
- On-site conversion of produced syngas to hydrocarbons



# Key Objectives: Solar Concentration

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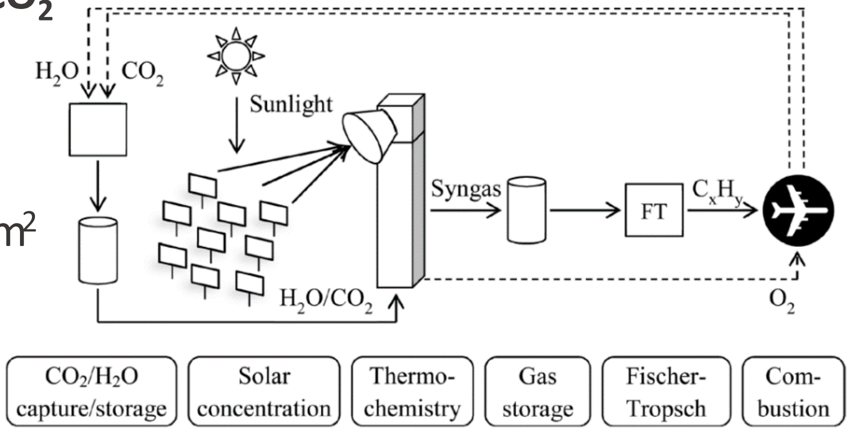
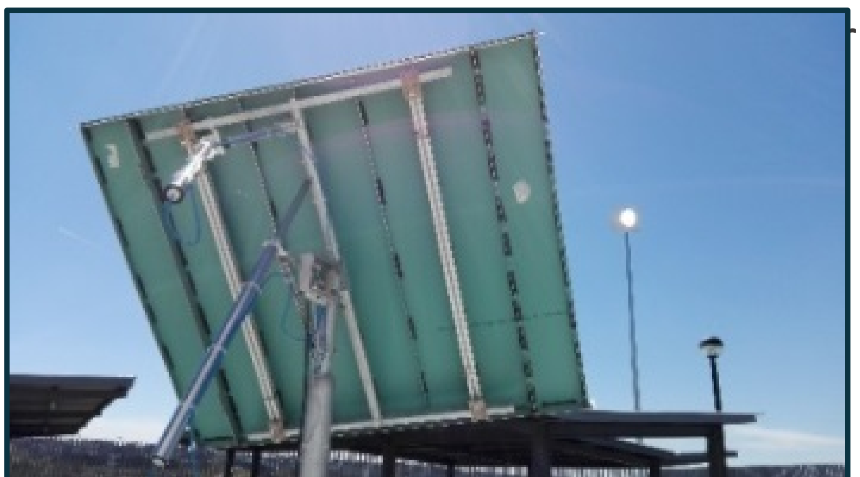
Fuels from concentrated sunlight

- **Key Objectives: Scale-up and experimental demonstration of the complete StL process chain to liquid hydrocarbon fuels from $H_2O$, $CO_2$ and solar energy at a pre-commercial scale**



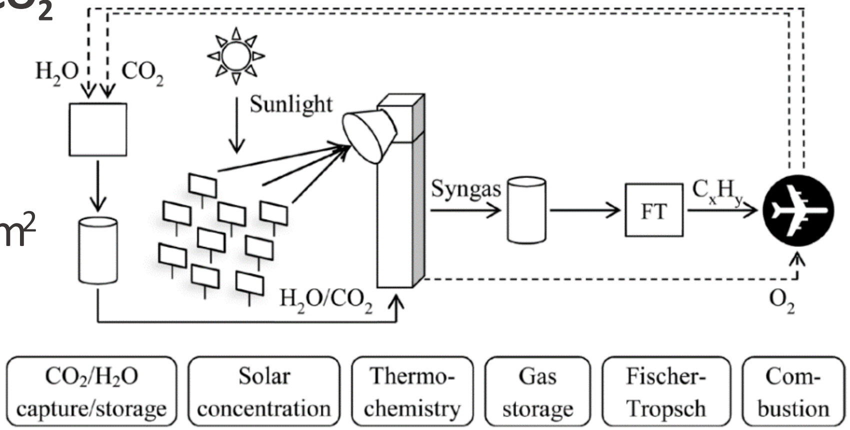

- High flux solar concentrating system
  - 50 kW radiative power, flux of 2500 kW/m$^2$ over a 16-cm diameter aperture
  - Field of 169 heliostats, 3 m$^2$ each, with 20 – 30 m focal length



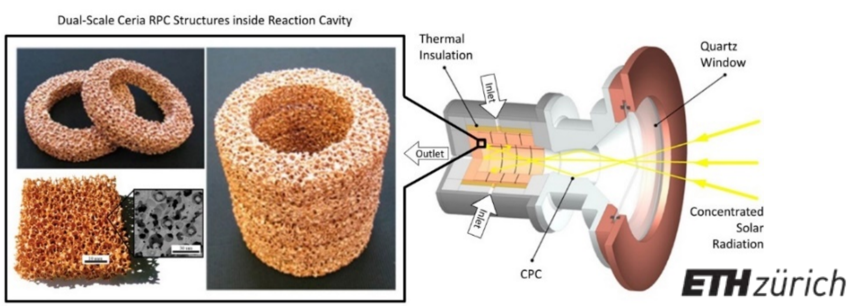
# Key Objectives: 50 kW Solar Reactor

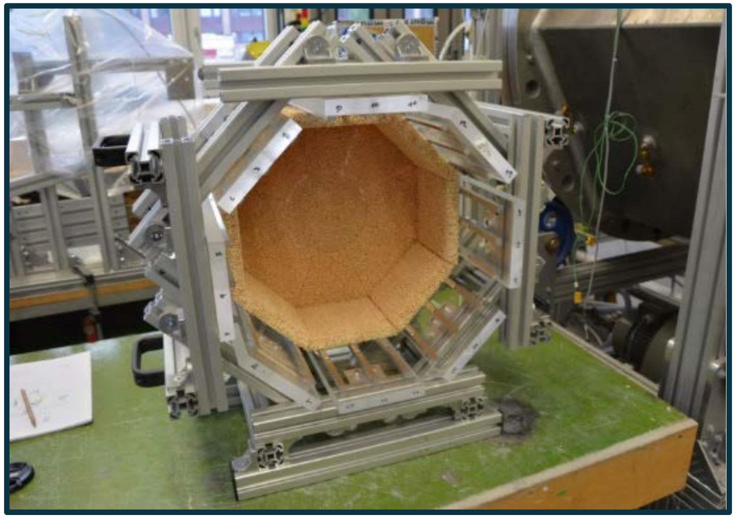
SUN to LIQUID
Fuels from concentrated sunlight

- **Key Objectives: Scale-up and experimental demonstration of the complete StL process chain to liquid hydrocarbon fuels from $H_2O$, $CO_2$ and solar energy at a pre-commercial scale**




- High flux solar concentrating system
  - 50 kW radiative power, flux of 2500 kW/m$^2$ over a 16-cm diameter aperture
  - Field of 169 heliostats, 3 m$^2$ each, with 20 – 30 m focal length
- 50 kW solar thermochemical reactor
  - Producing syngas via ceria-based thermochemical redox cycle



# Key Objectives: Gas-to-Liquid Plant

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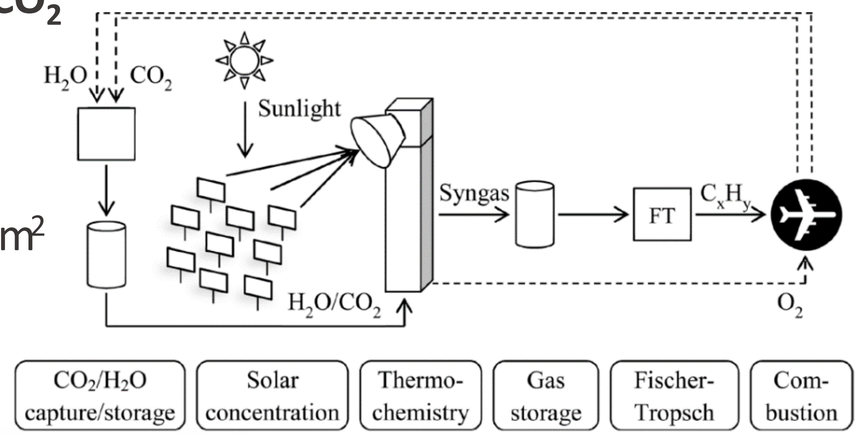
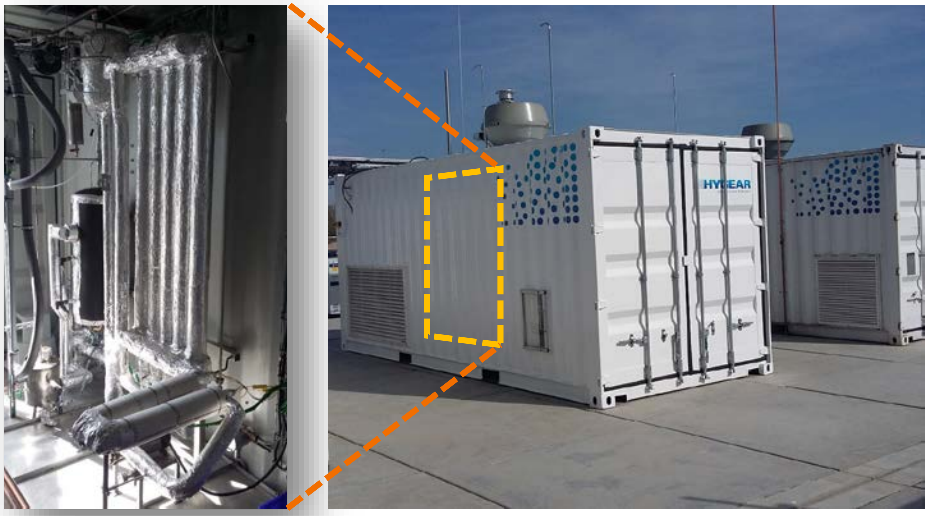
Fuels from concentrated sunlight

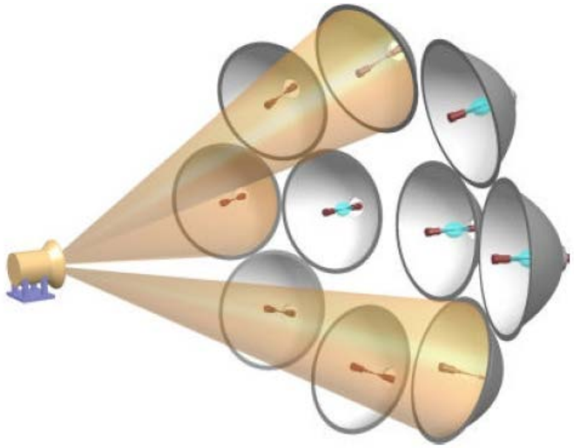
- **Key Objectives: Scale-up and experimental demonstration of the complete StL process chain to liquid hydrocarbon fuels from $H_2O$, $CO_2$ and solar energy at a pre-commercial scale**




- High flux solar concentrating system
  - 50 kW radiative power, flux of 2500 kW/m$^2$ over a 16-cm diameter aperture
  - Field of 169 heliostats, 3 m$^2$ each, with 20 – 30 m focal length
- 50 kW solar thermochemical reactor
  - Producing syngas via ceria-based thermochemical redox cycle
- Gas-to-liquid system
  - Compression and storage of syngas
  - Micro Fischer-Tropsch unit converts syngas to liquid hydrocarbon fuels



# STEPS TO SCALING-UP SOLAR CHEMISTRY



1-5 kW

30-50 kW

50-300 kW

300-3000 kW

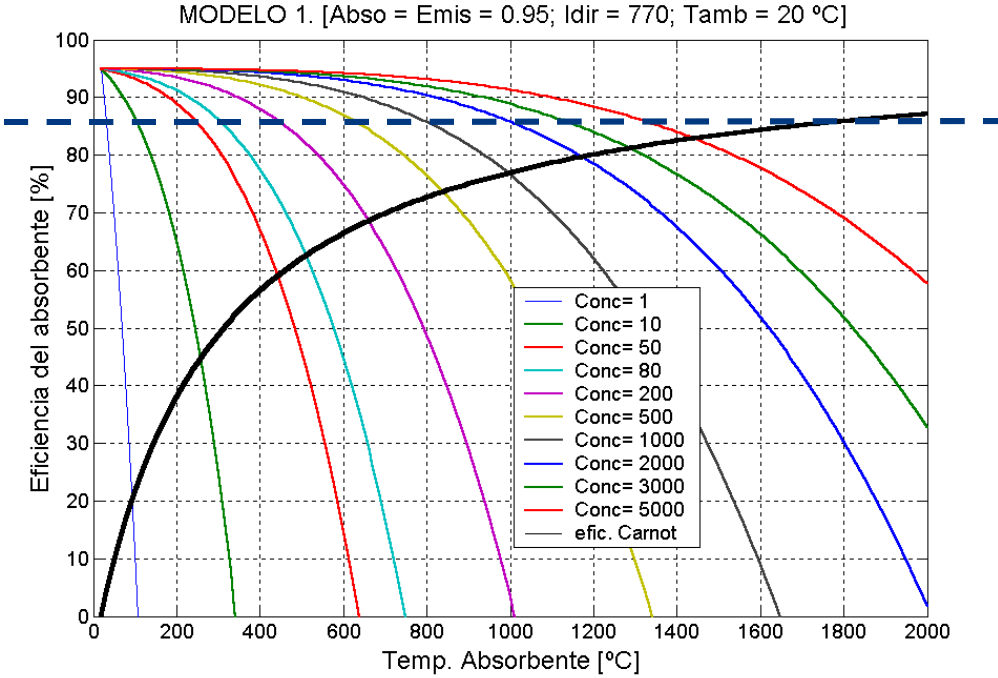
# Optimization of solar concentration systems

- Combined efficiency: Receiver + Power block

$$\eta_{rec} = \alpha - \sigma * \varepsilon * \frac{(T_{abs}^4 - T_{amb}^4)}{Conc * \phi}$$

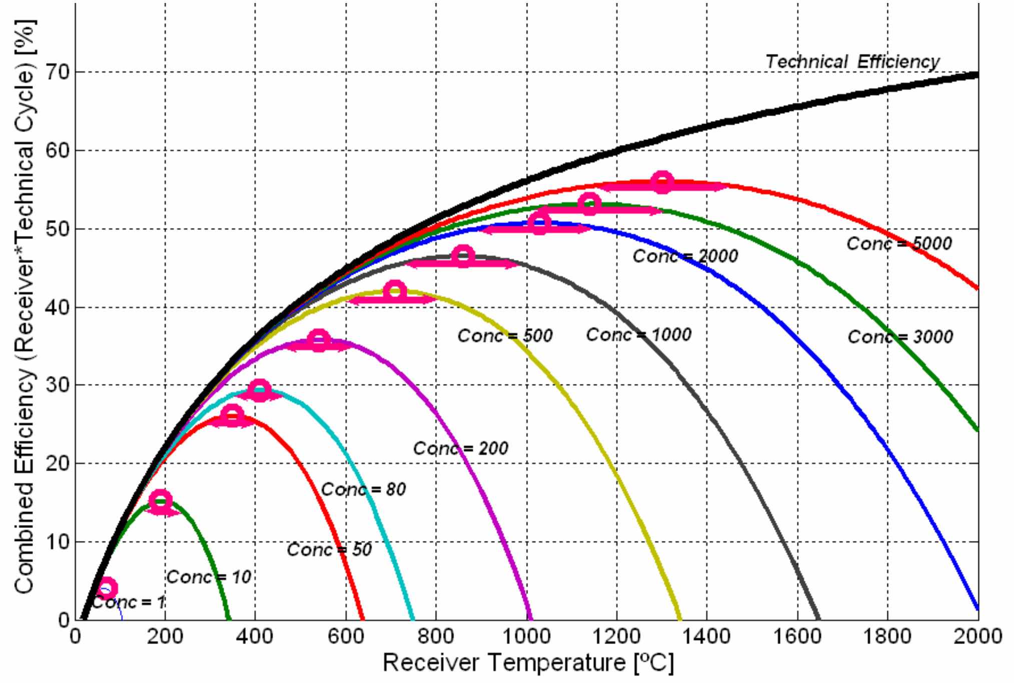
$$\eta_{Carnot} = \frac{T_{abs} - T_{amb}}{T_{abs}}$$

$$\eta_{tot\_rec} = \eta_{rec} * \eta_{Carnot}$$

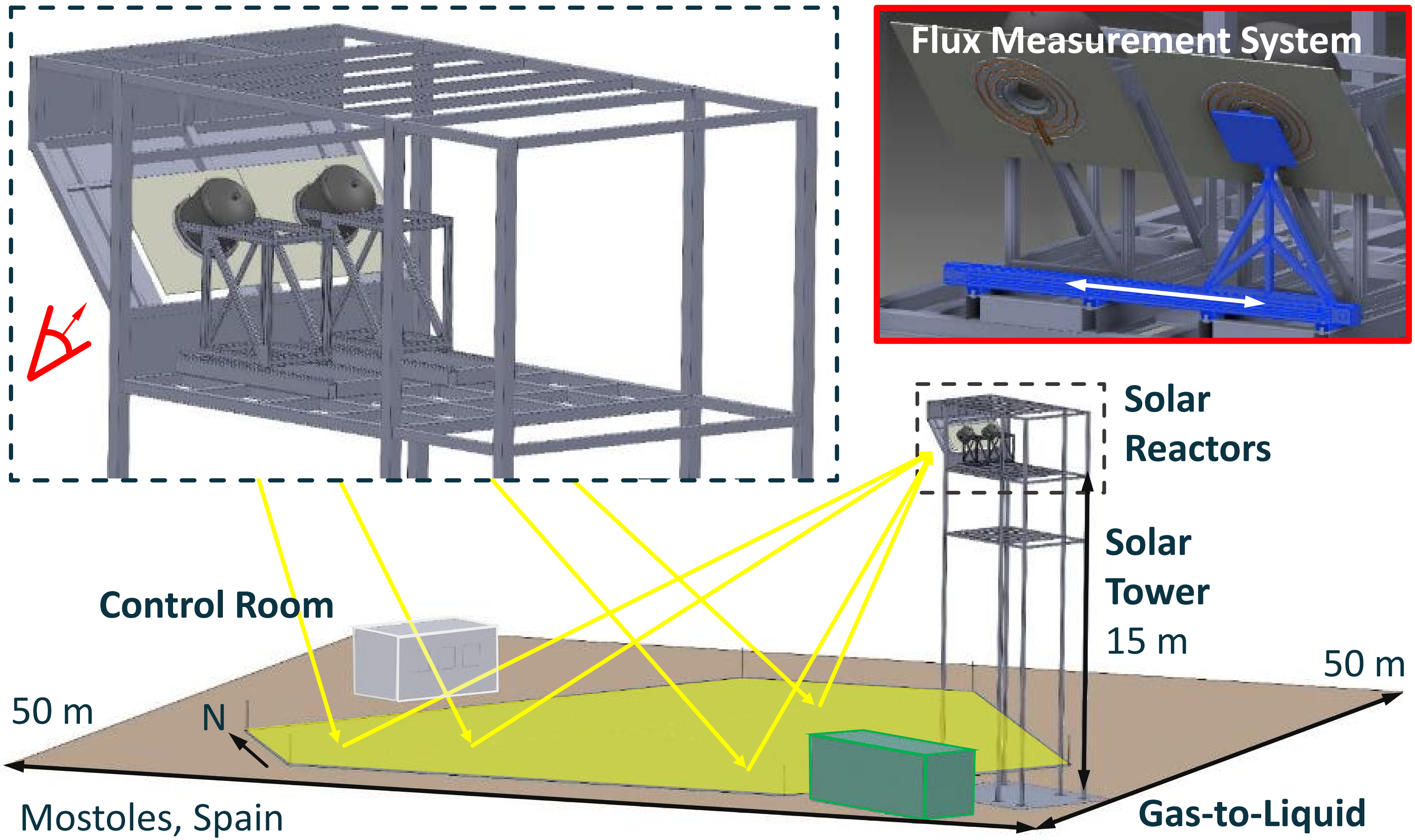



- Stagnation temperature:

$$\frac{d\eta_{tot\_rec}}{dT} = 0$$

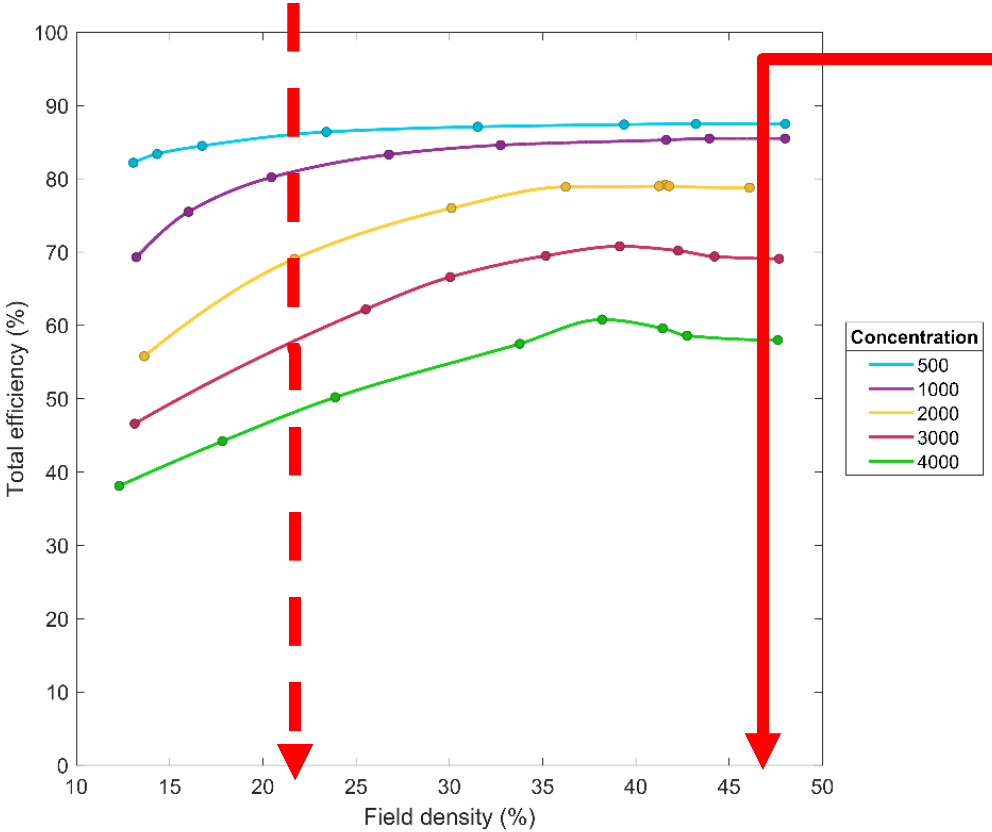


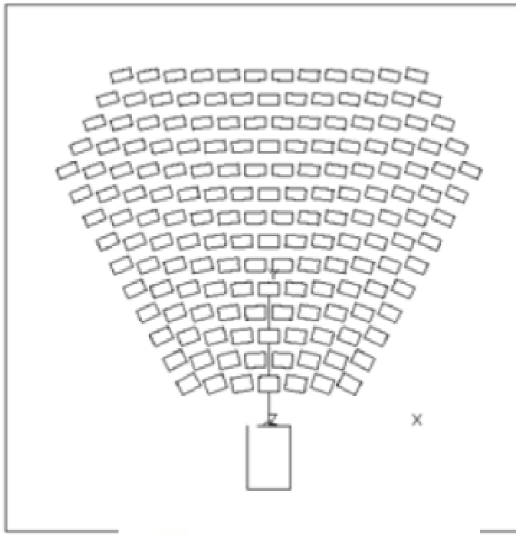
# Solar Chemical Plant Overview



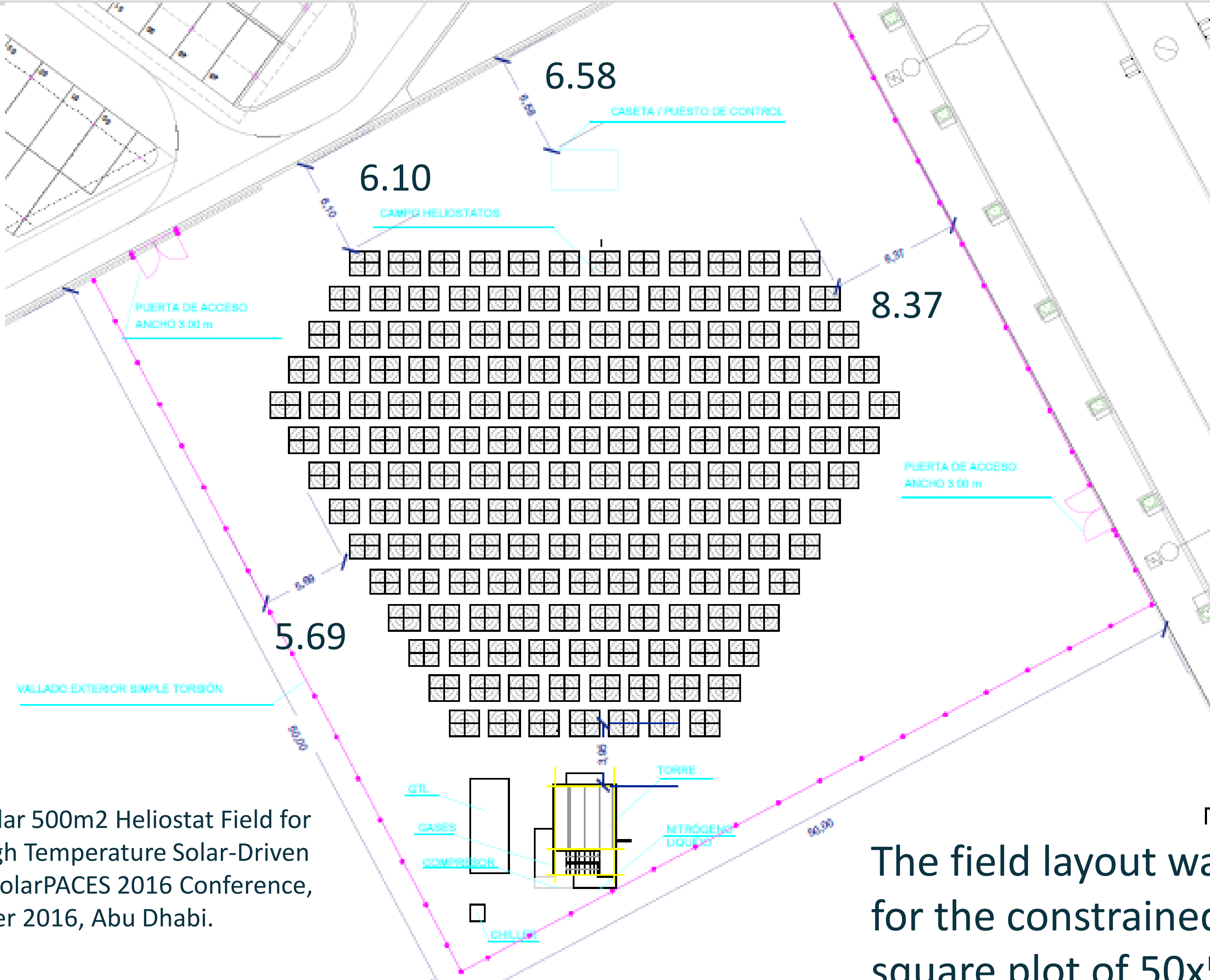
Field density above 45% leads to optical efficiency around 70%

SoA CSP



# Cornfield layout




"Ultra-Modular 500m2 Heliostat Field for High Flux/High Temperature Solar-Driven Processes," SolarPACES 2016 Conference, 11-14 October 2016, Abu Dhabi.

The field layout was optimized for the constrained land, a square plot of 50x50 m2.

# Design and construction of a 50 kW high-flux solar concentration system

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Heliostat with facet of 60 m radius (August 2016)

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RIOGLASS SOLAR

Dimensions: 1605 x 1900 mm x 3 mm
Fresh reflectivity: 94.3% average (93.8% minimum)
Low iron glass

## Design and construction of a 50 kW high-flux solar concentration system

SUN to LIQUID
Fuels from concentrated sunlight

Construction completed by end January 2017 (M13)

# Testing and characterization of high-flux solar concentration system

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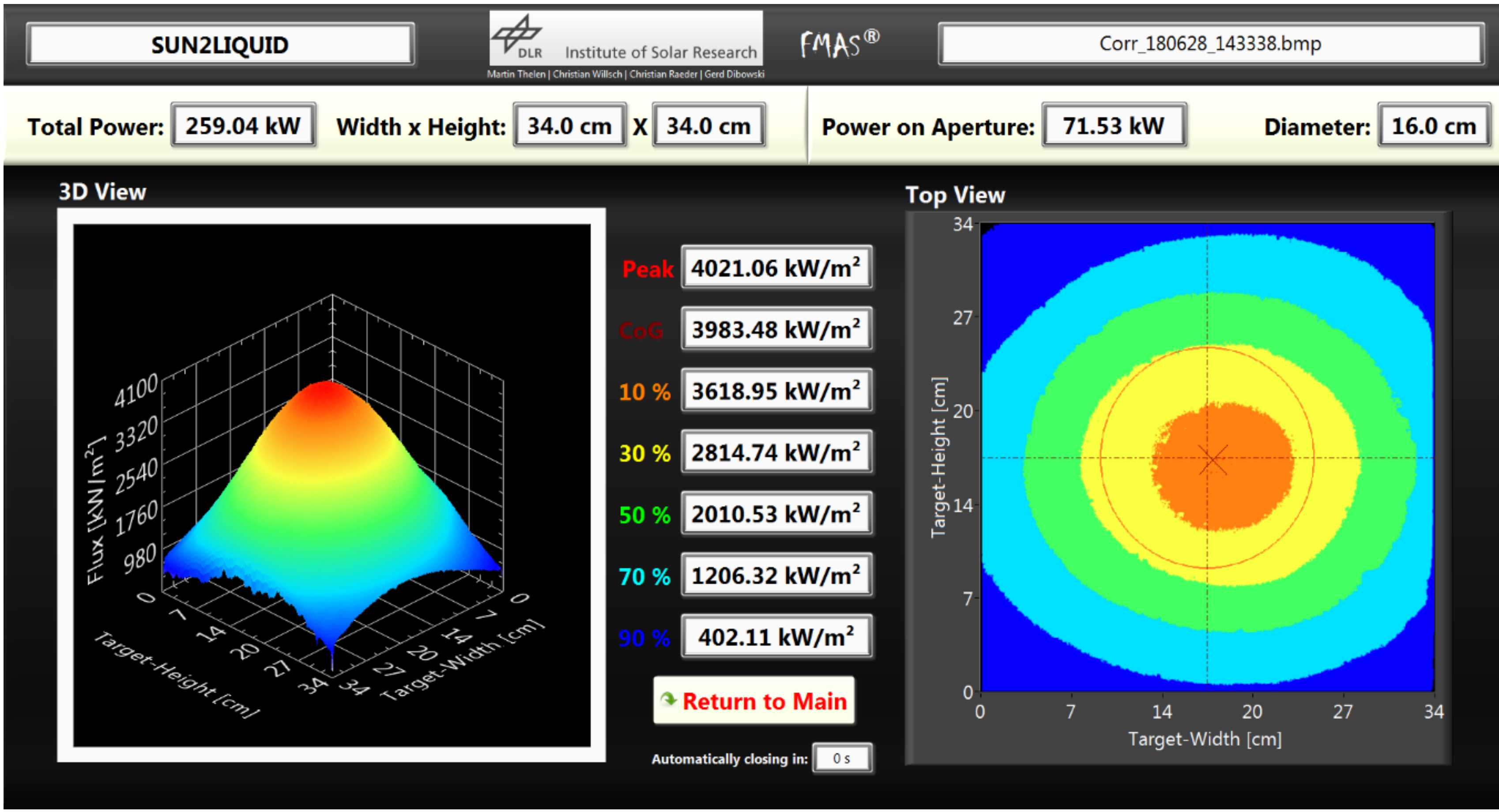
Fuels from concentrated sunlight

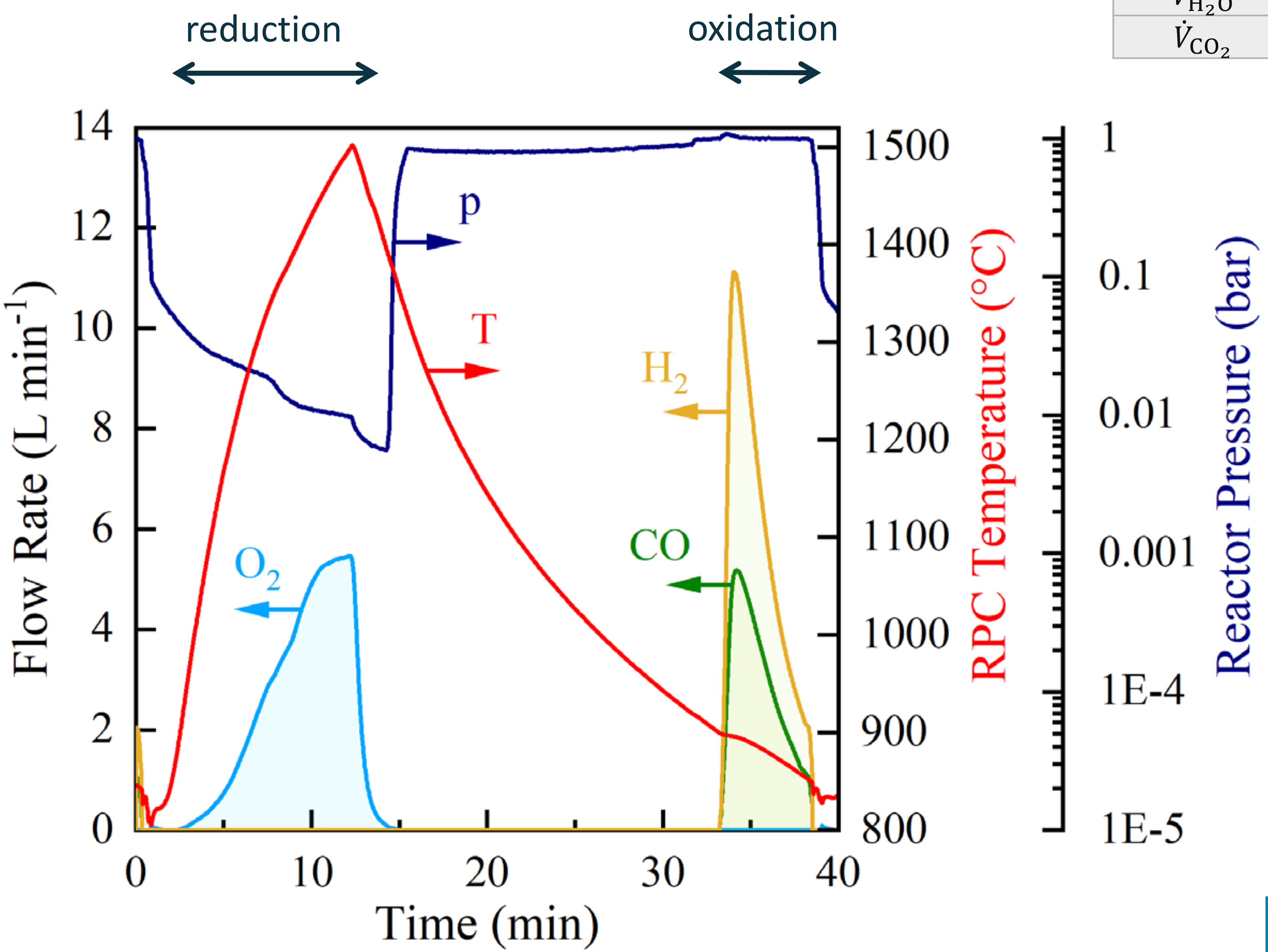
- Highest measured power ever achieved: 71.5 kW onto 16-cm aperture (new calorimeter on site), solar noon on 28th June 2018, for a DNI of 800 W/m$^2$



# Control Room

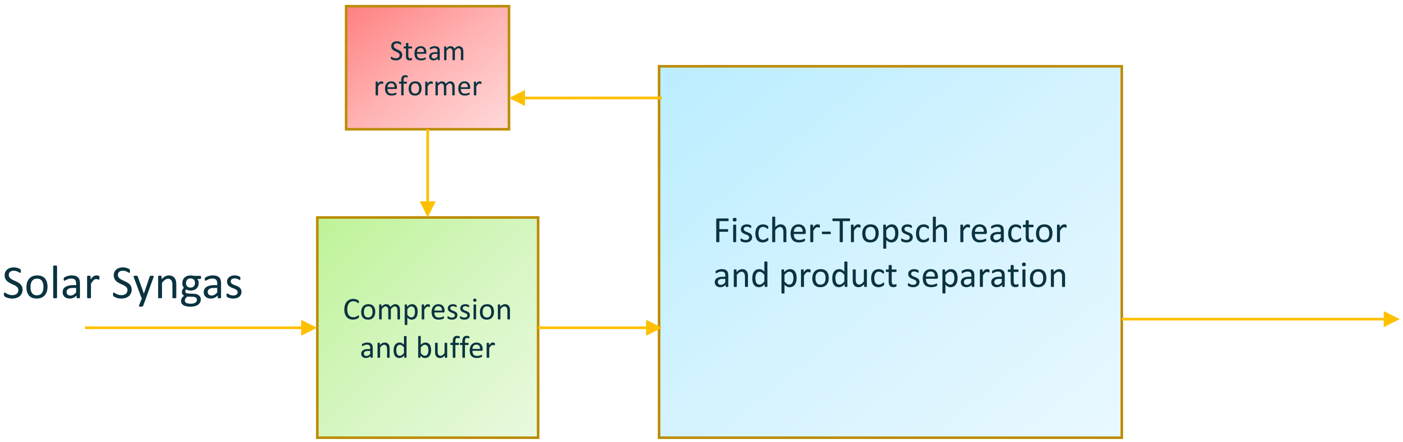
# Representative Solar Redox Cycle

| Experimental Conditions | |
|---|---|
| $T_{reduction, end}$ | 1500 °C |
| $T_{oxidation, start}$ | 900 °C |
| $\dot{V}_{H_2O}$ | 71.4 L/min |
| $\dot{V}_{CO_2}$ | 10 L/min |



# Specific test validation MS2

# Gas-to-liquid **plant**

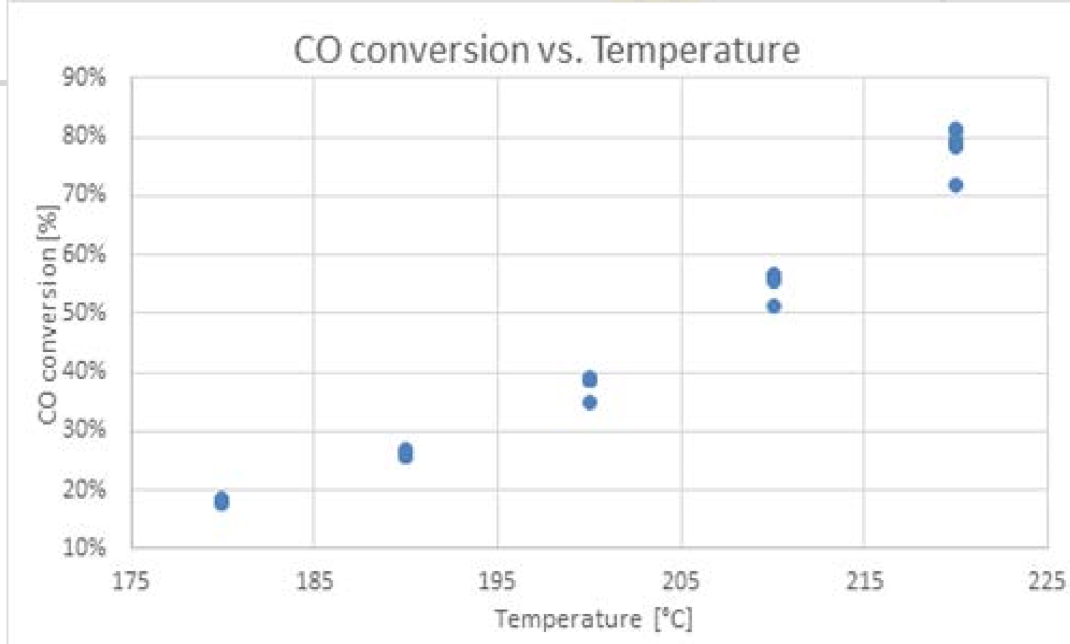




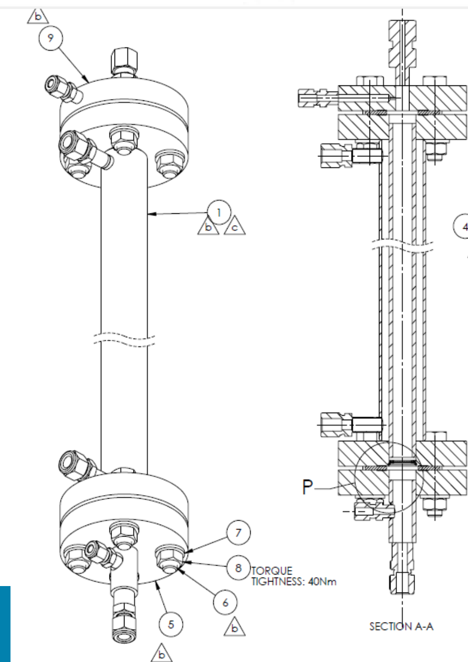
| Species | Concentration | Flow (SLM) |
|---|---|---|
| $H_2$ | 50% | 3.13 |
| CO | 15% | 0.94 |
| $CO_2$ | 25% | 1.56 |
| Ar | 10% | 0.63 |
| total | 100% | 6.25 |

# Design of GTL plant (FT reactor)

- Fischer Tropsch design
  - Annular reactor design with oil heating and cooling
  - Operating conditions for synthetic S2L syngas: 20 bar, 210°C
  - Production of Liquids and wax







# GtL plant: preparation

compressor

Gas drying

# GtL plant: Fischer-Tropsch reactor

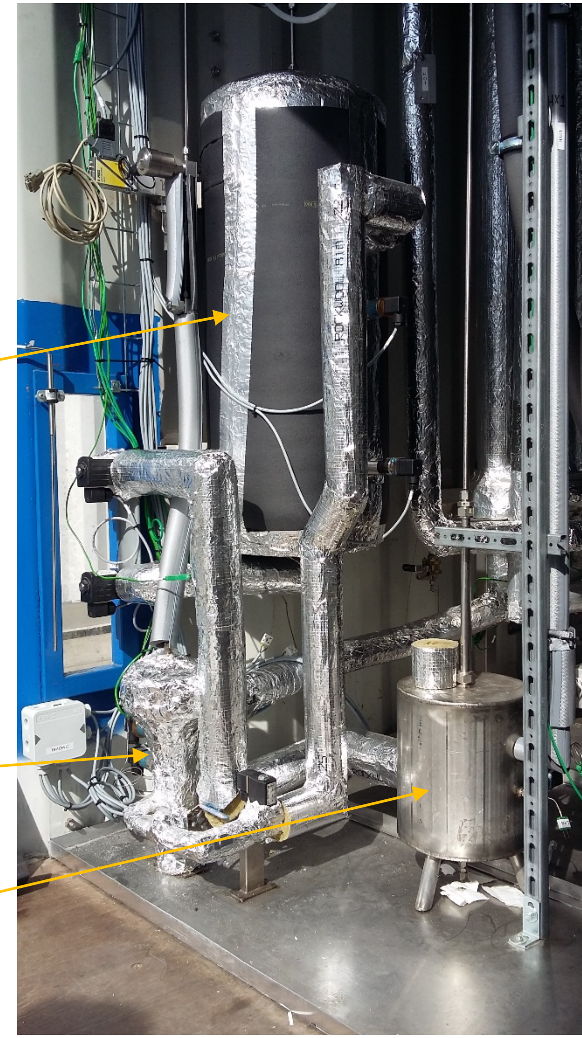
SUN to LIQUID
Fuels from concentrated sunlight

Fischer Tropsch reactor

Low pressure/ 80°C
separator

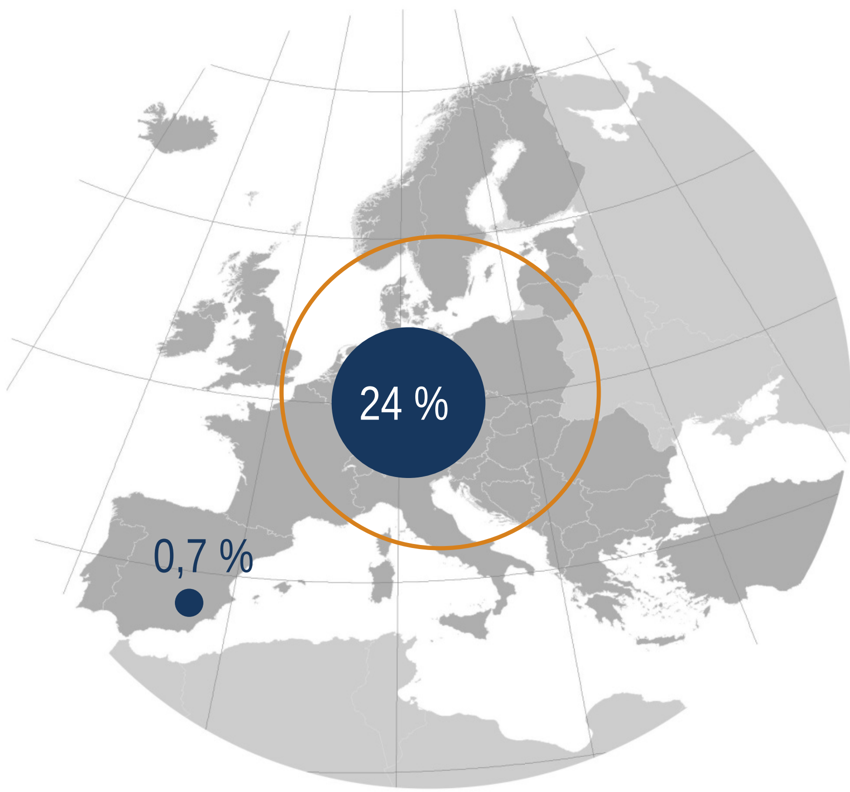
High pressure/ 80°C
separator

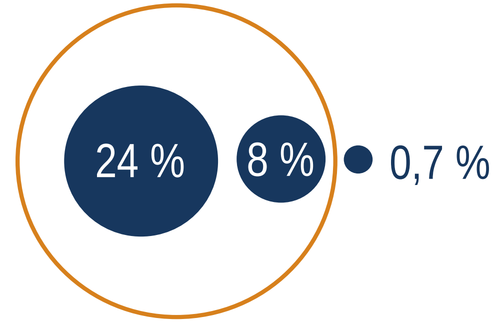
Low pressure/ RT
separator



# Perspectives: Resource Efficiency

- Area required for 100% substitution of European jet fuel demand




*European agricultural area (2005)[2]: 250 Mha*

*60 Mha HEFA (rapeseed)[3]*
*20 Mha BTL (woody biomass)[3]*
*1,7 Mha STL (DNI 2000 kWh/m$^2$)*

[1] EIA (2008), International Energy Annual 2006
[2] FAO (2010), ResourceSTAT-Land 2005
[3] BHL (2010), The Bauhaus Inventory of Energy Crops
Mha: Million Hectare; DNI: Direct Normal Irradiation

# Solar Themochemical Fuels: Water Demand

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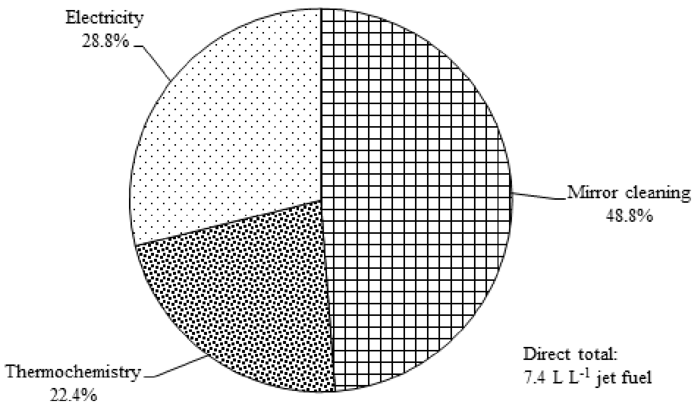
Fuels from concentrated sunlight

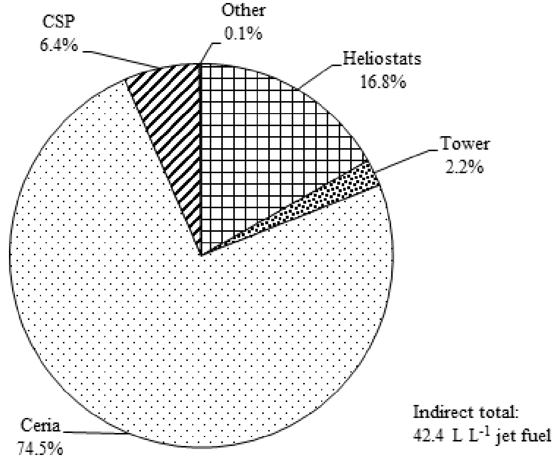
**Table 2** Overall direct water footprint for the production of solar thermochemical jet fuel.

| | L L$^{-1}$ jet fuel | L L$^{-1}$ Naphtha | L per functional unit |
|---|---|---|---|
| Mirror cleaning | 3.62 | 3.37 | 6.54 |
| Thermochemistry | 1.66 | 1.54 | 2.99 |
| Electricity | 2.14 | 1.99 | 3.86 |
| **Total** | **7.41** | **6.90** | **13.39** |

**Table 3** Overall indirect water footprint for the production of solar thermochemical jet fuel.

| **Solar concentration infrastructure** | L L$^{-1}$ jet fuel | L L$^{-1}$ Naphtha | L per functional unit |
|---|---|---|---|
| Heliostats | 7.10 | 6.61 | 12.83 |
| Tower | 0.95 | 0.89 | 1.72 |
| **Thermochemistry** | | | |
| Ceria | 31.5 | 29.4 | 56.9 |
| Alumina | 0.0031 | 0.0029 | 0.0055 |
| Steel | 0.043 | 0.040 | 0.078 |
| Glass | 0.011 | 0.010 | 0.020 |
| **CSP infrastructure** | 2.70 | 2.52 | 4.88 |
| **Fischer-Tropsch infrastructure** | | | |
| Steel | 0.0044 | 0.0041 | 0.0080 |
| Concrete | 0.00062 | 0.00057 | 0.0011 |
| **Total** | **42.4** | **39.4** | **76.5** |



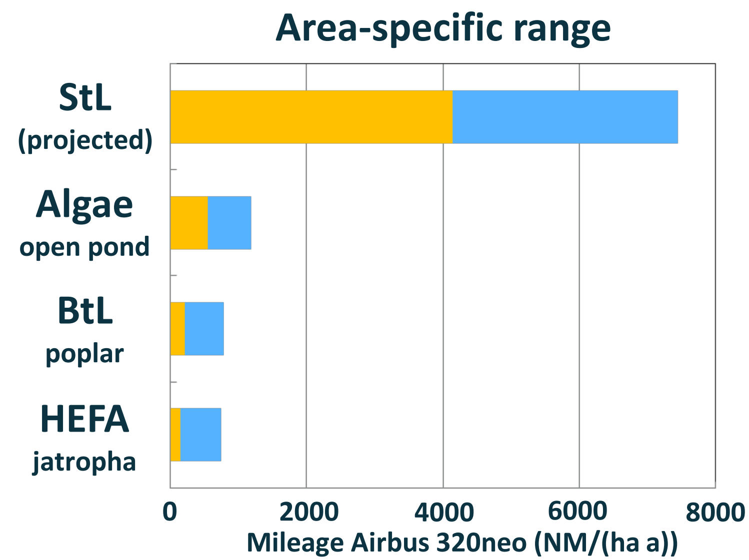



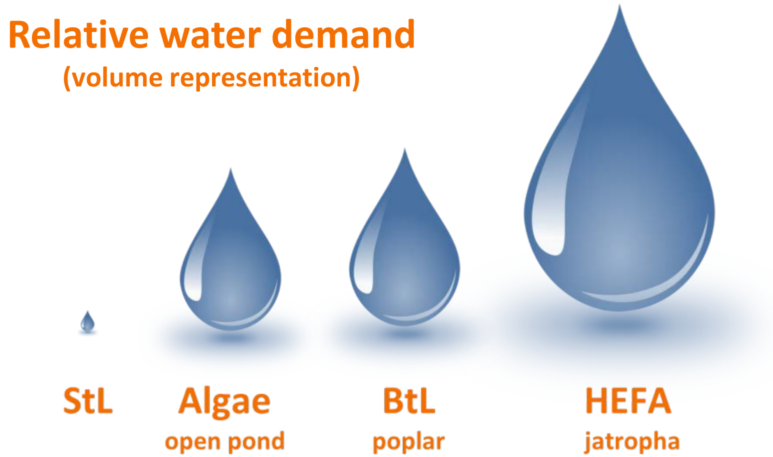

- **For comparison:** Water footprint of biofuels **from 500 to 18 000 L L-1** jet fuel equivalent

Source: C. Falter, R. Pitz-Paal, Water footprint and land requirement of solar thermochemical jet fuel production, Environmental Science and Technology 2017, doi: 10.1021/acs.est.7b02633, accepted for publication.

# Perspectives: Resource Efficiency

- Use of biofuels is controversial
  - Biofuels are available (TRL 9) and approved for civil aviation (e.g. FT-SPK, HEFA, AtJ)
  - Controversial environmental performance
  - Relatively low area specific yield
  - High water demand
  - Limited GHG reduction potential (LUC)
- Solar fuel production from $H_2O$ and $CO_2$
  - Large GHG reduction potential
  - Resource efficiency: High yield, no arable land required, very low water consumption
  - Complementary production to biofuels




Data: C. Falter, *Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production*, Environ. Sci. Technol., 2016, 50 (1)
German Environment Agency (UBA), *Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel,* 2016, Authors: LBST, Bauhaus Luftfahrt
M. S. Wigmosta et al., *National microalgae biofuel production potential and resource demand*, Water Resour. Res., 47, W00H04, 2011

# Scale of $CO_2$ demand for solar fuel production

- How much $CO_2$ would be required for 100% substitution with solar jet fuel?
  - **Stoichiometric demand to substitute current jet fuel: 850 $Mt_{CO2}$**
    - 2017 consumption 339 billion liters, specific demand about 3.14 $kg_{CO2}/kg_{jet}$
  - Adjusted demand: About a factor of two (GtL selectivity towards jet, fugitive losses)
  - 2030 scenario: Continued growth at 5% per year
    - Average growth rate during past five years (above historic average)

| Substitution target | Stoichiometric demand | Adjusted demand |
|---|---|---|
| 2017: Jet fuel consumption | 850 $Mt_{CO2}$ | ca. 1 700 $Mt_{CO2}$ |
| 2030 demand (5% growth/year) | 1 600 $Mt_{CO2}$ | 3 200 $Mt_{CO2}$ |
| Current diesel for road freight | 2 000 $Mt_{CO2}$ | 4 000 $Mt_{CO2}$ |
| Current oil consumption | 14 000 $Mt_{CO2}$ | NA |

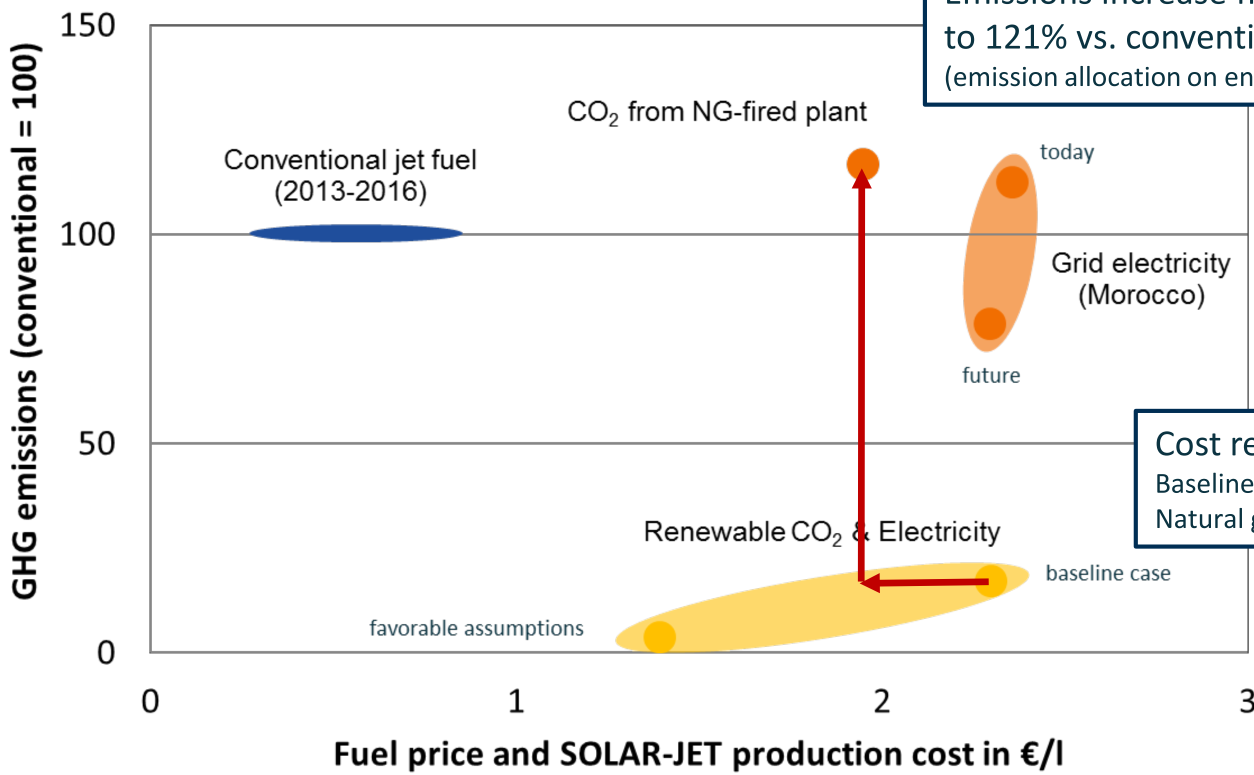
Sources: Jet fuel: IATA, *Economic Performance of the Airline Industry - 2017 mid-year report;* Road freight: IEA/OECD, *The Future of Trucks Implications for energy and the environment, 2017;* Crude Oil: *BP Statistical Review of World Energy June 2017*
Assumptions: Stoichiometry for $CH_2$ synthesis (14 amu) from $CO_2$ (44 amu): $CO_2 + H_2O \rightarrow$ "$CH_2$" + 3/2 $O_2$ ; density jet 0.8 kg/liter

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

1 solar tower (~1 km$^2$)
produces
16,000 liters/day
of
gasoline or kerosene

# Impact: Emission Reduction Potential

- Consideration of further carbon emissions along production chain can result in higher life-cycle emission compared to conventional fuel




Emissions increase from 20% to 121% vs. conventional jet fuel
(emission allocation on energy basis)

Cost reduction by 32 ct/L
Baseline, air capture: 100 €/$t_{CO2}$
Natural gas plant: 40 €/$t_{CO2}$

Source: C. Falter, V. Batteiger, A. Sizmann; *Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production*, Environ. Sci. Technol., 2016, 50 (1)

SUN to LIQUID

Fuels from concentrated sunlight

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**SUN-to-LIQUID**

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This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0330

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654408