# SUN to LIQUID

Fuels from concentrated sunlight

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# Synthetische Kraftstoffe für die Luftfahrt

## Entwicklungsperspektiven aus den EU-Projekten SOLAR-JET und SUN-to-LIQUID

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Munich (Taufkirchen), Germany

# EU-H2020 SUN-to-LIQUID approach to solar jet fuel

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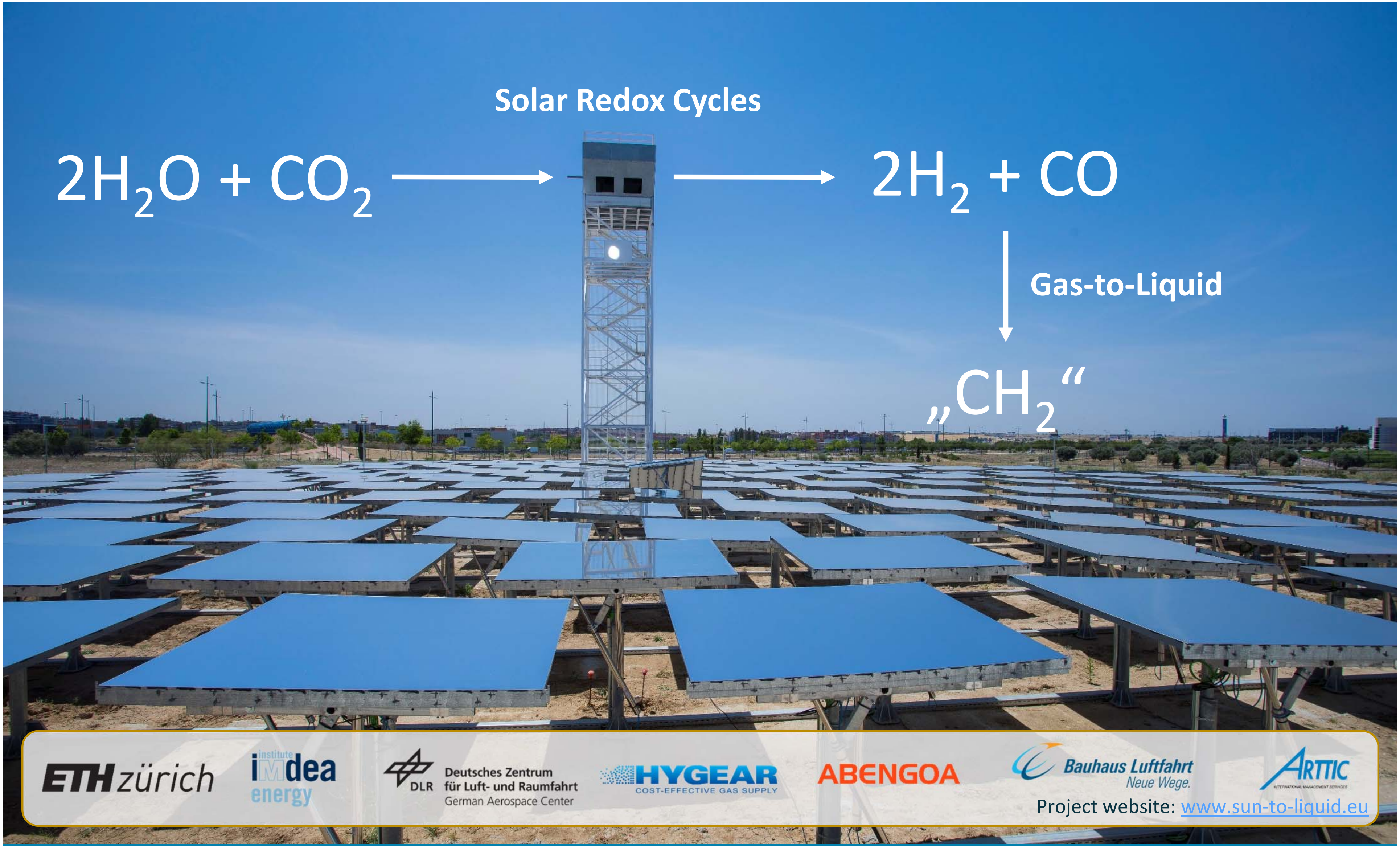

**Solar Redox Cycles**

$2H_2O + CO_2 \longrightarrow \longrightarrow 2H_2 + CO$

**Gas-to-Liquid**

$\downarrow$

„$CH_2$“

ETH zürich · imdea energy · DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center · HYGEAR COST-EFFECTIVE GAS SUPPLY · ABENGOA · Bauhaus Luftfahrt Neue Wege. · ARTTIC

Project website: [www.sun-to-liquid.eu](http://www.sun-to-liquid.eu)

# Outline

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- Introduction
  - Motivation for solar aviation fuels
- SOLAR-JET (2011-2015)
  - Laboratory synthesis of solar kerosene at 4 kW scale
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    - High-flux solar concentrating system in Móstoles, Spain (IMDEA Energía, DLR)
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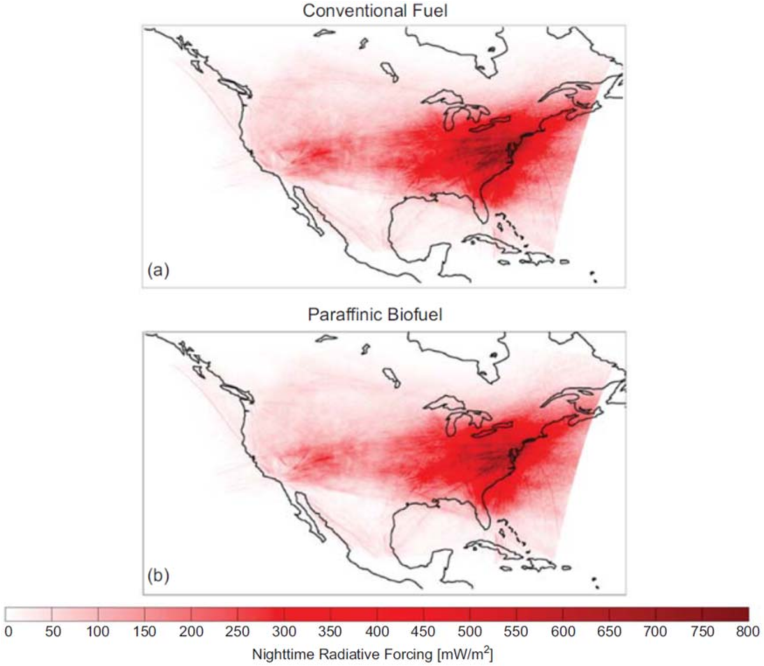
# Climate impact of aviation

- GHG emissions related to aviation fuel use:
  - 0.93 Gt$_{CO2}$ from combustion only (IATA 2019$_{est}$)
  - 1.1 Gt$_{CO2eq.}$ adjusting for upstream emissions (well-to-wake)
  - **Roughly 3% of total CO$_2$ emissions**
  - Growing share at nearly flat emission baseline
- Non-CO$_2$ contributions to global warming:
  - Contrails and contrail cirrus
  - Atmospheric chemistry (mainly NOx acting on O$_3$ and CH$_4$)
  - **Net effect: Additional warming, order of magnitude comparable to CO$_2$ effect**
  - Synthetic fuel use has an impact on non-CO$_2$ contributions

| | **0.93 Gt combustion** | **1.1 Gt well-to-wake** |
|---|---|---|
| **33.4 Gt combustion** | **2.7%** | **3.3%** |
| **40.7 Gt total CO$_2$** | 2.3% | **2.8%** |



Data sources: IATA “*Economic performance of the airline industry*” 2018 End year report; Adjustment of CO$_2$ emission from combustion to well-to-wake emissions according to Stratton, “*Live cycle greenhouse gas emissions from alternative jet fuel*” 2010, MIT report PARTNER-COE-2010-001 (in line with: Masnadi, *Global carbon intensity of crude oil production*, Science 2018); Le Quéré, *Global Carbon Budget 2017*, Earth Syst. Sci. Data, 10, 405-448, 2018; BP “*Statistical Review of World Energy*”, June 2018; Picture source: Fabio Caiazzo et al, *Impact of biofuels on contrail warming*, 2017 Environ. Res. Lett. 12 114013

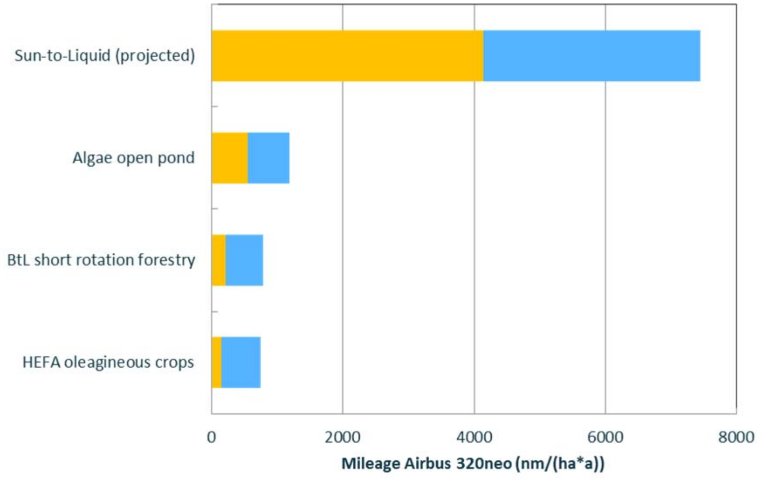
# Renewable energy options for aviation

- Aviation will rely on liquid hydrocarbons for decades
  - Electric flight limited by battery mass
    - Bauhaus Luftfahrt Concept Study Ce-Liner
    - Target: Cover 80% of air traffic (900 nm range)
    - Would require specific energy > 1 kWh/kg
  - Hybrid electric aircraft concepts still rely on liquid fuel
    - From fuel perspective: No change of primary energy carrier, essentially an efficiency measure
  - Liquefied gasses ($LH_2$ and LNG)
    - Feasible concepts, studies find no or marginal fuel efficiency benefits as turbines remain the technology of choice

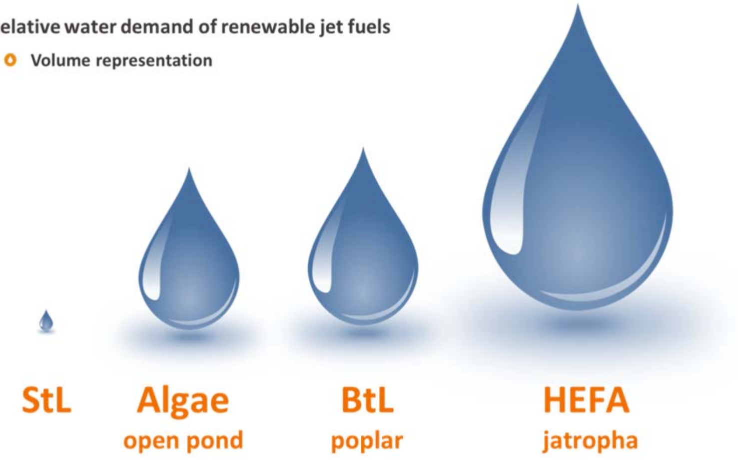
Sources: M. Hornung, *Ce-Liner – Case Study for eMobility in Air Transportation*, Aviation Technology, Integration and Operations Conference. Los Angeles. 12.8.2013
EU-H2020 Project Centreline: www.centreline.eu ; M.K. Bradley, *Subsonic Ultra Green Aircraft Research: Phase II N+4 Advanced Concept Development*, 2012. doi:2060/20150017039, Tupolev Tu-155 experimental aircraft: wikipedia

# Motivation for solar fuels

- Aviation biofuels are controversial
  - Biofuels are available (TRL 9) and approved for civil aviation (HEFA, FT-SPK, AtJ, DSHC)
  - 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



- Relative water demand of renewable jet fuels
  - Volume representation



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, BHL
M. S. Wigmosta et al., *National microalgae biofuel production potential and resource demand*, Water Resour. Res., 47, W00H04, 2011

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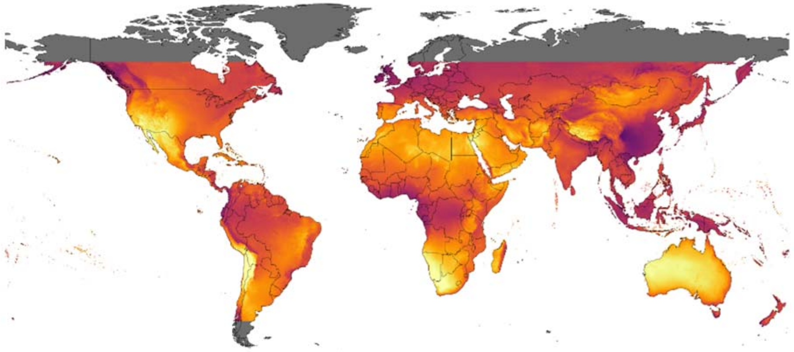

Sources: F. Riegel, *Global Assessment of Sustainable Land Availability for Food and Energy Production*, 27th European Biomass Conference and Exhibition, DNI data: World Bank, Global Solar Atlas, www.globalsolaratlas.info, (accessed 8 May 2018).

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# Thermochemistry: State-of-art in ETH laboratory

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

**Endothermic reduction:**

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

**Exothermic oxidation:**

$$(\sim 1000°C):\ CeO_{2\text{-}\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$
$$(\sim 1000°C):\ CeO_{2\text{-}\delta} + \delta CO_2 \rightarrow CeO_2 + \delta CO$$

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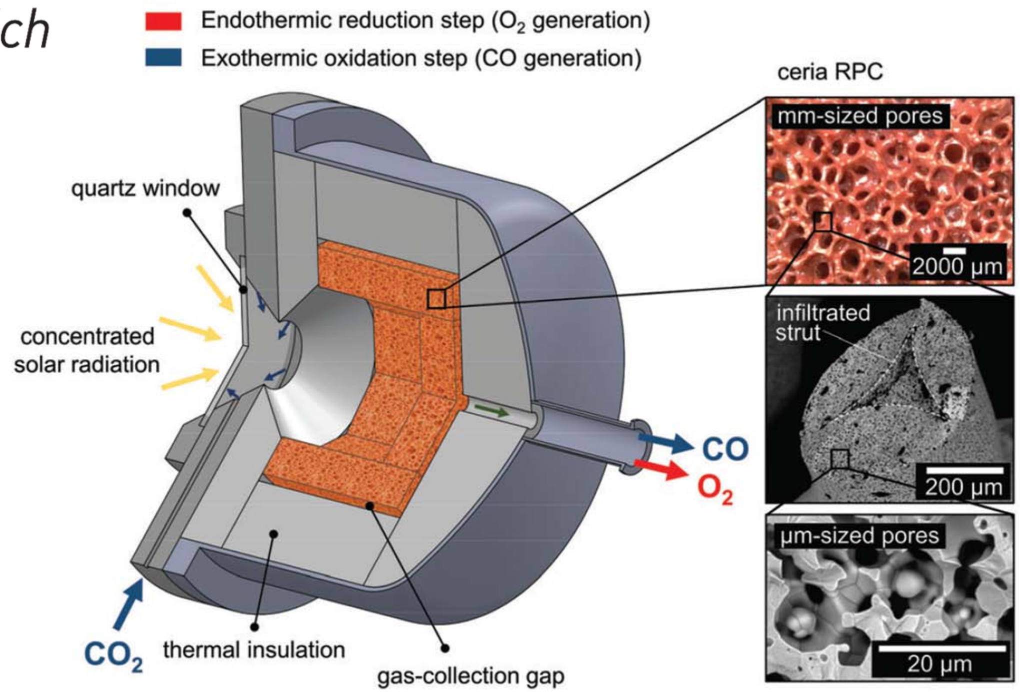
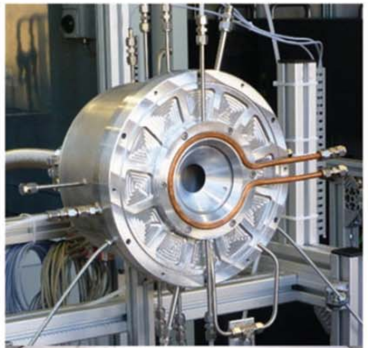
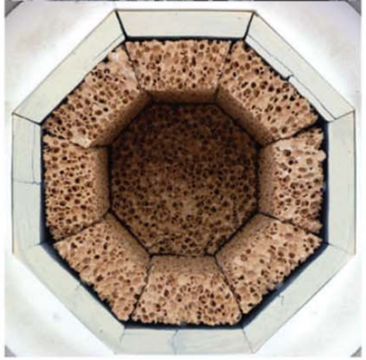
SOLAR-JET







Source: D. Marxer, *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; *: $\eta_{solar\text{-}to\text{-}CO}$ = (heating value of CO)/(solar energy input at aperture + energy penalties)

# FP7 SOLAR-JET (2011-2015)

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## Proof of principle: Laboratory synthesis of solar kerosene

SOLAR-JET

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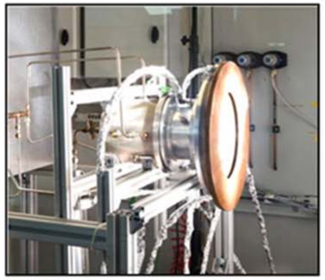
- **290 $H_2O/CO_2$-splitting redox cycles**
- 200 h operation



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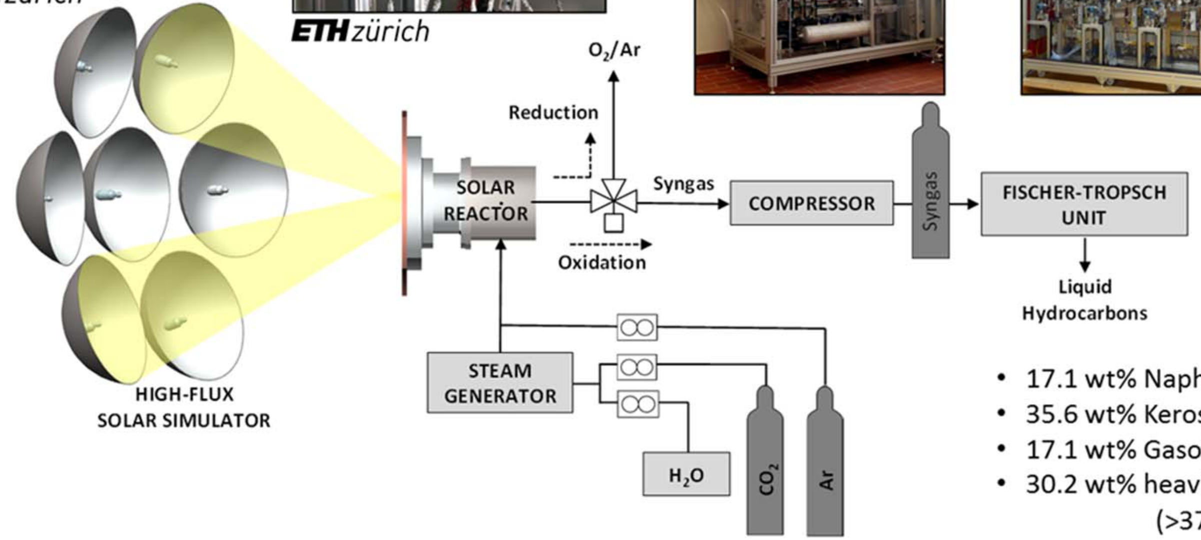
- 750 L syngas
- 33.7% $H_2$, 19.2% CO, 30.5% $CO_2$, 16.5% Ar

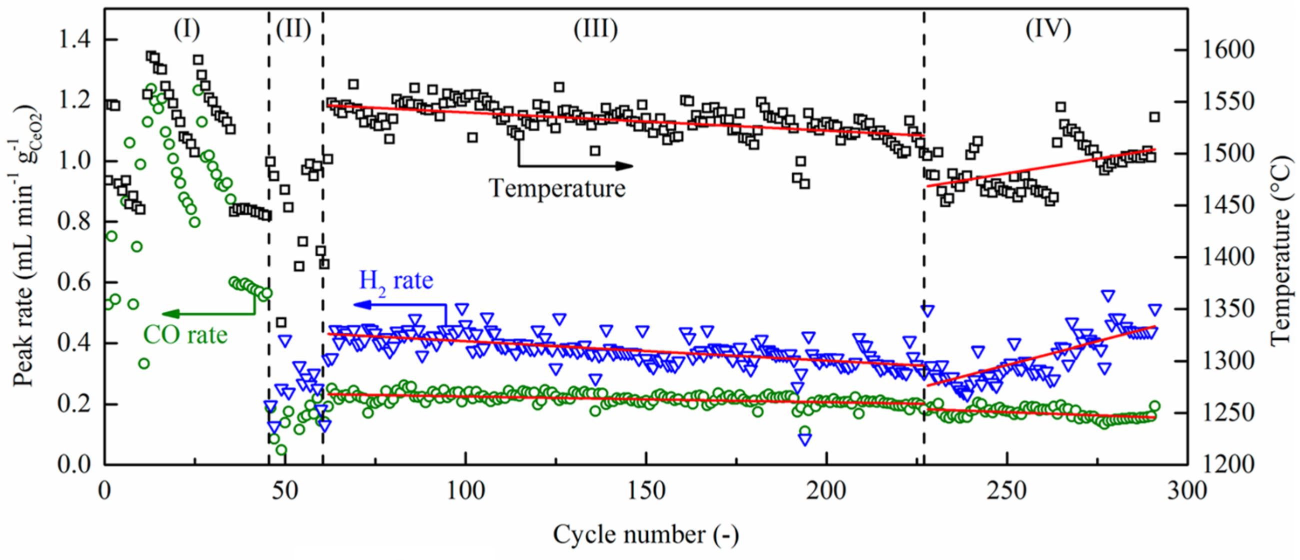


- 17.1 wt% Naphta (0-145°C)
- 35.6 wt% Kerosene (145-300°C)
- 17.1 wt% Gasoil (300-370°C)
- 30.2 wt% heavier fractions (>370°C)

Source: D. Marxer, *Demonstration of the entire production chain to renewable kerosene via solar-thermochemical splitting of $H_2O$ and $CO_2$*, Energy & Fuels, 2015; P. Furler, *Solar Kerosene from $H_2O$ and $CO_2$*, AIP Conference Proceedings 1850, 100006 (2017)

# Results from FP7 SOLAR-JET (2011-2015)

- First synthesis of solar-thermochemical kerosene at laboratory scale
  - 293 redox cycles for $H_2$ and CO production
  - Synthesis of mainly waxy species via Fischer-Tropsch process
  - Hydrocracking of wax sample yielded kerosene-range liquid



Heavy product (FT-waxes)

Light product ($H_2O$, hydro-carbons)

Liquids from hydrocracking (incl. kerosene)

Source: D. Marxer, *Demonstration of the entire production chain to renewable kerosene via solar-thermochemical splitting of $H_2O$ and $CO_2$*, Energy & Fuels, 2015; P. Furler, *Solar Kerosene from $H_2O$ and $CO_2$*, AIP Conference Proceedings 1850, 100006 (2017)

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# Plant Layout & Primary System Components

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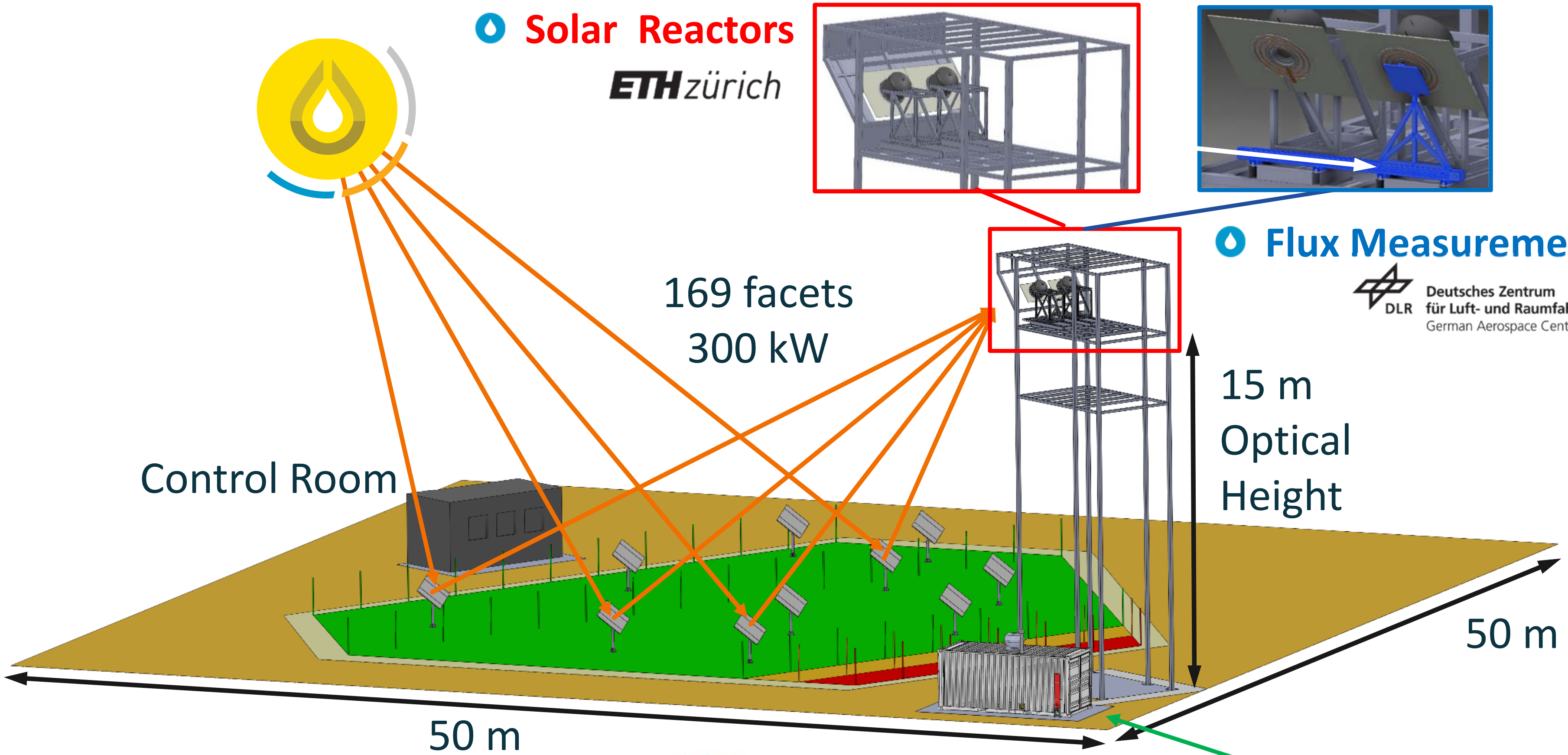


**Solar Reactors**
ETH zürich

**Flux Measurement**
Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

**Heliostat Field and Tower**
institute imdea energy

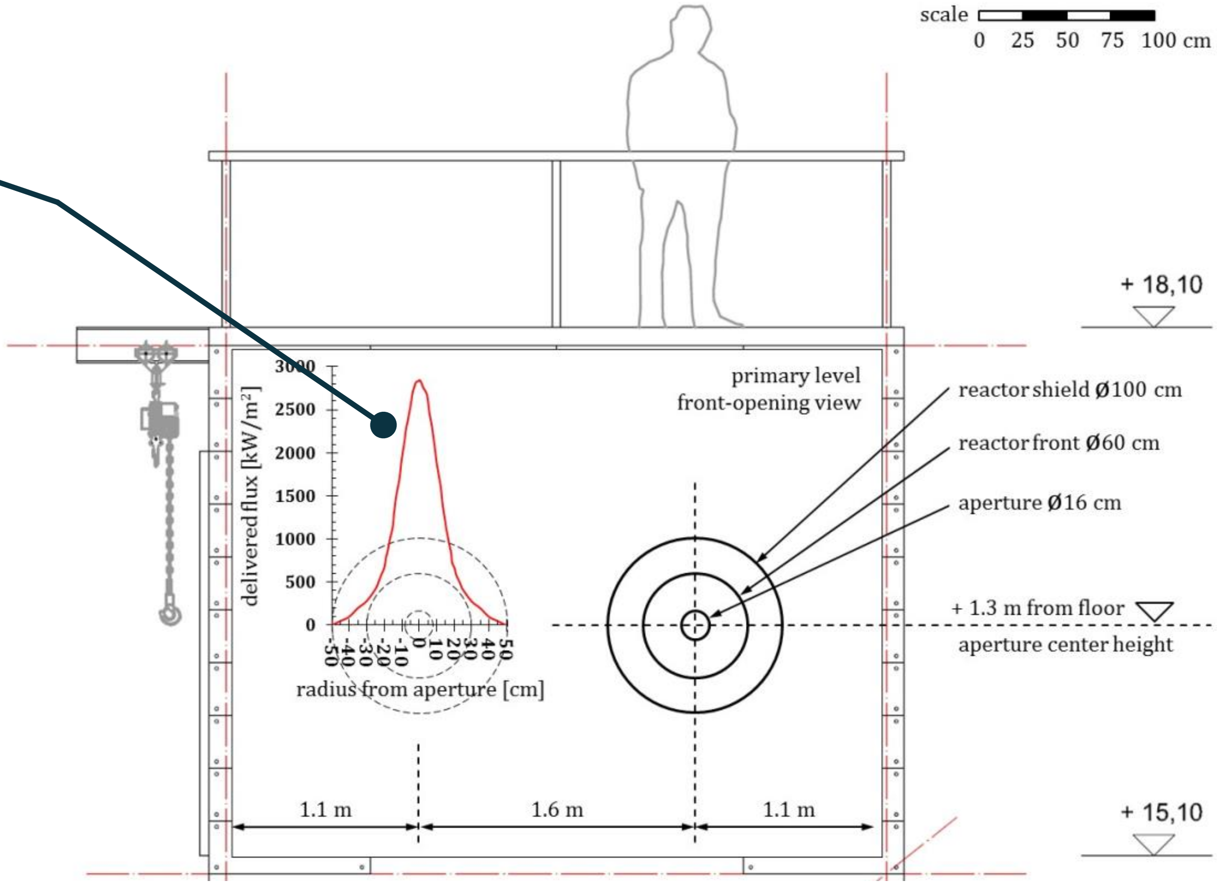
**GtL Plant**
HYGEAR
COST-EFFECTIVE GAS SUPPLY

adapted from E. Koepf, *Liquid Fuels from Concentrated Sunlight: Development and Integration of a 50 kW Solar Thermochemical Reactor and High Concentration Solar Field for the SUN-to-LIQUID Project*, SolarPACES2018

# High-flux solar concentrating system

- High-flux solar concentration system designed for SUN-to-LIQUID specifications

Specifications:
> 2500 suns average
16 cm diameter
50 $kW_{th}$ reactors



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German Aerospace Center

Source: M. Romero, J. González-Aguilar and S. Luque, *Ultra-Modular 500m² Heliostat Field for High Flux/High Temperature Solar-Driven Processes*, SOLAR-PACES, 2016; drawing by E. Koepf ETH Zurich

# High-flux solar concentrating system

- Final optical design:
  - Tower optical height 15 m
  - 169 heliostats (1.9 x 1.6 $m^2$, 14 rows)
  - Two focal legth (20 m, 30 m)

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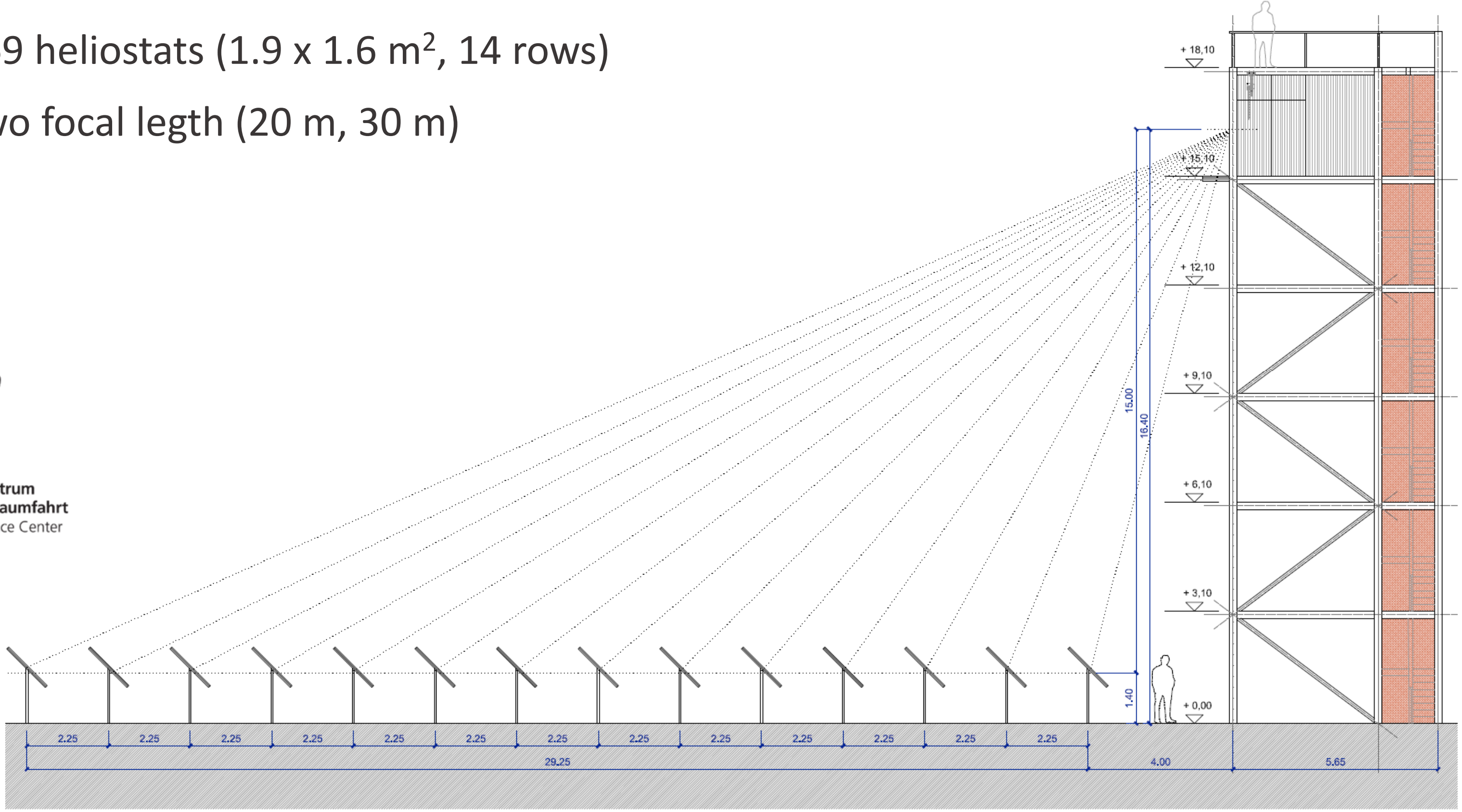


Source: M. Romero, J. González-Aguilar and S. Luque, *Ultra-Modular 500$m^2$ Heliostat Field for High Flux/High Temperature Solar-Driven Processes*, SOLAR-PACES, 2016

# Construction of SUN-to-LIQUID plant

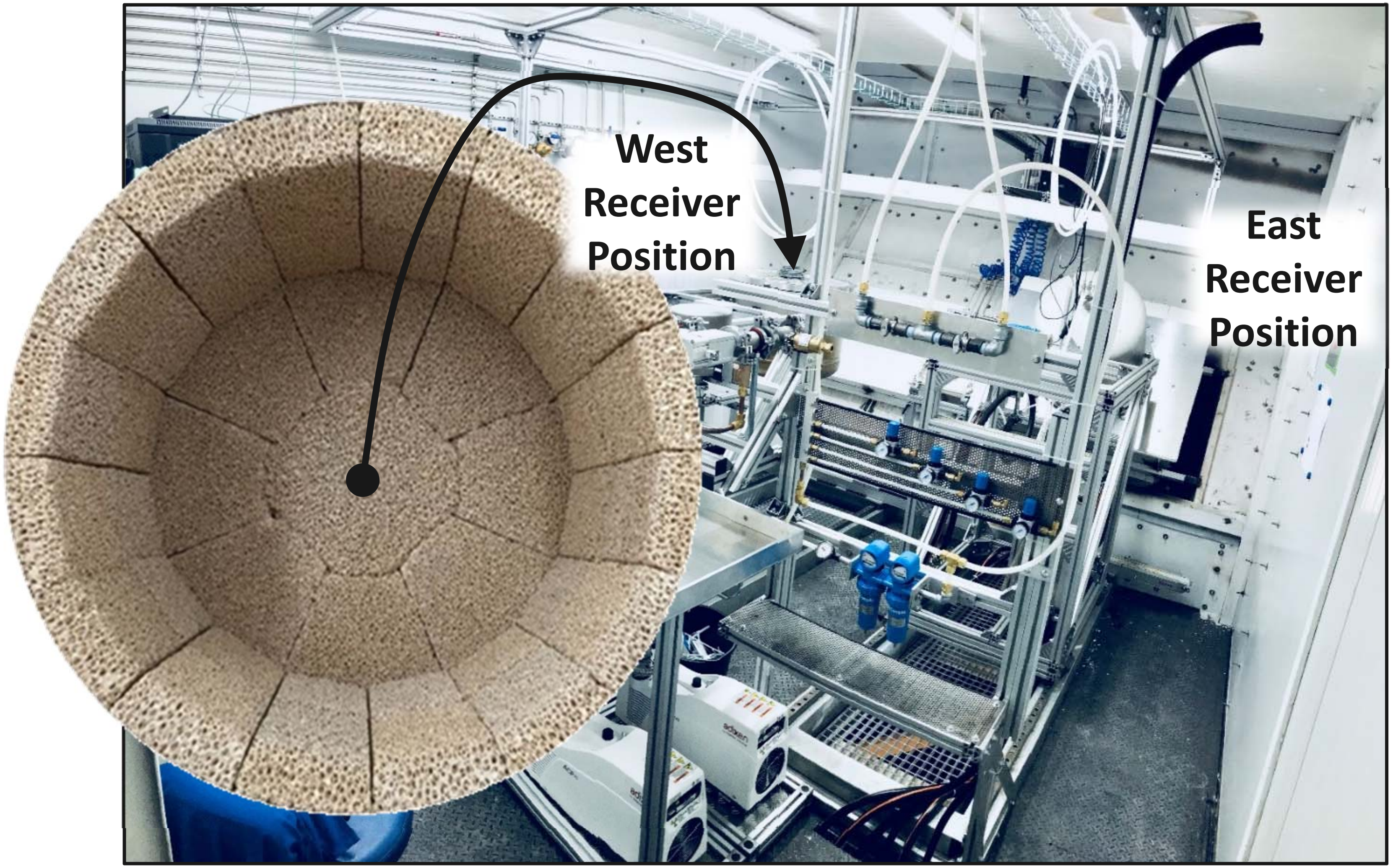
Picture source: SUN-to-LIQUID, IMDEA

# Construction of SUN-to-LIQUID plant

- Current status: All sub-systems are operational and integrated for field demonstration of solar fuel synthesis

Picture sources: SUN-to-LIQUID, E. Koepf

# Experimental Setup for Solar Reactor System



ETH zürich

Source: E. Koepf et al, *Liquid Fuels from Concentrated Sunlight: Development and Integration of a 50 kW Solar Thermochemical Reactor and High Concentration Solar Field for the SUN-to-LIQUID Project*, SolarPACES2018

# Flux measurement system

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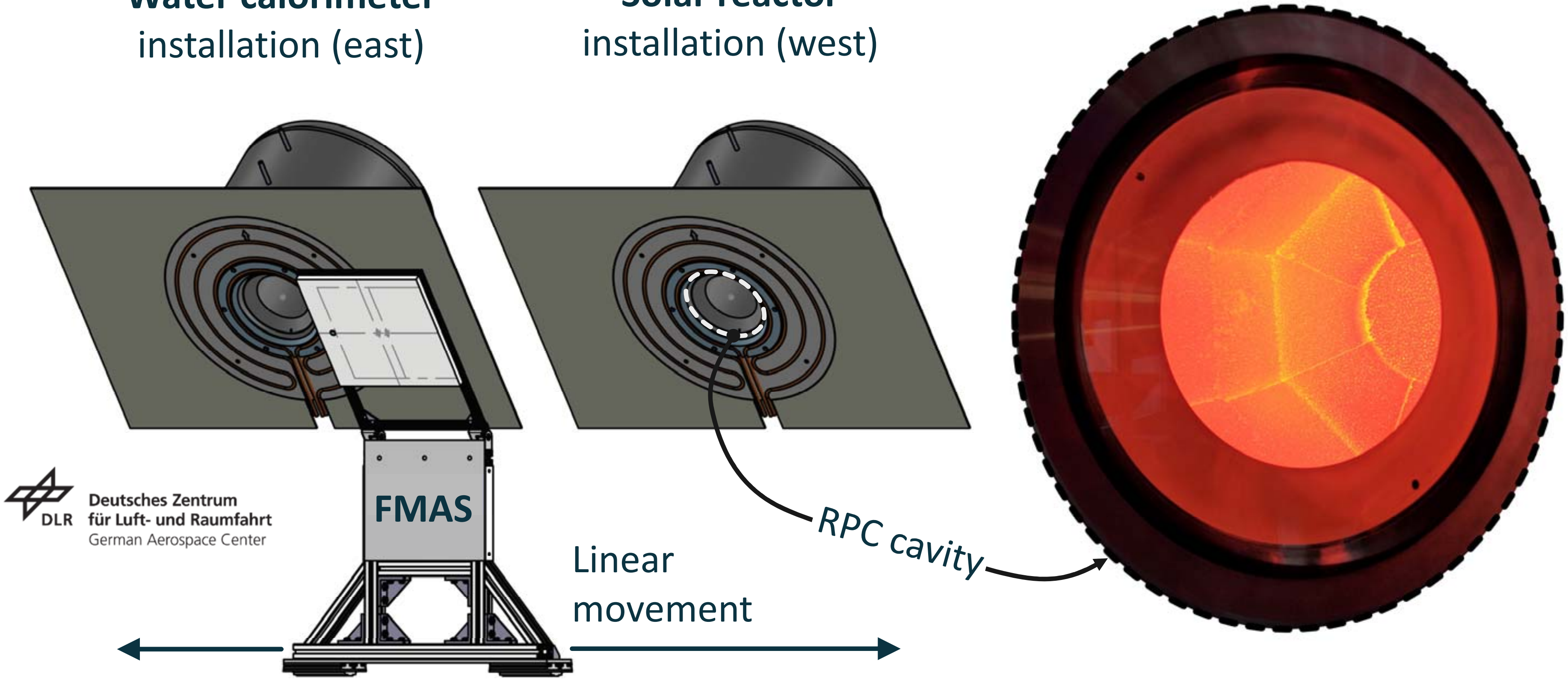
- Combination of a flux measurement system and water calorimeter for accurate determination of power at the solar reactor aperture

**Water calorimeter**
installation (east)

**Solar reactor**
installation (west)



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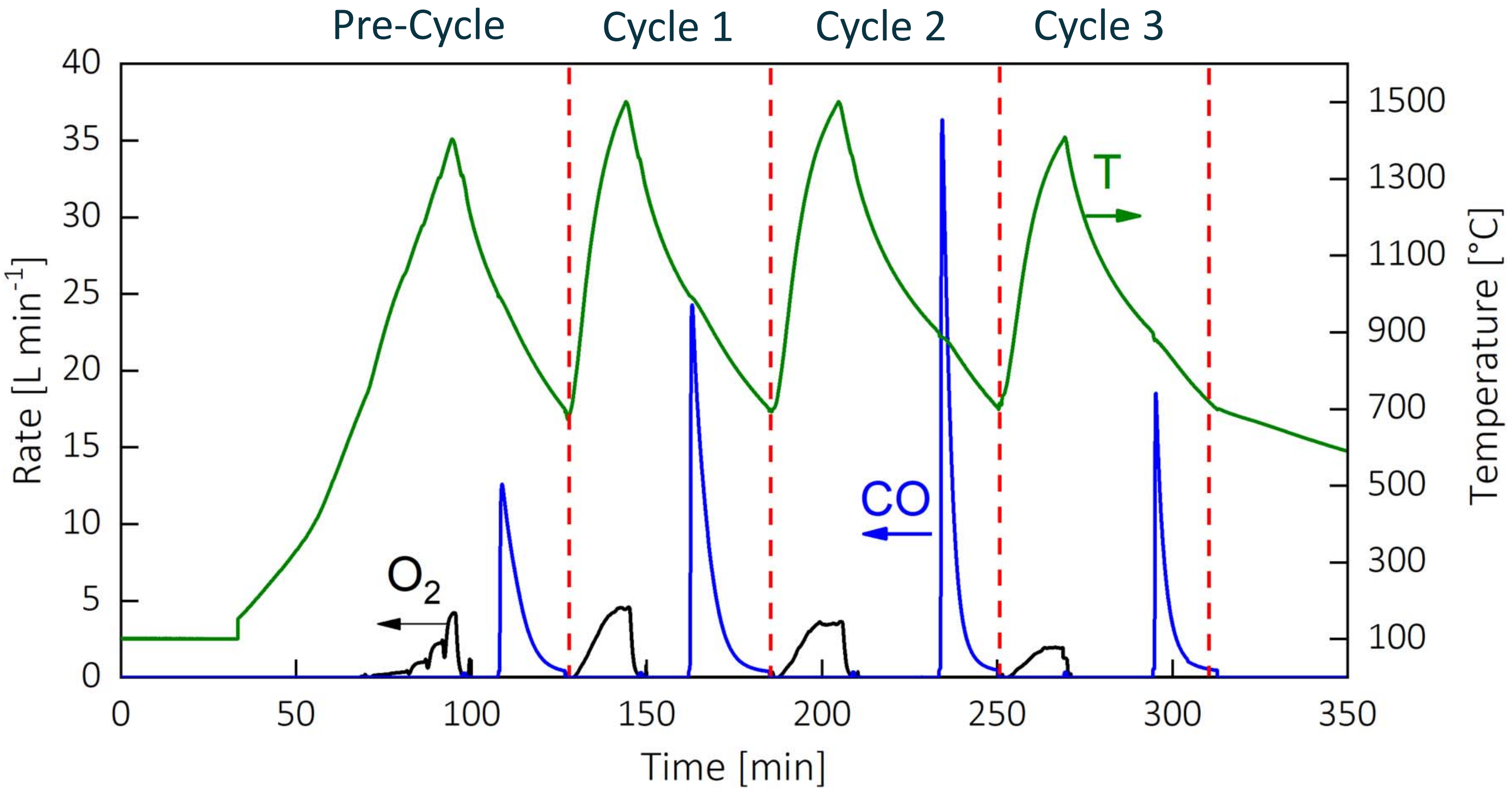
Source: FMAS methodology published by Thelen et al., *SolarPACES*, 2016

# Pre-Commissioning Experimental Results

- Three consecutive redox cycles for $CO_2$-splitting, approximately **30 kW** of power delivered through the aperture **on-sun**



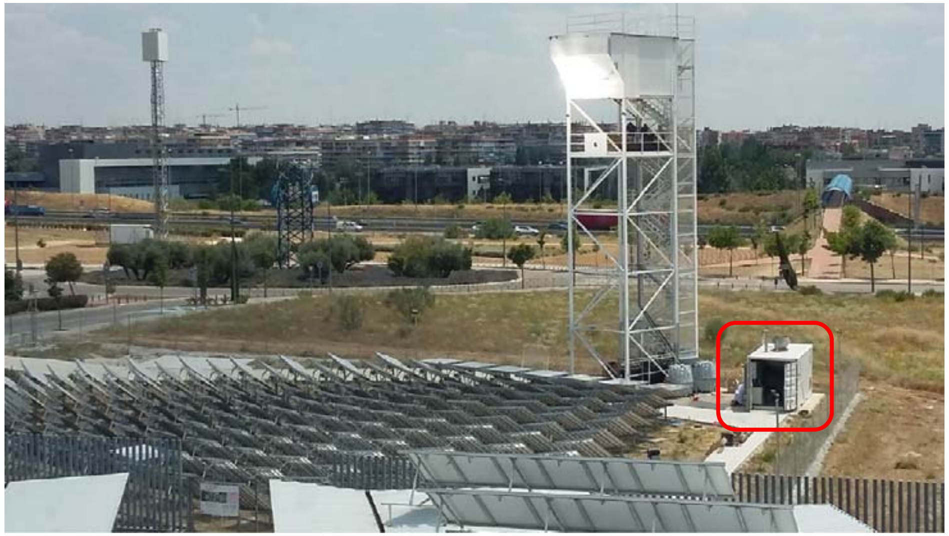
Source: E. Koepf et al, *Liquid Fuels from Concentrated Sunlight: Development and Integration of a 50 kW Solar Thermochemical Reactor and High Concentration Solar Field for the SUN-to-LIQUID Project*, SolarPACES2018, adapted from Carlos Larrea, Master Thesis, ETH Zurich, 2018

# Gas-to-Liquid system

- Gas-to-Liquids conversion of syngas to long-chained hydrocarbons:

$$(2n)H_2 + nCO \leftrightarrow n(CH_2) + nH_2O$$

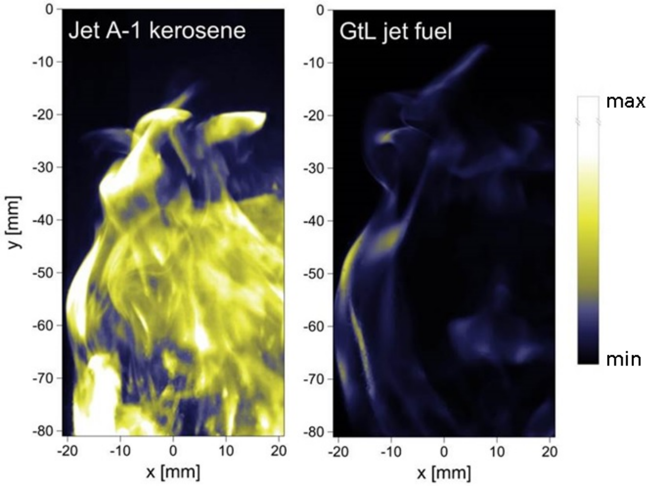
- Containerized solution comprising
  - Intermediate syngas storage
  - Low-temperature cobalt-based Fischer-Tropsch synthesis
  - Reforming of light hydrocarbons



# Gas-to-Liquid system

- SUN-to-LIQUID gas-to-liquid system
  - Much smaller than commercial scale
  - Important to demonstrate sufficient reliability and quality of solar syngas for GtL conversion
  - SUN-to-LIQUID stops at “syncrude”

- GtL process: Co-based Fischer-Tropsch synthesis
  - Refined GtL fuels resemble specifications of diesel or jet fuel, slightly improved performance, burn cleaner
  - “Fischer-Tropsch Synthetic Paraffinic Kerosene” approved for use in civil aviation (50/50 blend)



HYGEAR
COST-EFFECTIVE GAS SUPPLY

Picture source: SUN-to-LIQUID Project Brochure, DLR Institute of Combustion Technology

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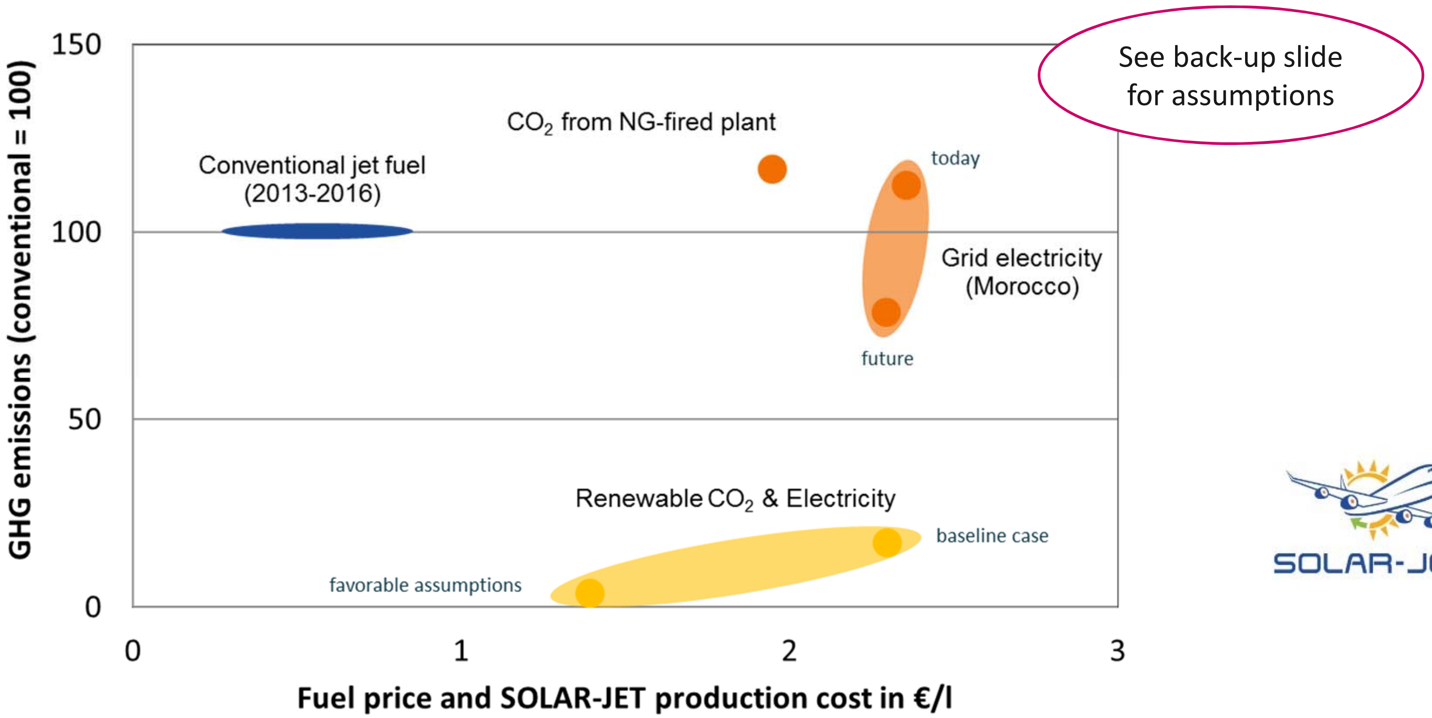
- Selected conclusions from system analysis and preparation of next steps

# System analysis, results from SOLAR-JET

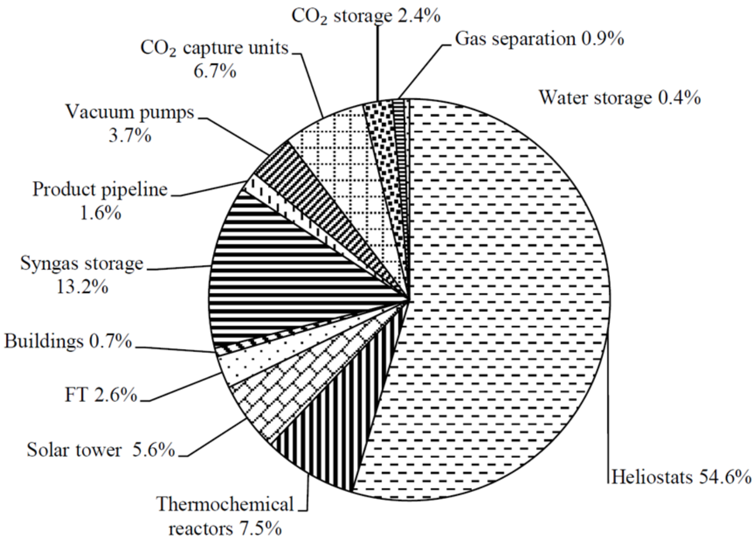
- GHG emission reduction sets on at $\eta_{\text{solar-to-fuel}} \approx$ 3-4% (for solar standalone plant)
  - Renewable $CO_2$ and renewable process energy required for GHG reduction!
- Economic analysis requires an efficiency target of $\eta_{\text{solar-to-fuel}} \geq$ 20%

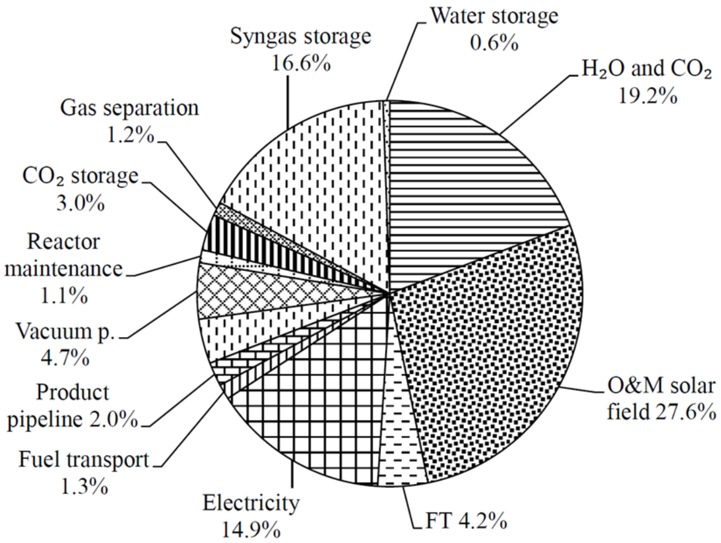


Source: C. Falter, *Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production*, Environ. Sci. Technol., 2016, 50 (1)

# SUN-to-LIQUID economic analysis, preliminary results

- Production cost: 2.28 €/L for baseline case (1.48 €/L for favorable set of assumptions)
  - Break-down of investment costs (left) and O&M cost (right) identifies solar field as main cost driver
  - Vacuum pumping: Optimization with respect to fuel costs suggests the use of jet pumps
    - More efficient mechanical pumps result in higher cost within our set of assumptions
  - Reforming of tail gas is crucial





Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

# SUN-to-LIQUID, regional analysis of fuel production cost

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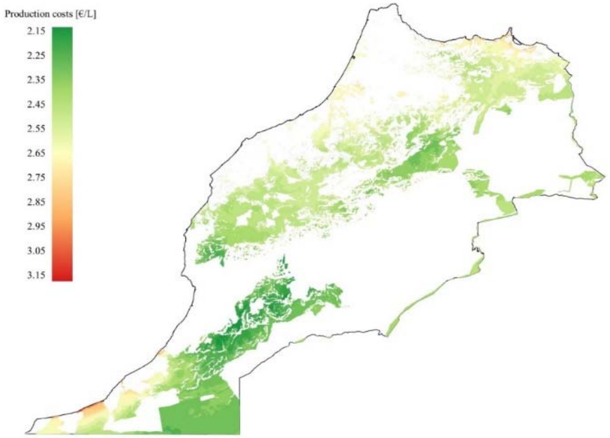
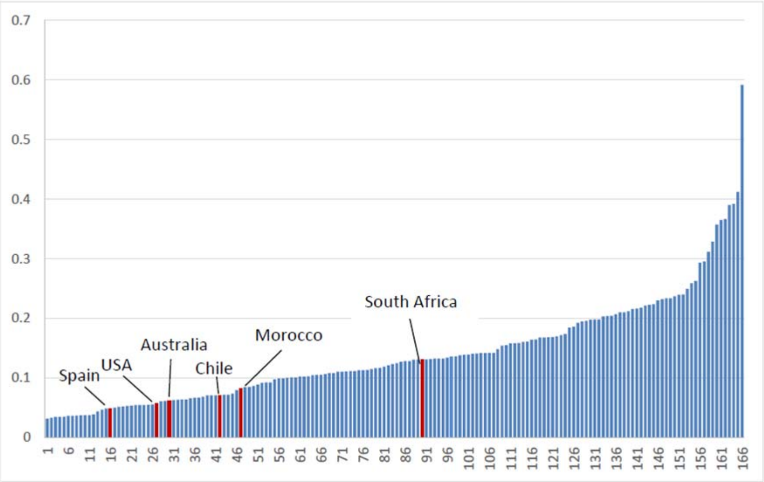
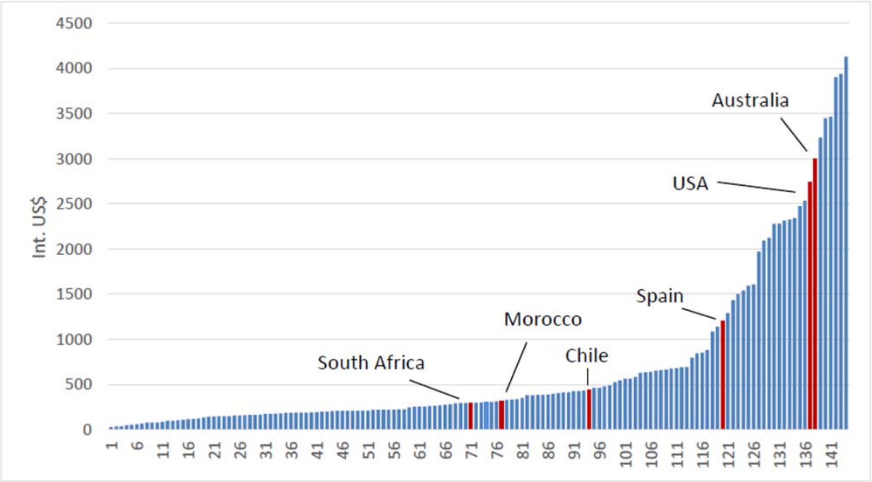
- Strong dependence on solar resource (DNI)

| | USA | Australia | Spain | Morocco | Chile | S. Africa |
|---|---|---|---|---|---|---|
| **DNI [kWh/(m² y)]** | 2800 | 2800 | 2000 | 2500 | 3500 | 3100 |
| **Mirror area [$10^6$ m²]** | 6.9 | 6.9 | 9.6 | 7.7 | 5.5 | 6.2 |
| **Labour costs [$10^6$ €]** | 18.7 | 19.2 | 8.52 | 2.09 | 3.35 | 3.41 |
| **Investment costs [$10^9$ €]** | 1.32 | 1.32 | 1.62 | 1.41 | 1.17 | 1.24 |
| **O&M costs [$10^6$ €]** | 70.8 | 71.2 | 66.1 | 55.8 | 53.1 | 54.2 |
| **WACC [%]** | 5.7 | 6.2 | 4.9 | 8.1 | 7.1 | 13.1 |
| **Production costs [€/$L_{\text{jet fuel}}$]** | 2.11 | 2.24 | 2.13 | 2.28 | 2.03 | 2.98 |



- Variation due to socio-economic parameters (left: cost of capital, right: labor cost)





Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

# Summary and outlook

- SOLAR-JET: Laboratory demonstration of solar kerosene synthesis

- SUN-to-LIQUID: All subsystems are integrated and operational
  - High-flux concentration system
  - 50 kW solar reactor
  - Gas-to-Liquids system
- Outlook to 2019
  - Long term operation campaign
  - Derive energy conversion efficiency from focused performance analysis
- System analyses
  - Economic analysis of SUN-to-LIQUID baseline plant finished
  - Preliminary results for LCA available

# FP7 SOLAR-JET (2011-2015), consortium

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SOLAR-JET

ETH zürich

Bauhaus Luftfahrt
Neue Wege.

DLR

ARTTIC

The research leading to these results has received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement no. 285098 – Project SOLAR-JET.

# H2020 SUN-to-LIQUID (2016-2019), Team

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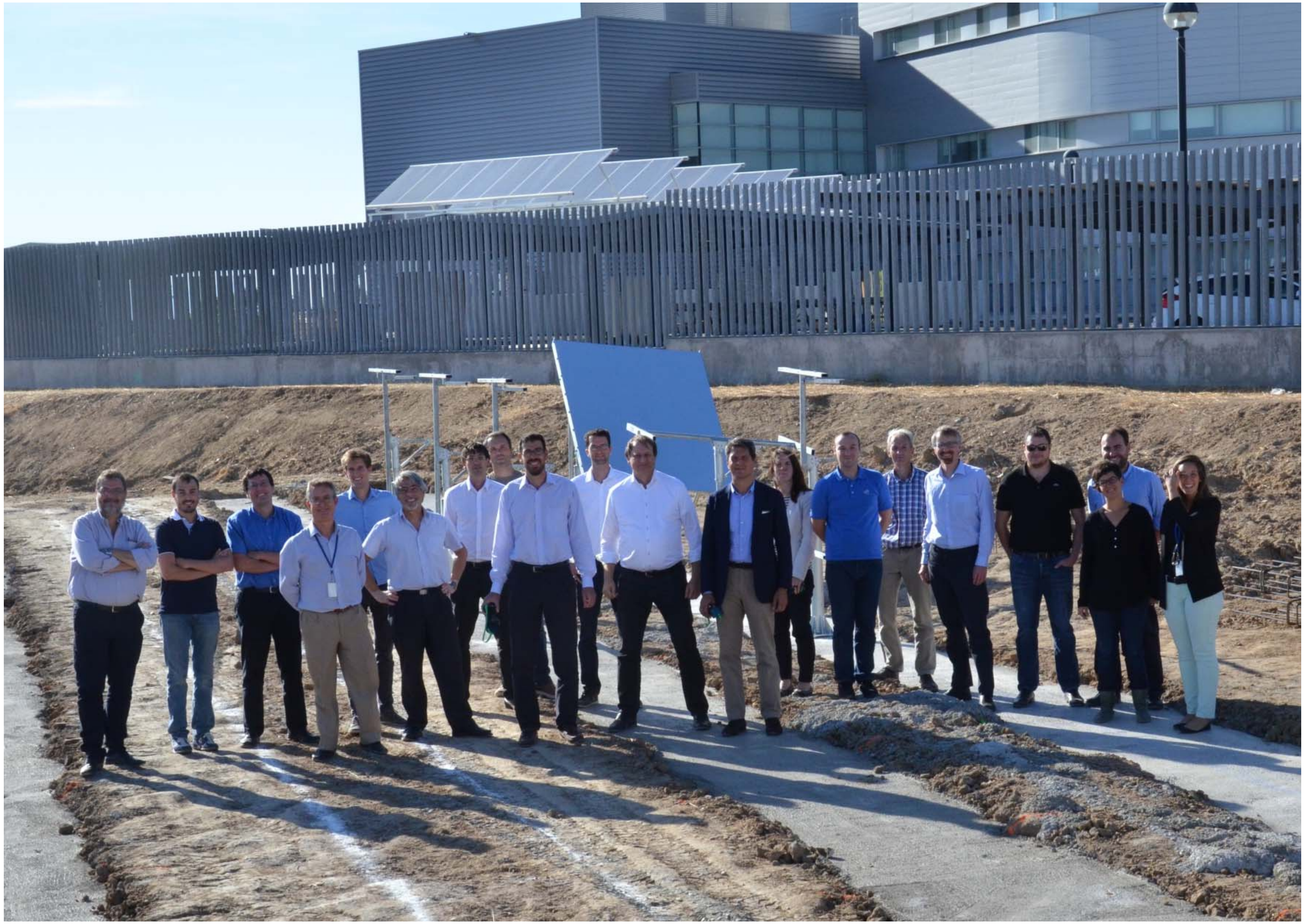

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A project gathering **7 partners** from **5 European countries:**

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HYGEAR
COST-EFFECTIVE GAS SUPPLY

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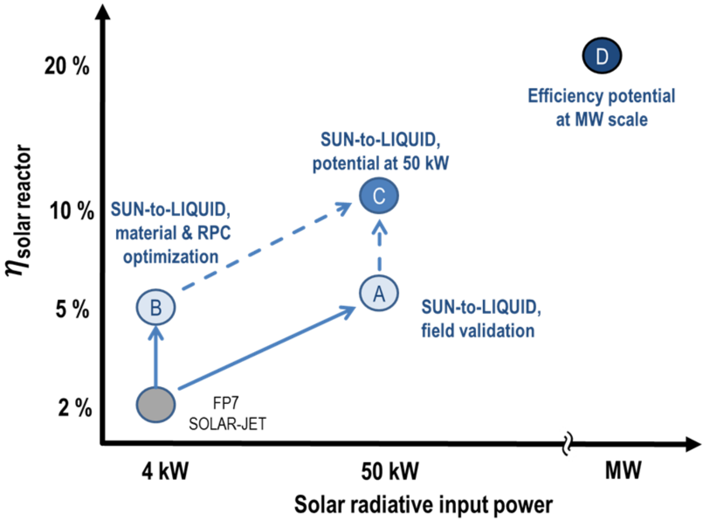
ARTTIC
INTERNATIONAL MANAGEMENT SERVICES

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

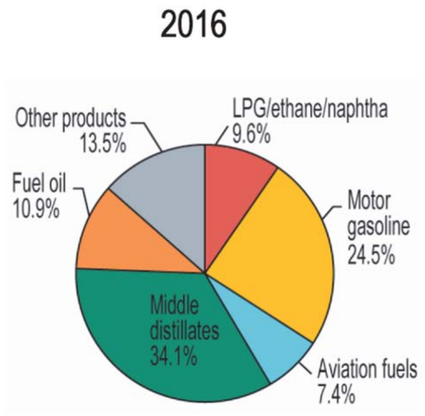
# SUN-to-LIQUID next steps

- Long-term target: Achieve $\eta_{solar\text{-}to\text{-}fuel} \geq 20\%$
  - Required for competitiveness
- Realistic target for SUN-to-LIQUID (WP3-WP4)
  - $\eta_{solar\text{-}to\text{-}fuel} \geq 5\%$ at laboratory scale (achieved)
  - Long-term operation campaign in field (2019)
  - $\eta_{solar\text{-}to\text{-}fuel} \geq 5\%$ for field demo (2019)

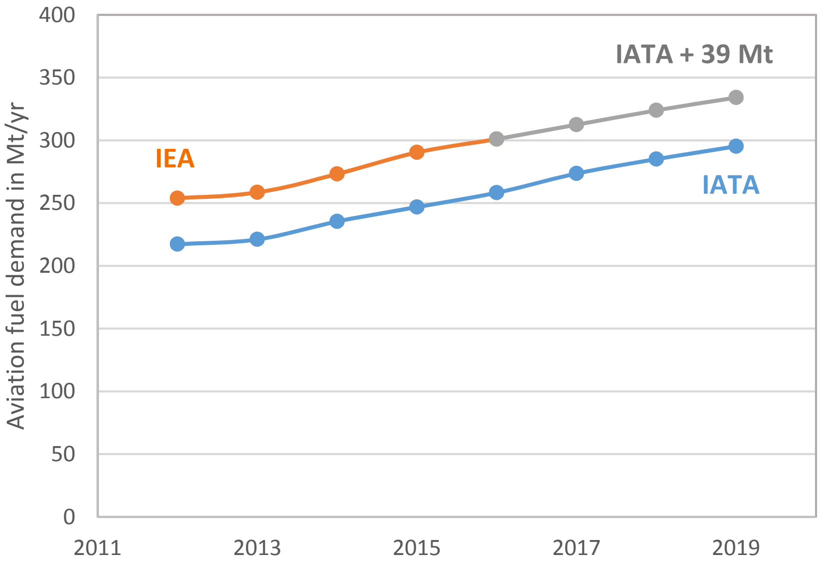


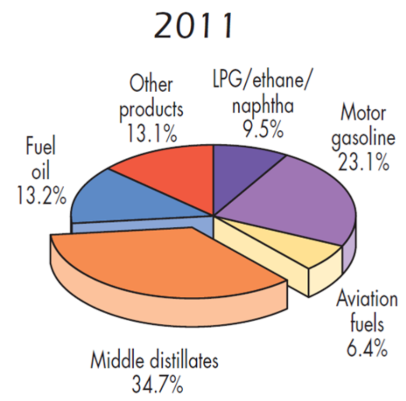
# Selected data on current fuel use of aviation

- Current fuel burn of aviation: ca. 300 Mt/yr
  - Strong growth since last downturn after 2008 financial crisis
- Strong growth of aviation fuel’s share of total refining:
  - 7.4% of refinery output in 2016 vs. 6.4% in 2011



4 067 Mt



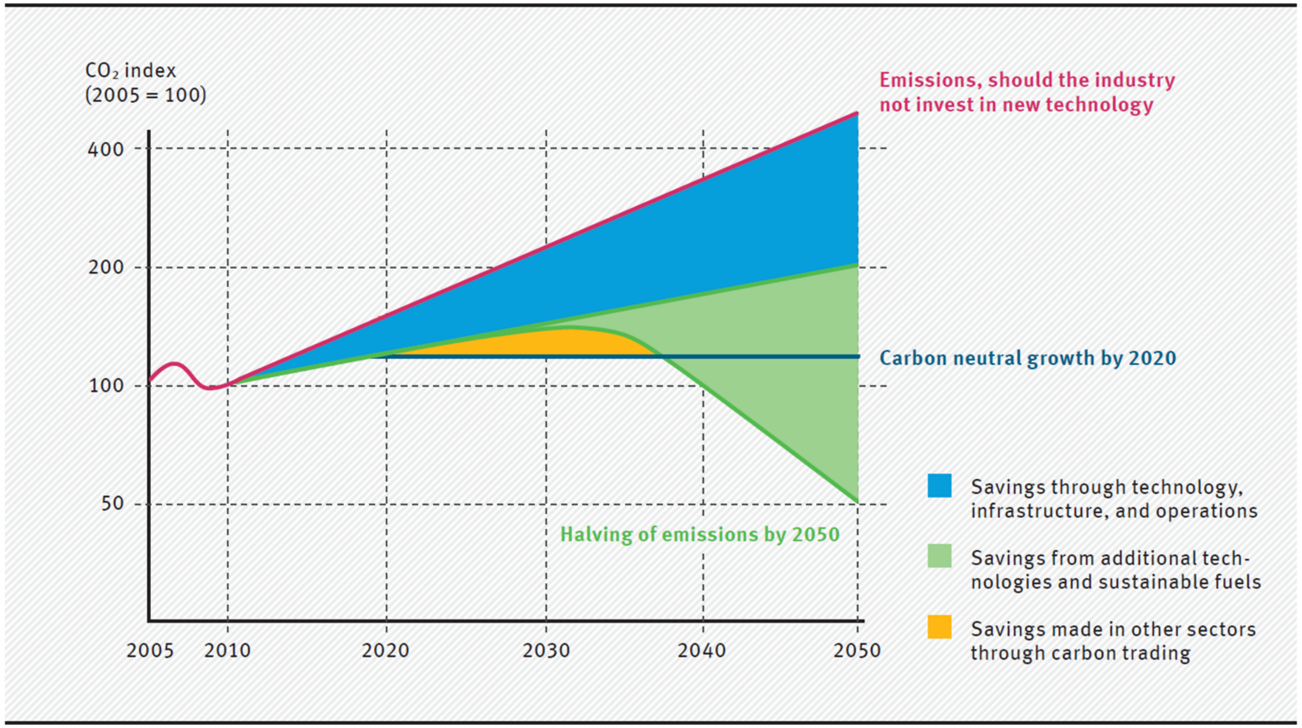


3 896 Mt

Source: Data derived from most recent issues of IEA “Key world energy statistics” and IATA “Economic performance of the airline industry” biannual reports

# Emission targets of aviation industry

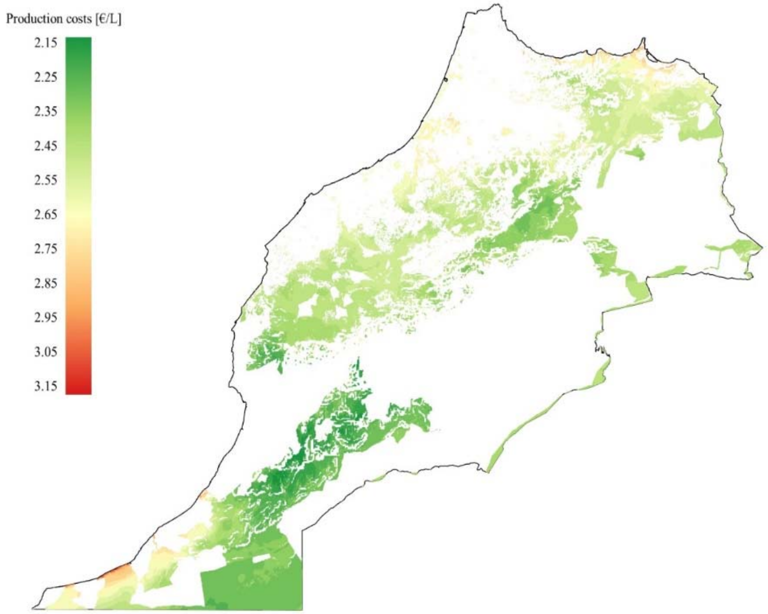
- Industry target: 50% reduction of $CO_2$ emissions by 2050 relative to 2005 baseline
  - Wide consensus in aviation: Renewable fuels are the key to achieve emission target
  - Necessary requirement: Large fuel production potential and low specific GHG emissions

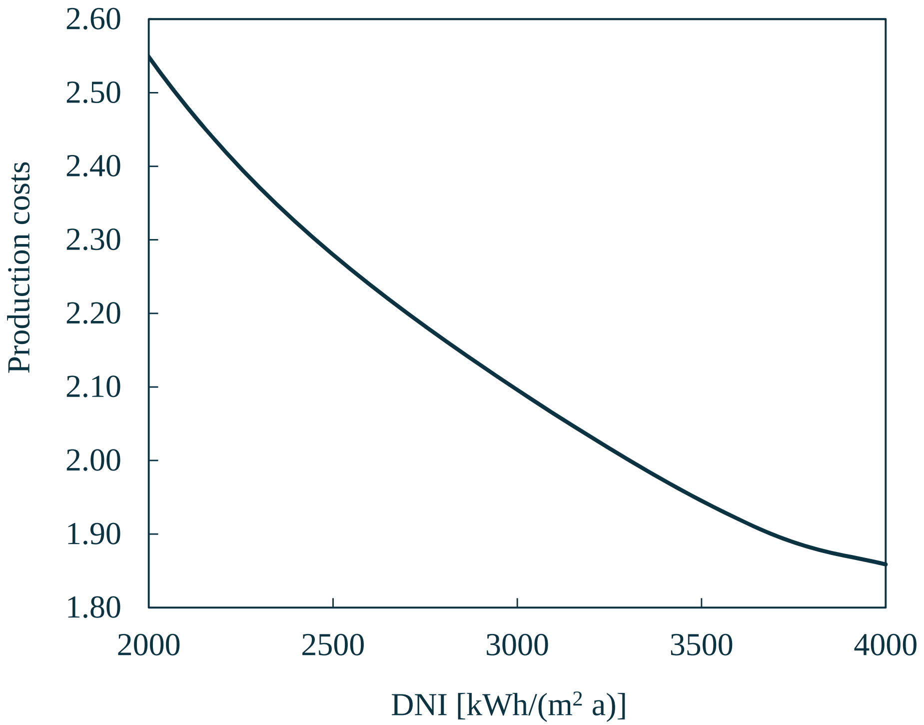


Source: German Environment Agency (UBA), *Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*, 2016, Authors: LBST, BHL; (adapted from ATAG 2012)

# SUN-to-LIQUID, regional analysis of fuel production cost

- Regional analysis of fuel production cost, strong dependence on solar resource





- Global analysis planned

Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

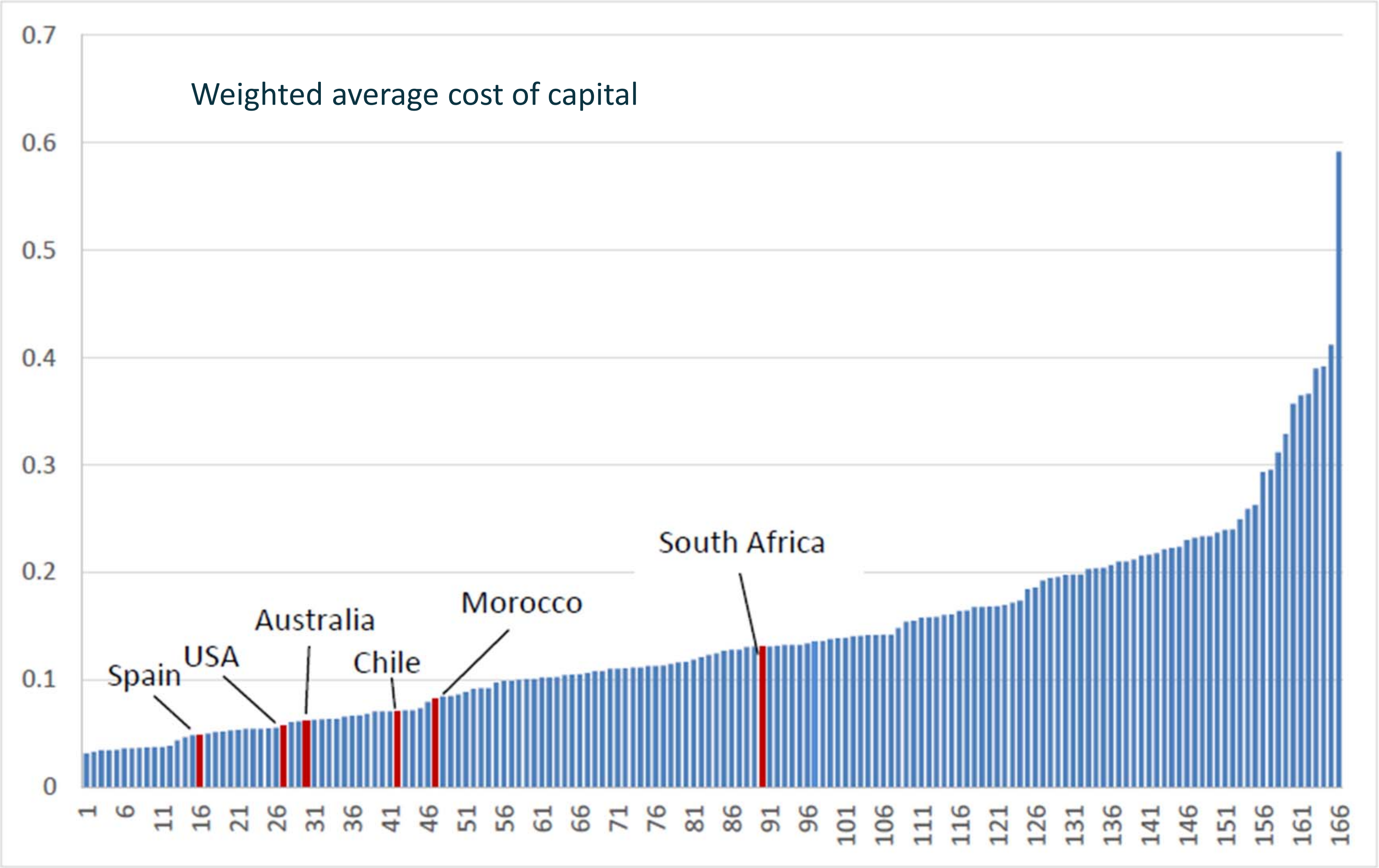
# SUN-to-LIQUID Economic analysis

*Production costs of jet fuel for six countries with favourable solar resource.*

| | USA | Australia | Spain | Morocco | Chile | South Africa |
|---|---|---|---|---|---|---|
| **DNI [kWh/(m$^2$ y)]** | 2800 | 2800 | 2000 | 2500 | 3500 | 3100 |
| **Mirror area [10$^6$ m$^2$]** | 6.9 | 6.9 | 9.6 | 7.7 | 5.5 | 6.2 |
| **Labour costs [10$^6$ €]** | 18.7 | 19.2 | 8.52 | 2.09 | 3.35 | 3.41 |
| **Investment costs [10$^9$ €]** | 1.32 | 1.32 | 1.62 | 1.41 | 1.17 | 1.24 |
| **O&M costs [10$^6$ €]** | 70.8 | 71.2 | 66.1 | 55.8 | 53.1 | 54.2 |
| **WACC [%]** | 5.7 | 6.2 | 4.9 | 8.1 | 7.1 | 13.1 |
| **Production costs [€/L jet fuel]** | 2.11 | 2.24 | 2.13 | 2.28 | 2.03 | 2.98 |

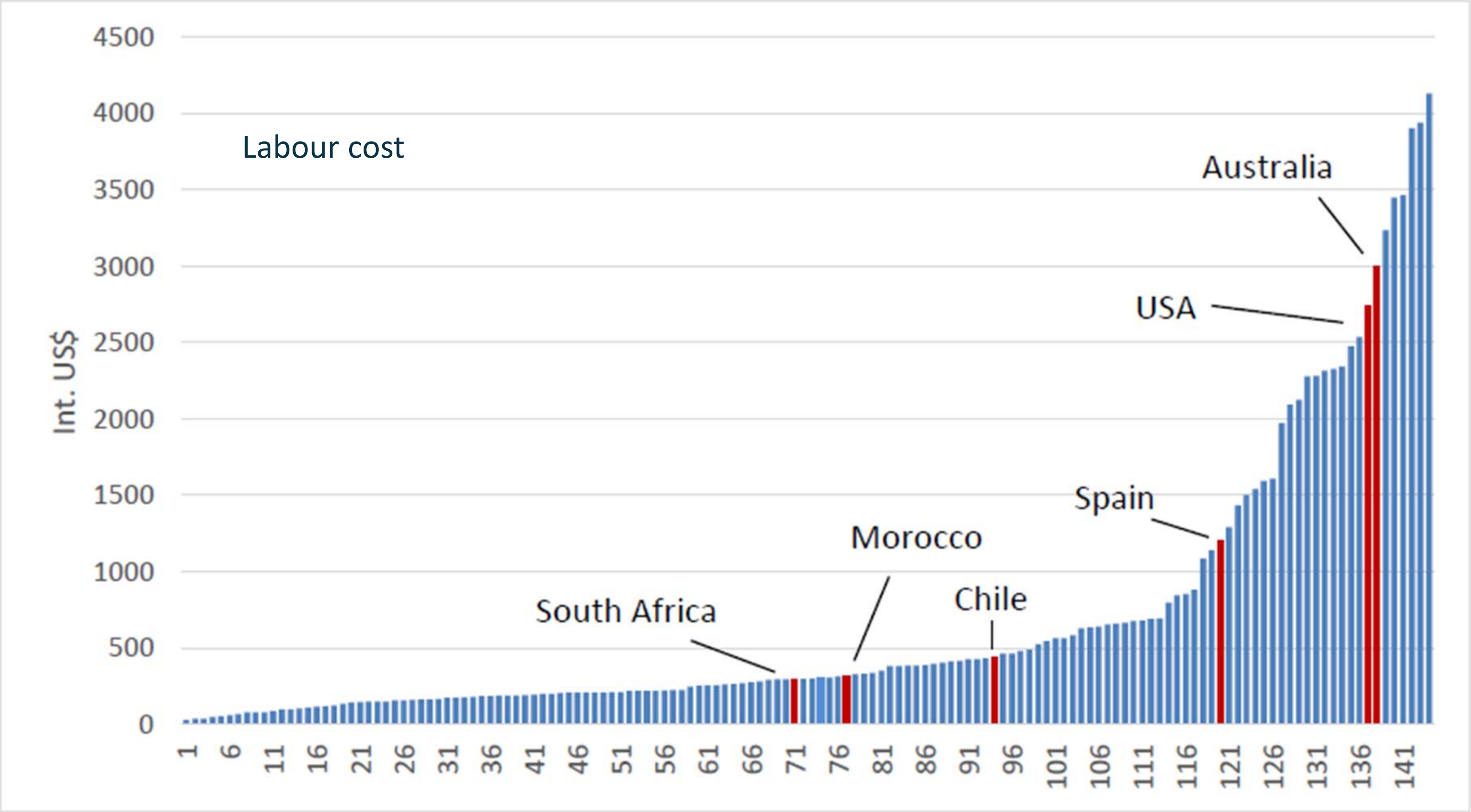
Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

# SUN-to-LIQUID Economic analysis



Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

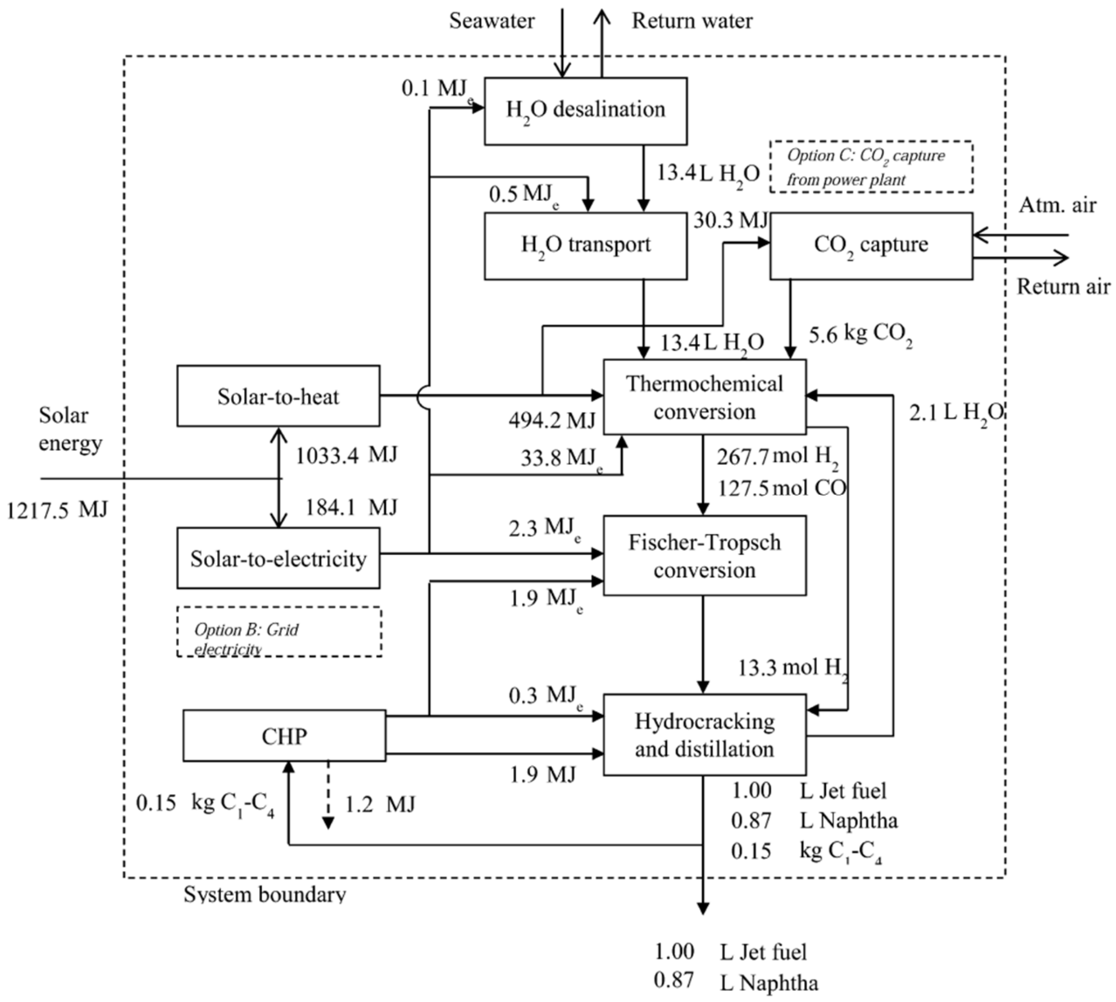
# SUN-to-LIQUID Economic analysis



Source: SUN-to-LIQUID Deliverable D1.6: Economic analysis and risk assessment

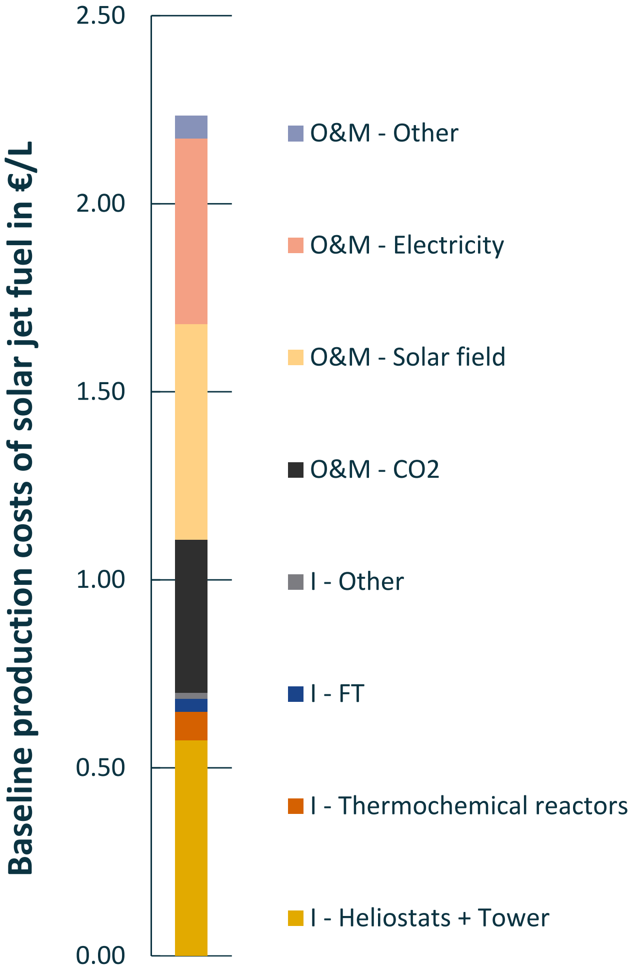
# Economic analysis and climate impact

- Energy and mass-flows for system analyses
- $CO_2$ capture within system boundary
  - $CO_2$ capture from air
  - $CO_2$ capture from power plant
- Solar standalone configuration
  - Solar electricity & heat
  - Option: Grid electricity



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

# Economic analysis



Important assumptions/projections:

Thermochemistry: 20% efficiency (conc. solar-to-syngas)

Solar plant: Concentration: 100 €/m$^2$, O&M 7 €/m$^2$
Tower: 20 €/kW$_{th}$
DNI: 2500 kWh/(m$^2$ a)

Electricity: Solar on-site, 0.06 €/kWh$_{el}$

$CO_2$: 100 €/t (air capture)

Plant size: 1000 bpd jet fuel, 865 bpd naphtha,

FT: 58% efficiency, 23000 €/bpd, 4 €/bbl

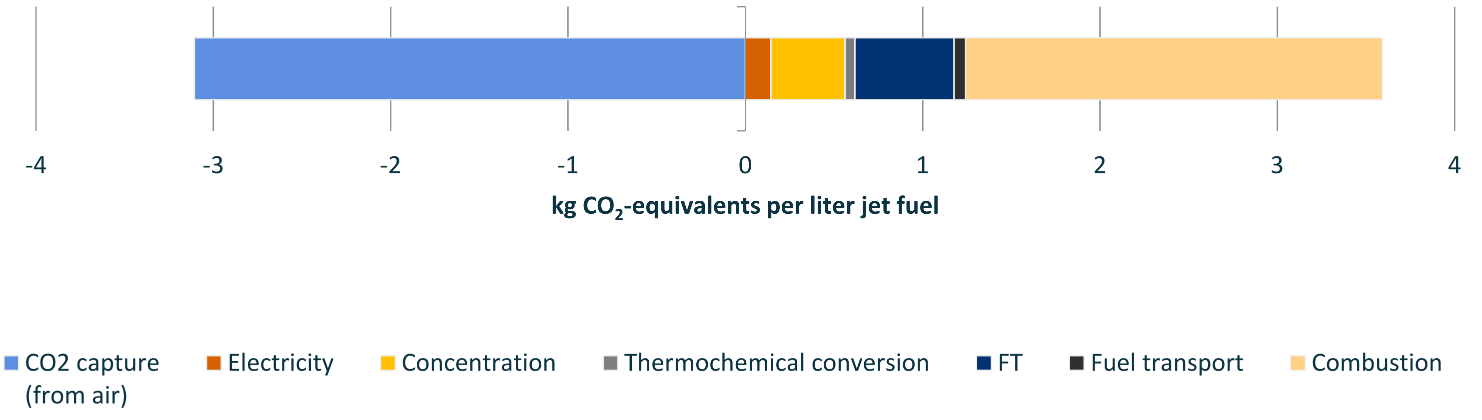
Nominal interest rate: 6%

By-product: Price (naphtha) = 0.8 x Price (jet fuel)

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

# Climate impact

- About 80% reduction in net GHG emission, in “all renewable” configuration



- Net reductions compared to the conventional fuel product **require** a negative contribution (credit) to compensate for the emissions from fuel combustion
  - Origin of $CO_2$ feedstock is most critical for environmental performance of solar fuels
  - Renewable electricity provision is a necessary assumption, too

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