# Solar Cracking and Solar Reforming

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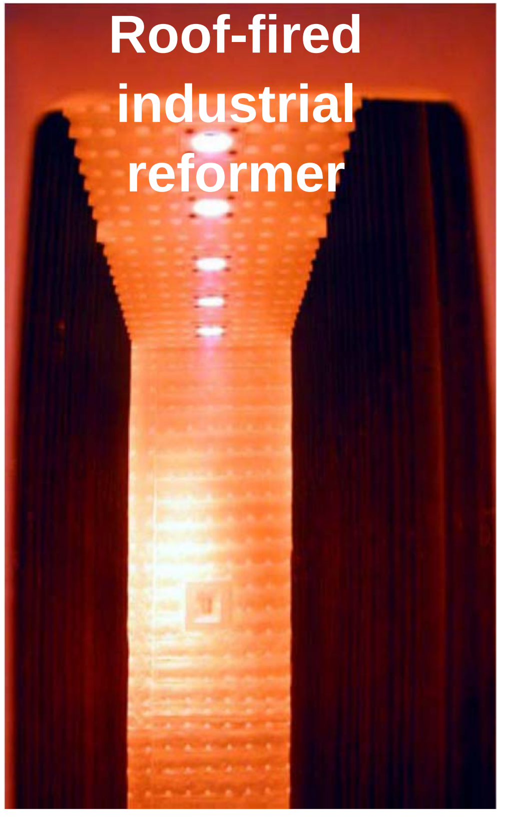
# Established High Temperature Industrial Processes

Cracking of natural gas to produce
- Hydrogen
- Carbon black

Goal: Two valuable products, easy storable solid (really?)

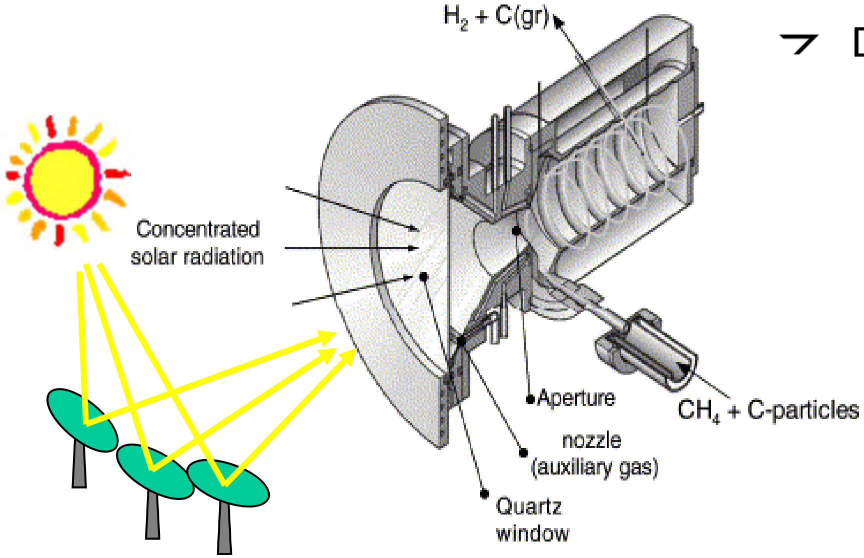
Gasification (see Dr. Meiers talk) and reforming of carbonaceous feedstock for the production of synthesis gas
- Natural gas
- Coal
- Petcoke
- Waste
- Biomass

Goal: Fuels with reduced $CO_2$ emissions for power production but also for air, land, and, sea transportation



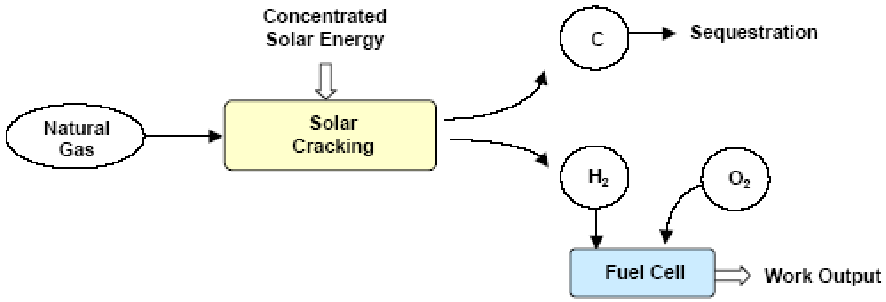


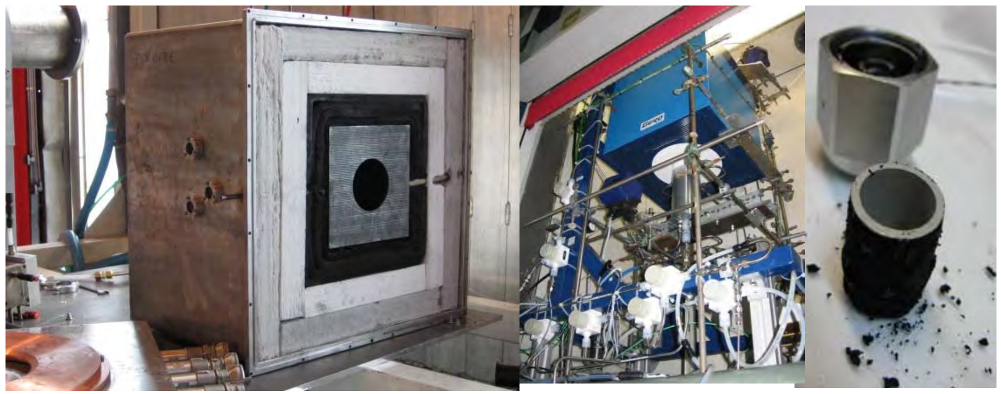

# $H_2$-Production by Solar Cracking of Hydrocarbons




**Source: Hirsch et al.**

- Decarbonisation of Methane $CH_4 \leftrightarrow C + 2H_2$
  - Temperature up to 1600° C
  - Ambient pressure.
  - Conversion 70%.
  - Theoratical system efficiency: 30%
  - EU Project SOLHYCARB 2006 - 2010
  - Partner CNRS/PROMES (FR) - ETH, PSI (CH), WIS (IL), CERTH/CPERI (EL), DLR (DE), TIMCAL



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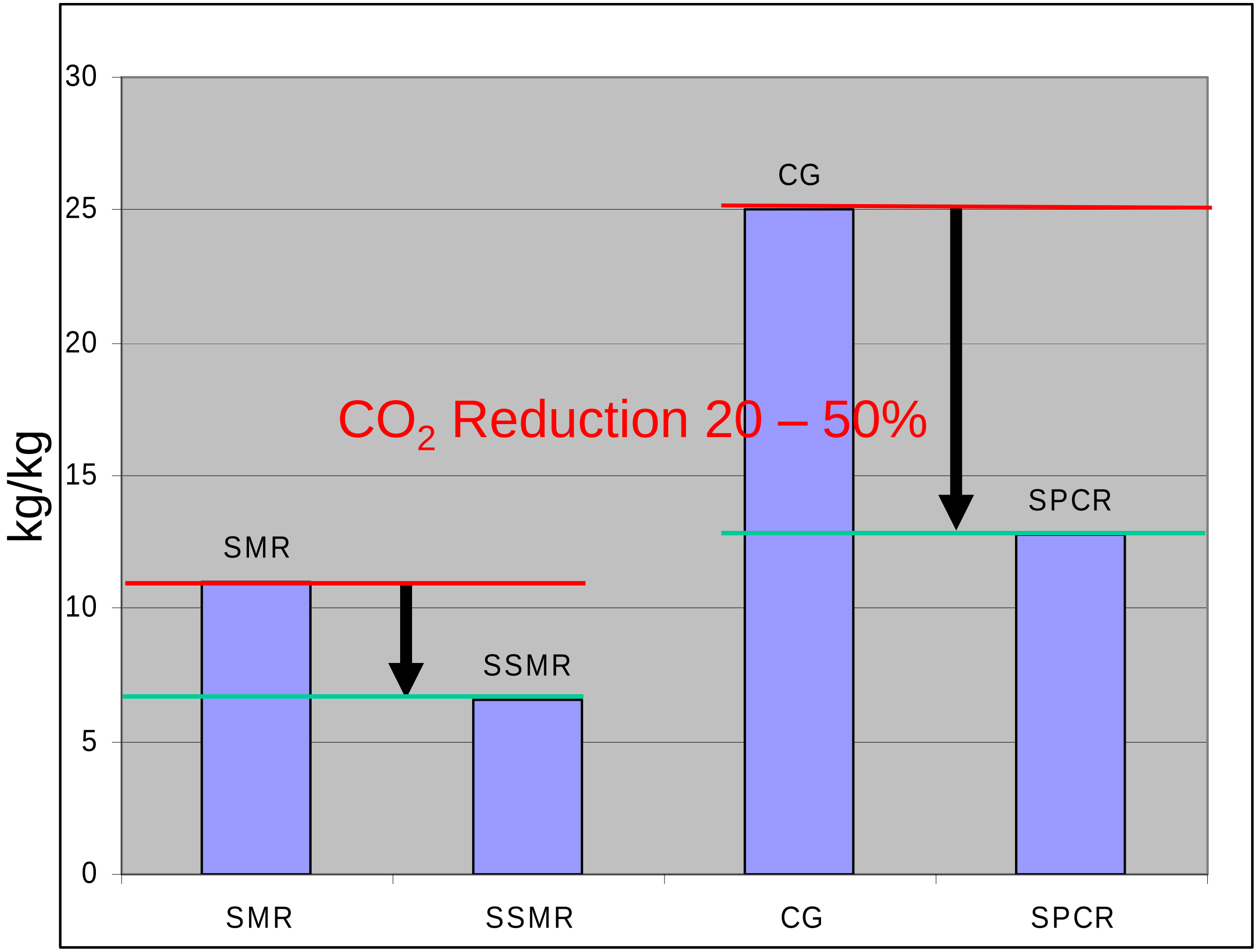
# $CO_2$ Reduction by solar heating of state of the art processes like steam methane reforming and coal gasification

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# Steam and $CO_2$-Reforming of Natural Gas

Steam reforming: $H_2O + CH_4 \rightarrow 3\ H_2 + 1\ CO$

$CO_2$ Reforming (Dry): $CO_2 + CH_4 \rightarrow 2\ H_2 + 2\ CO$

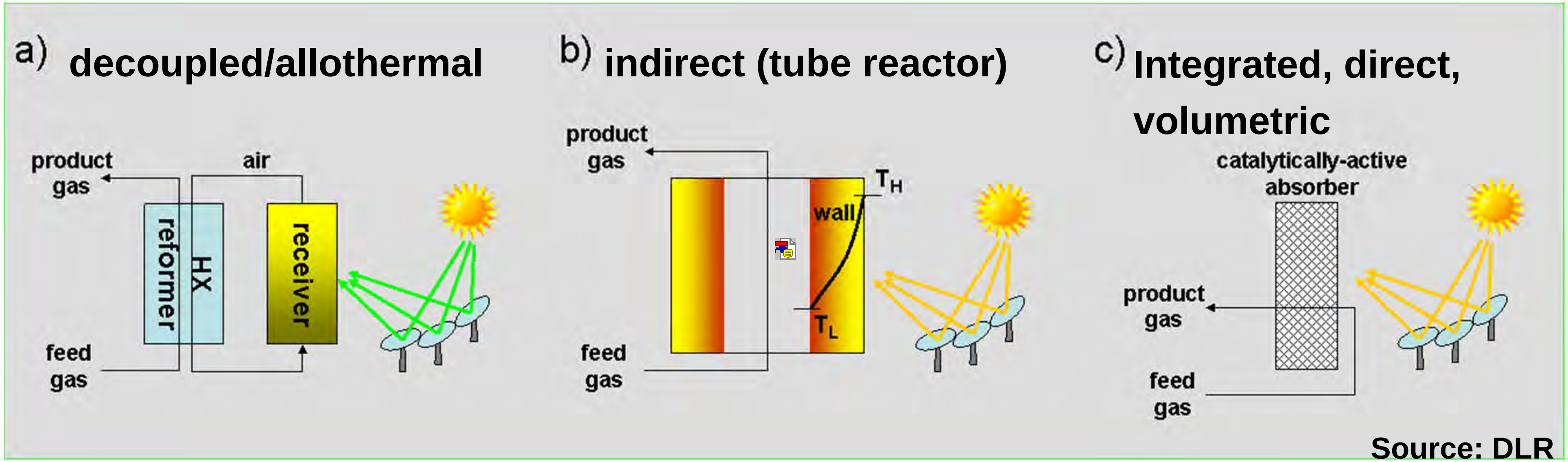
Reforming of mixtures of $CO_2/H_2O$ is possible and common

Use of syngas for methanol production:

e.g. $2H_2 + CO \rightarrow CH_3COH$ (Methanol)

Both technologies can be driven by solar energy as shown in the projects: CAESAR, ASTERIX, SOLASYS, SOLREF…

# Solar Methane Reforming – Technologies

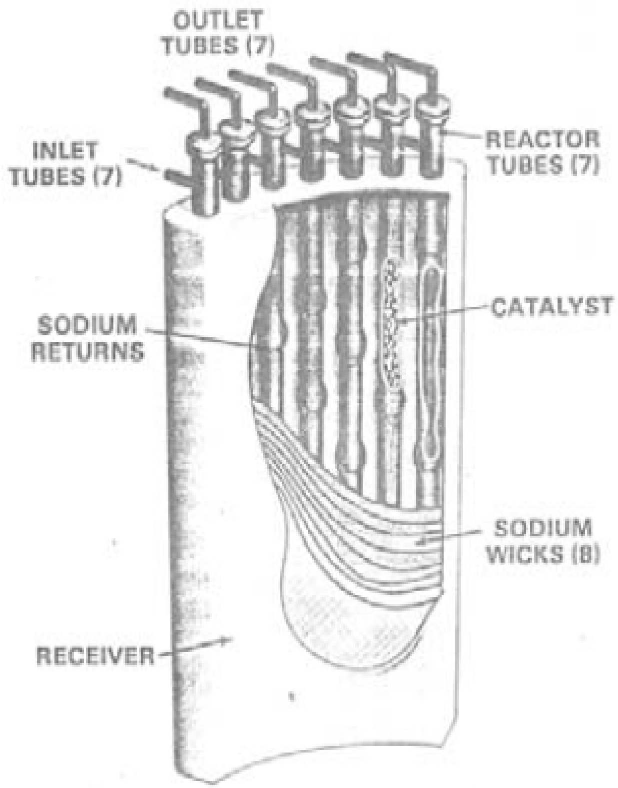


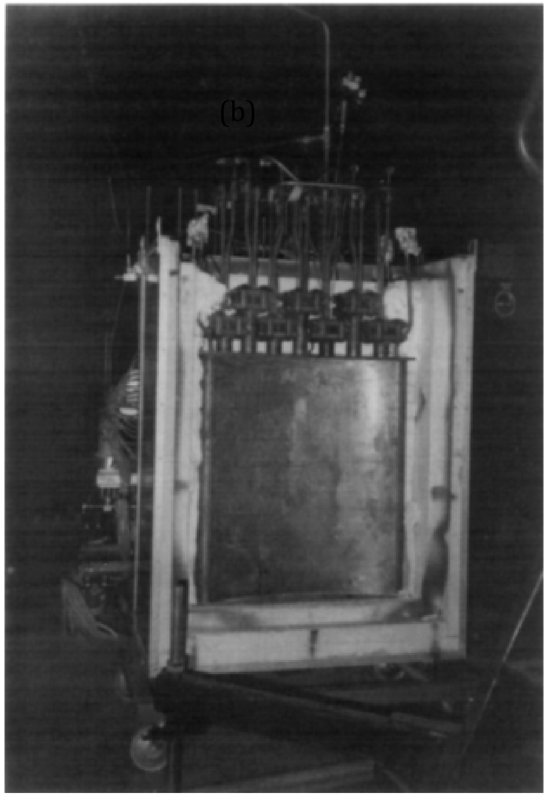

- Reformer heated externally (700 to 850° C)
- Optional heat storage (up to 24/7)
- E.g. **ASTERIX** project

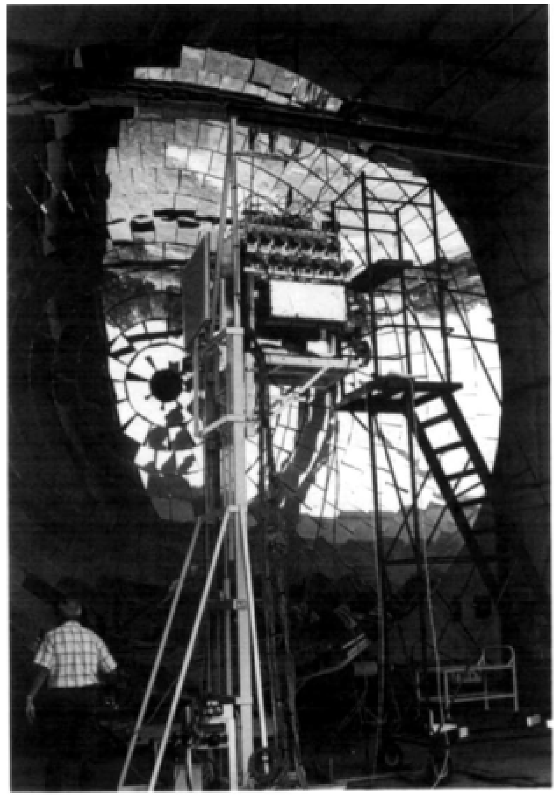
- Irradiated reformer tubes (up to 850° C), temperature gradient
- Approx. 70 % Reformer-h
- Development: Australia, Japan; Research in Germany and Israel

- Catalytic active direct irradiated absorber
- Approx. 90 % Reformer-h
- High solar flux, works only by direct solar radiation
- DLR coordinated projects: **SOLASYS, SOLREF**; Research in Israel, Japan

# SANDIA-WIS's sodium reflux heat pipe solar receiver-reformer (1983-1984)



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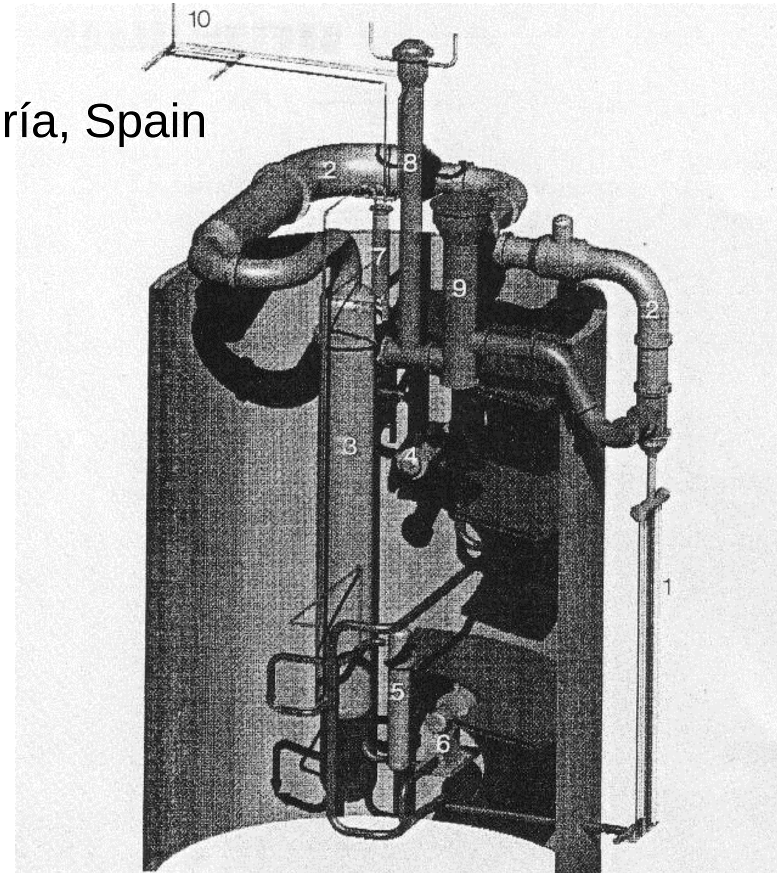
# ASTERIX: Allothermal Steam Reforming of Methan

- DLR, Steinmüller, CIEMAT
- 180 kW plant at the Plataforma Solar de Almería, Spain (1990)
- Convective heated tube cracker as reformer
- Tubular receiver for air heating

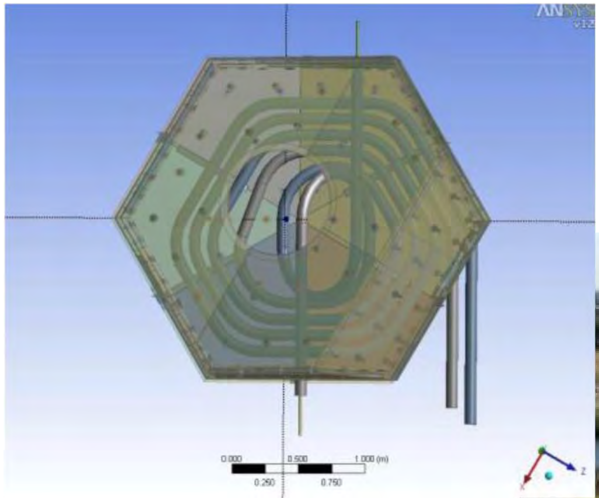
CESA-1, PSA, Spain. The solar radiation is collected by a field of heliostats and redirected to a tower, where different platforms allow the tests of various receiver technologies.

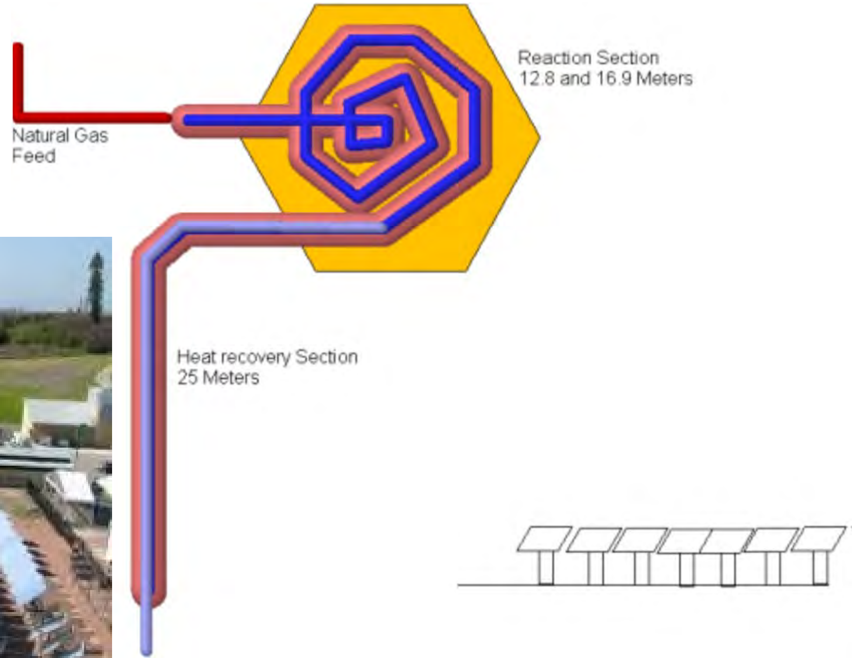



1 = Receiver, 2 = Heißgasleitungen, 3 = Rekuperator, 4 = Elektrischer Heizer, 5 = Kühler, 6 = Kompressor, 7 = Kühler E-106/7, 8 = Reformer V-101 mit Wärmeübertragern E-102/3/4, 9 = Elektrischer Heizer E-105, 10 = Fackel Z-102.

# Pilot Scale Solar Chemical Reactors - SolarGas

## Experimental set-up of the 200 kW SolarGas reactor






***Top view of DCORE reactor (right) layout of entire integrated reformer and HRU***

*Source: R. McNaughton et al., CSIRO, Australia*

# Direct heated volumetric receivers: SOLASYS, SOLREF (EU FP4, FP6)

- Pressurised solar receiver,
  - Developed by DLR
  - Tested at the Weizmann Institute of Science, Israel
- Power coupled into the process gas: 220 $kW_{th}$ and 400 $kW_{th}$
- Reforming temperature: between 765° C and 1000° C
- Pressure: SOLASYS 9 bar, SOLREF 15 bar
- Methane Conversion: max. 78 % (= theor. balance)
- DLR (D), WIS (IL), ETH (CH), Johnson Matthey (UK), APTL (GR), HYGEAR (NL), SHAP (I)

# Central Receiver Plants: Pressurized air receiver

-**Receiver heat transfer fluid:**

-Air (10-16 bar)

-**Hybrid system**:

-The maximum temperature acievable in solar operation is currently limited to 1000° C.

-Therefore natural gas firing is always needed for operation

-**Technology Status**

- 250 kWe (6.5 bar) demonstration at Plataforma Solar de Almeria

-**Companies:**

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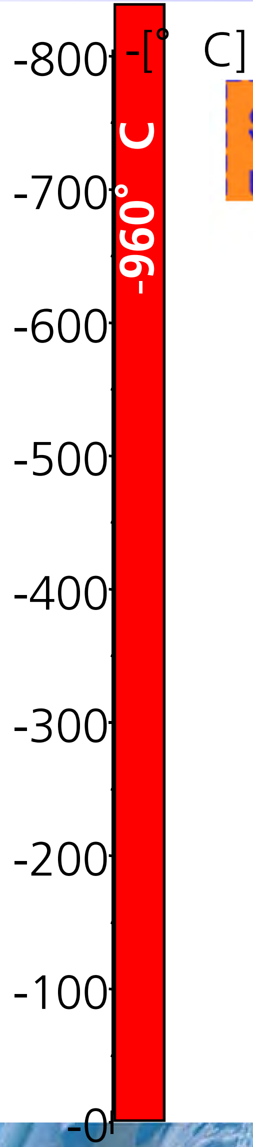
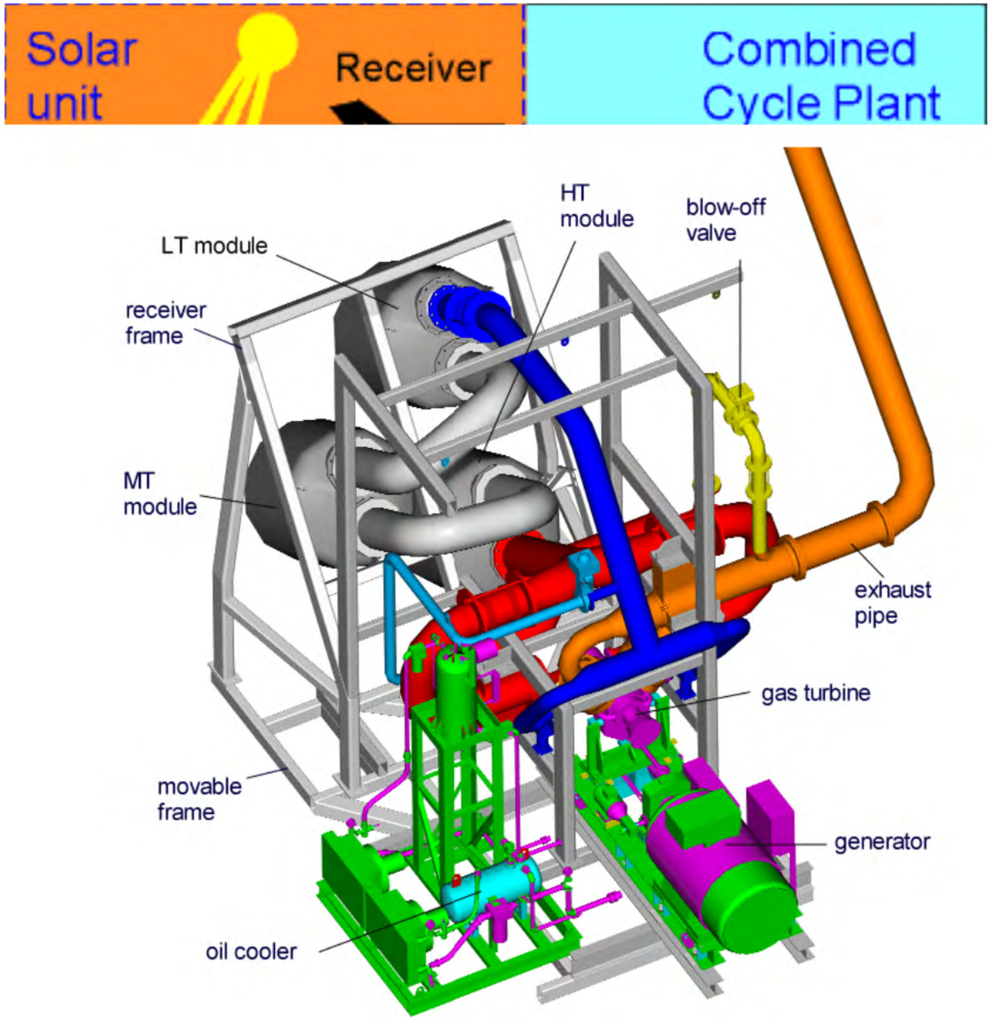
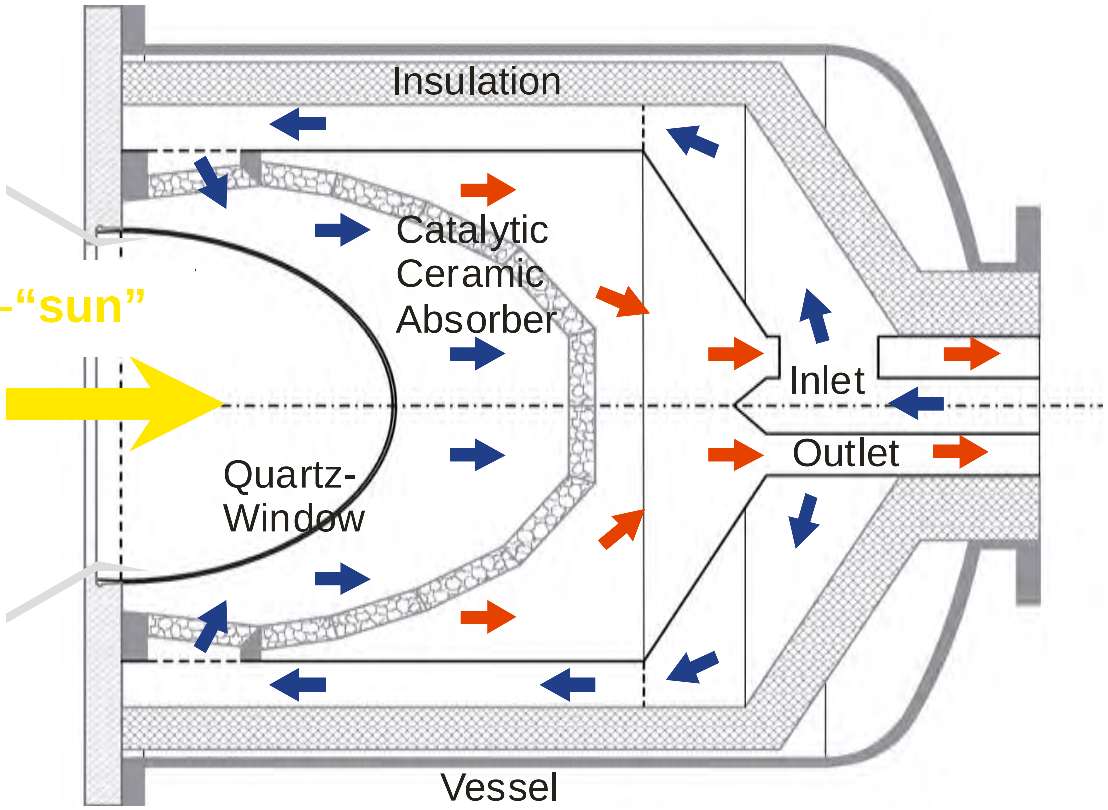


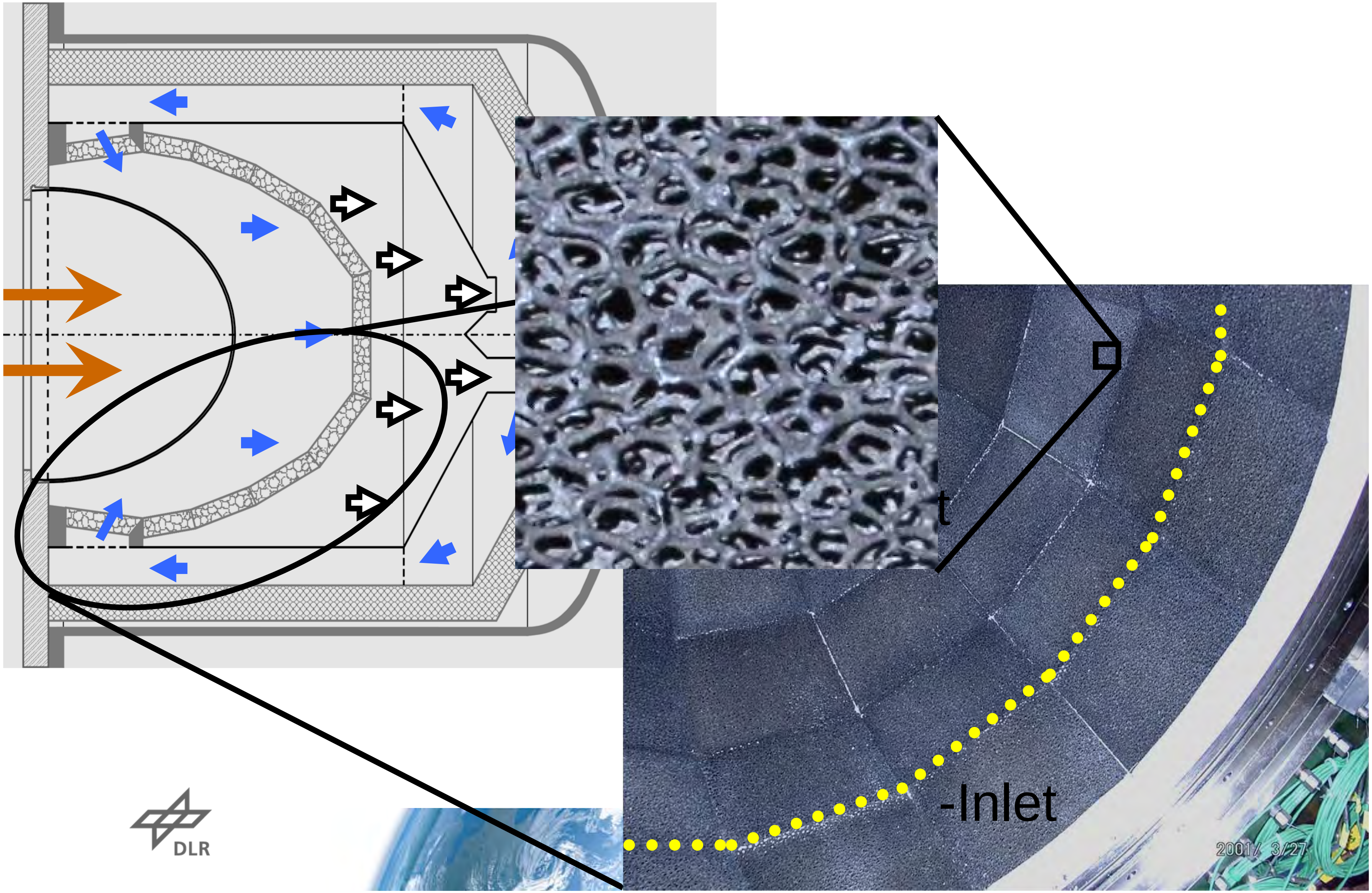




# Pressurized, directly irradiated, volumetric Solar Reformer

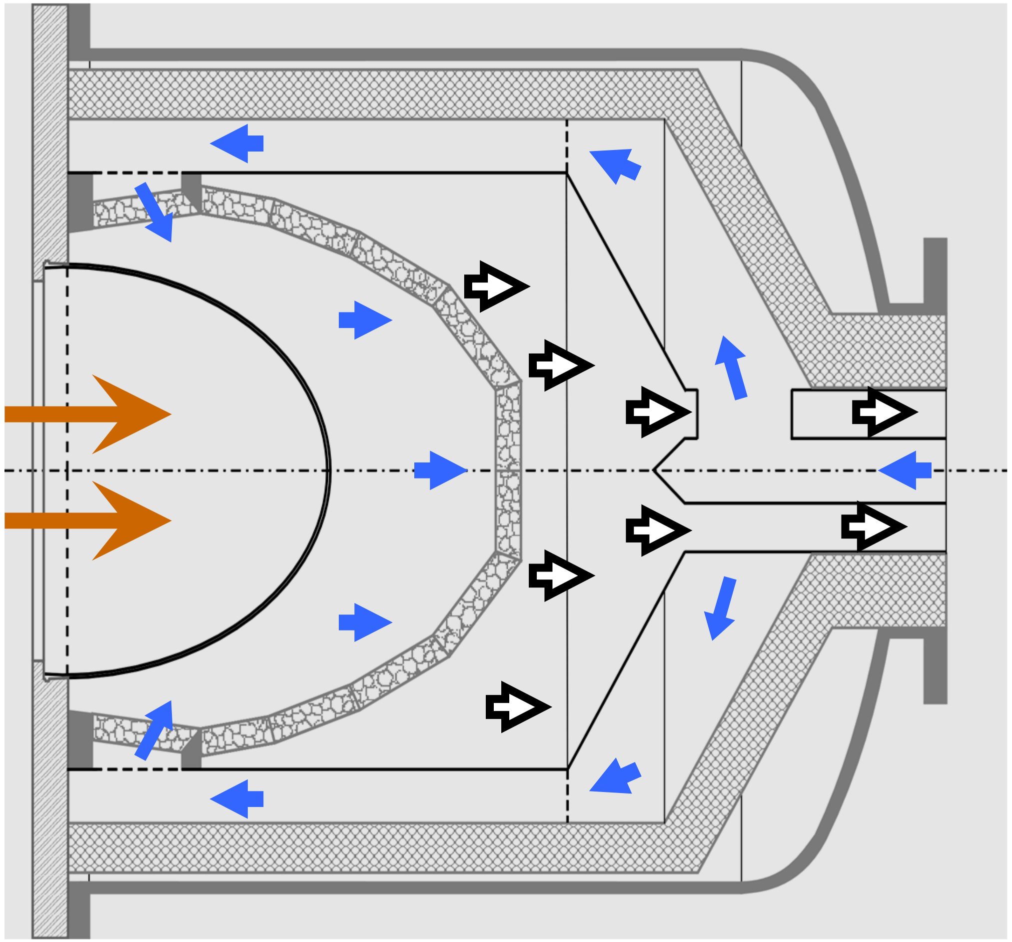



**The catalytically active absorber is directly heated by concentrated solar energy. Efficiencies above 90% can be achieved. (increase of sensible and chemical power of the gas mixture divided by the incoming solar power).**

# Receiver Lay-out

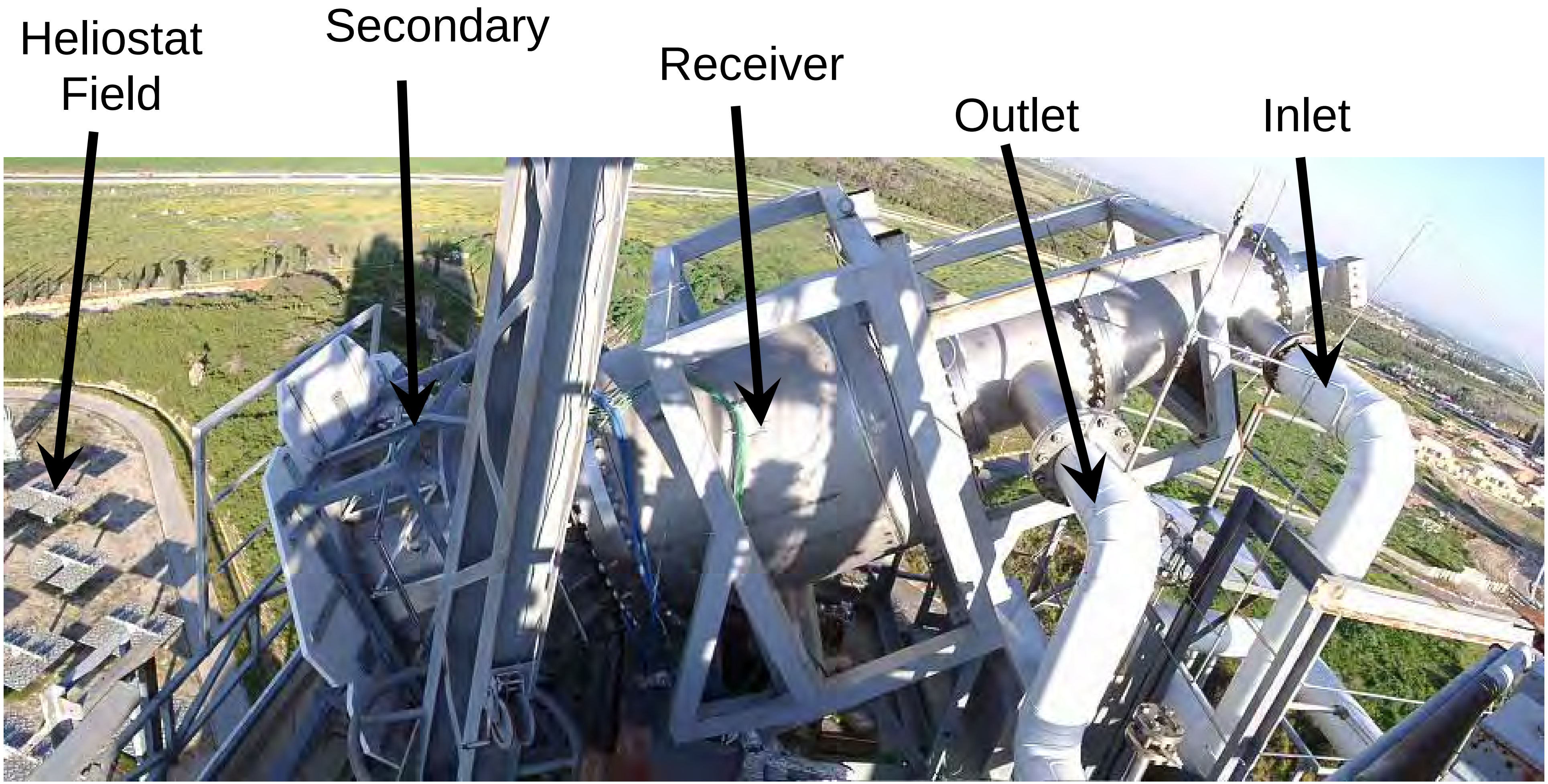


# Receiver Lay-out



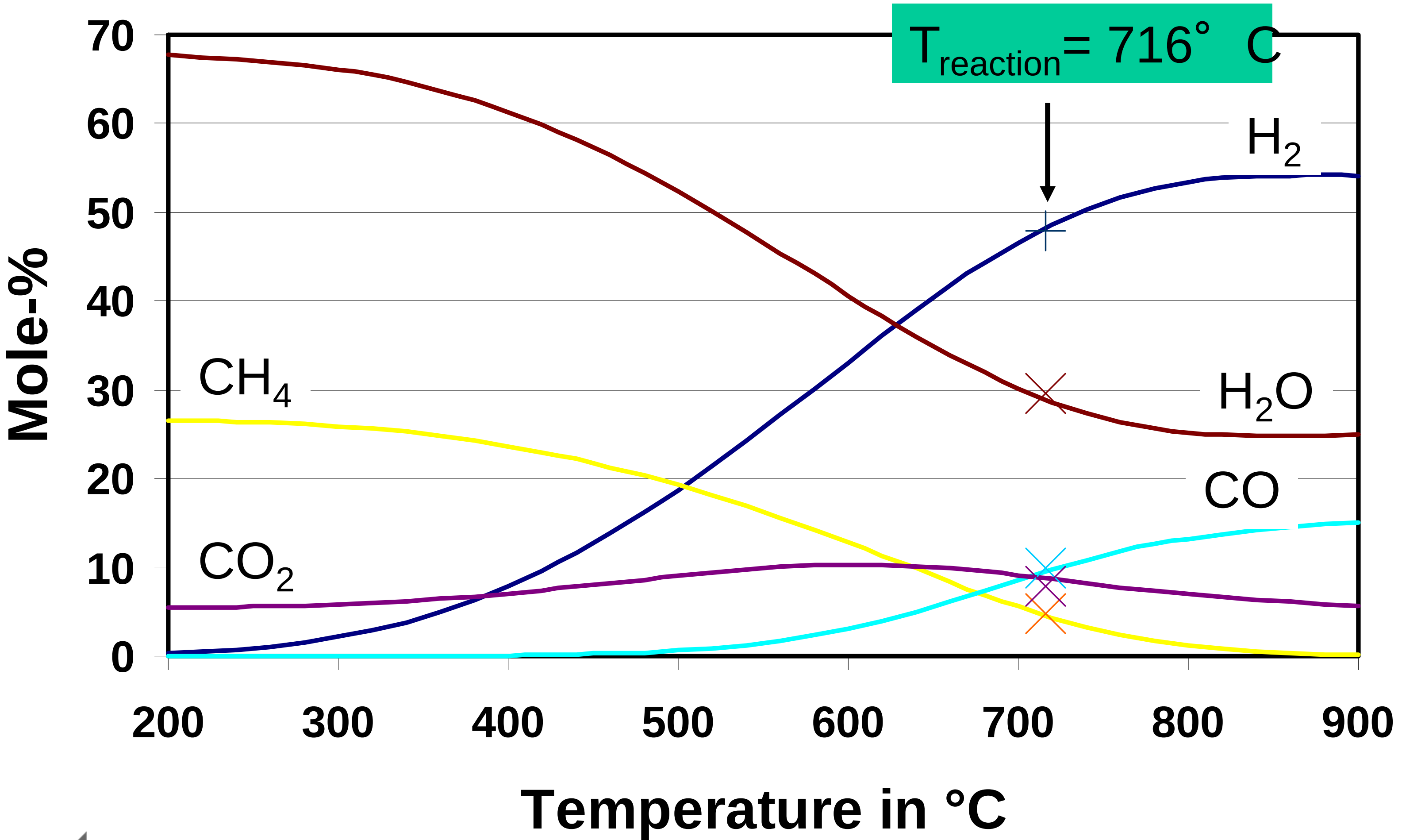
- Nominal layout data for the
- SOLASYS receiver-reactor:
- Absorbed power: 400 kW
- Methane conversion level: 80%
- Operating pressure: 10 bar
- Fluid inlet temperature: appr. 500° C
- Syngas outlet temperature: appr. 850° C

# Receiver Unit

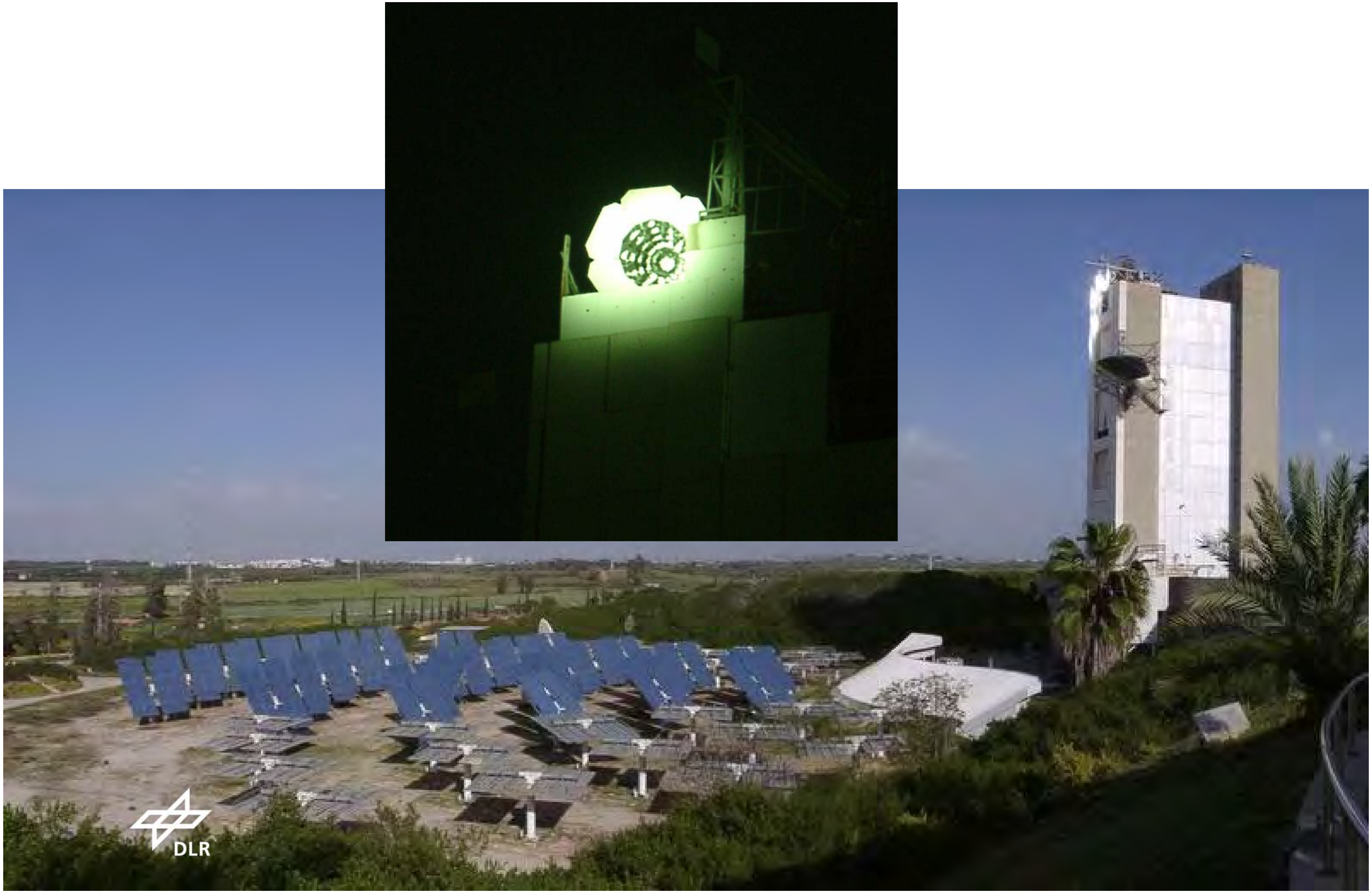


# Outlet gas composition at $p_{receiver}$ = 4.9 bar

Inlet gas composition: 22.7 mole-% $CH_4$, 7.6 mole-% $CO_2$, 0.0 mole-% CO, 59.3 mole-% $H_2O$, 10.3 mole-% $H_2$

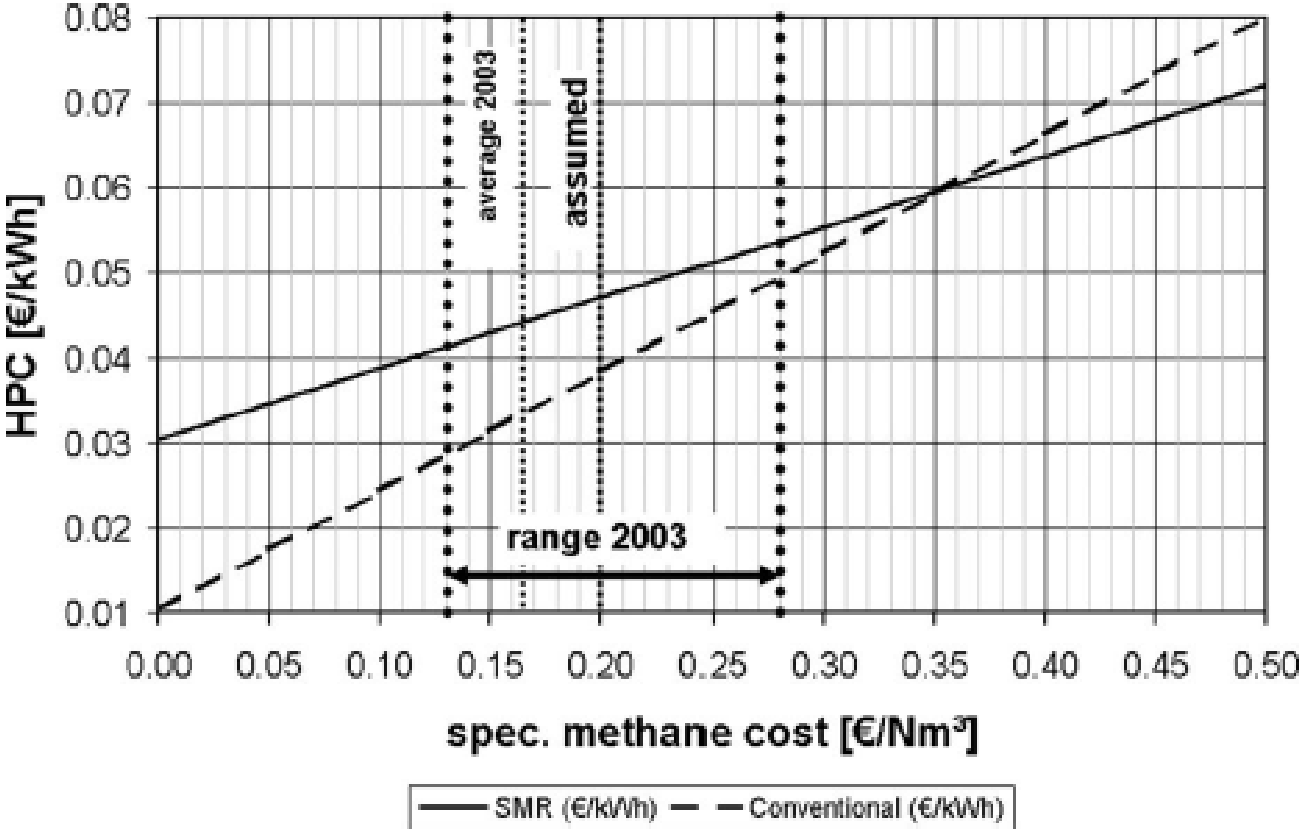


# SOLASYS - Test Plant in Operation



# SOLASYS Economic Analysis (2006)

Comparison of hydrogen production cost by conventional and solar reforming of natural gas (NG) depending on the NG price reported in 2004 by „www.oilenergy.com“



# SOLREF Solar Steam Reforming (SES6-CT-2004-502829)

**SOLASYS**

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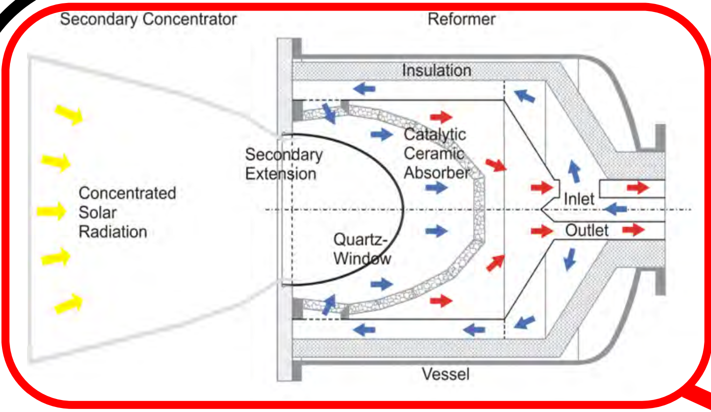
**SOLREF**




**Catalysis** → **Reformer** → **Operation** → **Pre-design of 1MW plant** → **Conceptual layout of 50 MW plant** → **Studies**

↓

## 1 $MW_{th}$ Prototype Plant e.g. in Southern Italy

# Motivation & Consortium

- Production costs of *partly-solar hydrogen* with less than *5 ct€/kWh* or 1.7 €/kg $H_2$ (large scale, solar-only) are possible.
- The solar driven process reaches profitability when the price of NG increases to about 40ct€/$Nm^3$
- Eight participants from seven countries:
    - DLR, coordinator Germany
    - APTL/CERTH/CPERI, Greece
    - Weizmann Institute of Science, Israel
    - ETH Zurich, Switzerland
    - Johnson Matthey Fuel Cell Ltd, UK
    - HyGear B.V., The Netherlands
    - SHAP S.p.A., Italy
    - Region Basilicata, Italy

# Project main objectives

- Develop an advanced 400 $kW_{th}$ solar reformer
- Investigate various catalyst systems
- Simulate mass and heat transport and reaction in porous absorber
- Perform thermodynamic and thermochemical analyses to support the system design phase
- Operate the reformer with gas mixtures which represent the variety of possible feedstock on the solar tower at WIS, Israel, producing partly-solar hydrogen
- Evaluate new operation strategies
- Pre-design of a 1 $MW_{th}$ prototype plant in Southern Italy
- Conceptual layout of a commercial 50 $MW_{th}$ reforming plant
- Assess on potential markets including cost estimation and environmental, socio-economic, and institutional impacts

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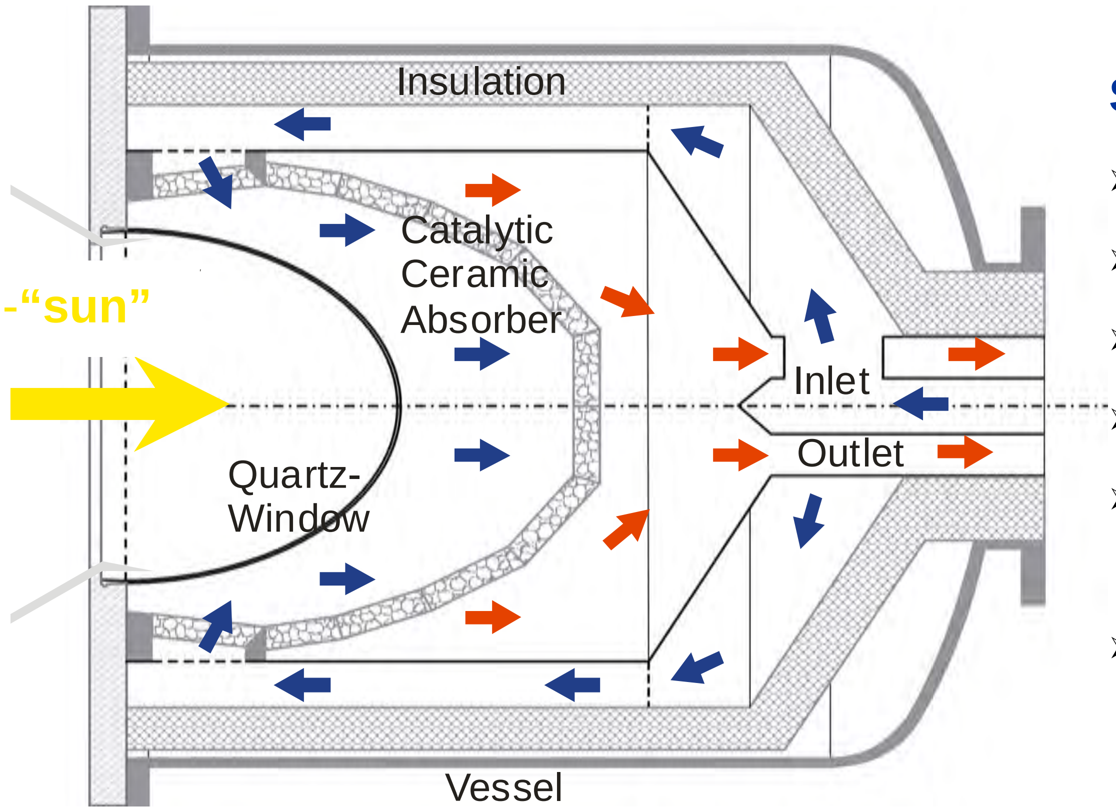
# Solar Reformer - Improvements




## SOLREF Reformer:

- Absorbed power: app. 400 $kW_{th}$
- Feed-temperature: app. 450° C
- Outlet-temperature: app. 900° C
- absorber temp.: max. 1100° C
- Operation pressure: optimal pressure 10 bars; max. 15 $bars_a$
- Mass flow: 0.12 kg/s



# Future Steps

-Areas for market introduction

-Addition of "solar upgraded fuel" into large scale CC power plants with mixing rate 5 -10 %

-Dual fuel operation

- Solar reforming of biogas or landfill gas

-Further research is directed to

-Flexible feed gas composition

-Modified process parameters including $CO_2$ separation and reforming

-Next step towards market introduction

-Pre-commercial solar reforming plant of **1-5 MW** size adapted to the specific fuel and process conditions

# Acknowledgement

- Thanks to all our funding agencies especially the European Commission for funding the projects.

- Thanks to all colleagues and partners who provided various contributions to this work.

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Thank you very much for your attention!

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