Solar sulphur – fuel for on-demand and carbon-free power production

2nd Middle East Sulphur, Abu Dhabi, 19th Mar. 2018

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German Aerospace Center (DLR)

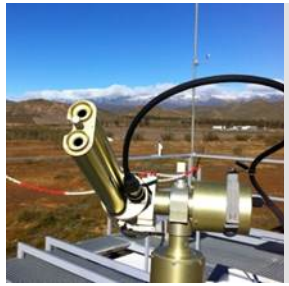
- Research Institution, Space Agency and Project Management Agency
- Research Areas:
  - Aeronautics
  - Space Research and Technology
  - Transport
  - Energy
  - Defence and Security
- 8000 employees across 33 institutes and facilities at 20 sites in Germany
- Offices in Brussels, Paris, Tokyo and Washington
- Total income 2015: 888 Mio. €

Institute of Solar Research

Point Focus Systems
- Heliostats
- High temperature receivers
- System technology

Qualification
- Components
- Component durability
- Systems

Line Focus Systems
- Heat transfer media
- Collector development
- Industrial process heat



Solar Energy Meteorology
- Solar radiation measurement and modelling
- Radiation nowcasting
- Other meteorological influences

New Materials
- Absorber materials
- High temperature redox systems
- Photocatalysts
- Heat transfer fluids

Solar Chemical Engineering
- Solar fuels
- Solar water treatment

Institute of Solar Research

Research Facilities in Cologne and Juelich (Germany)

Solar Tower Juelich
Experimental solar power plant, Germany‘s unique solar tower

Synlight
Solar simulator – the world‘s largest artificial sun

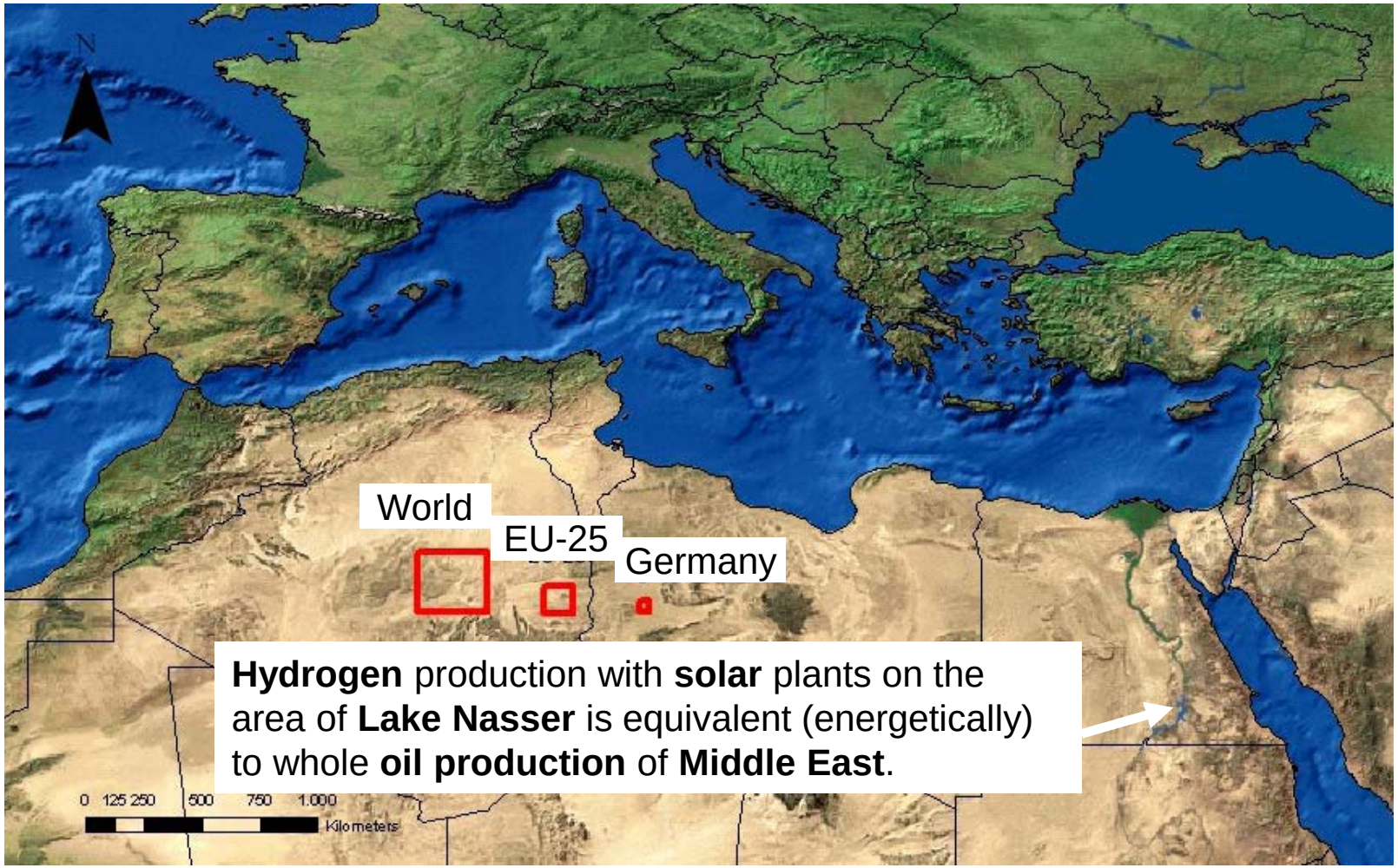
CeraStorE®
Competence center for ceramic materials and thermal storage technologies in energy research

High-flux Solar Furnace and Xenon High-flux Solar Simulator

Outdoor Test Installations

QUARZ®
Test and qualification center for CSP technologies

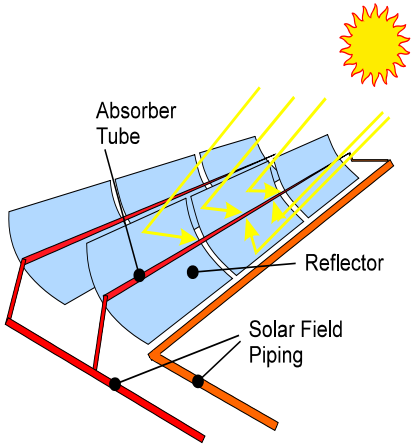
Potential of solar energy

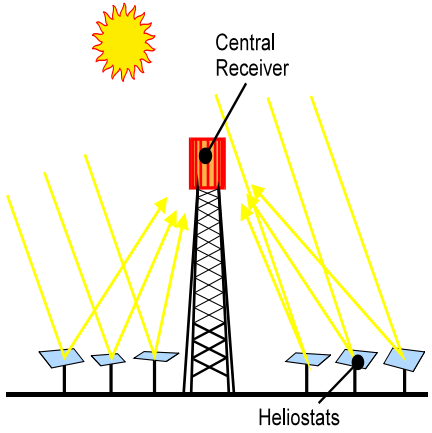


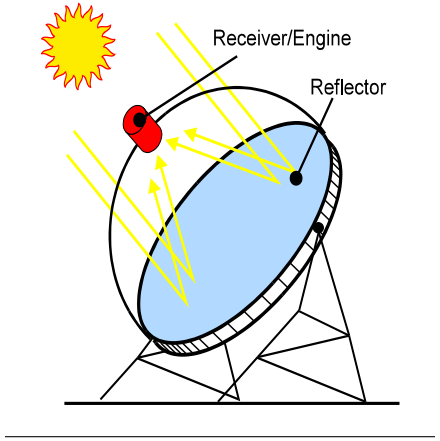
Hydrogen production with **solar** plants on the area of **Lake Nasser** is equivalent (energetically) to whole **oil production** of **Middle East**.

M. Schmitz, TSK Flagsol

Concentrated Solar Power (CSP) Plants







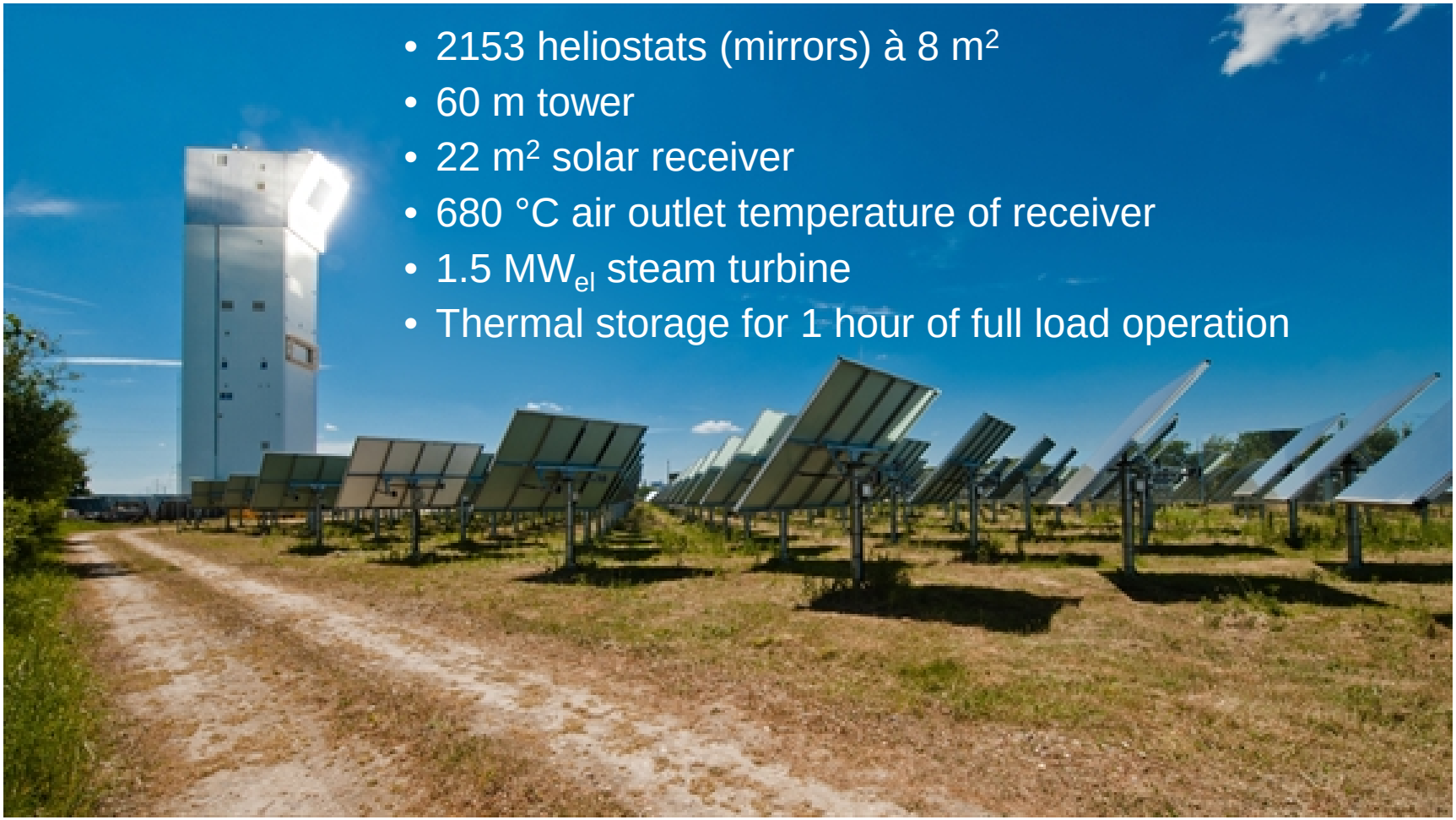
Parabolic Trough **400 °C**

Solar Tower **1000 °C**

Solar Dish **2000 °C**

DLR Solar Power Tower in Juelich, Germany

Research and demonstration plant



Crescent Dunes, Nevada, USA
110 MW, 10 h Storage, 2015

Khi Solar One, South Africa
50 MW, 2h Storage, 2016

Gemasolar
Seville, Spain (2011)
20 MW, 15 h Storage

PS10
11 MW, 2007

PS20
20 MW, 2009

Seville, Spain

Ivanpah, California, USA (2014)
377 MW, serves >140.000 homes

Comparison of energy storage densities

Technology	Energy density (kJ/kg)		Volumetric energy density (kJ/l)	
Hydrogen	141,886	1	~6,700	*
Gasoline	47,357	1	~35,000	
Sulphur	**9,281**	2	**~18,000**	
Lithium Ion Battery	580	2	~730	
Molten Salt	282	2	~540	
Elevated water Dam (100m)	1	2	~1	

[1]College of the Desert
[2]General Atomics
*at 700 bar

Thermochemical sulfur storage cycle for baseload solar power production

ΔH = -254 kJ/mol

$2\ H_2O + 3\ SO_2 \Rightarrow 2\ H_2SO_4 + S$

<200 °C (liq. phase)

ΔH = -572 kJ/mol

$S + 1.5\ O_2 + H_2O \Rightarrow H_2SO_4$

>1000 °C

$SO_2 + H_2O$

S

Sulphuric Acid Decomposition

SO_2 Disproportionation

Sulphuric acid plant

$3\ H_2SO_4 \Rightarrow 3\ H_2O + 3\ SO_2 + 1.5\ O_2$

>800 °C

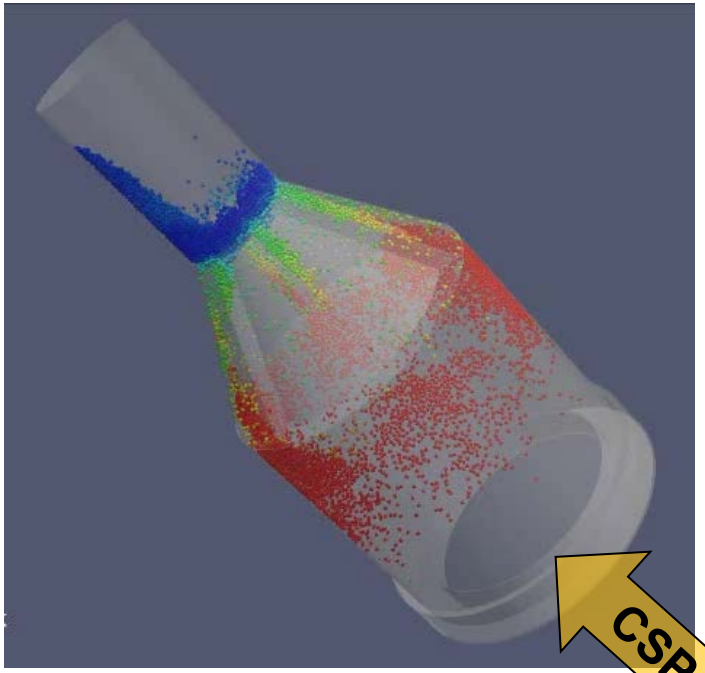
ΔH = +826 kJ/mol

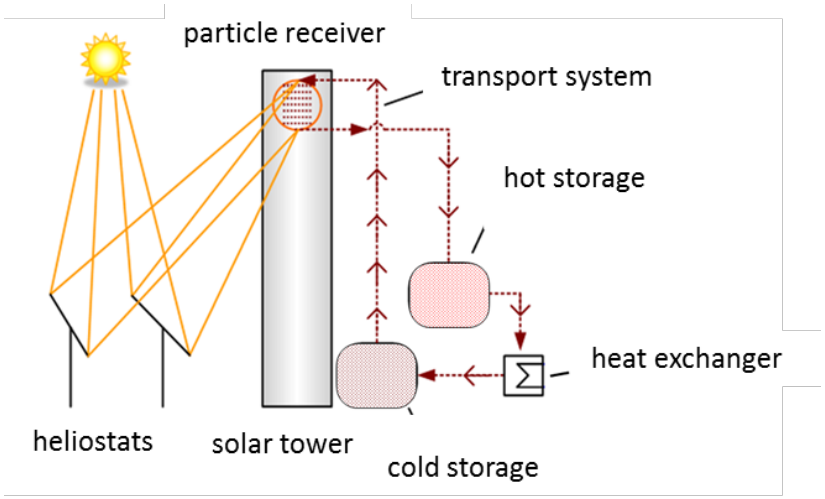
H_2SO_4

DLR

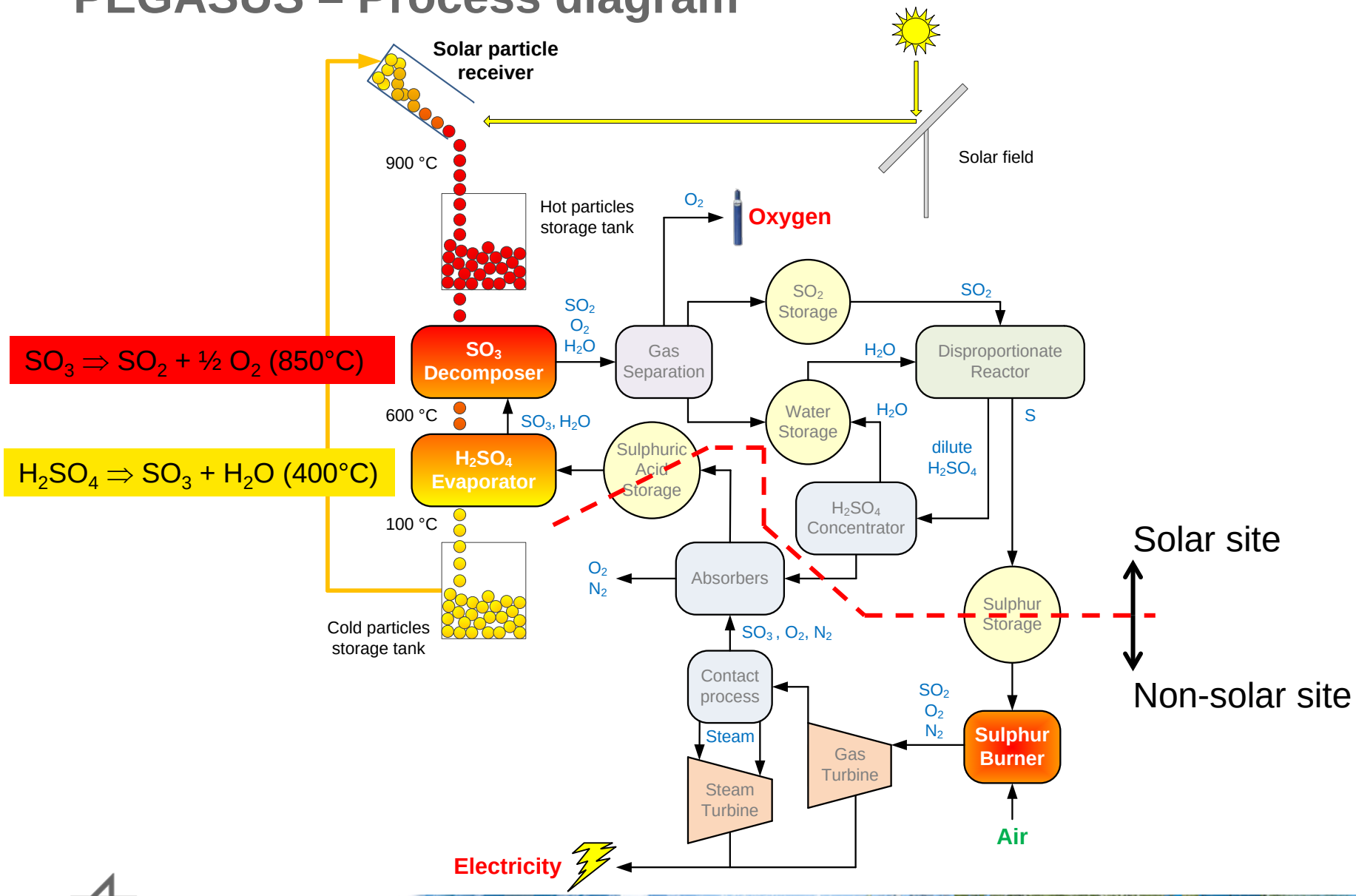
Solar particle technology

- Direct absorption ⇒ high efficiency and energy density
- Direct storage
- Receiver and storage at ambient pressure
- No freezing and no decomposition
- Low parasitic
- Low security requirements





PEGASUS – Process diagram



Integration of solar sulphur power generation

Solar particle plant

Hot particles

Particle reactor (sulphuric acid splitting)

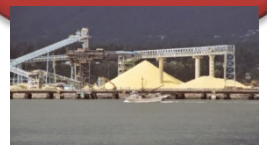
SO_2

Disproportionate reactor

Sulphuric acid

Sulphuric acid plant

Sulphur



Sulphur gas turbine plant

Refinery

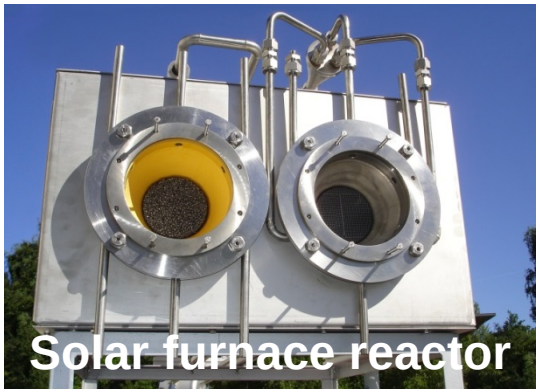
Electrical power

DLR

Research of DLR on sulphur cycles

- Experience on solar sulphuric acid cracking since more than 20 years
- Research on Hybrid Sulphur Cycle for **hydrogen** production in European projects HYTHEC, HycycleS and SOL2HY2 (2004 – 2016)
  - Development and on-sun testing of receiver/reactors in solar furnace
  - Construction of pilot unit and demo operation on solar tower
  - Modelling of reactors
  - Testing of catalysts and construction materials
  - Flowsheeting and techno-economics of HyS process
  - Scale-up concepts


Catalyst testing


Solar furnace reactor


Solar tower demo

Project Baseload (Sulfur Based Thermochemical Heat Storage for Baseload Concentrated Solar Power Generation)

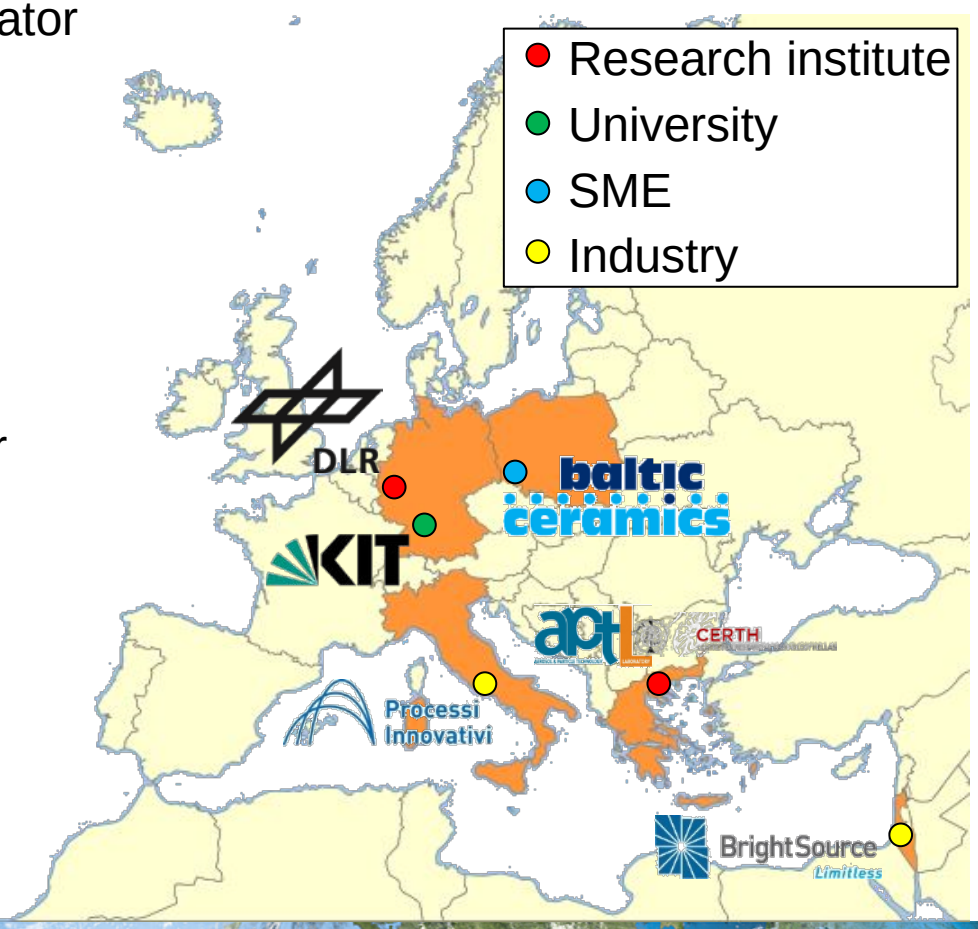
- Funding: United States Department of Energy (DOE)
  - 2 project phases from 2010 to 2013
  - GO/NO-GO review after phase I
  - Phase I completed in Mar. 2012
  - GO recommendation for Phase II (May 2012 – Oct. 2013)

- Coordinator: General Atomics (GA), USA
  - SO_2 disproportionation
  - Sulfur combustion
  - Experiments, plant design, flowsheeting, economics

- Subcontractor: German Aerospace Center (DLR)
  - H_2SO_4 decomposition
  - Experiments, modeling
  - Funded work and in-kind contribution

PEGASUS partners

- **DLR**, Germany (Coordinator)
  - Solar tower/simulator owner/operator
  - Solar receiver/reactor developer
- **APTL/CERTH**, Greece
  - Catalyst materials developer
- **KIT**, Germany
  - Combustion specialist
- **Baltic Ceramics**, Poland
  - Advanced ceramics manufacturer
- **Processi Innovativi**, Italy
  - Power plant designer/contractor
- **BrightSource**, Israel
  - CSP plant designer/contractor



PEGASUS – Work plan

- WP1: Catalytic particles development, manufacturing – APTL, Baltic Ceramics
- WP2: Centrifugal particle solar receiver – DLR
  - Preparation of existing test receiver
  - On-sun test operation with catalytic particles (WP1)
- WP3: Sulphur trioxide decomposer + WP4: Sulphuric acid evaporator – DLR
  - Development and construction of moving bed reactors with direct (WP3) and indirect (WP4) heat transfer
  - Off-sun test operation
- WP5: Sulphur Combustor – KIT
  - Development, construction and operation of sulphur burner
- WT6.1, 6.5, 6.6:Overall concept evaluation – Processi Innovativi, BrightSource
  - System modelling, flowsheeting, techno-economy
- WT6.2-6.4: System integration, test operation – DLR
  - Integrated operation of solar receiver (WP2) and sulphuric acid splitting reactors (WP3, WP4)

Centrifugal particle solar receiver optimization

Application of pilot receiver developed in CentRec project

- Centrifugal particle receiver was erected on scaffold in front of Juelich Solar Tower
  - Nominal power: 2.5 MW_{th}
  - Diameter of aperture: 1.13 m
  - Max. particle temperature: 1000 °C
- Commissioning completed
- Solar testing of CentRec started in autumn 2017

Project PEGASUS

- Solar testing of catalytic particles in CentRec pilot planned for Apr./May 2018
- Integrated testing together with particle reactors for sulphuric acid splitting planned in last project year

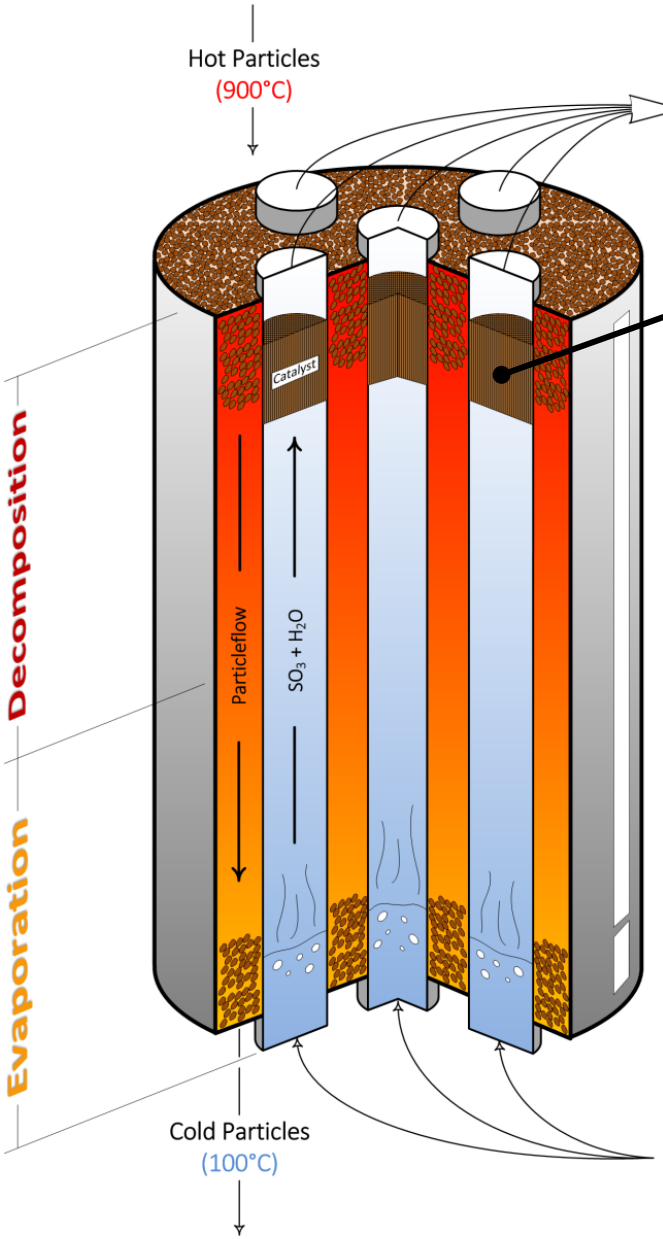
Design of particle reactor for sulphuric acid splitting

SO_3 decomposer

$SO_3 \Rightarrow SO_2 + ½\ O_2$ (850 °C)

Sulphuric acid evaporator

$H_2SO_4 \Rightarrow SO_3 + H_2O$ (400 °C)



$$\dot{m}_{Part} \approx 50\ \frac{kg}{h}$$

$$\dot{m}_{H2SO4} \approx 6\ \frac{kg}{h}$$

$theoretical!$

Conclusions and outlook

- Sulphur has high thermochemical energy density
- Efficient transportation and storage of solid or liquid sulphur
- Solar sulphur cycle allows for baseload power production
- Potential for integration of sulphur cycle into existing sulphuric acid plants
- Investigation of solar sulphur cycle in European project PEGASUS
  - Development and on-sun testing of catalytically active solar particles
  - Construction of particle reactor for sulphuric acid splitting
  - Prototype development of sulphur burner for gas turbine
  - Process simulation and techno-economic analysis

Thank you for your attention!

www.pegasus-project.eu

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