Baseload Power Production with Solar Sulphur

Hydrogen and Beyond, Workshop, 23rd Nov. 2021

SolarFuelsNOW

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Contents

- DLR Institute of Future Fuels
- Sulphur as solar fuel and thermochemical storage medium
- Solar sulphur power generation
- European project PEGASUS
- Conclusions and outlook

DLR – Institute of Future Fuels

- **Start**
  - 3rd Jul. 2020 – legally
  - 1st Jan. 2021 – operational
- **Locations in Juelich and Cologne**
  - Solar research facilities Cologne
  - Synlight solar simulator Juelich
  - Juelich Solar Fuels Hub J.SOF (planned)
- **Scientific topics**
  - Chemical and physical fundamentals
  - Solar-chemical process development
  - Solar process demonstration
  - Solar production assessment

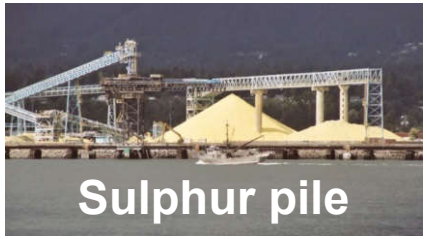
DLR

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	

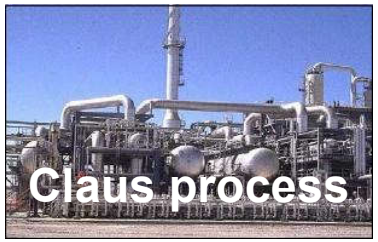
[1]College of the Desert
[2]General Atomics
*at 700 bar

Sulphur in industrial processes



- Sulphur is required for **sulphuric acid** (SA) production
  - SA is world's most produced chemical
    ⇒ Global annual rate **>200 Mio. tons**
  - SA is measure of industrial development
  - SA is mainly needed for **fertiliser production**

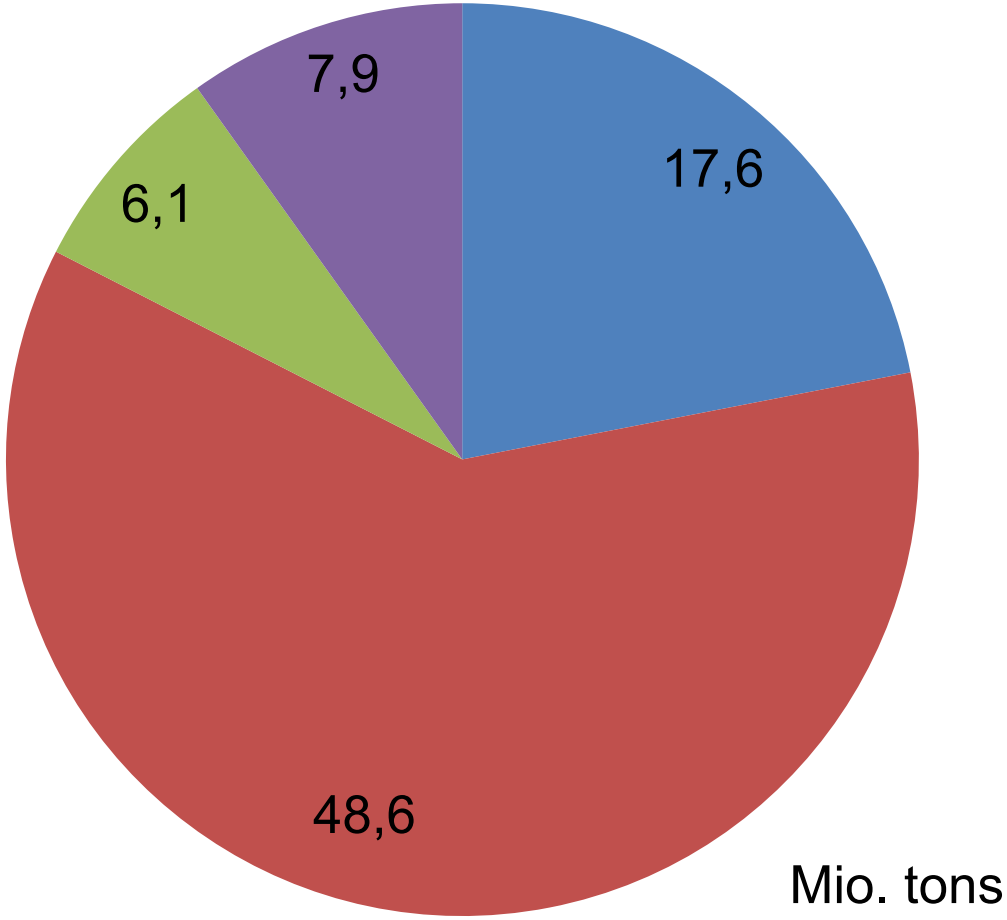
- Sulphur from **desulphurisation of hydrocarbons** via Claus process



- Sulphur is by-product of **metallurgic processes**

Sulphur world production 2017

Total of 80 Mio. tons (avg. world price of US$111 per ton)



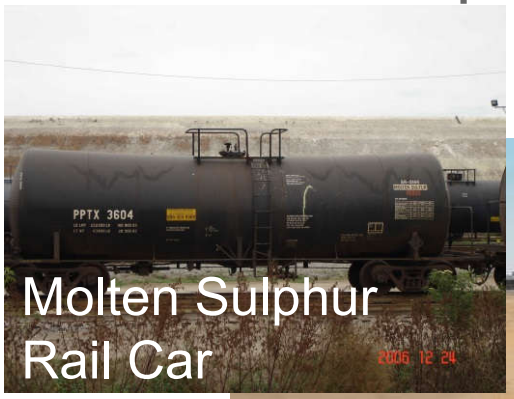
- Metallurgy (smelting of sulphide ores)
- By-product sulphur from refineries etc. (processing natural gas and petroleum)
- Mining (pyrite and native sulphur)
- Other

Source: 2017 Minerals Yearbook, SULFUR, U.S. Geological Survey

Transportation and storage of sulphur

In solid or liquid form

Train



Molten Sulphur Rail Car

Pipeline

Molten sulphur in heated pipelines (~140 °C)

Truck

Molten sulphur trailer

Ship

Thermochemical sulfur storage cycle for baseload solar power production

$\Delta H = -254$ kJ/mol

$2\ H_2O + 3\ SO_2$
$\Rightarrow 2\ H_2SO_4 + S$
<200 °C (liq. phase)

$\Delta H = -572$ 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

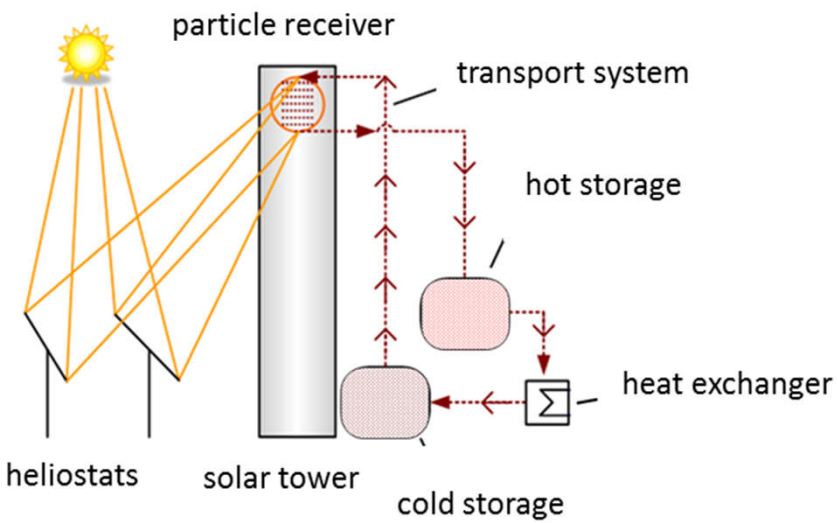
$\Delta H = +826$ kJ/mol

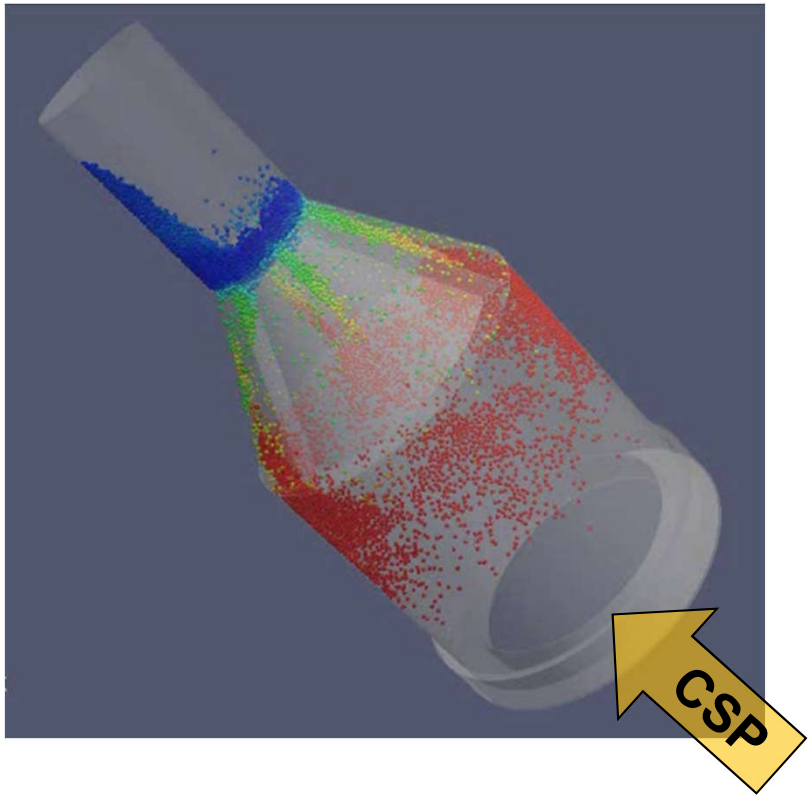
H_2SO_4

DLR

Solar particle technology
Centrifugal receiver CentRec®

- 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

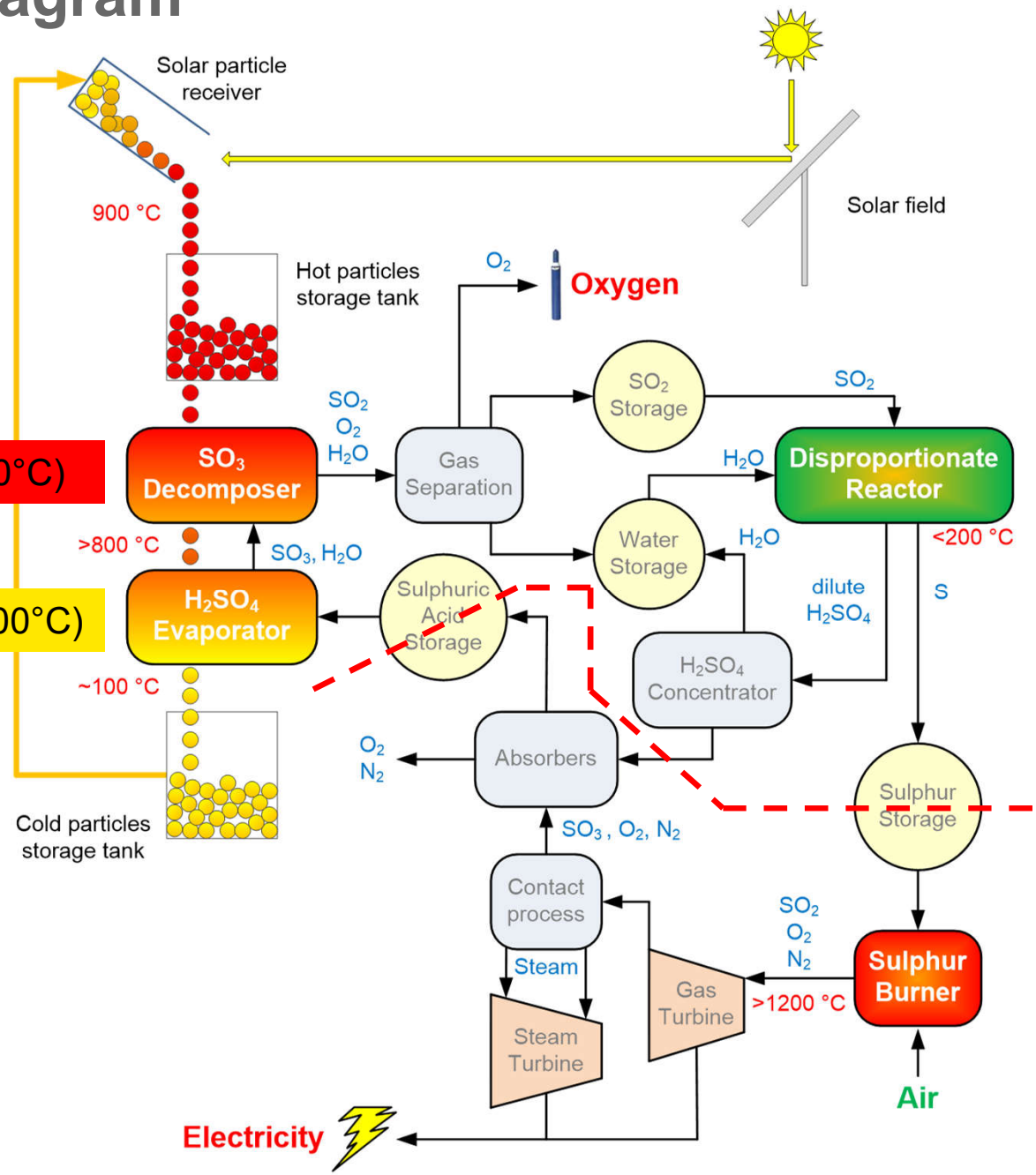


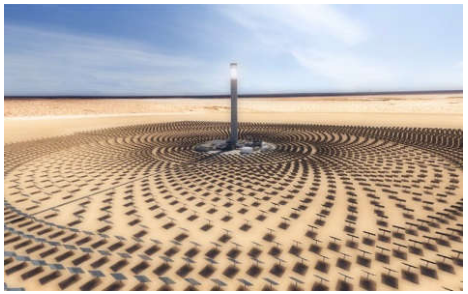


Process diagram

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

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





Solar site

Non-solar site

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

SO_2

Sulphur gas turbine plant

Electrical power

Sulphur

Refinery

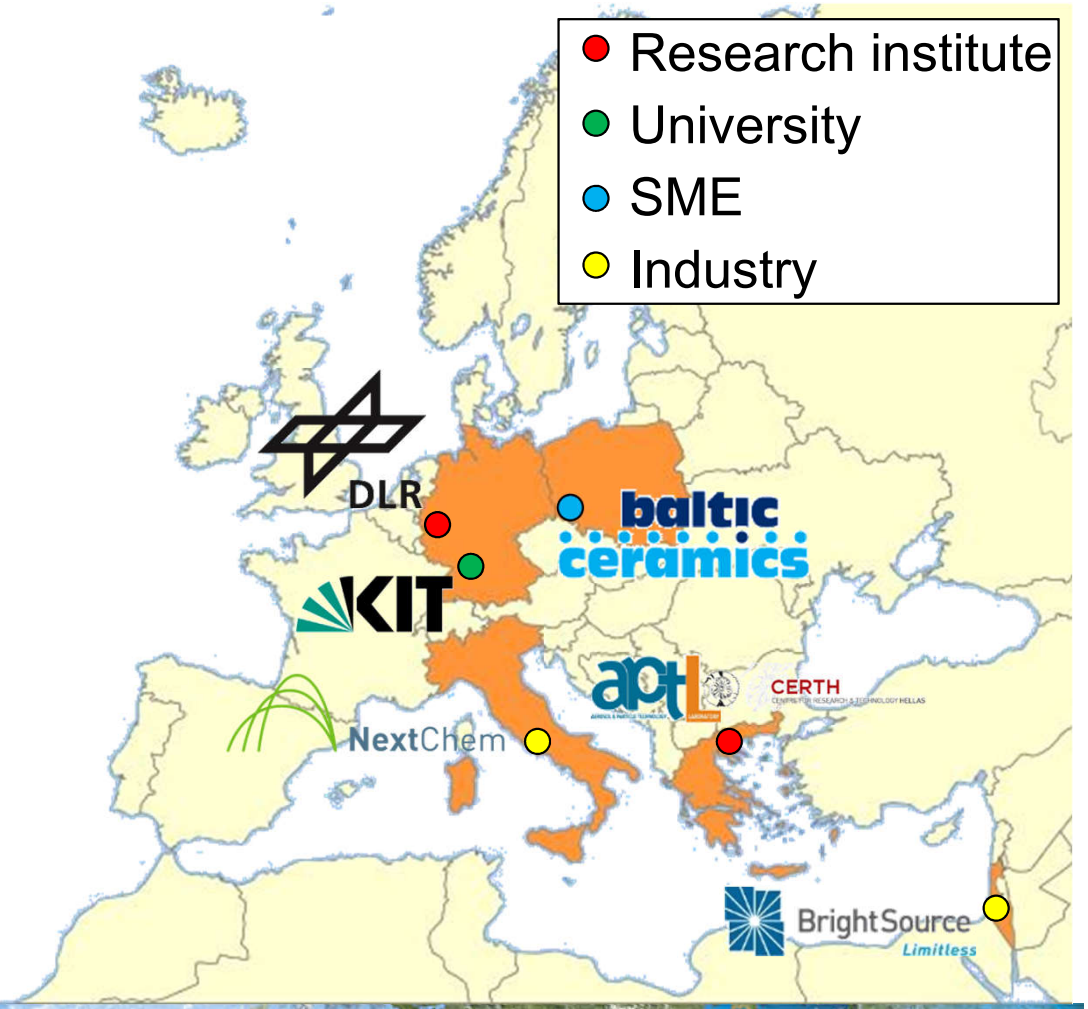
EU-Project PEGASUS (2016-2021) completed

Renewable **P**ow**e**r **G**eneration by Solar P**a**rticle Receiver Driven **Su**lphur **S**torage Cycle

Partners

- **DLR**, Germany (Coordinator)
  - Solar sulphuric acid splitting
- **APTL/CERTH**, Greece
  - Catalyst materials developer
- **KIT**, Germany
  - Combustion specialist
- **Baltic Ceramics***, Poland
  - Advanced ceramics manufacturer
- **NextChem**, Italy
  - Power plant designer/contractor
- **BrightSource**, Israel
  - CSP plant designer/contractor

*) excluded in Aug. 2019

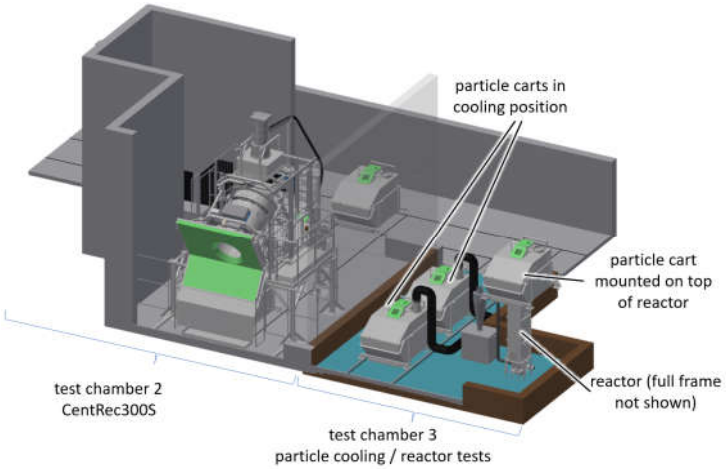


Results:
Centrifugal receiver and particle heat-exchanger

- On-sun capability of prototype centrifugal particle solar receivers demonstrated
- High-temperature particle storage and transport system developed (4 x 1 ton)
- Integrated operation of 300 kW CentRec with particle heat-exchanger prototype under simulated solar irradiation

500 kW prototype
@solar tower Juelich
Temp. **>900°C** achieved

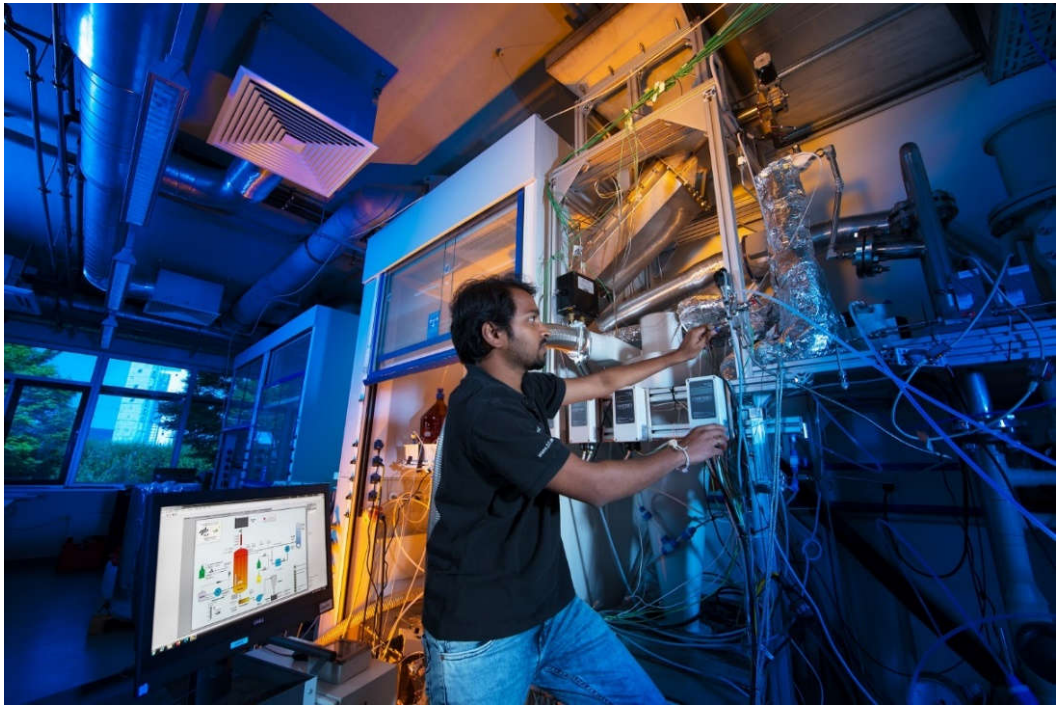
300 kW prototype
@Synlight solar simulator Juelich
efficiency **>80%** achieved

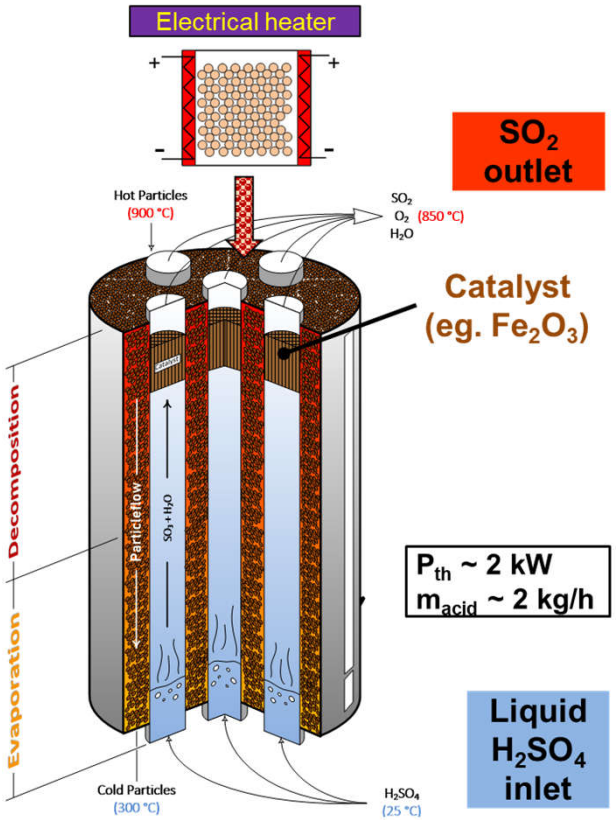


Integrated operation of
300 kW CentRec with
particle heat exchanger

Results:
H_2SO_4 splitting particle reactor

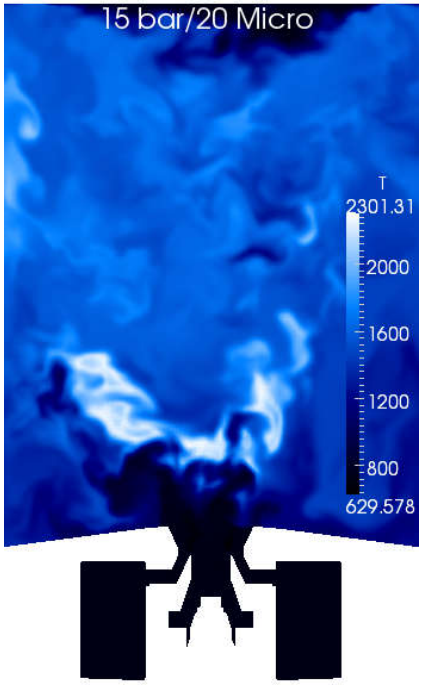
- Laboratory prototype **shell-and-tube** particle reactor for sulphuric acid decomposition cascade employing **moving particle bed**
- **7 kW electrical heater** as heat source achieving **870 °C particle temperature**
- **Thermal efficiency** of **70 %**
- **Chemical conversion** of **mean 44 %** and **max. 86 %**

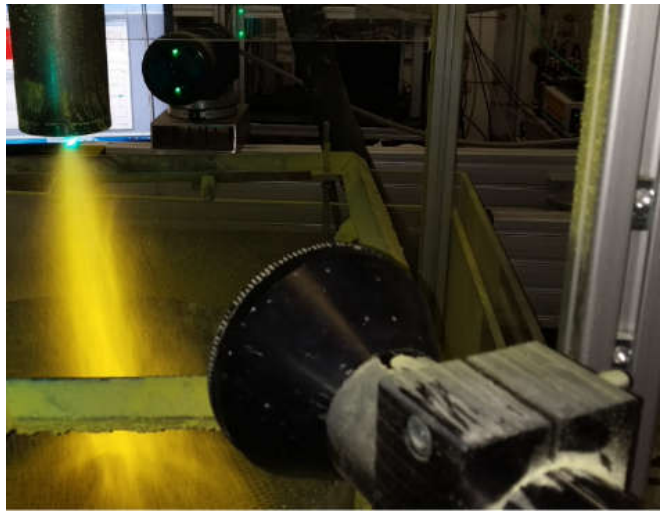




Results:
Sulphur burner prototype for gas turbines

- Novel lab-scale sulphur burner in **10 kW** range able to modulate **up to 15 bar** outlet pressure for gas turbine application



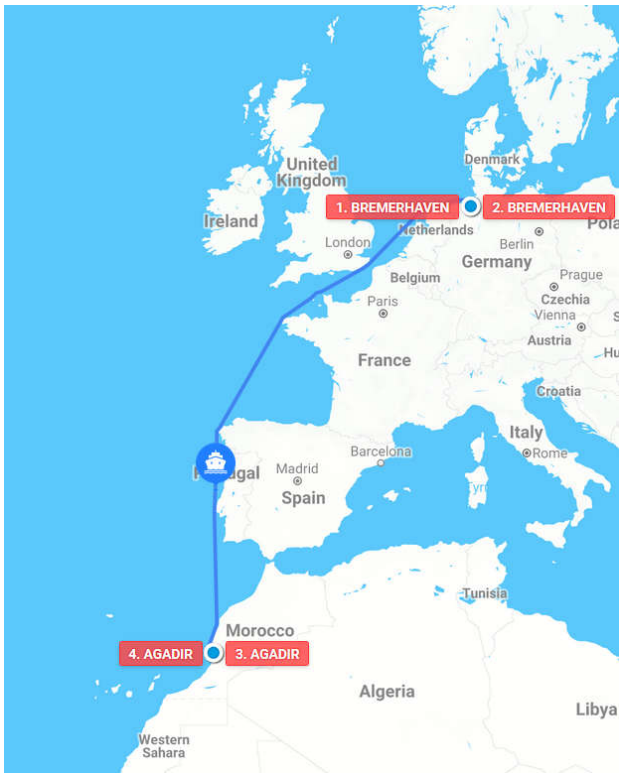


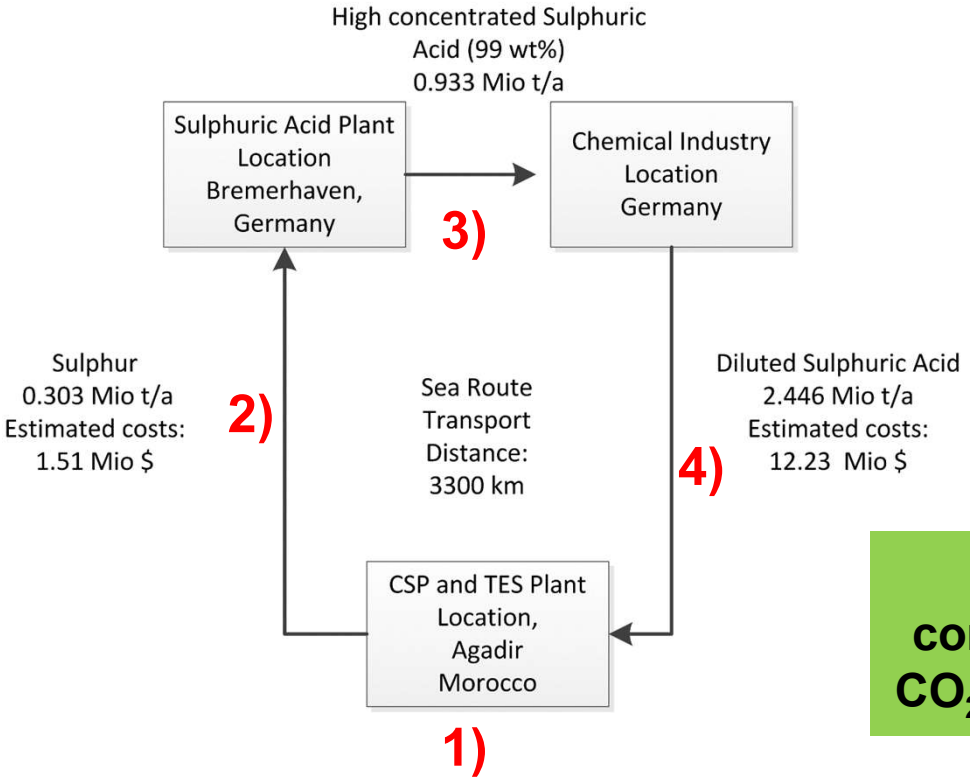
Process simulation and techno-economic evaluation

Concept: Solar sulphur & combined sulphuric acid recycling

Exemplary application for Morocco/Germany

1. Solar recycling of spent sulphuric acid and sulphur production in Morocco
2. Transportation of solar sulphur to Germany
3. Sulphuric acid and baseload electricity production by chemical industry
4. Transportation of spent sulphuric acid back to Morocco





Solar to sulphur
$\eta_{sulphur}$ = 25 %

Solar to electricity
η_{electr} = 8.8 %

Economic competitiveness at CO_2 price of ~130 €/t

Source: A. Rosenstiel 2018

Conclusions and outlook

Conclusions

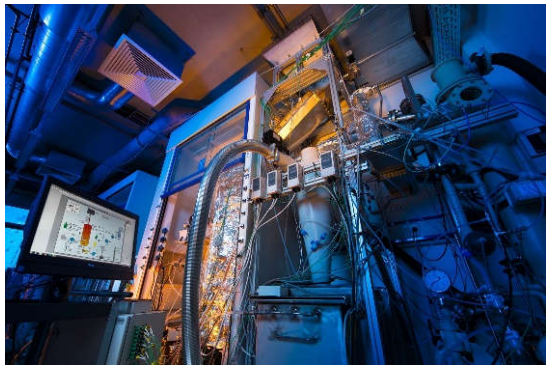
- Sulphur has high thermochemical energy density
- Efficient transportation and storage of solid or liquid sulphur
- Solar sulphur cycle allows for baseload power production
- Potential for integration of sulphur cycle into existing sulphuric acid plants
- Results of European project PEGASUS:
    - Construction and on-sun testing of particle centrifugal receiver prototypes
    - Integrated test operation of CentRec® and particle heat-exchanger
    - Construction and testing of particle reactor for sulphuric acid splitting
    - Prototype testing of sulphur burner for gas turbines
    - Process simulation and techno-economic analysis

Outlook

- Sulphur production via disproportionation investigated by DLR in German national project
- Planning of follow-up European project

Thank you for your attention!

www.pegasus-project.eu



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