Schwefel – Brennstoff für kontinuierliche Solarstromproduktion

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Inhalt

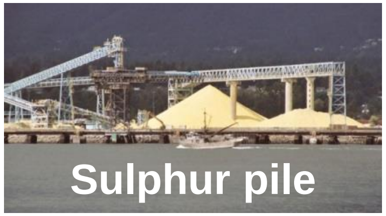
- Schwefel als solarer Brennstoff und thermochemisches Speichermedium
- Kontinuierlicher Solarstrom mittels Schwefel-Kreisprozess
- Expertise des DLR zu Schwefelprozessen
- Aktuelle Forschungsprojekte des DLR
- Zusammenfassung

Vergleich von spezifischen Energiespeicherdichten

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

Schwefel in der Industrie



- Sulphur is required for **sulphuric acid** (SA) production
  - SA is world's most produced chemical
    $\Rightarrow$ 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**

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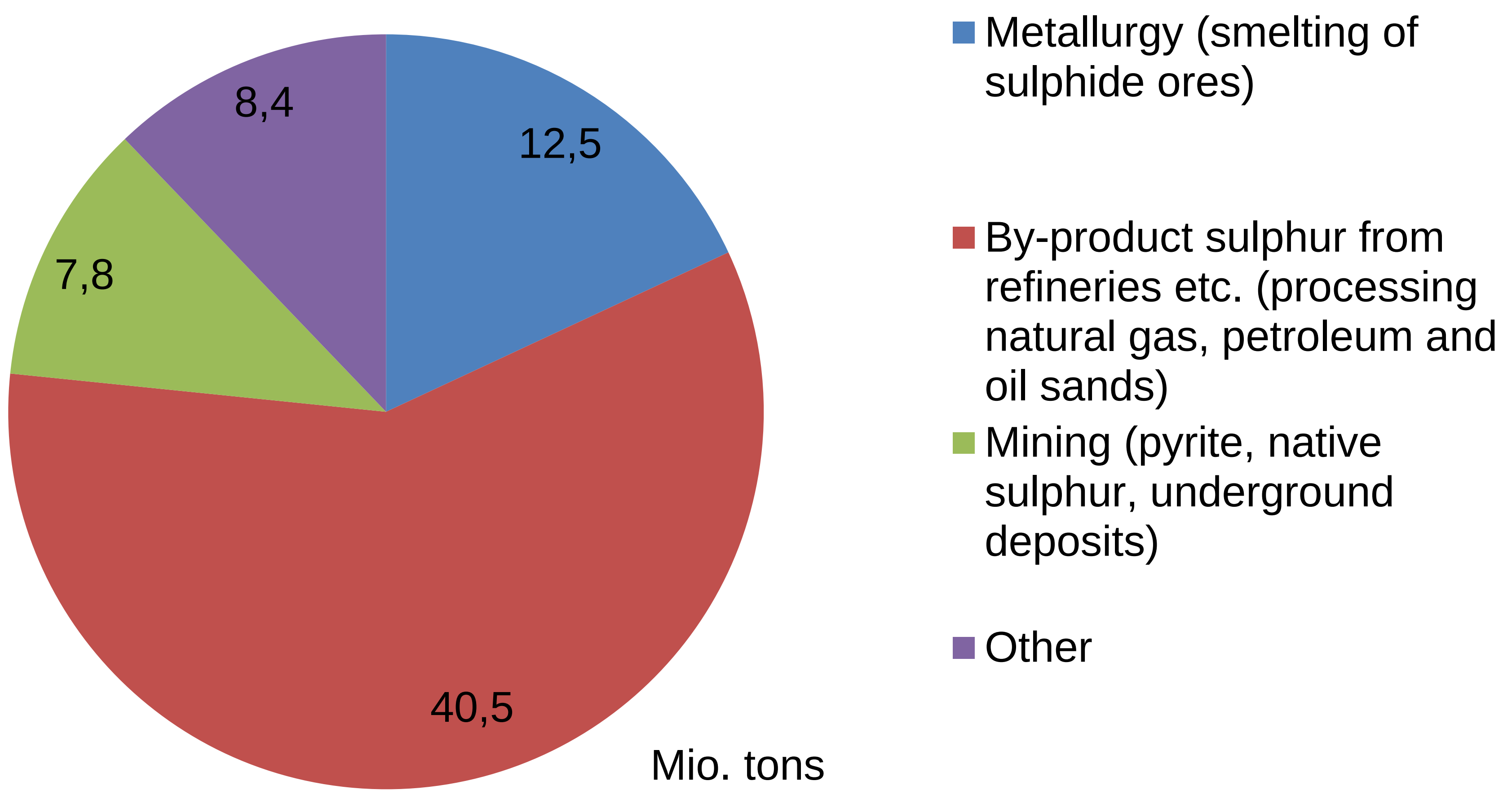
Globale Jahresproduktion an Schwefel (2014)

69 Mio. t (mittlerer Weltmarktpreis von US$160 pro Tonne)



Quelle: 2014 Minerals Yearbook, SULFUR, U.S. Geological Survey

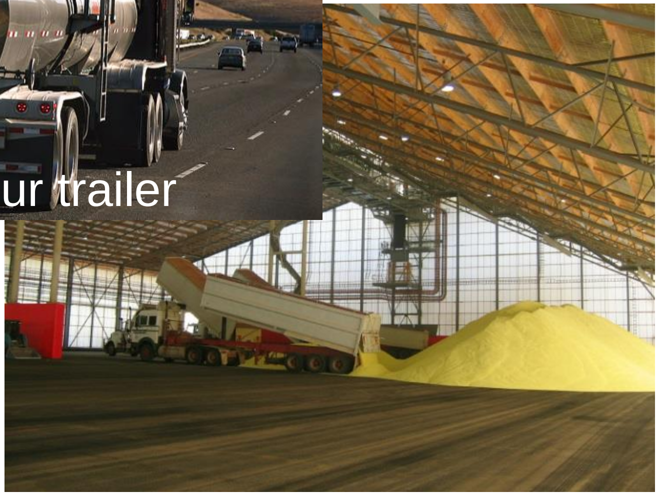
Transport von Schwefel
Als Feststoff oder Flüssigkeit

Train

Pipeline

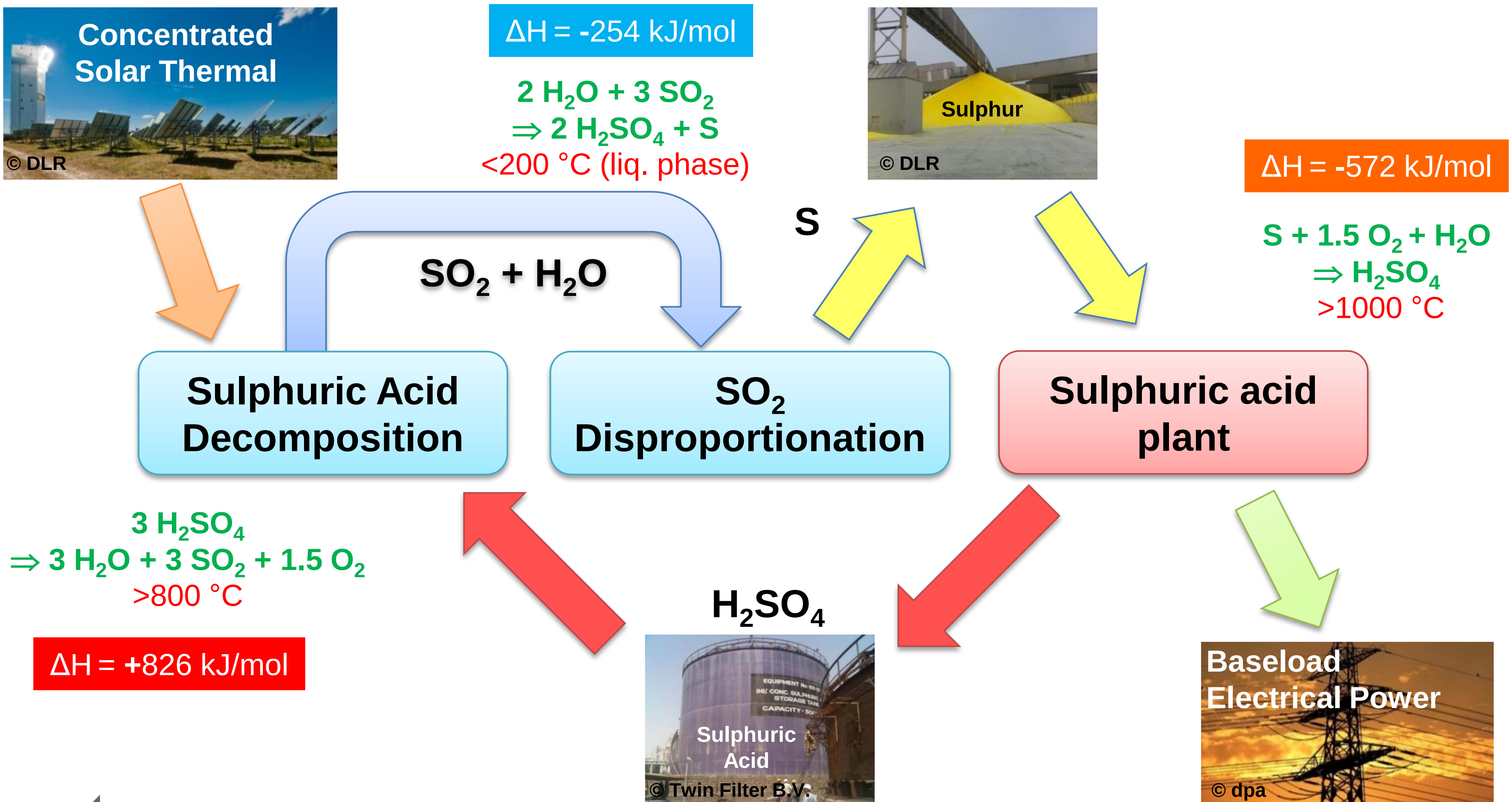
Molten sulphur in heated pipelines (~140 °C)

Truck



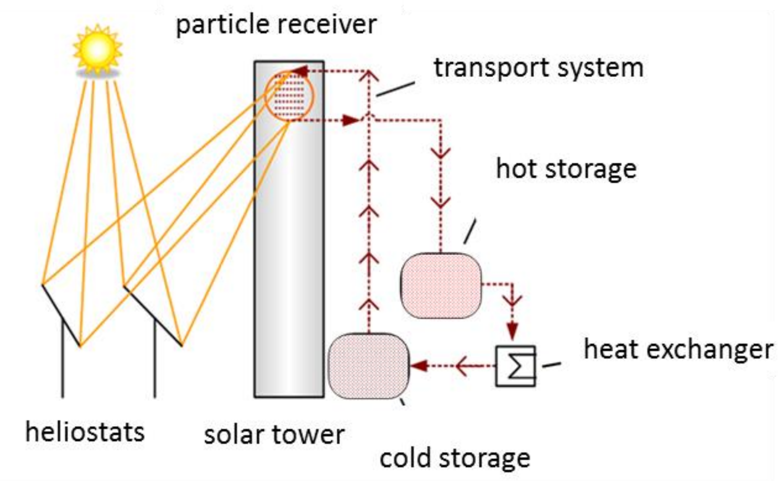
Ship

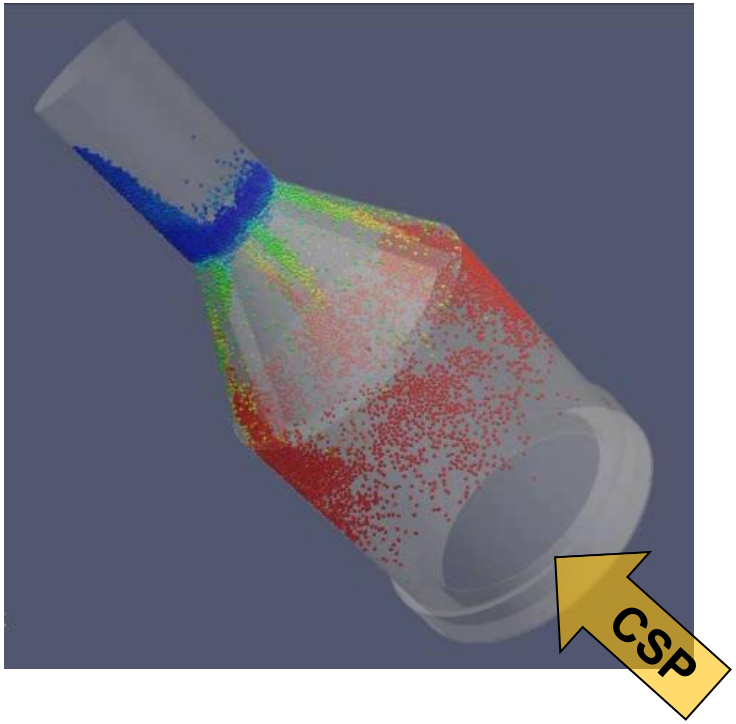
Thermochemischer Schwefelspeicher-Kreisprozess für eine kontinuierliche Solarstromproduktion



Solarpartikel Technologie

- 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

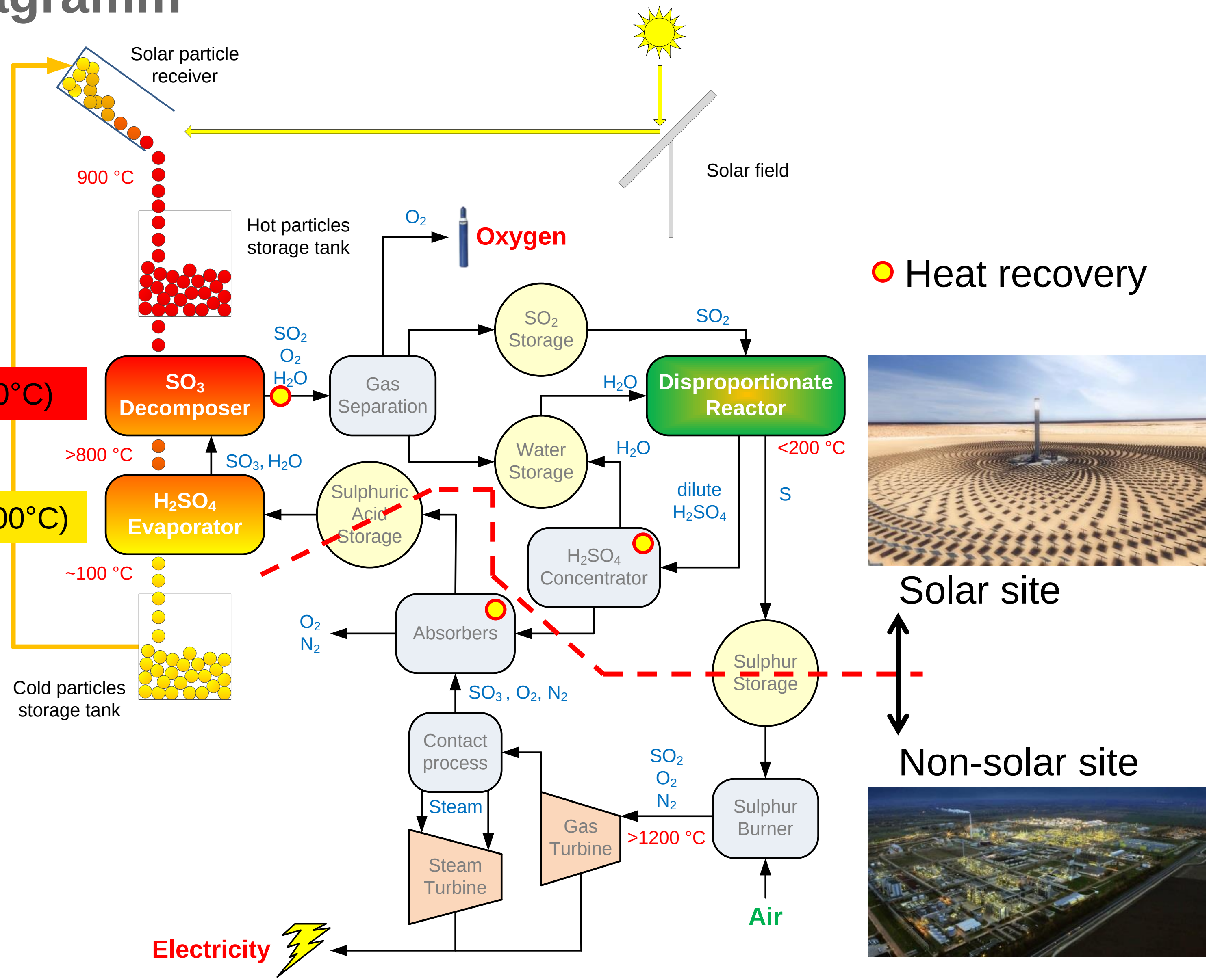




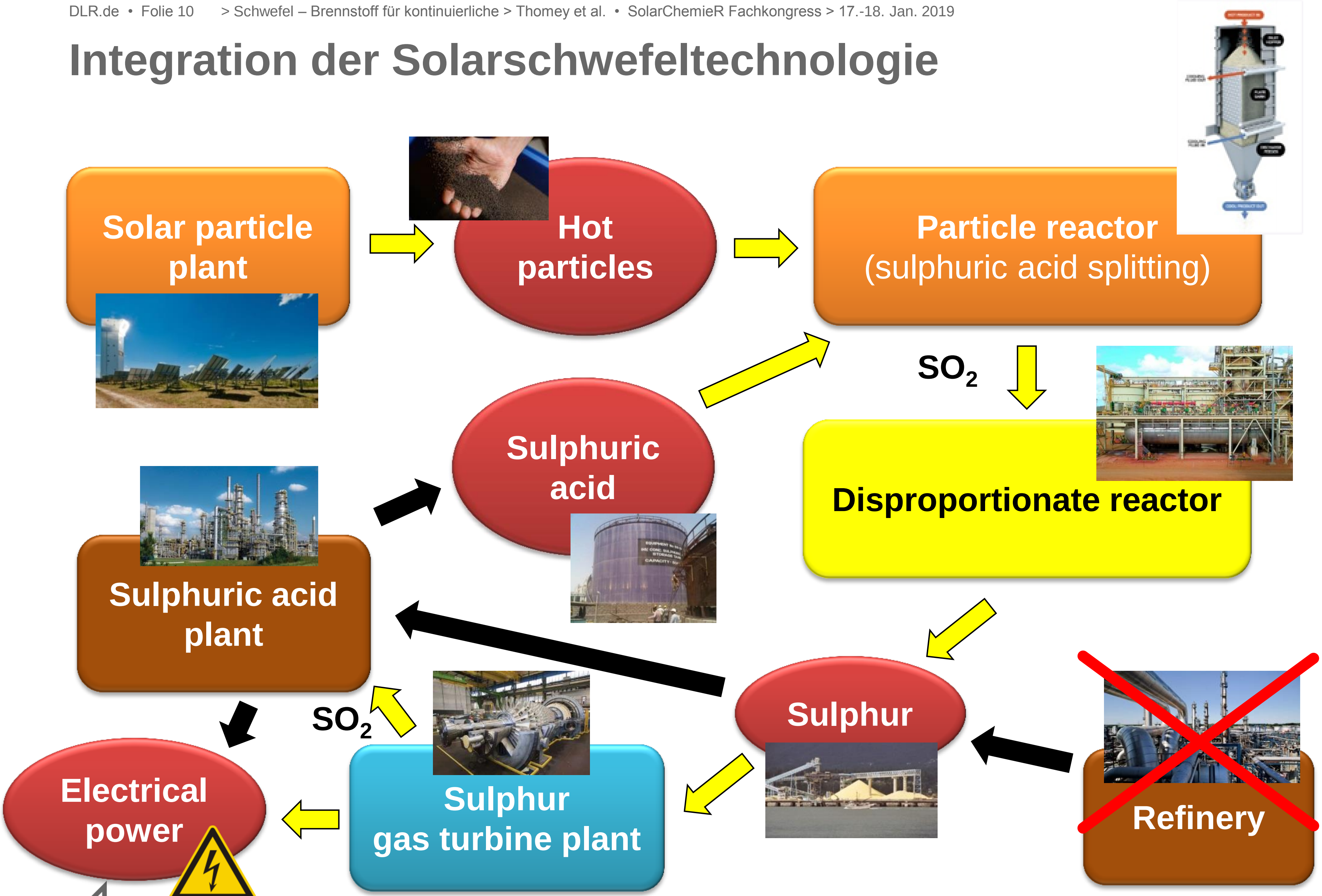
Prozessdiagramm

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

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



Integration der Solarschwefeltechnologie

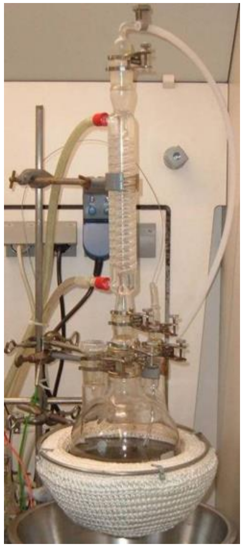


Research at DLR on solar sulphuric acid splitting

- 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

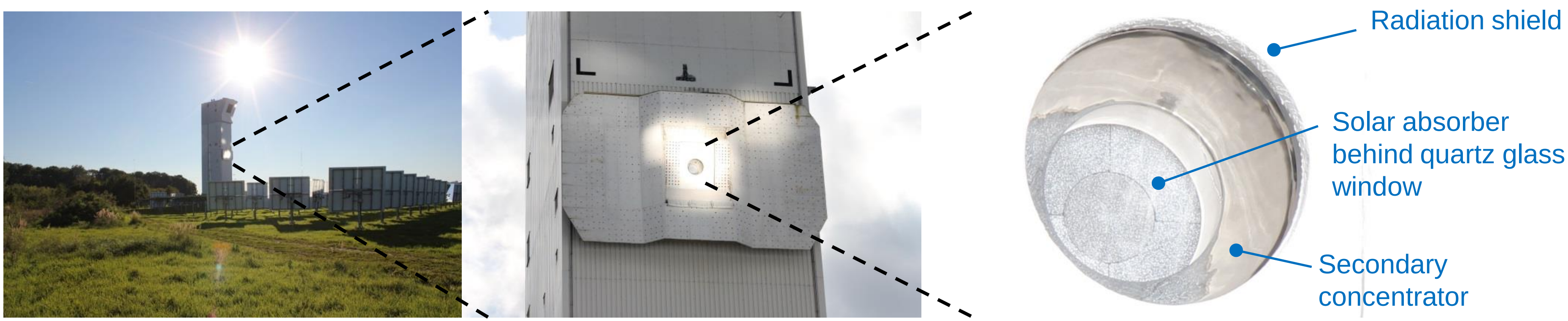


Long-term corrosion test (5000 h)

EU project SOL2HY2

100 kW pilot unit for solar sulphuric acid splitting

- Investigation of solar sulphuric acid splitting as part of Hybrid Sulphur Cycle (HyS) for thermochemical hydrogen production
- Development and test operation of demonstrator for sulphuric acid cracking on research platform of solar tower Juelich in 2015-16
- Detailed modelling solar receiver-reactor and tube-type (electrical) evaporator
- Process simulation and techno-economic analysis of industrial HyS plant



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
  - Total budget of $2.7 Mio.

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

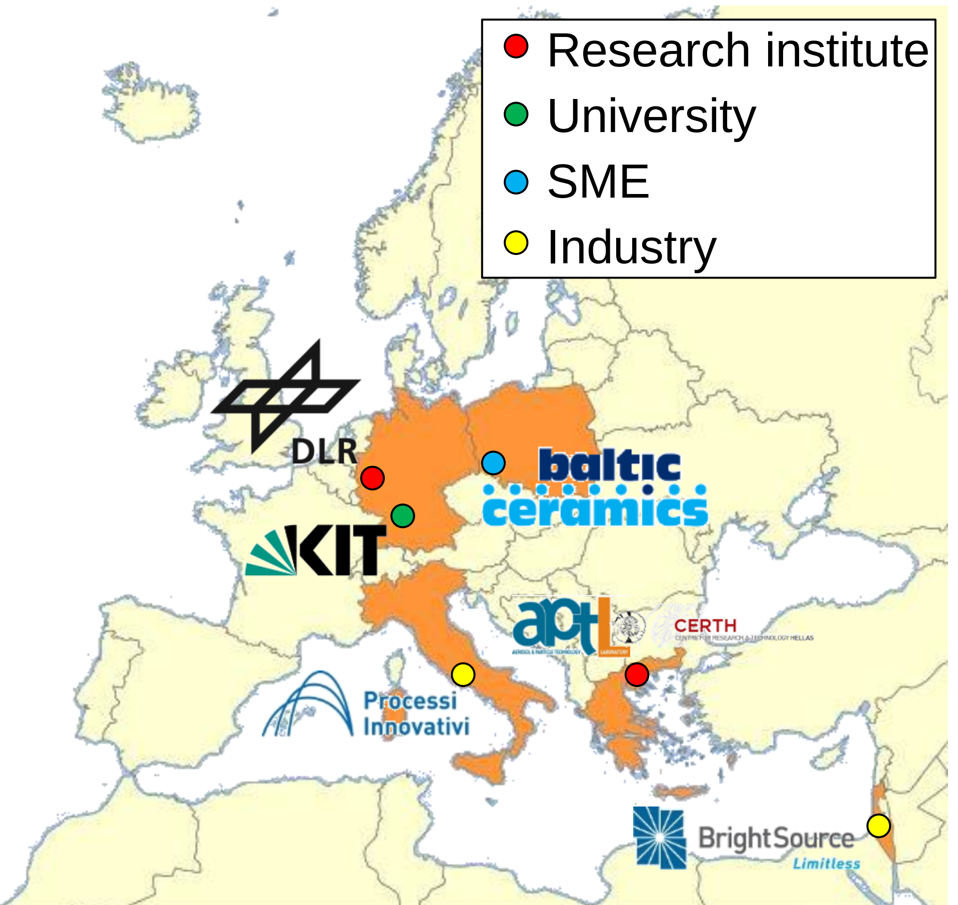
- Subcontractor: German Aerospace Center (DLR)
  - H_2SO_4 decomposition
  - Experiments, modeling
  - Funded work and in-kind contribution

EU-Project PEGASUS (2016-2020)

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

Partners

- **DLR**, Germany (<u>Coordinator</u>)
  - Solar sulphuric acid splitting
- **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



Centrifugal particle solar receiver optimization
Application of pilot receiver developed in CentRec project

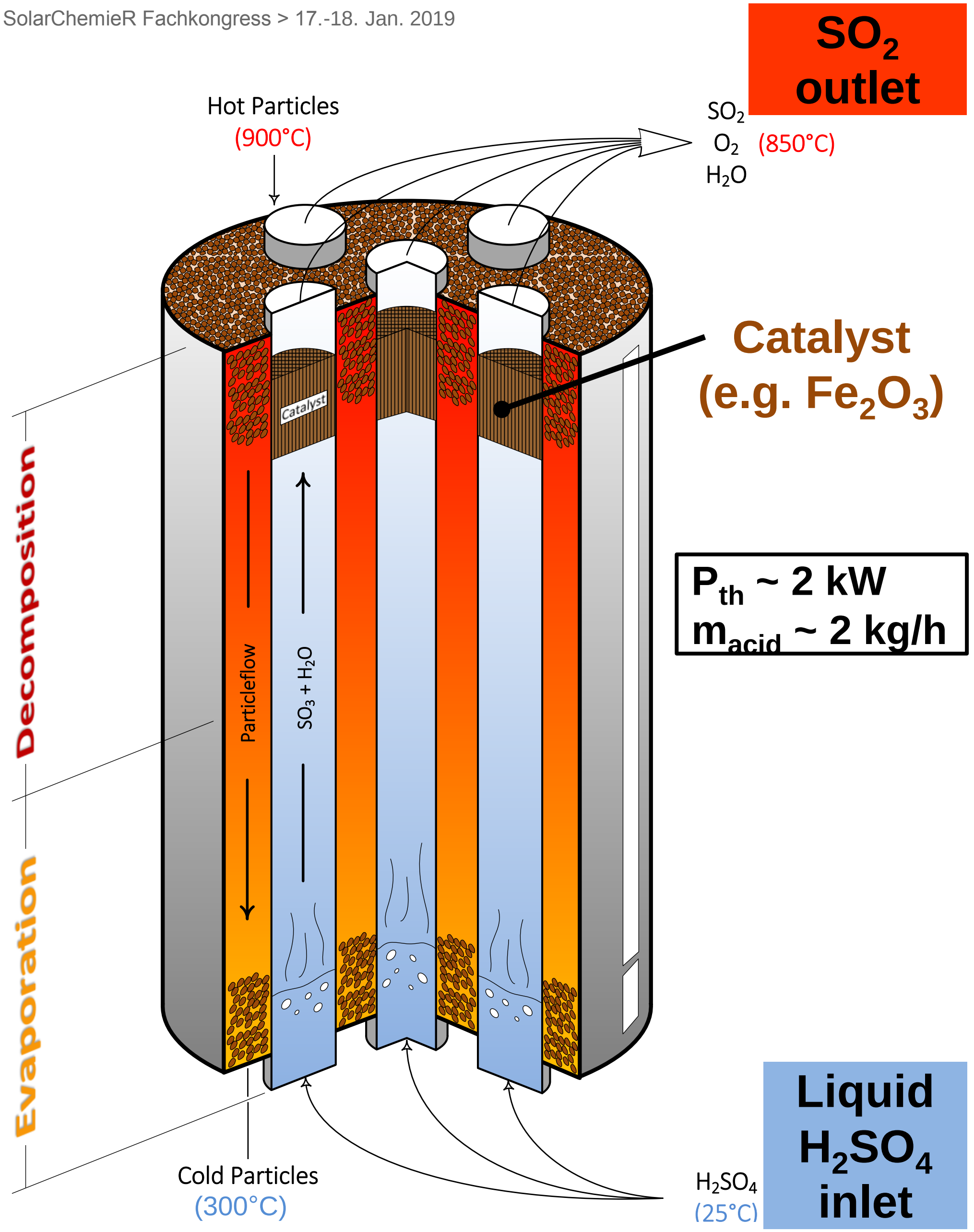
- Centrifugal particle receiver was erected on scaffold in front of Juelich Solar Tower
    - Nominal power: 2.5 MW_{th}
    - Diameter of aperture: 1.13 m
    - Max. particle temperature: 1000 °C
- Commissioning completed
- Solar testing of CentRec from Sep. 2017 to Jun. 2018
    - Milestone $T_{particles,out}$=990 °C reached May 2018

Project PEGASUS

- Solar testing of particles in CentRec pilot in Jun. 2018
    - Stationary operation for receiver model validation
- Integrated testing together with particle reactors for sulphuric acid splitting planned in last project year

Design of particle reactor for sulphuric acid splitting

- Lab scale moving bed reactor
- Indirect contact – particles on the shell-side, fluid on the tube-side
- Evaporation and decomposition in one reactor
- Catalytic material will be placed inside the tubes
- Particles are driven by gravity and controlled via a particle feeder
- Electrical particle heater provide hot non-solar heated particles



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Projektüberblick BaSiS

Bedarfsgerechte Solarstromproduktion mittels Schwefelspeichertechnologie

- Fördergeber: Projektträger Jülich ETN
  - Leitmarktwettbewerb Energieumweltwirtschaft.NRW
- Geplante Gesamtausgaben ~1 Mio. €
- Durchführungszeitraum von 36 Monaten (Aug. 2018 – Jul. 2021)

- Partner:
  - DLR e.V., Köln/Jülich (Koordinator)
  - Hilger GmbH, Wipperfürth
  - Heliokon GmbH, Bergisch Gladbach

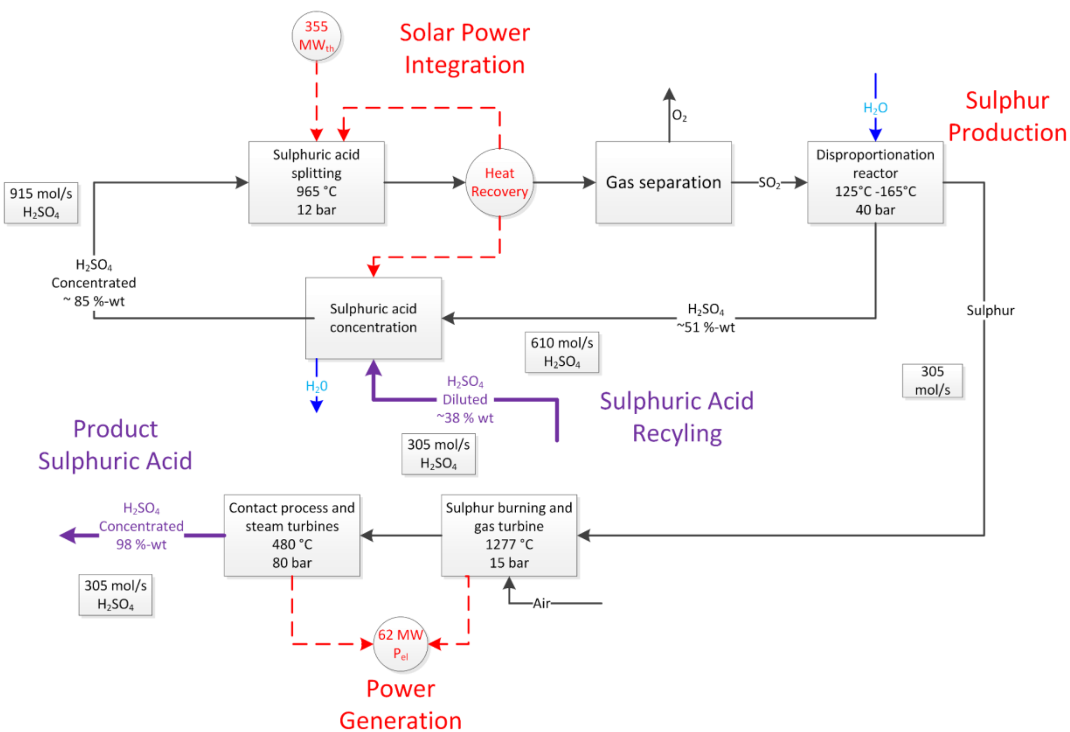
Projekt BaSiS – Zielsetzung

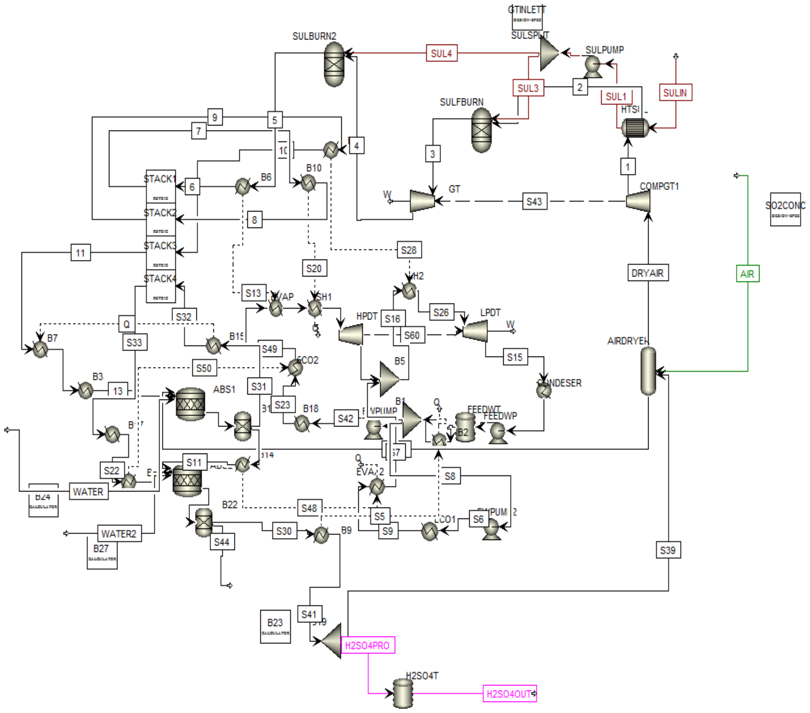
a) Optimierte Schwefelsäurespaltung in druckaufgeladenem Solarpartikelreaktor
b) Maßgeschneidertes Mess-, Steuer- und Regelungssystem für die Partikelströmung
c) Neuartigen Reaktorkonzepte für die kontinuierliche Schwefelerzeugung mittels SO_2-Disproportionierung
d) Umsatzsteigerung der Disproportionierung durch verbesserte Katalysatoren
e) Techno-ökonomie des Schwefelspeicher-Kreisprozesses
f) Skalierungskonzept für die industrielle Anwendung
g) Machbarkeitsstudie und Sicherheitsanalyse

Process simulation of solar sulphur cycle (1)

Flowsheet (Aspen Plus®) and techno-economic analysis

1. Regeneration of spent acid and sulphur production in Morocco
2. Sulphuric acid and electricity production in Germany

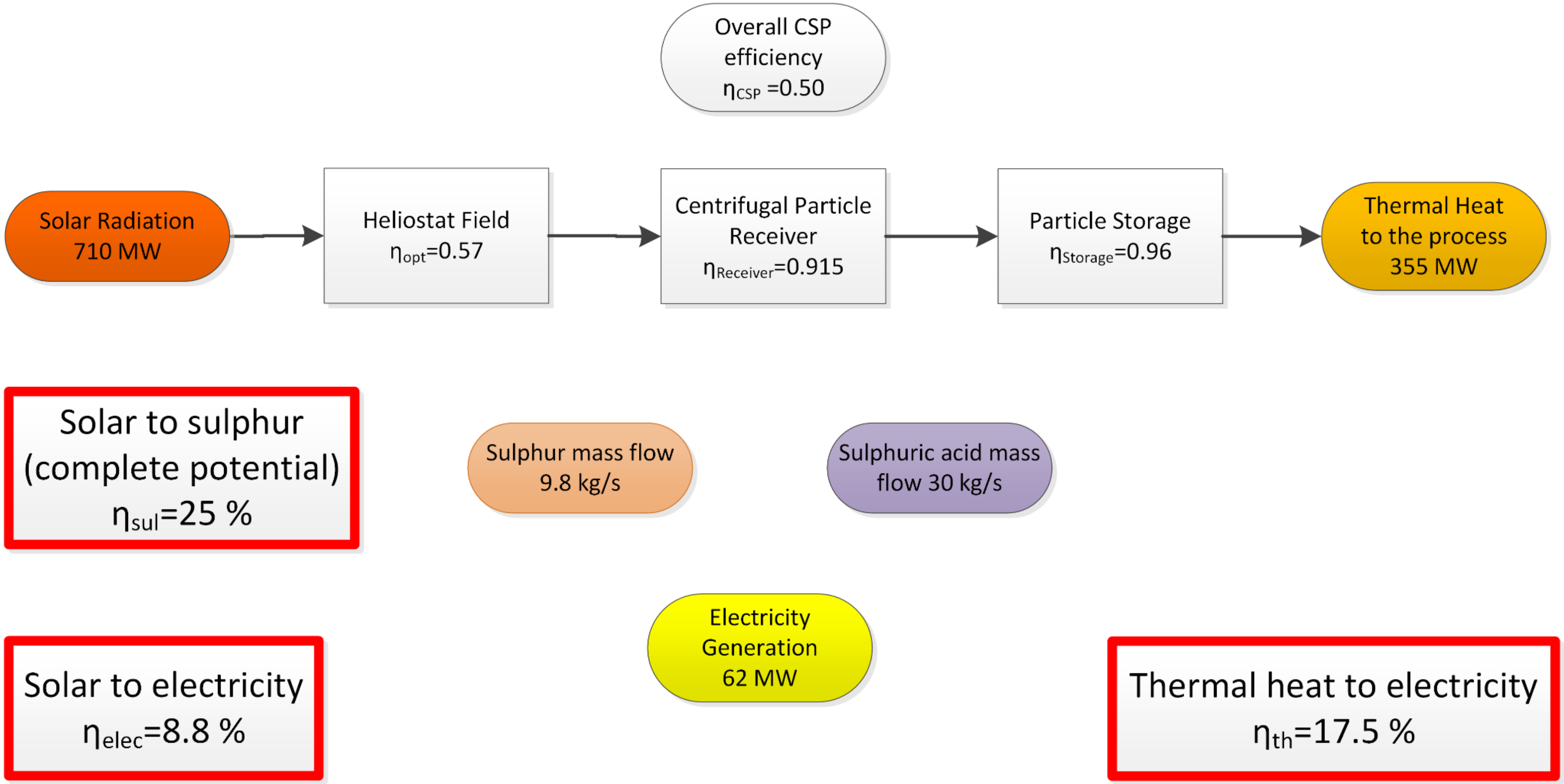




Source: A. Rosenstiel 2018

Process simulation of solar sulphur cycle (2)

Energetic process evaluation: Process efficiencies

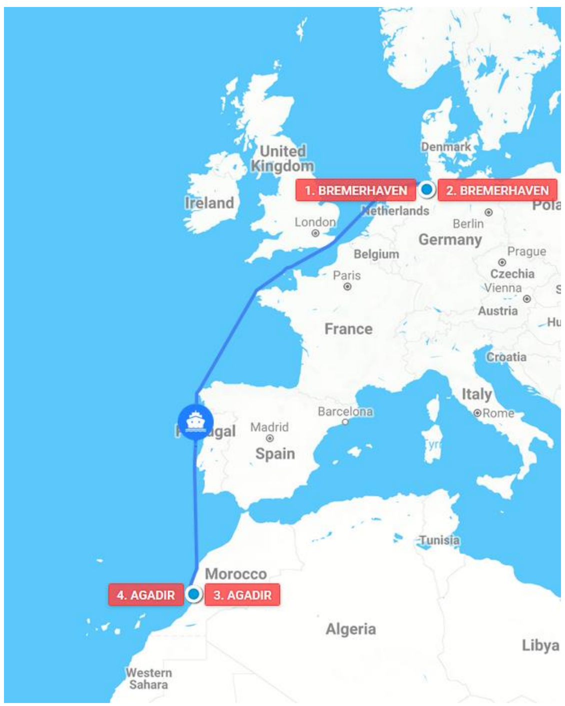


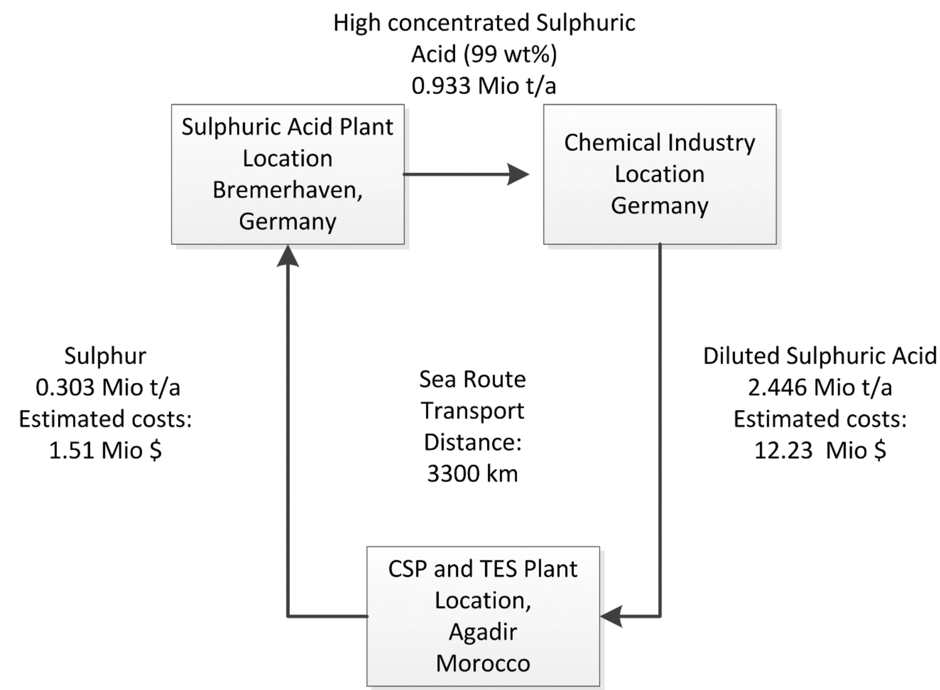
Source: A. Rosenstiel 2018

Process simulation of solar sulphur cycle (3)

Concept: Solar sulphur & combined sulphuric acid recycling

- Sulphuric acid: most produced chemical worldwide (~ 200 Mio t/year)
- Production in Germany (~ 5 Mio t/year)→Usage in chemical industry
- Recycling of H_2SO_4 by thermal splitting (~ 1.2 Mio t/year in Germany), currently by fossil fuels

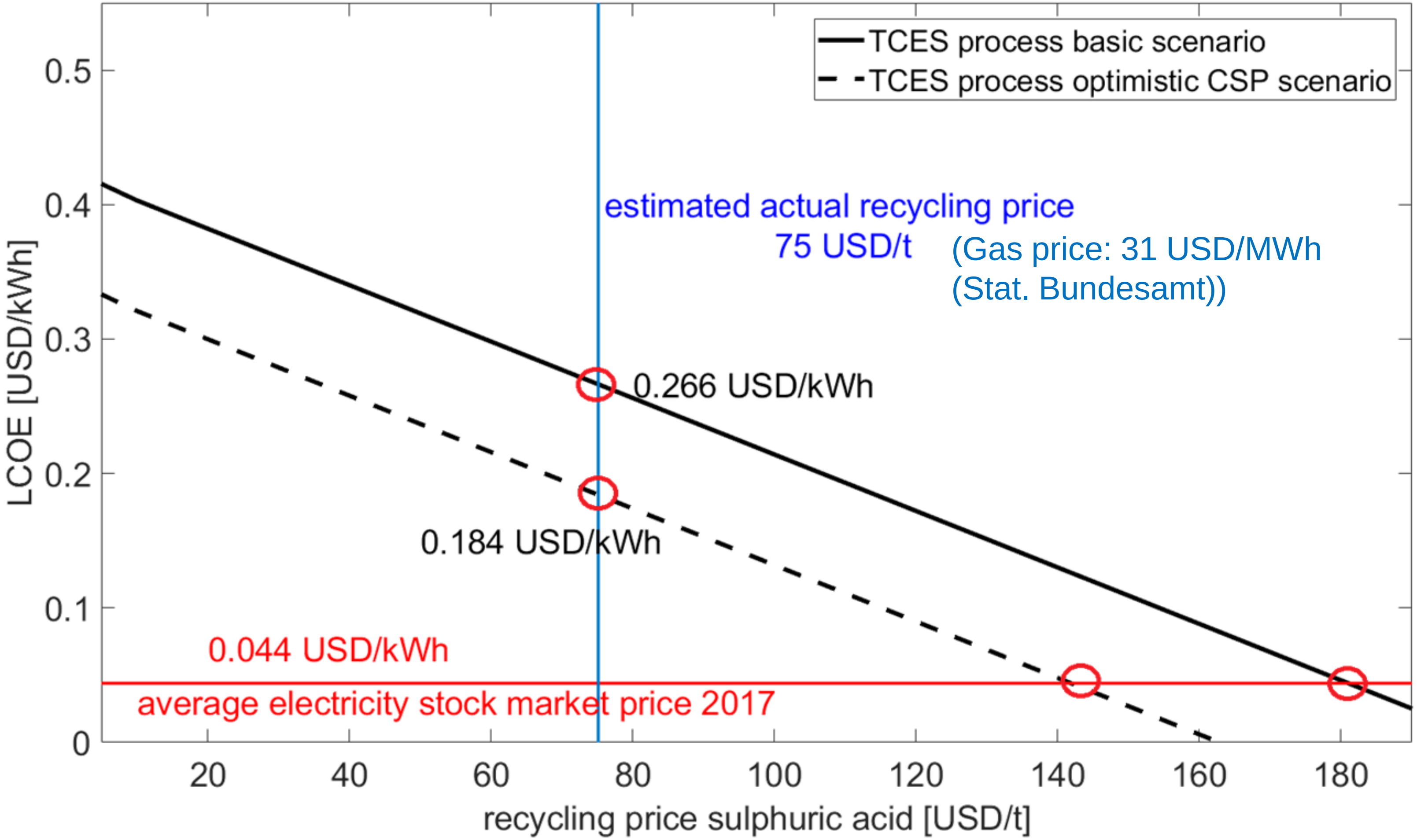




Source: A. Rosenstiel 2018

Process simulation of solar sulphur cycle (4)

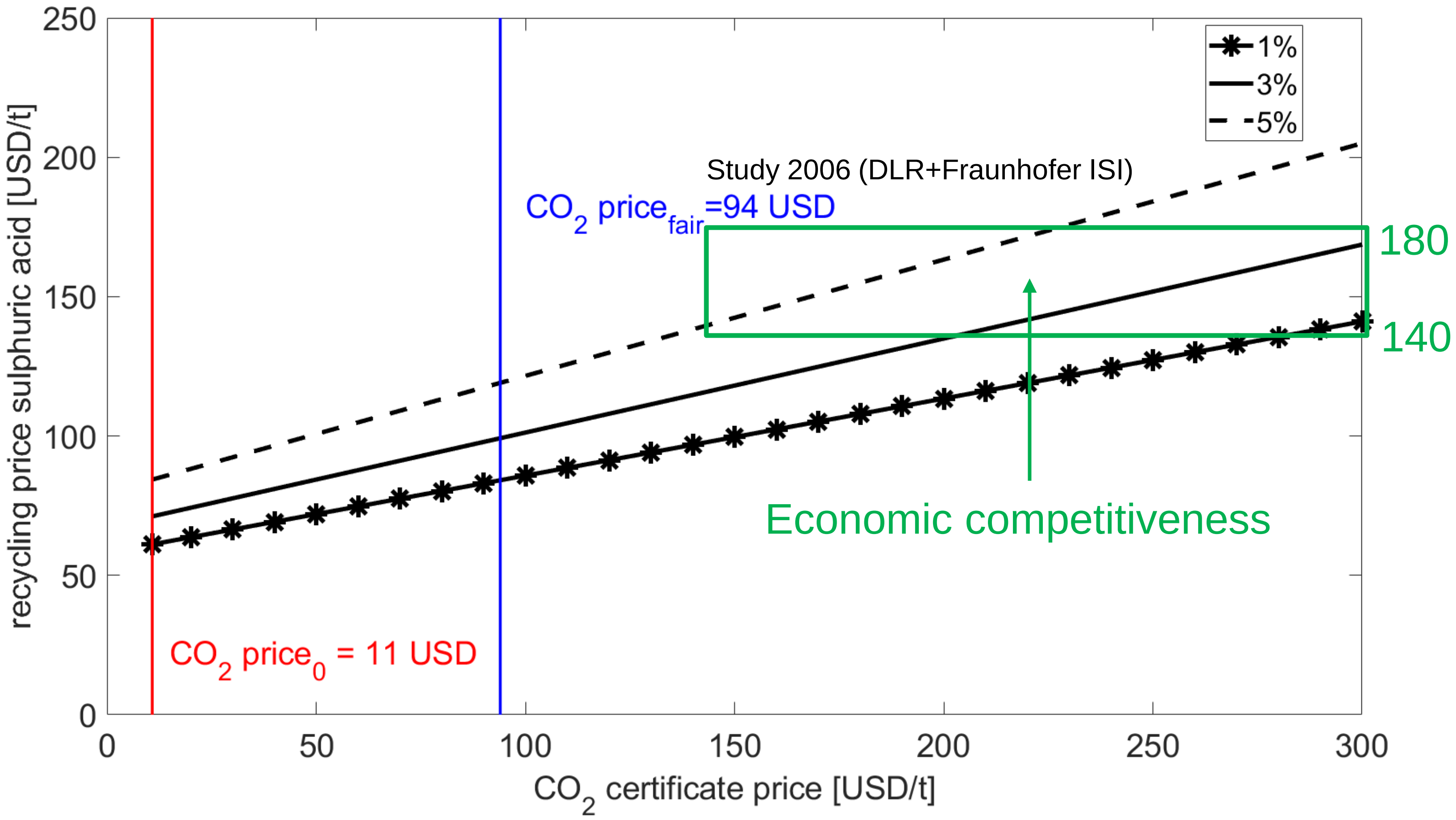
Economic process evaluation: Basic vs. optimistic scenario



Source: A. Rosenstiel 2018

Process simulation of solar sulphur cycle (4)

Economic process evaluation: Effect of CO_2 penalty



Source: A. Rosenstiel 2018

Zusammenfassung

- Schwefel ist eine der bedeutendsten Grundstoffe der chemischen Industrie
- Schwefel hat eine hohe thermochemische Energiedichte
- Transport und Lagerung von Schwefel als Feststoff oder Flüssigkeit ist industrielle Praxis
- Der thermochemische Schwefel-Kreisprozess ermöglicht eine dauerhafte Speicherung von Solarenergie und grundlastfähige Stromproduktion
- Der solare Schwefel-Kreisprozess hat das Potential in existierende Schwefelsäureanlagen integriert zu werden
- EU-Projekt PEGASUS:
    - Entwicklung und Solartest von katalytisch aktiven Partikeln
    - Aufbau es Partikelreaktors zur Schwefelsäurespaltung
    - Prototypentwicklung eins Schwefelbrenners für Gasturbinen
- NRW-Projekt BaSiS:
    - Reaktorentwicklung für SO_2-Disproportionierung
    - Prozesssimulation und Technoökonomische Analyse

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