The EU Horizon 2020 project PEGASUS and its role in the CSP

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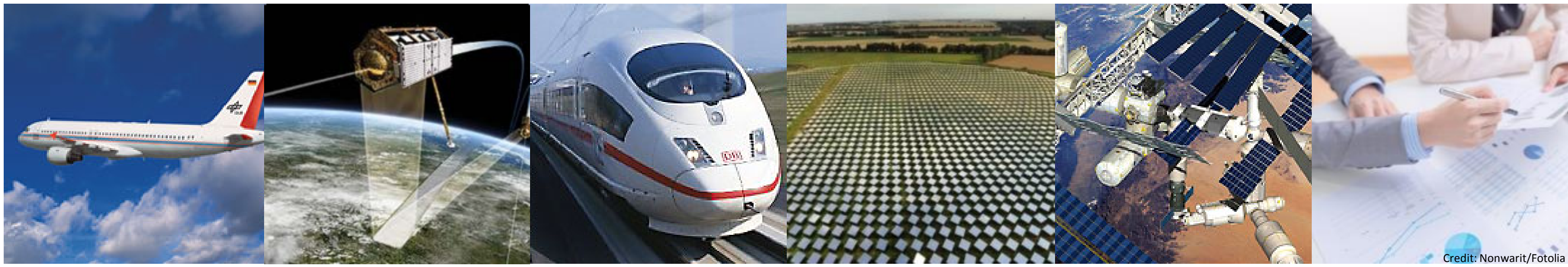
Contents

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

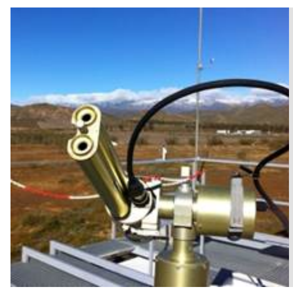
- Heliostats
- High temperature receivers
- System technology

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

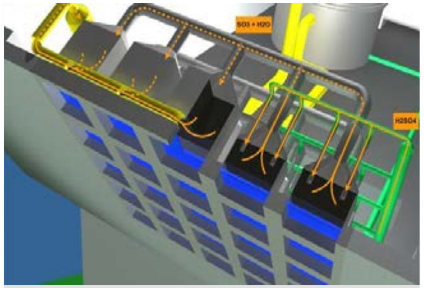
- Solar fuels
- Solar water treatment

Institute of Solar Research
Solar Chemical Engineering

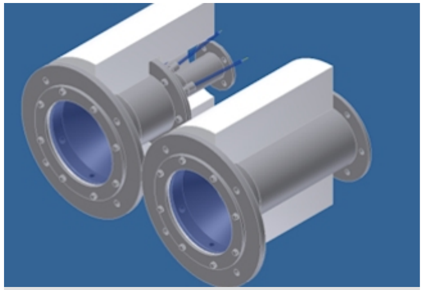
Solar Fuels

Technical development in all dimensions

Solar Plant
- Site assessment
- Solar field simulation
- Environmental impact



Receiver
- Design
- Simulation
- Construction
- Testing
- Next generation development



Receiver Components
- Materials
- Design
- Heat and mass transport
- Simulation
- Testing and Development

Reactive Systems
- Simulation
- Synthesis
- Chemical characteristics
- Physical characteristics

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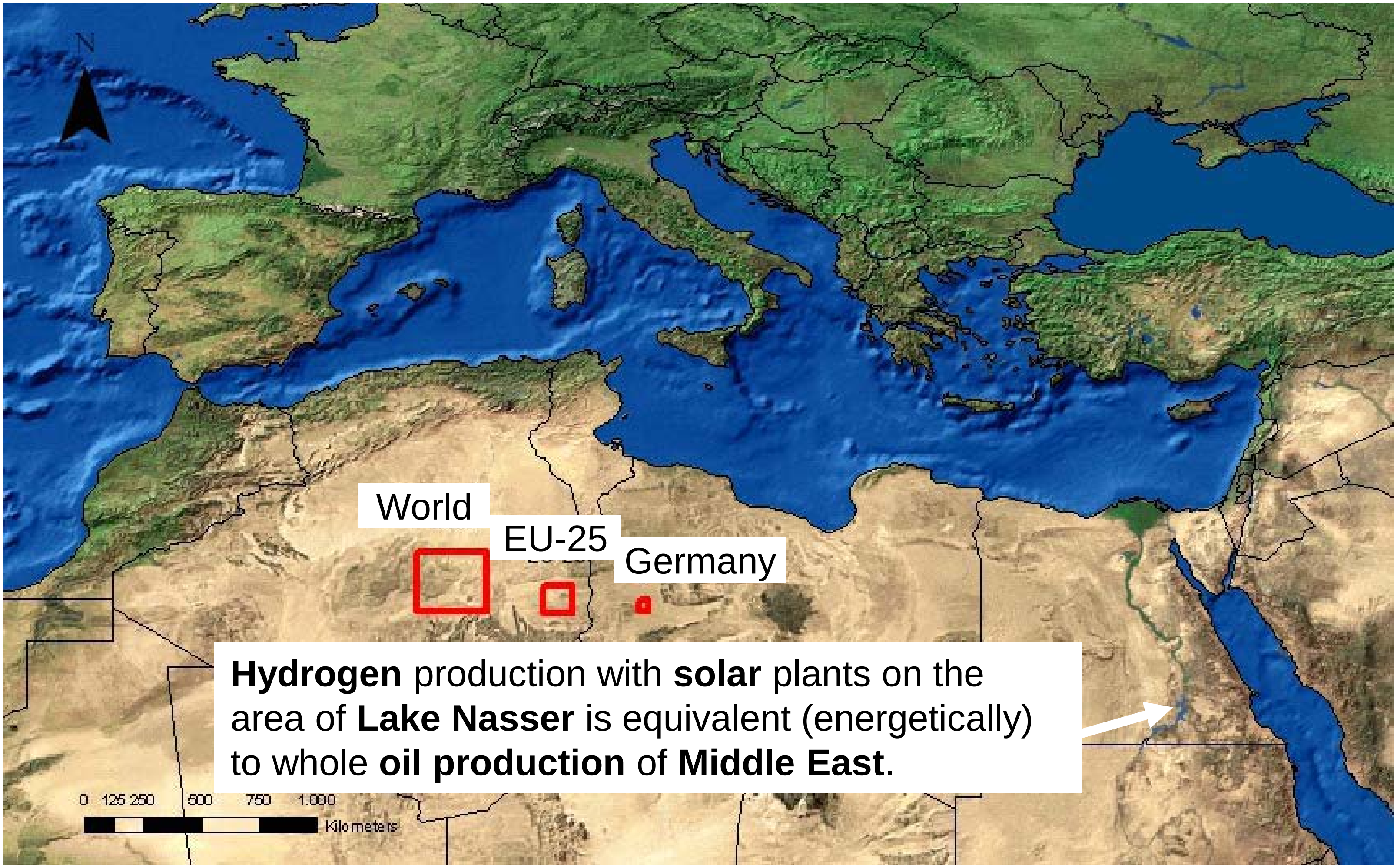
Potential of solar energy



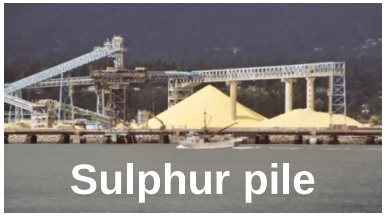
M. Schmitz, TSK Flagsol

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



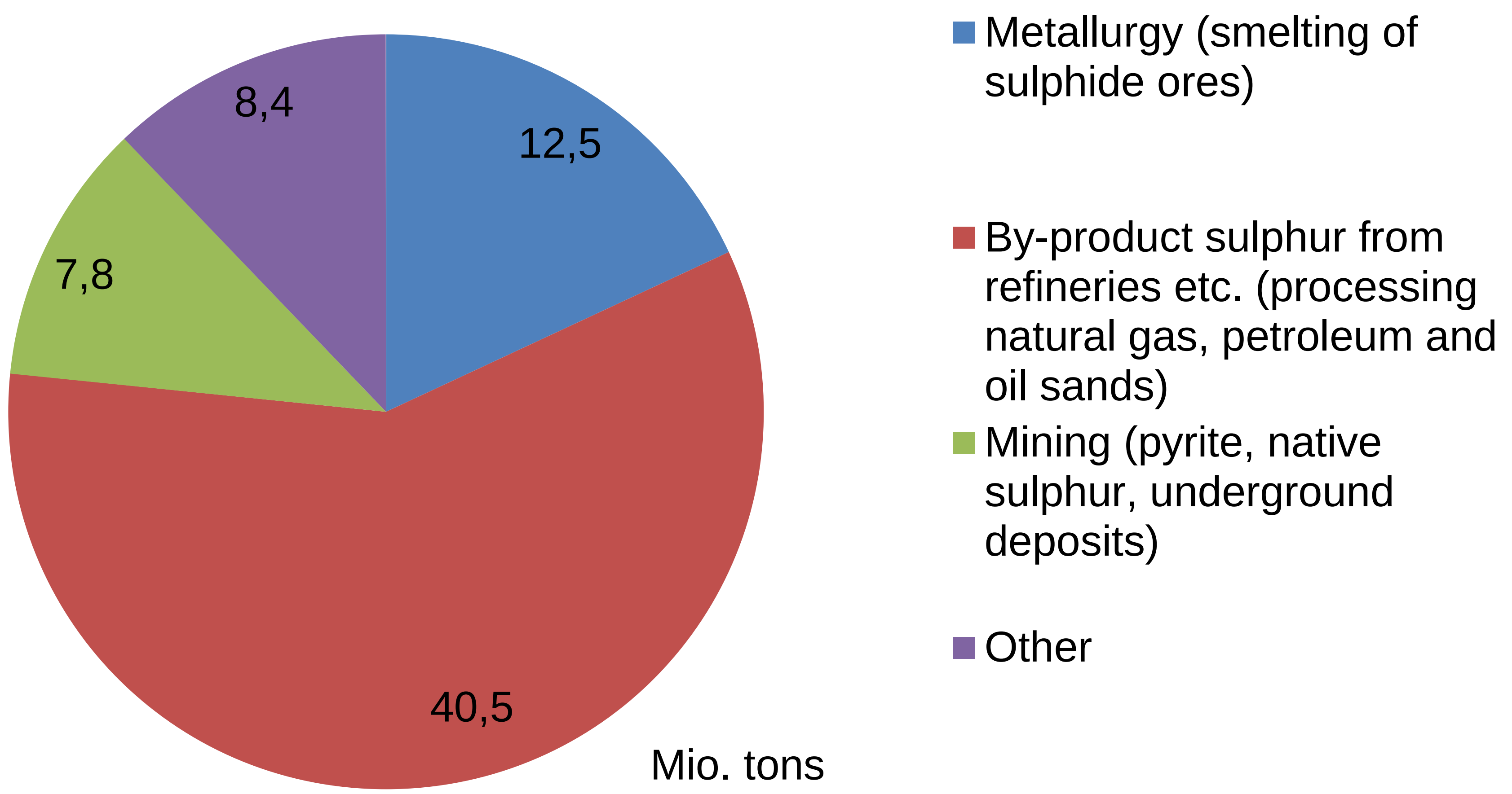
- Sulphur is required for **sulphuric acid** (SA) production
  - SA is world's most produced chemical
    ⇒ Global annual rate **>200 Mio. tons**
  - SA is measure of industrial development
  - SA is mainly needed for **fertiliser production**

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

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

Sulphur world production 2014

Total of 69.1 Mio. tons (avg. world price of US$160 per ton)

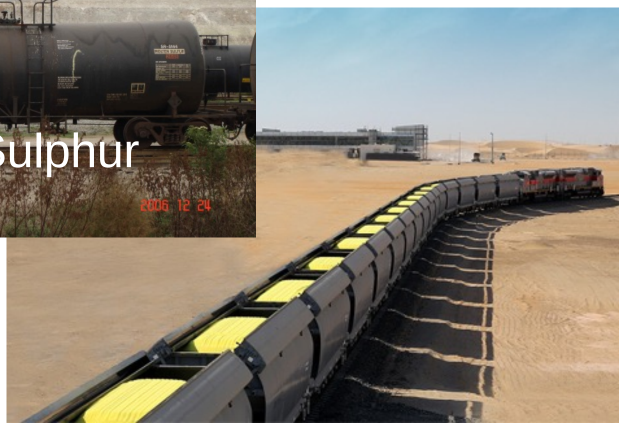


Source: 2014 Minerals Yearbook, SULFUR, U.S. Geological Survey

Transportation and storage of sulphur

In solid or liquid form

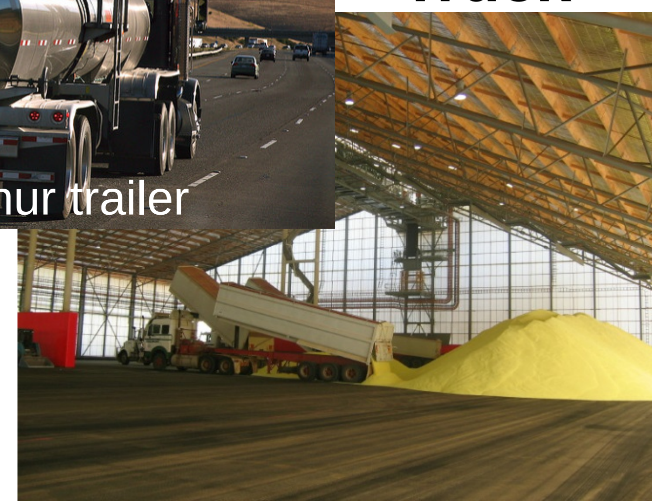
Train



Pipeline

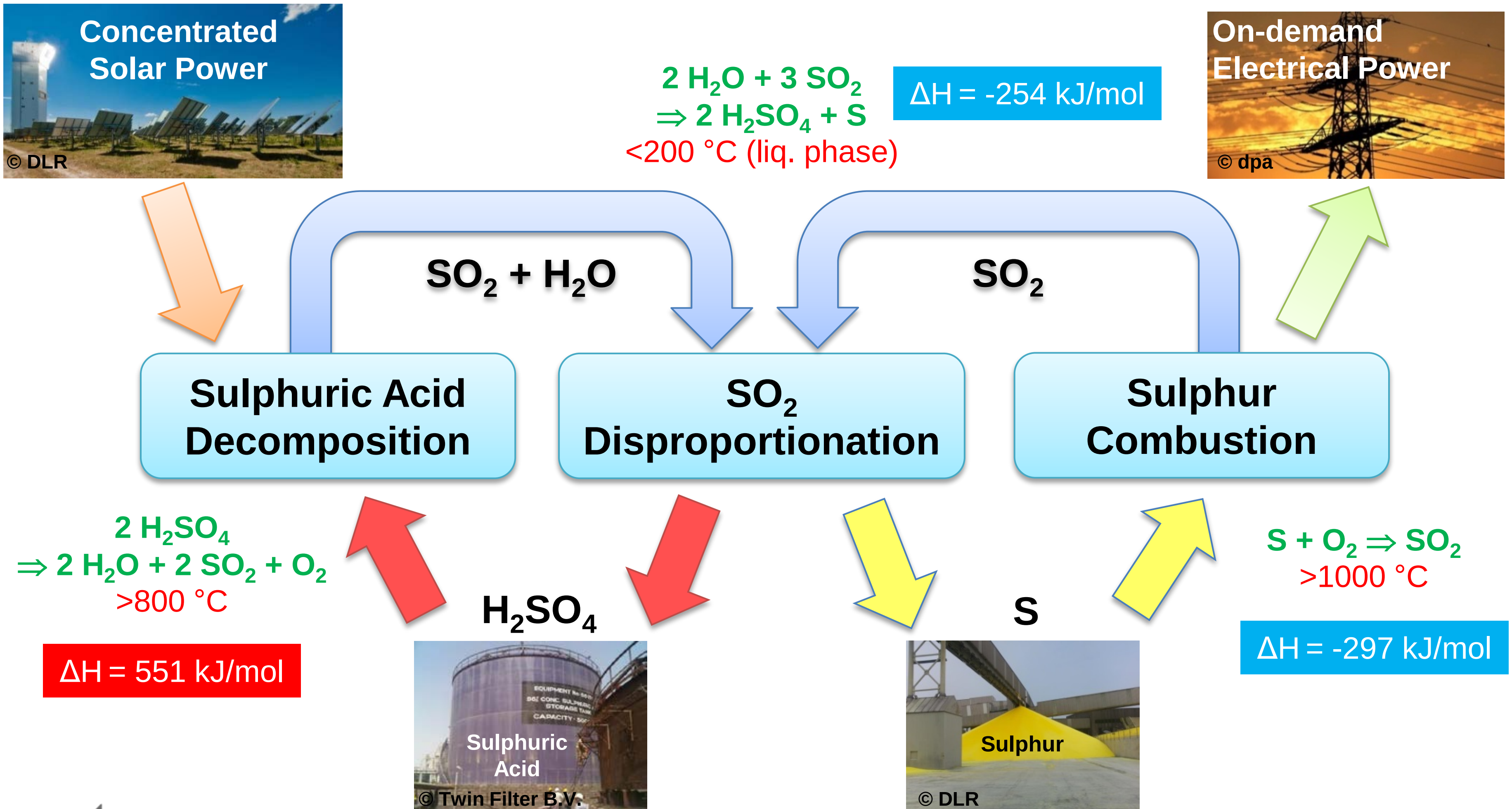
Molten sulphur in heated pipelines (~140 °C)

Truck



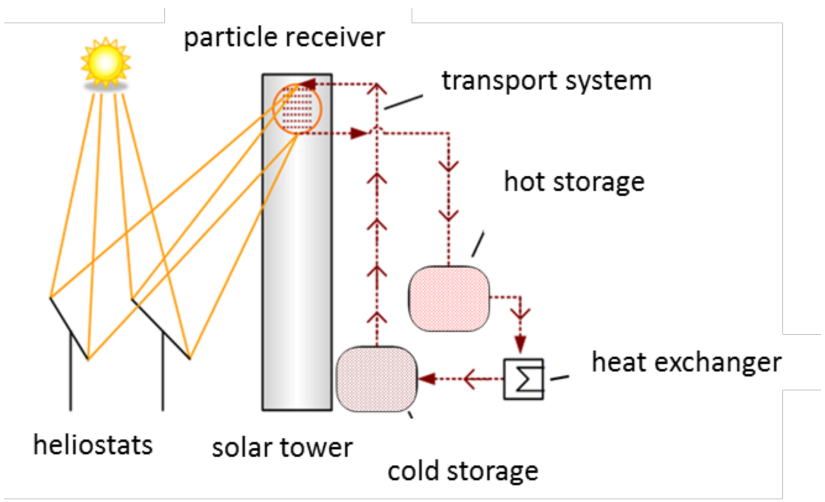
Ship

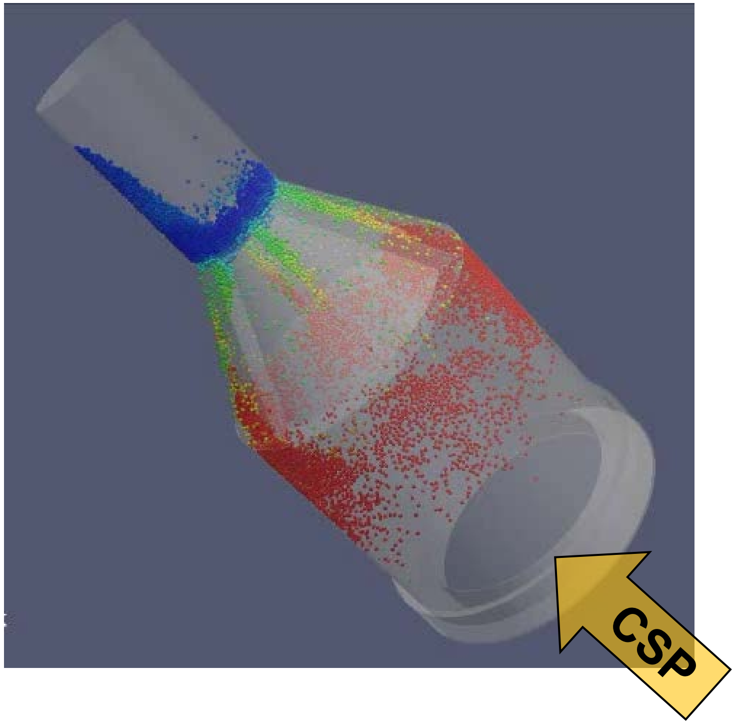
Thermochemical sulfur storage cycle for on-demand solar power production



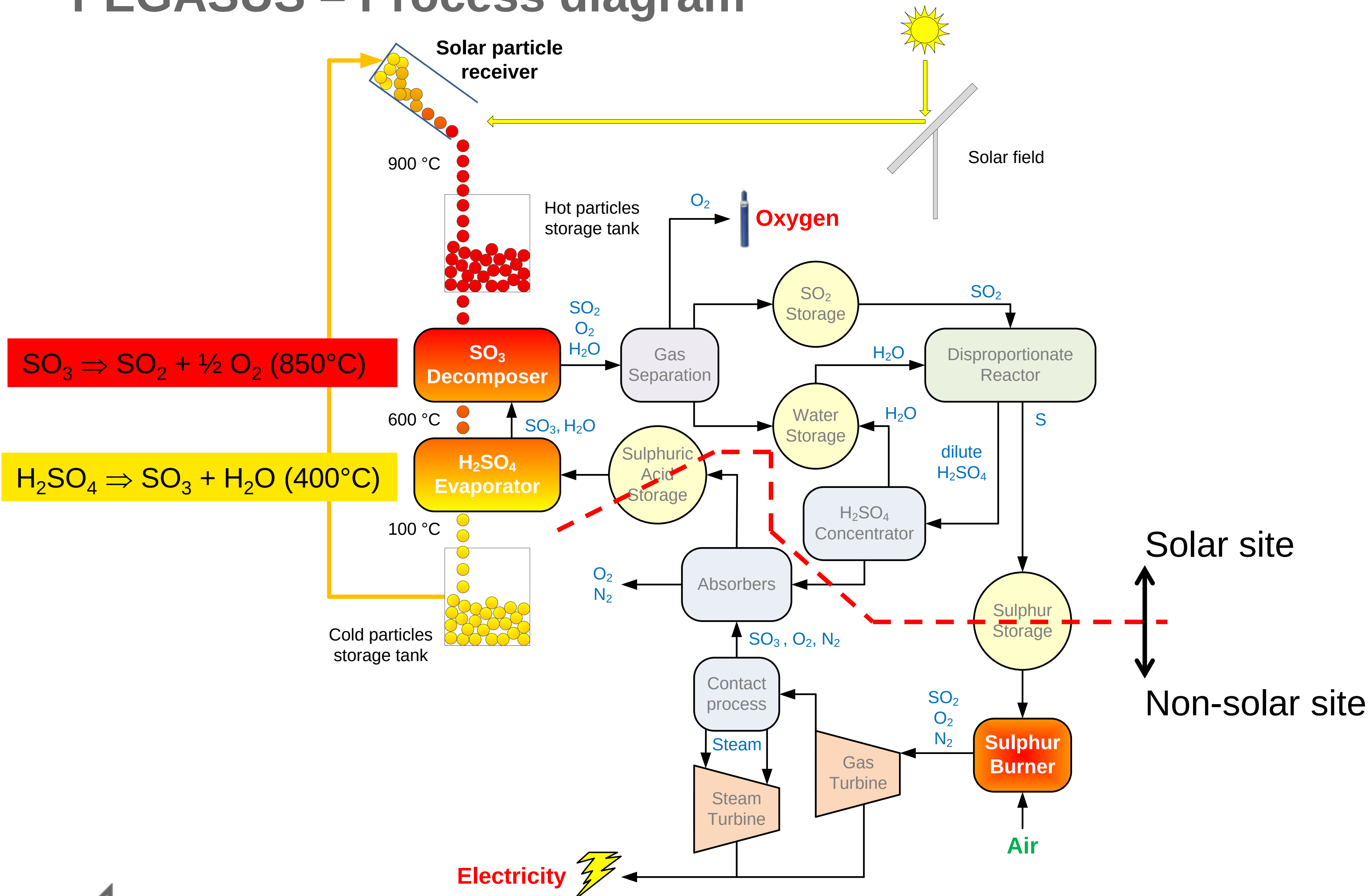
Solar particle technology

- 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

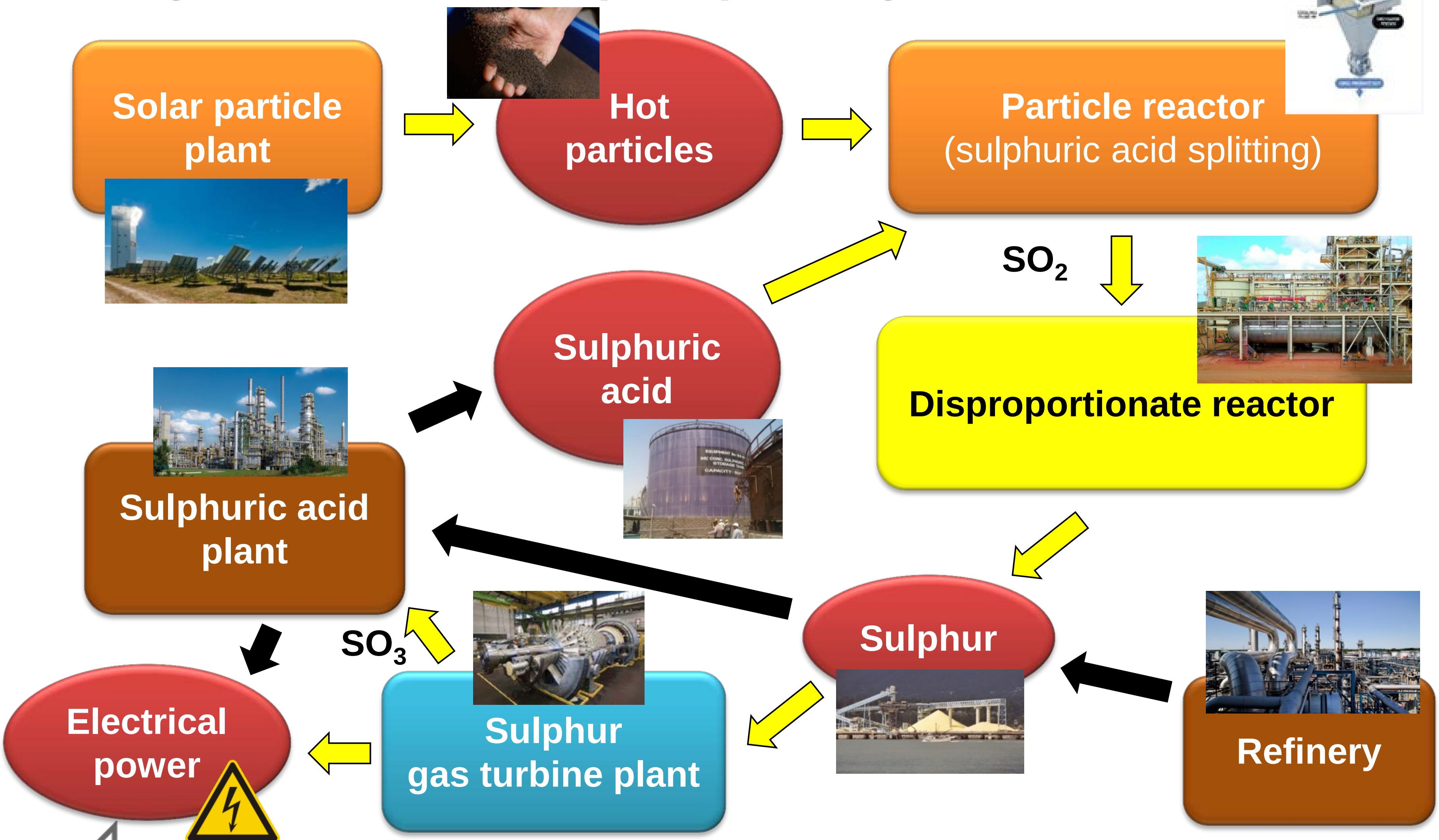




PEGASUS – Process diagram



Integration of solar sulphur power generation



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

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

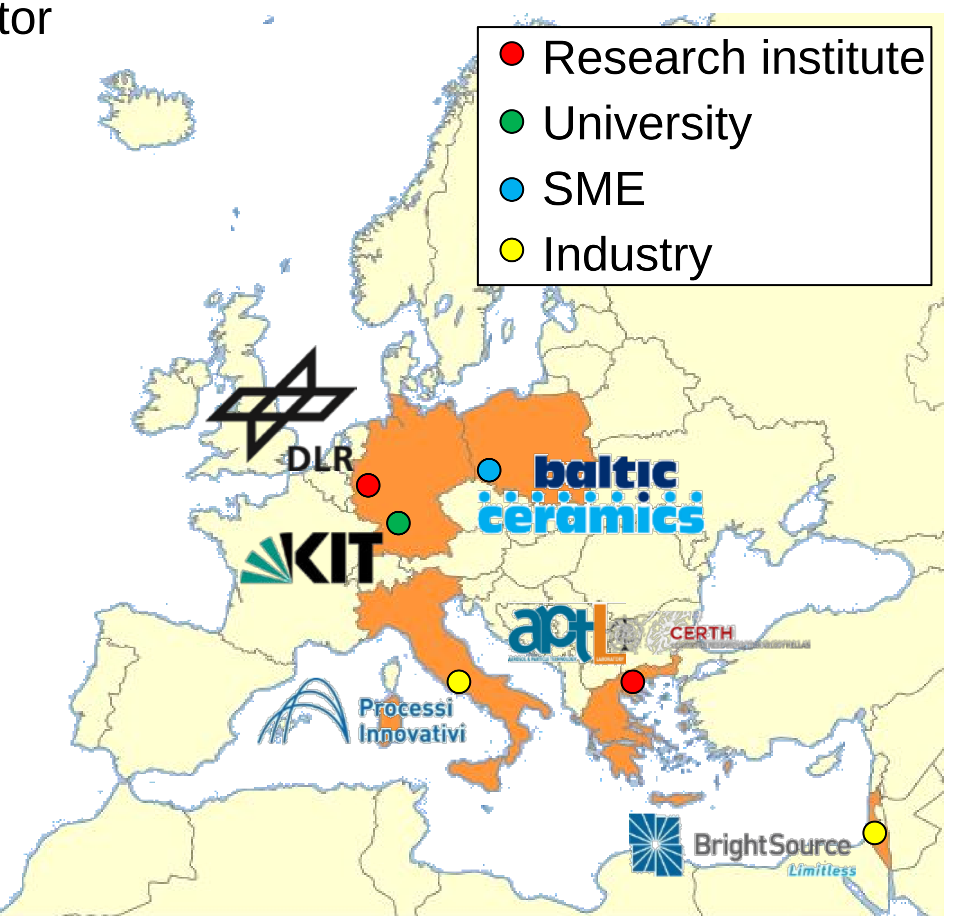
- Funding: United States Department of Energy (DOE)
  - 2 project phases from 2010 to 2013
  - GO/NO-GO review after phase I
  - Phase I completed in Mar. 2012
  - GO recommendation for Phase II (May 2012 – Oct. 2013)

- 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 (<u>Coordinator</u>)
  - 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

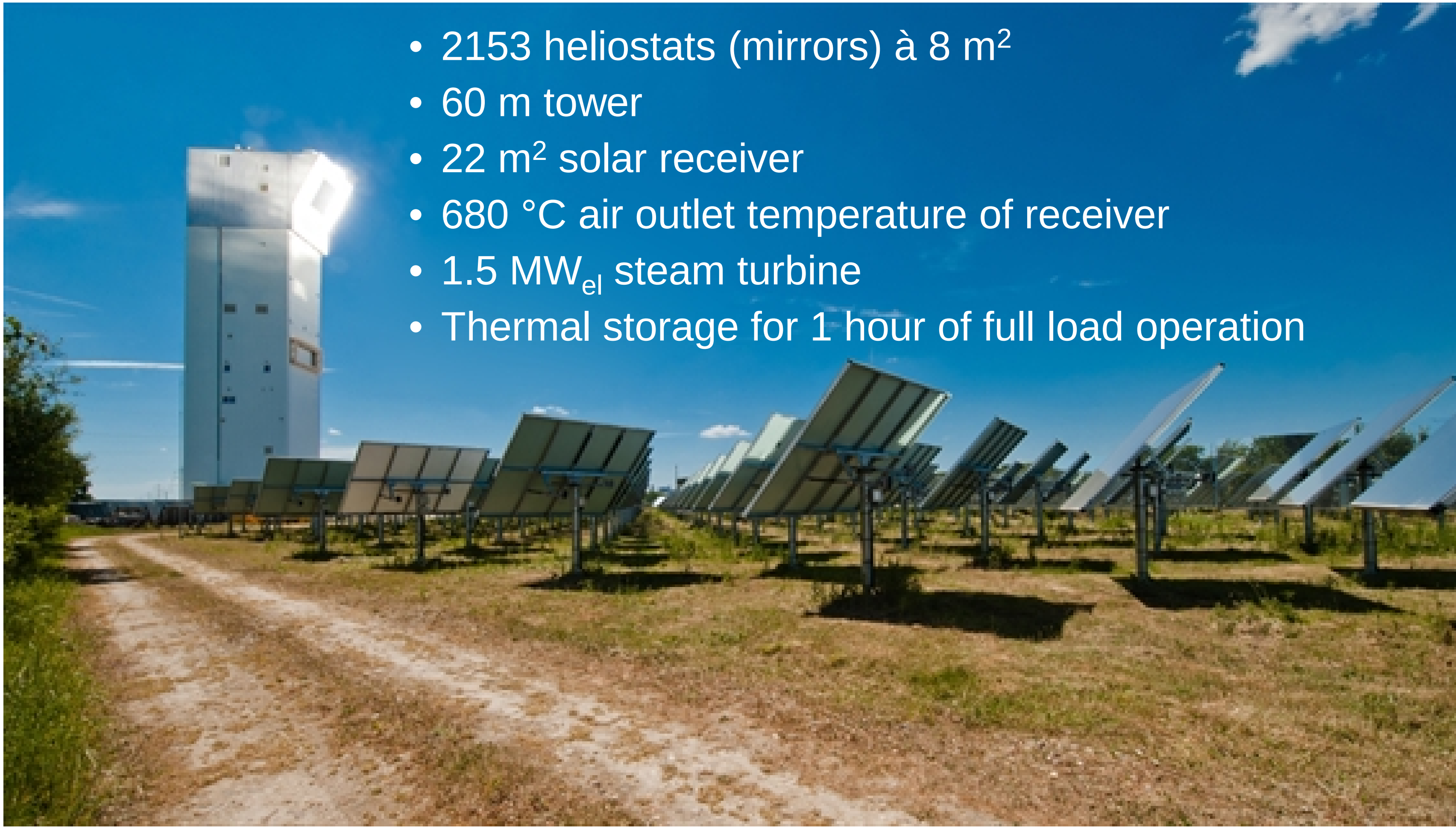


PEGASUS – Work plan

- 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)

DLR Solar Power Tower in Juelich, Germany

Research and demonstration plant



- 2153 heliostats (mirrors) à 8 m^2
- 60 m tower
- 22 m^2 solar receiver
- 680 °C air outlet temperature of receiver
- 1.5 MW_{el} steam turbine
- Thermal storage for 1 hour of full load operation

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

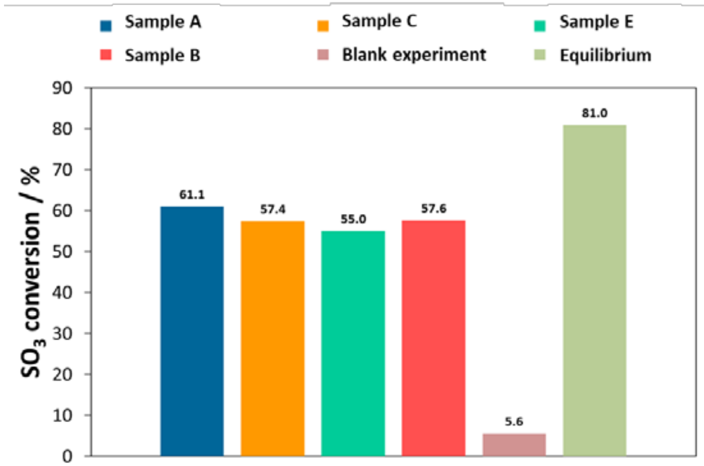
- Solar testing of catalytic particles in CentRec pilot
- Integrated testing together with particle reactors for sulphuric acid splitting planned in last project year

Development of catalytic particles

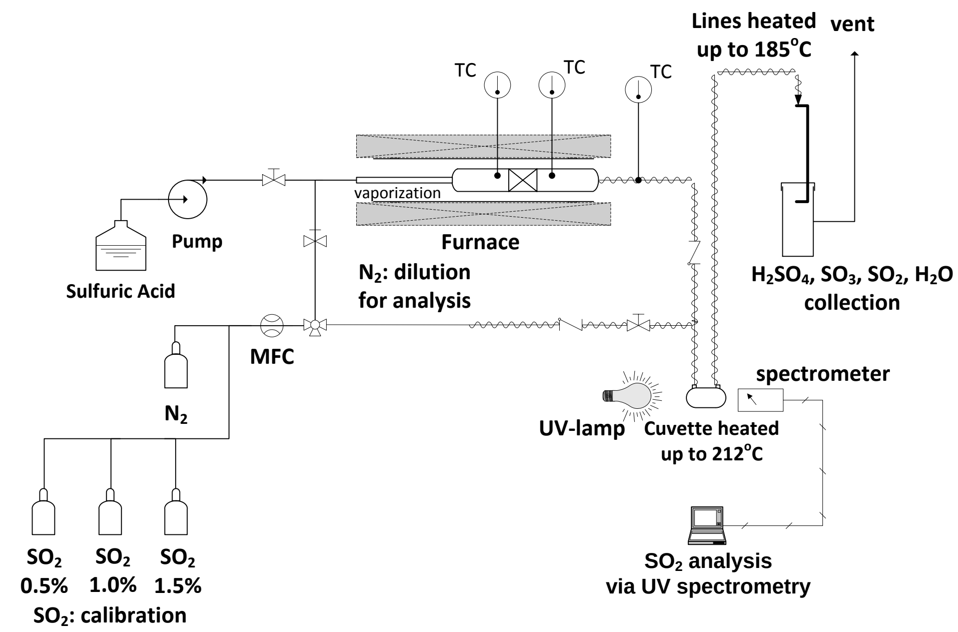
Experimental conditions

- Reaction temperature: 850 °C
- Pressure: 1 bar
- Feed: liquid sulfuric acid 95-98 w%
- Catalyst quantity per test: 1 g
- On-stream exposure per test: 60 min

Results of CuO enriched particles



Setup for catalytic activity measurements



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Preparation and qualification of catalytic particles

Required quantity for solar testing: 3 tons

Particle preparation (capacity of 3000 tons/year)

Particle characterisation

Crush test

Abrasiveness

Density

Roundness and sphericity

Solubility in acid

Development of particle reactor for sulphuric acid splitting

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

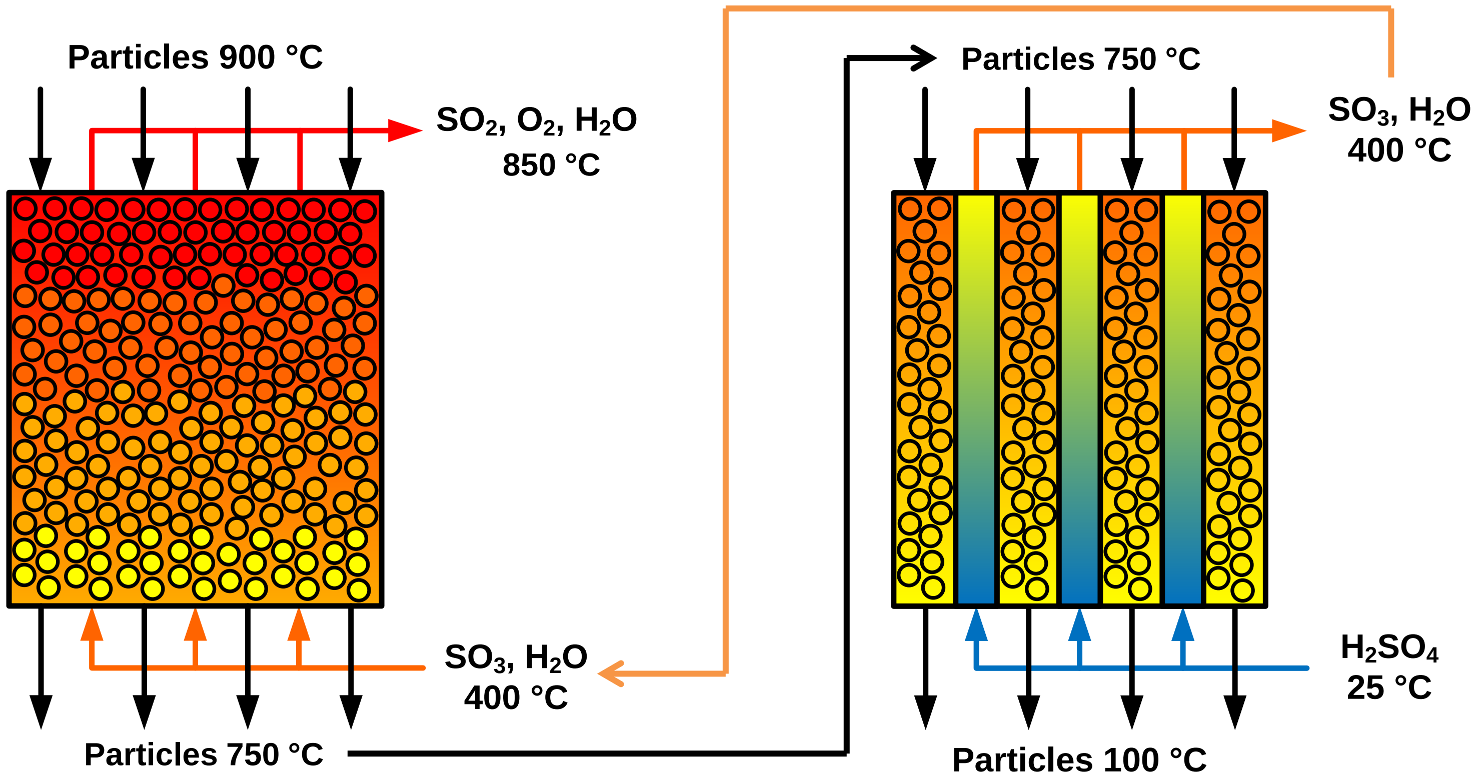
$SO_3 \Rightarrow SO_2 + ½ O_2$ (850 °C)

SO_3 decomposer

- Direct contact

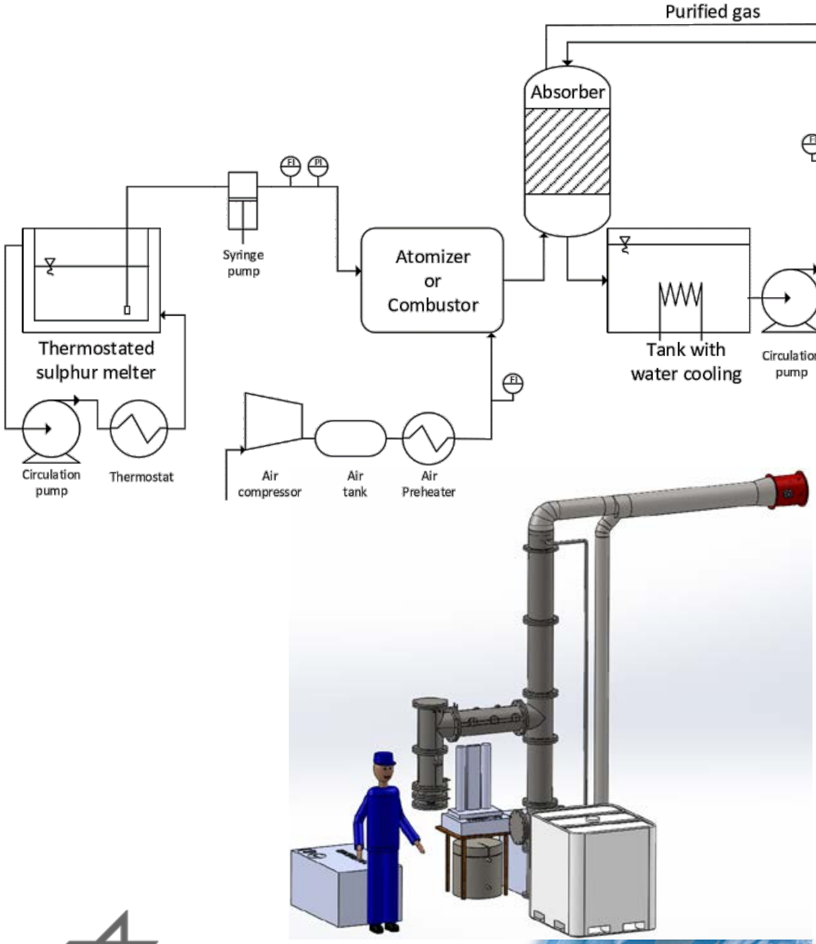
Sulphuric acid evaporator

- Indirect heat transfer (tube type)

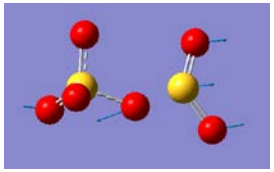


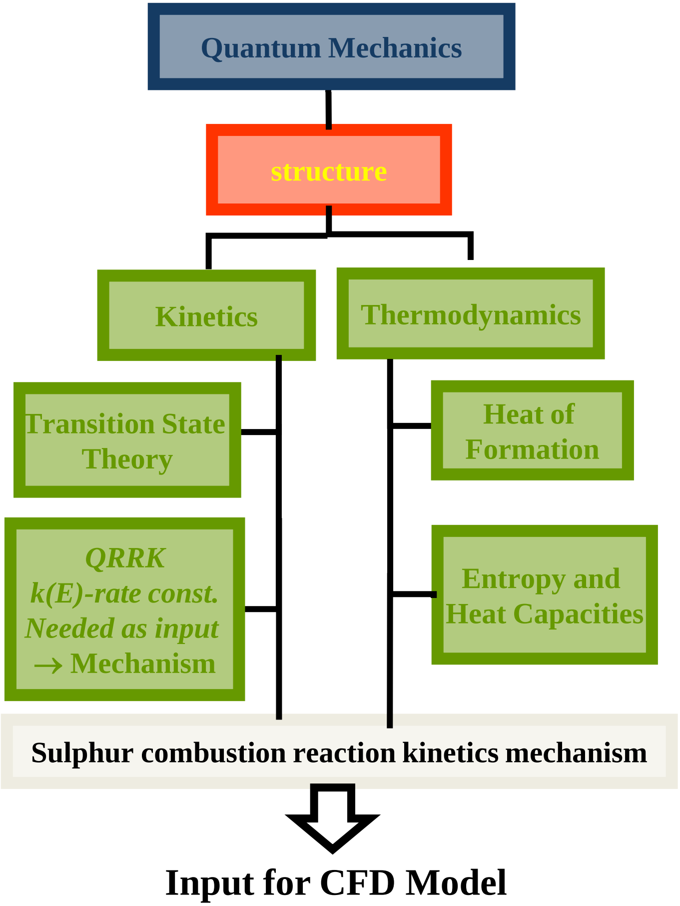
Development of sulphur burner for gas turbines

Test rig for atomization and combustion of sulphur



Development of chemical kinetics and CFD aided burner development

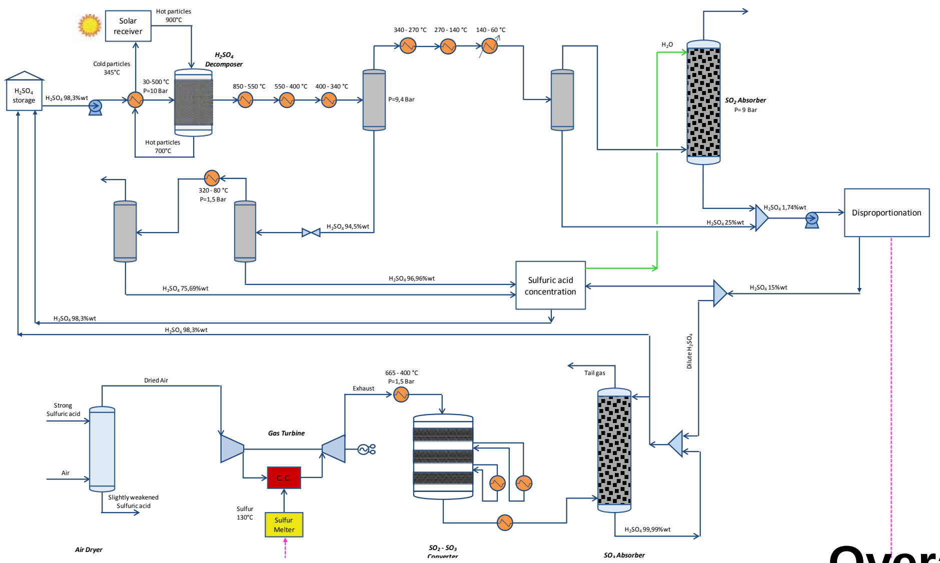




Processi Innovativi

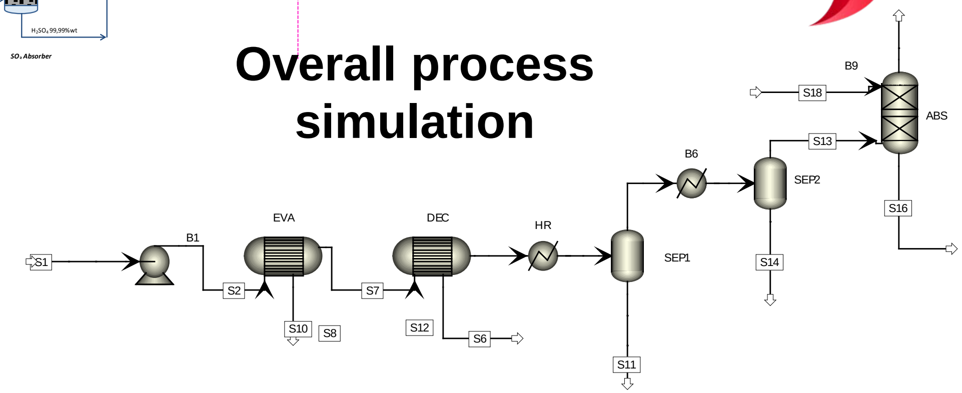
Process simulation and techno-economics

Flowsheet development



Techno-economical evaluation

Overall process simulation



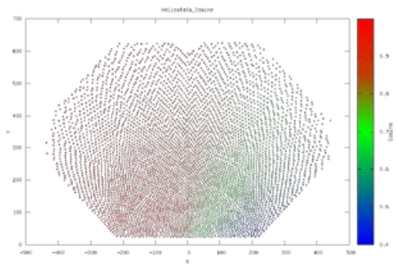
BrightSource Limitless

Solar field design and modelling

Reference site: Ouarzazate, Morocco

Cosine effect (e.g. 1st Jan.)

Blocking & Shadowing (e.g. 21st Mar.)



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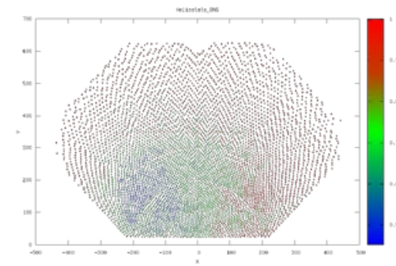

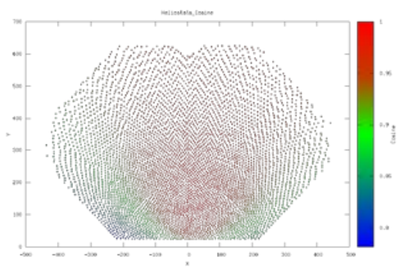

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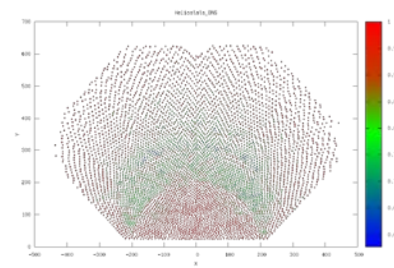

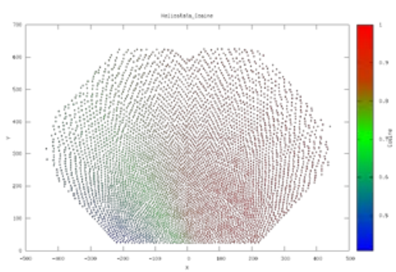

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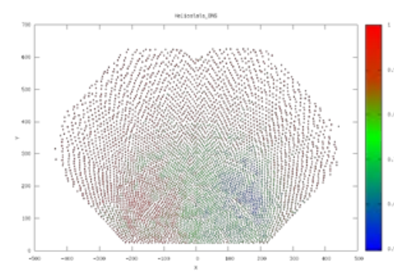

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Conclusions and outlook

- Sulphur is one of the most important commodity of chemical industry
- Sulphur has high thermochemical energy density
- Transportation and storage of solid or liquid sulphur is industrial practice
- Solar sulphur cycle allows for baseload and on-demand 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
    - Component modelling and solar field design
    - Process simulation and techno-economic analysis

Thank you for your attention!

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