European Commission

Horizon 2020
European Union funding
for Research & Innovation

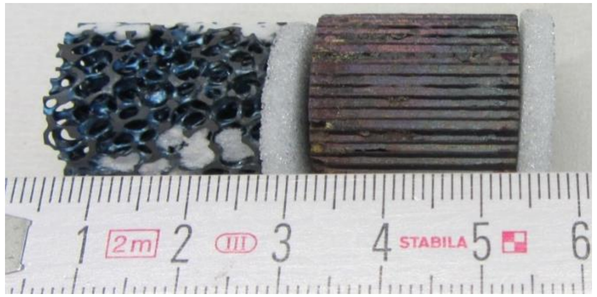
Future perspectives of the technology & closing remarks

Christos Agrafiotis, Dennis Thomey

PEGASUS Final Workshop
09.09.2021

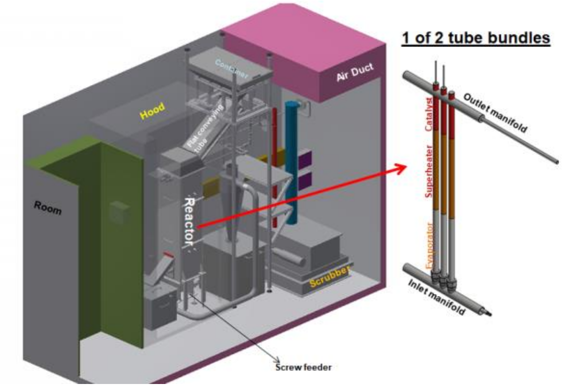
Building blocks of PEGASUS technology:

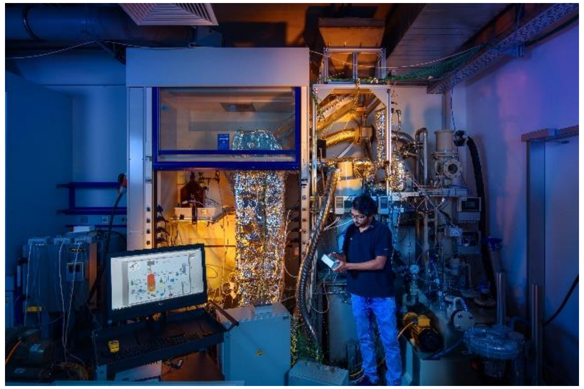
High-temperature SO_3 splitting catalytic systems



Centrifugal particle receiver

Particles-heated SO_3 splitting reactor/HX





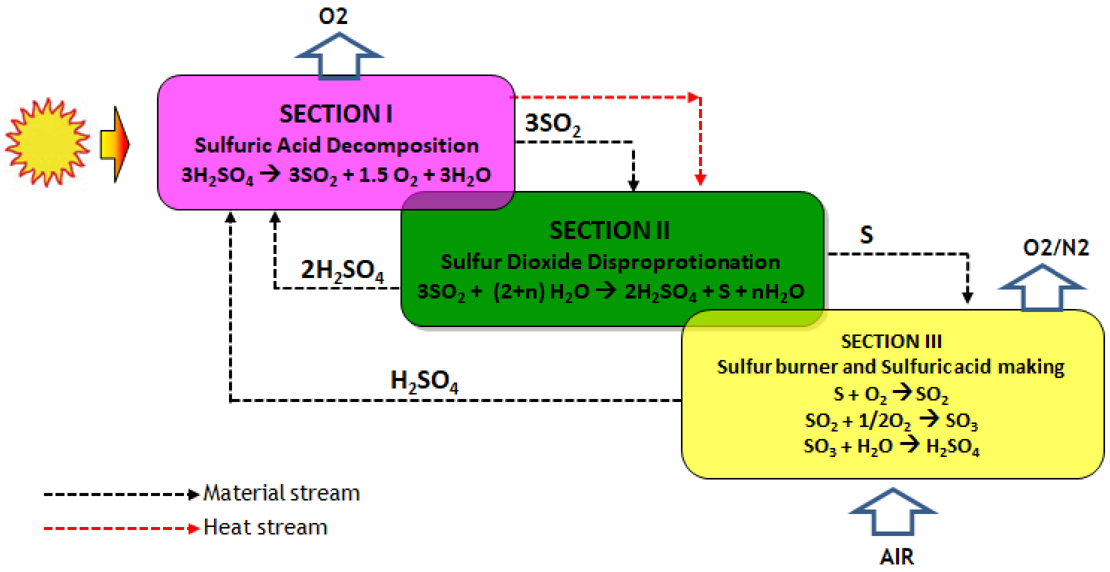
Sulphur combustor for gas turbines

Building blocks of PEGASUS technology:

Development of overall flowsheet:

- Identified pressurized operation of SO_3 splitting reactor as optimal w.r.t. overall plant requirements (separation of SO_2 from O_2 by cooling and condensation or by water absorption required before disproportionation, favored at high pressure) and 10 bar as a preliminary reasonable compromise.

- Allowed to define on the overall a conversion efficiency of solar energy into electric power in order of 20%, thus in line with high efficiency CSP range.



Progress beyond state of the art achieved in PEGASUS:

High-temperature SO_3 splitting catalytic systems

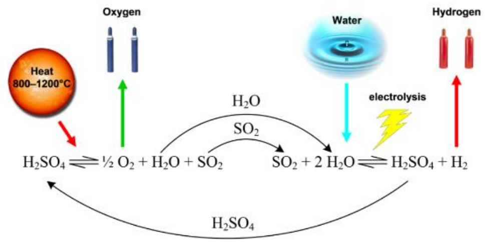
Inexpensive catalyst:
Cu-Mn-doped bauxite proppants: SO_3 conversion > 60 % at 850 °C, steady for **1000 h on-stream,** no degradation in crushing strength; very high pristine-state absorptance **> 94 %** and minor reduction after on-SO_3/steam-stream exposure.

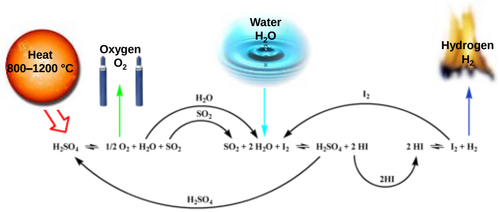
Fe_2O_3-coated SiC foams: uniform, high catalyst loading (35-44 wt.% of dry support) & minute catalyst-induced pressure drop; **near-equilibrium conversion, 89 %** at 850 °C, reproducible in **362 h** on-stream.

Challenge (for the particular targeted application in PEGASUS): demonstrated near-equilibrium operation at very long exposure times.

Current-future work: Extent Fe_2O_3-coated catalytic foams tests to > 1000 h; investigate lower-temperature catalytic systems.

Impact: results relevant to all sulphr thermochemical cycles (HyS, SI).

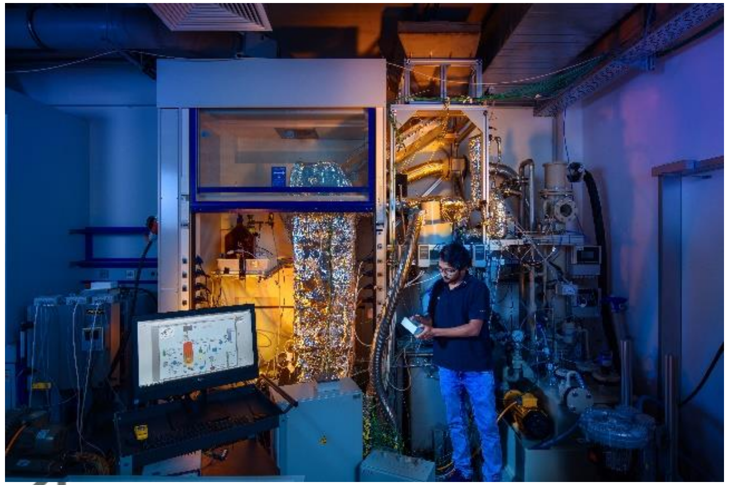




Progress beyond state of the art achieved in PEGASUS:

Particles-heated SO_3 splitting reactor/HX

First-of-its-kind SO_3 splitting /H_2SO_4 decomposer reactor indirectly ("allothermally") heated via hot moving particles stream (allothermally heated reactors already explored by nuclear industry but with He gas as HTF).



Challenge: required temperature level for chemical reaction only slightly less than that achieved for particles in centrifugal receiver: **850 vs. 925 °C.**

Consequences: Heat transfer issues if entire (SO_3 splitting) reactor has to be constantly maintained above that temperature.
In this HX/reactor: particles delivered at top: T = 890 °C.
Maximum temperature of SO_3 splitting region: T = **750 °C.**
Maximum temperature of H_2SO_4 decomposition region: T **= 400 °C.**
Temperature uniformity among the 6 tubes can be improved.

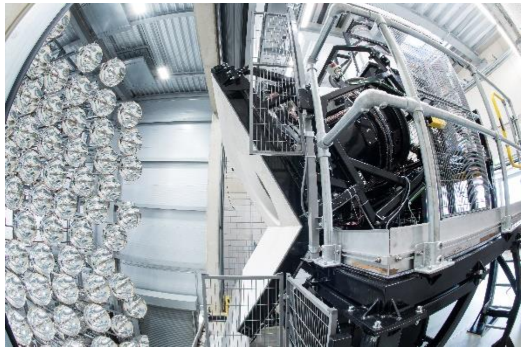
Current-future work: issues can be addressed in current assembly with mitigation measures like enhanced insulation on top feeding area, change of particles entrance point etc.; further "debugging" experiments scheduled (catalytic/thermal decomposition beds are still inside, full system operational).

Future assembly to be designed for pressurized operation and taking into account the lessons learned.

Progress beyond state of the art achieved in PEGASUS:

Centrifugal particle receiver

First-of-their-kind 500 and 300 kW_{th} centrifugal particle receivers tested on solar tower and solar simulator facilities, respectively.



Challenge (for the particular targeted application in PEGASUS): reproducible demonstration of delivering reliably particles at temperatures higher than 900 °C in 24/7 operation.

500 kW_{th}: $T_{particlesout}$ **= 925 °C ; 200** kW/m²,

300 kW_{th}: $T_{particlesout}$ **= 681 °C ; 757** kW/m², thermal efficiency **80 ± 16 %**

Lower temperature cause in second case under investigation.

Consequences: Integration at high-temperature solar chemical plants still an issue in contrast to integration in (steam cycle) solar power plants or supply of industrial heat that seems much more short-term-feasible (see ongoing Project HIFLEX).

Current-future work: ongoing Project HIFLEX http://hiflex-project.eu/ ; issues to be addressed in new receiver scheduled to be tested at SANDIA in further campaigns.

Progress beyond state of the art achieved in PEGASUS:

Sulphur combustor for gas turbines

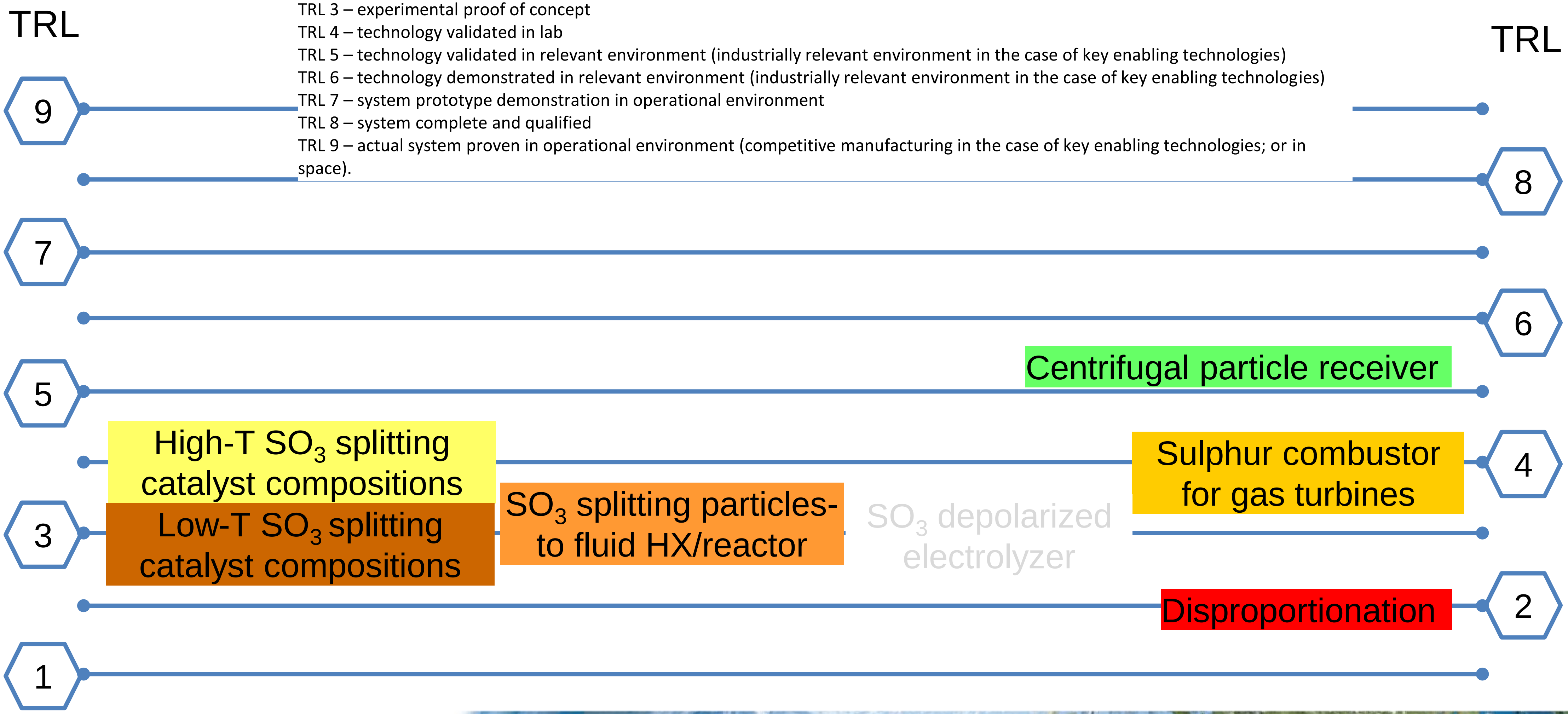
First-of-its-kind sulphur burner operating at power density > 5 MW/m³ ($P_{ambient}$); Sulphur auto ignition, very large stability range; operation at 1-15 bar and 20-300 kW shown feasible by simulations.

Challenge (for the particular targeted application in PEGASUS): demonstrated prolonged operation at power densities of > 45 MW /m³ for typical operating pressure of e.g. 15 bar; stability of combustor and turbine blade materials with flue gases of high SO_2/SO_3 concentrations 10-13 vol.% and high exhaust gas temperatures > 1200 °C , as in turbines operated with pure sulphur.

Current-future work: Measurement of laminar flame speed & auto ignition times; detailed validation of kinetics; burner upscaling and optimization; prolonged studies of combustor and turbine blade materials for sulphur combustion.

Current TRL of PEGASUS technology's components

TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).



Issues of further research:

- Disproportionation.
- Pressurized operation of SO_3 splitting reaction due to overall plant requirements (easier to be implemented in tubes only in a shell-and–tube heat exchanger, adverse effect on SO_3 conversion).
- Cascades of high- and lower-temperature catalysts to enhance conversion and address potential temperature differences along catalytic tubes.
- Optimize centrifugal receiver operation.
- Indirectly-heated implementation of other endothermal processes in particles moving bed heat-exchanger (MBHE) permitting their 24/7 operation.

Sulfur cycles SWOT (Strengths, Weaknesses, Oppotunites, Threats) analysis

Strengths

High theoretical efficiency potential
Excellent long-term storage option
Low price long-distance transportation
Continuous operation of reactor (off-sun)
Inexpensive construction/catalyst materials
Low operating temperatures

Weaknesses

Often needs large scale
Corrosive and toxic working fluids
Some components have low TRL (e.g. sulphur generation reactor)
Complicated process difficult to explain to policy makers

Opportunities

Different cycle variants possible
(e.g. HyS or SI for hydrogen generation)
Internal heat recovery (to increase total efficiency)
EU as technology provider
Market entry via existing sulphuric acid plants
Straightforward hybridisation with fossil sulphur
Recycling of spent sulphuric acid
Sulphur fired gas turbine for efficiency increase
Potential for substitution of current refinery-based/ high carbon footprint sulphur production

Threats

Bias against sulphur compounds
Sulphuric acid industry reluctant to innovation
Not enough funding
Instability of sun belt countries
Financing – high upfront costs
Solar thermal industry still not big enough to allow companies-oriented investment for emerging related technologies

Sulfur cycles: outlook / roadmap for R&D+i & market

2021-2027 | 2027-2030 | 2030-2035

Iterative improvement of reactor, process, material

Demonstration at 50 kW

Demonstration of most promising types at several 100 kW

Optimization

Demonstration of most promising types at multi MW plant

Potential routes for further scale-up and commercialisation

- Consideration of appropriate Call Topics within the recently launched HORIZON EUROPE Call.
- Natural or bi-lateral research call topics focused on “parts” of the overall approach, e.g. disproportionation.
- Strengthen contacts and formulate joint projects with sulphuric acid industries.

Thank you for your attention!

www.pegasus-project.eu

Co-funded by the Horizon 2020 Framework Programme of the European Union