Development of solar rotary kiln technology at the DLR for heating and treatment of particles

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Outline

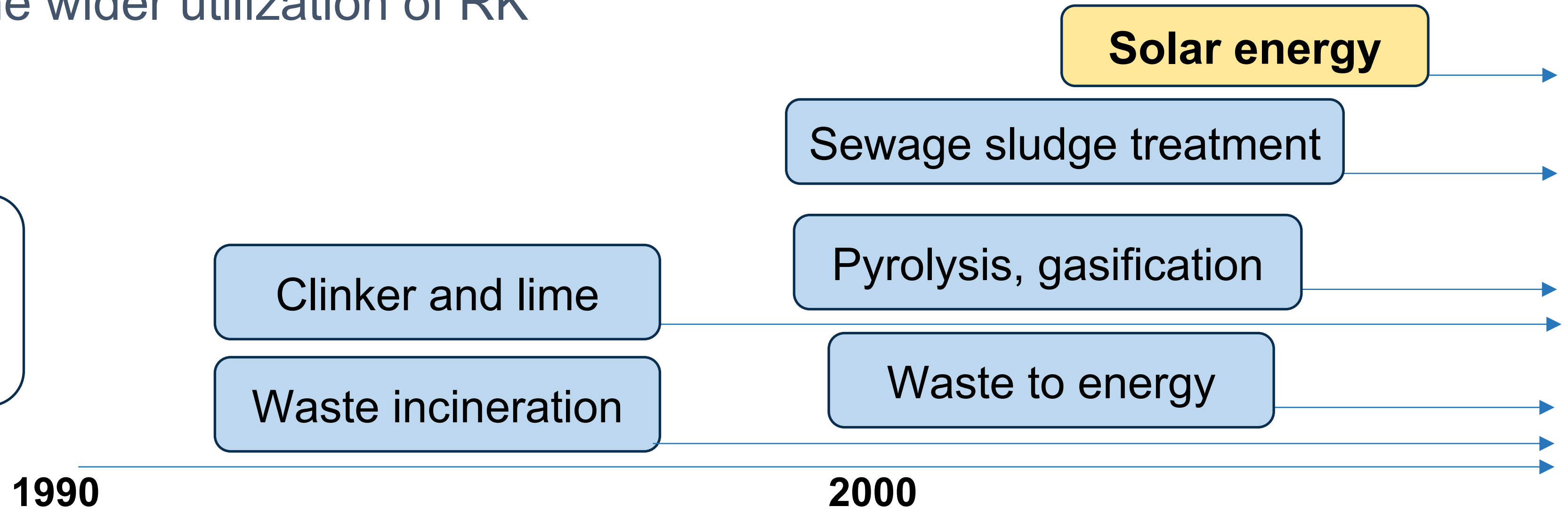
- Introduction: solar rotary kiln technology
- Technology development at DLR
- Challenges and main achievements
- Further technological development in project PYSOLO
- Outlook

Introduction

Some interesting facts about conventional rotary kilns (RK)

- A RK is a cylindrical vessel that rotates around the longitudinal axis
- It is a device on the border between energy and process engineering
- Suitable for drying, combustion, calcination, pyrolysis, or the thermochemical treatment of various materials. Device able to **process diverse feedstock and control the residence time** (tilt and rotation speed).
- A RK is heated by gas (process burners), liquid, or solid fuel → **usually high energy demand**
- **Other aspects**: dust generation, varying product quality, and tendency to lower thermal efficiency are barriers to the wider utilization of RK

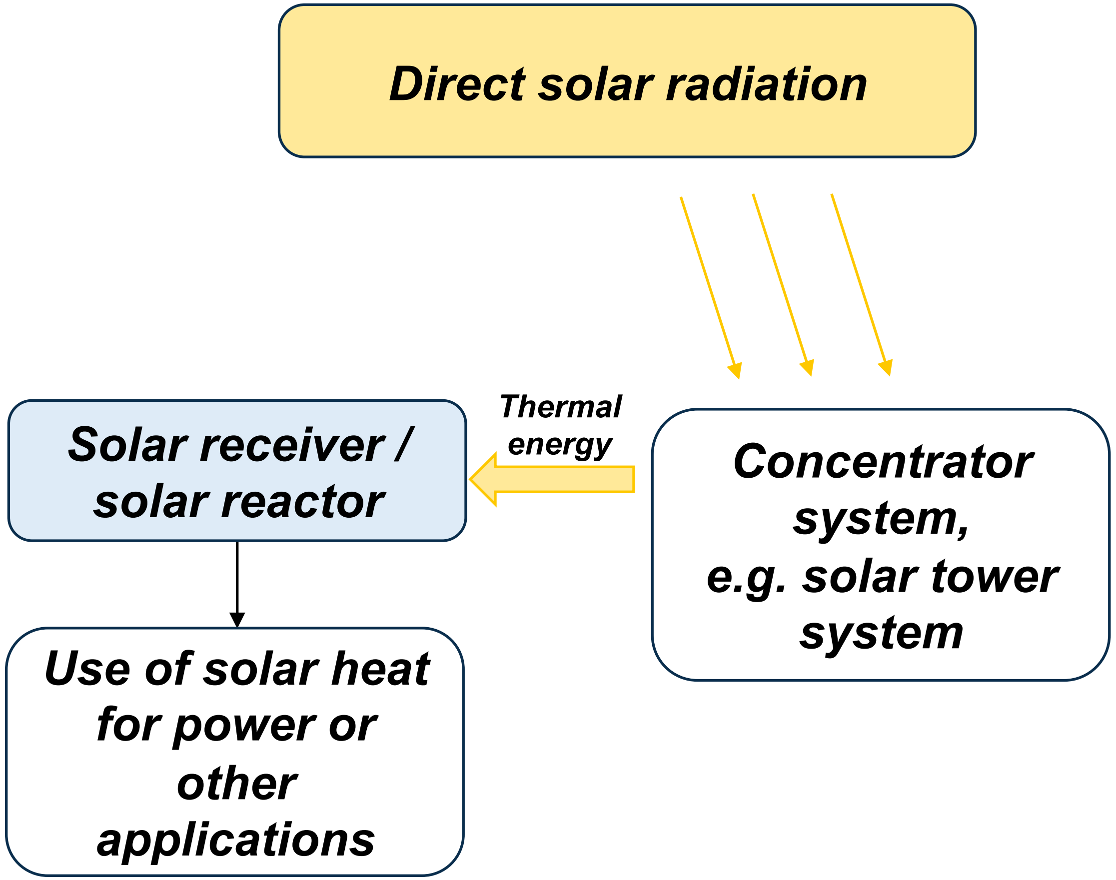
Development of main research areas in the past three decades



Source: 2022, Bojanovsky et. al., Rotary kiln, current state and perspectives

Introduction

Use of concentrated solar energy and solar rotary kilns



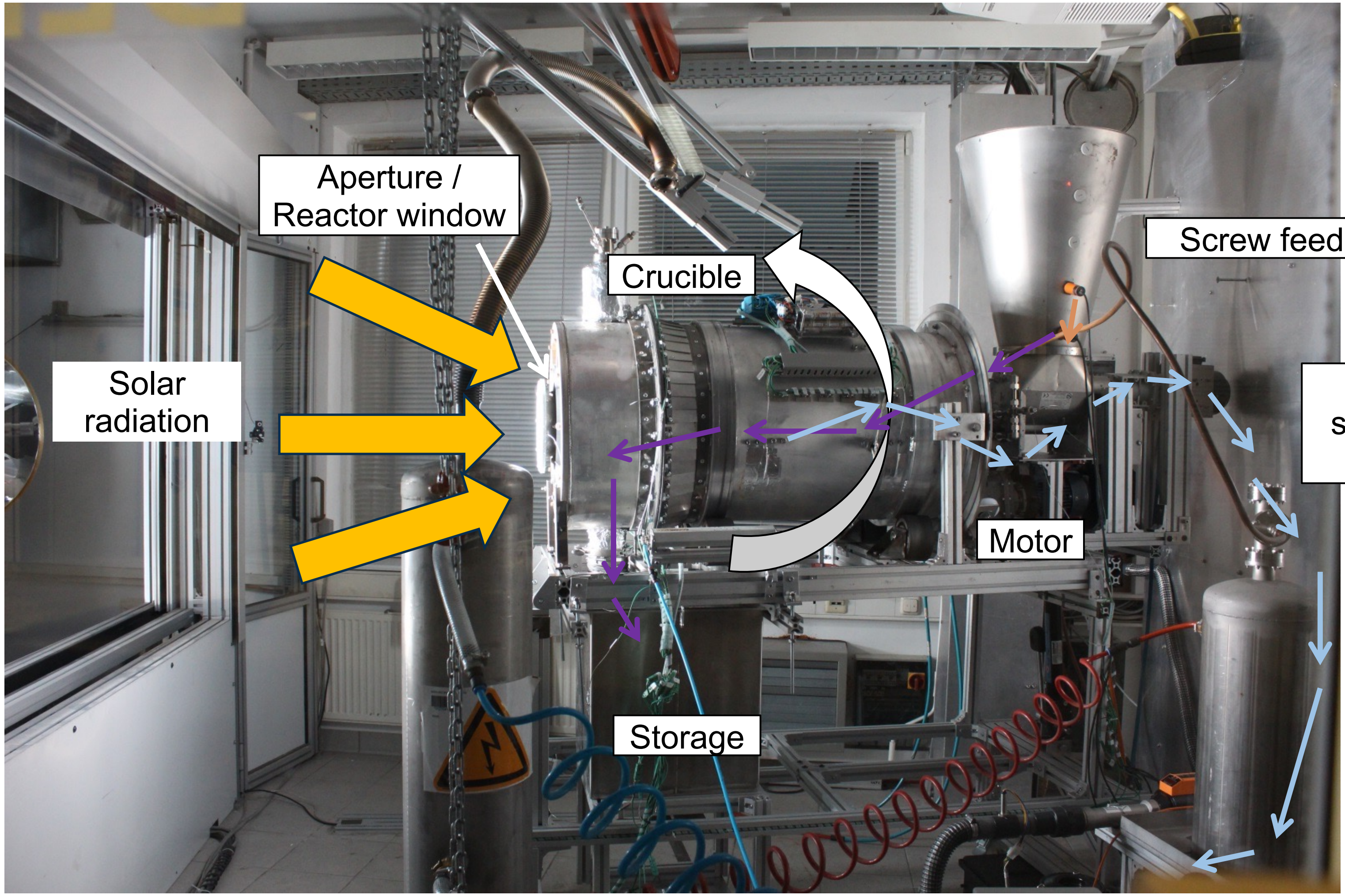
1980, G. Flamant et. al.

Study on solar fluidized bed and solar rotary kiln:

*"Such reactors could find applications for conversion of concentrated solar energy, e.g. heating of gas by means of fluidized bed receiver, **high temperature thermal storage with solid material**, **thermochemical storage** involving gas-solid systems, **preparative chemistry of carbonated materials**, **thermal treatment** of ores, drying and dehydration"*

Solar rotary kiln description

Example of DLR-rotary kiln with direct irradiation of treated material

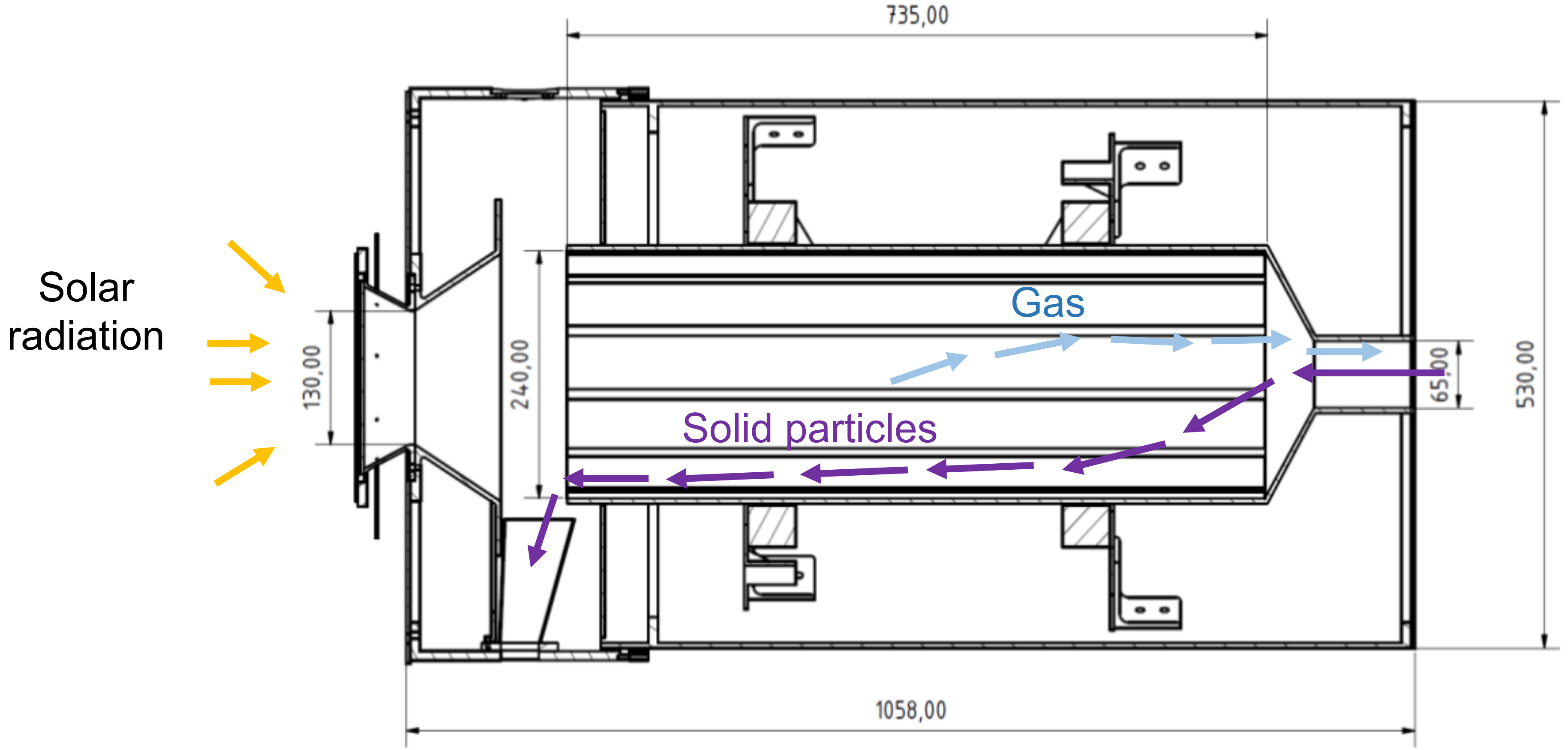


Gas

Solid material

Solar rotary kiln description

Example of DLR-rotary kiln with direct irradiation of treated material



Research at DLR with solar rotary kilns

Some of the processes that we have studied

	Commodities / CO_2 capture		Heat storage (sensible / thermochemical heat) / N_2 purification purposes	
Process	Metal recycling 700 – 850 °C	Thermochemical reactions with solid particles 650 – 1000 °C	Thermal reduction of solid particles ~ 1000 °C	Heating of solid particles 600 – 1200 °C
Material	Aluminium	Limestone, cement raw meal, lime, kaolin	Cobalt oxide, MnFeOx, SrFeOx	Aluminium oxide, bauxite, **sand, olivine**

Application

Commodities

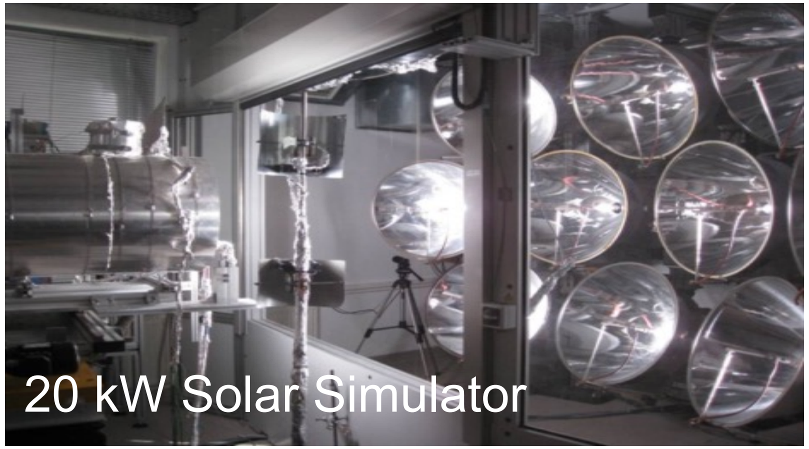
CO_2 capture

Heat storage (sensible / thermochemical heat)

N_2 purification purposes

Research at DLR with solar rotary kilns

Solar test facilities for technology development at DLR

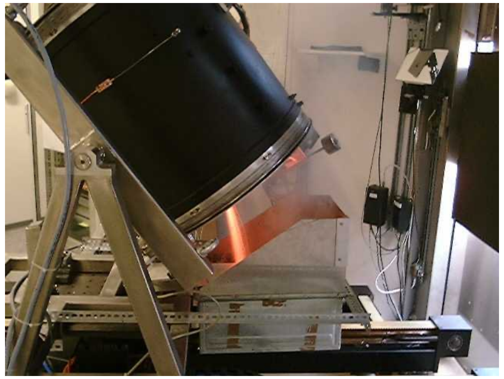


Cologne site

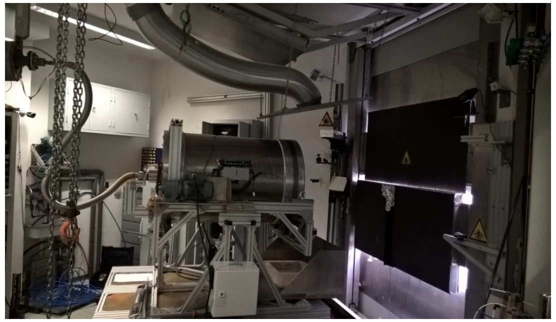
Jülich site

Research at DLR with solar rotary kilns

Batch-operated concepts



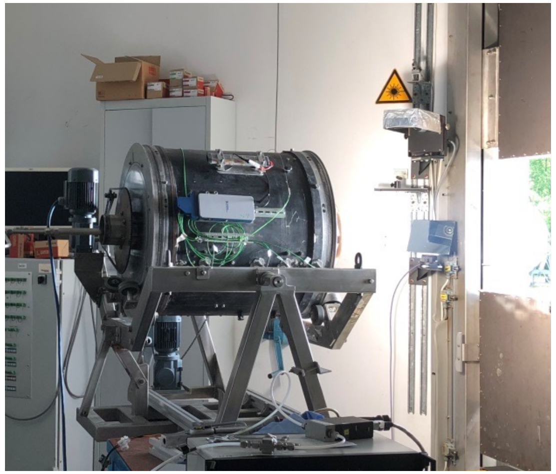
Al smelting, 2000



SOLAM, 2015

https://elib.dlr.de/108902/

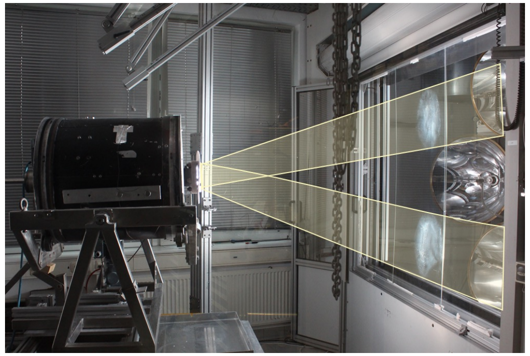
Solar Aluminum Recycling in a Directly Heated Rotary Kiln



DÜSOL, 2019

https://elib.dlr.de/131236/

Design of a rotary kiln for a solar-powered air separation process



SOLARTWINS, 2024

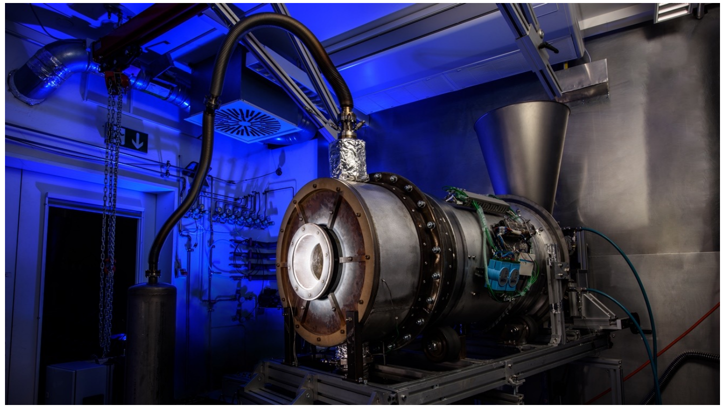
https://doi.org/10.1016/j.jclepro.2023.137611

Solarization of the zeolite production: Calcination of kaolin as proof-of-concept

Time

Research at DLR with solar rotary kilns

Calcination of materials



SOLPART
2016-2020

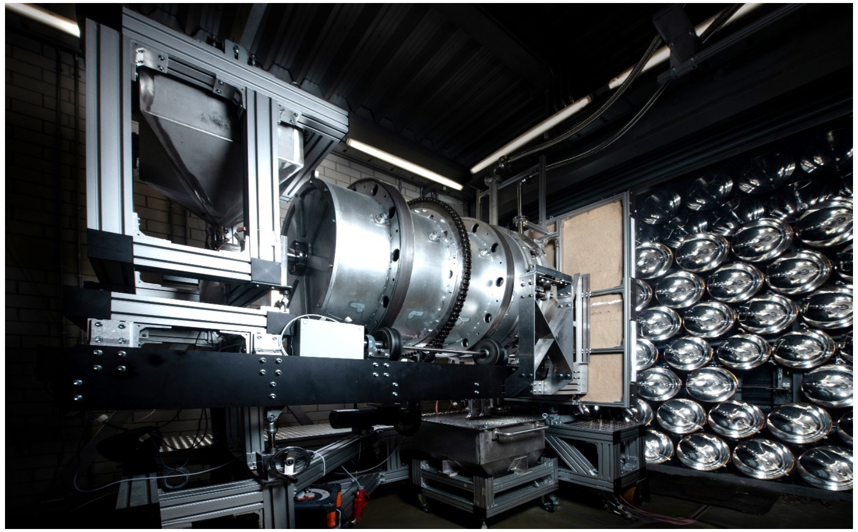
https://doi.org/10.1016/j.solener.2019.01.093

Solar treatment of cement raw meal

CALyPSOL
2018 – 2021

https://doi.org/10.1115/ES2024-130660

Carbonator reactor for solar calcium-looping cycle



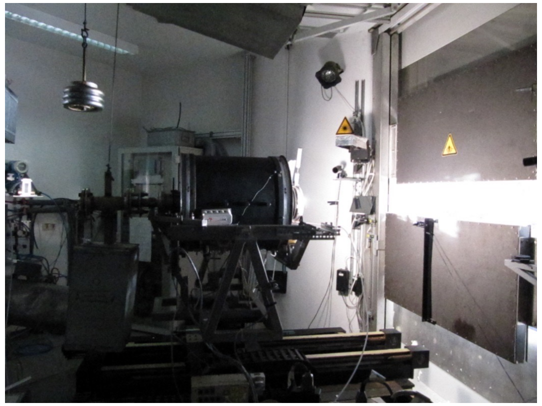
CemSol
2021-2025

Solar calciner 65 kW, calcination > 90% achieved Experimental campaign Sep-Oct 2025

Time

Research at DLR with solar rotary kilns

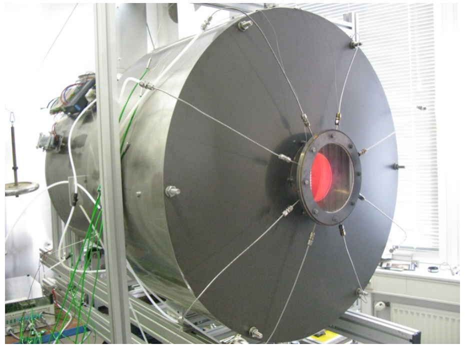
Thermal storage applications



TES, 2012

https://doi.org/10.1016/j.solener.2012.07.012

Solar-heated rotary kiln for thermochemical energy storage



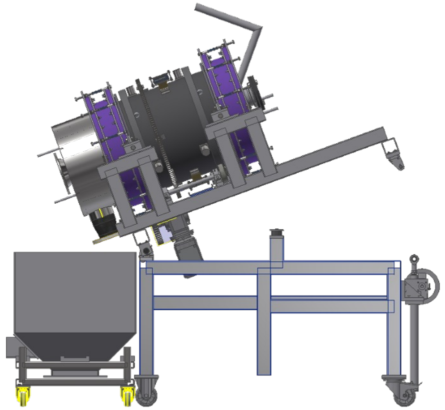
RedoxStorE, 2019

https://doi.org/10.1016/j.apenergy.2021.118271

Storing solar energy in redox particles

HOTPORT, 2020

Closed cycle for a particle system with a solar particle receiver



PYSOLO, 2023 - 2027

https://doi.org/10.1115/ES2025-156580

Solar rotary kiln integrated in a biomass pyrolysis process

Time

Some challenges for technology development

- **Scaling down rotary kilns?**
  - Difficulties to find material suppliers for small systems, e.g. ceramic bricks
- **Undesired reactions between processed particles and reactor material**
  - CaO and high temperature steel → chromate formation
- **Integration of ceramic crucible in the design**
  - Stainless steel or nickel alloys are not suitable for some processes; thermal expansion of ceramic and metals have to be considered for the design
- **High temperature sealings for connection between fixed and rotating parts**
  - Most of the commercial solutions are limited in temperature or size
- **Contamination of the reactor window**
  - Turbulence inside the reactor and fine particles are critical for this reactor component
- **Temperature measurements of particle bed**
  - Direct irradiation affects signal of temperature sensors

Main achievements with our solar rotary kilns

Demonstration of solarisation of thermochemical processes

Treatment of cohesive material

Calcination rates up to >95%

Investigation of mixing and heat input

Continuous processing of materials

Progress in scalability of the technology

2 kW_t → 15 kW_t → 65 kW_t

Development of designs and models to fulfil requirements of Concentrated Solar Thermal energy

Integration of ceramic-metal parts in the systems

Strategies for measuring and controlling process parameters

Sealings for high temperature applications

Ray-tracing analysis and CFD modelling

Strategies for reactor window protection

Further technological development in project PYSOLO

PYSOLO

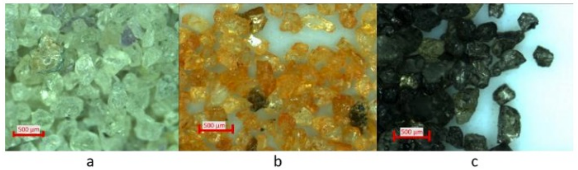
- Particle Heat Carriers
  - Characterization of different potential materials for the process
- Solar rotary kiln
  - Thermal efficiency 70 – 80 %
  - Mixing of particles
  - Operation in open and closed modes
- Integration of Concentrated Solar Thermal energy and Pyrolysis
  - Particle storage
  - Particle transport
  - Particle-air separation system

Solar rotary kiln + Integration of Concentrated Solar Thermal energy and Pyrolysis → Analysis for the scalability of the system → **inclination at the solar tower**

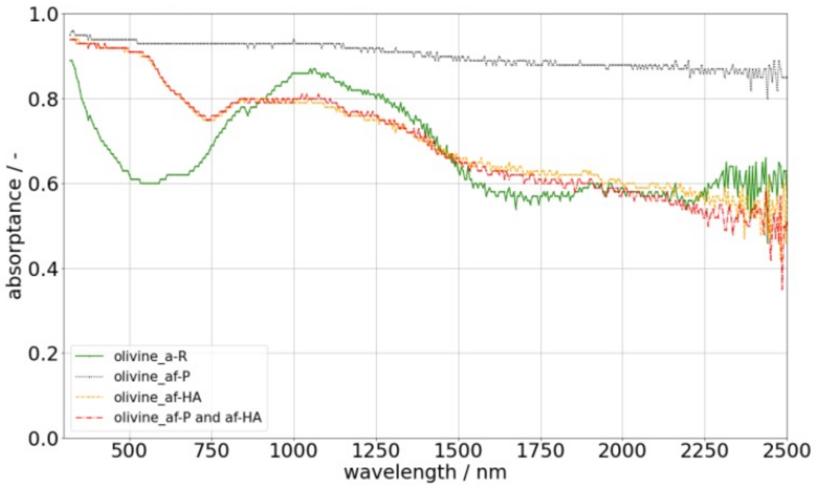
Further technological development in project PYSOLO

Characterization of PHC

Optical properties of PHC in PYSOLO process – olivine example



MICROSCOPY IMAGES OF OLIVINE SAMPLES: (a) AS RECEIVED, (b) AFTER HEATING IN AIR AT 950 °C, (c) AFTER PYROLYSIS AT 800 °C.



ABSORPTANCE OF OLIVINE SAMPLES AS FUNCTION OF THE WAVELENGTH.

https://doi.org/10.1115/ES2025-156580

Heat carrier characterization for solar operation

	Bauxite	Olivine	Sand	SiC	Biochar	MgO
Flowability	3	2	2	2	0	1
Abrasiveness	3	3	3	2	3	3
TGA	3	3	3	3	-	2
Conductivity	2	2	2	2	2	3
Volumetric heat capacity	2	2	1	1	0	2
Optical properties	3	2.5	2	3	3	1.8
Price	2	3	3	1	3	1
Others aspects					-1	
Total	18	17.5	16	14	10	13.8

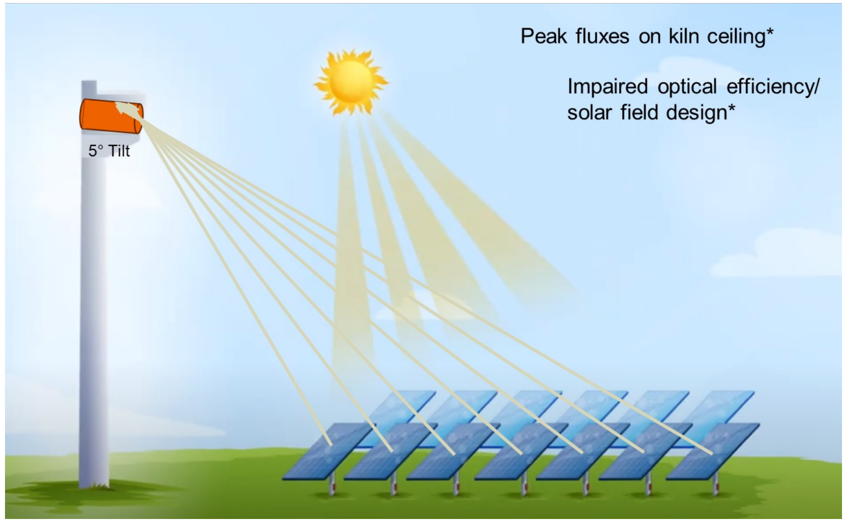
Bauxite, olivine and sand were identified as the best options for the PYSOLO process

Publication in review process

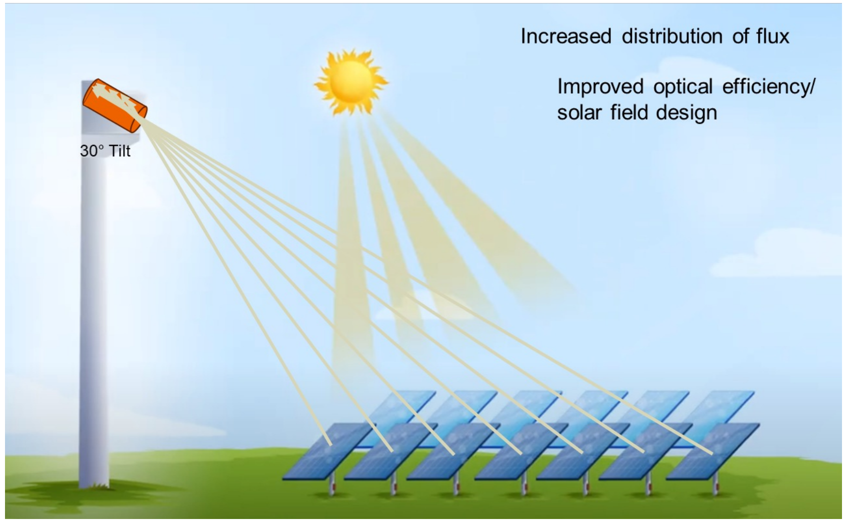
Further technological development in project PYSOLO

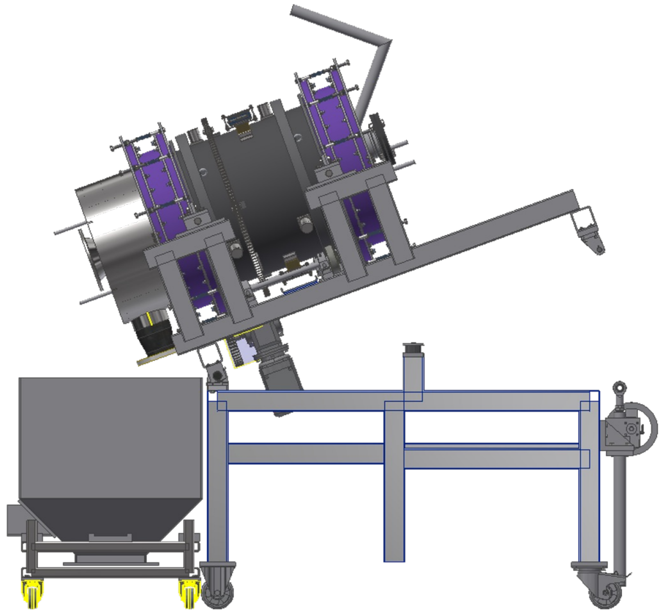
Solar receiver design

Conventional Rotary Kilns



Desired Solar Rotary Kiln



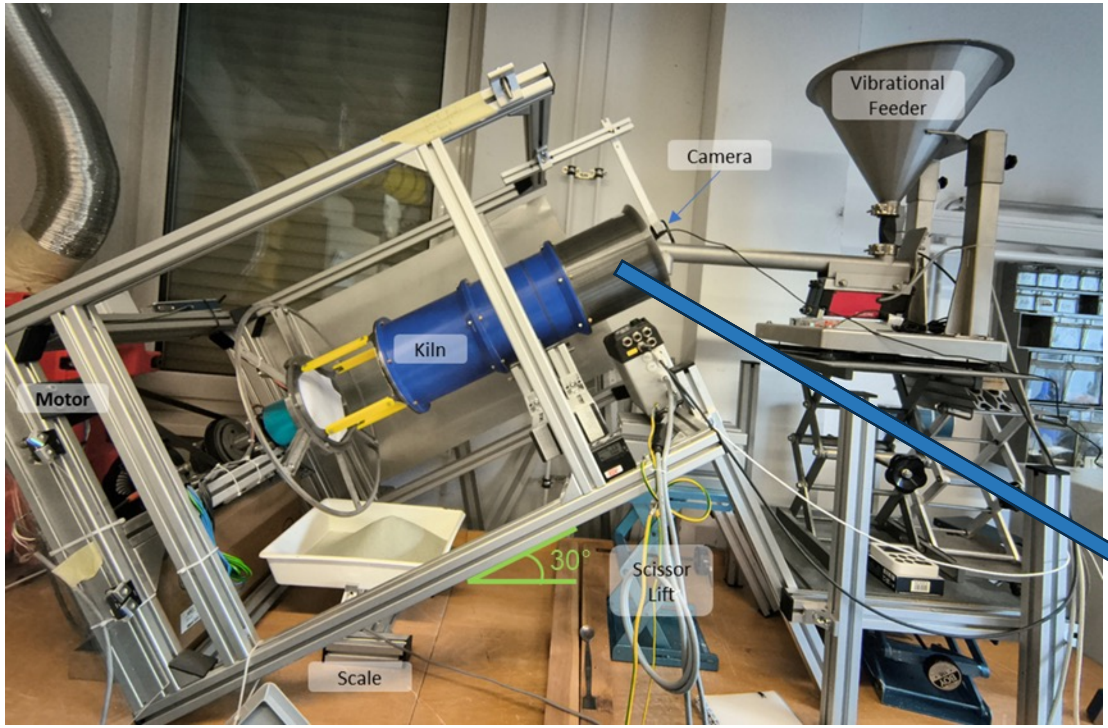


Ongoing solar receiver design and commissioning

- 15 kW_t power
- Open and closed operation
- System inclination up to 20°
- To be tested at the solar simulator and solar furnace in Cologne

Further technological development in project PYSOLO

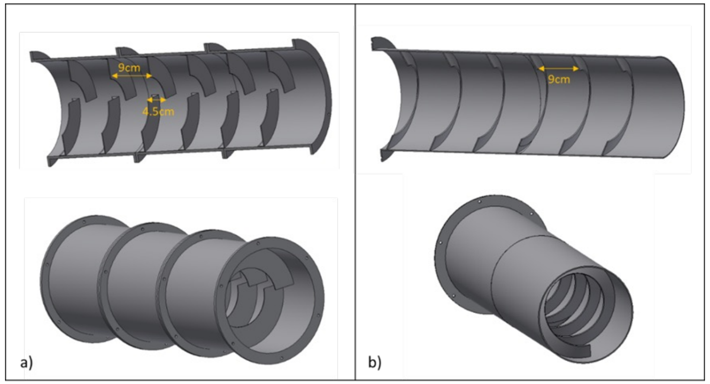
Solar receiver design



Particle Material	Olivine (d_p = 250 µm; $\rho_b \approx 1900$ kg/m^3)
Inclination Angles	3-30°
Rotational Speeds	1-8 RPM (For rolling regime)
Mass Flow Rates	10-130 kg/hr

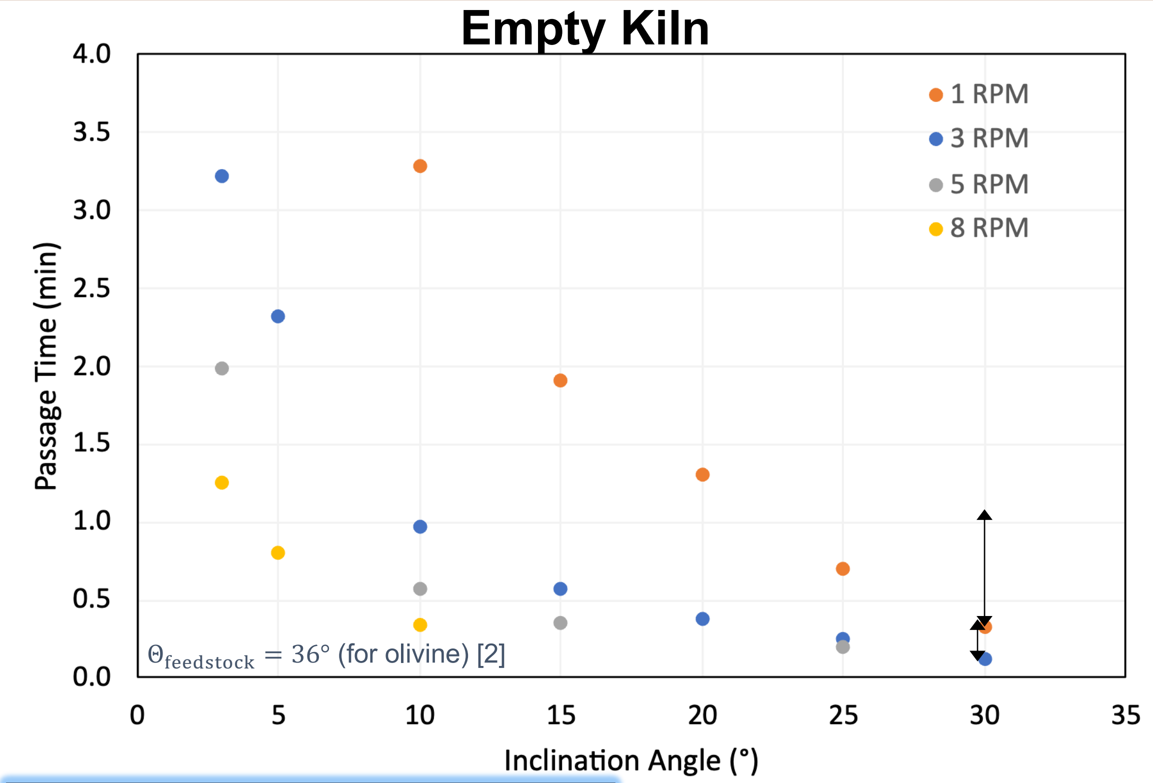
- Room temperature setup to understand:
  - How time of passage is affected by steep inclination angles
  - Increase in passage time possible with internal lifting structures
- Results presented at SolarPACES 2025, publication in review process

Internal Lifting Structures



Further technological development in project PYSOLO

Solar receiver design



Sullivan et al. (1927) Correlation [1]

* Derived using data for inclination angles of 1-6°

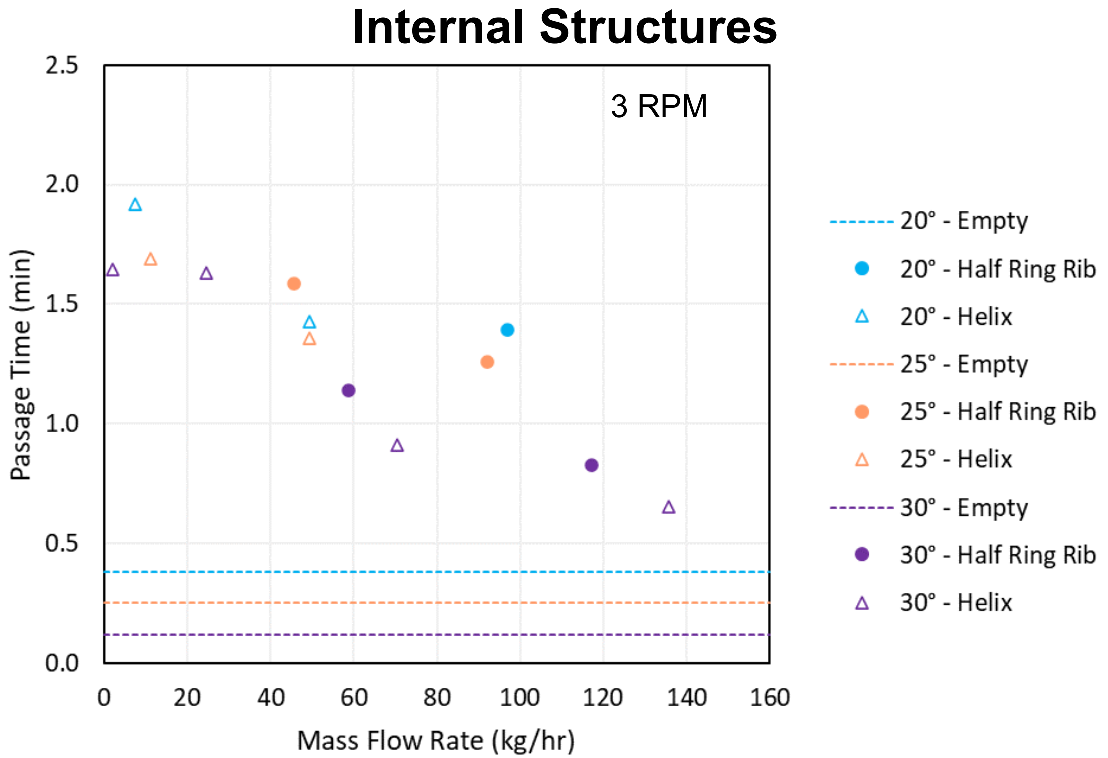
$$\tau = 1.77 \cdot \frac{L_{kiln}}{D_{kiln}} \cdot \frac{\sqrt{\Theta_{feedstock}}}{\delta_{kiln} \cdot \omega_{kiln}}$$

Angle of Repose

Inclination angle

Rotation speed

- Results deviate from correlation by 100% at 30°



- Maximum passage time → no particles flowing over the structures
- 10.4x increase in passage time at 30°

Outlook

PYSOLO

Finalize commissioning of solar receiver

Integration of internal structures

Experimental testing at the solar simulator and solar furnace in Cologne scheduled for 2026

Validation of model for solar receiver (POLIMI-DLR)

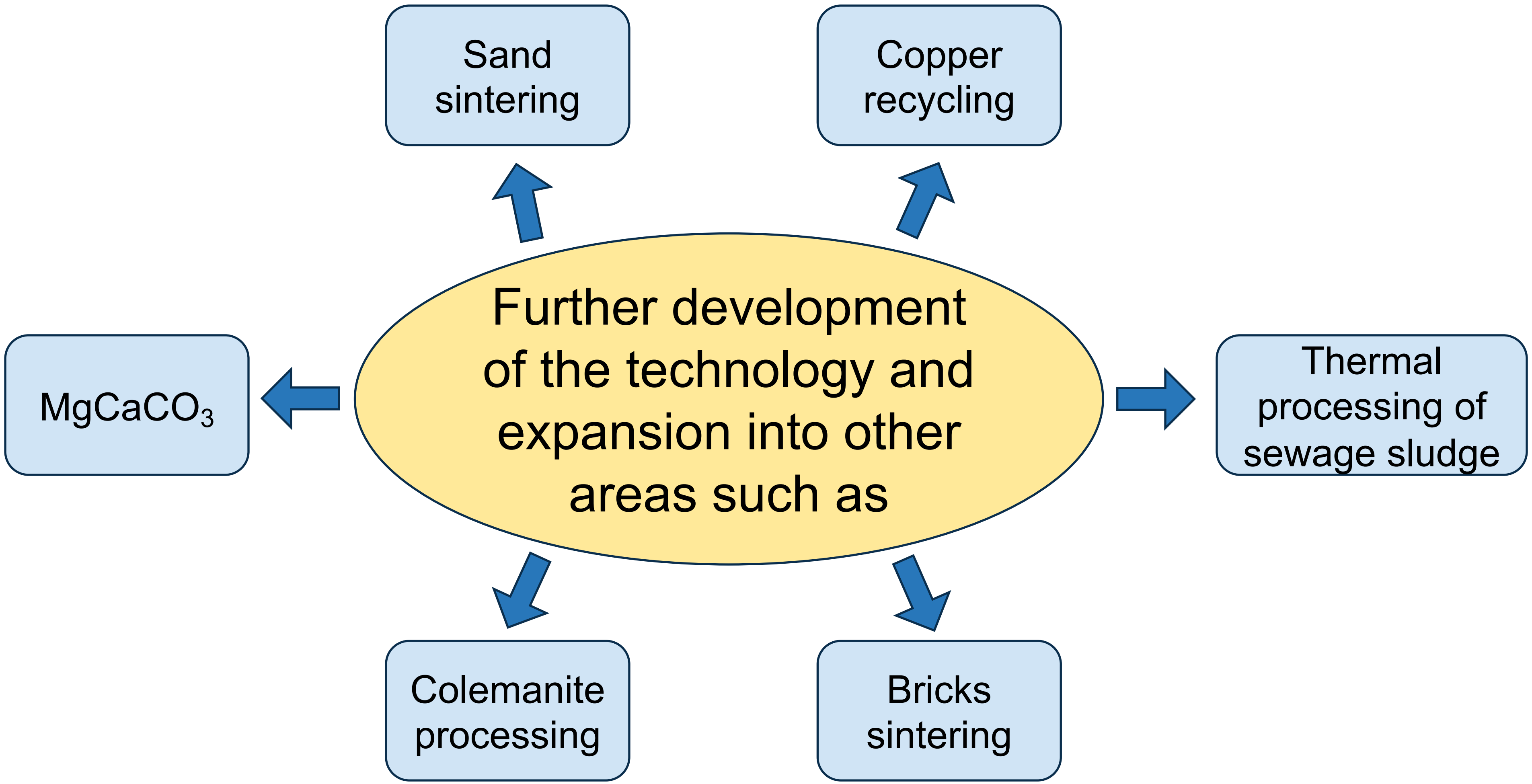
Support activities for the overall system analysis and scale up

2026

2027

Outlook

Research activities at DLR



Thank you for your attention!

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Department of Solar Chemical Process Development

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