# Demonstration of a Model Predictive Control for a Cluster of Solar Chemical Batch Reactors

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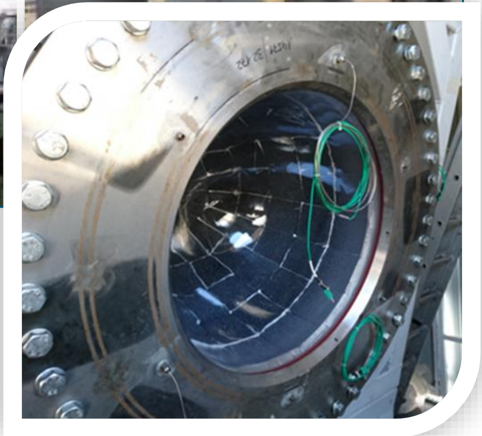
DLR

# Solar Thermochemical Hydrogen Production

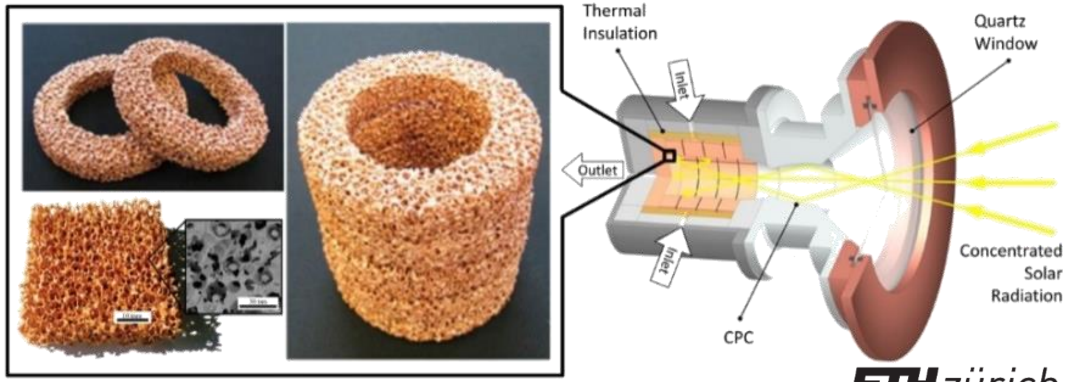
## State of the Art: Batch Reactors with Fixed, Porous Monoliths of Redox Material


Source: Plataforma Solar de Almeria (Owned by the Spanish research centre CIEMAT)



Source: DLR


Source: IMDEA / SUN-to-LIQUID project

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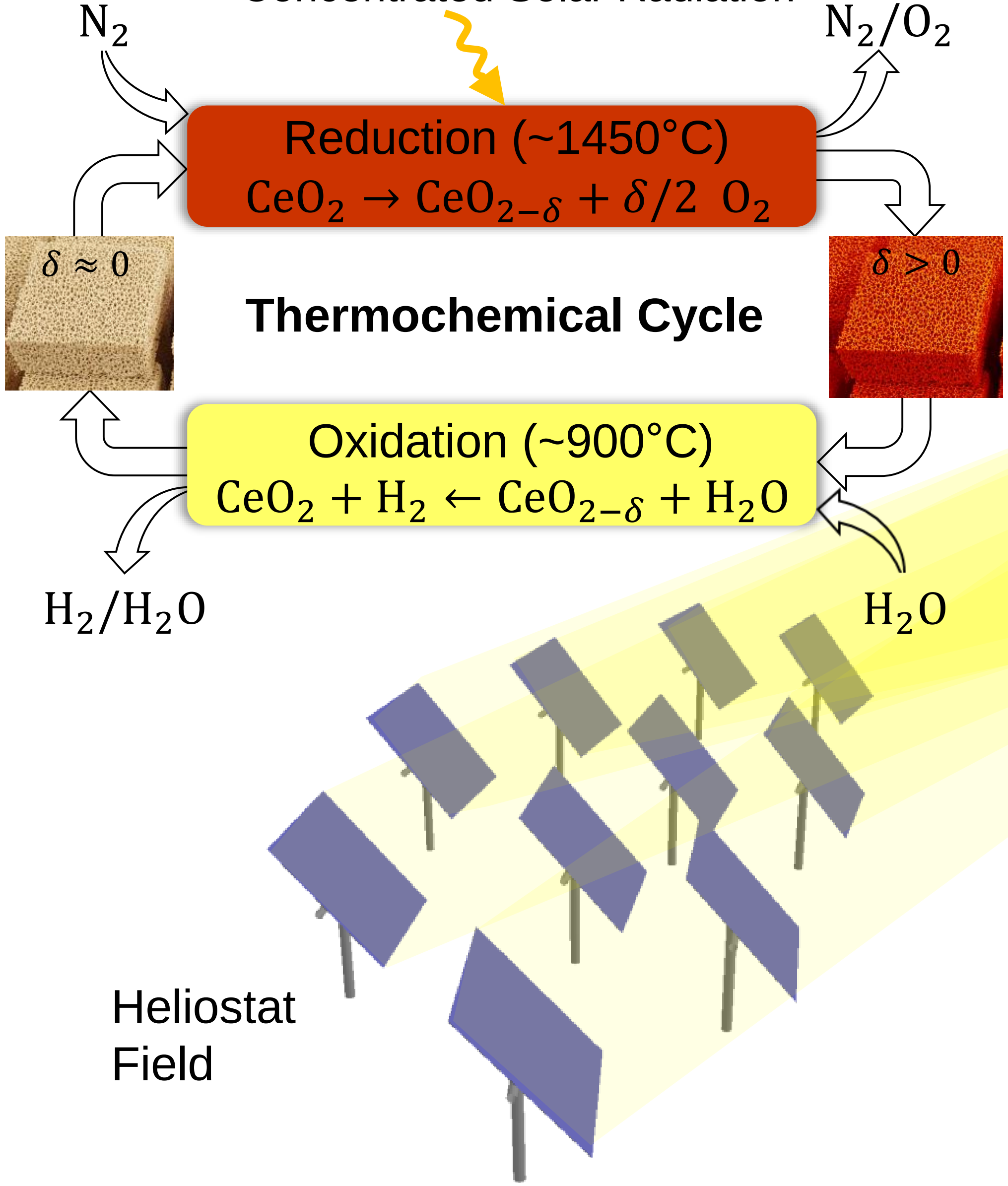
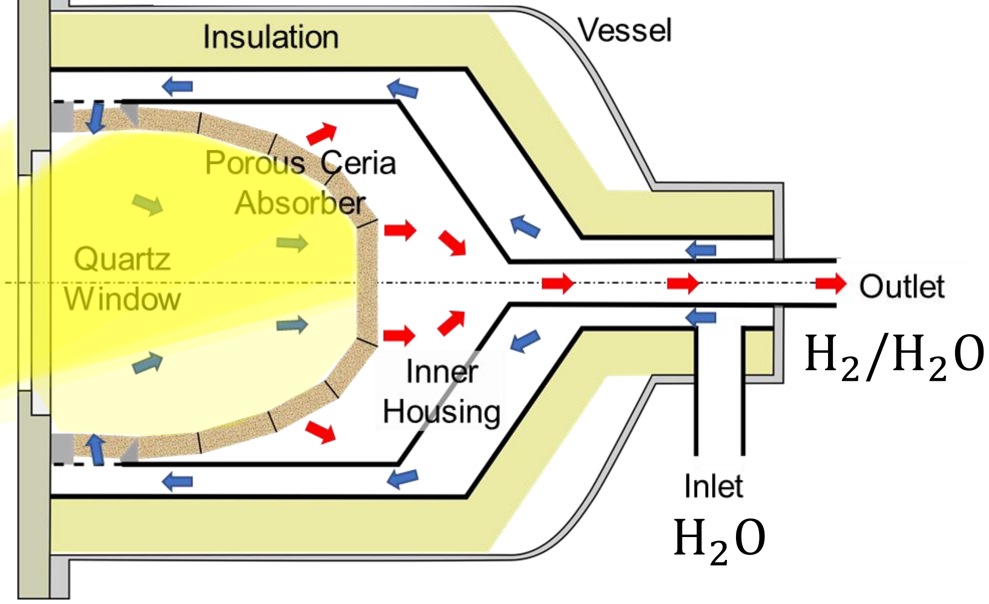
# Thermochemical Redox Cycle for Hydrogen Generation

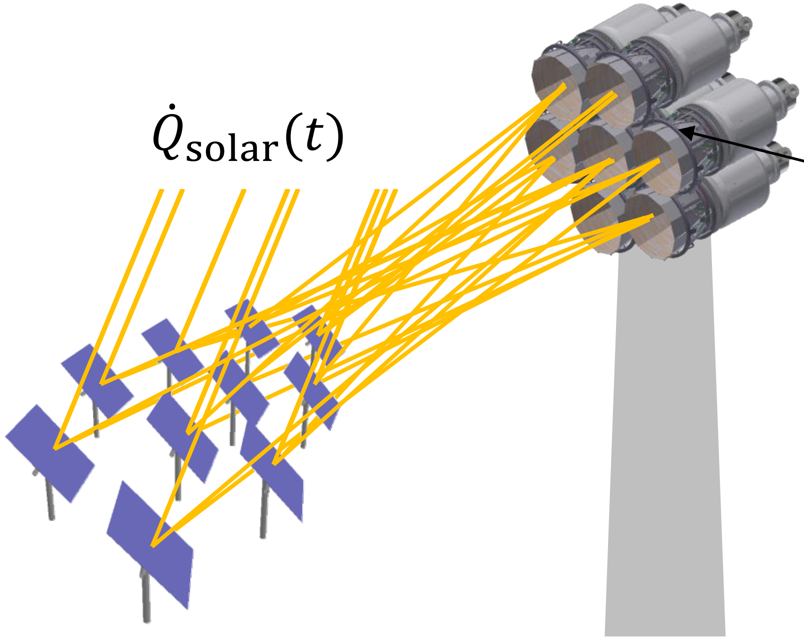



## Hydrosol/ASTOR Batch Reactor Concept

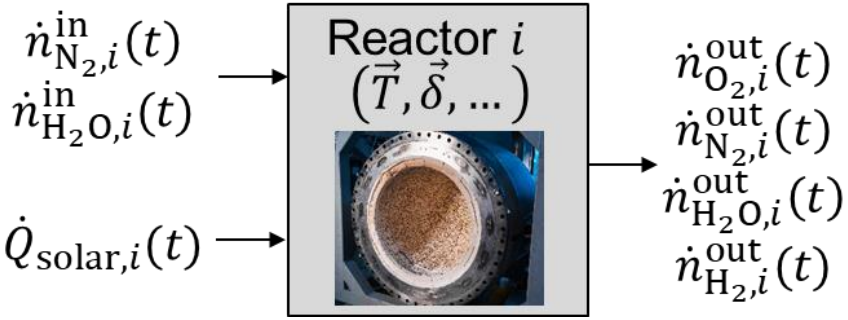



Solar Batch Reactor (window removed)

# Scaled Plant with Multiple Reactors




Receiver with several reactors $i$:




**Overall Hydrogen Production:** $n_{\mathrm{H_2}} = \int_{(1\ \mathrm{day})} \sum_{i}^{n_{\mathrm{react}}} \dot{n}^{\mathrm{out}}_{\mathrm{H_2},i}(t)\,\mathrm{d}t$

750 kW Hydrosol Plant (3 reactors)

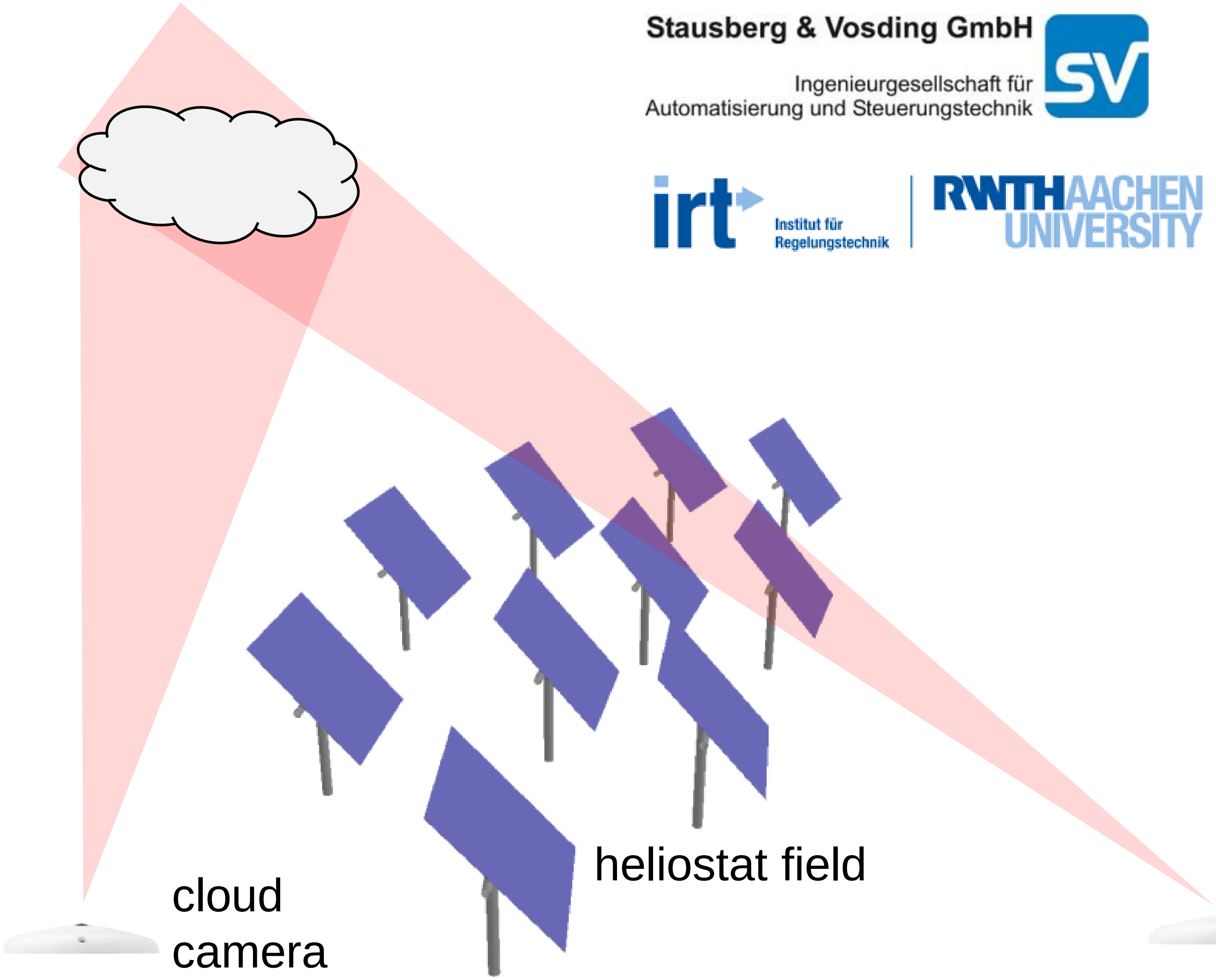
**Control Tasks:**

- maximize overall hydrogen production
- safe operation within the material limits of the reactors

**Manipulated Variables:**

- irradiation to each reactor $\dot{Q}_{\mathrm{solar},i}(t)$ by setting the heliostat aim points
- the inlet gas flows of each reactor (having only limited temperature control capability)

# Project SolarFuelNow
## Model Predictive Controller (MPC) with DNI Nowcasting




**Partners:**

Stausberg & Vosding GmbH – Ingenieurgesellschaft für Automatisierung und Steuerungstechnik

cspservices – concentrating solar power services

irt – Institut für Regelungstechnik | RWTH AACHEN UNIVERSITY

DLR – Institute of Future Fuels & Institute of Solar Research

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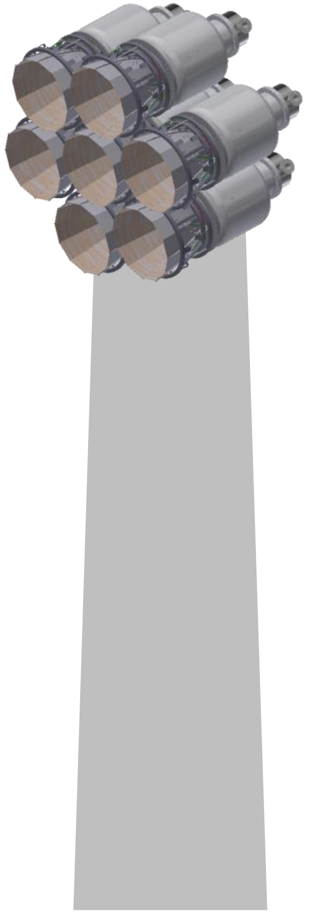
on the basis of a decision by the German Bundestag



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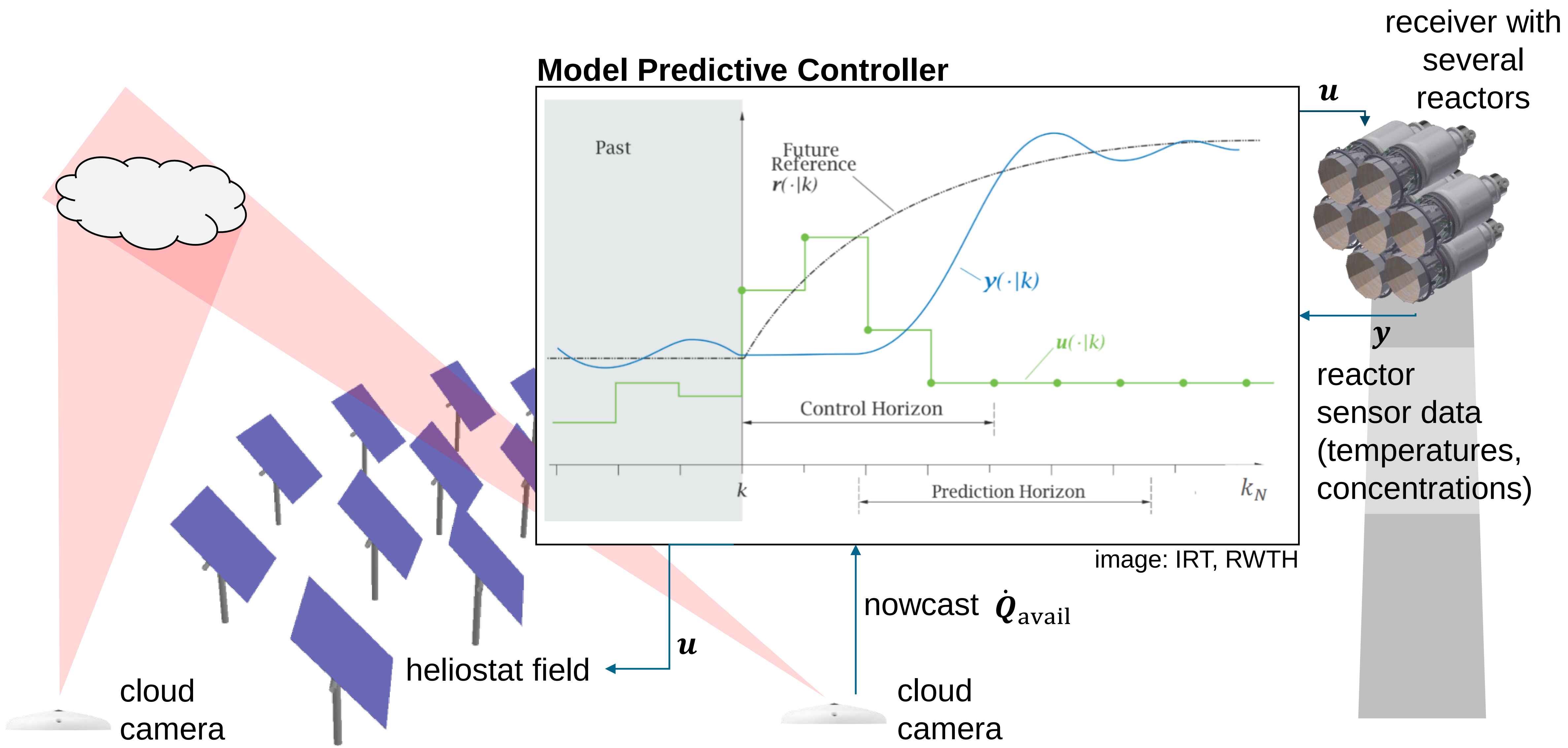

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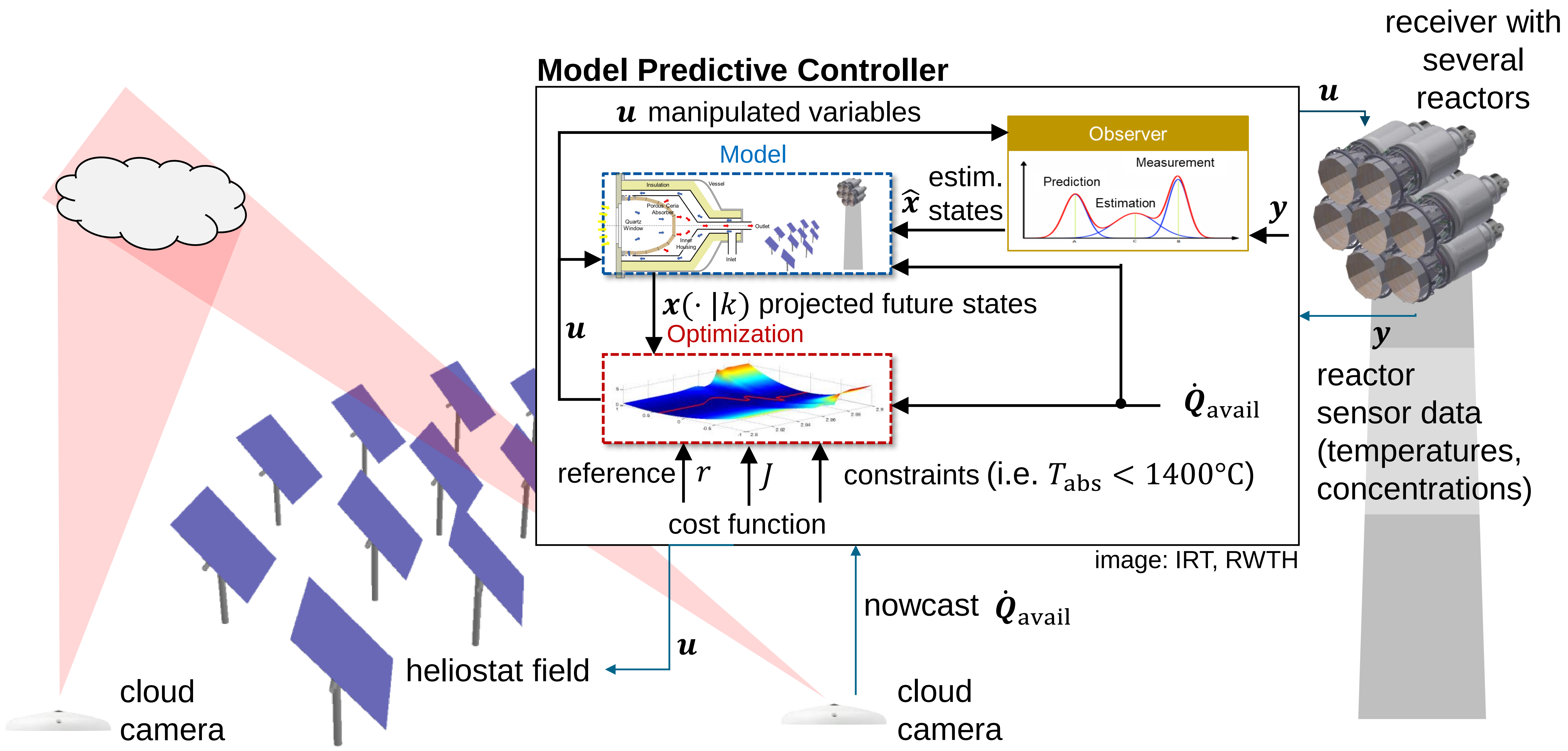
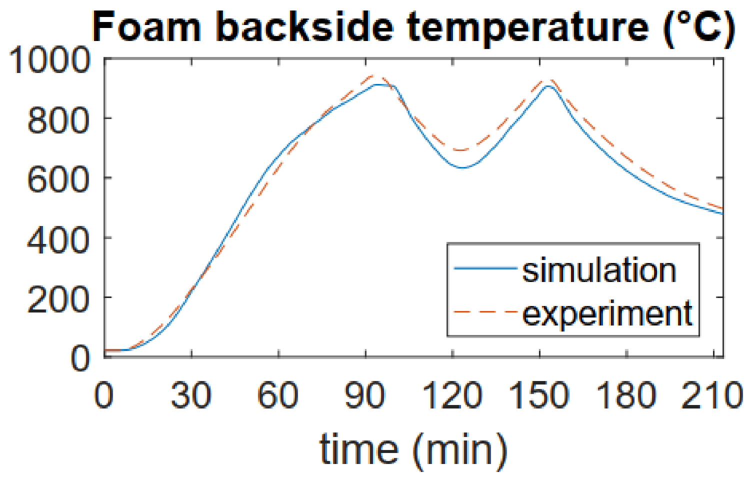
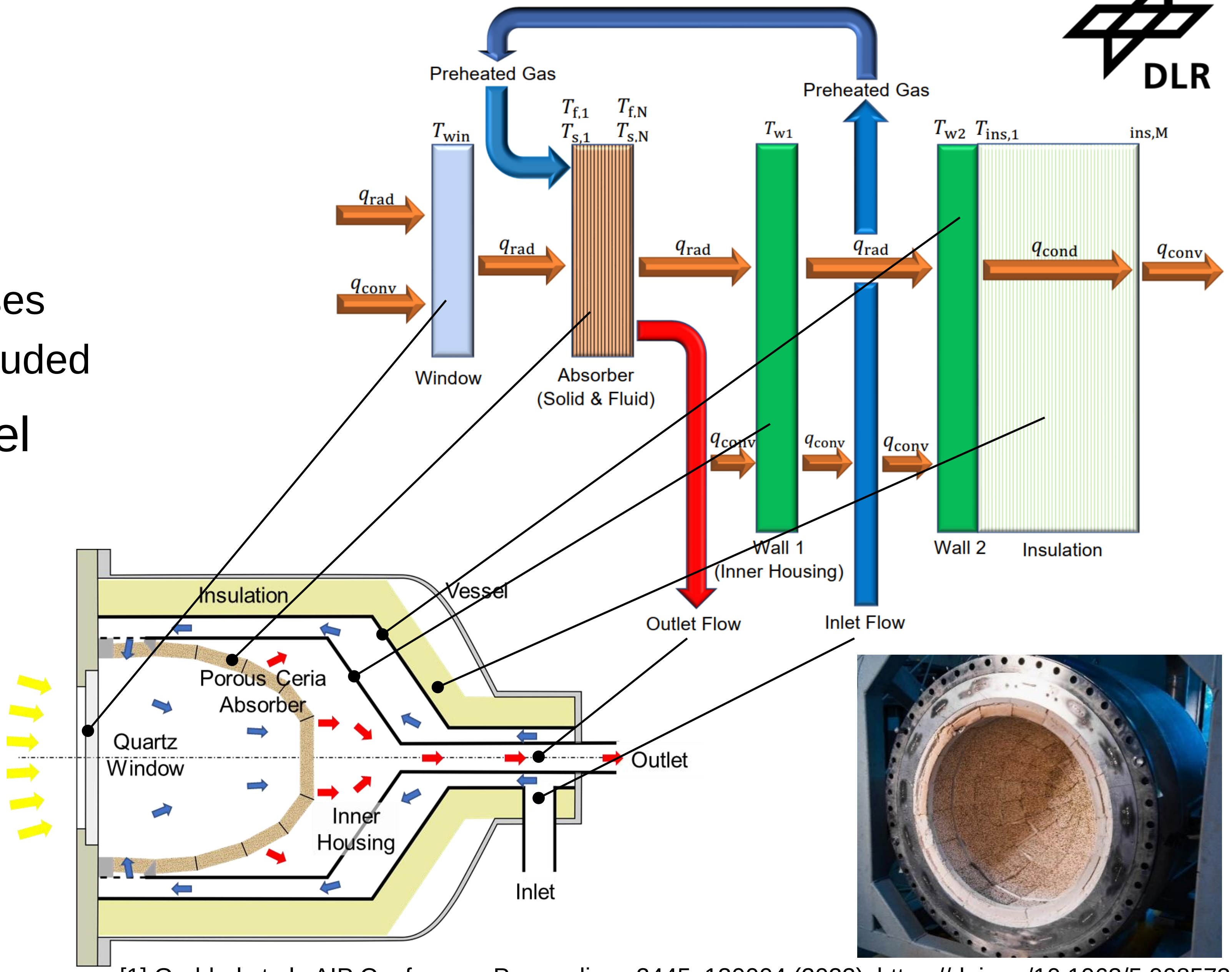


# Reactor Model

- Absorber:
  - 1-D finite volume method
  - Coupled fluid & solid phases
  - Reduction & oxidation included
- Spectral view factor model
- Gas preheating included
- Validated

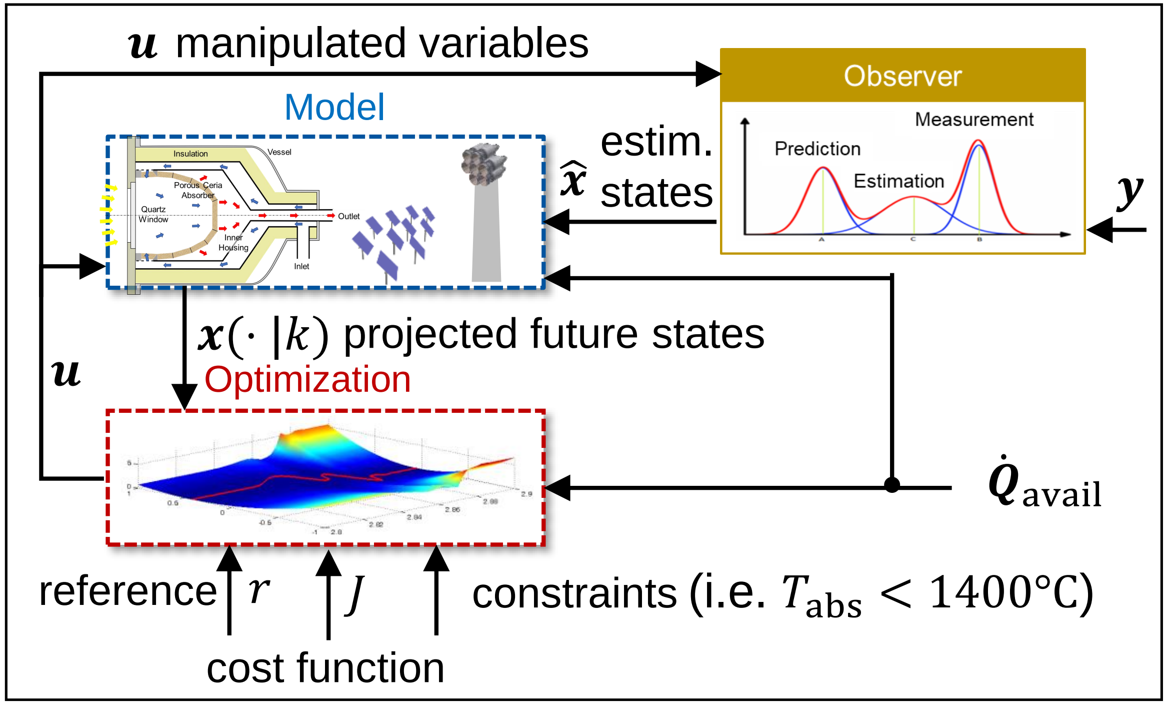




[1] Grobbel et al., AIP Conference Proceedings 2445, 130004 (2022); https://doi.org/10.1063/5.0085738
[2] Oberkirsch et al., *Solar Energy* 243 (2022): 483-493. https://doi.org/10.1016/j.solener.2022.08.007

# MPC: Working Principle and Cost Function




$$\boldsymbol{u} = \begin{pmatrix} \dot{Q}_1 \\ \dot{Q}_{n_\text{react}} \\ \vdots \\ \dot{n}^\text{in}_{\text{N2},1} \\ \dot{n}^\text{in}_{\text{H2O},1} \\ \vdots \\ \dot{n}^\text{in}_{\text{N2},n_\text{react}} \\ \dot{n}^\text{in}_{\text{H2O},n_\text{react}} \end{pmatrix}$$

minimize $J(\boldsymbol{u}(\cdot\,|k))$

subject to:

$\boldsymbol{x}_{k+1} = f(\boldsymbol{x}_k, \boldsymbol{u}_k)$ (model)

$0 < \sum u_{i,k} < \dot{Q}_{\text{avail},k}$

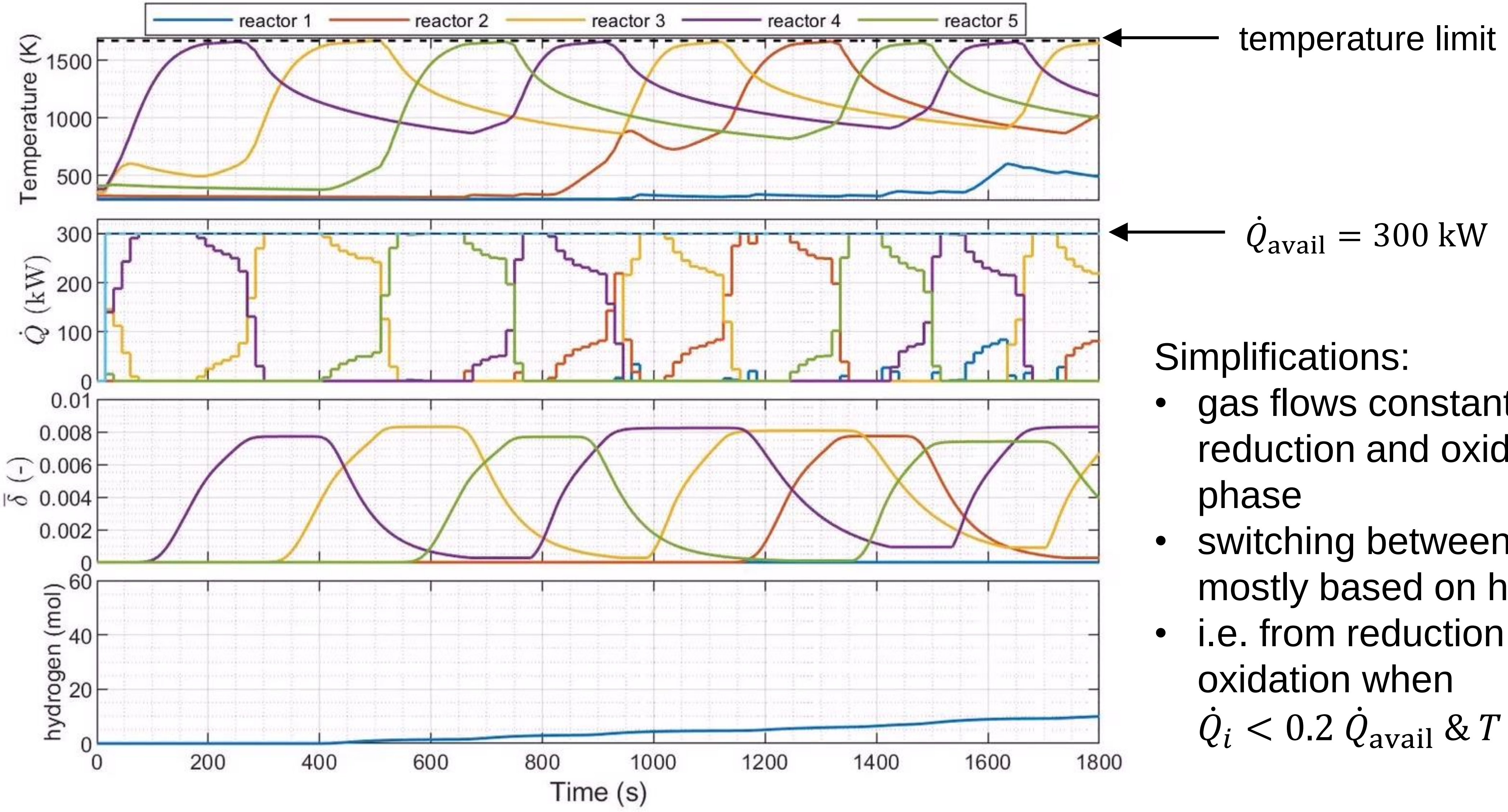
$0 < T_\text{front} - s_k < 1673\ K$

$0 < s_k$ (constraints)

$$J(\boldsymbol{u}(\cdot\,|k)) := \sum_{j=k+1}^{k+10} \left[ \left\| r_j - \sum_{j=1}^{n_\text{react}} \bar{\delta}_{i,j} \right\|^2_{\boldsymbol{R}_\delta} + \left\| s_j \right\|^2_{\boldsymbol{R}_s} + \left\| s_j \right\|_{\boldsymbol{R}_{sl}} \right] + \sum_{j=k}^{k+9} \left[ \left\| \dot{Q}_{\text{avail},j} - \sum_{i=1}^{n_\text{react}} u_{i,j} \right\|^2_{\boldsymbol{R}_{Q1}} + \left\| \Delta \boldsymbol{u}_j \right\|^2_{\boldsymbol{R}_{Q2}} \right]$$

- increase overall reduction extent
- avoid exceeding absorber front temperature
- use as much radiation as possible
- avoid rapid changes in flux

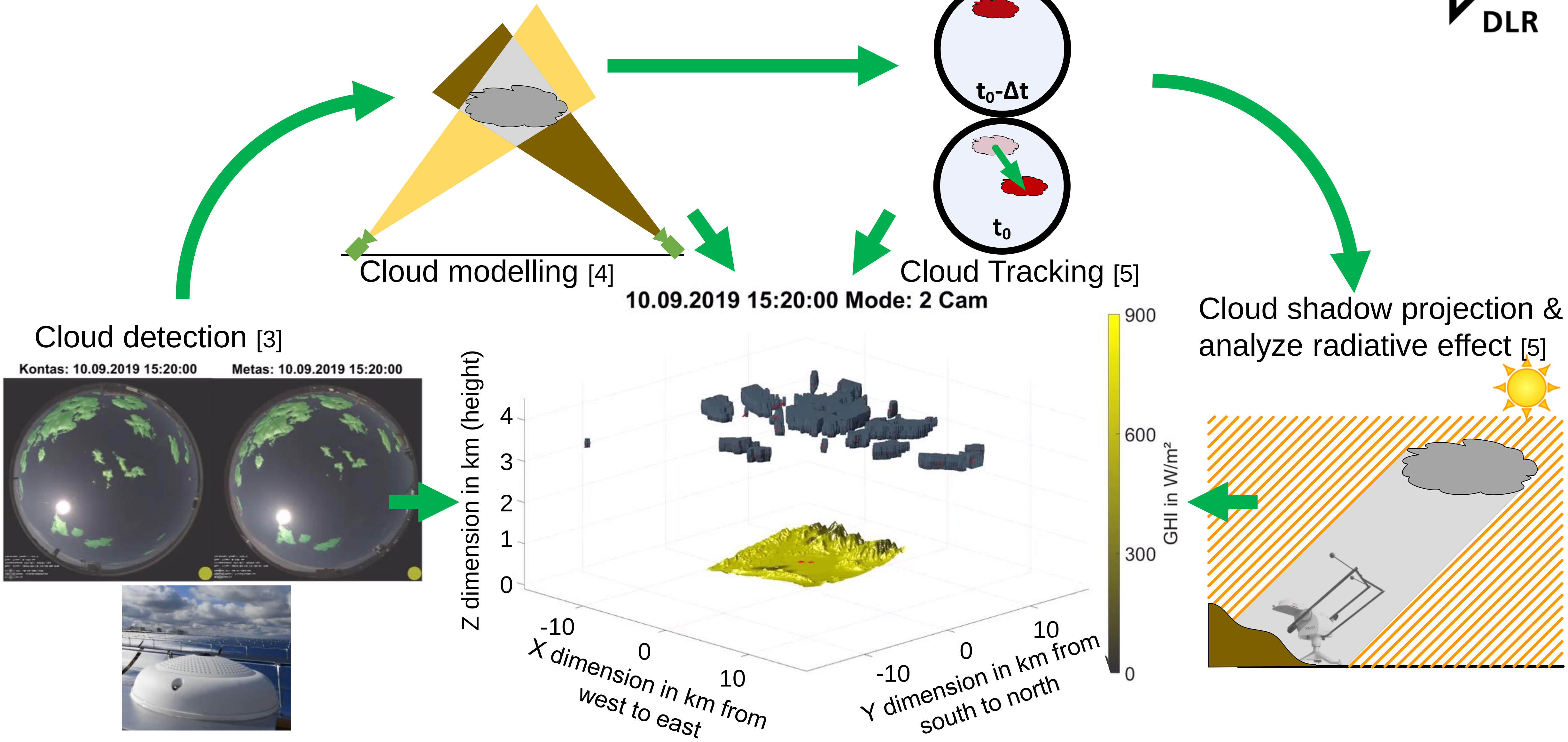
# Constant $\dot{Q}_{\mathrm{avail}}$ and 5 Reactors




Simplifications:

- gas flows constant during reduction and oxidation phase
- switching between states mostly based on heuristics
- i.e. from reduction to oxidation when $\dot{Q}_i < 0.2\,\dot{Q}_{\mathrm{avail}}\ \&\ T > 1300\ K$

# All Sky Imager-Based Nowcasting



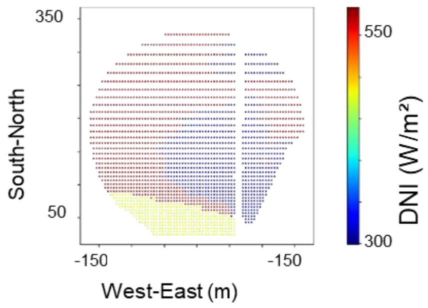



[3] Fabel, Yann, et al., doi: 10.5194/amt-15-797-2022 [4] Nouri, Bijan, et al., doi: 10.1016/j.solener.2018.10.079 [5] Nouri, Bijan, et al., doi: 10.1016/j.solener.2019.02.004

# Implementation at Solar Tower Jülich: System Overview

- has access to all system data from PLC
- uses physical model of reactor in state space form
- plans which reactors will be operated in the next 15-20 minutes
- decides when to start the reduction or oxidation in each reactor

- nowcasts with probability information
- DNI predicted for next 20 minutes




**Model Predictive Controller (MPC)**

$$\max_{\dot{Q},\dot{n}_{N2},\dot{n}_{H2O}} n_{H_2}$$

sets fluxes and gases for reactors

sensor data, nowcast information

**WobaS (nowcasting)**

**STRAL (raytracer)**

possible reactor irradiations

**Programmable Logic Controller (PLC)**

**User Interface**

sensor data

actuator set points

**Solar Reactors**

set fluxes to reactors

- aim point optimization

**STRAL (raytracer)**

**HeliOS**

- heliostat field control software

safety defocus

**Heliostat Field**

- acts as OPC UA Server
- collects, distributes and stores data
- monitors variables and ensures safe operation

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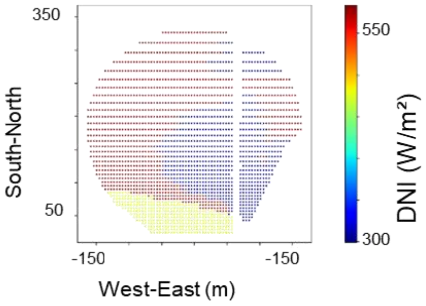



**Model Predictive Controller (MPC)**

$$\max_{\dot{Q},\dot{n}_{N2},\dot{n}_{H2O}} n_{H_2}$$

sets fluxes and gases for reactors

sensor data, nowcast information

**WobaS (nowcasting)** → **STRAL (raytracer)** — possible reactor irradiations → **Programmable Logic Controller (PLC)**

**User Interface** ↔ **Programmable Logic Controller (PLC)**

PLC — sensor data / actuator set points — **1 Real Solar Reactor**, **4 Reactor Mock-Ups**

PLC — set fluxes to reactors → **STRAL (raytracer)** ↔ **HeliOS** → **Heliostat Field**

PLC — safety defocus → **Heliostat Field**

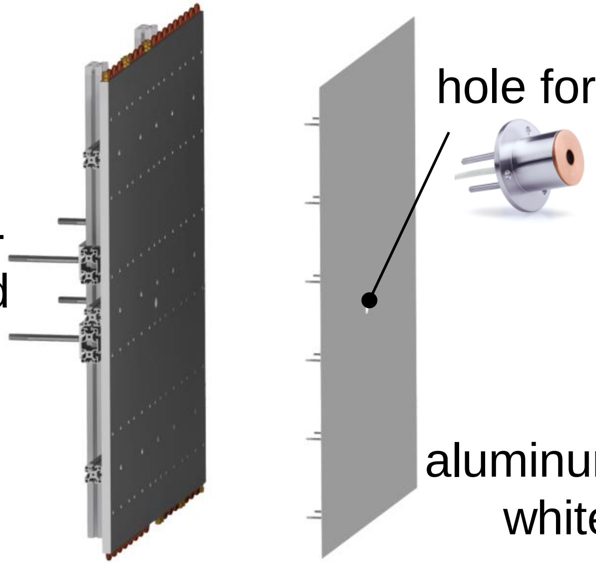
- aim point optimization

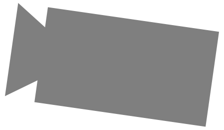
- heliostat field control software

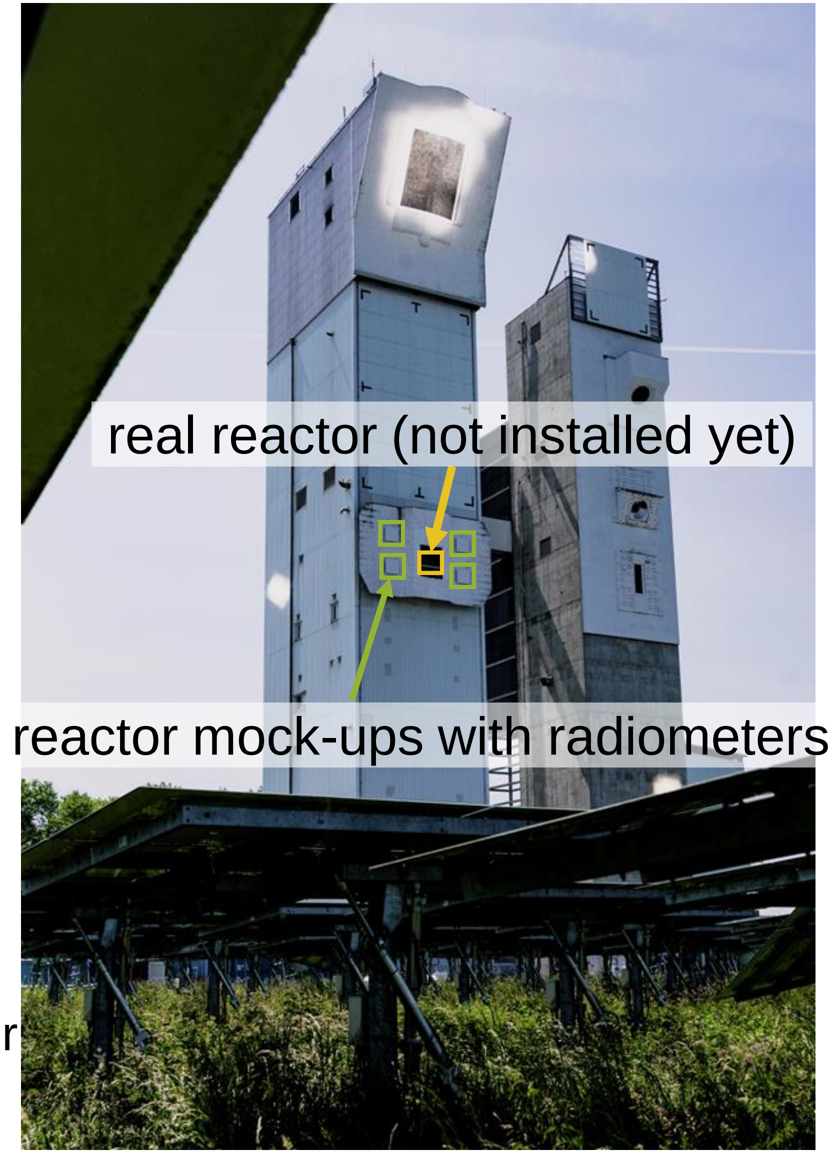
- acts as OPC UA Server
- collects, distributes and stores data
- monitors variables and ensures safe operation

- Only one real reactor
- Replacement of other reactors by cheap reactor mockups
- Sufficient to test the control approach

# Reactor Mockups




camera image → **flux density meas. FMAS** ← radiometer meas.

flux density meas. FMAS → flux in (virtual) secondary concentrator → **Detailed Reactor Model**

(virtual) inlet gas flows → **Detailed Reactor Model**

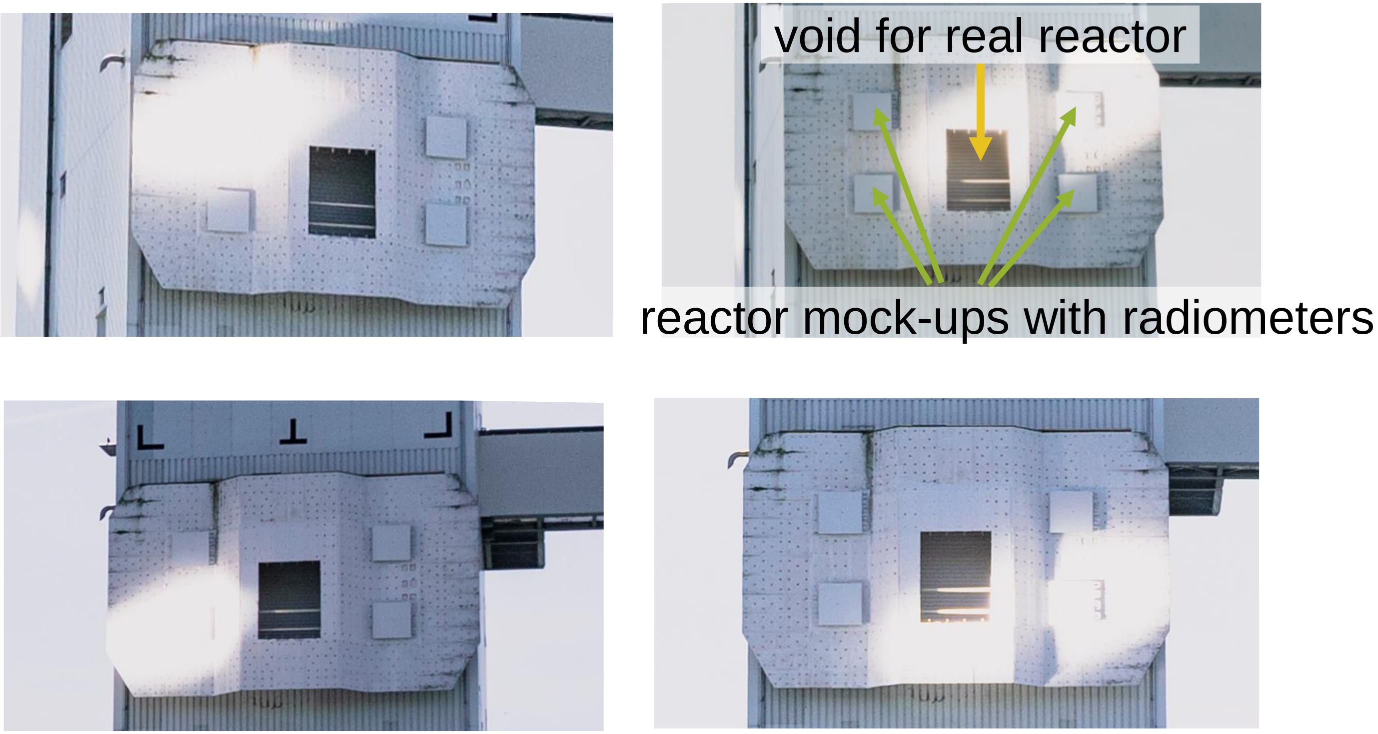
Detailed Reactor Model → temperatures…

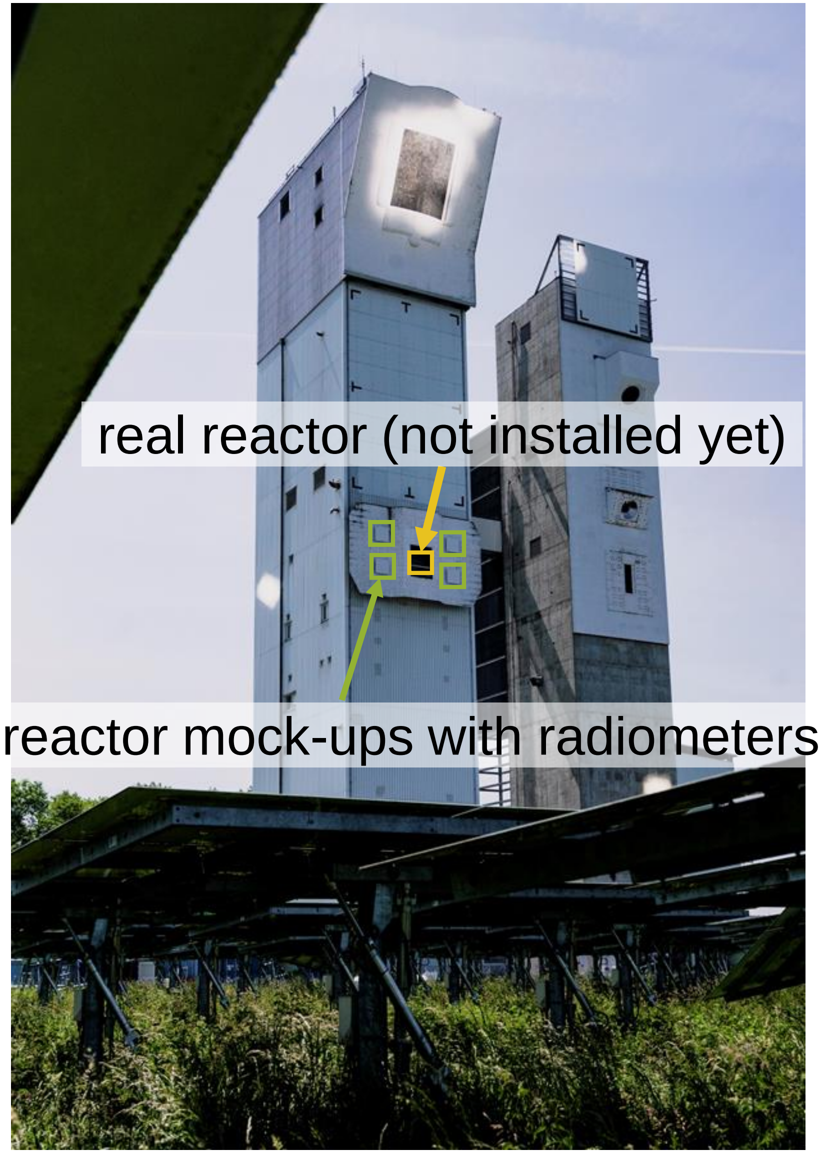
Detailed Reactor Model → outlet gas flows…

…at the same probe locations like in real reactor

**→Same I/O signals as for real reactor**

# Demonstration of MPC at Solar Tower Jülich




- First tests with reactor mockups ongoing
- Real reactor currently being installed
- Full system test in autumn this year

Images: DLR

# Summary

- Solar chemical processes have special characteristics
  - requirements for control differ from the ones for CSP plants
  - time-varying non-uniform flux density profile required at receiver
- A Model-predictive control for batch reactors has been developed
  - captures interdependency between reactors through coupling with heliostat field control
  - considers material constraints
  - incorporates probabilistic nowcasting information
  - most sophisticated control approach for these batch reactors so far
- The automatization of solar chemical processes is necessary to realize plants in larger scale

# Outlook

- Further demonstration at Jülich Solar Tower with one real reactor and 4 reactor mockups
- Control behavior strongly dependent on switching heuristics
  → should be improved (i.e. by long-term target selector)

# Acknowledgements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- Thanks to: Rudolf Popp, David Zanger, Ante Giljanovic, Thomas Fend, Gregor Piesche, Bijan Nouri, Yann Fabel, Birk Kraas, Laurin Oberkirsch, Stefan Schmitz, Dennis Thomey, Christian Sattler

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Federal Ministry
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# Imprint

Topic: Demonstration of a Model Predictive Control for a Cluster of Solar Chemical Batch Reactors

Date: 10.07.2023

Autor: Johannes Grobbel

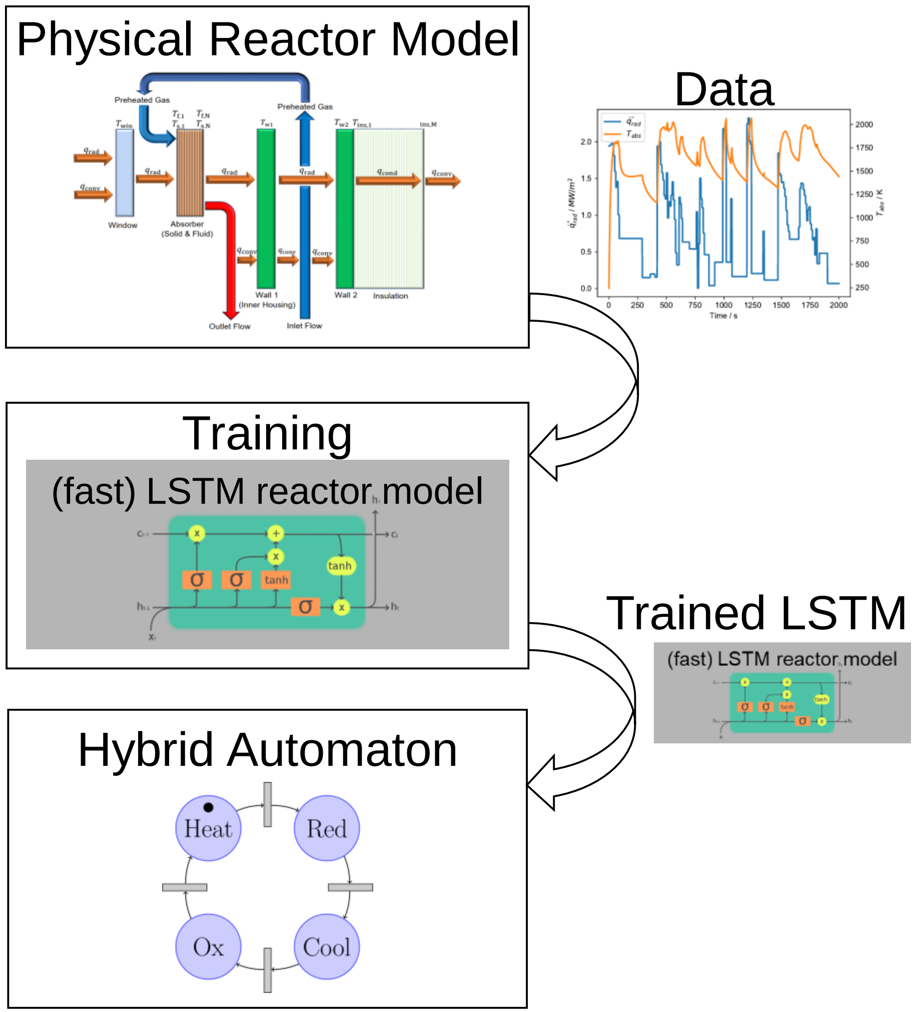
Institute: DLR Institut für Future Fuels

Images: DLR, RWTH Aachen, Plataforma Solar de Almeria, IMDEA

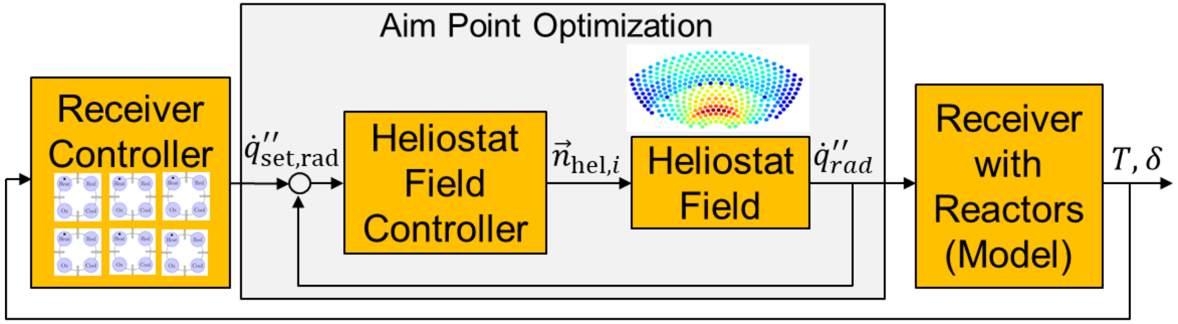
# BACKUP

# First Approach: Cascade Control in Project H2Loop

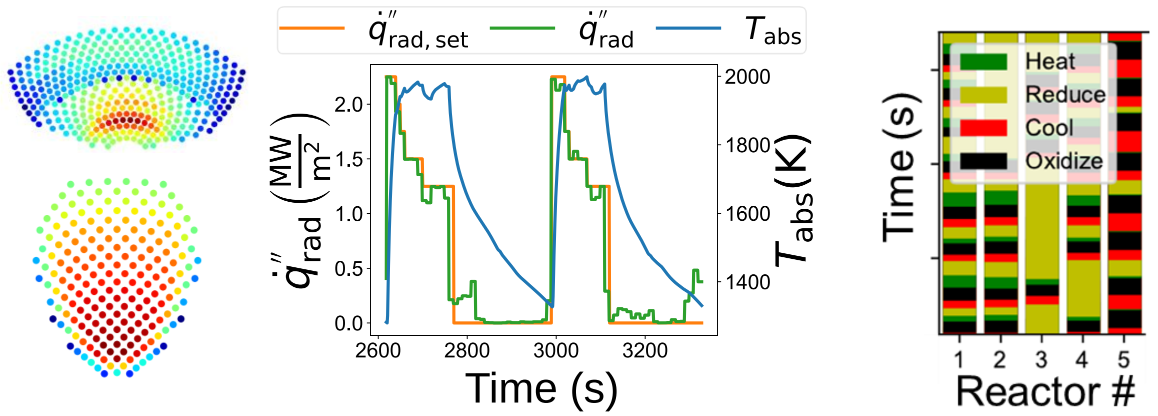
## Data-Driven Reactor Model




## Cascade Control




## Optimized Operation

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