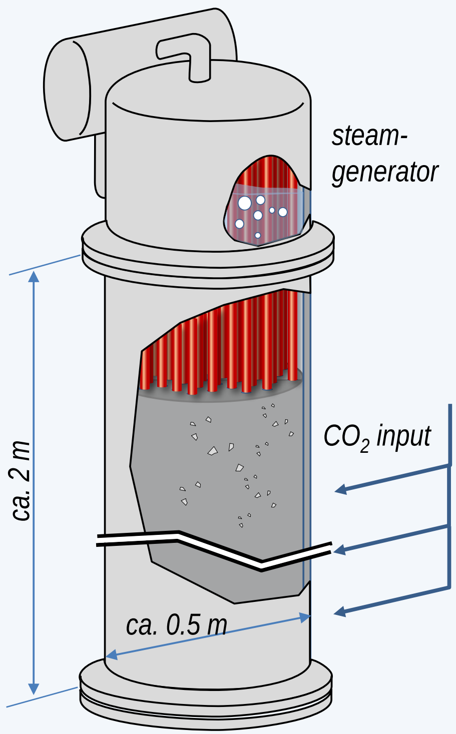
7th Intl. Conf. on Engineering for Waste and Biomass Valorisation, 02.07.2018

# Peak-Load High-Temperature Carbonate Storage




Christoph Lange
Chair of Energy Process Engineering
Friedrich-Alexander University
Erlangen-Nürnberg

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

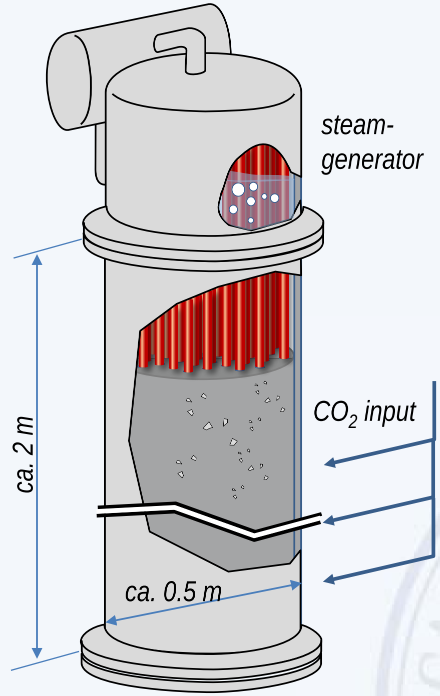
christoph.lange@fau.de
www.evt.tf.fau.de

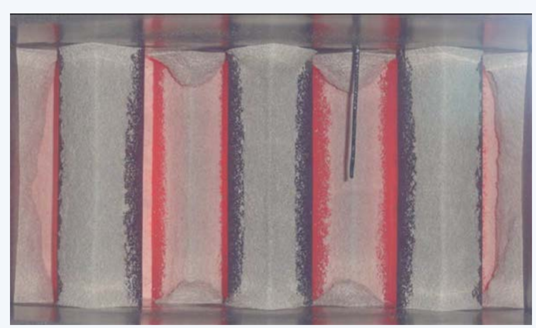
ENERGIE CAMPUS NÜRNBERG

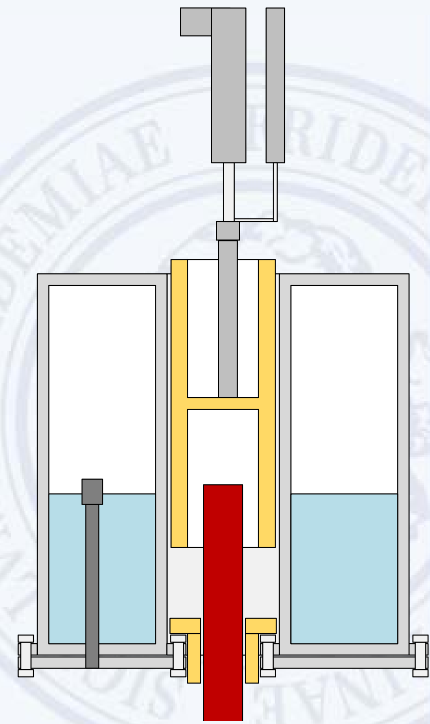
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT









Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

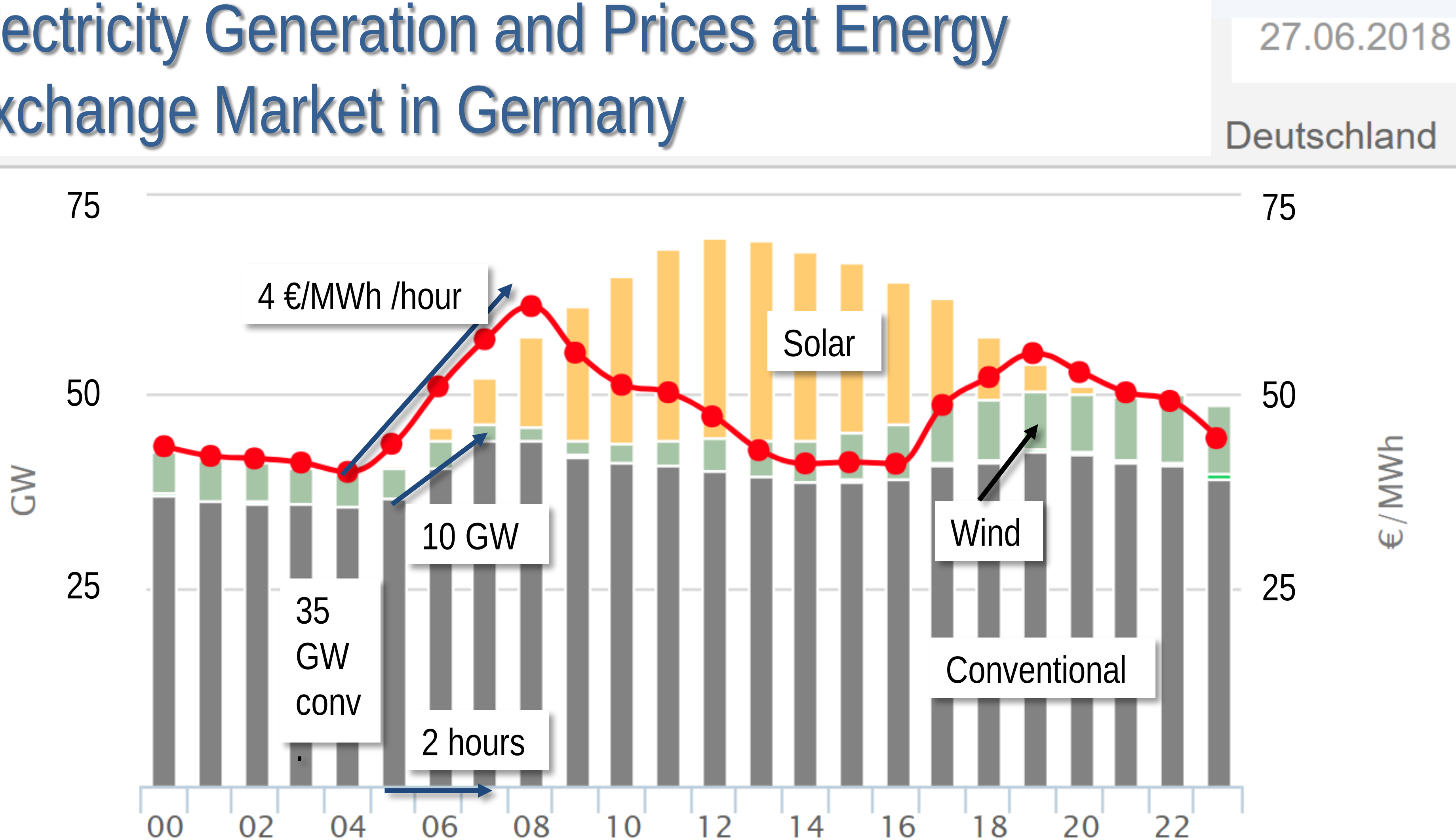


Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE CAMPUS NÜRNBERG

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE FAKULTÄT

# Electricity Generation and Prices at Energy Exchange Market in Germany




https://www.eex-transparency.com

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie



Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE CAMPUS NÜRNBERG

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE FAKULTÄT

# Why Peak-Load High-Temperature Storage?



power demand peaks

- high **load gradients** in morning and evening hours
- additional load fluctuation through renewables (> 35 % in Germany 2017)
- conventional power plants not flexible enough to compensate
- → need to enhance ability of steam power plants for load flexibility

high temperature storage → solution

- load shift: dynamic (high power density) and flexible (quick start up)
- high storage capacity (cheap material)
- but: short operating times:
  - high electricity prices available to make it feasible
  - lower investment costs through integration with existing infrastructure

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie



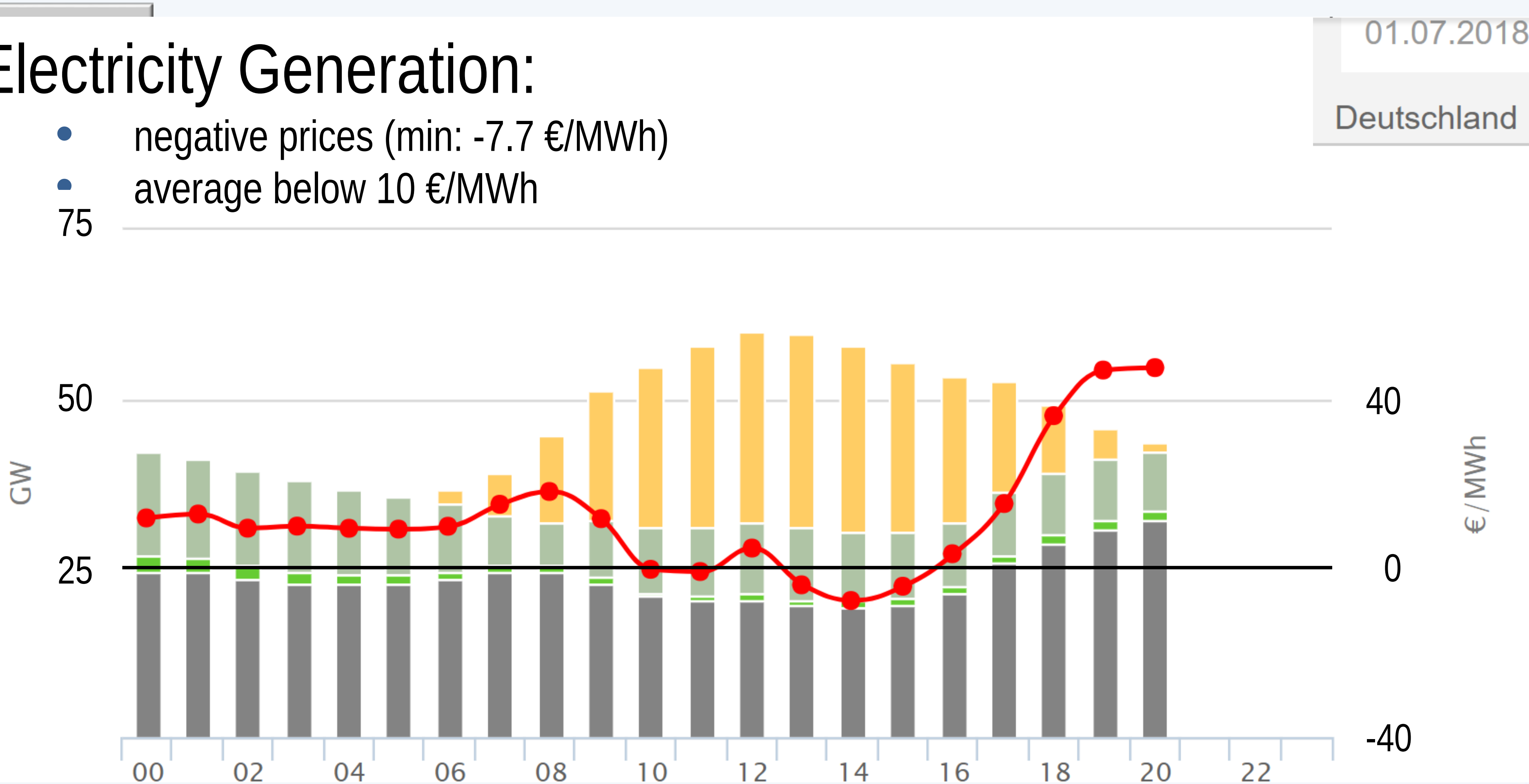
Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

# Why Peak-Load High-Temperature Storage?

Motivation

## Electricity Generation:

- negative prices (min: -7.7 €/MWh)
- average below 10 €/MWh






Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

ENERGIE CAMPUS NÜRNBERG

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

# Concept: High Temperature Carbonate Storage

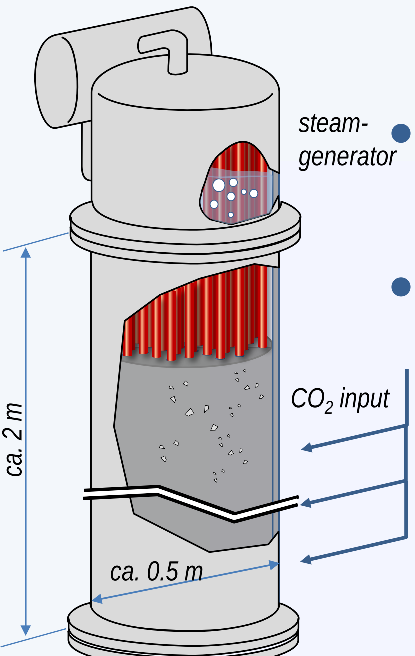


- calcination heated through **surplus electricity**
- carbonation for discharge/heat output to steam generator

$$CaCO_3(s) \leftrightarrow CaO(s) + CO_2(g)$$

$$\Delta h_R^0 = 182\ kJ/mol$$

→ high energy/power density (630 kWh/m³//65 kW/m³ reactor volume)




- sodium heat pipes: ideal heat transfer and isothermal temperature profile
  - increased reaction zone, high power output possible
- Pressure variation for fast change variation of equilibrium at 850 °C
  - → no need for heating up or cooling down
  - even if storage cools down a little, carbonation works even better

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie



christoph.lange@fau.de
www.evt.tf.fau.de

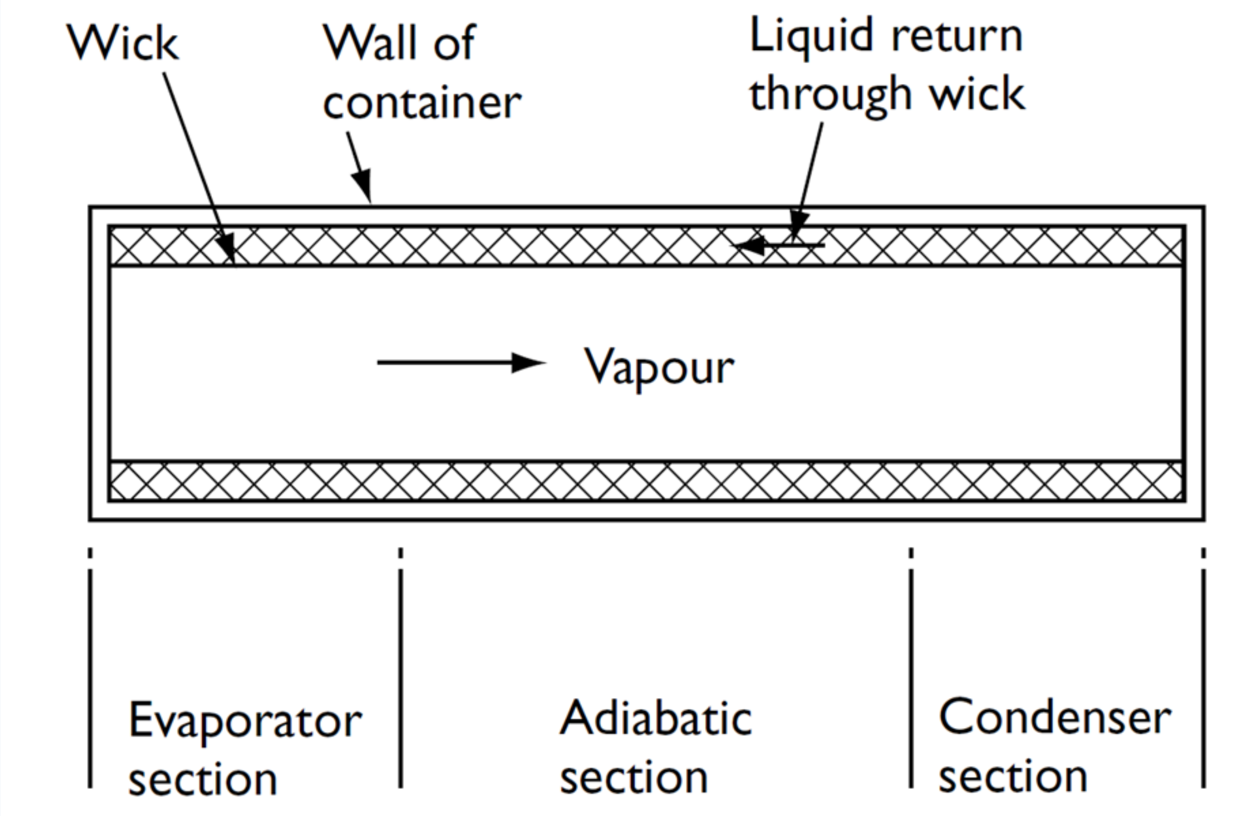
ENERGIE CAMPUS NÜRNBERG

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

# Function of heat pipe



- isothermal temperature over whole length
- evaporation/condensation heat transfer >> latent/convection heat transfer




Quelle: Kew, D. R. (2007). Heat Pipes Theory, Design and Applications; 5th Edition





Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE CAMPUS NÜRNBERG

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE FAKULTÄT

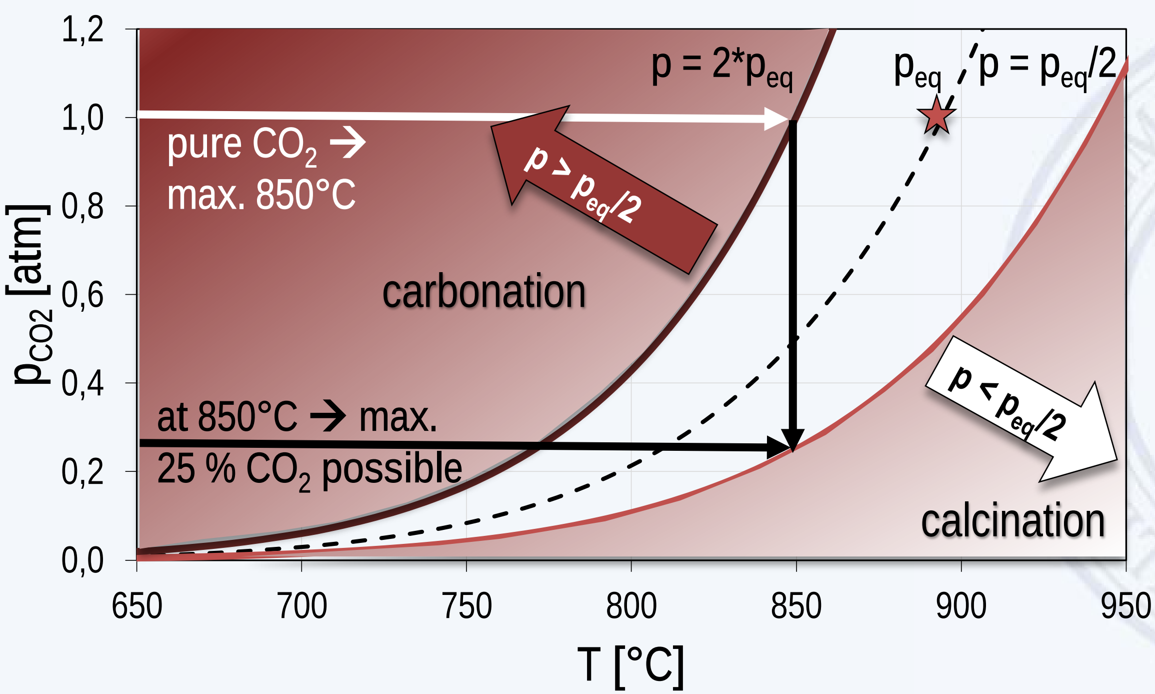
# Equilibrium



- carbonation with high $p_{CO2}$ and „low" temperatures
- calcination with low $p_{CO2}$ (< ½ $p_{eq}$) [1] and „high" temperatures
- TGA result: at 850 °C similar reaction times carbonation/calcination in TGA

isothermal?!

equilibrium pressure carbonation/calcination




1 Kubato et al. 2000 – Study of decarbonation of CaCO3 for high temperature thermal energy storage



Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

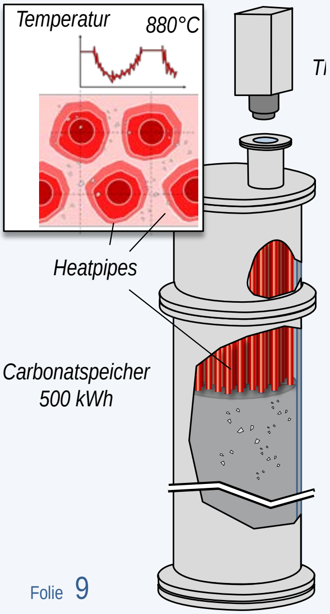
ENERGIE CAMPUS NÜRNBERG

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

# Project goals


Motivation
Concept
Charge
Discharge
Summary


- proof-of-concept in pilot plant: 250 kWh, 20 $kW_{th}$
  - isothermal temperature profile in carbonate bed through heat pipes
  - isothermal operation: carbonation and calcination at same temperature level
- experimental investigations:
  - fluidisation with varying $CO_2$ partial pressure
  - heat transfer measurements in fixed/fluidised bed
  - optimisation of process conditions
    – dynamic power output
    – cyclic stability and cycle number of $CaO/CaCO_3$
- feasibility analysis:
  - technical and economical investigation
  - steam injection to different pressure levels in power plants



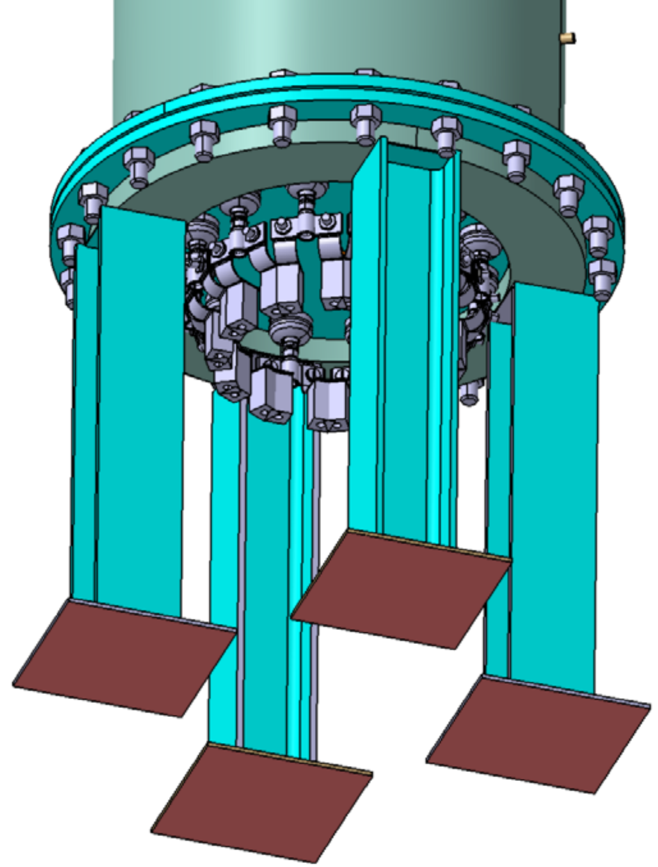



Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl
christoph.lange@fau.de
www.evt.tf.fau.de

# Charging/Heating





## design challenges

- 20 kW electrical heating
- 2 kW/heat pipe at 1000 °C
- heat transfer in & out with heat pipes
- minimisation of losses during storage

## idea

- integration of heating elements in heat pipe bottom


| | heating wire Kanthal | SiC heating element |
|---|---|---|
| surface load density | up to 2 W/cm² | up to 16.5 W/cm² |
| stability up to | 1300 °C | 1600 °C |
| required heated length | 2 m | 0,25 m |

Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE CAMPUS NÜRNBERG

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE FAKULTÄT



# Charging/Heating

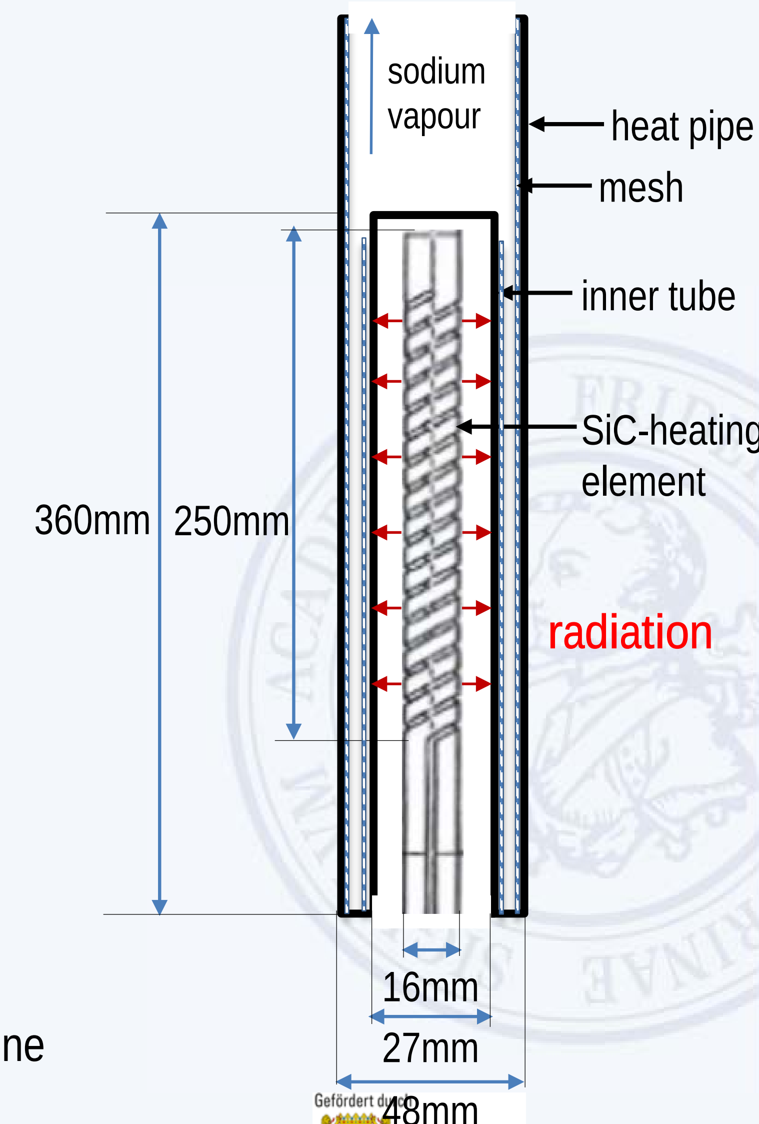
## challenges

- electrical insulation, fragility, thermal expansion
- temperature control essential
- HP dry-out: inner mesh & sodium filling ratio

| Location | Temperature |
|---|---|
| $CaCO_3$ | ca. 850°C |
| heat pipe | ~~ca. 900°C~~ 850°C |
| inner tube | ca. 930°C |
| SiC-element | ca. 1250°C |

ΔT ≈ 50K

ΔT ≈ 300K




## first results

- 2 kW transferred
- increased heat transfer resistance in heating zone through new HP concept → solve!



Gefördert durch Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE
CAMPUS
NÜRNBERG

Gefördert
Bayerisch
Wirtschaf
und Techn

arl

ENERGIE CAMPUS NÜRNBERG

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE FAKULTÄT

# Discharge with fluidized bed carbonation



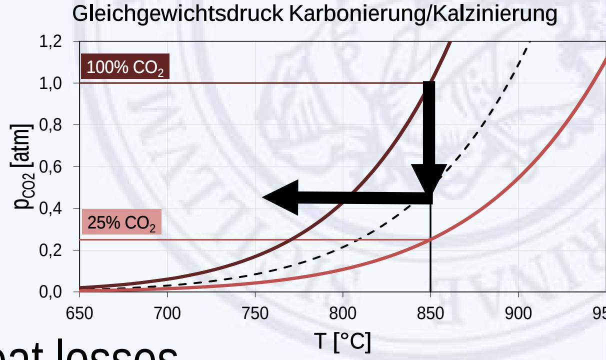
challenge

- $CO_2$ flow/fluidisation diminishes in reactor
- limitation for heat transfer: heat transfer from $CaCO_3$ to heat pipes

→ sufficient/stable fluidization in whole reactor necessary (u/u0 > 1.5)!

options

1. reactor diameter < 0.4 m. **but**: constant capacity makes it taller
2. higher $CO_2$ volume flow. **but:** added heat losses/higher power output
3. fine particles < 200 µm for lower $u_{mf}$, **but**: cohesive
4. dilution with $N_2$/steam during carbonation
   - higher fluidisation at bed surface
   - possibly higher cyclic CaO conversion
   - **but**: decreasing operating temperature, added heat losses




→ **compromise to be found in pre-tests**

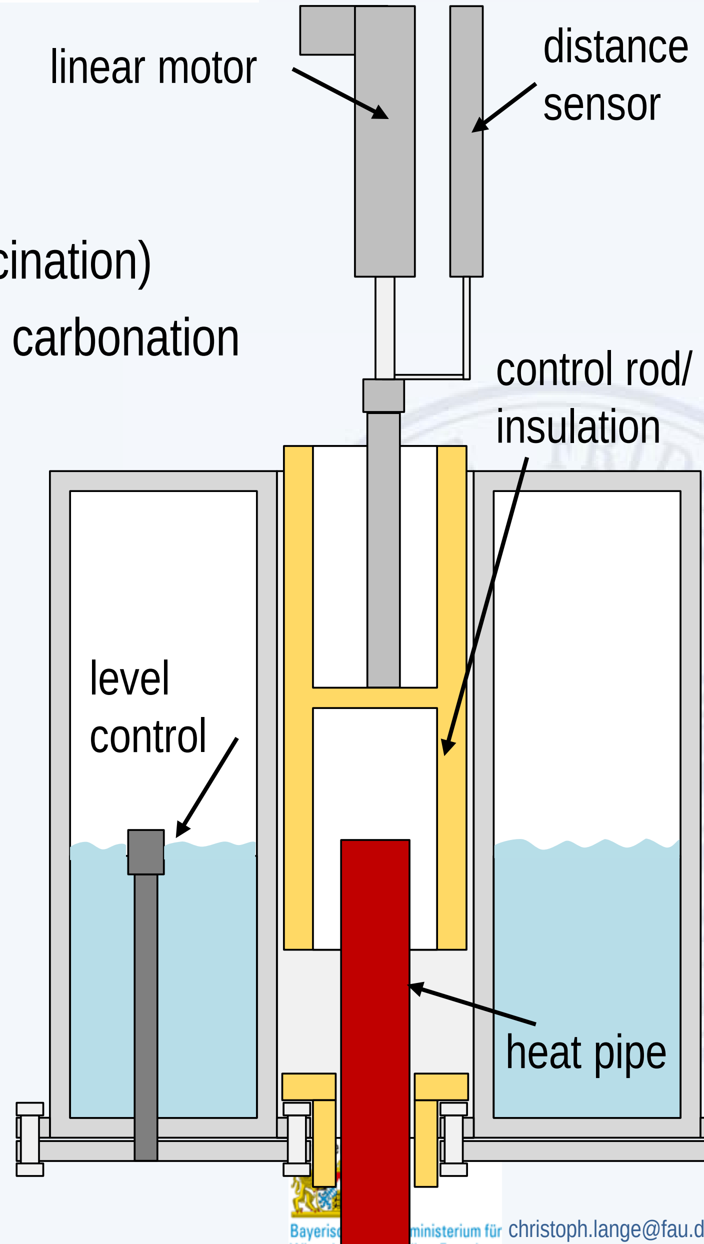
Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie



christoph.lange@fau.de
www.evt.tf.fau.de
Department Chemie- und Bioingenieurwesen (CBI) • Lehrstuhl für Energieverfahrenstechnik • Prof. Dr.-Ing. Jürgen Karl

# Discharge/Steam Generator






## challenge

- insulation during storage and charging (calcination)
- dynamic & flexible power generation during carbonation
- → dynamic control and safety

## experimental

- 1 HP, pressure up to 5 bar, saturated vapour
- characterisation of operating behaviour depending on power demand
- fluidised bed reactor under construction

## results

- first tests with 20 mm microporous insulation
- 350 W loss over steam generator for 850°C heat pipe



christoph.lange@fau.de
www.evt.tf.fau.de

ENERGIE CAMPUS NÜRNBER

# Summary

Thank you for your Attention!



- **isothermal** high temperature carbonate storage can support conventional power plants during **high load gradients**
- multiple applications for integration to power plant
- variation of $p_{CO2}$ allows quick switch between charge/ discharge mode and variety of temperature levels
- currently test of different components regarding charge/discharge
  → compromise for fluidised bed operation
- construction of pilot plant in 2019 for proof-of-concept
- optimisation of operating conditions
  - for dynamic operation
  - for cyclic stability of $CaO/CaCO_3$