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TECHNISCHE HOCHSCHULE MITTELHESSEN
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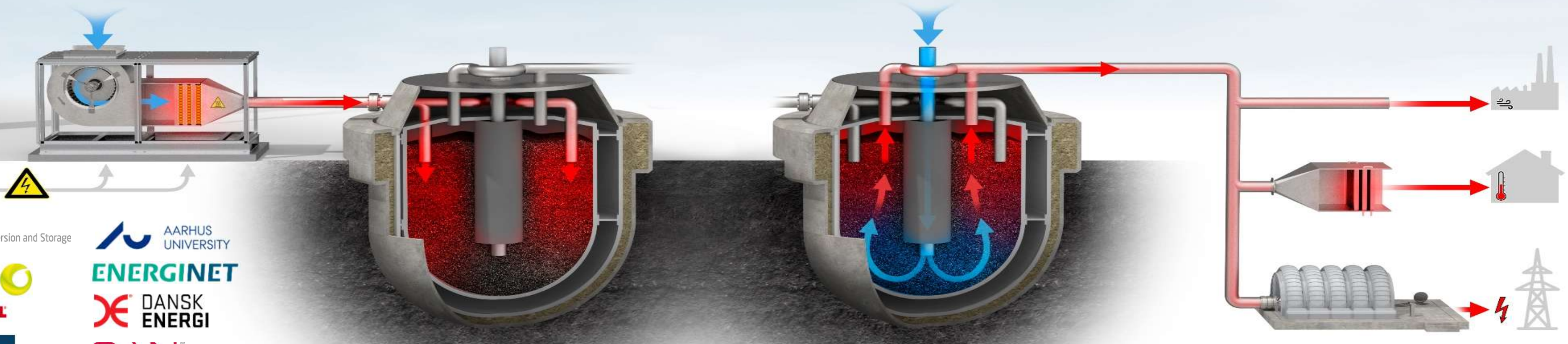
Zentrum für Energietechnik
und Energiemanagement

Hochtemperaturspeicher
und ihre Einbindung in Quartierskonzepte

Innovativer Schüttgut-Hochtemperaturspeicher

DTU

Kai Knobloch
Department of Energy Conversion and Storage, Technical University of Denmark



DTU Energy
Department of Energy Conversion and Storage
AARHUS UNIVERSITY
seas-nve
ENERGINET
ROCKWOOL
DANSK ENERGI
eUDP
Energiteknologisk udvikling og demonstration
SAN
Electro Heat

Energy Technology Development and Demonstration Program

EUDP
Energiteknologisk udvikling og demonstration

ROCKWOOL

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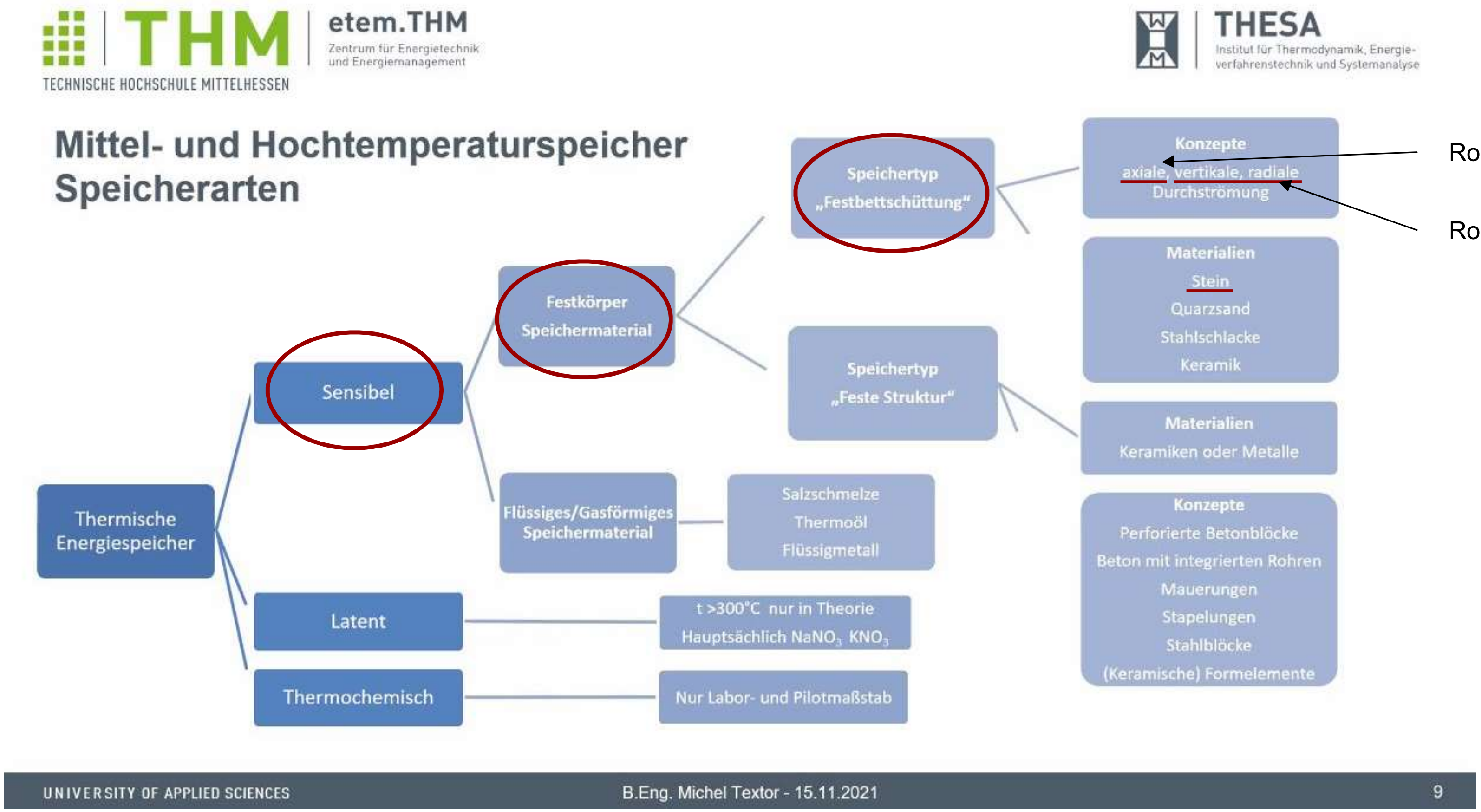

TECHNISCHE HOCHSCHULE MITTELHESSEN

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Zentrum für Energietechnik
und Energiemanagement

THESA
Institut für Thermodynamik, Energieverfahrenstechnik und Systemanalyse

Mittel- und Hochtemperaturspeicher
Speicherarten

Thermische Energiespeicher

- Sensibel
  - Festkörper Speichermaterial
    - Speichertyp „Festbettschüttung“
      - Konzepte: axiale, vertikale, radiale Durchströmung
      - Materialien: Stein, Quarzsand, Stahlschlacke, Keramik
    - Speichertyp „Feste Struktur“
      - Materialien: Keramiken oder Metalle
      - Konzepte: Perforierte Betonblöcke, Beton mit integrierten Rohren, Mauerungen, Stapelungen, Stahlblöcke, (Keramische) Formelemente
  - Flüssiges/Gasförmiges Speichermaterial
    - Salzschmelze, Thermoöl, Flüssigmetall
- Latent
  - t >300°C nur in Theorie
  - Hauptsächlich $NaNO_3$ KNO_3
- Thermochemisch
  - Nur Labor- und Pilotmaßstab

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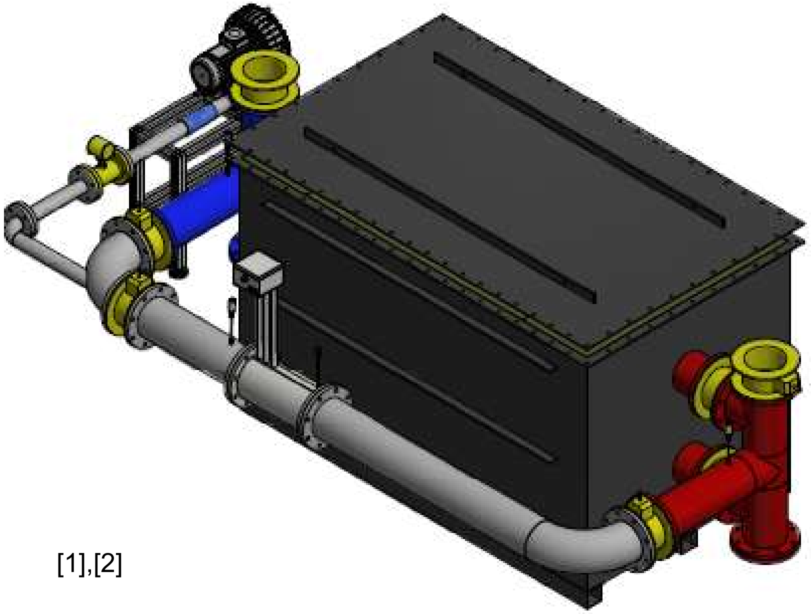
Rock bed 1.0

Rock bed 2.0

Design ● ○ ○ Testing ○ ○ ○ ○ Degradation ○ ○

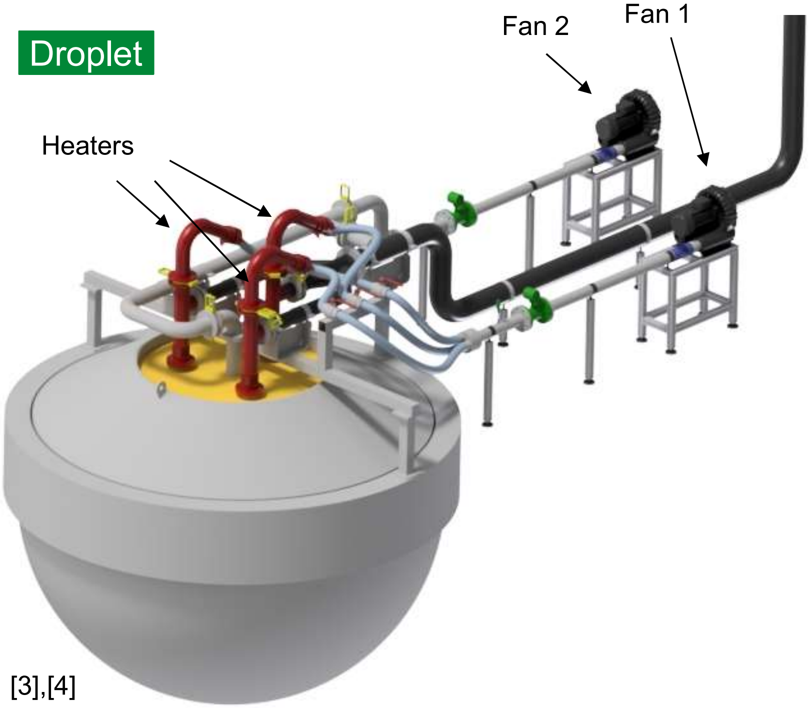
Rock Bed 1.0 and 2.0 at DTU Energy

Shoebox



[1],[2]

Droplet



[3],[4]

Rock Bed 1.0 and 2.0 at DTU Energy

Shoebox

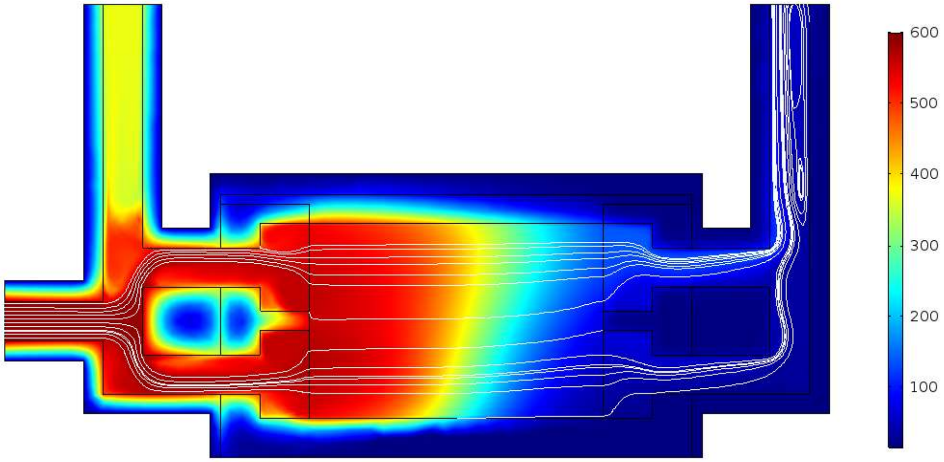
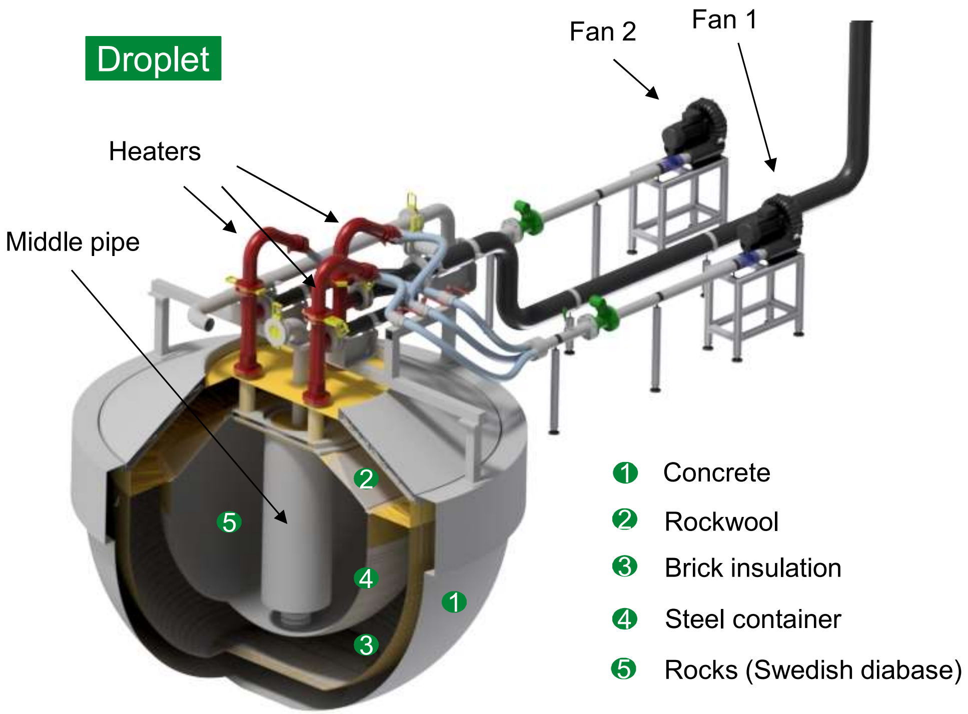


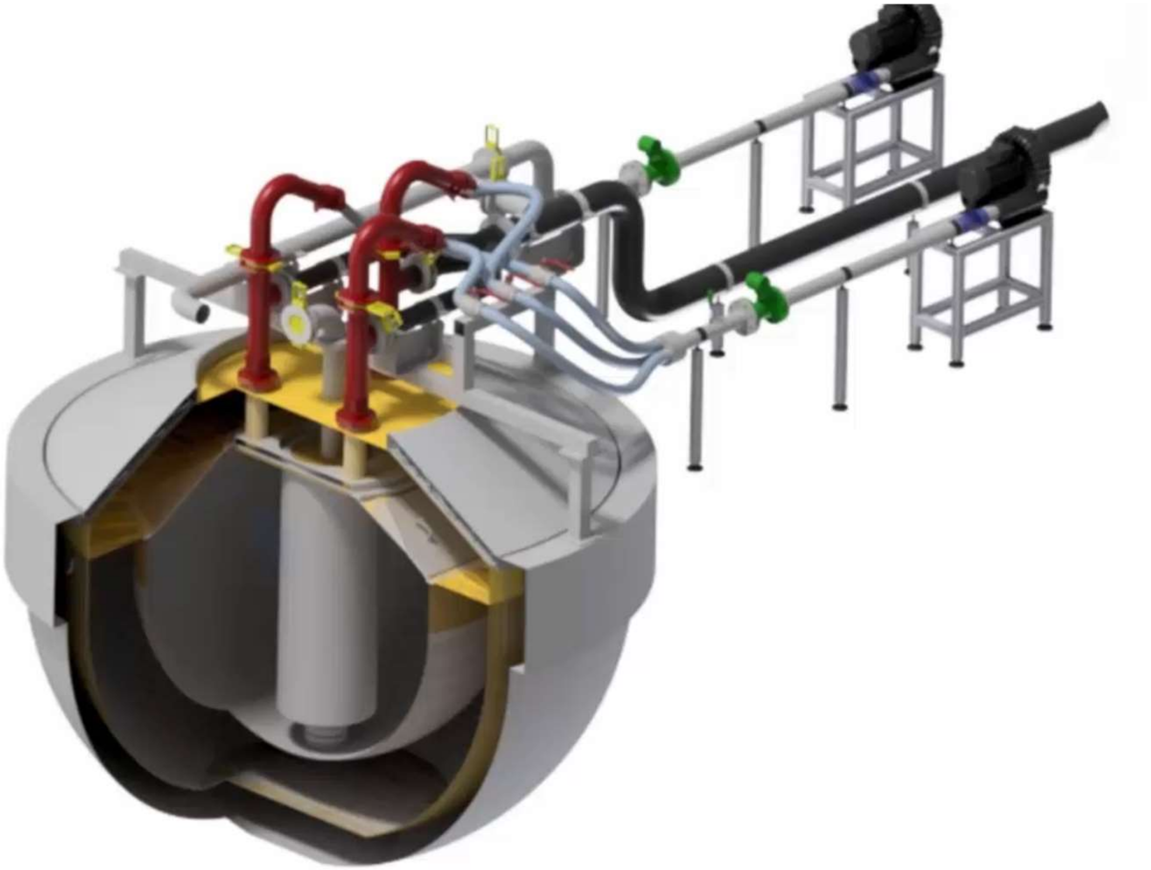
Fig. 1 Temperature and air flow streamline after 6h charge with *Re* = 12 and *NTU* = 56 [2].

Droplet



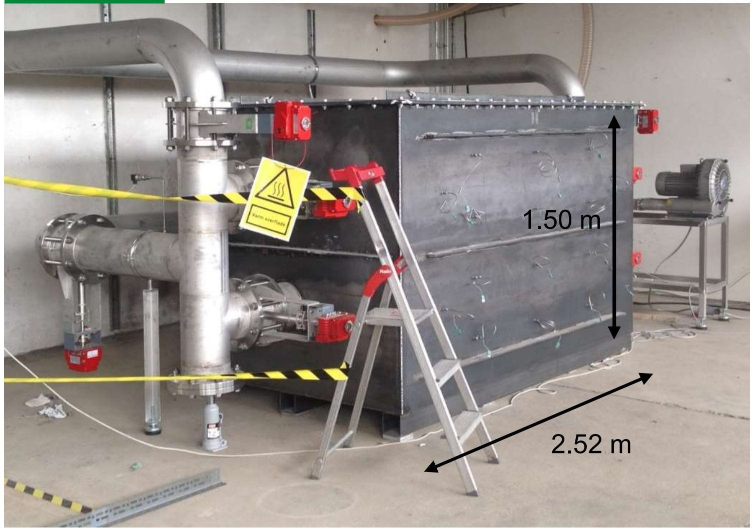
- two different rock sizes (8-11 mm and 16-22 mm)
- piping and heaters mounted on top of the storage
- middle pipe for reversed flow direction

Video of (dis-) charge flow direction



HT-TES pilot plants built at DTU Energy

Shoebox



[1],[2]

V_{pb} = 1.5 m^3

P_{ch} = 30 kW_{el}

T_{ch} = 600 °C

C_{th} = 450 kWh_{th} (ΔT = 600 °C)

η_{RT} < 68.5 % (with one layer)

Droplet

247 cycles, approx. 3500h

[3],[4]

V_{pb} = 3.2 m^3

P_{ch} = 45 kW_{el}

T_{ch} < 675 °C

C_{th} = 1000 kWh_{th} (ΔT = 600 °C)

η_{RT} < 80.7 %

Videos of 2-D temperature reconstruction

a)

b)

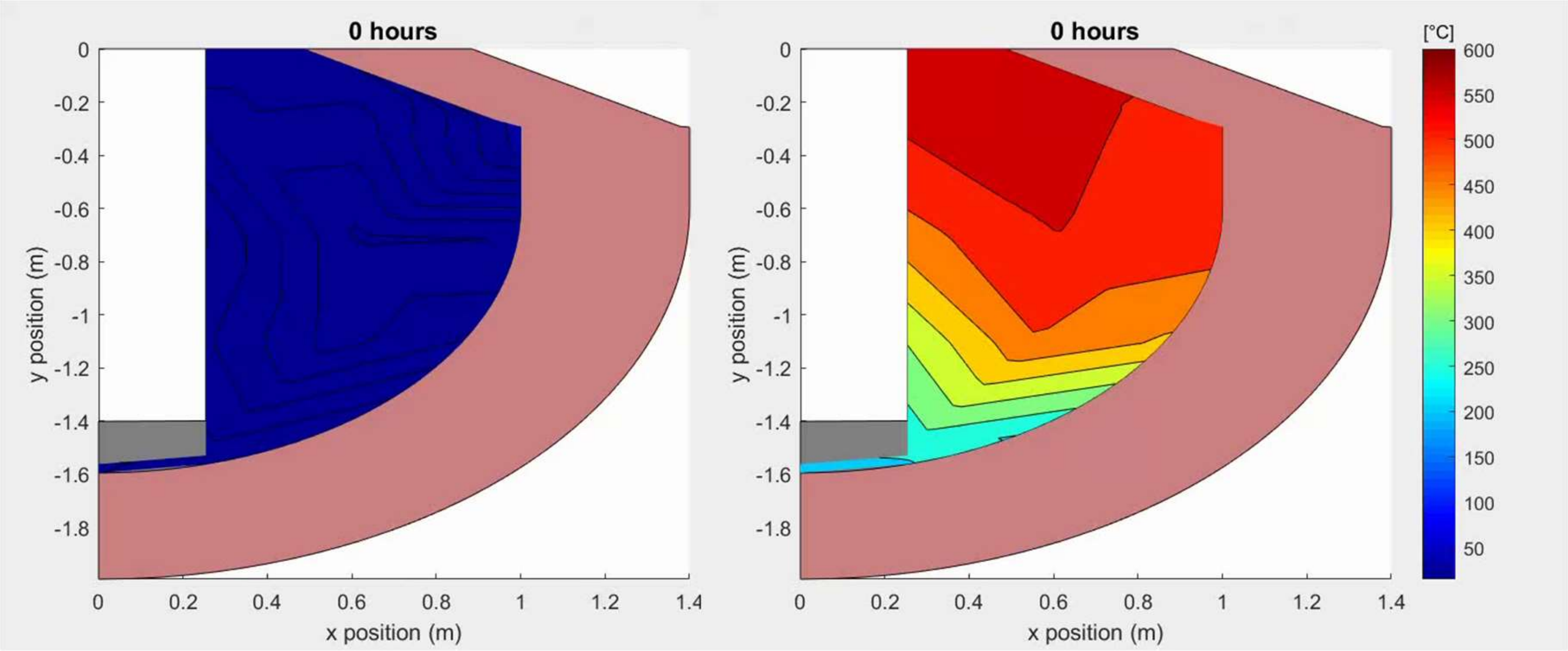


Fig. 2 Reconstructed temperature profile during a) 600℃/200 m³/h charge and b) following 200 m³/h discharge.

Heater set temperature and flow rate

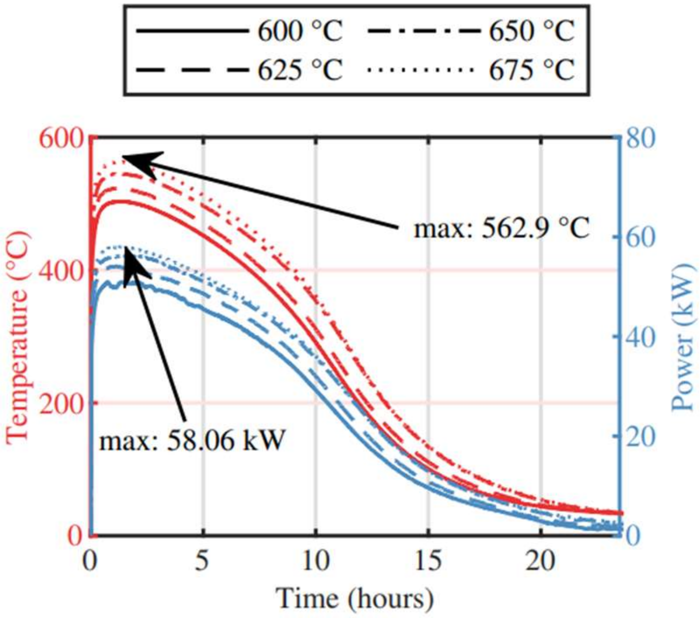


Fig. 3 Outlet temperature and power over time for a 300 m^3/h discharge following a 24h/140 m^3/h charge with different heater set temperatures [3].

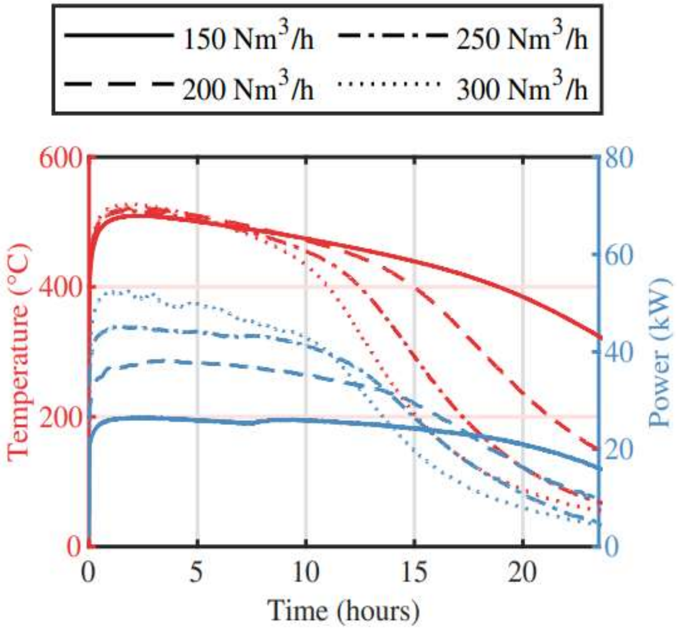
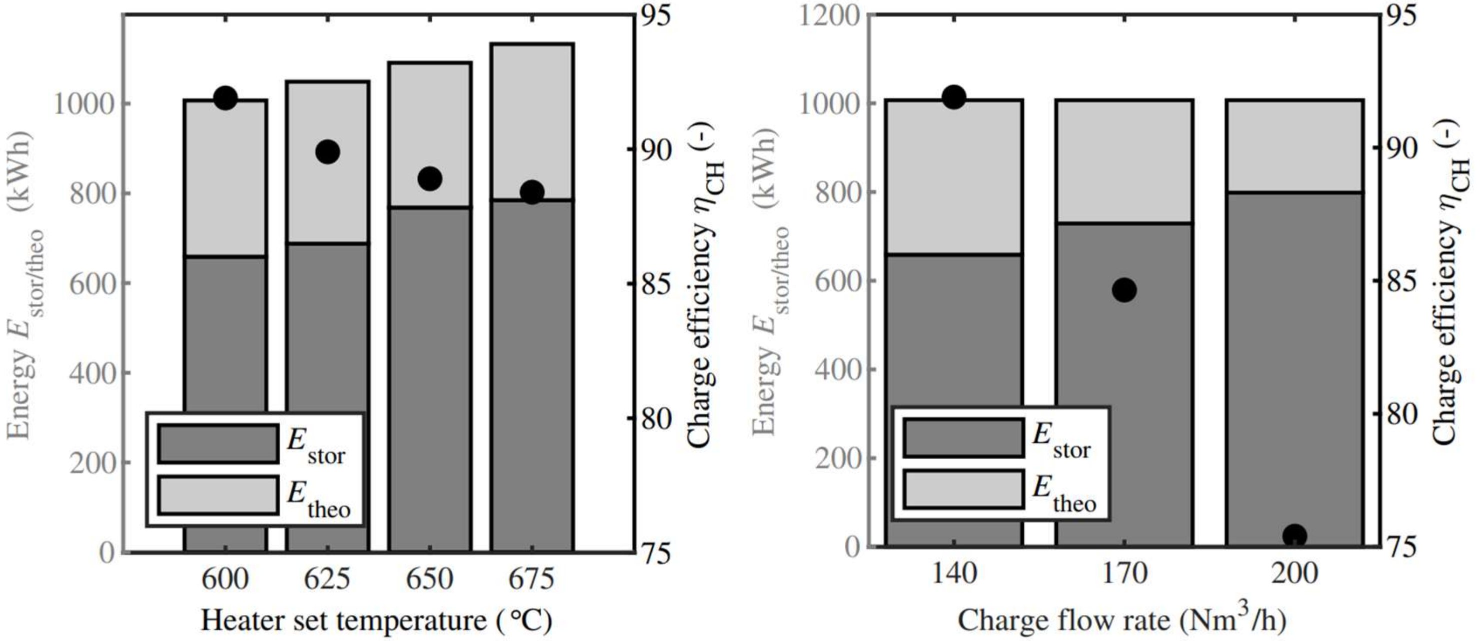


Fig. 4 Outlet temperature and power over time for four different discharge flow rates following a 24h/200m^3/h charge with 600 °C [3].

Heater set temperature and flow rate II



a) 140 m^3/h charge with four different heater set temperatures [3].

b) 600℃ charge with three different charge flow rates [3].

Fig. 5 Energy $E_{stor/theo}$ (bars) and charge efficiency η_{CH} (bullets) for different 24h charge operations.

Consecutive cycles

Tab. 1 Round-trip efficiency and maximum outlet temperature of four consecutive cycles each consisting of 24h charge (600 °C, 200 m^3/h), 24h rest and 24h discharge (200 m^3/h) [3].

	Cycle 1	Cycle 2	Cycle 3	Cycle 4
η_{RT} [%]	68.8	70.4	70.7	70.8
$T_{max,out}$ [°C]	442.1	448.8	450.2	451.6

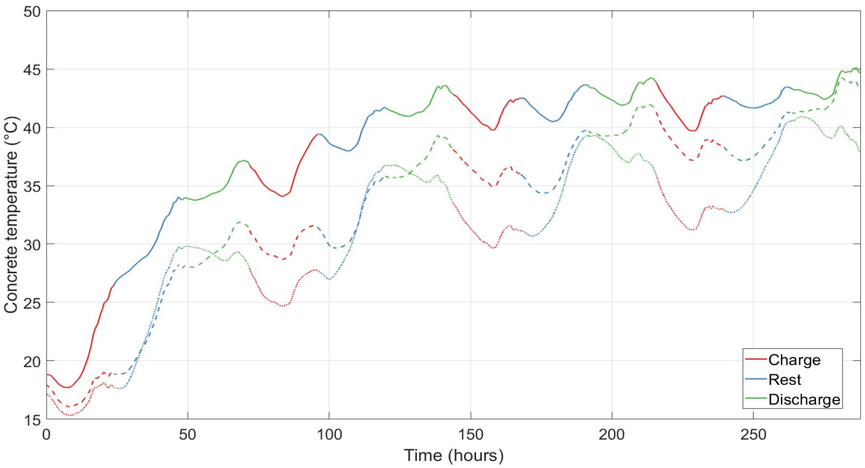


Fig. 6 Average concrete temperature during four consecutive cycles constisting of 24h charge (600 °C, 200 m^3/h), 24h rest and 24h discharge (200 m^3/h). Solid: top position, loosely dotted: middle position, densely dotted: bottom position [3].

Design ● ● ● Testing ● ● ● ● Degradation ● ○

Performance loss after 3500h cycling

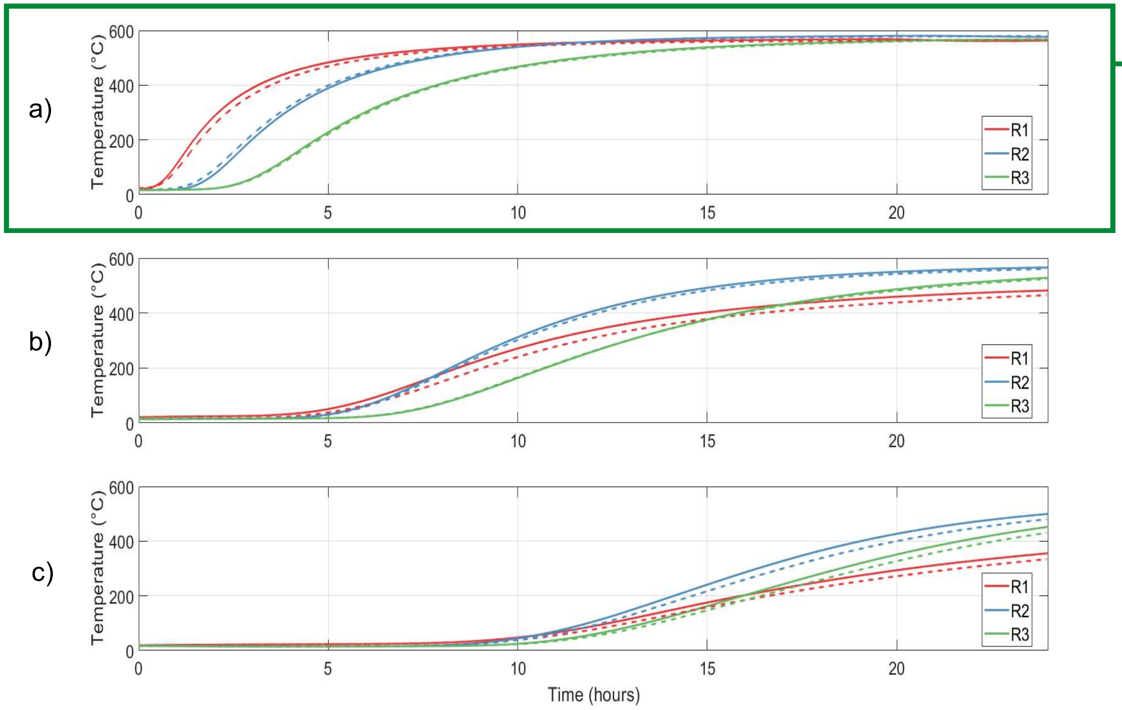
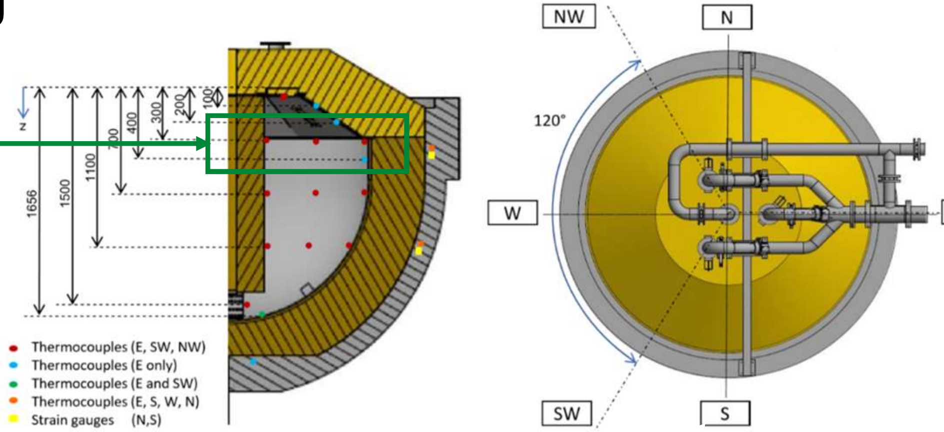


Fig. 7 Temperature as a function of time for all three radial positions (R1,R2,R3) and three axial positions a) z=300 b) z=700 c) z=1100) in NW orientation during 200 m^3/h 600°C charge in April 2019 (solid) and July 2020 (dashed) [4].



Performance loss after 3500h cycling

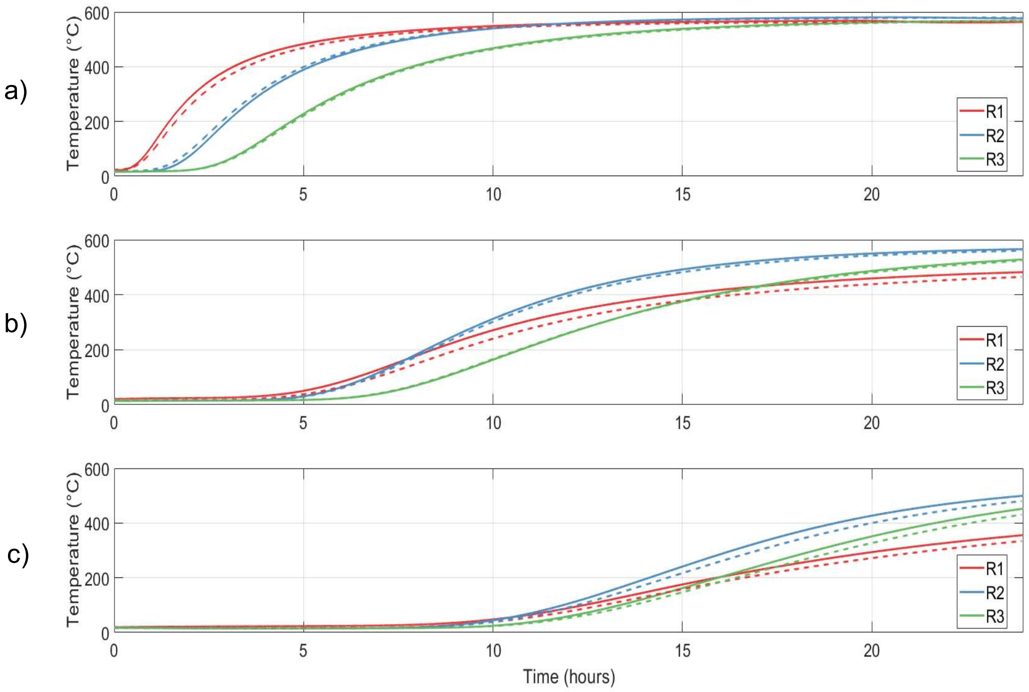
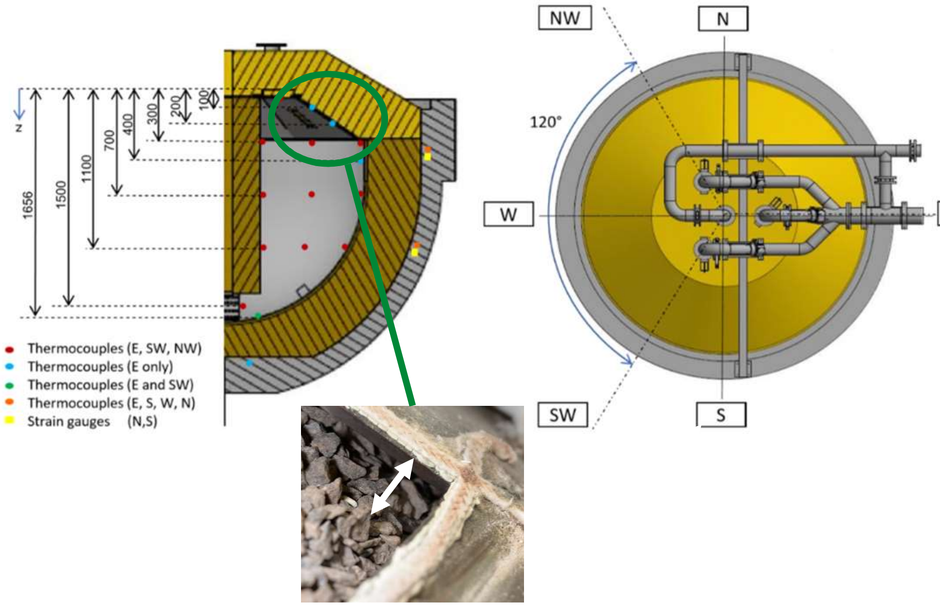


Fig. 7 Temperature as a function of time for all three radial positions (R1,R2,R3) and three axial positions a) z=300 b) z=700 c) z=1100) in NW orientation during 200 m^3/h 600°C charge in April 2019 (solid) and July 2020 (dotted) [4].



Possible reasons for performance difference:

- Ambient temperature
- Rearrangement of rocks and thermocouples
- Degradation of rocks
- Degradation of insulation
- Dust
- …

Material-level degradation

Fig. 8 Single-lens reflex camera and SEM imaging of raw and cycled diabase. Numbered areas in SEM images correspond to main minerals identified with their chemical composition in EDS [4].

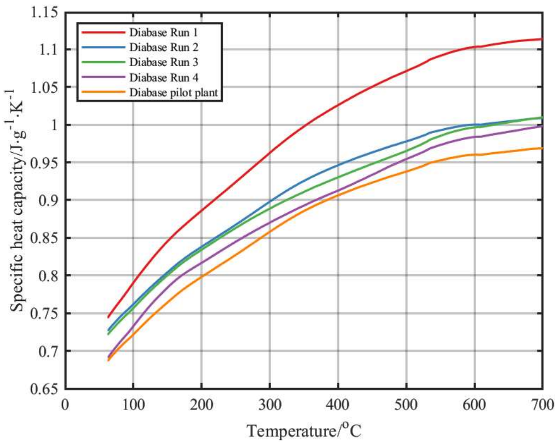


Fig. 9 Specific heat capacity over temperature based on DSC measurements [4].

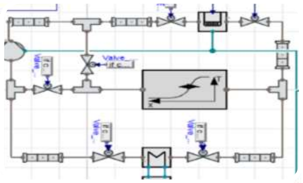
Tab. 2 Densitometry for raw and cycled diabase [4].

Bulk density of raw diabase (10^3 kg/m^3)	Bulk density of cycled diabase (10^3 kg/m^3)
3.02 ± 0.01	2.98 ± 0.01

Additionally, thermal expansion is measured experimentally in order to investigate if thermal ratcheting leads to a) cracking of rocks and b) abrasion and dust formation.

Ongoing activities

Test method for accelerated lifetime testing of storage material



Integration case studies in Denmark (dynamic system models in Modelica)

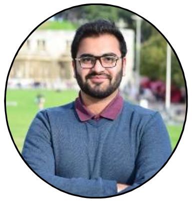
TASK36
CARNOT
BATTERIES

IEA Task 36 ”Carnot Batteries” (Task manager: Dr.-Ing. Dan Bauer, DLR) [5],[6]

Thank you.

Kai Knobloch
kaikn@dtu.dk

Kurt Engelbrecht
kuen@dtu.dk



Yousif Muhammad
youmu@dtu.dk

Associated DTU publications

[1] Design and testing of a horizontal rock bed for high temperature thermal energy storage, Soprani et. al., Applied Energy, 2019, doi: 10.1016/j.apenergy.2019.113345.

[2] Modeling of high temperature thermal energy storage in rock beds – Experimental comparison and parametric study, Marongiu et al., Applied Thermal Engineering, 2019, doi: 10.1016/j.applthermaleng.2019.114355.

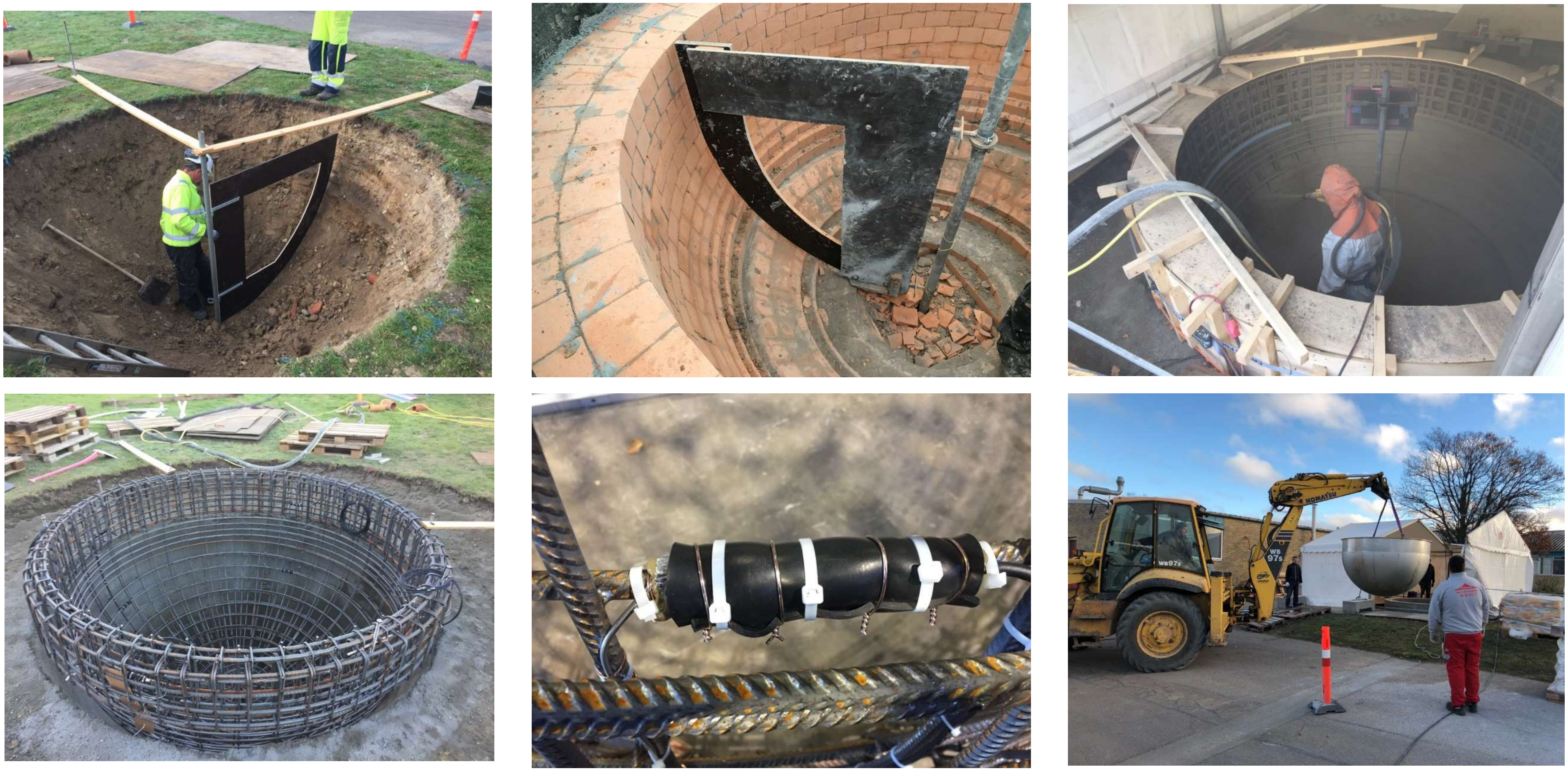
[3] A Partially Underground Rock Bed Thermal Energy Storage with a Novel Air Flow Configuration, Knobloch et al., Applied Energy, 2021, under review.

[4] Degradation of a Packed Bed Thermal Energy Storage, Knobloch et al., Applied Thermal Engineering, 2021, under review.

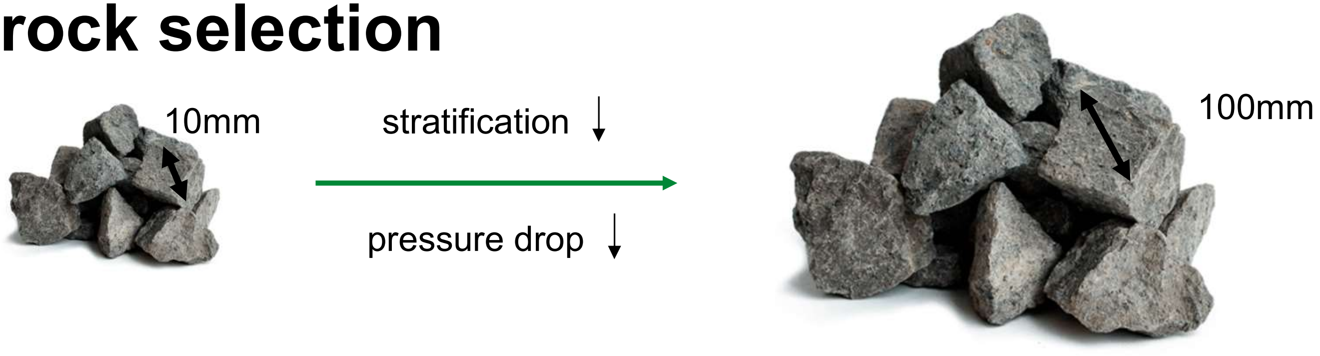
[5] Carnot Batteries (CB): A State-of-the-art Review on CB Components, Ting et al., Renewable and Sustainable Energy Reviews, 2021, under review.

[6] Carnot Batteries (CB): Techno-economic Assessment and System Integration, Vecchi et al., Renewable and Sustainable Energy Reviews, 2021, in preparation.

Back up: Construction of the Rock Bed 2.0

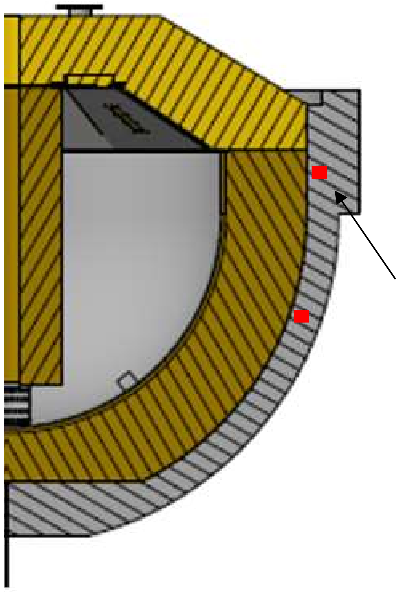


Back up: rock selection

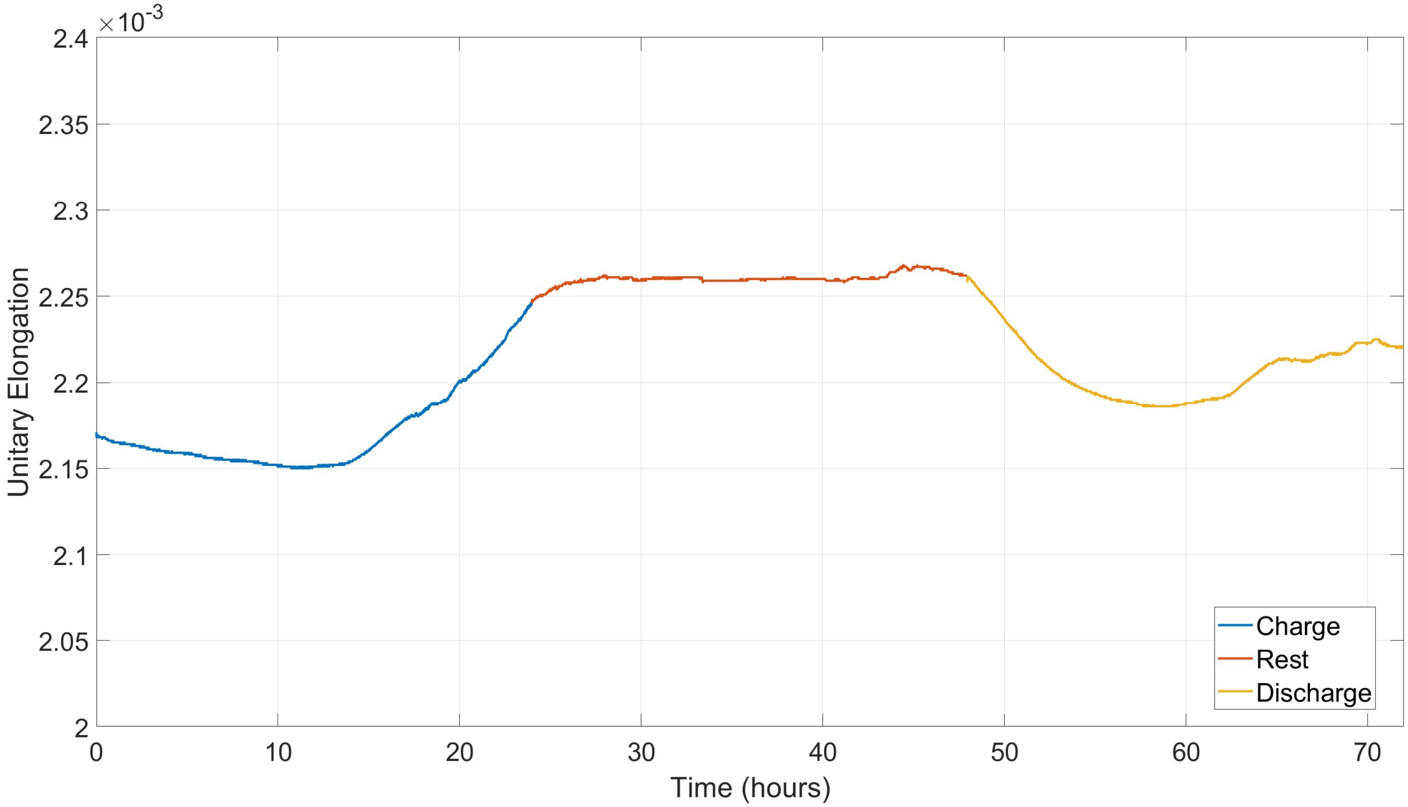


Nr	Petrologic classification	Origin	High temp.	Average c_p raw [J/(K*g)]	Average c_p after heating [J/(K*g)]	Density [g/cm^3]	Average c_p after heating times Density [J/(K*m^3)]
~~1~~	~~Magnetite~~	~~Sweden~~	~~Yes~~	~~0.93~~	~~0.82~~	~~4.68 ± 0.23~~	~~3.8~~
~~2~~	~~Dunite~~	~~Norway~~	~~No~~	~~n/a~~	~~n/a~~	~~2.74 ± 0.10~~	~~n/a~~
~~3~~	~~Ilmenit-norite/Gabbro~~	~~Sweden~~	~~Yes~~	~~0.90~~	~~0.82~~	~~2.82 ± 0.28~~	~~2.2~~
5	Anorthosite	Norway	Yes	1.08	0.95	2.71 ± 0.09	2.6
→ 6	Diabase	Sweden, Finland	Yes	1.13	0.96	2.75 ± 0.09	2.6
7	Basalt	Germany, Austria	Yes	1.08	0.85	3.09 ± 0.39	2.6
~~8~~	~~Quartzite~~	~~Sweden~~	~~No~~	~~n/a~~	~~n/a~~	~~2.66 ± 0.07~~	~~n/a~~
~~9~~	~~Granite~~	~~Denmark~~	~~No~~	~~1.18~~	~~n/a~~	~~n/a~~	~~n/a~~

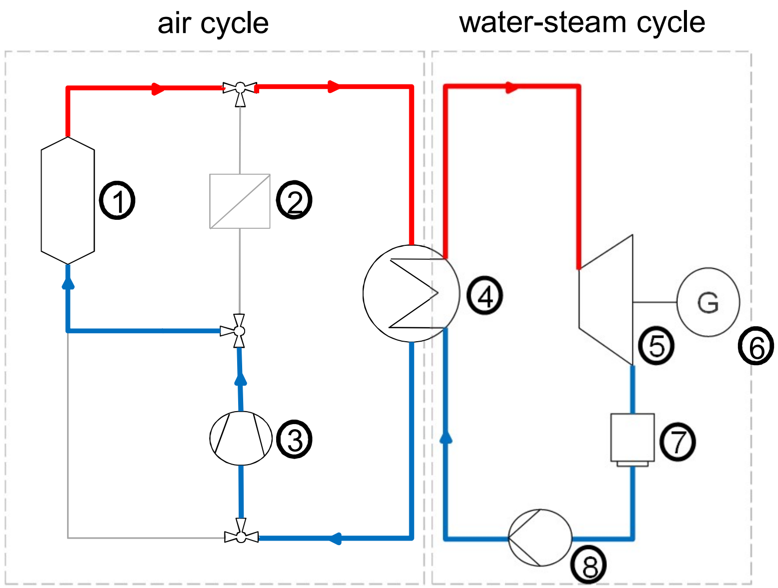
Back up: strain gauges



🟥 Strain gauges



Back up: P2H2P with conventional WSC



① packed bed
② resistive heater
③ blower
④ boiler
⑤ turbine
⑥ generator
⑦ condenser
⑧ pump