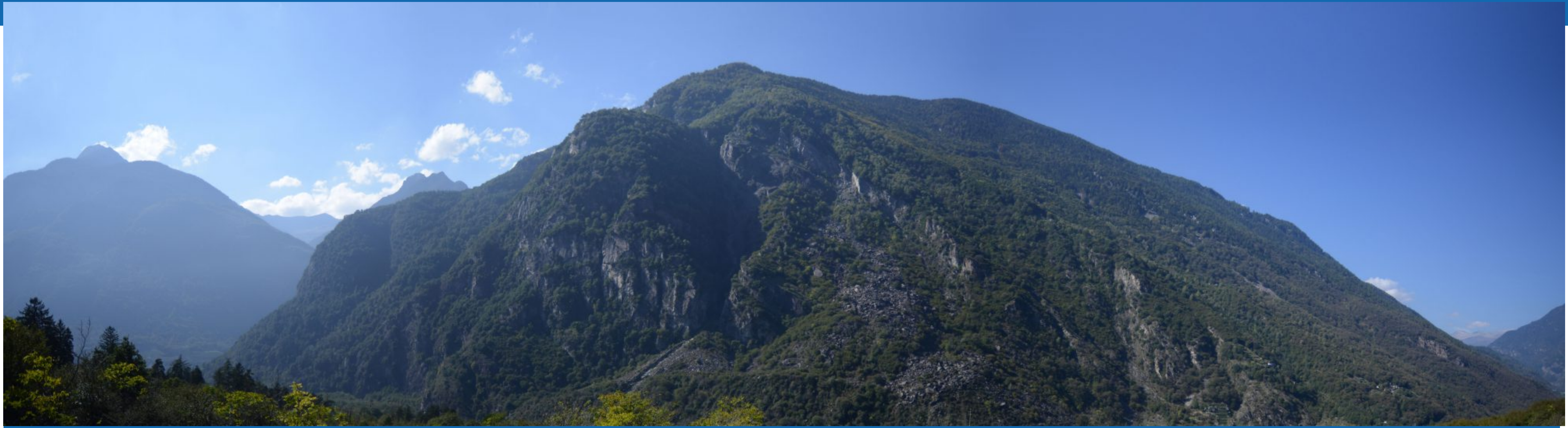
ETH zürich



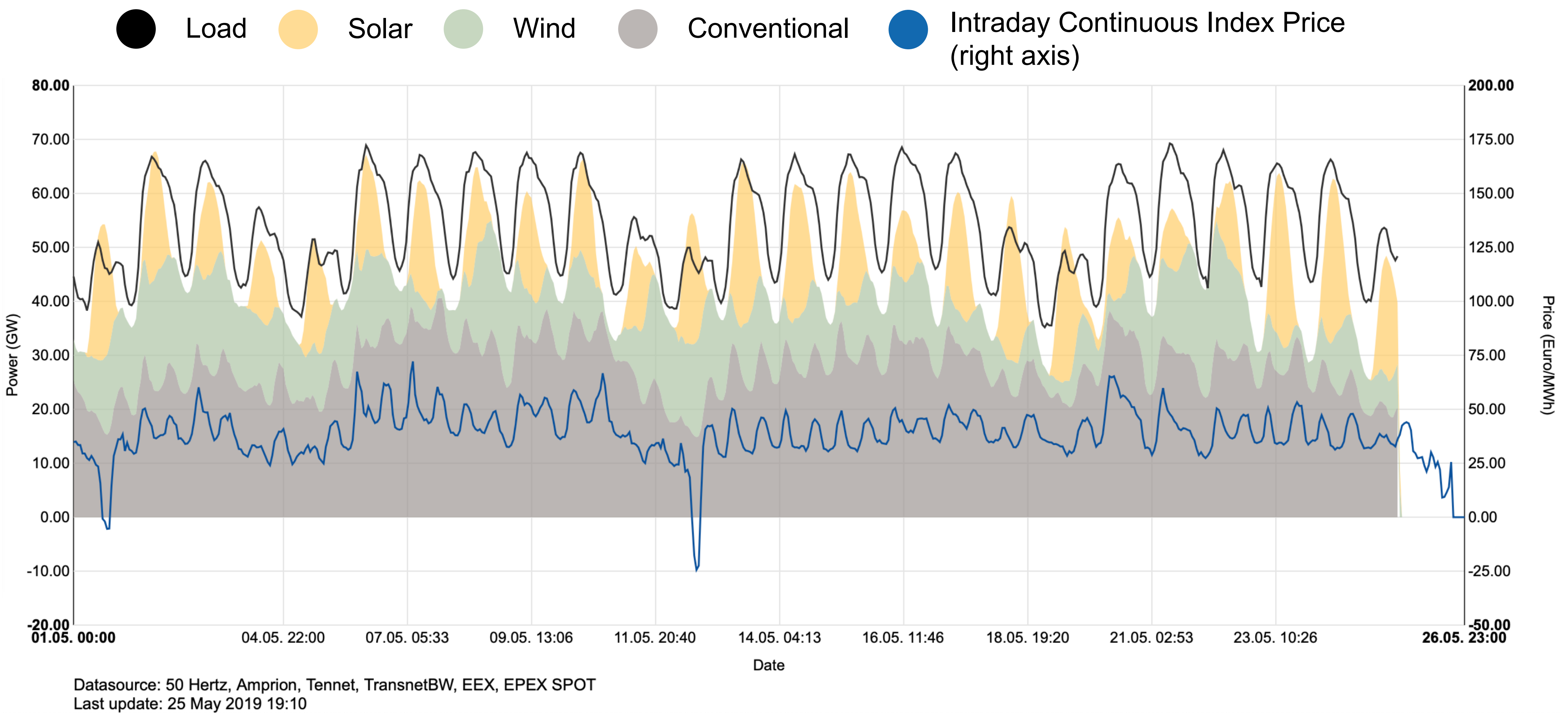
# Thermal-energy storage system integration with focus on advanced adiabatic compressed air energy storage

Philipp Roos

Professorship of Renewable Energy Carriers

Frontiers in Energy Research, 28.05.2019

PREC
Professorship of Renewable Energy Carriers



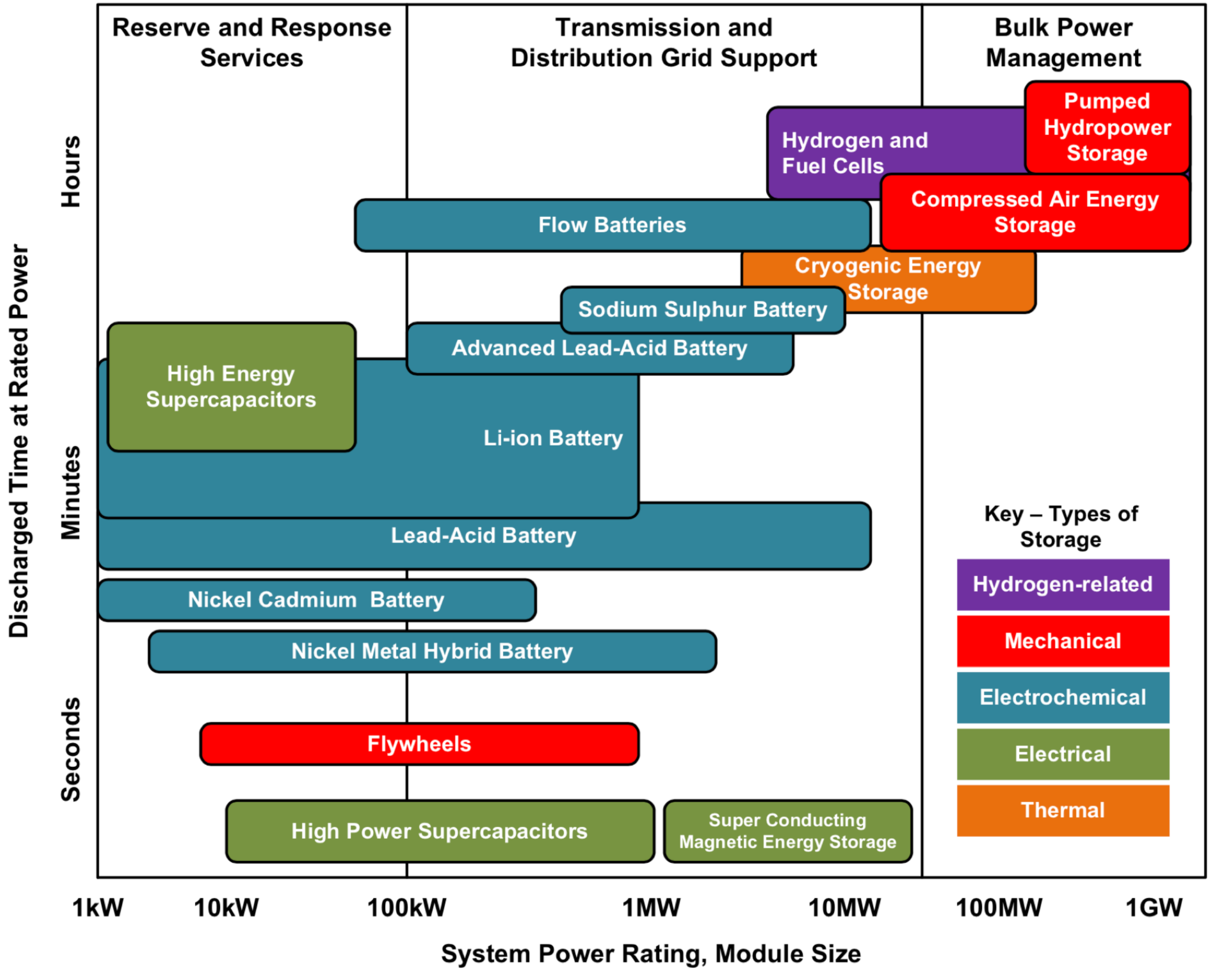

Source: Energy Charts by Fraunhofer Institute for Solar Energy Systems ISE [Online, accessed May 26, 2019], https://energy-charts.de/price.htm

# How do we store electricity?

State of the art → As little as possible, supply base-load energy and follow load with peakers

Bulk energy storage technologies:

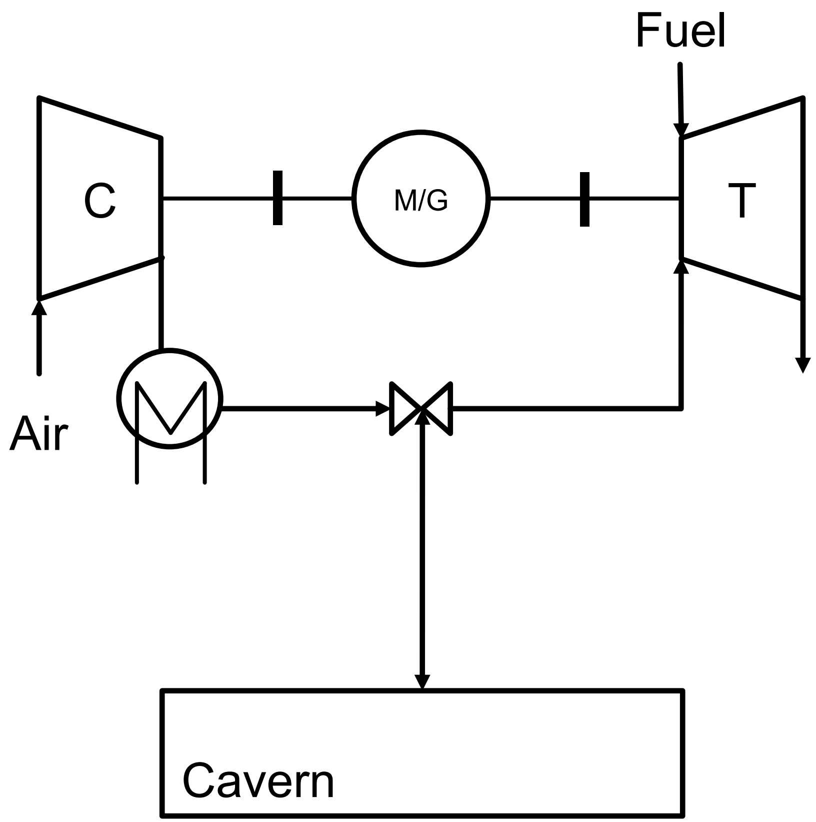
- Hydrogen and fuel cells
- Pumped hydropower storage
- Compressed air energy storage




Source: E. Barbour. (2014) Energy Storage Technologies [Online, accessed May 24, 2019] http://energystoragesense.com/energy-storage-technologies/

# Compressed air energy storage

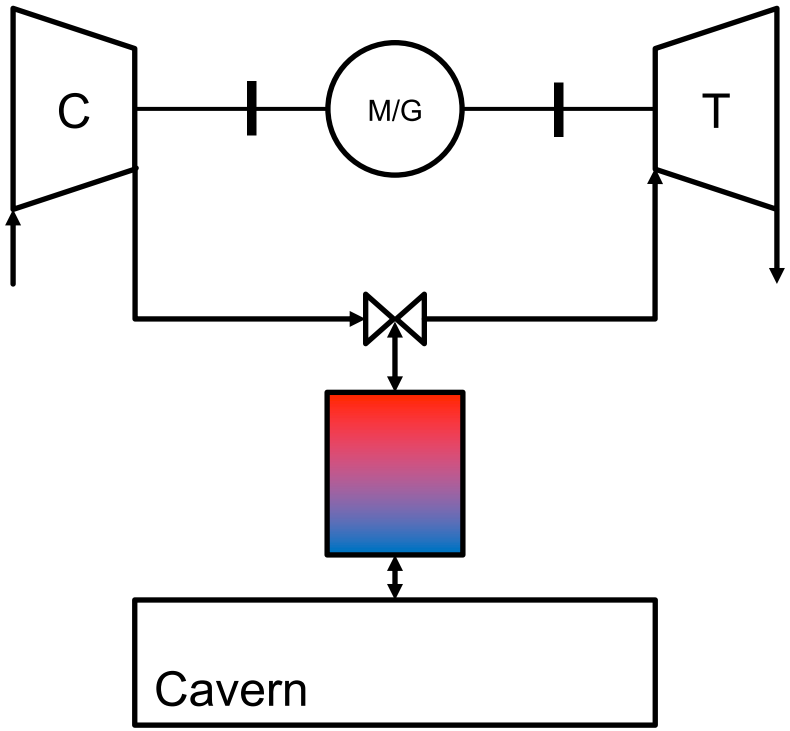
- Diabatic CAES systems
  - 42% - 54% round trip efficiency[1]
  - Fuel consumption




[1]Venkataramani et al. Renewable and Sustainable Energy Reviews 62 (2016)

# Compressed air energy storage

- Diabatic CAES systems
  - 42% - 54% round trip efficiency[1]
  - Fuel consumption
- Adiabatic CAES (AA-CAES)
  - 70% round trip efficiency projected[2]
  - Compression heat is stored and released in TES




[1]Venkataramani et al. Renewable and Sustainable Energy Reviews 62 (2016)
[2]Hartmann et al. Applied Energy 93 (2012)

# Existing diabatic compressed air energy storage plants

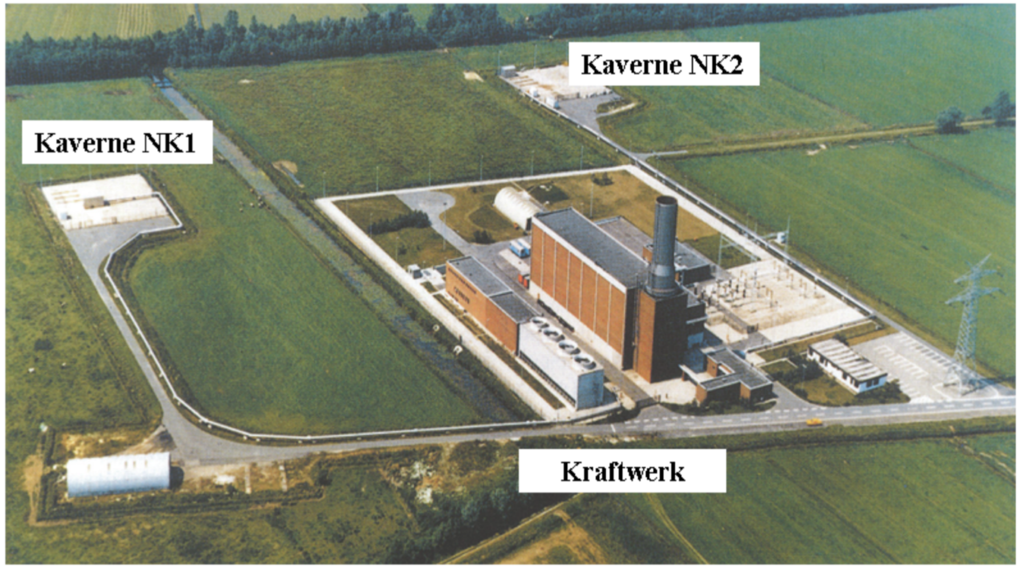
Potential energy storage capacity in salt formations in northern Germany is 4.5 TWh[1]

Huntorf, Germany (commissioned 1978)

- 290 MW discharge, 60 MW charge
- 310’000 $m^3$ salt cavern volume
- Efficiency 40%

McIntosh, US (commissioned 1991)

- 110 MW
- 5x capacity of Huntorf
- Efficiency 54%




[1]Donadei et al., InSpEE technical report, KBB Underground Technologies GmbH, 2016

# Thermal Energy Storage (TES)

Different storage mechanisms

- Sensible
  - Water
  - Rock beds
  - Ground
- Latent
  - Ice storage
  - Paraffins
  - Sodium acetate (hand warmers)
- Thermochemical
  - Reversible chemical reactions

Sensible:

Characterized by a heat capacity and a temperature change of the material

$$Q_\mathrm{s} = mc_\mathrm{p}\Delta T$$

Latent:

Characterized by the latent heat of fusion

$$Q_\mathrm{s} = m\left[c_\mathrm{p,s}(T_\mathrm{m} - T_\mathrm{i}) + f\Delta \mathrm{q} \;+ c_\mathrm{p,l}(T_\mathrm{f} - T_\mathrm{m})\right]$$

Thermochemical:

Characterized by reaction heat

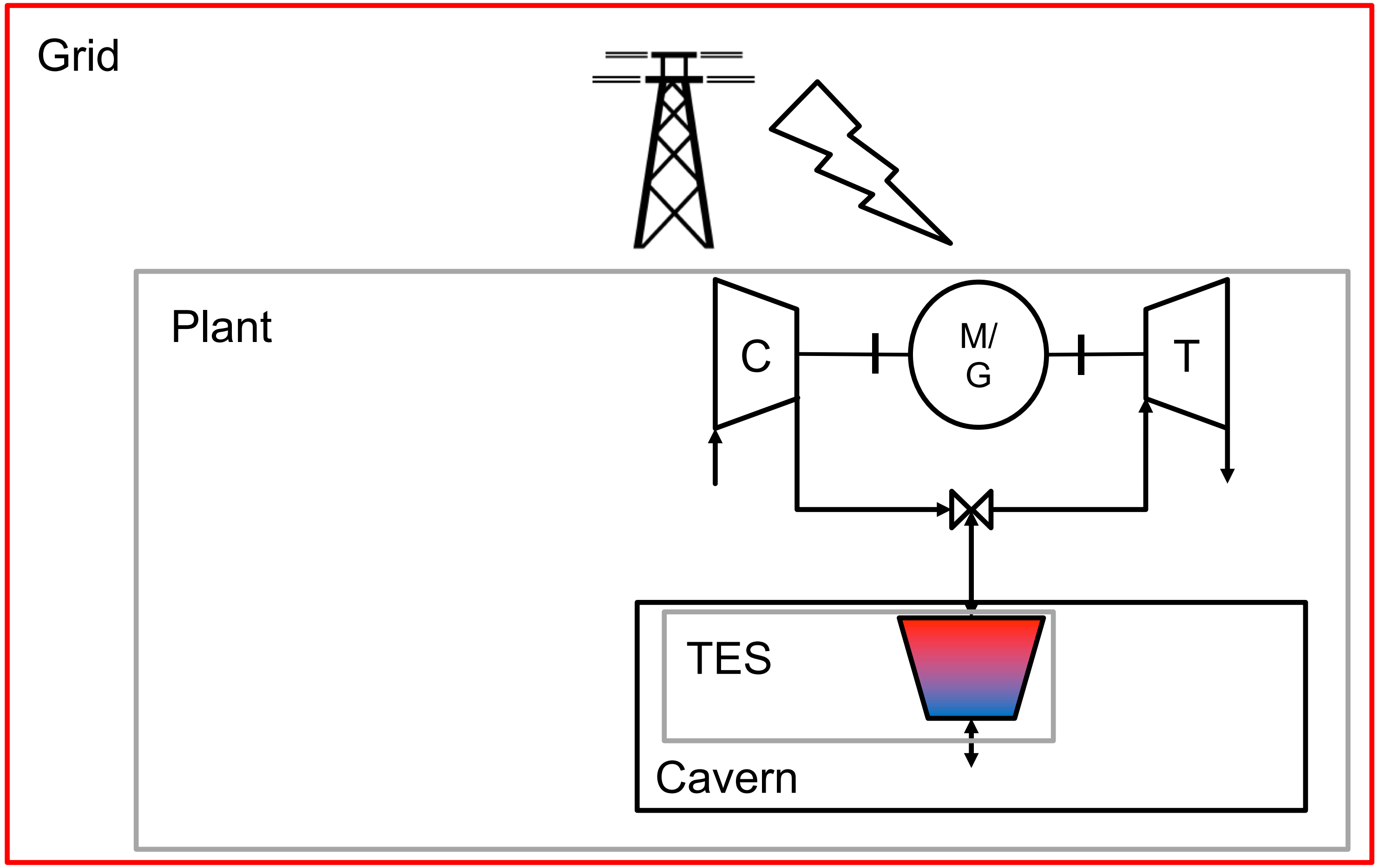
$$6Mn_2O_3 + \Delta H \leftrightarrow 4Mn_3O_4 + O_2$$

$$\Delta \mathrm{H} = +416\ \mathrm{kJ/kmol}$$

# Scope of SCCER Phase II

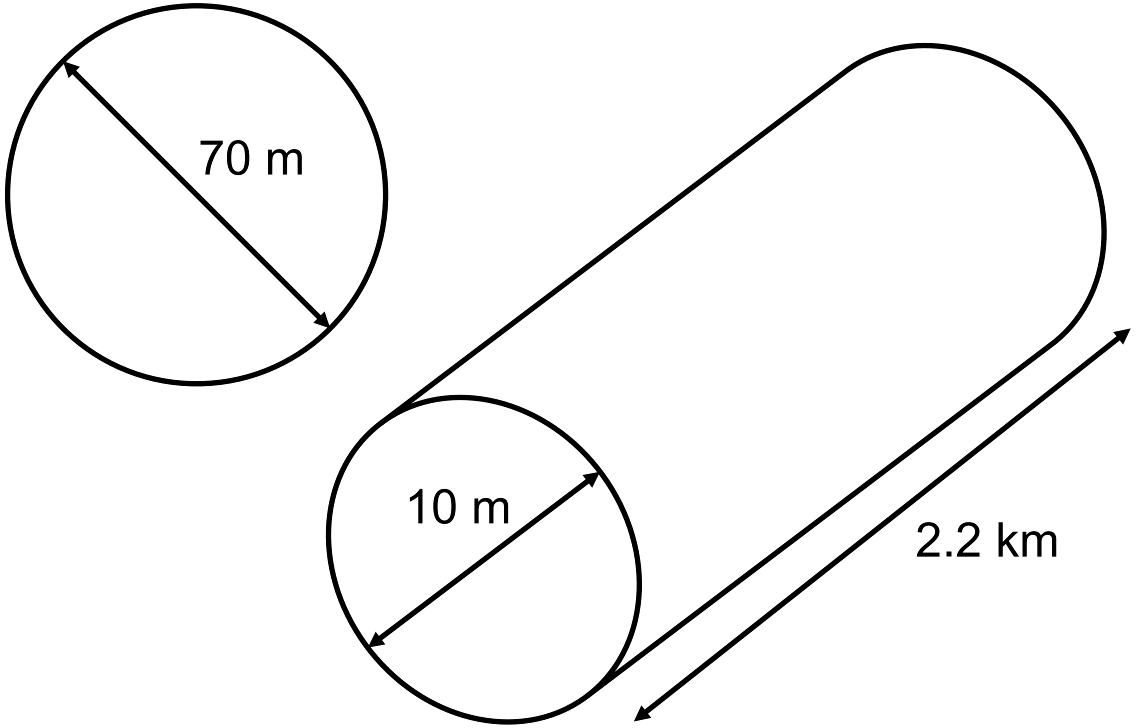
AA-CAES plant in Switzerland:

- Where should it be sited?
- What is the best plant configuration?
- Can it be operated profitably?



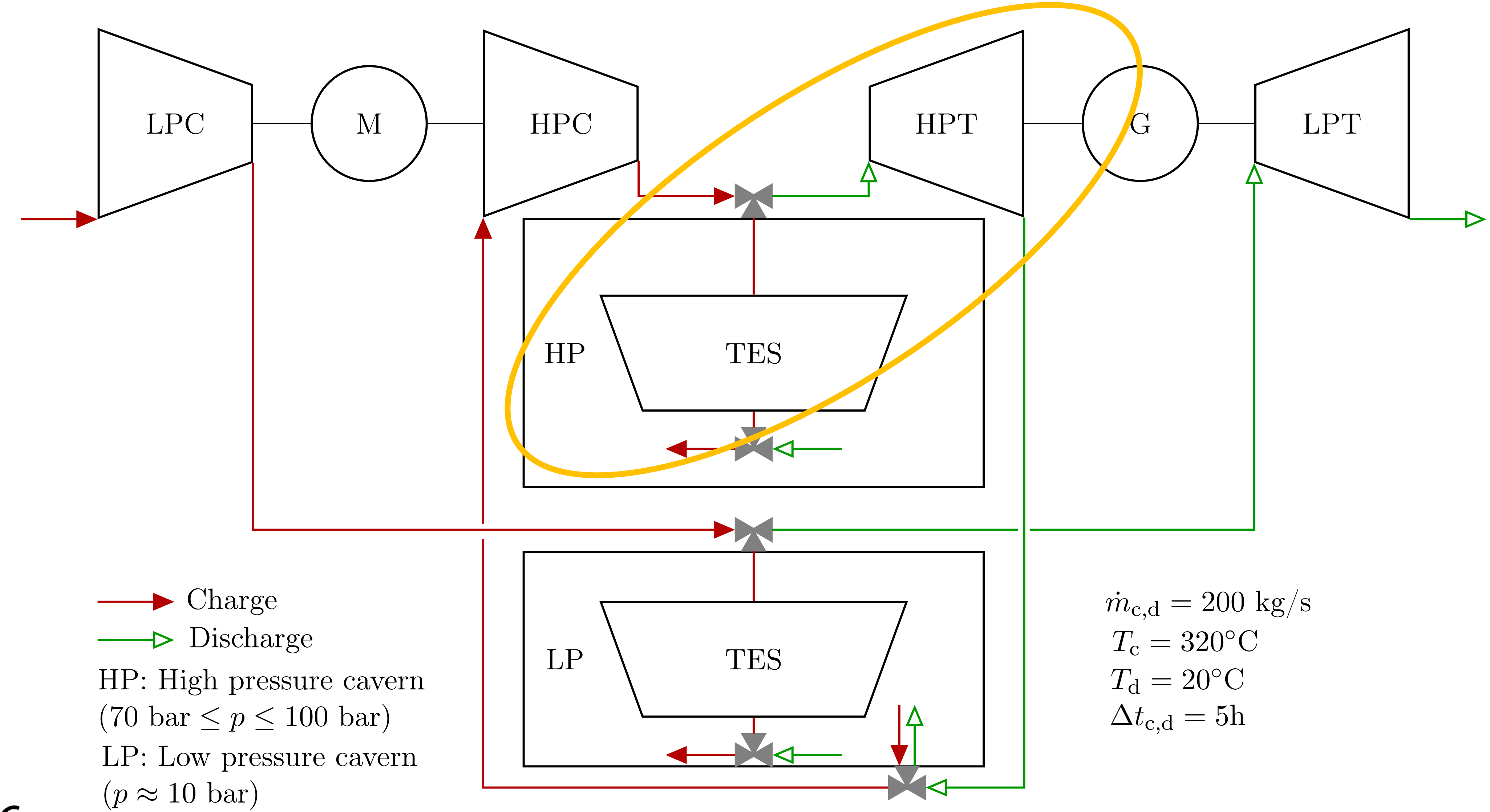
# AA-CAES Plant configuration

| | |
|---|---|
| Power | 100 $MW_{el}$ |
| Capacity | 500 $MWh_{el}$ |
| Minimum/Maximum pressure | 70/100 bar |
| Cavern volume | 170’000 $m^3$ |
| Calculated efficiency | 70-75% |




Zurich HB main hall
≈ 100’000 $m^3$

# AA-CAES Plant configuration




Charge
Discharge

HP: High pressure cavern
($70 \text{ bar} \leq p \leq 100 \text{ bar}$)

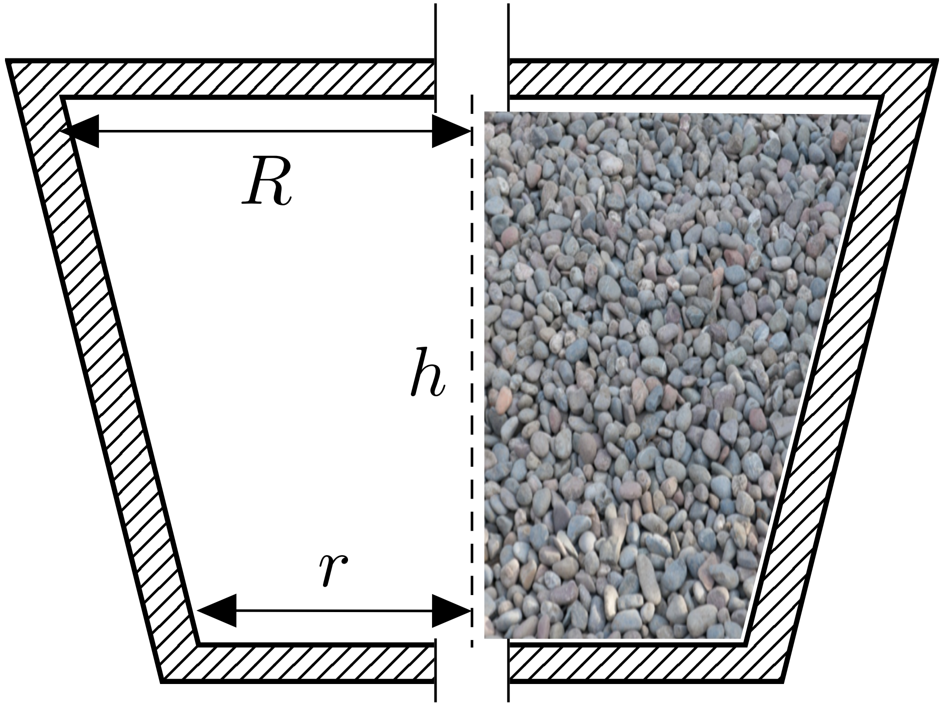
LP: Low pressure cavern
($p \approx 10 \text{ bar}$)

$\dot{m}_{\mathrm{c,d}} = 200 \text{ kg/s}$
$T_{\mathrm{c}} = 320°\mathrm{C}$
$T_{\mathrm{d}} = 20°\mathrm{C}$
$\Delta t_{\mathrm{c,d}} = 5\mathrm{h}$

# Packed-bed TES

Quasi-one-dimensional heat-transfer model[1]:

- Energy equations solved for two phases (solid and fluid)
- Separate formulation for sensible and latent heat sections
- Convective, conductive and radiative heat transfer
- Thermal losses
- Temperature-dependent properties of materials and air

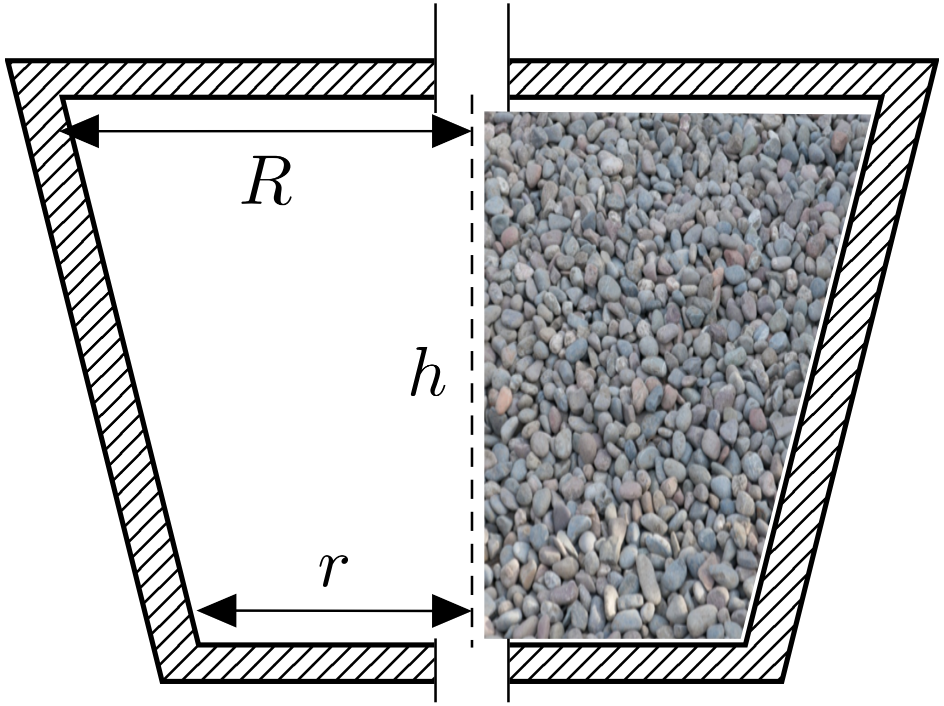



[1]Geissbühler et al. Appl. Therm. Eng. 101 (2016).

# Packed-bed TES

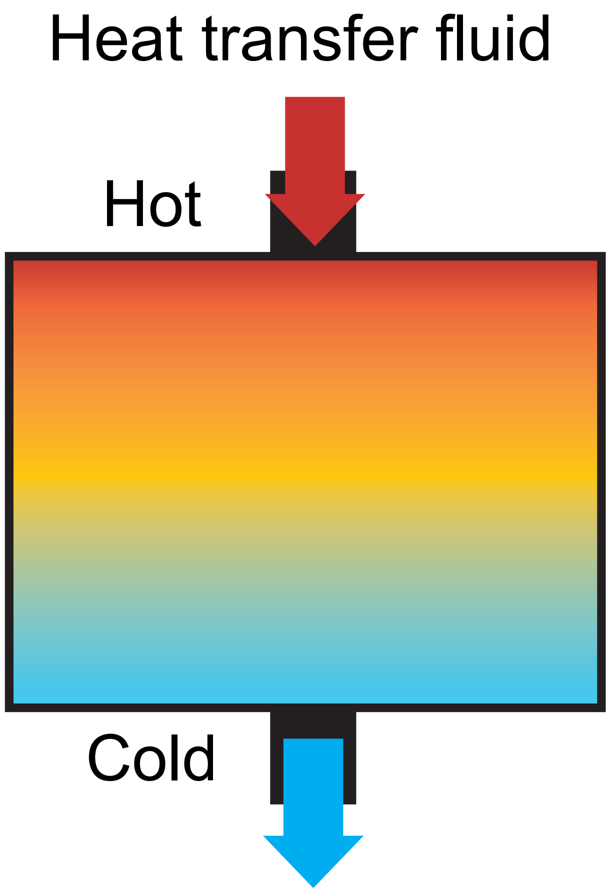
Stand-alone performance[1]:

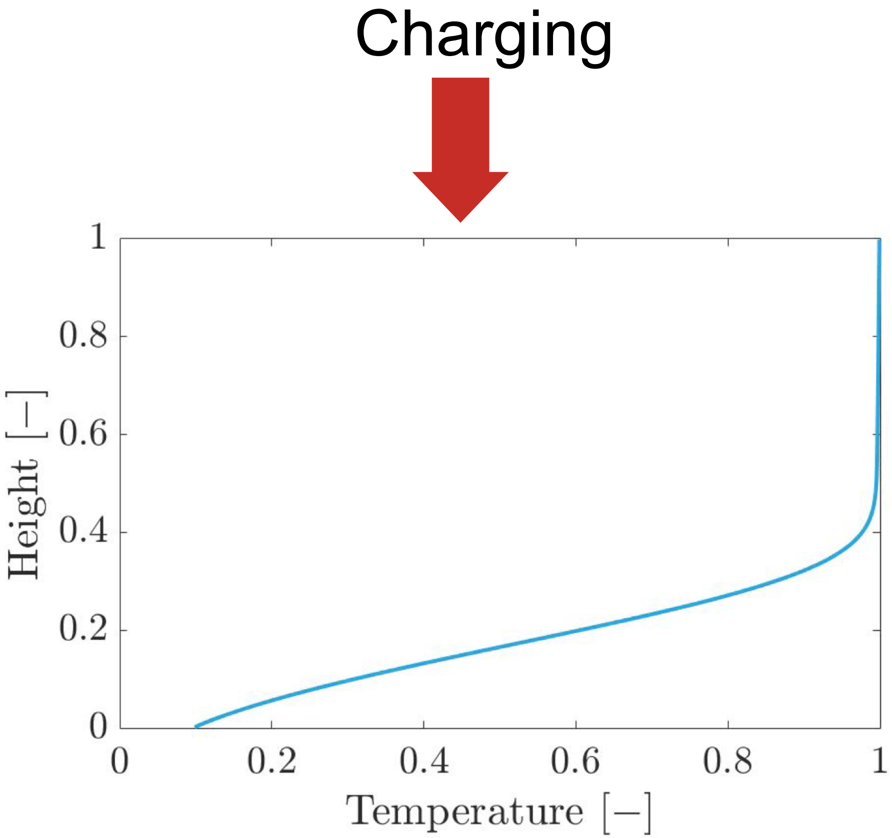
- High exergy efficiency > 95%
- Low pressure drop
- Low specific costs
- Storage material: Fluvial rocks[2]



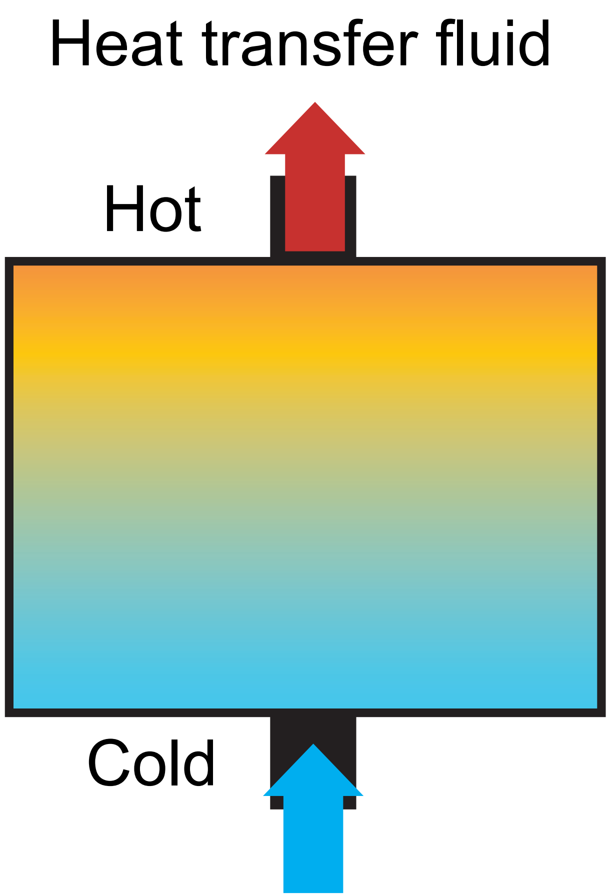

[1]Geissbühler et al. Appl. Therm. Eng. 101 (2016).
[2]Becattini et al. Applied Energy 203 (2017).

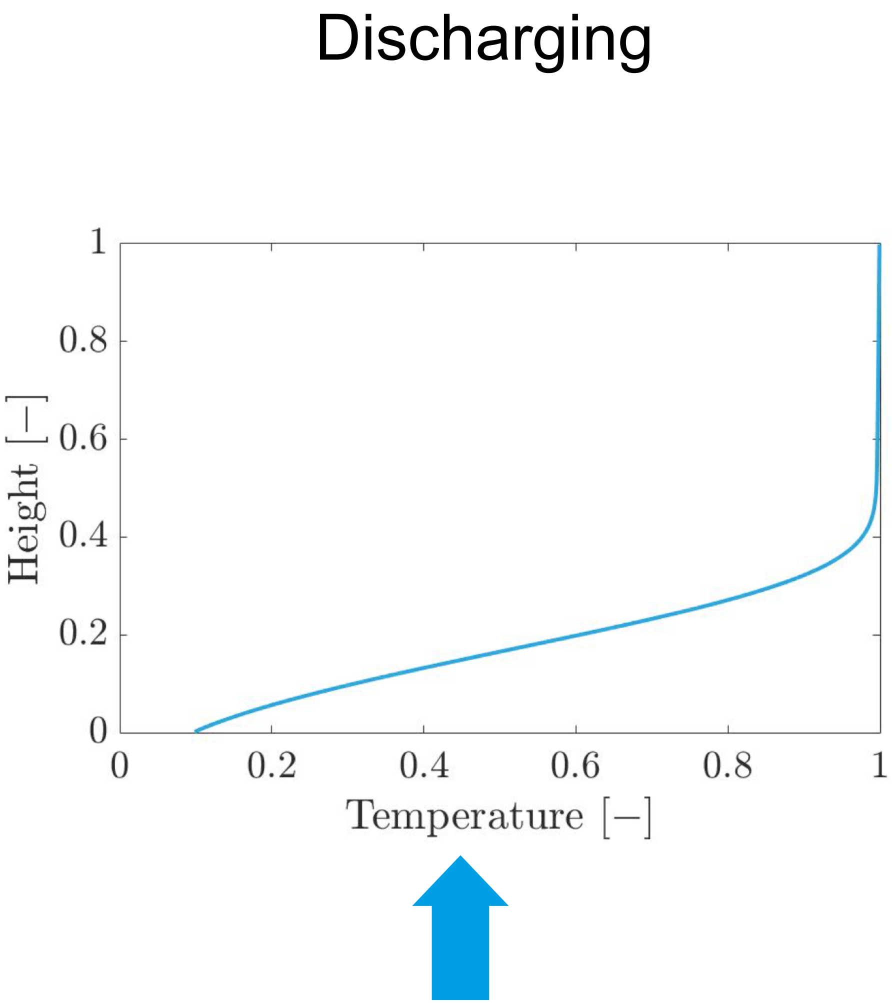
# Thermocline TES



# Thermocline TES



# Single-tank TES performance

- Effect on turbine?

$T_c = 320°C \quad \dot{m}_{c,d} = 200 \text{ kg/s}$

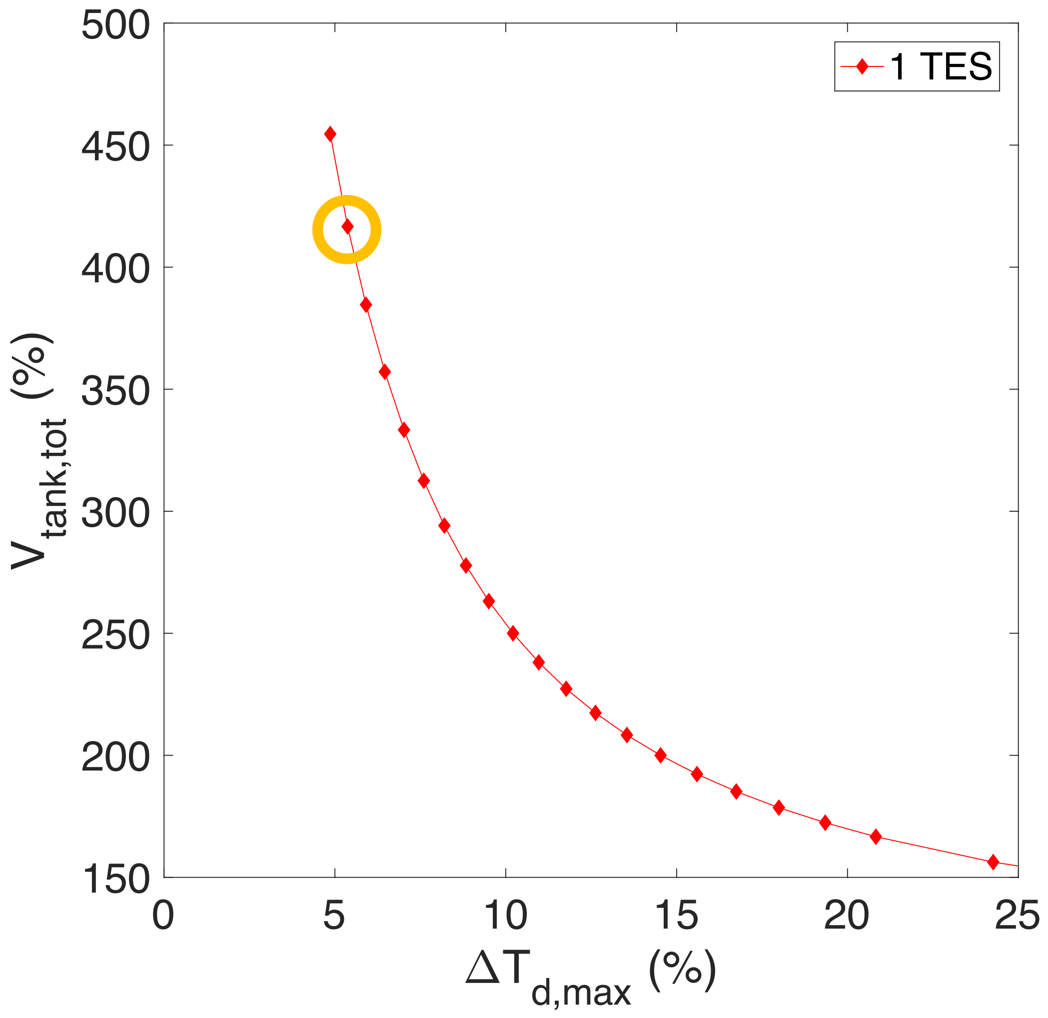
$T_d = 20°C \quad \Delta t_{c,d} = 5\text{h}$

$R = 15.7\text{m}$

$h = 14.7\text{m}$

$r = 12.0\text{m}$

$$\Delta T_{d,max} = \frac{T_c - T_{d,out,end}}{T_c - T_d}$$



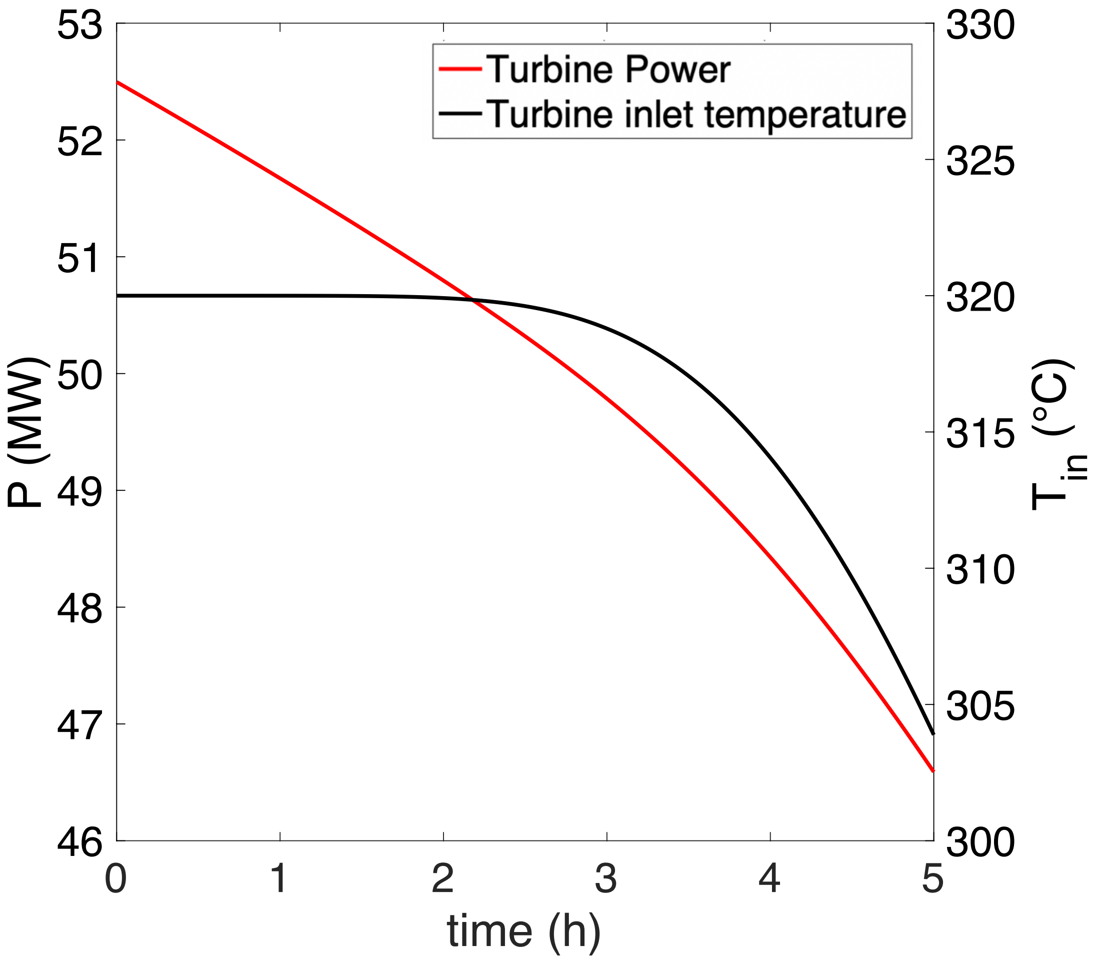
# Single-tank TES: Turbine power output

$$P = \dot{m}_T c_{\mathrm{p,f}} T_{\mathrm{in}}(t) \eta_{\mathrm{s,T}} \left[1 - \left(\frac{p_{\mathrm{out}}}{p_{\mathrm{in}}(t)}\right)^{(\gamma-1)/\gamma}\right]$$

$$p_{\mathrm{in}}(t) = p_0 \left(1 - \frac{\dot{m}_{\mathrm{T}} t}{m_0}\right)^{\gamma}$$

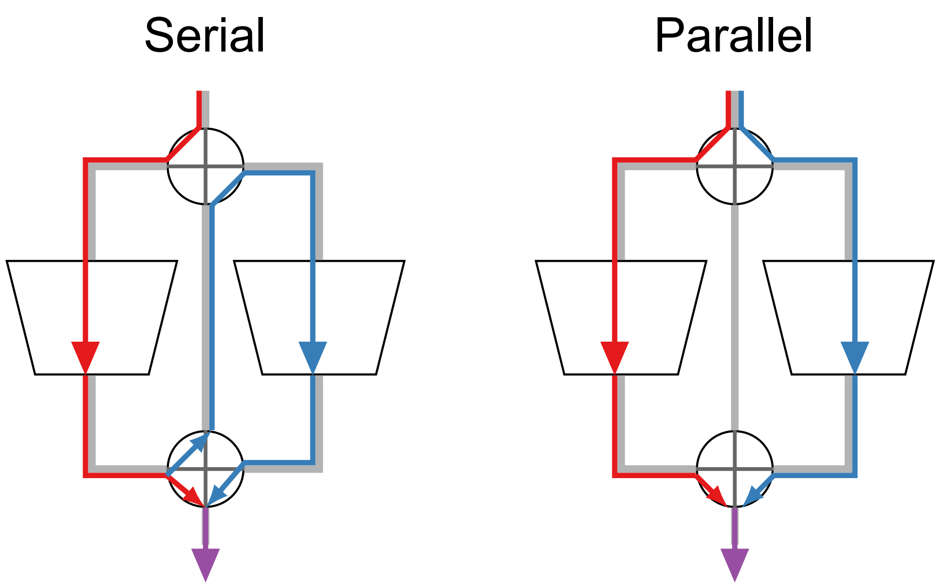
$T_{\mathrm{in}}(t)$ depends on TES design

- Unsteady power output due to
  - Sliding pressure in cavern
  - Temperature drop at TES outlet



# Potential issues for AA-CAES plant

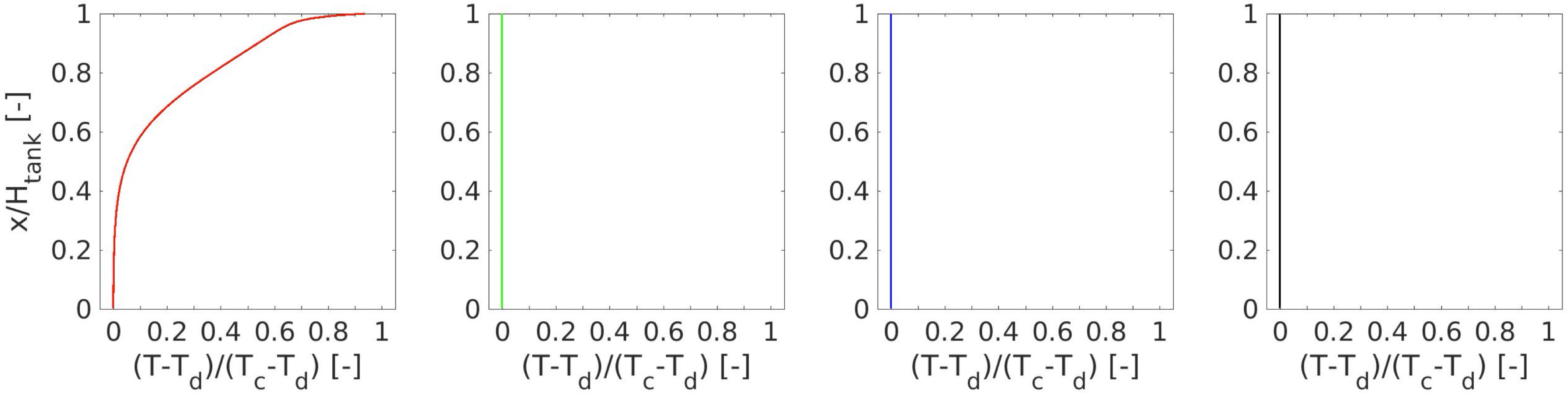
- Unsteady power output
  →Penalty costs from Swissgrid
- TES size vs. cavern geometry
- No flexibility regarding unsteady operation



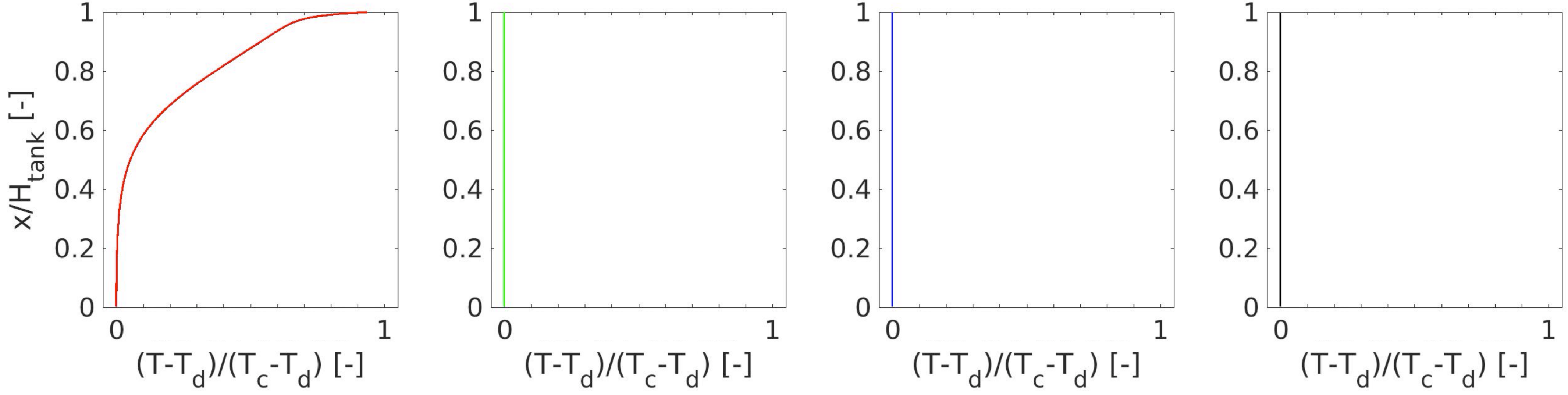

→ Multi-tank TES, connected by controlled valves
Thermocline Control[1,2] (TCC) methods can be applied

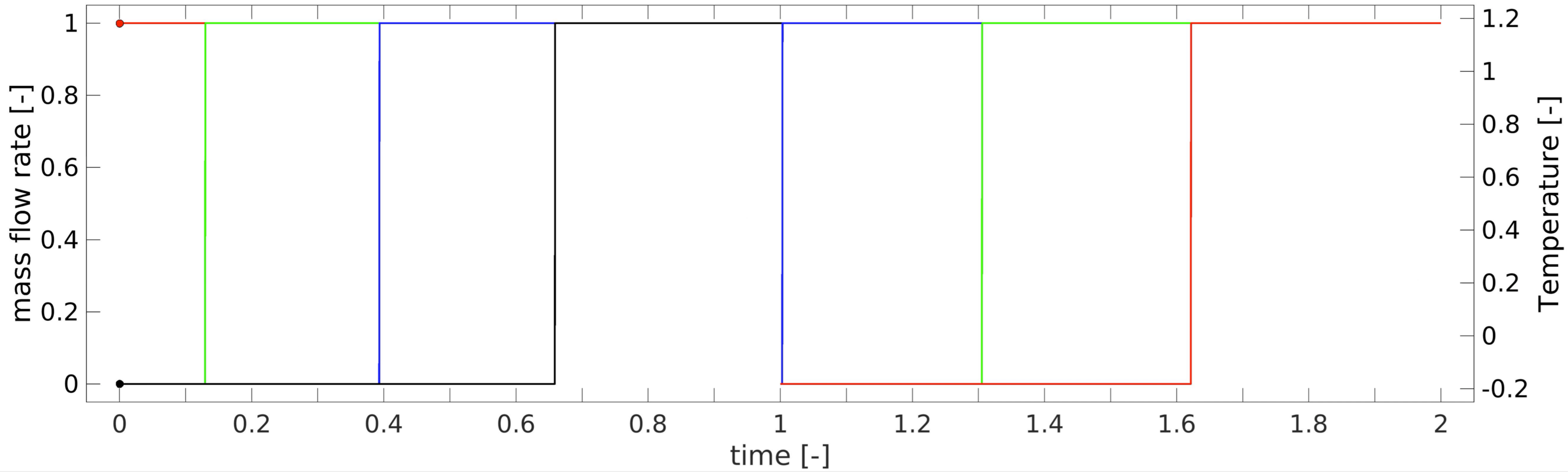
[1]Geissbühler et al., Solar Energy, 178, 2019a
[2]Geissbühler et al., Solar Energy, 178, 2019b

# Multi-tank TES

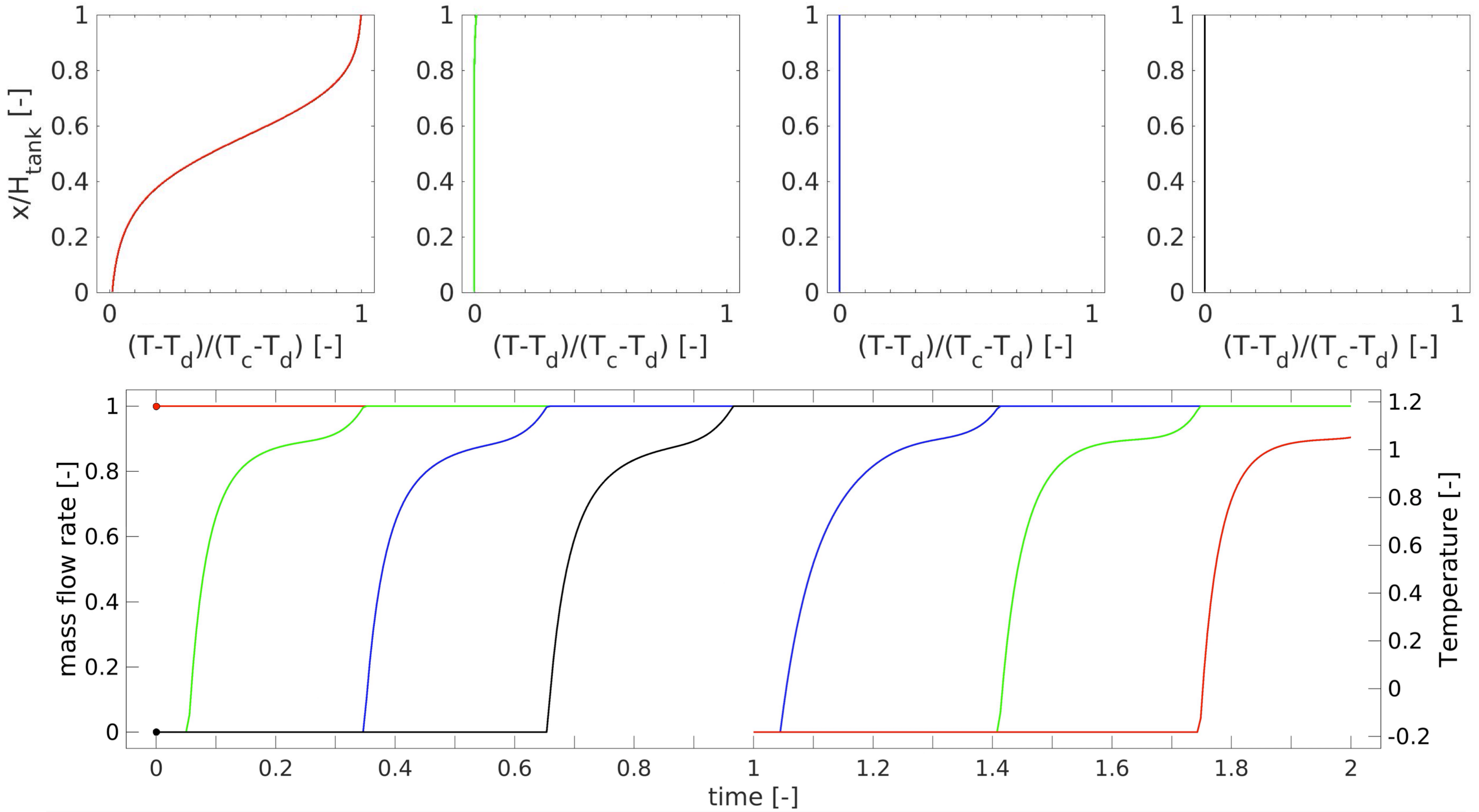


# Extraction TCC Method



# Mixing TCC Method



# Multi-Tank TES – Research questions

- Does a multi-tank TES system offer cost and performance benefits for operating cycles typical of AA-CAES plants?
- Under which conditions?
  - Application of thermocline control methods (Extraction & Mixing)
  - Which temperature drops are achieved with each method?
  - Constant (vs. variable) operating conditions

# Results

Result slides have been removed because they contain unpublished material.

# Summary

- TES outlet temperature control in AA-CAES plant is required
- Potential solution with multi-tank TES and TCC methods
- Efficiency loss is expected with turbine control

# Outlook

- Analyze performance of entire plant including multi-tank TES
- Analyze AA-CAES plant behavior under grid operating conditions with multi-tank systems
- Numerical optimization of multi-tank TES systems

# Acknowledgements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