# Design of Thermal Energy Storage with Phase Change Materials

## Investigations within Material, Device and System Scale

PhD Dissertation

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June $8^{th}$ 2020

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# Examples on how to store thermal energy within materials

**Scope:** Building application with working temperatures above 0 degC

### Sensible heat

Alternate temperature e.g. of liquid or solid material

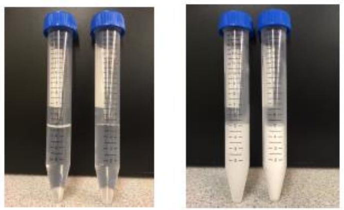

Water tank

Rock bed

### Latent heat

Alternate state of phase e.g. from liquid to solid

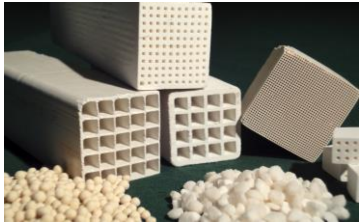
Snow/Ice storage



Paraffins, Salt-Hydrates

### Thermochemical / Thermophysical

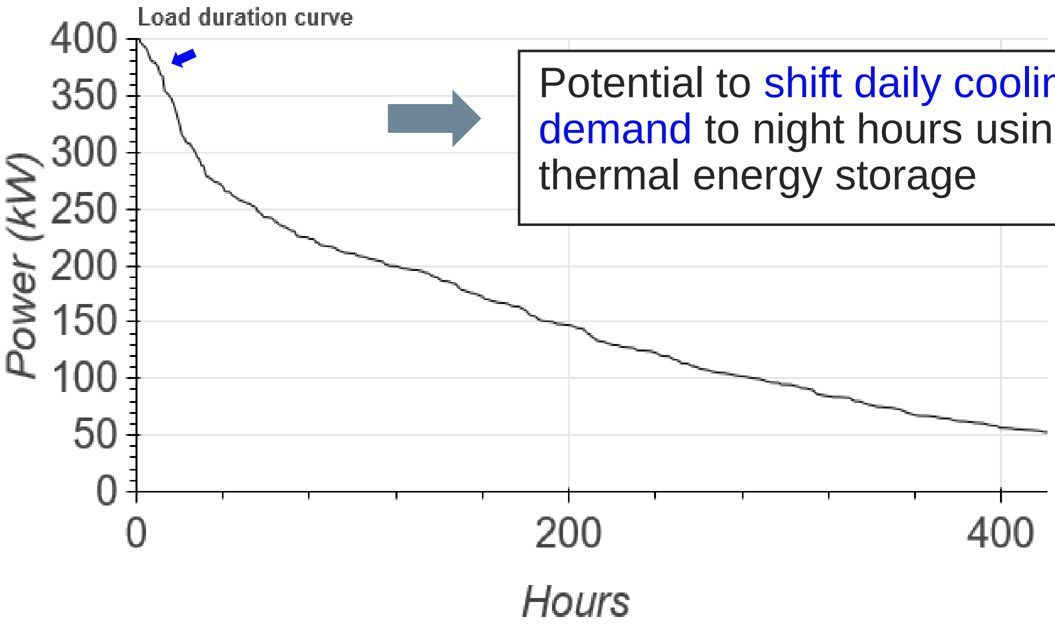
Alternate chemical composition or state of sorption



Zeolites

*Images: Wikipedia, https://forschung-energiespeicher.info, Nordell et al.*

# Application example: PCM TES for peak shaving cold energy demand in an office building




Potential to shift daily cooling demand to night hours using thermal energy storage

AWL case study

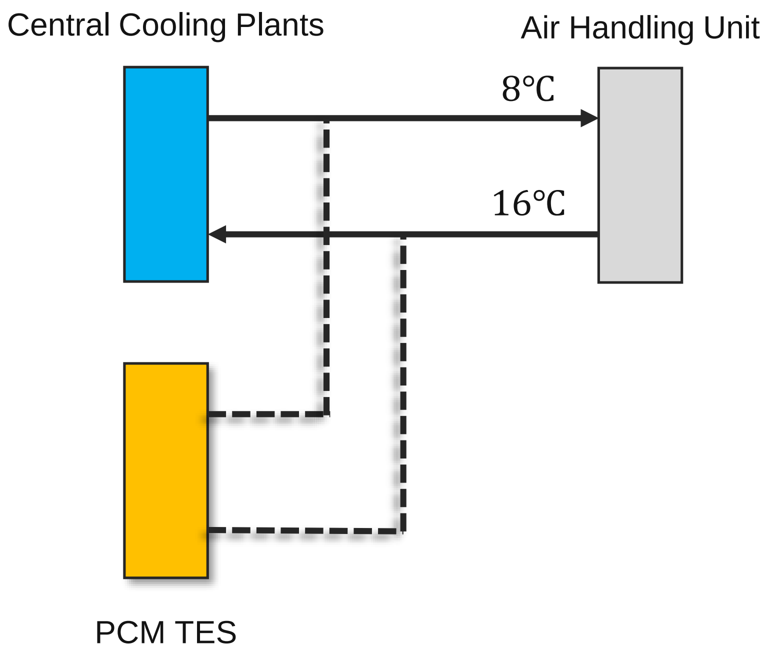
AKADEMISKA HUS

AFRY

ÅF PÖYRY

*Sources: Cooling load simulation, ÅF, A working lab*

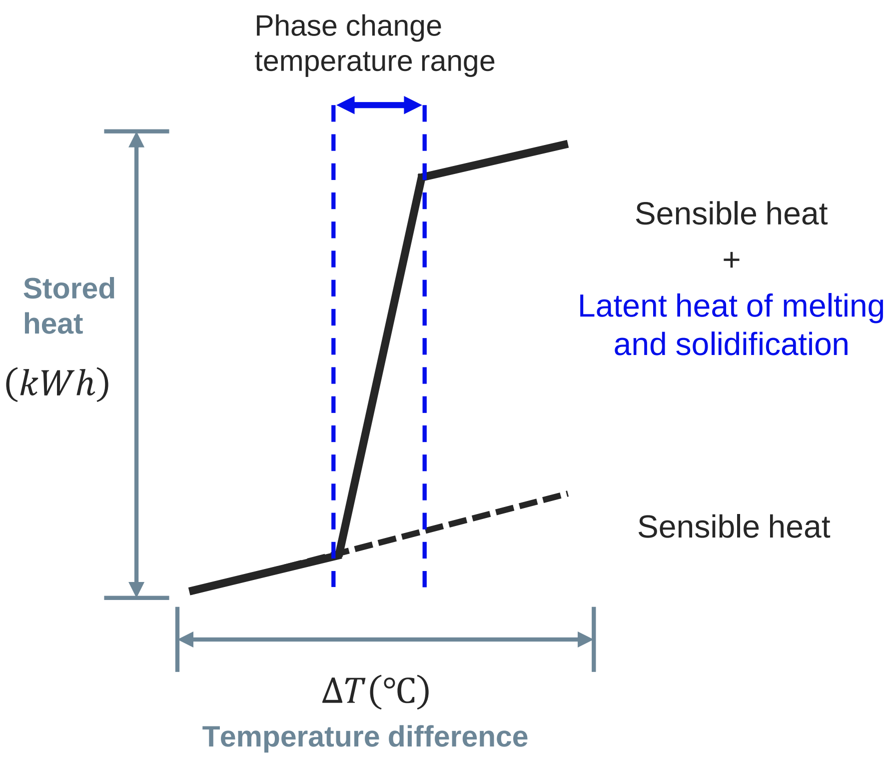
# AWL Case Study: PCM TES installed in district cooling network




- PCM TES: Heat exchanger that transfers energy between PCM and the process heat transfer fluid across time

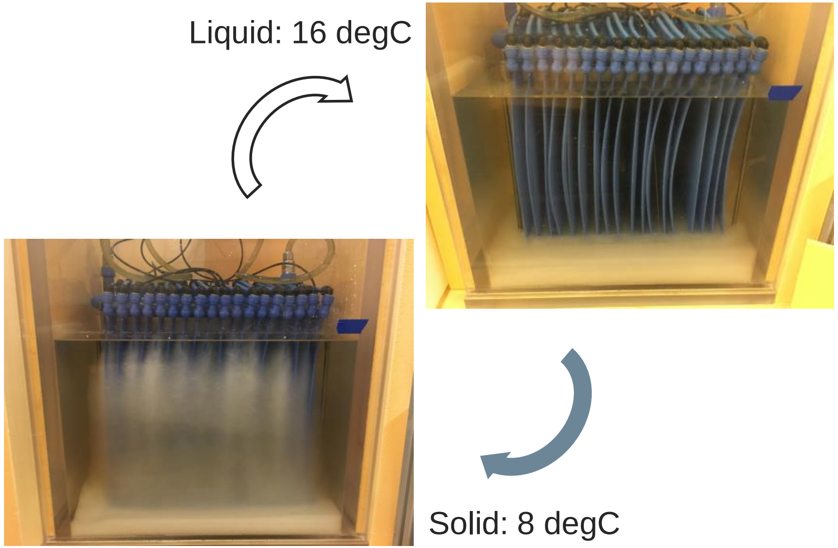
- Potential benefits:
  - Process flexibility increased
  - Charging: Utilization of lower energy prices during off-peak hours
  - Discharging: Decrease necessary max. capacity of cooling plants

# Theoretically higher storage densities with liquid/solid phase transition of storage material




**Theoretical example: 100 kWh**

- Delta T = 8 K
- Water: ca. 11 tons, 11 000 L
- Commercial Salt-Hydrate: ca. 20-30% of that mass/volume



# Gap exists between high research interest and low number of actual full scale applications using PCM TES

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General design guidelines for PCM TES missing

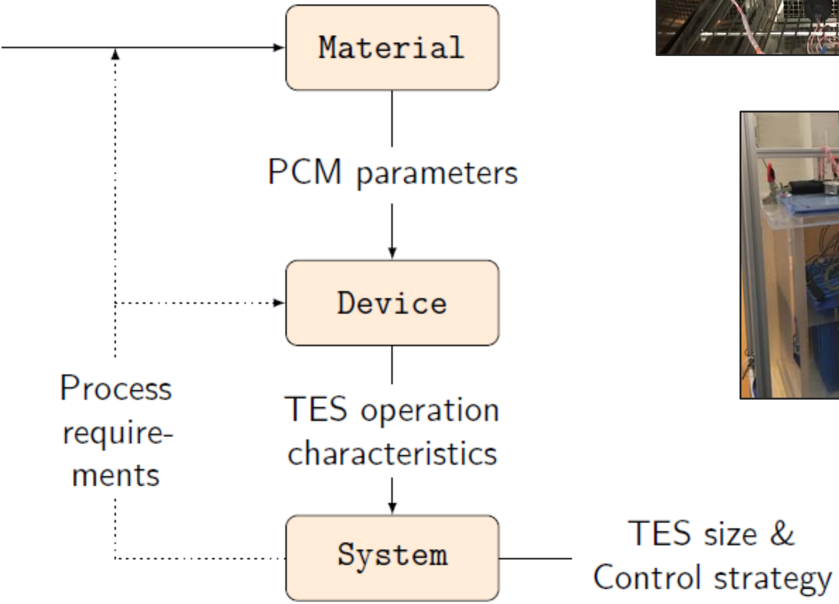
## Overall aim:

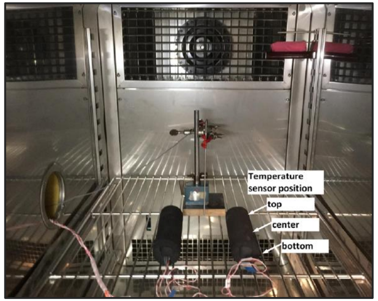
Contribute to better understanding of PCM TES design using AWL as a case study.

→

- Material selection
- Testing of PCM TES
- Quantification of PCM TES benefits vs. investment

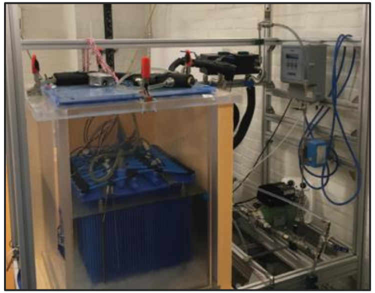
# Work follows bottom up principle of PCM TES Design




**T-History method (10g PCM)**

- Determines phase change temperature and storage capacity
- Common alternative to DSC (mg)
- **No standardization**



**Laboratory test (168 kg PCM)**

- Custom built test setup
- Estimate storage performance (power and capacity)
- **Testing under approximate process conditions**

**Full scale installation (9.4 t PCM)**

- Installation by project partners
- **Testing under actual process conditions**
- **Quantification of PCM TES benefits**

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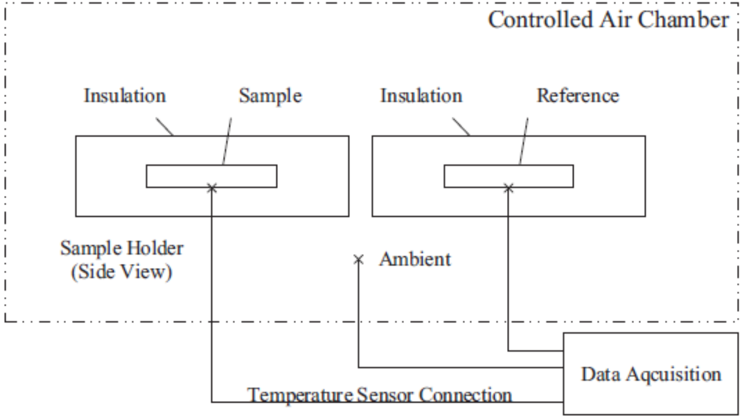
# Methodology consists of numerical and experimental work

| | T-History | Lab scale PCM TES | Full scale PCM TES |
|---|---|---|---|
| **Numerical** | Method assumptions | | Economic KPI |
| **Experimental** | Precision and Accuracy | Cycling performance | Technical KPI |
| **Collaboration** | ZAE BAYERN Bayerisches Zentrum für Angewandte Energieforschung | AKADEMISKA HUS | AFRY ÅF PÖYRY |

# T-History: Key research questions (1)



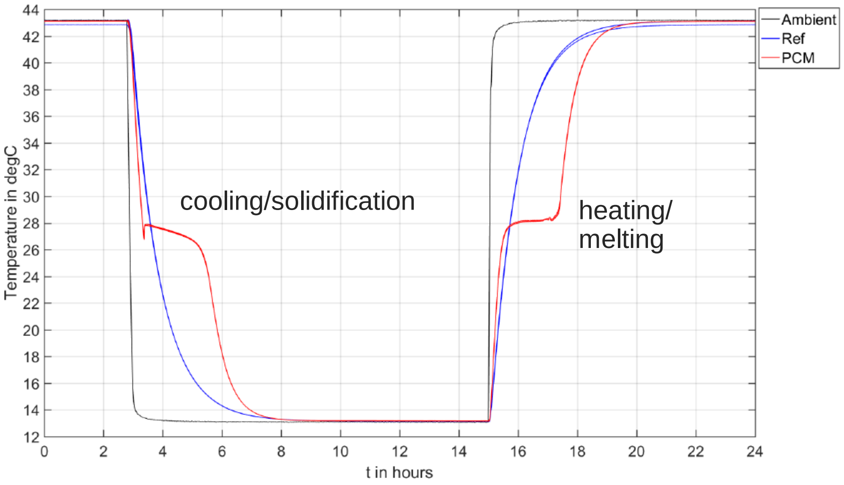

Existing T-History variants…

- can be grouped into setups with and without sample holder insulation
- but they use the same method assumptions:

(1) Uniform temperature

(2) Equal heat flux $\dot{Q}_{PCM}(T) = \dot{Q}_{ref}(T)$

- Present insulation is not taken into account explicitly

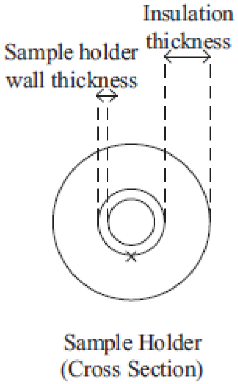


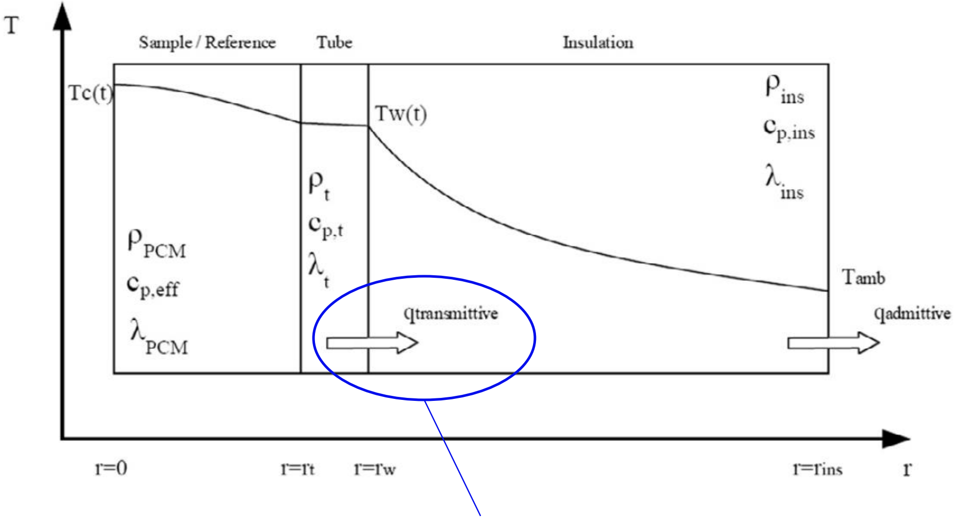

## Q1: Which systematic errors are present in the current methodology?

## Q2: How does the presence of insulation influence the results?

# Method: Check consistency of assumptions by simulations

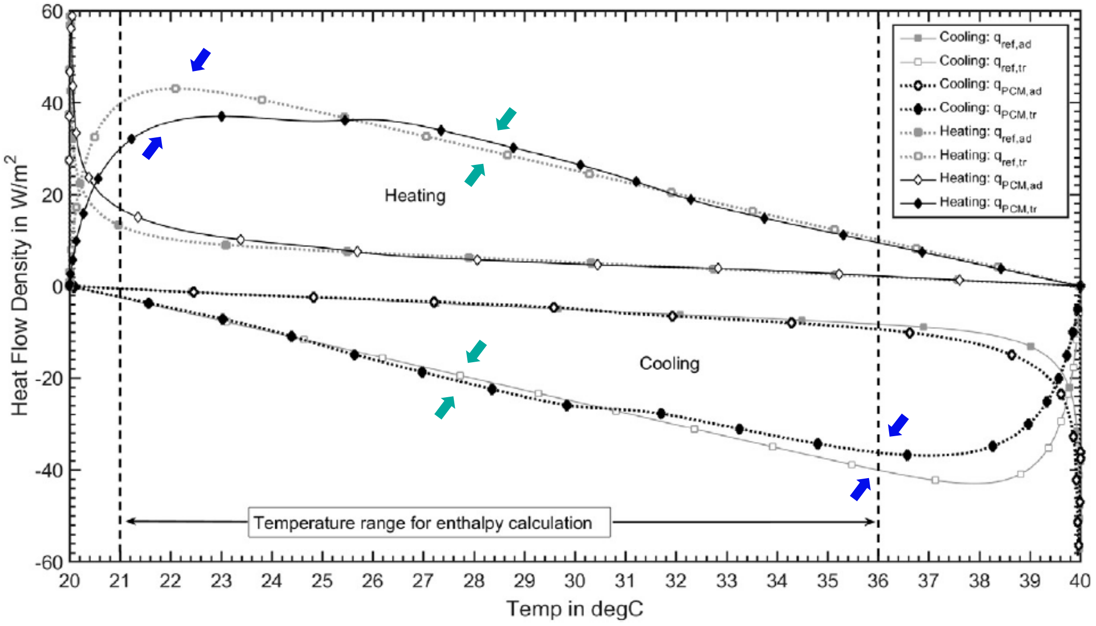
- 1-D heat conduction model to simulate T-History experiment
- Quantifiable transmittive heat flux for PCM sample and reference




Location of temperature sensor

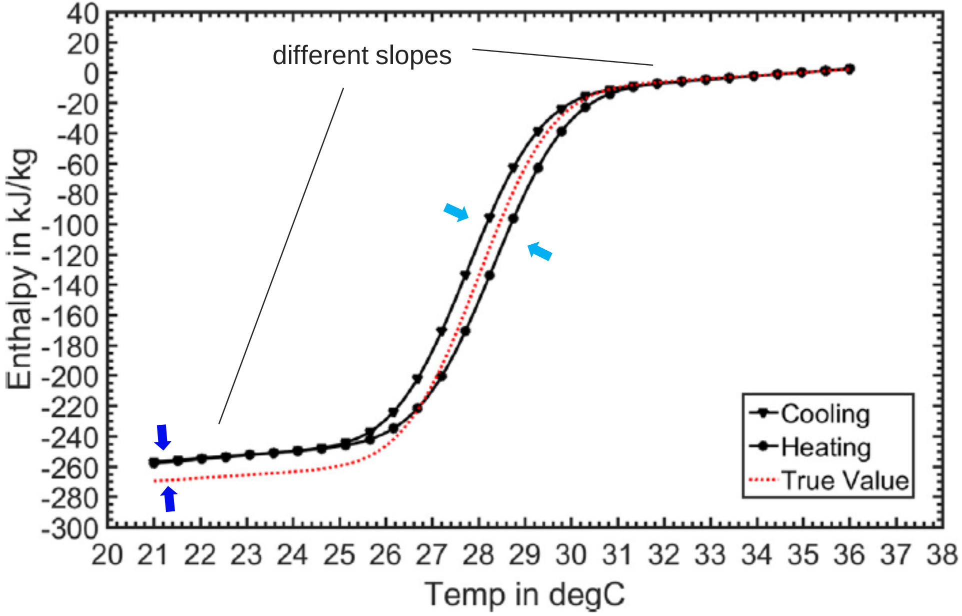
# Simulation revealed two regions with systematic difference of (transmittive) heat flux between PCM and reference




Instead of overlapping, transmittive heat flux deviate due to:

- Initial region: Different thermal diffusivity of PCM and reference
- Phase transition: Near steady state heat transfer for PCM

# Conclusion: True PCM values can only be approximated by T-History




## Q1: Which systematic errors are present in the current methodology?

- Underestimation of overall latent heat
- Overestimated liquid/solid specific heat capacities was also observed
- Artificial hysteresis

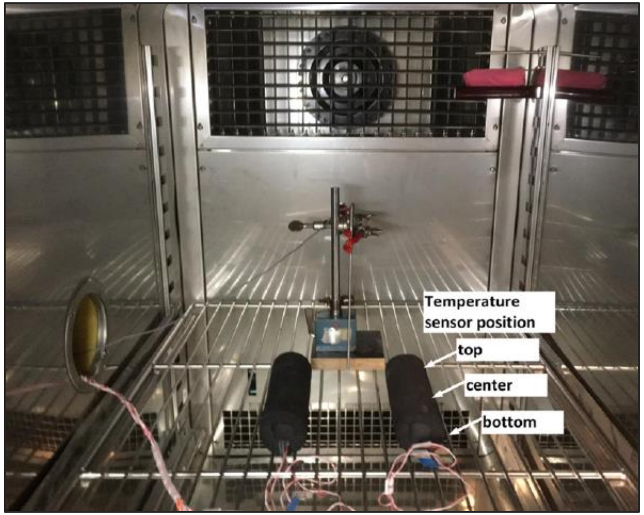
→ Correction possible

## Q2: How does the presence of insulation influence the results?

- Larger thermal mass of the insulation leads to larger underestimation of latent heat
- Low density insulation recommended
- Trade-off between artificial hysteresis and enthalpy values exists

# T-History: Key research questions (2)

- Lack of experimental study on systematic deviations (accuracy) and repeatability (precision)
- Thus, few recommendations exist on how to choose experimental parameters for insulated T-History setups




## Q3: Are the predicted systematic errors observable in a real experiment?

## Q4: What are the main factors influencing precision and accuracy in the experiment?

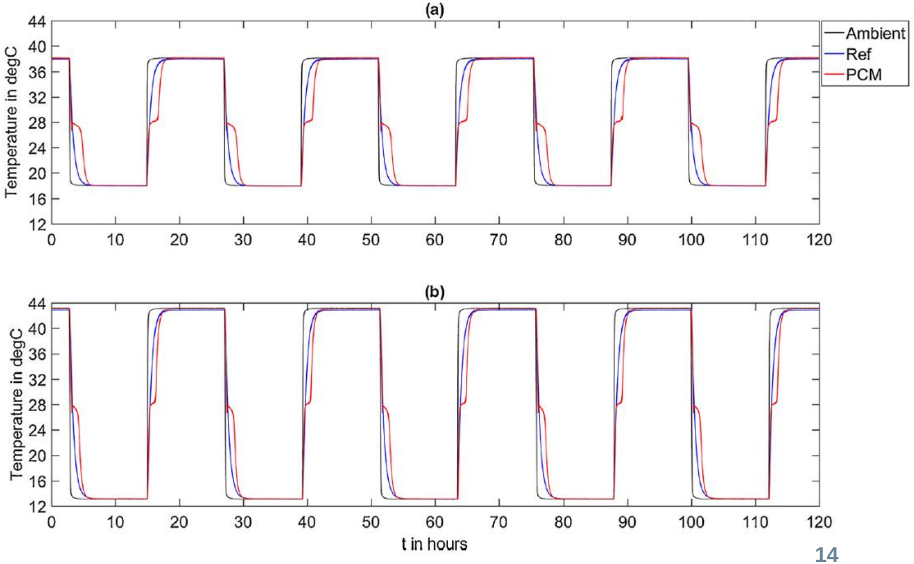
# Method: Vary experimental parameters systematically and develop a robust data evaluation method

- PCM: RT28HC (commercial paraffin)
- 6x Experimental variants
  - 3x sample holder / insulation variants
  - 2x climate chamber temperature step changes
- Repeatability: 5 cycles

PCM mass

$4g \leftrightarrow 10g$

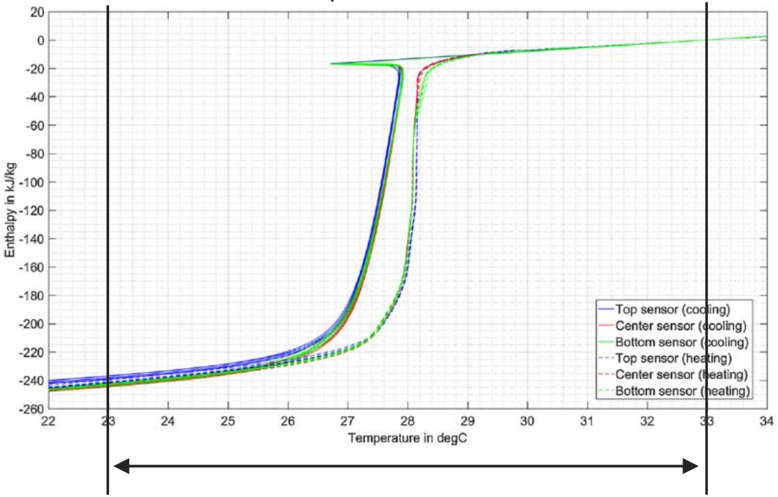
Similar insulation thickness



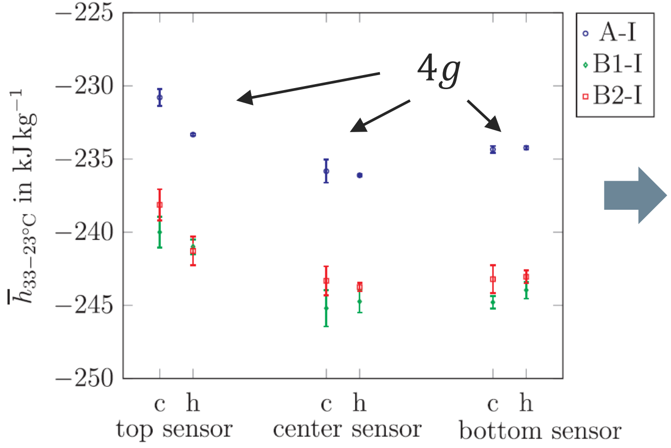

- Smoothing of apparent noise $T(t) \rightarrow \frac{dT}{dt}$
- Supercooling approximated as adiabatic case
- Uncertainty estimation using Monte Carlo

# Conclusion: Systematic deviations between different variants are observable

Results of 5 repeated measurements for one variant




mean + std.




Low standard deviation reveals systematic underestimation with smaller PCM samples

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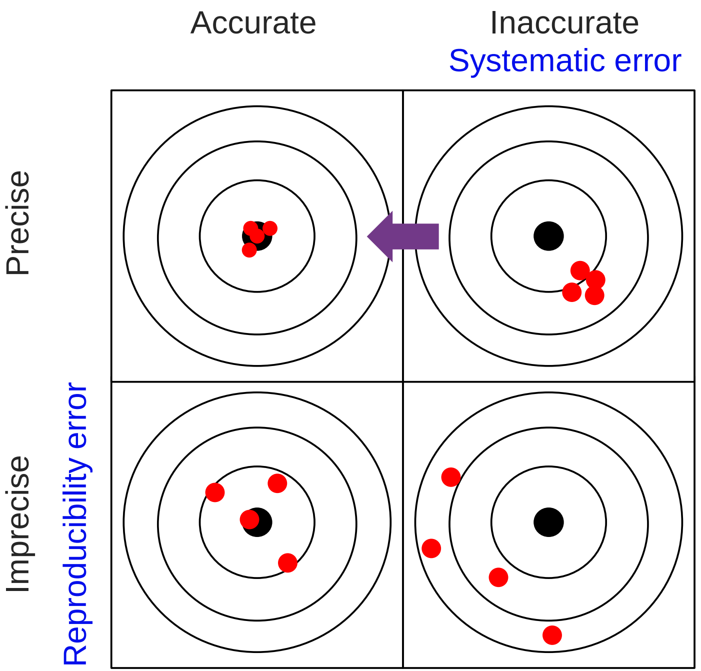
## Q3: Are the predicted systematic errors observable in a real experiment?

- Yes. Recommended to increase PCM sample size with respect to insulation thickness
- Depends on tradeoff between artificial hysteresis and enthalpy value

## Q4: What are the main factors influencing precision and accuracy in the experiment?

- Derivative of noisy data leads to low accuracy and precision, but can be systematically addressed to yield high repeatability
- Results are sensitive to both data evaluation method and experimental parameters

# Standardization of T-History method should focus on reducing systematic errors




Sources of systematic errors:

- Unequal transmittive heat flux (insulation neglected)
- Artificial hysteresis (temperature gradients exist)
- Smoothing technique?
- Treatment of supercooling?

# Lab scale and full scale studies are applied to case study

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| | T-History | Lab scale PCM TES | Full scale PCM TES |
|---|---|---|---|
| **Numerical** | Method assumptions | | Economic KPI |
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# Selection of PCM TES for the case study

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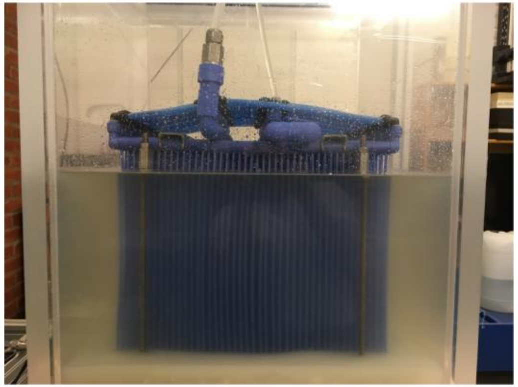
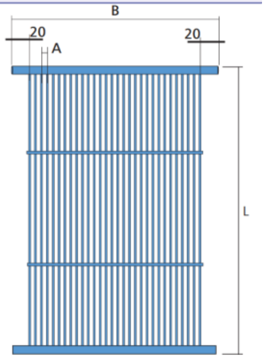


| P.VG10 | BEKA Capillary Tube Mat for pressure PN20 |
|---|---|
| Material | Polypropylene Random Copolymer Type 3, DIN 8078 |
| Ø Collector pipe<br>Ø Capillary tube<br>Capillary tube distance (A) | 20 × 3,4 mm<br>4,5 × 0,8 mm<br>10 mm |
| Length (L)<br>Width (B) | 750 - 6000 mm (in steps of 10 mm)<br>410 - 1200 mm (in steps of 10 mm) |
| Massis filled<br>Exchange surface<br>Water contents | 1438 g/m² (without collector)<br>1,357 m²/m²<br>0,64 l/m² |
| Cooling capacity *<br>Allow. heating water temp.<br>Operating pressure | 80 W/m²<br>80°C<br>max. 20 bar |
| Connection variation with quick-action couplings | 00, without connections |
| Operation area | Earth absorber<br>Surface heating in concrete |




* Capacity is reached at defined conditions
Other collector pipe dimensions (20x2 PN10 or 22x2,1)
for BEKA plug-in systems are available per your inquiry.
Ordering example:
BEKA Capillary tube mat type P.VG10, length 6000mm width 1000mm, without connections: P.VG10.6000.1000.00

**PCM TES Specifications:**

System Temperatures: 8-16 degC

**PCM Temperature: 8-12 degC**

At least 190 kWh over 5 h discharged for cooling load reduction

**Licentiate Thesis (2018):**

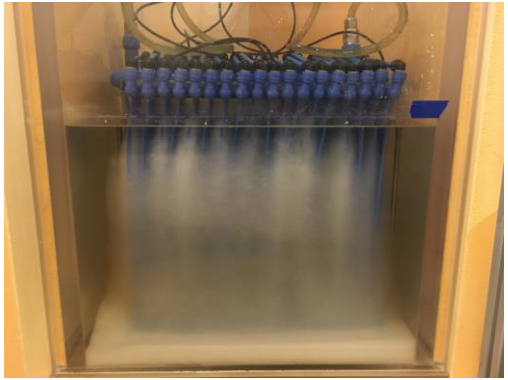
Numerical studies on heat exchanger geometry (using RT10HC, commercial paraffin)

**PCM TES supplier considerations:**

- Supplied both PCM (SP11, commercial Salt-Hydrate) and HEX (commercial capillary tube mats)
- Fire safety & leakage
- Price / availability of storage
- Ready with building inauguration

# Laboratory and full scale PCM TES

## Lab scale storage



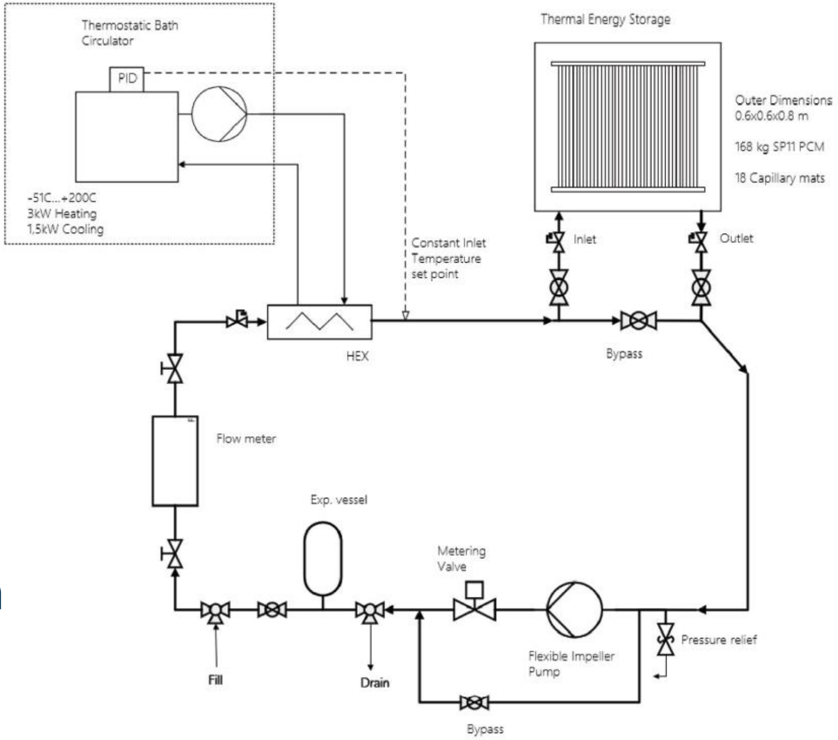
- 125L SP11
- Theoretical capacity: 4.9 kWh
- 18 mats, 396 parallel tubes

## AWL storage

- 7000L SP11 + thickening agent
- Theoretical capacity: 275 kWh
- 100 mats, 8600 parallel tubes

# Lab scale PCM TES: Continuous cycling of storage in a test bed

- Process conditions are replicated
  - Constant (dis)charging temperatures: ca.17-7 degC
  - 12h time for charging and discharging
- 6 experimental series with up to 16 cycles
- Temperature & flow rate measurements
- Study supercooling, phase separation of Salt-hydrate

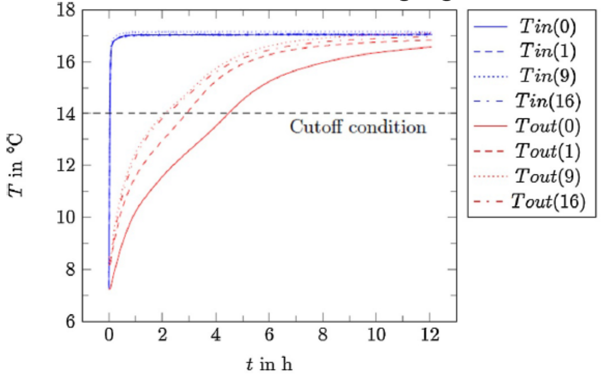



## Q1: How does the PCM TES perform under process conditions?

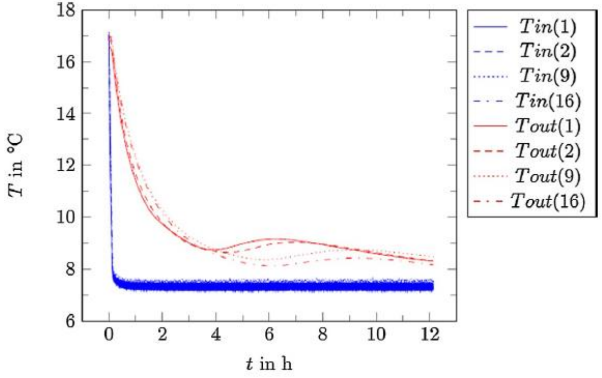
## Q2: What are the reasons behind lower than expected performance?

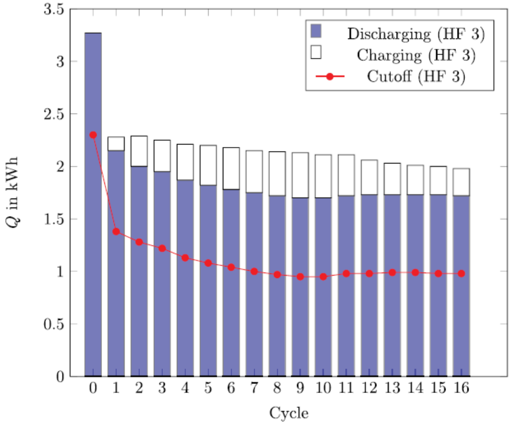
# Continued cycling show subsequent decrease of storage capacity

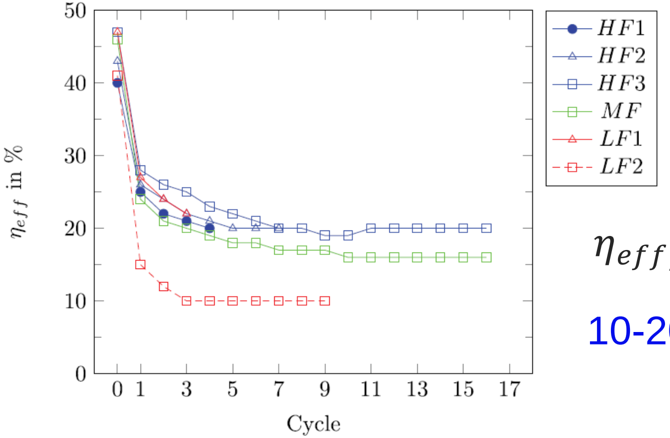
discharging




charging



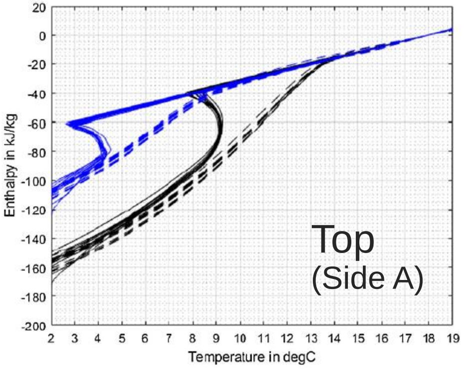

Observable for all experimental series

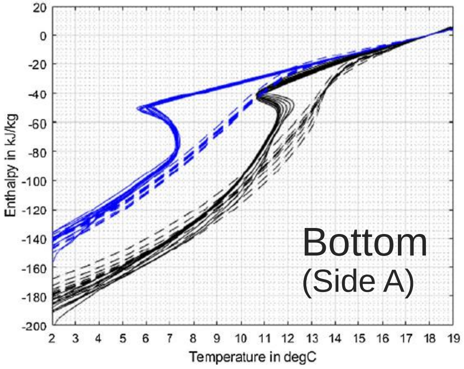
$$\eta_{eff/Q} = \frac{Q_{eff}}{Q_{max}}$$

10-20% useful capacity

# PCM samples before and after cycling show heterogeneity and shift to lower phase change temperatures

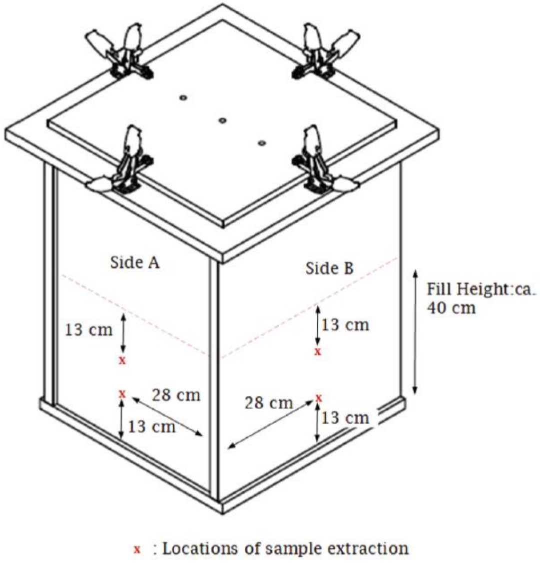
T-History results




before cycling

after cycling



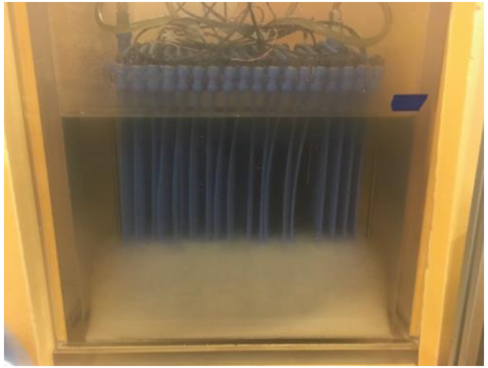



Photo from last charging occasion

# Conclusion: Phase separation has to be prevented with this PCM TES

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## Q1: How does the PCM TES perform under process conditions?

- Unstable performance. Vertical phase separation of the liquid phase leads to phase change occurring outside of process temperatures
- Phase separation can be reset by increasing temperature and mixing

➡ **To prevent liquid phase stratification:** Manufacturer added superabsorbent polymer as thickener to Salt Hydrate in full scale storage

## Q2: What are the reasons behind lower than expected performance?

- Likely, manufacturer material scale testing was not representative for the storage
- No information on exact composition for commercial PCM
- Individual T-History samples showed stable cycling performance of PCM compared to the storage

➡ Cycling instability wouldn't have been detected using T-History alone

# Full scale PCM TES: Key research questions

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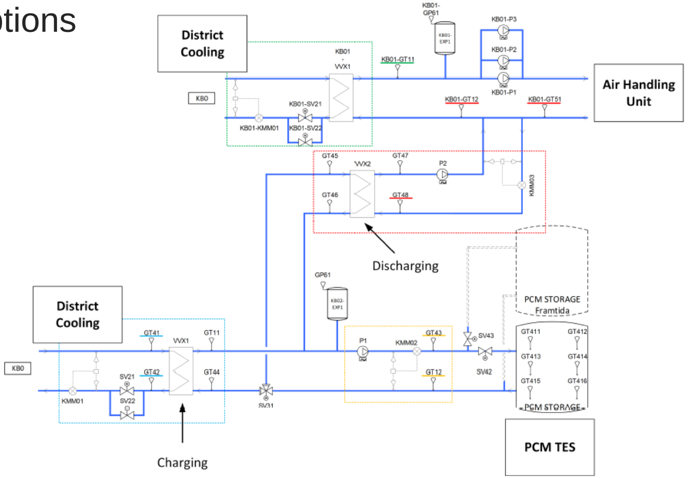
- First operational test of PCM TES during final building construction phase (Summer 2020)

- Real scale PCM TES applications have not been studied holistically
- Economic key performance indicators (KPI's) are usually not provided
- KPI's should enable investment decisions between various storage options



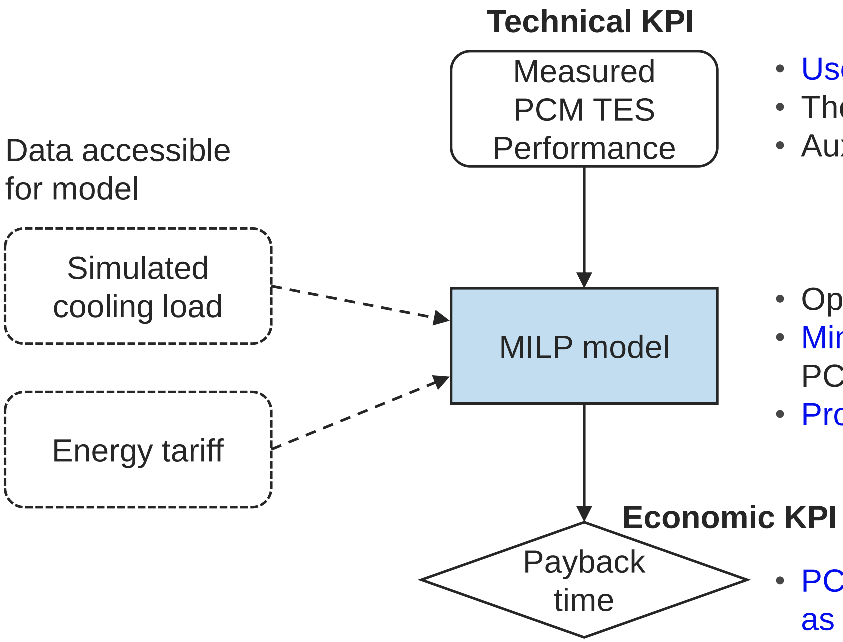

## Q1: What are the technical KPI's of the PCM TES?

- via measurement system

## Q2: What are the economic KPI's of the PCM TES?

- estimate via simulation

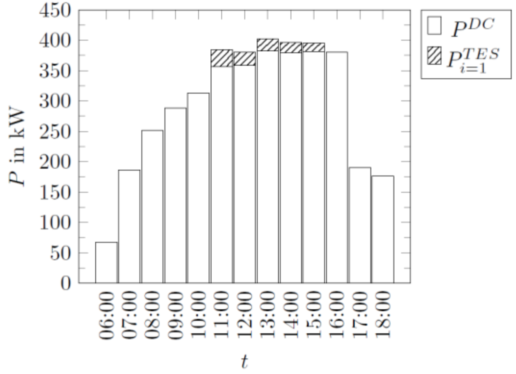
# Method: Economic KPI's estimated in a holistic way



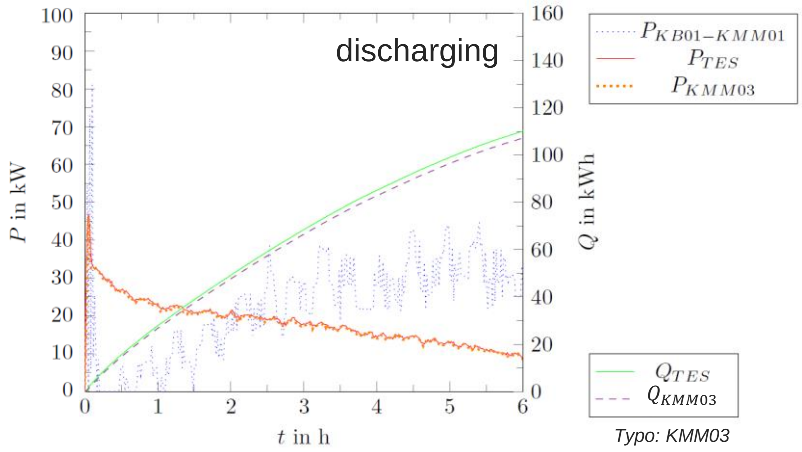

- Useable power and capacity
- Thermal losses
- Auxiliary energy consumption

- Optimizes daily charge/discharge schedule over a year
- Minimizes total energy cost / max. cost savings from PCM TES
- Proxy for control strategy

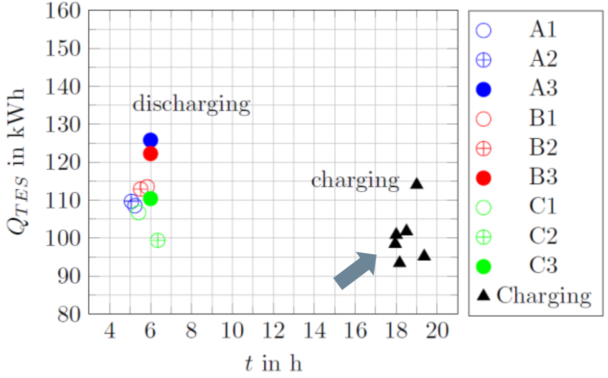
- PCM TES vs. business as usual
- Investment cost limit for 5 yr. payback

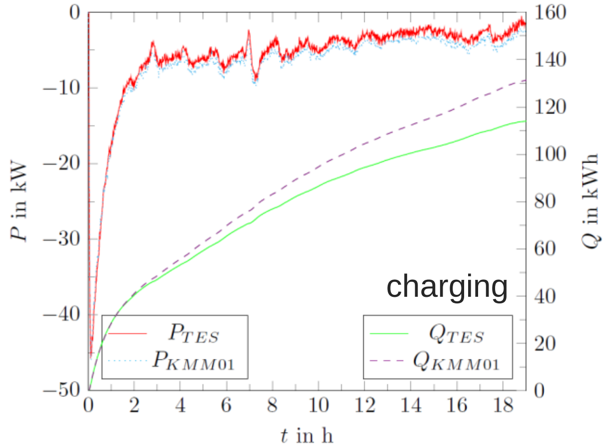


# PCM TES can use 36% storage capacity of manufacturer value




*Typo: KMM03*



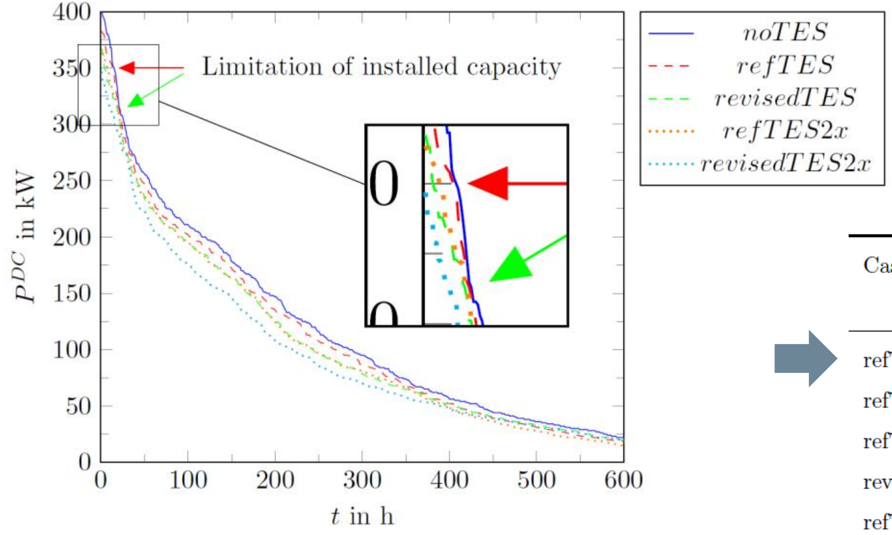

## Q1: What are the technical KPI's of the PCM TES?

- 99 kWh of 275 kWh for daily (dis)charging
- Discharging time: 5h
- Charging time: 14-18h

**Limiting factor**

# Investment costs have to be decreased significantly to be economically feasible

Reduction of duration curve for
district cooling power via PCM TES




- Different scenarios studied
  - Power output increased by factor 2
  - 2x independent dischargeable PCM TES

| Case | Cost reduction: Power (%) | Cost reduction: Energy (%) | Cost reduction: Total (%) | Investment cost limit (SEK/EUR) |
|---|---|---|---|---|
| refTES | -8.19 | -0.76 | -4.17 | 9804 / 921 |
| refTESnoETA | -8.19 | -1.16 | -4.38 | 10303 / 967 |
| refTESnoAux | -8.19 | -3.60 | -5.71 | 13425 / 1261 |
| revisedTES | -13.03 | -1.08 | -6.55 | 15421 / 1448 |
| refTES2x | -15.10 | -1.42 | -7.68 | 18076 / 1697 |
| revisedTES2x | -22.84 | -2.06 | -11.58 | 27235 / 2557 |

Actual investment costs: 546 452 SEK / 51 310 EUR

## Q2: What are the economic KPI's of the PCM TES?

- Current investment cost exceeds limit for five year payback time by several orders of magnitude

# Outlook: More work is needed on each scale to enable more real life usage of PCM TES

- T-History needs standardization
  - With respect to both experimental setup and data evaluation
  - Round-robin tests similar to DSC recommended

- Long-term stability of full scale PCM TES needs to be monitored
  - Reasons behind low performance need to be determined and fixed
  - Thickened PCM should be studied on laboratory PCM TES
  - Actual operational benefits of PCM TES have to be determined

- Focus on economic feasible PCM TES applications
  - Are there currently feasible applications?
  - What conditions have to be met for PCM TES to be feasible?
  - What are the ecological KPI’s of a PCM TES application?

# Summary of work

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| | T-History | Lab scale PCM TES | Full scale PCM TES |
|---|---|---|---|
| Numerical | **Paper [1]:** Method assumptions | | **Paper [4]:** Economic KPI |
| Experimental | **Paper [2]:** Precision and accuracy | **Paper [3]:** Cycling instability | Technical KPI |


[1] Tan P, Brütting M, Vidi S, Ebert H-P, Johansson P, Jansson H, Sasic Kalagasidis A. Correction of the enthalpy–temperature curve of phase change materials obtained from the T-History method based on a transient heat conduction model. ***International Journal of Heat and Mass Transfer*** 2017; 105:573–588.

[2] Tan P, Brütting M, Vidi S, Ebert H-P, Johansson P, Sasic Kalagasidis A. Characterizing phase change materials using the T-History method: On the factors influencing the accuracy and precision of the enthalpy-temperature curve. ***Thermochimica Acta*** 2018; 666:212–228.

[3] Tan P, Lindberg P, Eichler K, Löveryd P, Johansson P, Sasic Kalagasidis A. Effect of phase separation and supercooling on the storage capacity in a commercial latent heat thermal energy storage: Experimental cycling of a salt hydrate PCM. ***Journal of Energy Storage*** 2020; 29:101266.

[4] Tan P, Lindberg P, Eichler K, Löveryd P, Johansson P, Sasic Kalagasidis A. Thermal energy storage using PCMs: Techno-economic evaluation of a cold storage installation in an office building. Manuscript submitted to *Applied Energy (under review)*.


## More numerical studies on PCM TES (idealized PCM, not included in thesis)


Tan P. On the Design Considerations for Thermal Energy Storage with Phase Change Materials. **Licentiate thesis** 2018; https://research.chalmers.se/en/publication/500367


## Typographical corrections

*Ch.3 / Paper 3:* $\eta_{eff/Q}$

*Ch.4 / Paper 4: Discharging: KMM03 not KMM01*

# Acknowledgements

CHALMERS


| | T-History | Lab scale PCM TES / Full scale PCM TES |
|---|---|---|
| Collaboration | ZAE BAYERN<br>Bayerisches Zentrum für Angewandte Energieforschung | AKADEMISKA HUS<br>AFRY<br>ÅF PÖYRY |
| Funding | Swedish Energy Agency<br>IQ Samhällsbyggnad<br>ENERGY<br>A CHALMERS AREA OF ADVANCE | FED<br>FOSSIL-FREE ENERGY DISTRICTS<br>IRIS<br>Smart cities<br>NATUR VÅRDS VERKET |

Material samples

RUBITHERM<br>PHASE CHANGE MATERIAL

Climator<br>moving energy in time


## Thank you for your attention!