Technical insights in development of Thermal Energy Storage: from system integration to State of Charge estimation

10 December 2025 | 16:00 - 18:00 | Teams Webinar

TES Cluster
Thermal Energy Storage

ECHO
EFFICIENT COMPACT MODULAR THERMAL ENERGY STORAGE SYSTEM

ThumbsUp

HYSTORE

BEST-Storage

CET Partnership

LoCoMoSa

ISSDEMO

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Agenda

16:00 - 16:05 | | Welcome and Opening remarks | Alberto Birga , AEIT Liguria Regional Section – President & Stefano Bianchi, AEIT Liguria Regional Section - Councelor

16:05 - 16:25 | | **Concept evaluation of a novel three layer steam generator for the industrial heat industry |** Francesca Valentini, PhD candidate in Mechanical Engineering at INFN–DIAM

16:25 - 16:45 | | **Thermal Discharge Behaviour of the ISSDEMO Storage System** | Jonas Reinholz, Research associate and doctoral candidate at Fraunhofer UMSICHT

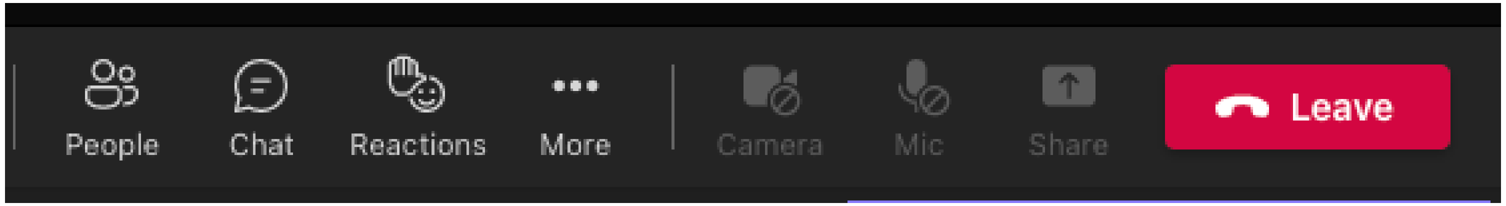
16:45 - 17:05 | | **State-of-Charge Determination in Thermal Energy Storage – Outlooks for R&D and Scalability** | Louis Desgrosseilliers , Research Associate at SPF Institute for Solar Technologies at OST

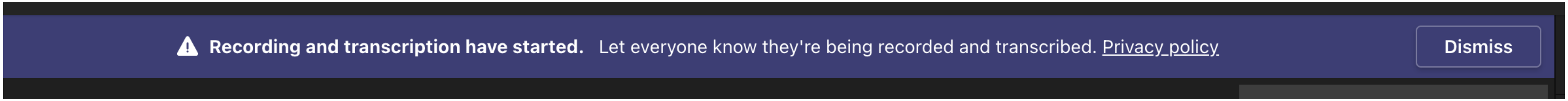
17:05 – 17:25 | | **State of Charge analysis of PCM Heating solution for implementation in KTH Live-in-Lab** | Saman Nimali Gunasekara, Assistant Professor at Energy Technology, KTH & Aditya Singh Suswal, Doctorate student at Energy Technology, KTH

17:25 – 17:45 | | Q&A

17:45 – 18:00 | | Final Questions & Closing

Teams Webinar Platform interactions





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Concept Evaluation Of A Novel Three-layer Steam Generator For The Process Industry

Francesca Valentini at INFN (Italian National Institute for Nuclear Physics)

EUROPEAN PARTNERSHIP

Co-funded by the European Union

Outline

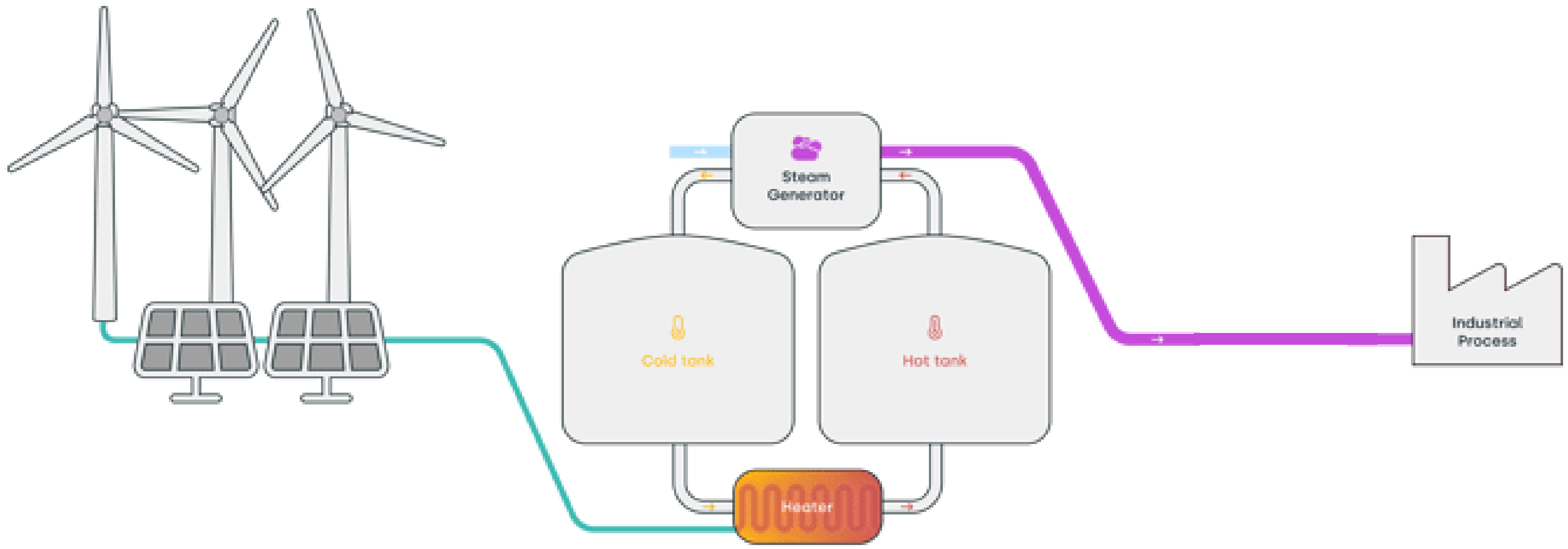
- Intro: Background: LoCoMoSa Project
- 1: The salt selection challenge.
- 2: The need for an innovative solution.
- 3: 3D printed solutions.

LoCoMoSa Project Overview

Low-Cost Molten Salt Thermal Energy Storage for Industrial Processes

Objective:

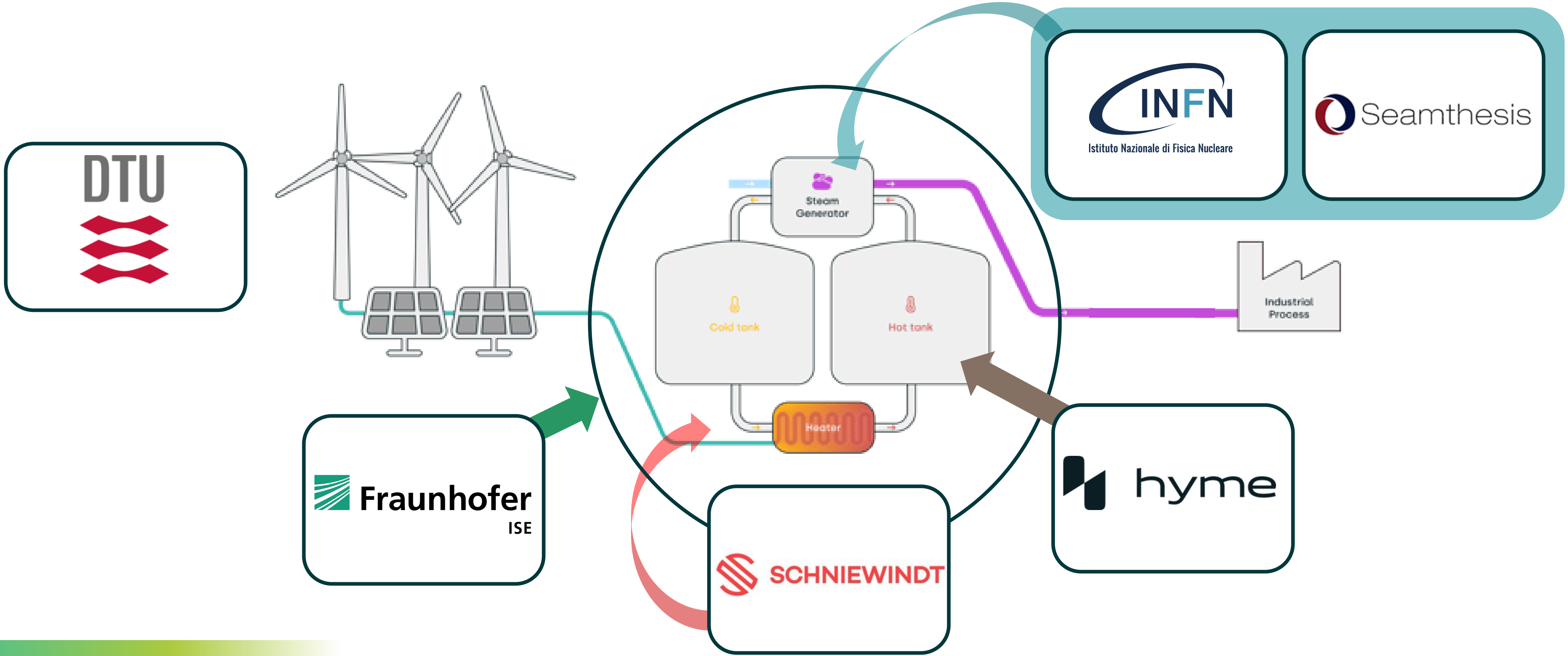
Demonstrate a *medium-to-long duration* molten-salt TES delivering heat at **120–450 °C** for industry.



TRL 6–7 Scale: 150 kW heater, ≈150 kWh storage

LoCoMoSa Project Overview

Low-Cost Molten Salt Thermal Energy Storage for Industrial Processes

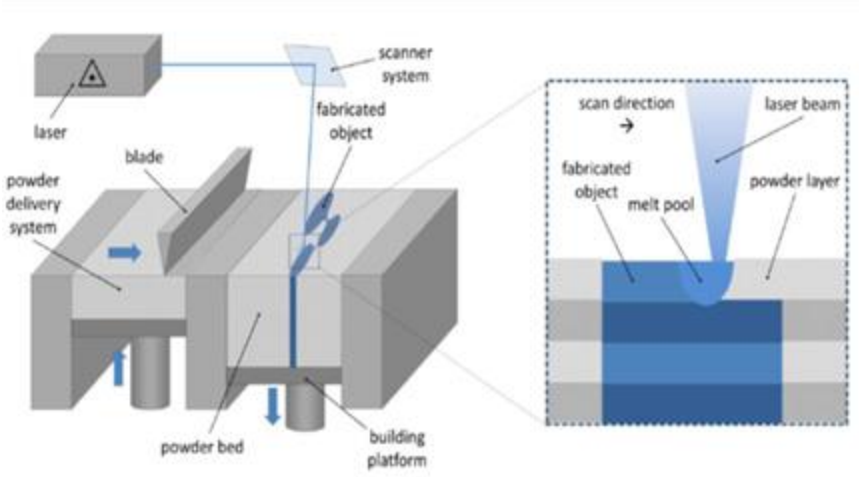


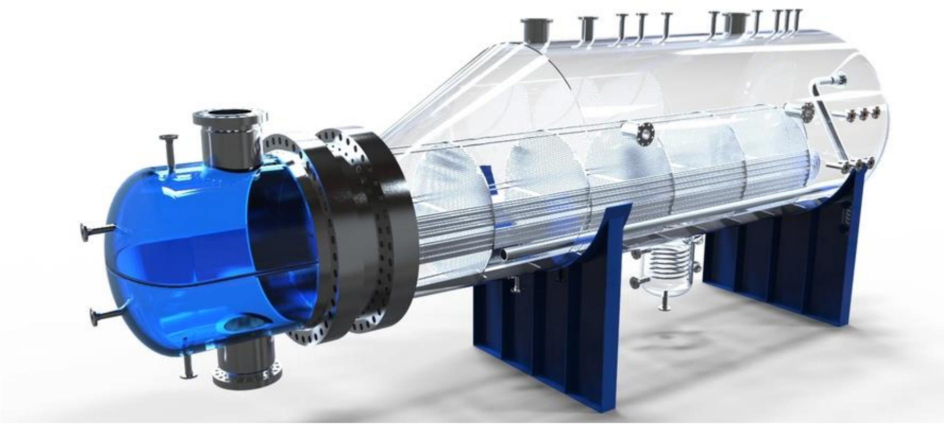
Project partners role

INFN
Istituto Nazionale di Fisica Nucleare

- Designs and models the AM steam generator between molten salt TES and steam user.
- Translates TES conditions (salt T, flow) into steam-side requirements.

- Exploit design flexibility of additive manufacturing to propose innovative and functional designs.



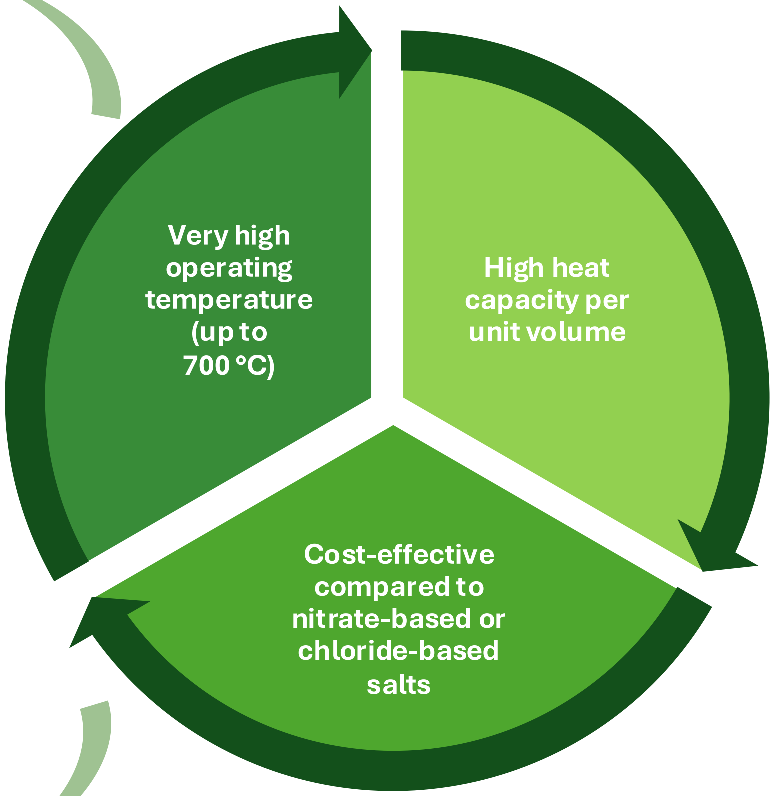


Low-Cost Molten Salt

NaOH

Ideal for:

- High-temperature power cycles (e.g., supercritical CO_2, Rankine)
- Industrial process heating above 400 °C
- Reduced thermal storage size



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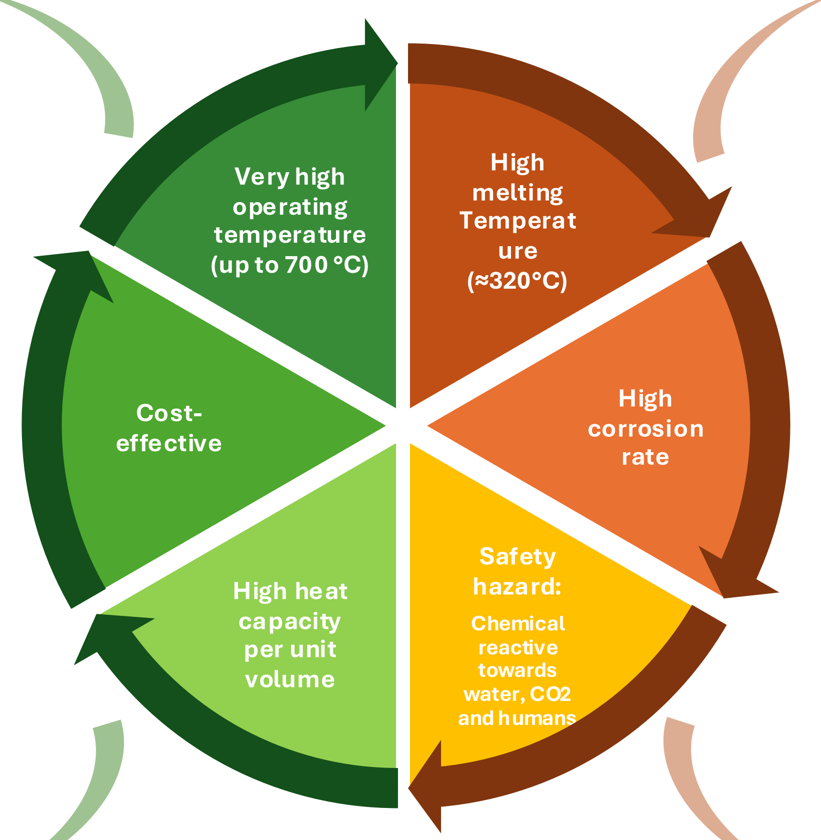


Challenges:

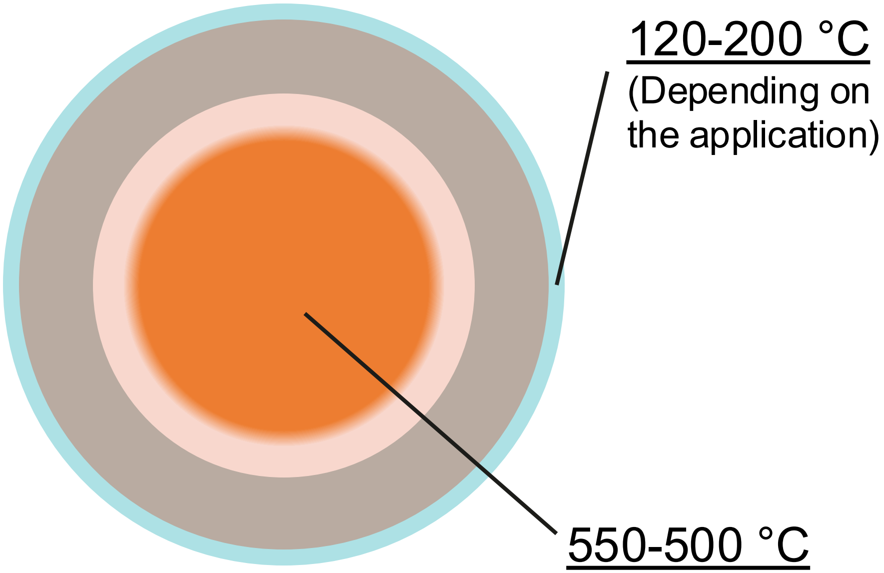
- Solidification risk
- Possible boiling instabilities issue
- Corrosive and dangerous, needs suitable material selection and safety measures

Low-Cost Molten Salt

NaOH

High temperatures are chosen since :

- NaOH's temperature must stay above the melting point (safety margin of 350°C)



Is NaOH feasible for low pressure steam production?

Does it require an innovative design to avoid solidification?

Low-Cost Molten Salt

1

Demonstrate the need for a special steam generator design for low pressure steam production

2

Explore potential solutions:

Steam generator with a thermal regulation layer

1 Numerical Model Description

1D finite volume model for heat transfer simulation.

Key assumptions and simplifications.

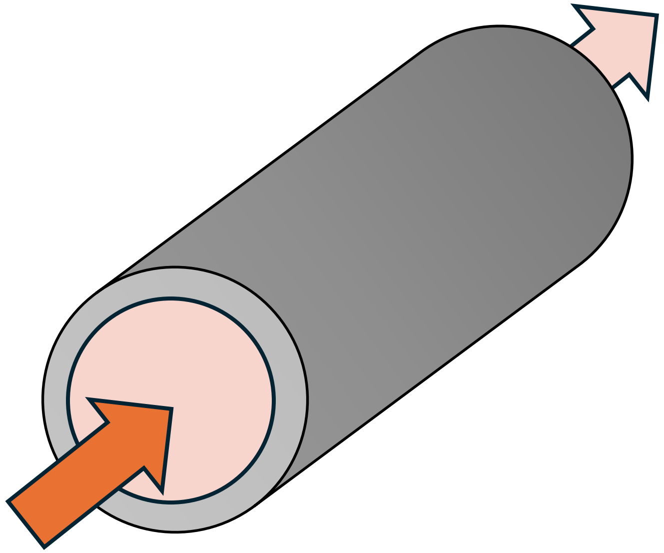
- 1D model along the axial direction of the tube
- Steady-state

Fluid and geometry:

- Inner fluid: molten NaOH
- Outer fluid: boiling water at constant temperature and pressure
- Wall: Inconel 718.

Goal: Explore the effect of

- Salt inlet temperature from 350 to 600°C
- Pressures: 1–10 bar
- Boiling curve dependence considered



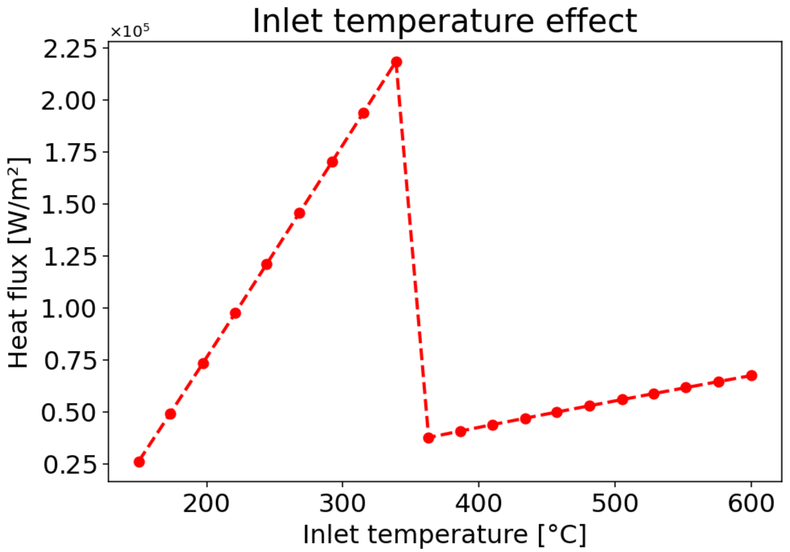
Tube geometry:

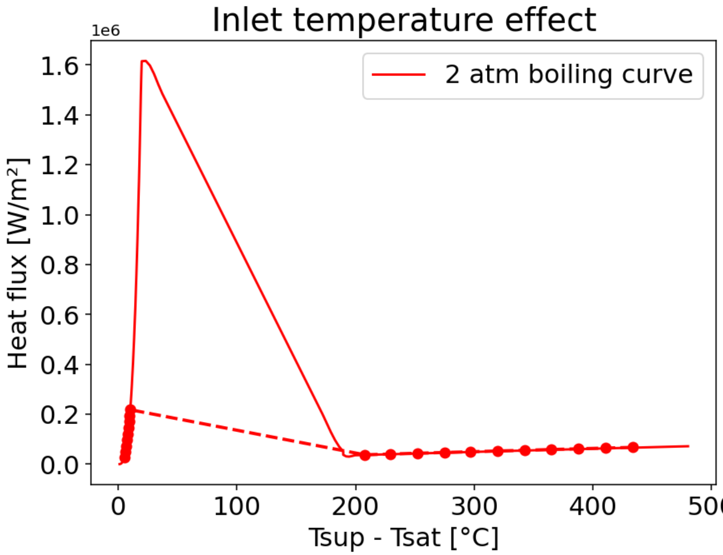
- ID: 25,4 mm
- OD: 33,4 mm
- L: 1m

1 Key results

1D finite volume model for heat transfer simulation

Low inlet temperatures	Stable nucleate boiling, efficient heat transfer that increases with superheat.
As inlet temperature increases:	Heat flux rises until it reaches the maximum allowable.
Post-transition behavior:	Further increase in inlet temperature pushes the wall into film boiling regimes.
	Heat flux drops significantly.
	Heat transfer becomes potentially unstable





1 Key results

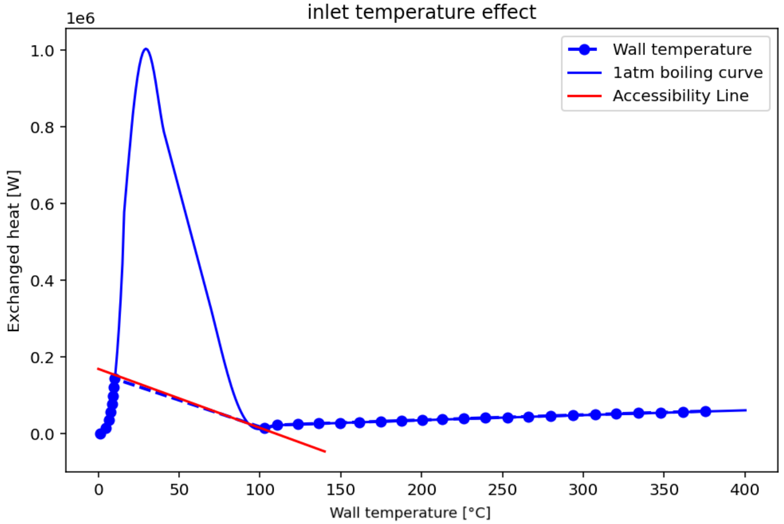
1D finite volume model for heat transfer simulation

Unreachable States: Some points on the boiling curve in the transition region are not accessible.

Stability: Points between two intersections of an accessibility line are avoided; the system favors stable outer points.

Accessibility lines: Depend on the system thermal resistance:

$$q = -\frac{T_{sup} - T_{sat}}{R_{salt} + R_{wall}} + \frac{T_{salt} - T_{sat}}{R_{salt} + R_{wall}}$$



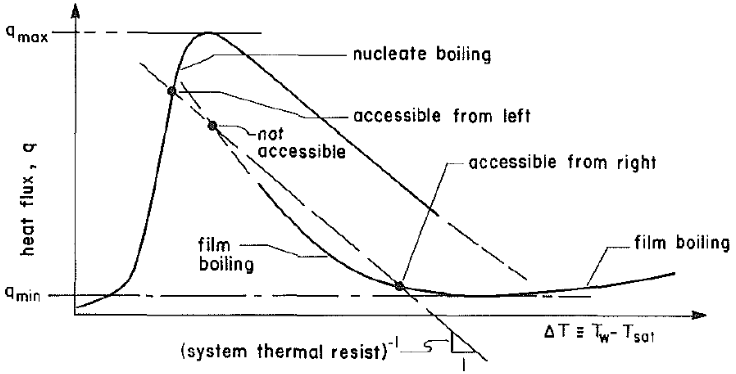


Fig. 1 Accessibility lines on Witte and Lienhard's double boiling curve (coordinates are linear)

Transition Boiling Heat Transfer and the Film Transition Regime. J.M- Ramilison, J.H.Lienhard, Mechanical Engineering Department, University of Houston, 1987

1 Key results

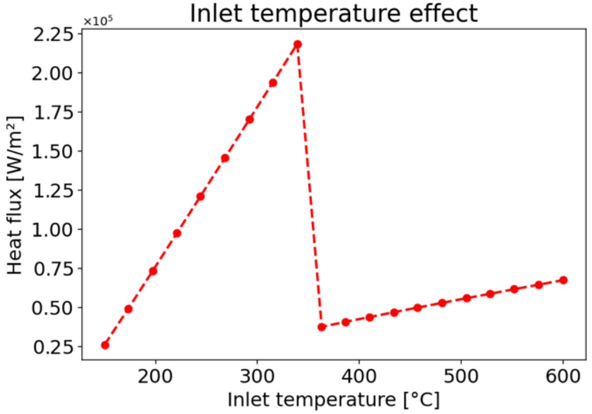
1D finite volume model for heat transfer simulation

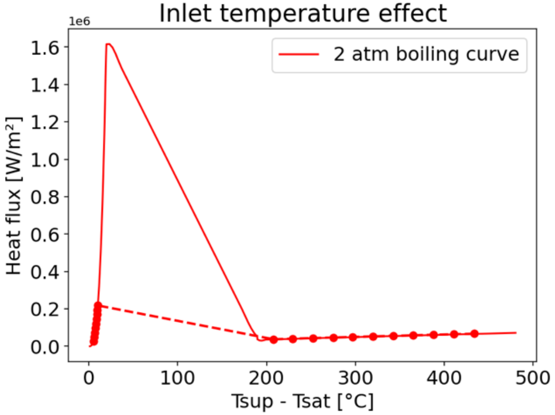
As water pressure increases

The transition to film boiling is delayed to higher superheat.

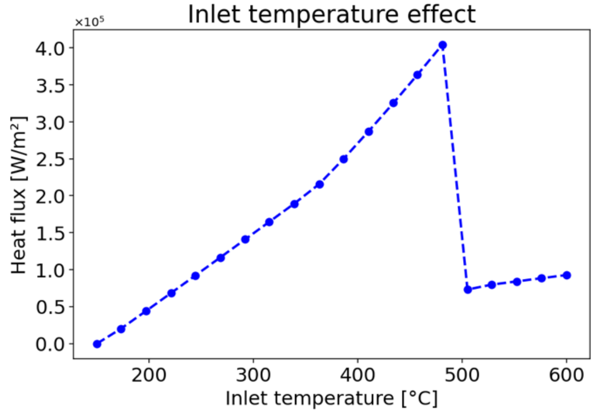
It disappears for the higher pressures.

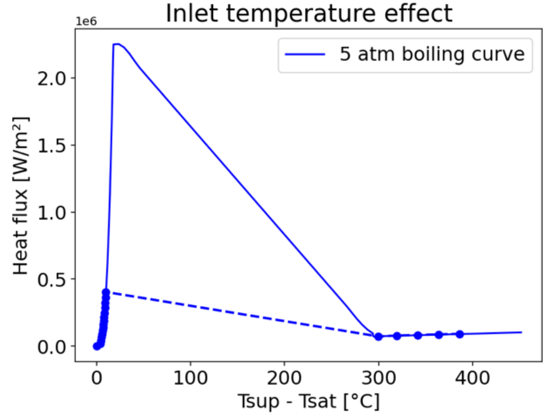
2atm



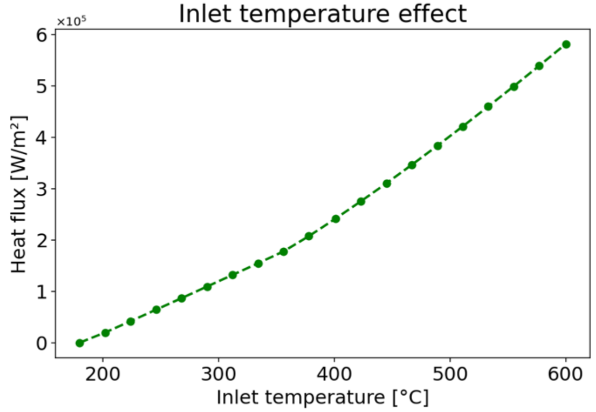


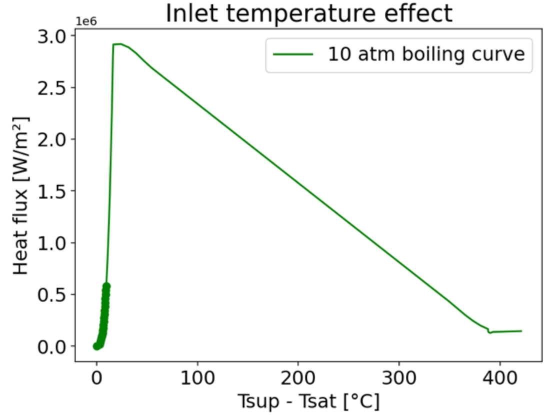
5atm





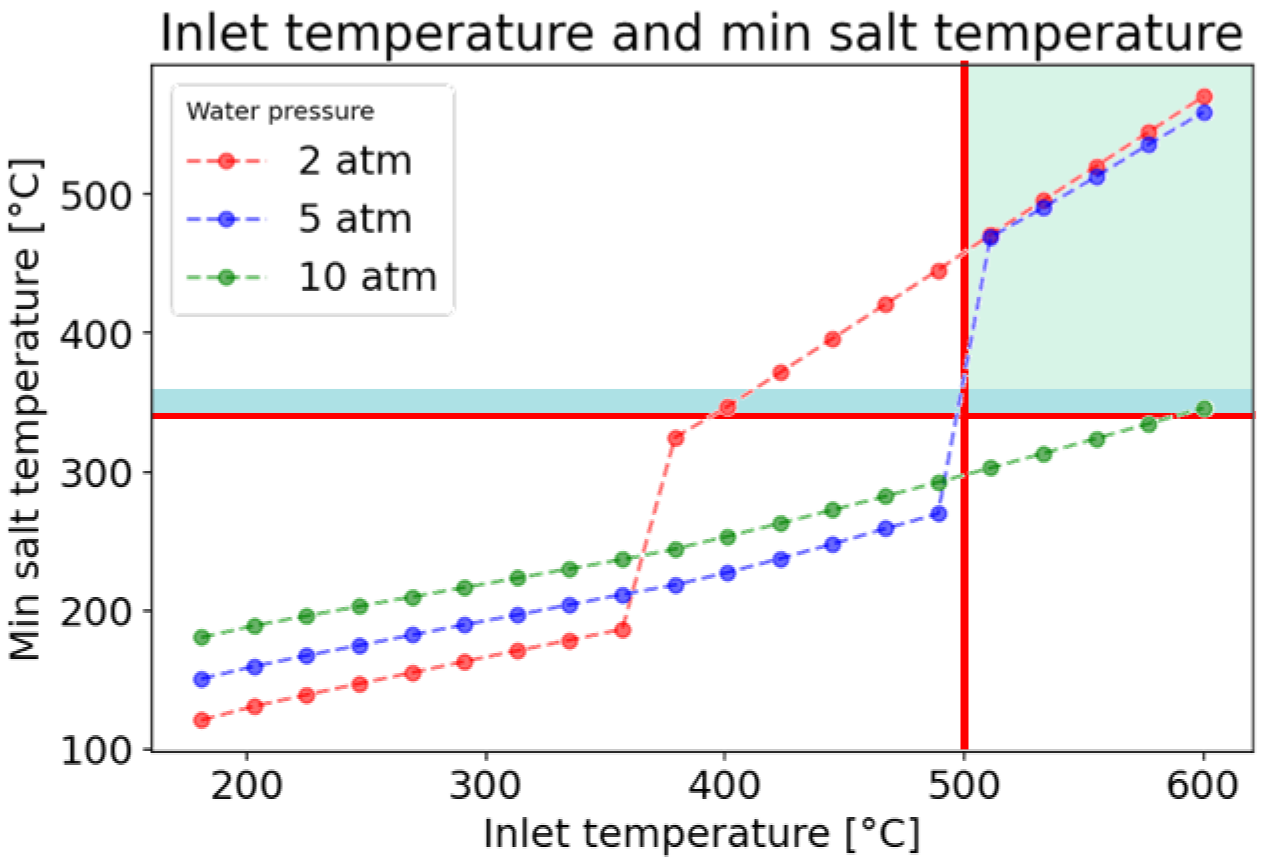
10atm





1 Key results

1D finite volume model for heat transfer simulation



Nucleate boiling

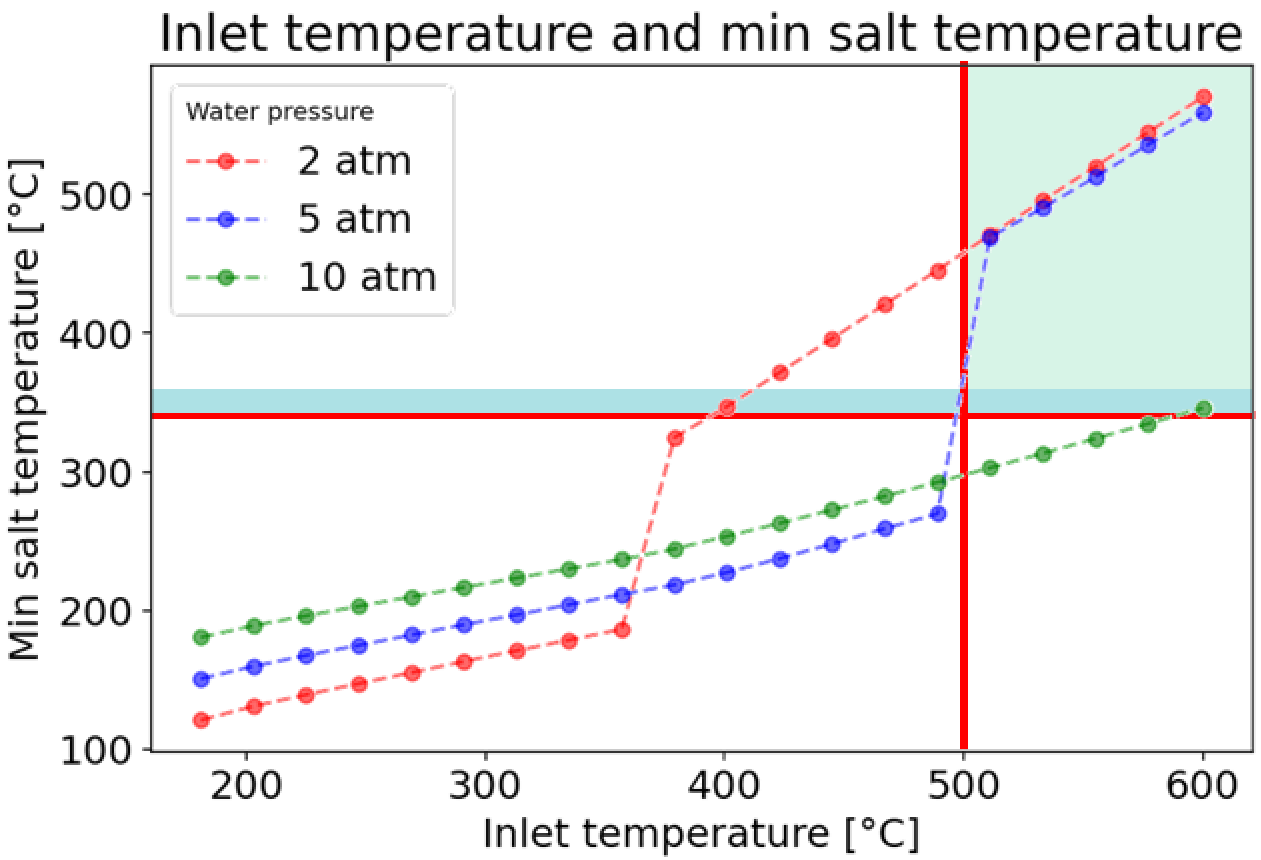
- Heat is removed too efficiently
- The salt risks solidification

Film boiling

- Vapor film acts as an insulator
- Wall stays hot, salt remains molten
- Efficiency very low

1 Key results

1D finite volume model for heat transfer simulation



Nucleate boiling

- Heat is removed too efficiently
- The salt risks solidification

Film boiling

- Vapor film acts as an insulator
- Wall stays hot, salt remains molten
- Efficiency very low

Is adding a thermal resistance a possible solution to avoid salt solidification?

Can additive manufacturing enable smart thermal resistance?

Objectives of this study

Demonstrate the need for a special steam generator design

1

Explore potential solutions:

Steam generator with a thermal regulation layer

Novel Concept Overview

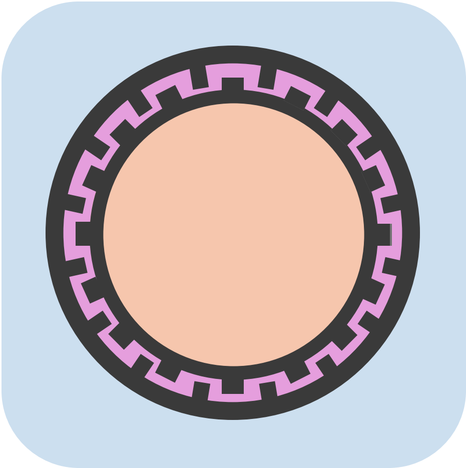
Tailored thermal resistance proposal

Three layers:

- Tube side: molten salt,
- Shell side: Saturated water
- Intermediate layer: thermal regulation layer.

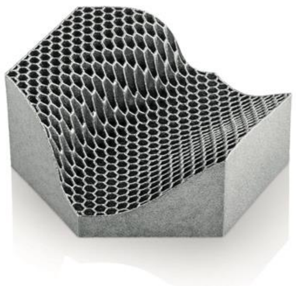
Double-wall tube architecture enabled by additive manufacturing.

- High precision in wall thickness
- Small internal channeling



A layer with flowing gasses and surface area enhancement:

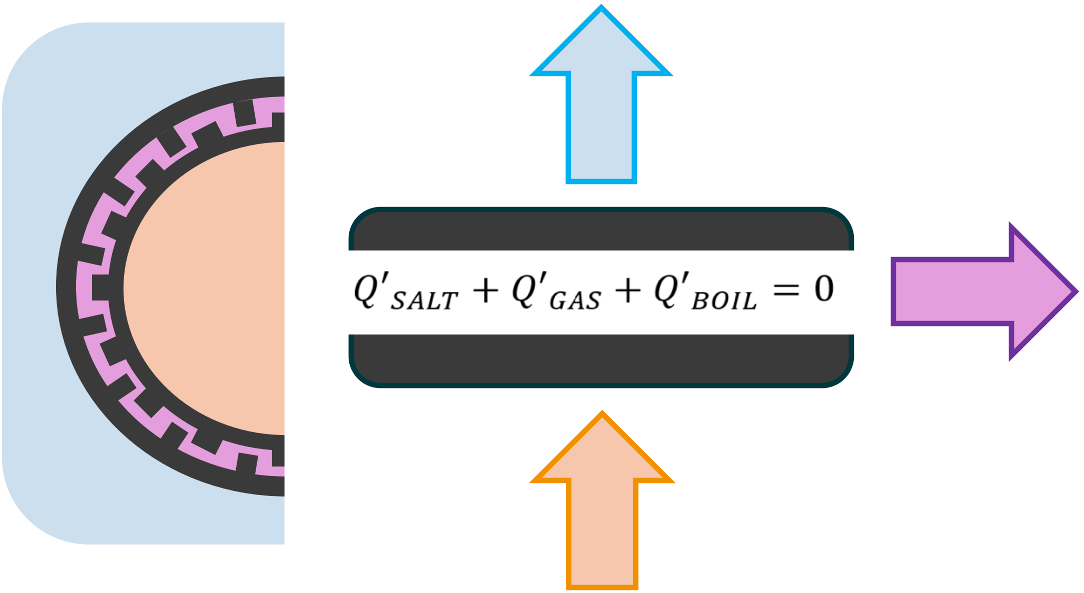
- Corrosion control inert gass (N_2 or Ar)
- Steam: recirculated to provide controlled superheating
- Thermal control parameter Additional area is the



Novel Concept Overview

Tailored thermal resistance proposal

- Acts as a thermal resistance between hot molten salt and water/steam.
- Works like a thermal valve:
  - Too high wall temperature → overheating,
  - Too low → salt solidification
- By changing the internal geometry, we can tune the heat flux.



$$Q'_{SALT} + Q'_{GAS} + Q'_{BOIL} = 0$$

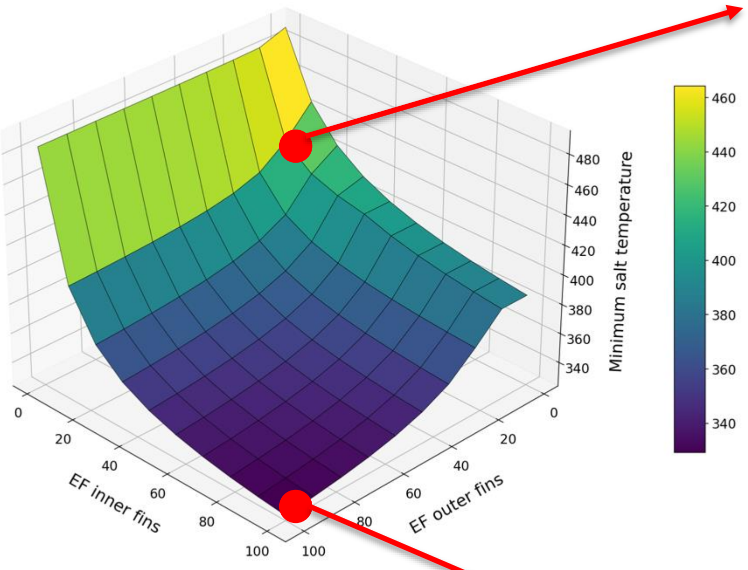
$$R'_{GAS,IN} = \frac{1}{htc_{GAS} \cdot \pi \cdot ID_{layer} \cdot EF_{fins,IN}}$$

$$R'_{GAS,OUT} = \frac{1}{htc_{GAS} \cdot \pi \cdot OD_{layer} \cdot EF_{fins,OUT}}$$

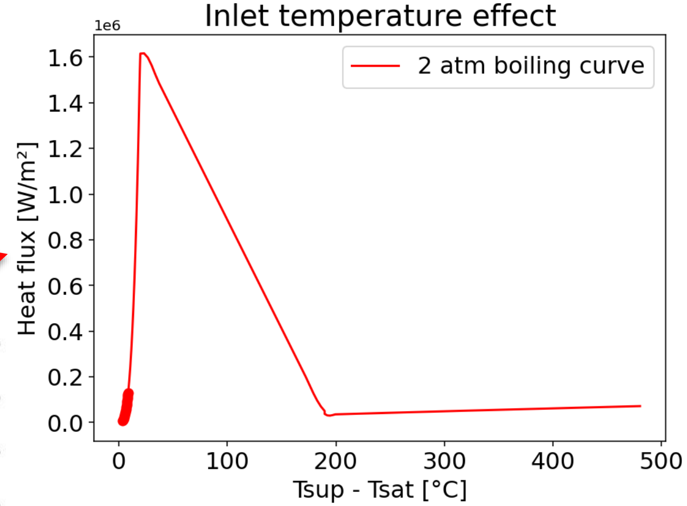
2 Concept Results

Results calculated for 2 atm and T_{IN} =500°C.

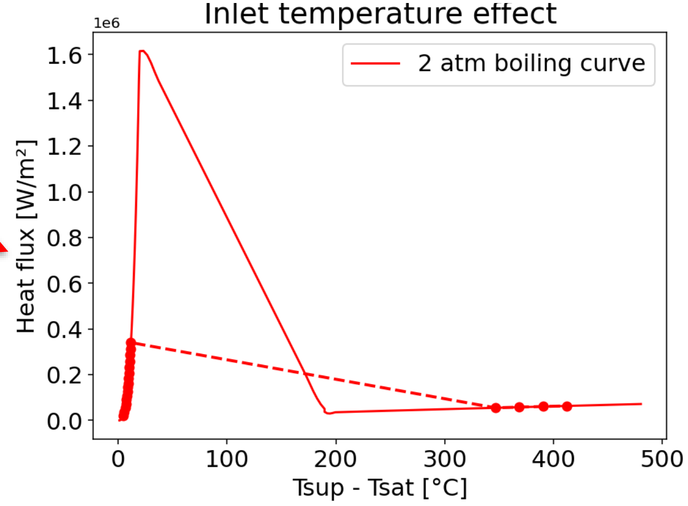
As the efficiency factor increases:	The minimum salt temperatures decreases.
	High inner fin efficiency has the strongest impact on cooling.
By tailoring the efficiency factor one can:	Find a set of parameters that avoid the film boiling transition.
	Sustain acceptable heat transfer.



$$EF_{fins,OUT} = EF_{fins,IN} = 8$$



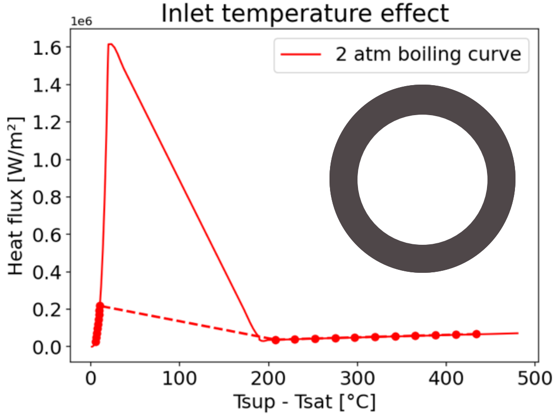
$$EF_{fins,OUT} = EF_{fins,IN} = 100$$

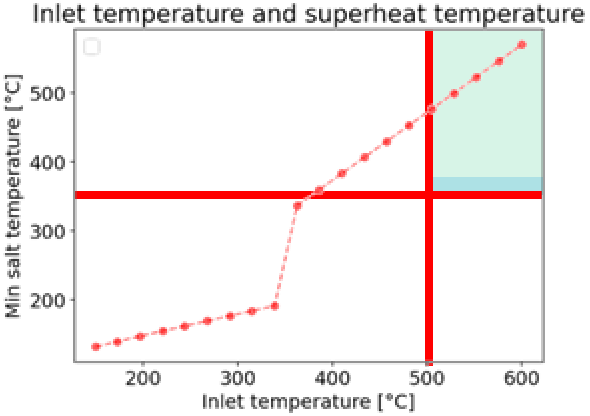


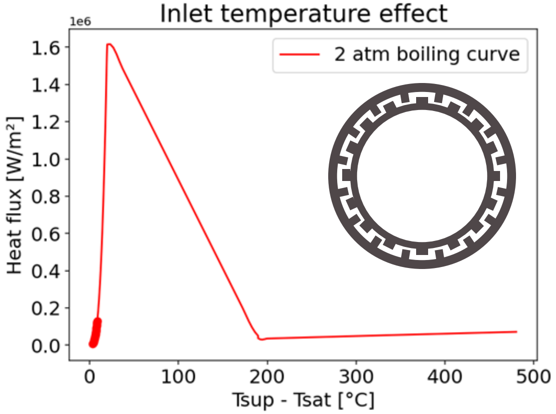
2 Conclusion

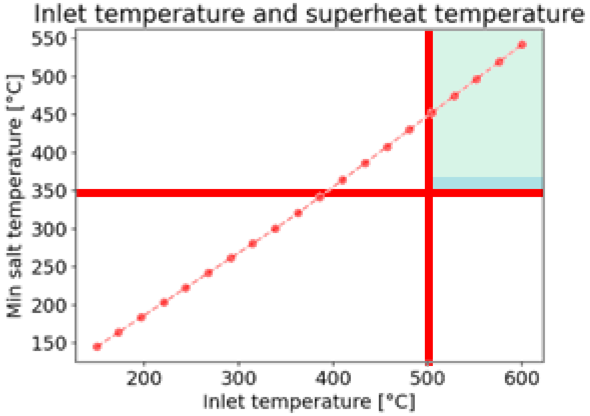
1D finite volume model for heat transfer simulation

To have an efficient and reliable operatrion	The heat transfer needs to be balanced with the thermal stability of molten salt and the boiling regime efficiency.
	It is important that in every part of the steam generator the temperature is higher than 350°C
	It is important to ensure the steam generator is operating in nucleate boiling.
By adding a tailored thermal resistance	One can select how much heat one can exchange allowing operation at temperatures that were dangerous before.









Thank you!

Questions?

Acknowledgement

This project is supported under the Clean Energy Transition Partnership (CETPartnership, 2022 call, project no. Cetp-2022-00044)

Energiteknologisk udvikling og demonstration

This project is also co-funded by the national programs:

- Denmark – EUDP, project no. 640235-510582
- Germany – Fise, Schniewindt, Fraunhofer
- Italy – *Seamthesis, INFN*

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Research associate and PhD candidate at Fraunhofer UMSICHT

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AEIT WEBINAR – Technical insights in development of TES: from system integration to State of Charge estimation
December 10, 2025
Jonas Reinholz

Thermal Discharge Behavior of the ISSDEMO Storage System

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AGENDA

1. Introduction
2. General information TES
3. ISSDEMO Project
    - General information
    - Integration
    - Thermal Discharge Behavior
    - CFD Simulations by SUT

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Fraunhofer-Gesellschaft

Leading organization for application-oriented research in Europe

over

30,000

employees

€ 3.0 billion

financial volume
therof € 2.6 billion contract research

76

institutes and
research facilities

Funding mix

70% orders
from industry and public sector
30% base funding
from Germany‘s federal and state governments

6200

customers from
industry

Figures refer to the year 2022: Status as of May 15, 2023

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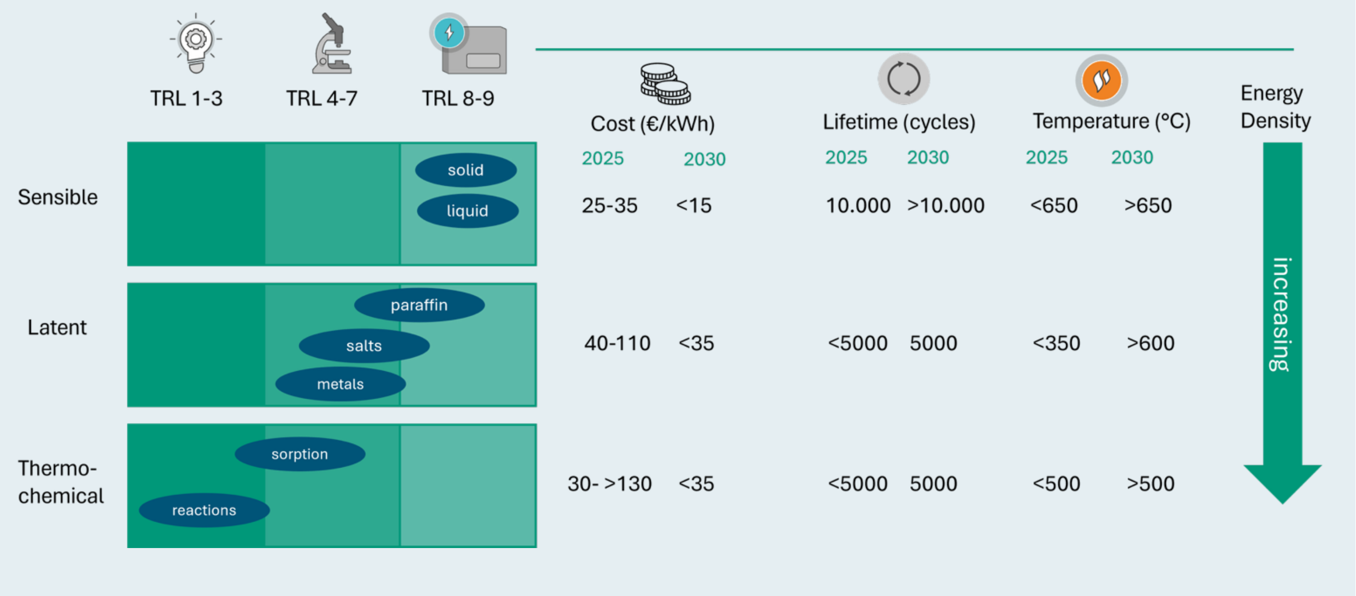
Technology Landscape & Research on TES

Three families of thermal storage technologies:

1. Sensible heat storage
   - Stores energy via temperature increase
   - Mature, robust, wide temperature range
2. Latent heat storage
   - Uses melting/solidification enthalpy
   - Higher energy density but more complex design
3. Thermochemical storage
   - Uses reversible reactions or sorption

Research trends focus on:

- Higher temperature capability (200–1500 °C)
- New materials: metals, advanced PCMs, ceramics
- Improved cycling stability and cost efficiency
- Sector coupling between electricity & heat



Source: Based on data from IRENA (2020) "Innovation Outlook: Thermal Energy Storage", complemented with additional values and own elaboration

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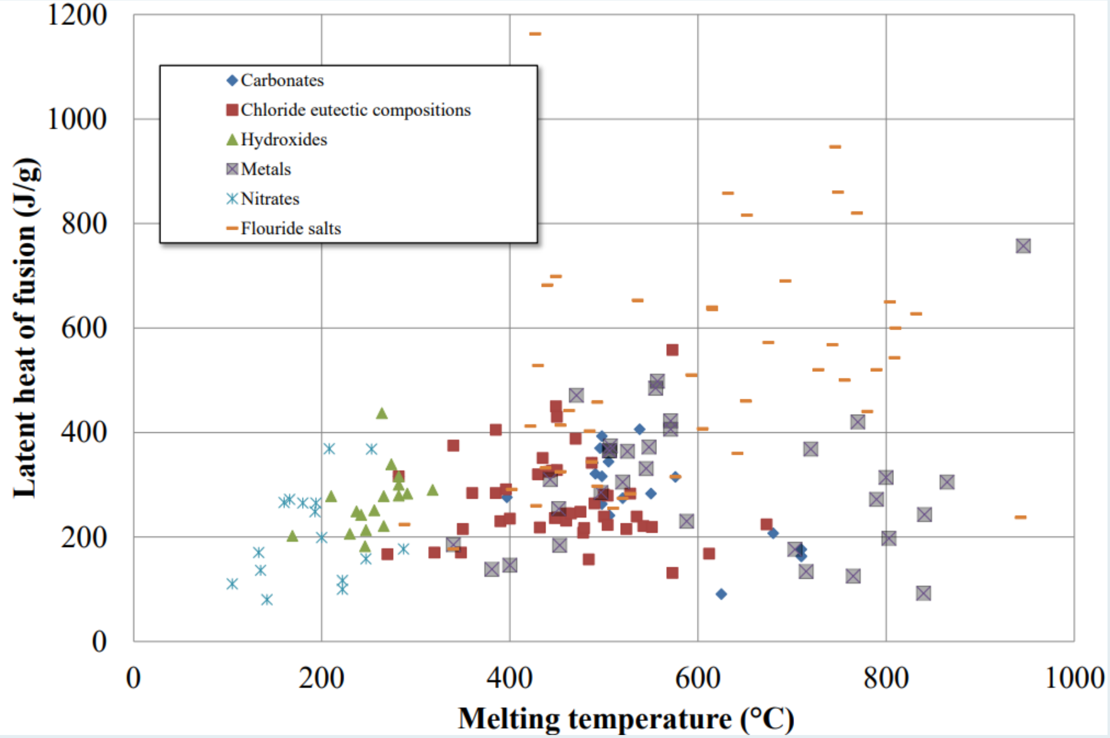
PCM Landscape (Melting Temperature vs. Latent Heat)

Key takeaways

- Fluoride salts reach 300–600 °C, but are highly corrosive and require costly containment
- Low thermal conductivity and degradation limit fluoride salts in real applications
- Above ~500 °C, virtually no conventional PCM family remains viable
- Metallic PCMs provide high latent heat at >500 °C and offer excellent thermal conductivity
- Metals enable fast charging/discharging and robust high-temperature cycling
- Metallic PCMs fill a unique technological gap for high-temperature industrial TES.



Source: Kotzé, Thermal energy storage in metallic phase change materials (PhD, Stellenbosch, 2013

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ISSDEMO

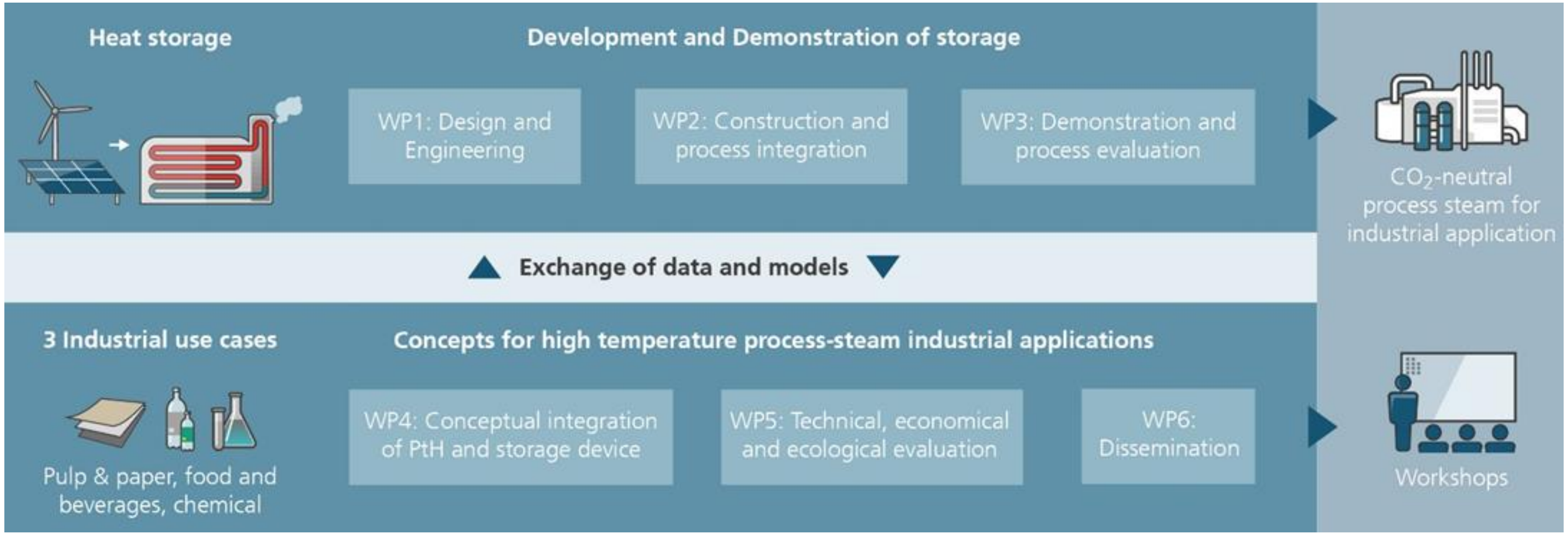
Industrial process Steam Supply – DEMOnstration of an ultra-dynamic thermal energy storage

Objective:
- Integration of renewable energies into industrial process steam applications using the example of a beverage manufacturer
- Demonstration of a high-temperature latent heat storage system (TRL7)
- Testing of transferability to other industrial processes

Basic:
- Duration: 01.12.2023 – 30.11.2026
- FKZ 03EN4071
- Ansprechpartner: Felix Kugler

Partners

Universitat de Lleida
Fraunhofer UMSICHT
Silesian University of Technology
BUILD TO ZERO
proen gliwice



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aufgrund eines Beschlusses des Deutschen Bundestages

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ISSDEMO

Industrial process Steam Supply – DEMOnstration of an ultra-dynamic thermal energy storage

ISSDEMO

Projektpartner:

Projektkoordinator

Fraunhofer UMSICHT

Silesian University of Technology

proen gliwice

Universitat de Lleida

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Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

5

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High-temperature latent heat storage
Design

Basic operating principle

Charging

Outer pipe

Insulation

Electric heating

Storage material

Metal alloy

Evaporator pipe

Discharging

[redacted] Steam

[redacted] Water

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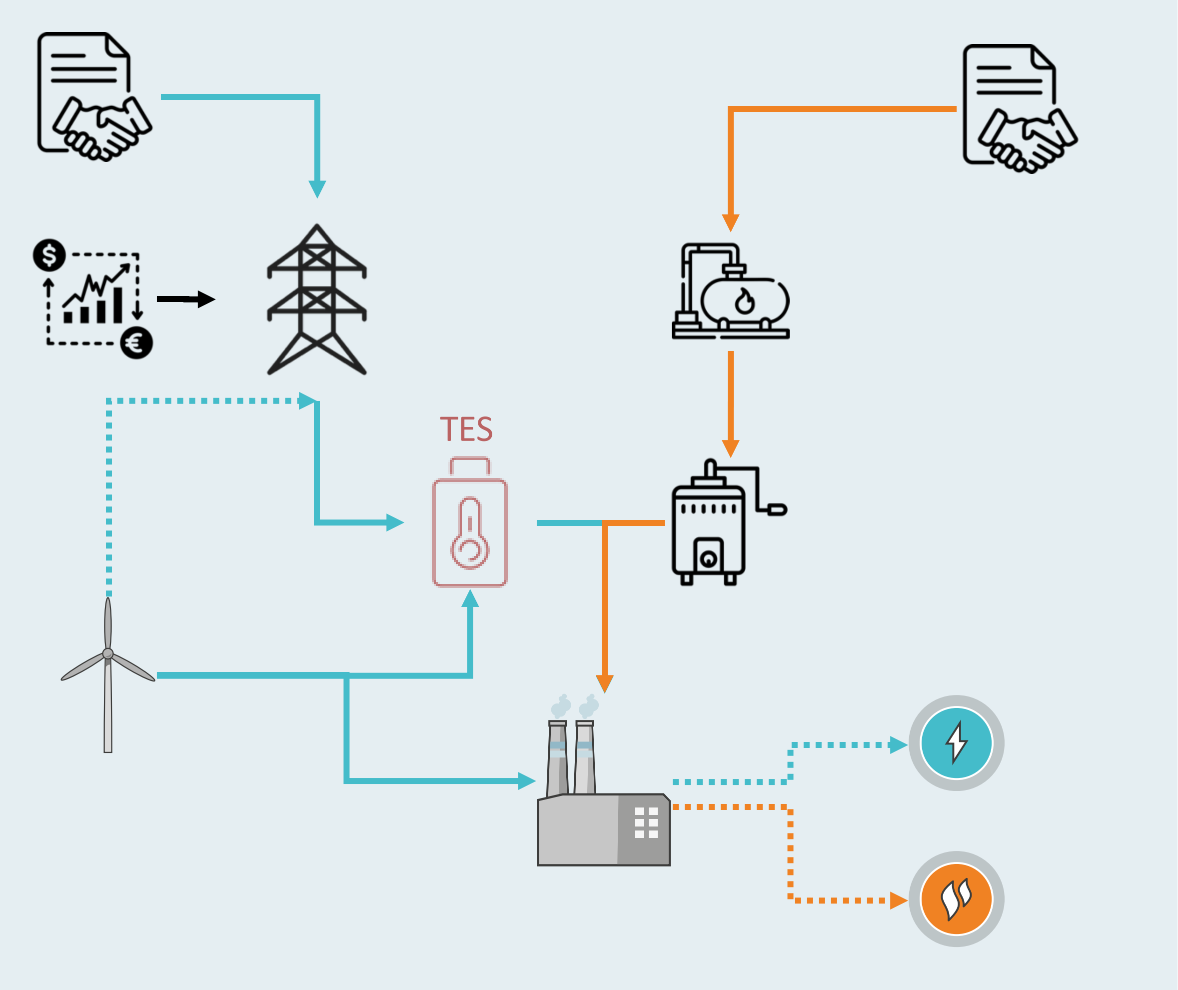
System integration of ISSDEMO storage

Key takeaways

- PtH storage integrated into existing brewery steam network
- Current supply: two natural-gas boilers (baseload & security)
- Storage converts renewable/grid electricity → process steam
- Use cases: peak shaving, surplus electricity use, CO_2 reduction
- Fast steam support for dynamic processes (e.g., CIP)
- Backup during boiler start-up or partial failure
- Storage supplements, but does not replace boilers



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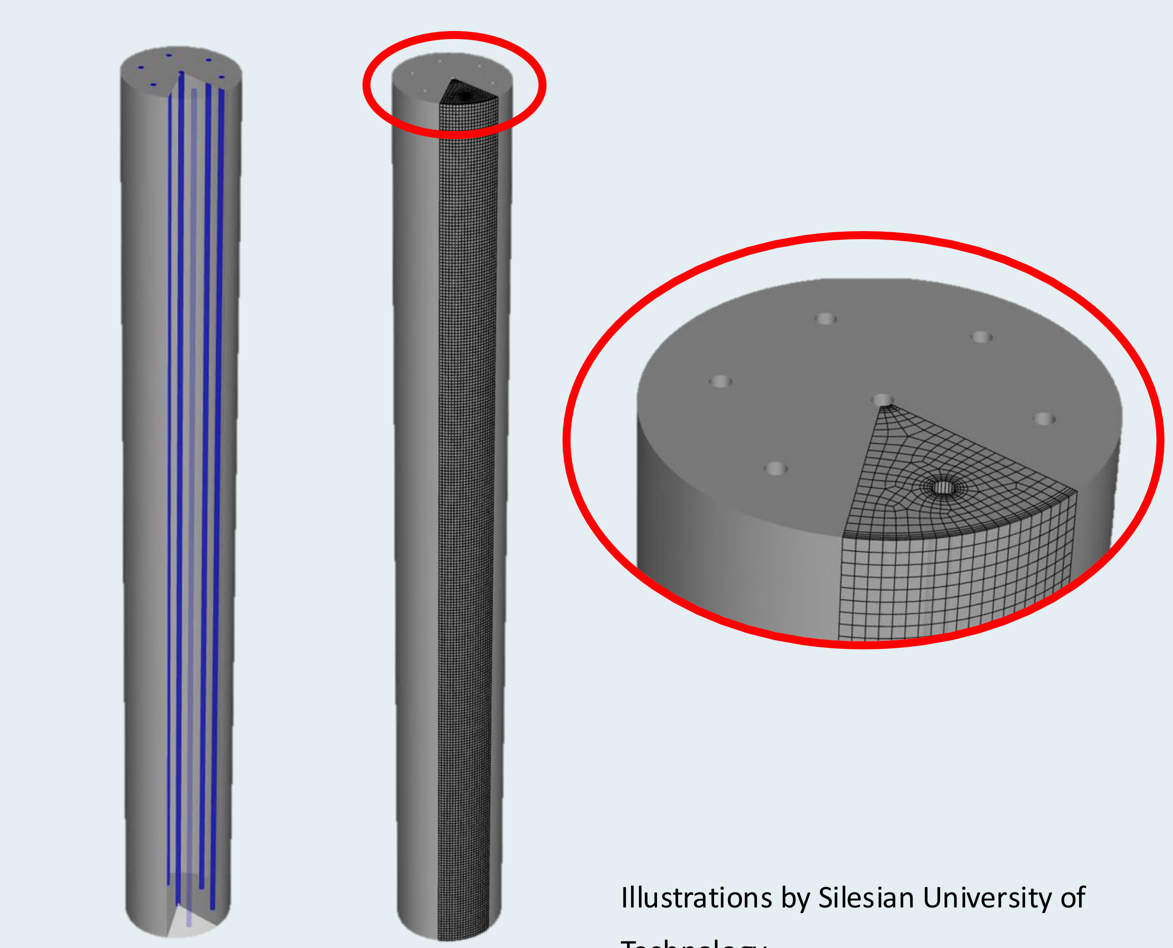
CFD Simulations

General informations provided by SUT

Boundary Conditions – Discharge Process

- External coating & cups: adiabatic walls (perfect insulation)
- CFD–1D H_2O Model Coupling
  - 1D H_2O model developed in Python using empirical equations
  - Temperature field transferred CFD → 1D model
  - Heat flux field transferred 1D model → CFD
- Constant pressure: 10 bar
- Feed water temperature: 100 °C
- 200 kW constant power:
  - Decreasing output H2O temperature with the lowering charge state
  - Increasing H2O stream to keep constant power



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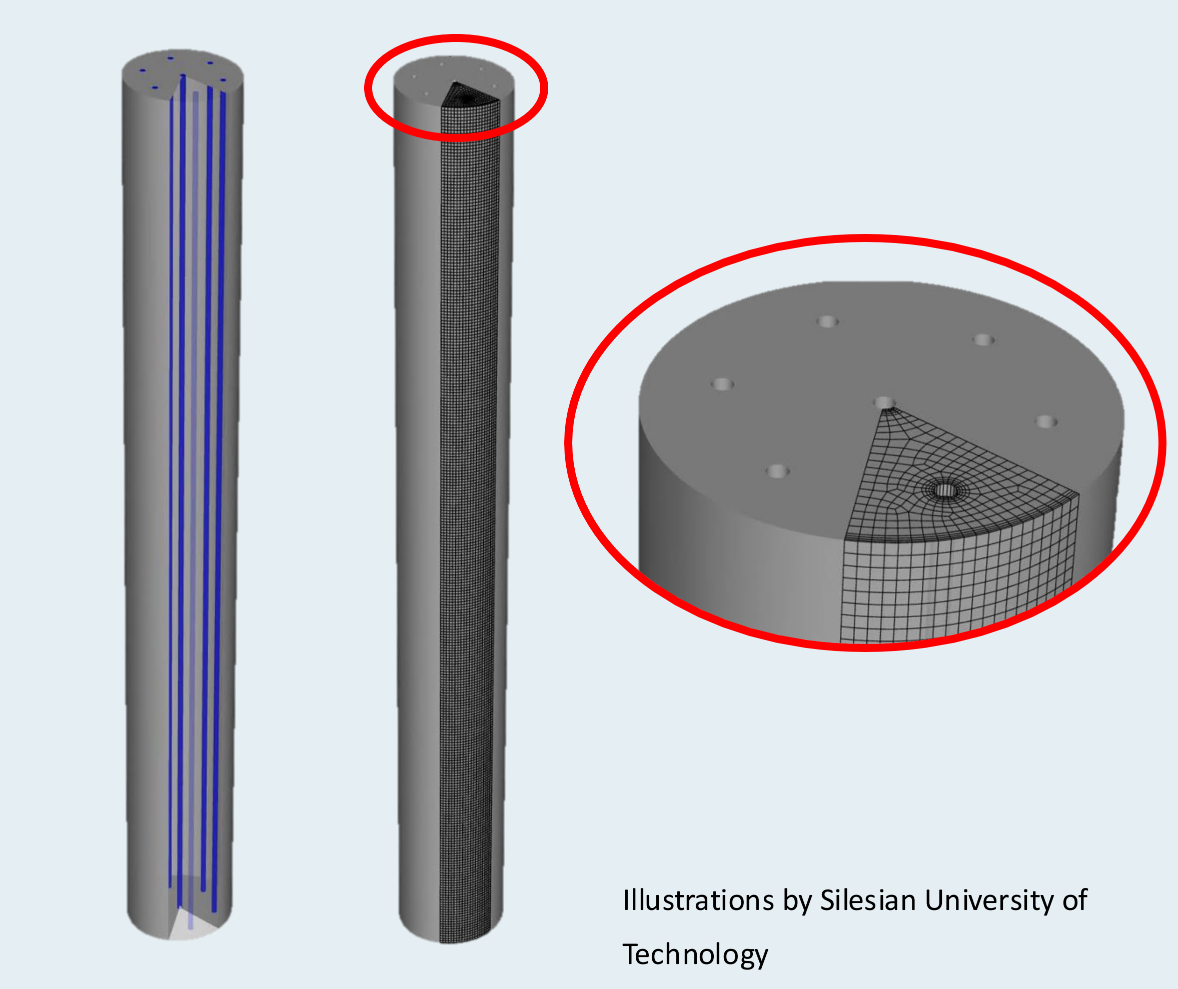
CFD Simulations

General informations

Parameter	Value	Unit
Phase change temperature	380.5-381.5	°C
Phase change enthalpy	110	kJ/kg
Specific heat capacity (solid)	0.66	kJ/(kg·K)
Specific heat capacity (liquid)	0.93	kJ/(kg·K)
Thermal conductivity (solid)	140	W/(m·K)
Thermal conductivity (liquid)	70	W/(m·K)
Density (solid)	6870	kg/m³
Density (liquid) dependent on temp	6320	kg/m³



Illustrations by Silesian University of Technology

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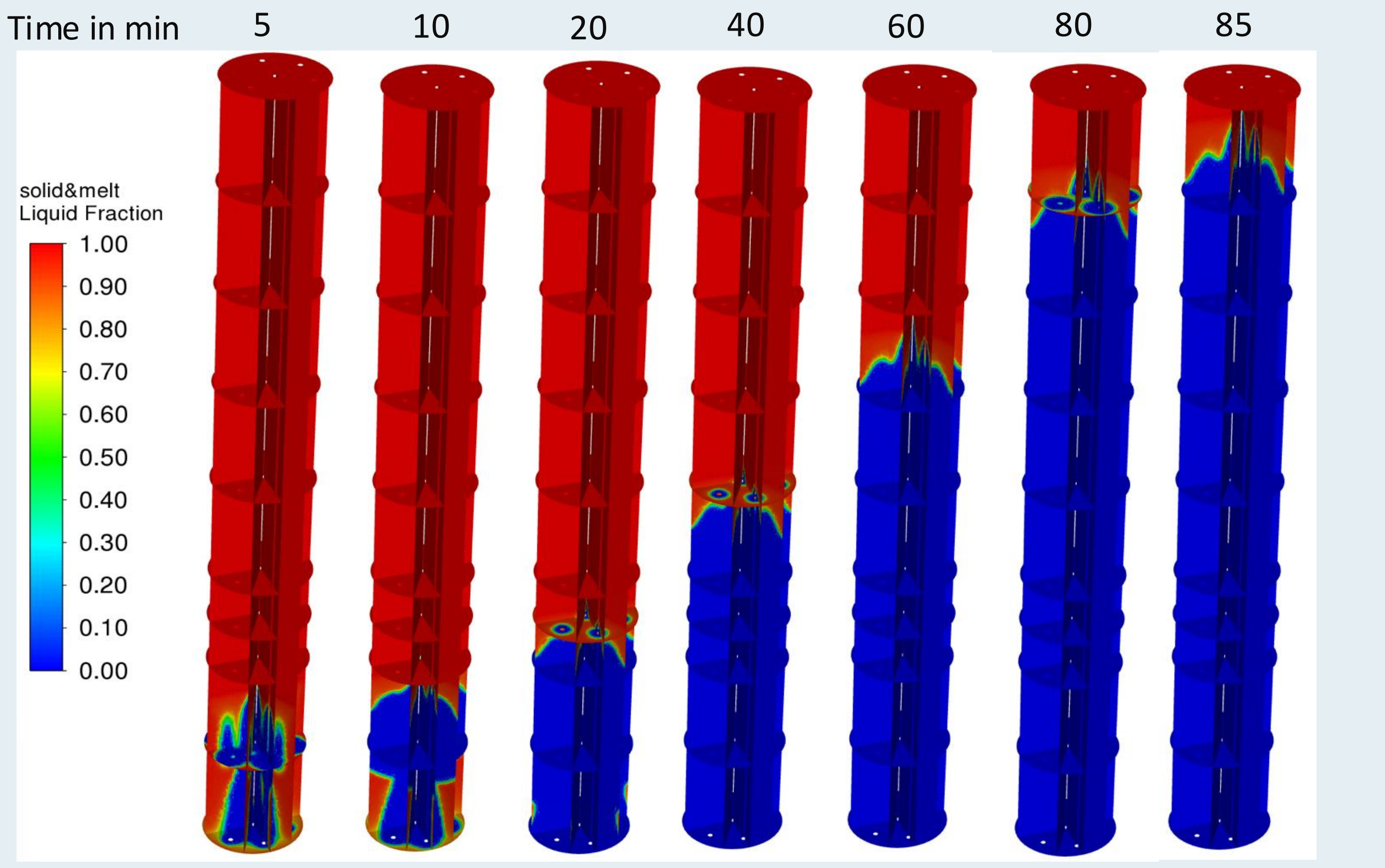
CFD Results

Discharge Process



Illustrations by Silesian University of Technology

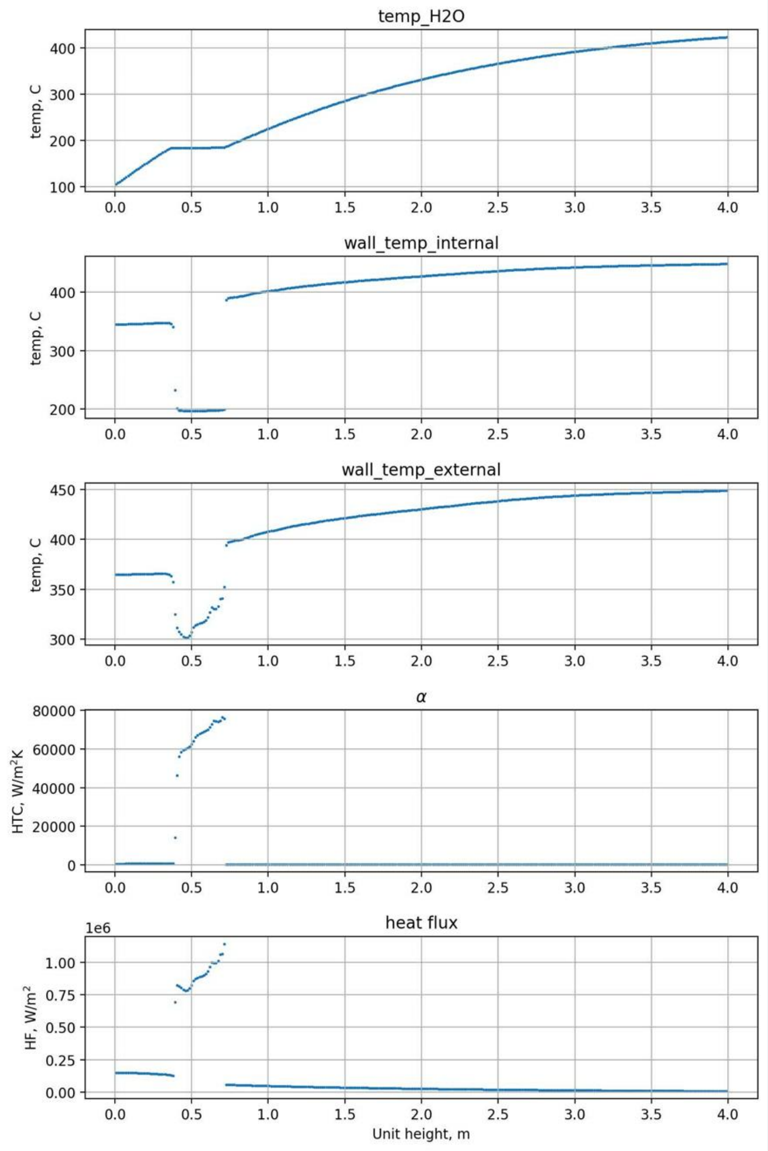
- Cooling progression bottom → top clearly visible
- Upward movement of PCM solidification front
- Lower regions lose latent heat first → reduced thermal output
- After ~85 min: storage module almost fully discharged
- Small remaining liquid PCM fraction at top (final energy reserve)
- Stratified temperature layers indicating discharge dynamics
- Increasing dominance of sensible heat transfer in late discharge
- Visual confirmation of non-uniform thermal depletion

 © Fraunhofer UMSICHT Public

CFD Results

Discharge Process

- Phase front shifts continuously through PCM domain
- Outlet steam temperature declines with shrinking liquid PCM fraction
- Coupled CFD–1D model captures heat flux & temperature interactions
- Heat transfer driven by:
  - Temperature difference PCM ↔ water/steam
  - PCM thermal conductivity (reduced when solid)
  - Local heat flux distribution and flow regime
- Latent heat plateau stabilizes steam temperature until solidification reached
- Reduced heat transfer once solid PCM dominates → rapid outlet temp decline
- Clear link between phase-front position and steam temperature



Illustrations by Silesian University of Technology

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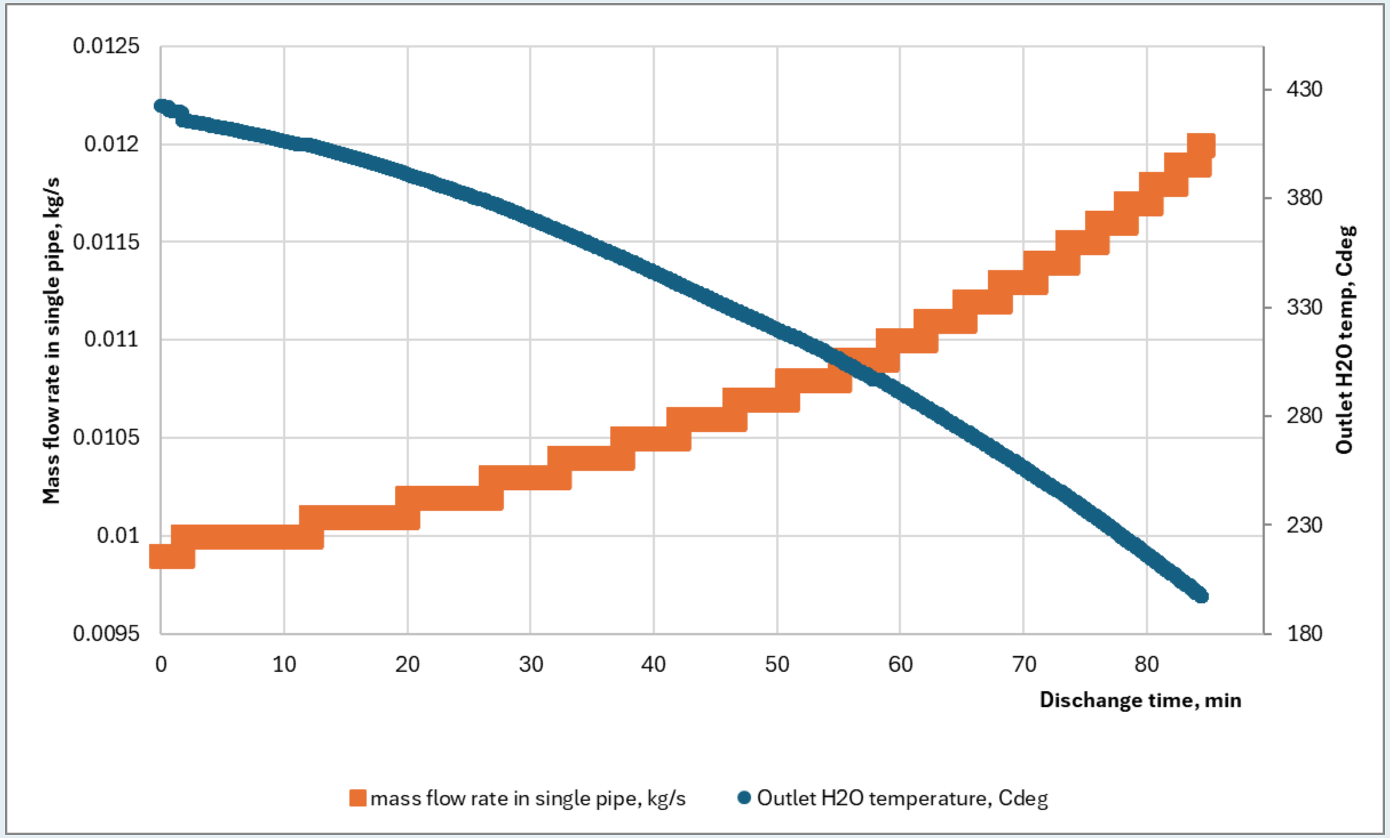
CFD Results

Discharge Process



Illustrations by Silesian University of Technology

Discharge Process

- Mass flow increases over time to maintain constant 200 kW output
- Decreasing outlet temperature due to PCM cooling & solidification
- Higher mass flow compensates for reduced enthalpy content
- Transition from latent-heat-dominated to sensible-heat-dominated discharge
- Increasing steam volume but decreasing temperature level

 © Fraunhofer UMSICHT Public

Pilot Plant System

Test results

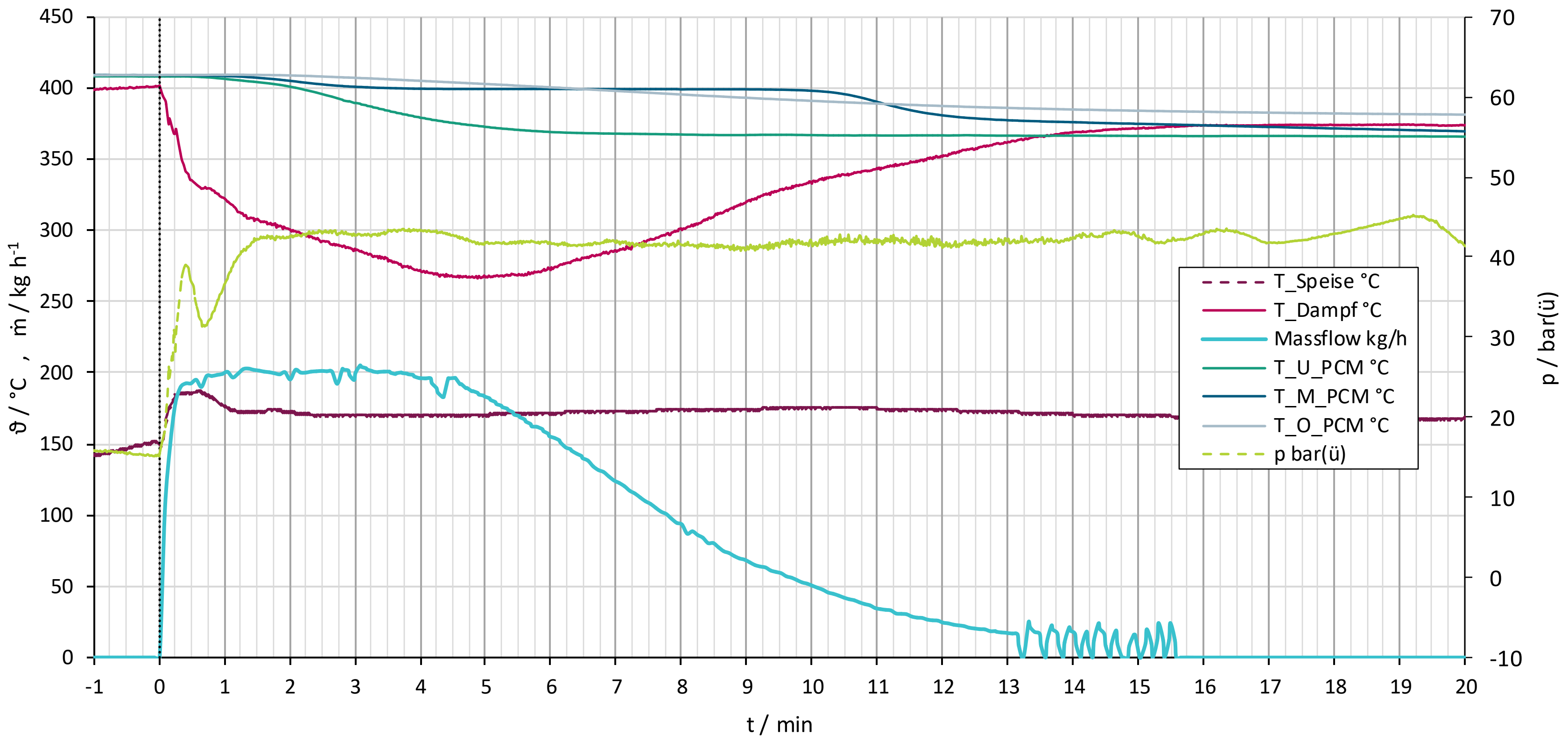
–

Reproduction of Safety Case for 20 Minutes

$\dot{m}_{100\%} = 200$ kg/h

$t(\dot{m}_{50\%}) = 4{,}8$ s

$t(\dot{m}_{90\%}) = 14{,}4$ s

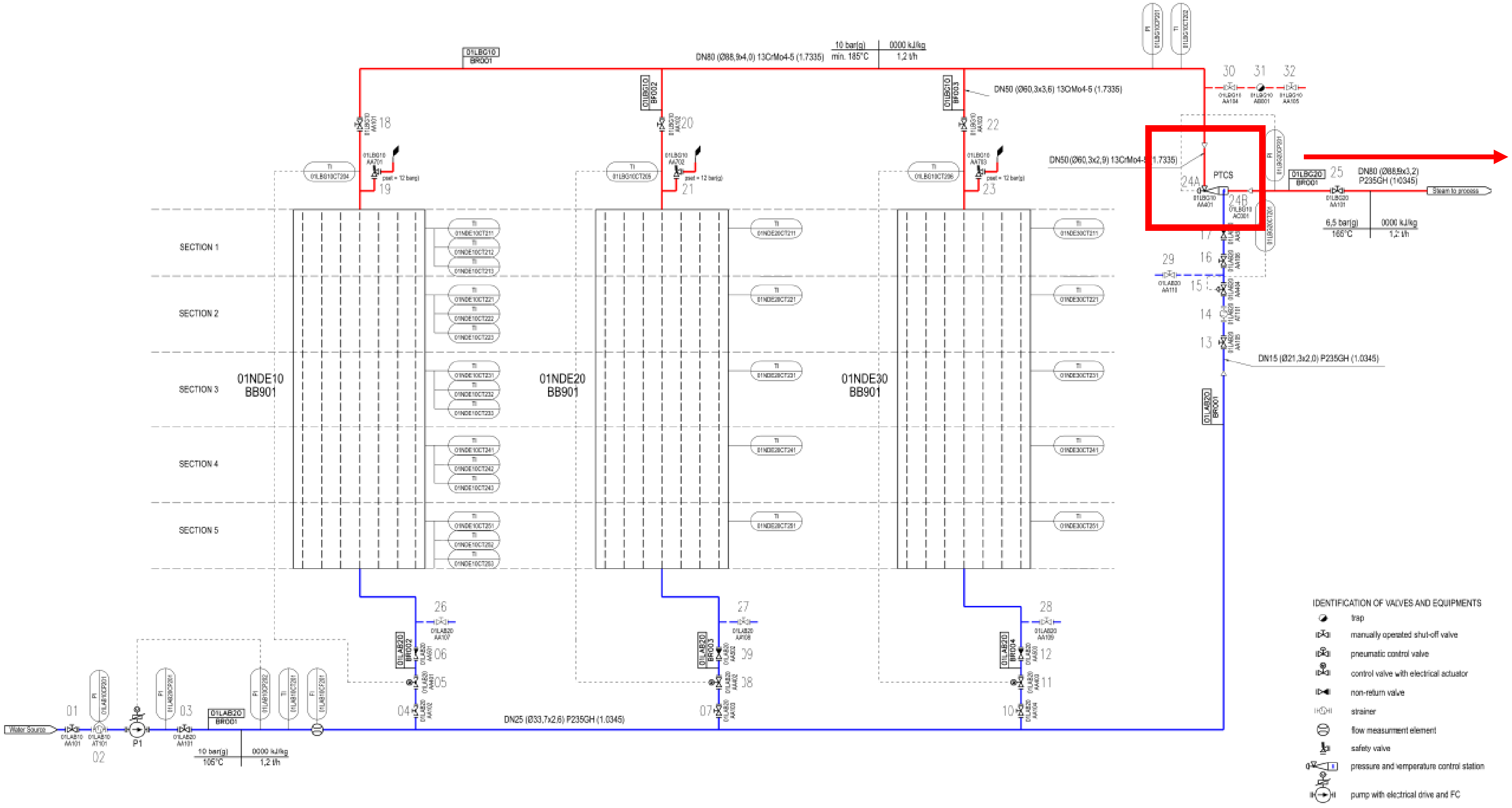


- Superheated steam is available within a few seconds at full mass flow
- The dynamics are purely a matter of control technology and the response behavior of the feed pump/valve

 © Fraunhofer UMSICHT

Solution

Keeping temperature levels at outlet constant



Solution –

Fraunhofer UMSICHT

Key Takeaways

ISSDEMO

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz
aufgrund eines Beschlusses des Deutschen Bundestages

- High-temperature latent heat storage enables ultra-dynamic steam generation for industrial applications
- PtH integration provides a flexible and low-carbon steam source, unlocking use of renewable electricity for process heat
- CFD and 1D modelling reveal clear discharge mechanisms: phase-front movement, outlet temperature decline, rising mass flow
- Simulations show strong correlation with laboratory experiments, validating modelling accuracy and real-world applicability
- Storage demonstrates extremely fast steam availability, supporting peak loads, process fluctuations, and operational resilience
- Effective control (PID) is essential to maintain stable steam temperature, mass flow, and steam quality

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UMSICHT

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Technical insights in development of Thermal Energy Storage: from system integration to State of Charge estimation

10 December 2025 | 16:00 - 18:00

Teams Webinar

Louis Desgrosseilliers

Research Associate at SPF Institute for Solar Technologie

CET Partnership

ISSDEMO

LoCoMoSa

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TES Cluster
Thermal Energy Storage

ECHO

ThumbsUp

HYSTORE

BEST-Storage

State-of-Charge Determination in Thermal Energy Storage

<u>Outlooks for R&D and Scalability</u>

Louis Desgrosseilliers, PhD
SPF Institut für Solartechnik –
Ostschweizer Fachhochschule
Rapperswil, Switzerland

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State-of-Charge Determination in TES

- Coordination of international R&D in new IEA ES TCP Task 47 Subtask on TES SoC determination (2025-2028)
- Building on previous work in IEA ES TCP Task 40 (final report available)
- SoC subtask co-lead by Dr. Desgrosseilliers (CH) and Dr. Englmair (DK)

DEFINITIONS from ES T40/SHC T67:

Thermal Battery: A TES with instantaneous State of Charge determination

State of charge determination utilizes measurement techniques of **material bulk response**

State of charge is a **component level property** (analogy: electrical battery)

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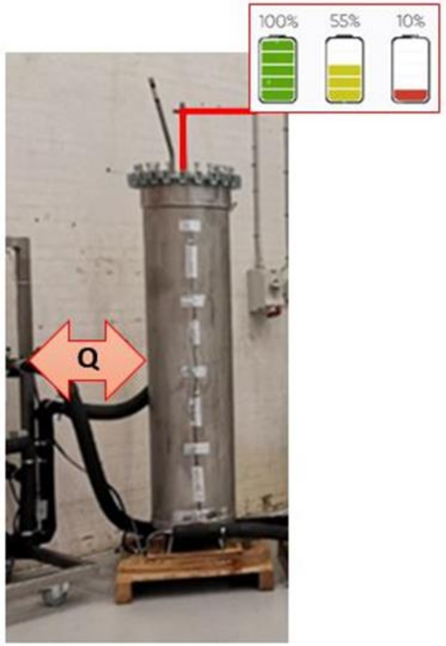
SPF-OST Rapperswil
Email: Louis.Desgrosseilliers@ost.ch

Gerald Englmair, PhD
Associate Professor
Technical University of Denmark
Email: gereng@dtu.dk



"Thermal battery" - schematic

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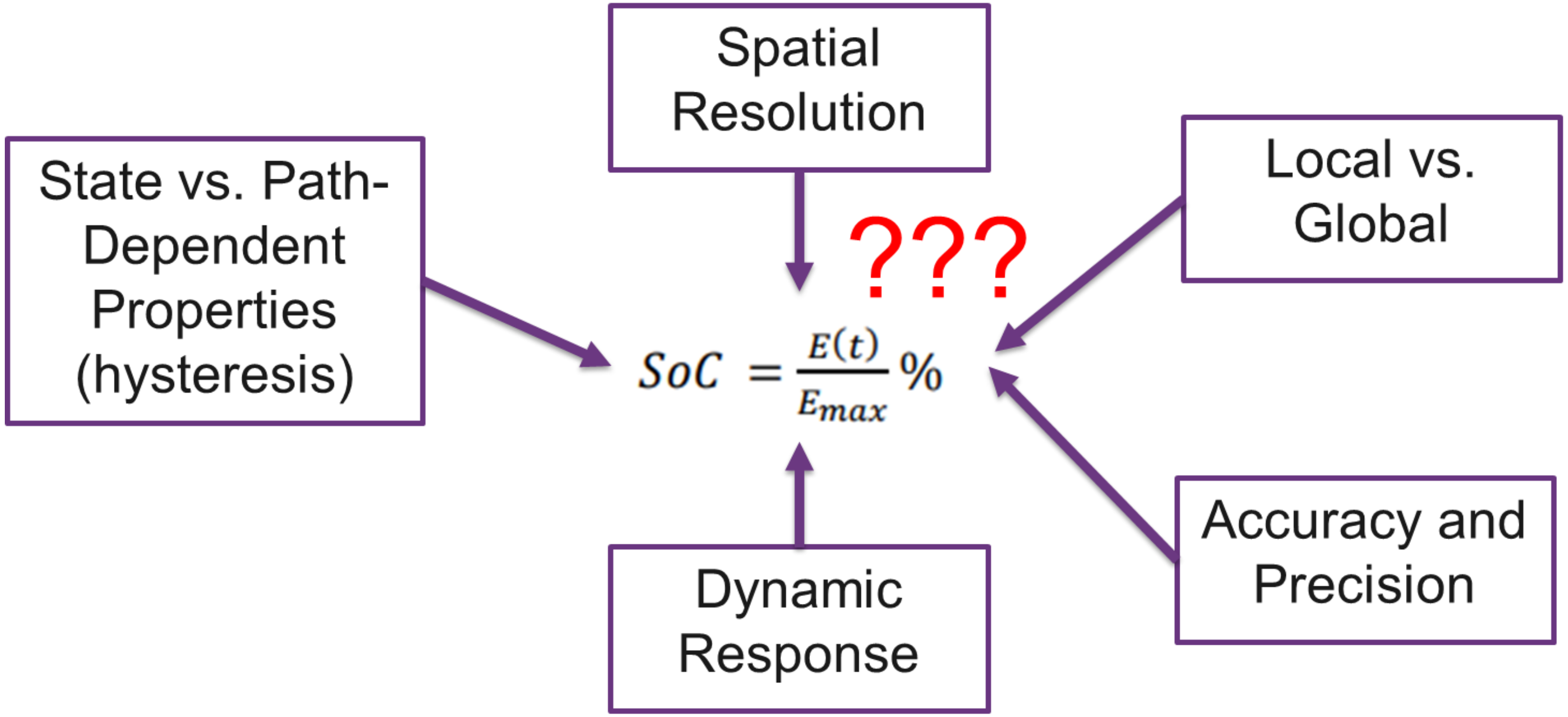
Simple Concept…Complex in Practice



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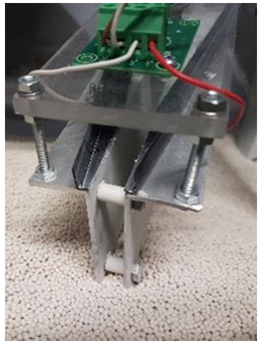
SoC determination – research classification

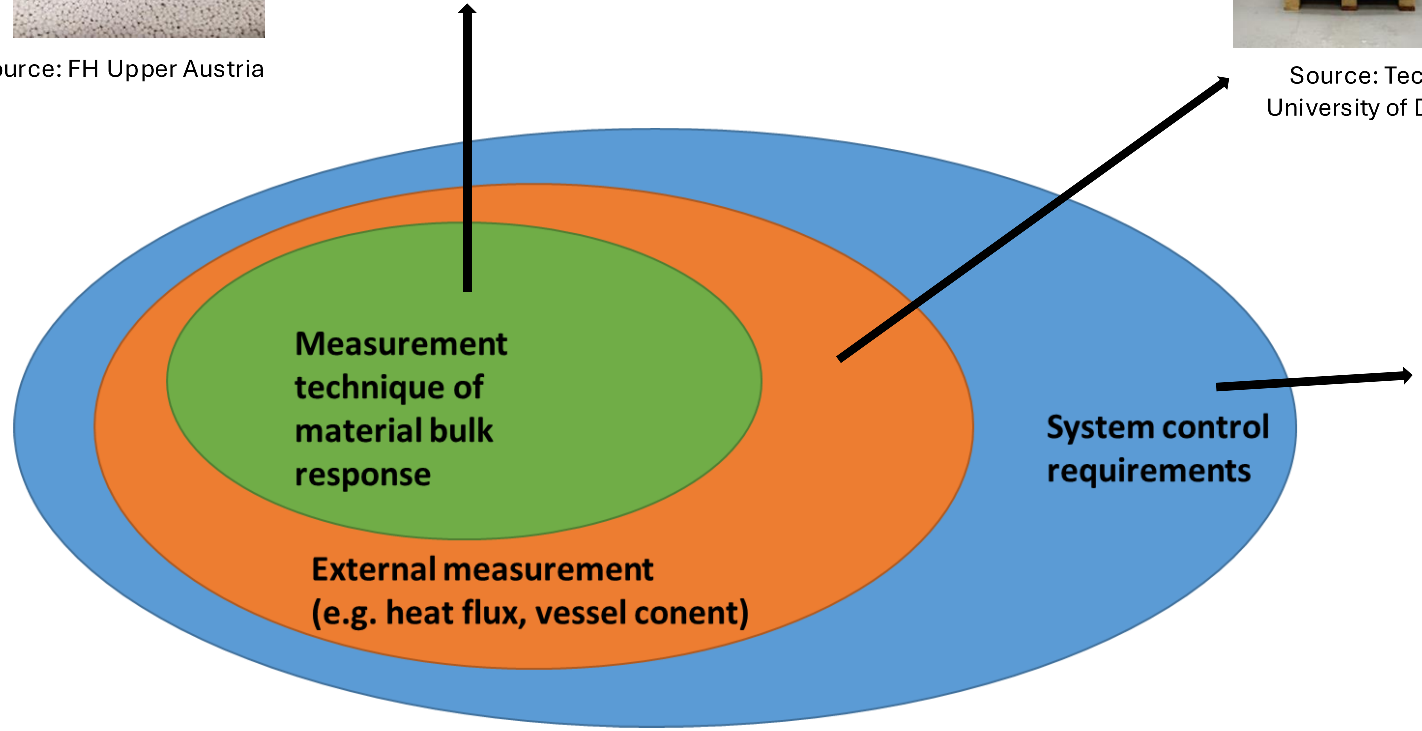


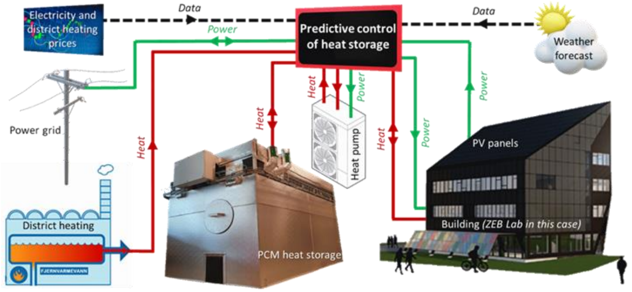
Source: FH Upper Austria

Material laboratory:
Material response with charging/ discharging can be reproduced

Source: Technical University of Denmark

Pilot testing:
Correlation of material response to heat flux
→ Calibration at test stand





Reliable, instantaneous SoC determination enables CTES in flexible systems

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Key Variables in TES Technologies

	Sensible TES	Phase Change TES	Thermochemical TES
Principal Variable	Temperature	Phase fraction	Extent of reaction
Proxy Variables	Pressure, Volume, Optical	Temperature, Pressure, Volume, Electrical (resistance, capacitance), Acoustic (speed of sound), Optical (transmission, refraction), Viscosity	Concentration (reactants/products), Partial Pressures, Mass, Optical, Electrical, Acoustic

<u>Suggested Criteria for Material Bulk Response properties:</u>

- High contrast between states (**high signal to noise**)
- Repeatability of measurement at same state (**path independent**)
- Possibility for system average/global measurement preferred (**CAPEX, scalability**)

* Accuracy/precision are control system & application dependent requirements

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Status of TES SoC Determination R&D

Sensible TES

- Mature at consumer scale (kWh)
- Challenges
  - Scalability at MWh scale
  - **High temperatures (>1’000°C)**
  - **Thermocline**
  - Vapour pressure of liquid TES
- Promising Solutions
  - **1D thermal expansion (dilatometry)**
  - Cover gas pressure
  - IR emissions
  - **“State-observer” model**

PCM TES

- Semi-mature at consumer scale (kWh)
- Challenges
  - System-average
  - Particle-size distribution
  - **Background signal – vessel and heat exchanger**
  - **Phase change kinetics (phase fraction lag)**
- Promising Solutions
  - “State-observer” model
  - **Acoustic “time of flight”**
  - Electrical resistance
  - **T-w-H (example to follow)**

TCM TES

- Low-maturity, lab-only techniques
- Challenges
  - Chemical “working pair” specific – **lacks generalization**
- Promising Solutions
  - **Industrial flow sensors** (calibrated to concentration)
  - Refractive index (liquid media only)
  - **Optical Spectroscopy (solid media only)**

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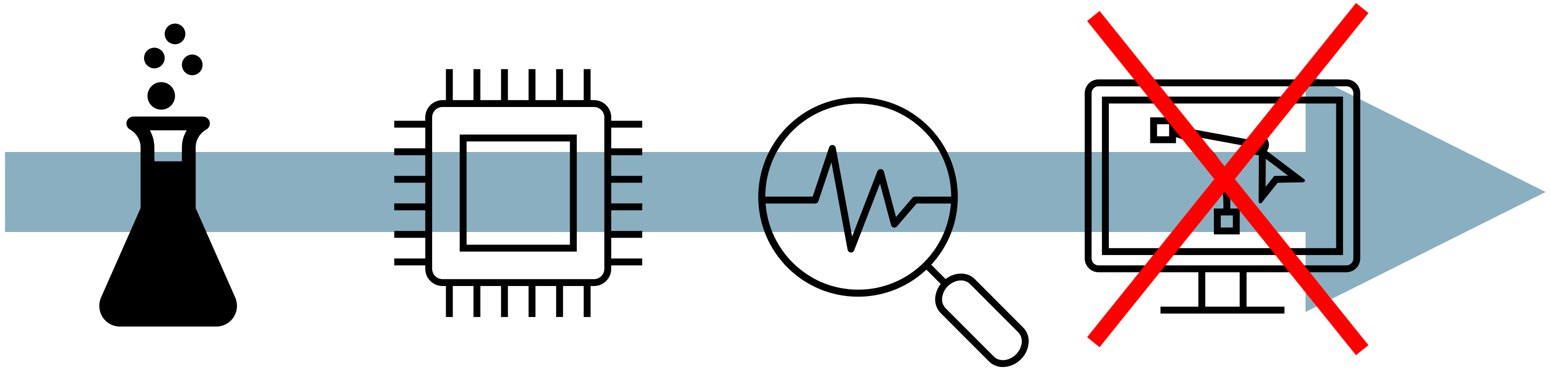
Machine Learning - Perspectives



- Used to find correlations for problems too complex for conventional R&D
- What happens when the model fails under new conditions? – **False positive**
- How can discoveries be made? – **Knowledge vs. tool**
- How can models be deployed to common control electronics (e.g., PLC, microcontrollers)? – **Scalability**

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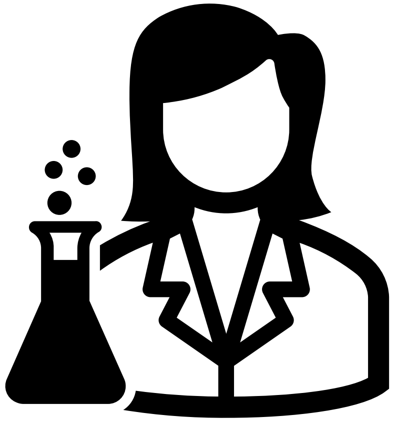
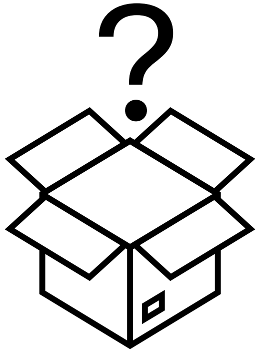
Machine Learning - Perspectives

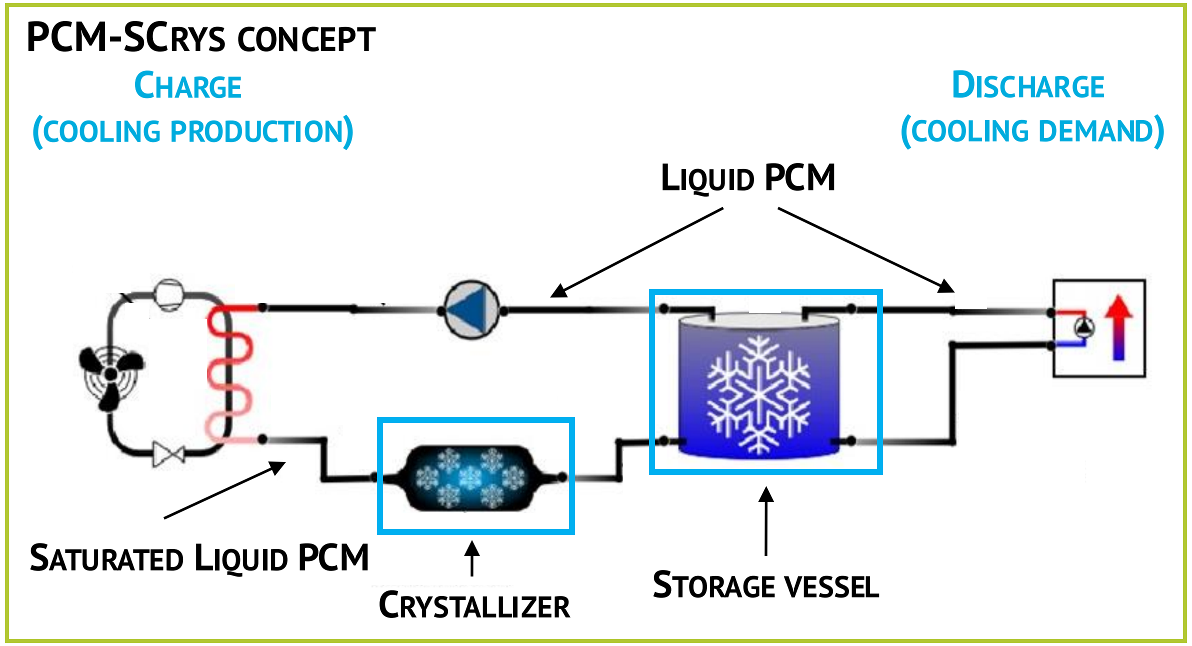


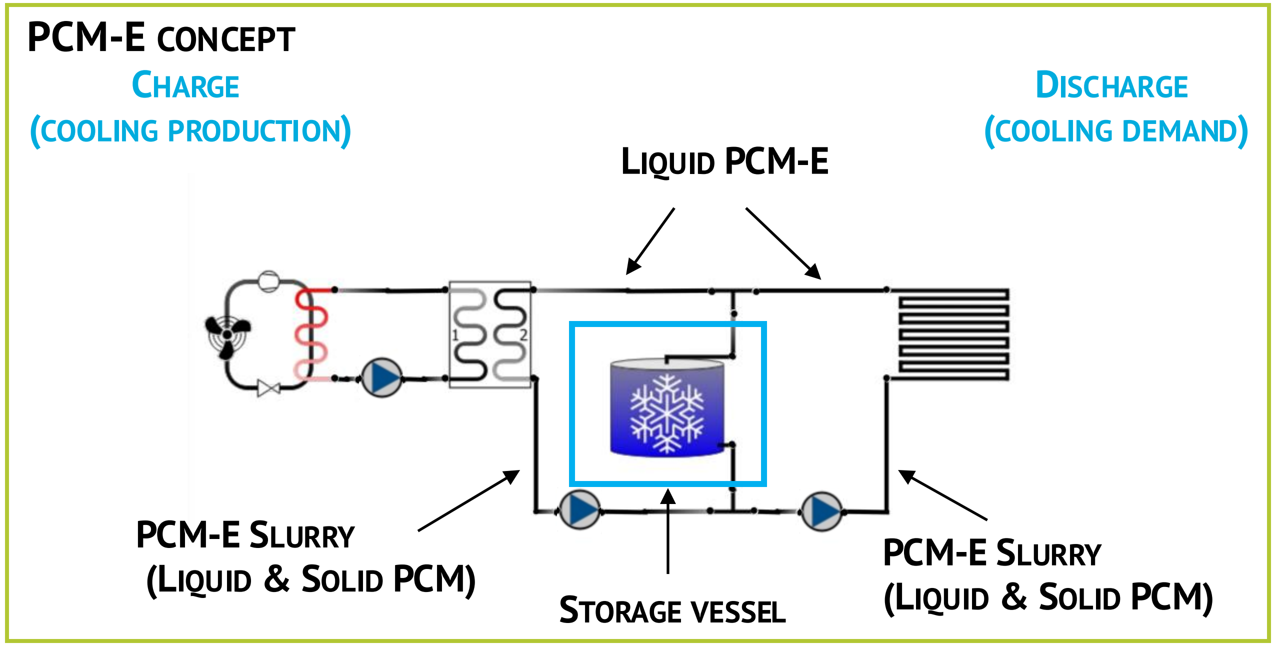
- Use best practice workflows
  - Reduction of order
  - Statistical pre-screening of inputs vs desired output

- **<u>Science requires the Scientist to open the black box</u>**
  - A sound and clear hypothesis must be proposed
    - **<u>Must consider “why?”</u>**
    - Fundamental design of experiment
    - Consider boundary condition limitations
  - Investigate the significant model fitting coefficients – e.g., **<u>what do they mean wrt observations and the hypothesis?</u>**
  - Rigorously test the model & quantify uncertainties – is it reproduceable?
  - Have deployment plan for common, “dumb” control hardware



Example: BEST-Storage PCM Slurries





For 5-12 °C space cooling supply in buildings (fan coil)

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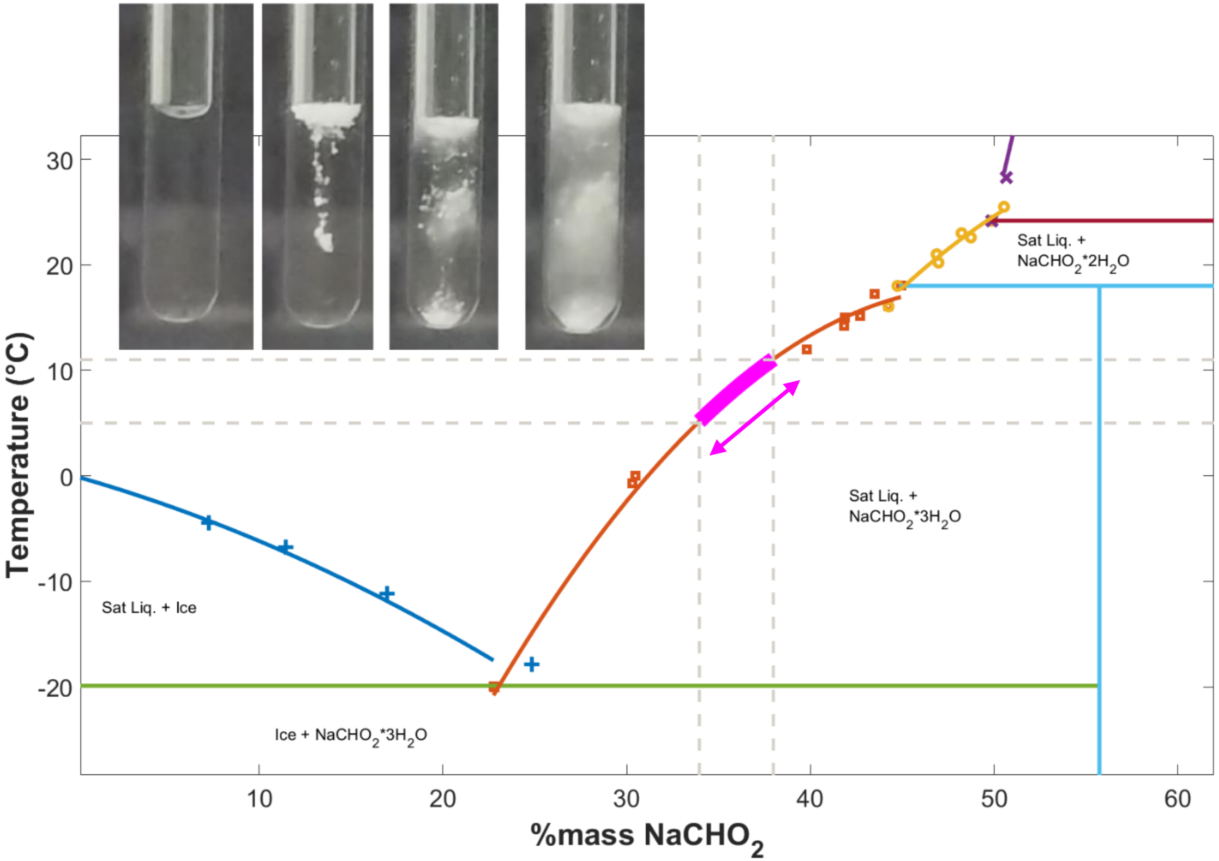
Example: BEST-Storage PCM Slurry

PCM-SCrys

- Selected **$NaCHO_2 \cdot 3H_2O$-water**
  - Non-hazardous, non-toxic
  - **39 %mass $NaCHO_2$**
  - ~12 °C saturated liquid
  - pH ~ 9
  - **24 %mass slurry at 5 °C**
  - 1.8 €/kg, 28.5 kWh/m^3, 1.27 kg/L

- 500 L, 14 kWh vessel



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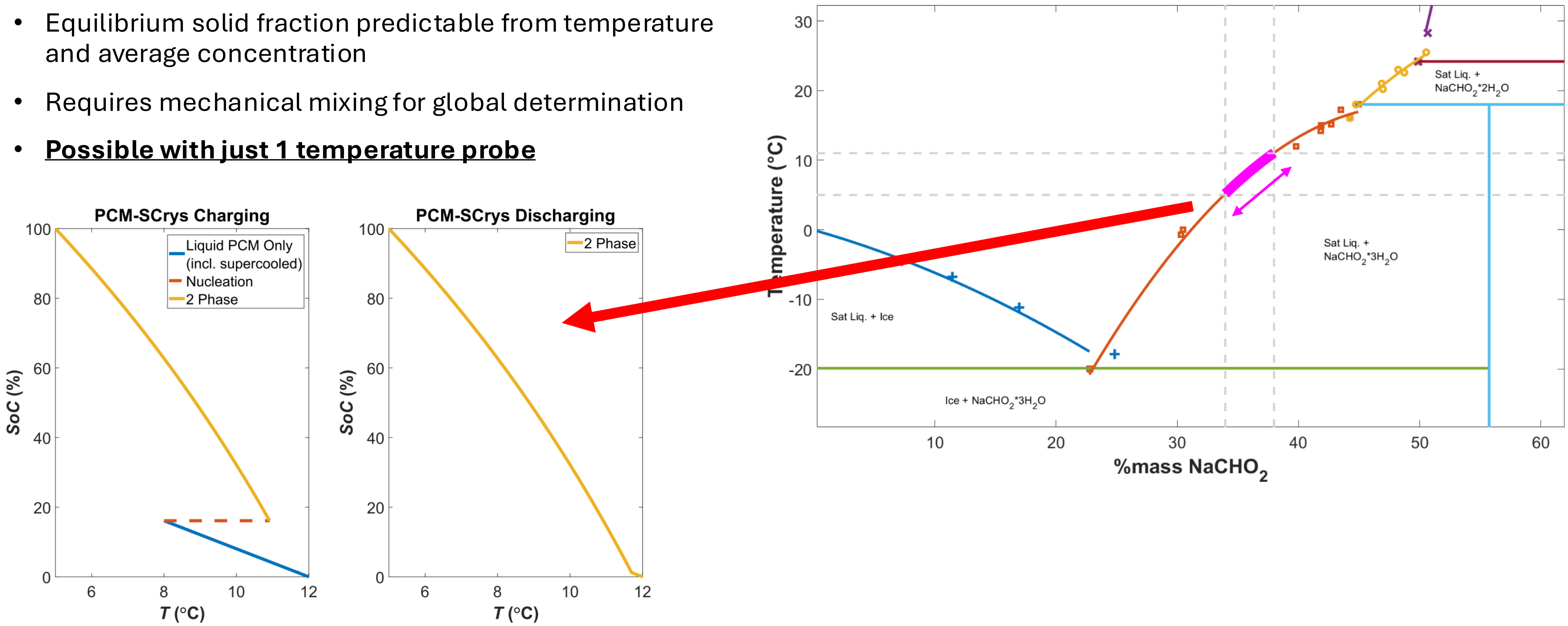
Example: BEST-Storage PCM Slurry

Exploits T-w-H relationship of mixtures

- Equilibrium solid fraction predictable from temperature and average concentration
- Requires mechanical mixing for global determination
- **Possible with just 1 temperature probe**



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Final Remarks

- Fundamental knowledge is still the cornerstone to discover/refine new SoC solutions for TES
  - **<u>Must be able to propose a sound and clear hypothesis</u>**
  - Minimizes biases in experiments and results
  - Identifies application limitations (e.g., boundary conditions)

- Machine Learning: helps solve problems too complex for conventional R&D – e.g., multi sensory inputs
  - **<u>Rigorous design of experiment (see above) remains essential</u>**
  - Statistically pre-screen signal features to reduce computational scale of analysis and avoid false positives
  - **<u>Investigate model's fit coefficient to discover "what worked" to learn "why"</u>**
  - Deploy reduced order coefficient models in control hardware

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Thank you!

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www.best-storage.eu

www.spf.ost.ch

iea-es.org/task-47/

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Technical insights in development of Thermal Energy Storage: from system integration to State of Charge estimation

10 December 2025 | 16:00 - 18:00

Teams Webinar

Saman Nimali

Assistant Professor at Energy Technology, KTH

Aditya Singh Suswal

Doctoral Candidate at Energy Technology, KTH

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CET Partnership ISSDEMO LoCoMoSa

TES Cluster Thermal Energy Storage

ECHO ThumbsUp HYSTORE BEST-Storage

This project has received funding from the European Union Horizon Europe Programme under grant agreement N. 101096789 (HYSTORE).

Approaches on measuring the SoC of TES with PCMs- HYSTORE PCM Heating Solution at KTH


Dr. Qian Wang (Coordinator@KTH, PI @ ABE & BTD),
Dr. Mustapha Habib et al.
ABE school, Building Technology and Design (BTD), KTH
qianwang@kth.se





Assist. Prof. Saman Nimali Gunasekara (PI @ ITM & EGI),
MSc. **Aditya Singh Suswal**, Assoc. Prof. Justin Ningwei Chiu,
Prof. Björn Palm & Prof. Per Lundqvist
ITM school, Energy Technology (EGI), KTH
saman.gunasekara@energy.kth.se; adityass@kth.se


Dr. Marco Molinari (PI @ KTH LiL) & Dr. Jonas Anund Vogel
ITM School, KTH Live-in-Lab
marcomo@kth.se

HYSTORE: Hybrid services from advanced thermal energy storage systems

HYSTORE project web
HYSTORE @EGI-KTH

Nº	Name	Acronym	Country	Type
1-Coord.	ARC	ARC	ES	SME
2	Consiglio Nazionale delle Ricerche	CNR	IT	RTO
3	KTH Royal Institute of Technology	KTH	SE	UNI
4	Rubitherm GmbH	RUBI	DE	SME
5	Austrian Institute of Technology	AIT	AT	RTO
6	OCHSNER	OCHS	AT	SME
7	PINK GmbH	PINK	AT	SME
8	Sorption Technologies	SOR	DE	SME
9	Inovalab	INOVA	IT	LE
10	STAM	STAM	IT	SME
11	Maston AB	MAST	SE	SME
12	Dublin City University	DCU	IE	UNI
13	EURAC	EUR	IT	RTO
14	R2M solutions s.r.l	R2M	IT	SME
15	University College Dublin	UCD	IE	UNI
16	Central de reserves Montserrat	CRM	ES	SME
17	RAAL	RAAL	RO	SME
18	European Innovation Marketplace	EIM	BE	NGO

HYSTORE IN A NUTSHELL

- Technological advancement of thermal energy storage (TES) with **up to +150% energy density and -50% CAPEX compared to state-of-art (SoA)**
- Significant **lower design and installation effort** thanks to pre-defined and standardized guidelines
- **allow TES to be coupled and integrated with grid-level aggregators** that can be federated in the context of both single buildings and local energy communities
- **4 use case application** in different climates both for DHC (District Heating/Cooling) connected and non DHC-connected buildings with high-impact and replication potential.
- LCOS in line with EU targets from IRENA annual reports and SET-plan.

This project has received funding from the European Union Horizon Europe Programme under grant agreement N. 101096789 (HYSTORE).

Overall Concept of HYSTORE

PCM: Phase Change Materials
TCM: Thermochemical heat storage materials

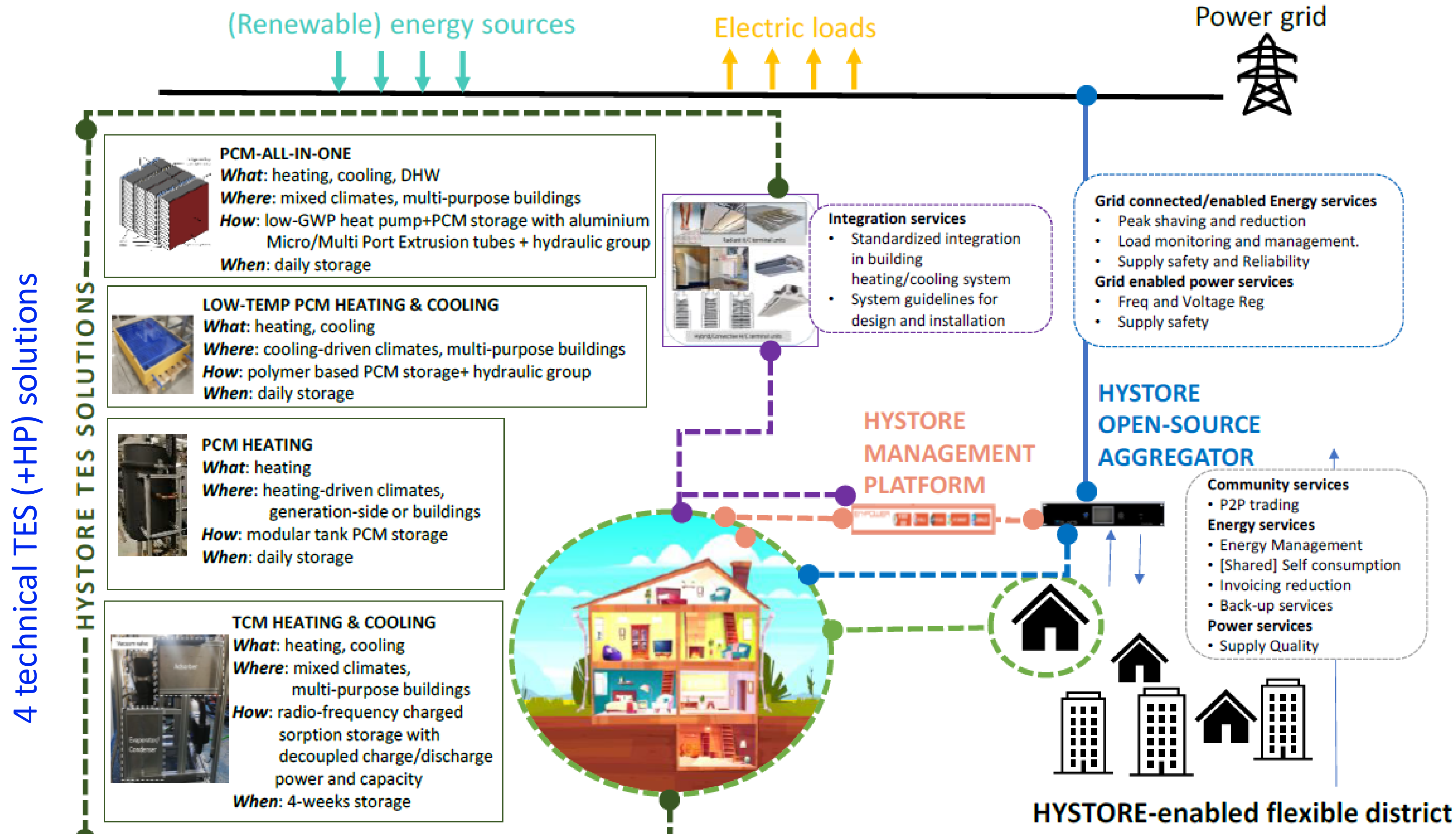

Figure 1: HYSTORE overall concept

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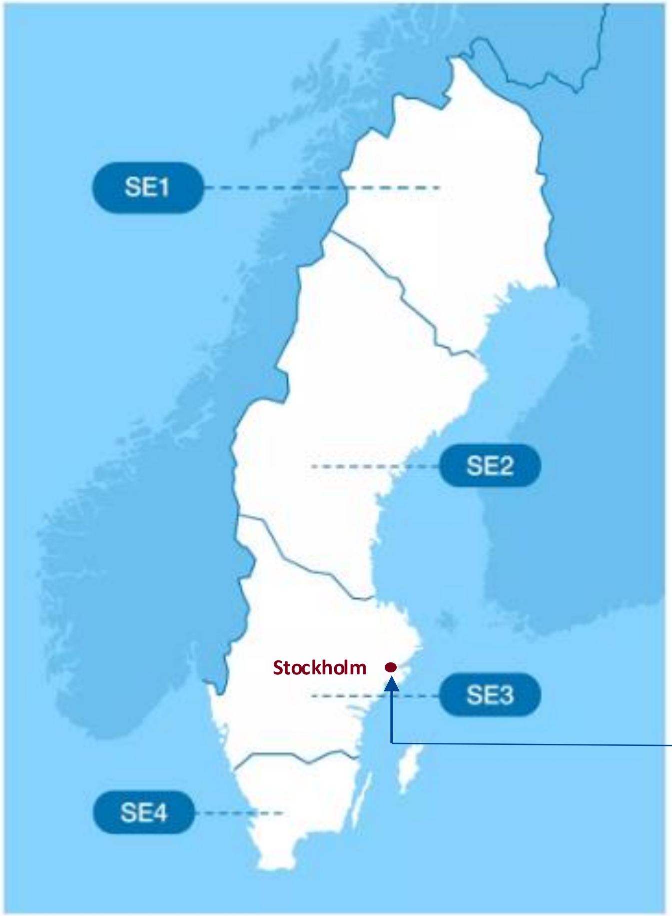
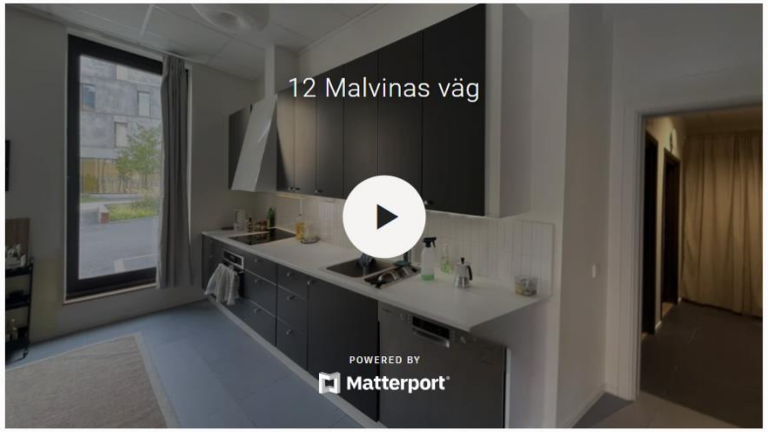
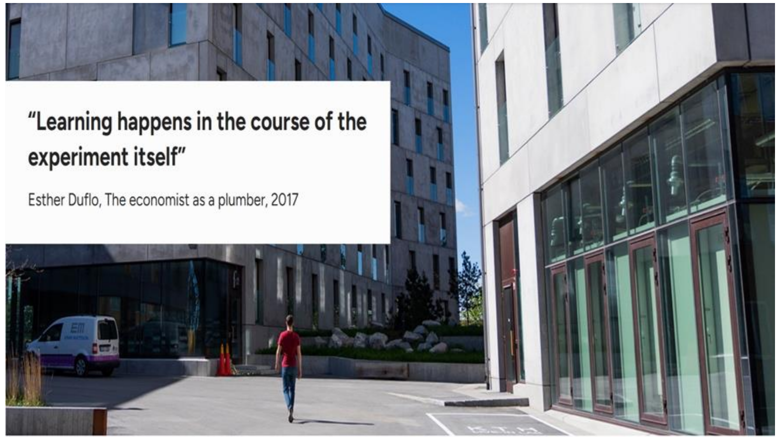
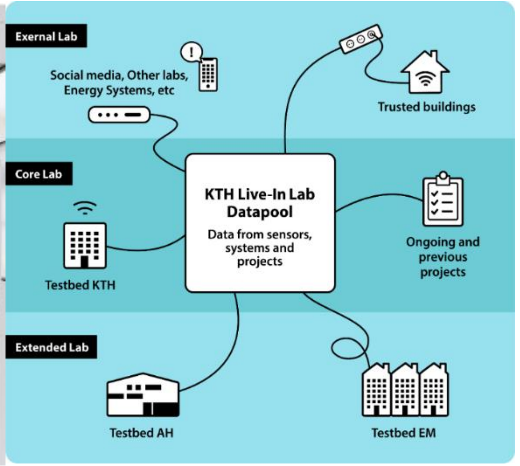
PCM Heating Solution (@ KTH - Stockholm)



Live-in-Lab Testbed KTH







https://www.liveinlab.kth.se/start-1.1064463

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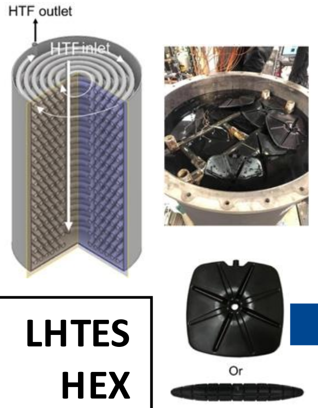
“PCM Heating” Solution @KTH…

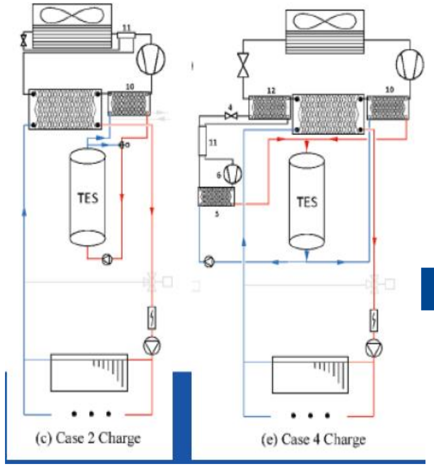
This project has received funding from the European Union Horizon Europe Programme under grant agreement N. 101096789 (HYSTORE).



LHTES HEX

Improved design of LHTES+ HEX (submerged: HEX in PCM or encapsulated PCM in HTF

Pilot-scale LHTES to be further designed & optimized **for combined operation with a HP**



LEFT: The pilot-scale LHTES system at KTH that will be further developed and designed, and *RIGHT*: conceptual designs of this developed LHTES for combined operation with HPs (Air-source and Ground-source) → **PCM Heating Solution**

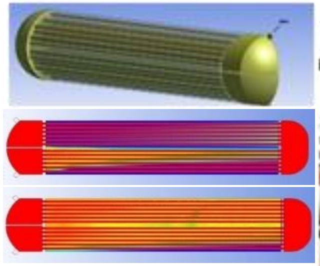
KTH Live-in-Lab

The demo site: where **PCM Heating Solution** will be run for optimized operation &control

BMS, Internet of Things (IoT) & Techno-economic optimization

Bench-scale LHTES material testing)

LHTES with a shell-and-tube HEX for supercooling & hysteresis analysis



This project has received funding from the European Union Horizon Europe Programme under grant agreement N. 101096789 (HYSTORE).

PCM Heating Solution

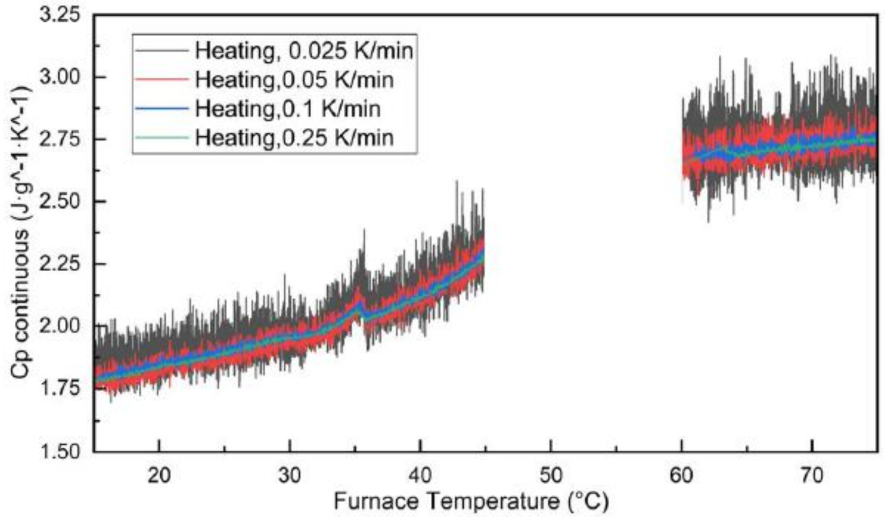
State-of-Charge (SoC) analysis at EGI lab

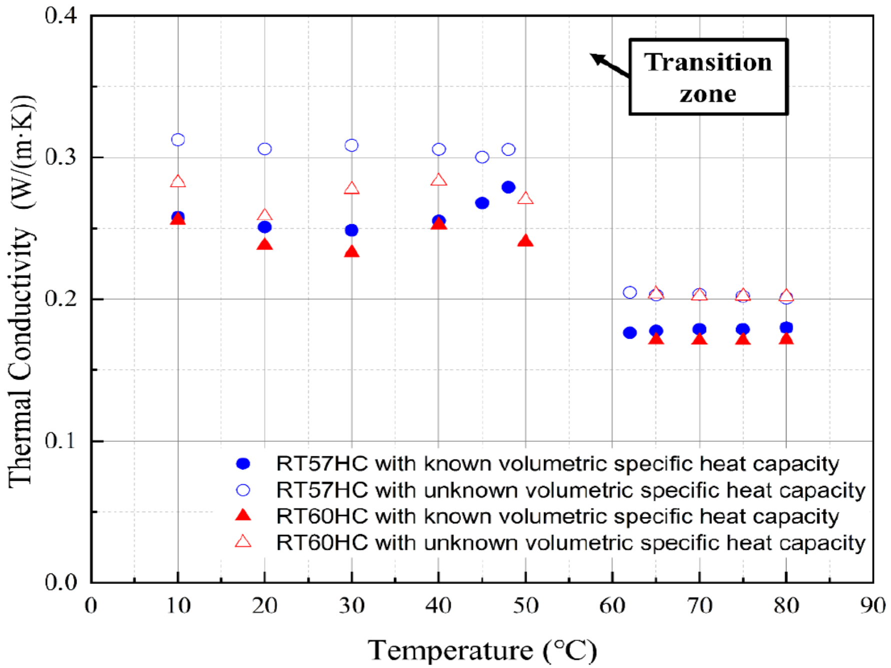
2025-12-10

PCM: RT57HC properties

Properties	Phase/ state	Temperature	Values	Expanded uncertainty*
Density	Solid	20 °C	0.883 g/ml	±0.006 g/ml
	Liquid	65 – 80 °C	0.769 – 0.7601 g/ml	±0.002 g/ml
Specific heat capacity	**(Solid → Liquid)**	**10 – 80 °C**	**1.73–2.75 J/(g·K)**	±0.07 J/(g·K)
Phase change Enthalpy	**Melting**	**57.1 – 59.4 °C**	**246.35 J/g**	±14.48 J/g
	Freezing	**51.9 – 52.4 °C**	**242.30 J/g**	
Thermal conductivity	Solid	10 – 50 °C	0.254 -0.263 W/(m·K)	±0.003 W/(m·K)
	Liquid	62 – 80 °C	0.172–0.176 W/(m·K)	
Dynamic viscosity	Liquid	62 – 80 °C	10.1 – 5.8 mPa·s	± 0.5 mPa·s

*95% confidence

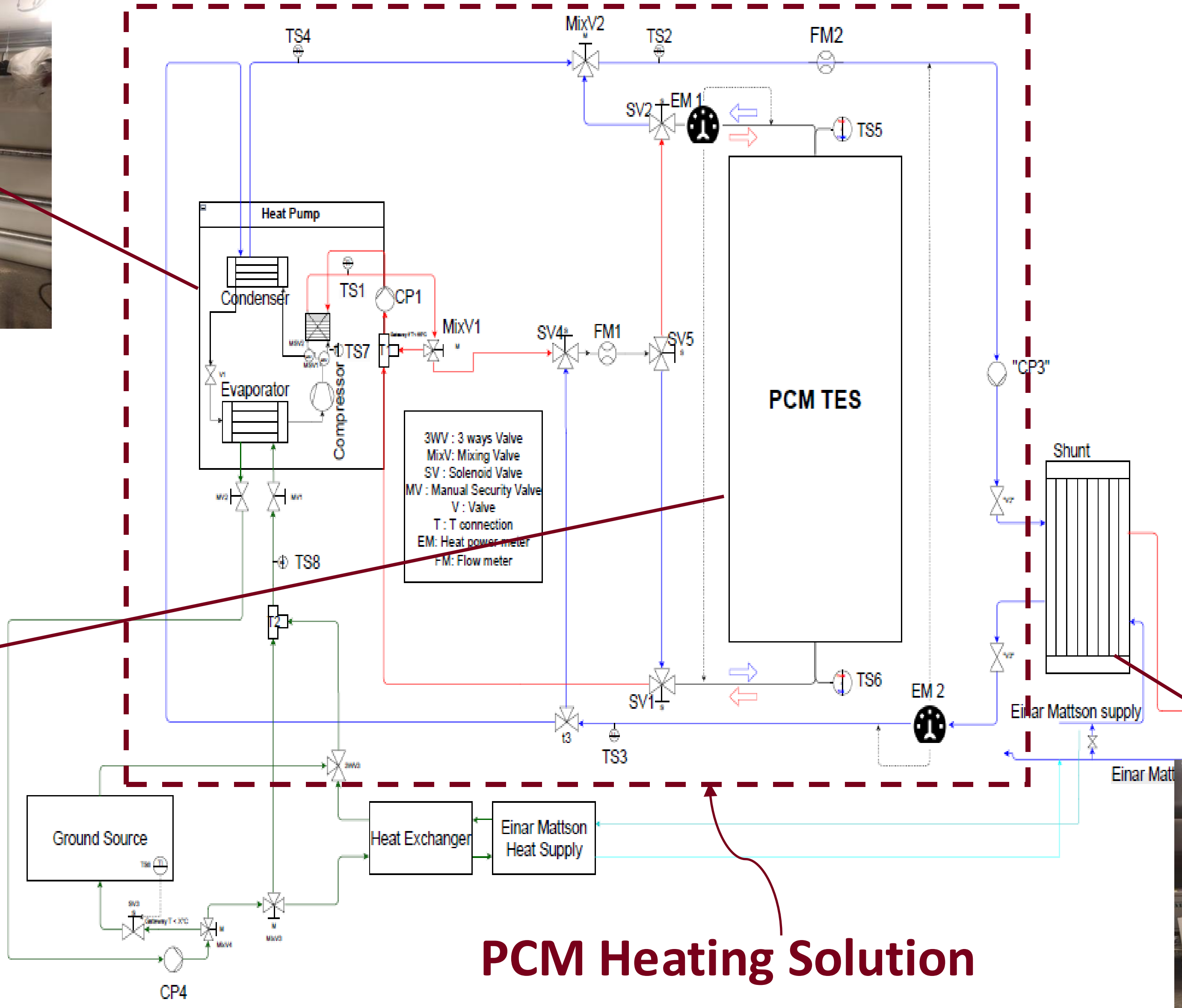




PCM Heating Solution Planning

18 kW

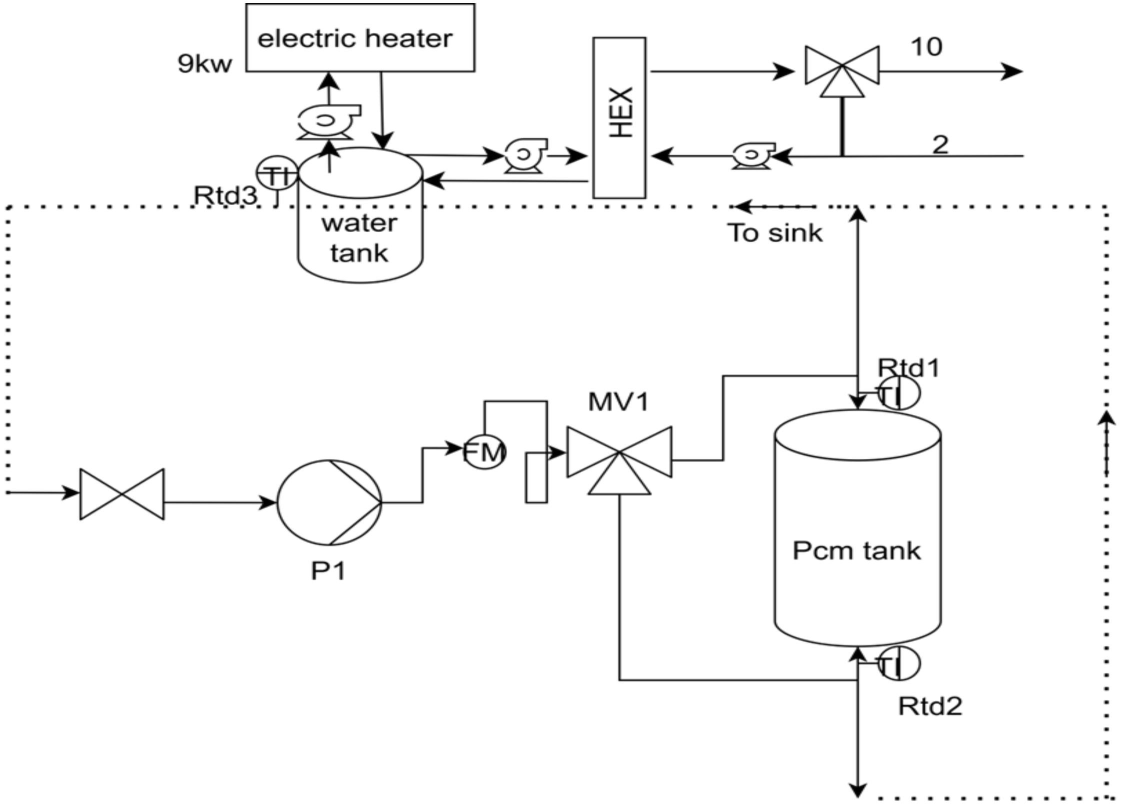
69 kWh/m³



PCM Heating Solution

This project has received funding from the European Union Horizon Europe Programme under grant agreement N. 101096789 (HYSTORE).

Lab Characterization of the PCM-TES



Lab-based system set-up used for PCM TES initial performance characterization (prior to moving to KTH Live-in-Lab). The electric heater and the cooling loop respective mimicked the heat pump heat supply and the space heating demand (by respectively heating or cooling the water tank)

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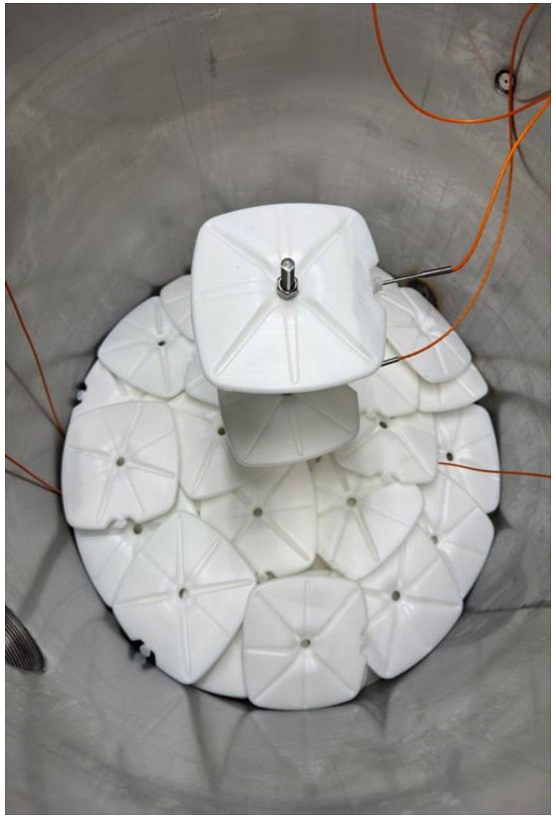
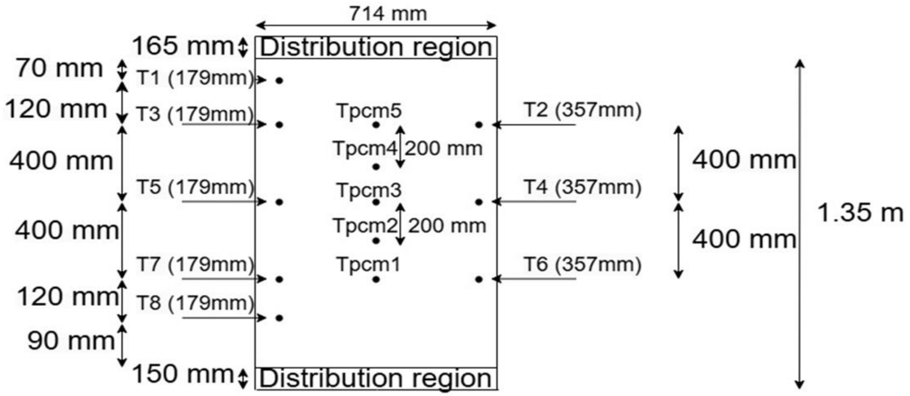
Temperature analysis in the PCM-TES

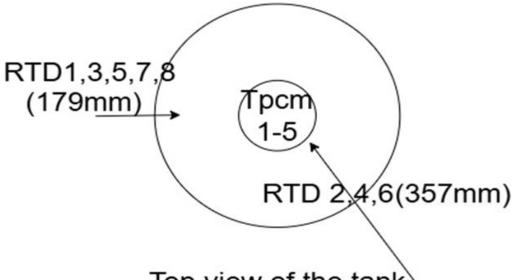


RTDs: measurement of HTF temperature in the tank

Tpcms: measurement of PCM (capsule) tempertaure in the tank



Front view of the tank



Top view of the tank

Dedicated temperature sensors measure the temperature inside the PCM-TES both at PCM side (inside several capsules) and also at HTF (water) side outside the capsules, as shown

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PCM-TES SoC estimation

$$SoC(t) = \frac{\Delta H_{available}(t)}{\Delta H_{\max\_available}(t)}$$

$SoC(t)$ = State of Charge at time t (expressed as a ratio from 0 to 1) (-)
$\Delta H_{available}(t)$ = Available energy at time t (can be + or – for charging and discharging respectively) (kJ)
$\Delta H_{max\_available}(t)$ = Maximum available energy capacity under current conditions (kJ)

Total theoretical maximum PCM enthalpy change in melting (charging)

$$\Sigma^{n}_{i} \Delta H_{\max\_PCM}, i = \Sigma_i^5 \{$$

$m_i \times c_{p,S} \times (T_{inlet}(t) - T_{tank\_initial});$ if $T_{inlet} < T_{onset}$

$m_i \times c_{p,S} \times (T_{onset}(t) - T_{tank\_initial}) + \psi_{i(T_{inlet}(t))} \times m_i \times L;$ if $T_{onset} < T_{inlet} < T_{offset}$

$m_i \times c_{p,S} \times (T_{onset}(t) - T_{tank\_initial}) + m_i \times L + m_i \times c_{p,L} \times (T_{inlet} - T_{offset});$ if $T_{offset} < T_{inlet}$

$\}$

$$\psi_{i(T_{inlet}(t))} = \frac{T_{tank,i} - T_{offset}}{T_{onset} - T_{offset}}$$

Where for each sensor position i:

- m_i = Mass of PCM in zone i (kg)
- $c_{p,S}$ & $c_{p,L}$ = Specific heat capacity of PCM for solid and liquid phases respectively (kJ/(kg·K))
- $T_{initial}$ = Initial temperature in the TES unit (°C)
- T_{onset} = Phase change onset temperature (°C)
- T_{offset} = Phase change completion (offset) temperature (°C)
- T_{inlet} = Inlet temperature of HTF (°C)
- L = Latent heat of fusion (kJ/kg)
- $\psi_{i(T_{inlet}(t))}$ = Liquid fraction coefficient (0 to 1) as a function of inlet temperature and time, in zone i

Charging / Discharging Energy Balance

$$\Delta H_{\max\_available}(T_{inlet(t)}) = \Delta H_{\max\_PCM} + \Delta H_{\max\_HTF} - \Delta H_{losses}$$

ΔH_{max_PCM} = Total energy capacity from the PCM-TES over the full charging/discharging temperature range (kJ)
ΔH_{max_HTF} = Total energy capacity from the HTF in the PCM-TES over the full charging/discharging temperature range (kJ)
ΔH_{losses} = heat losses to or heat gain from the ambient environment (kJ)

Total theoretical maximum PCM enthalpy change in freezing (discharging)

$$\Sigma^{n}_{i} \Delta H_{\max\_PCM}, i = \Sigma_i^5 \{$$

$m_i \times c_{p,L} \times (T_{inlet}(t) - T_{tank\_initial});$ if $T_{inlet} > T_{onset}$

$m_i \times c_{p,L} \times (T_{onset}(t) - T_{tank\_initial}) - \psi_{i(T_{inlet}(t))} \times m_i \times L;$ if $T_{onset} > T_{inlet} > T_{offset}$

$m_i \times c_{p,L} \times (T_{onset}(t) - T_{tank\_initial}) - m_i \times L + m_i \times c_{p,S} \times (T_{inlet} - T_{offset});$ if $T_{offset} > T_{inlet}$

$\}$

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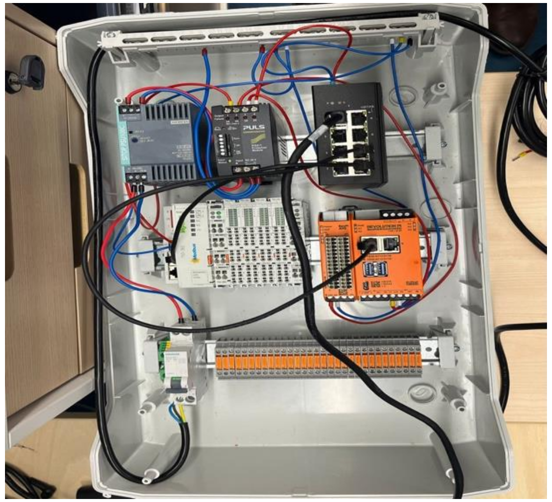
PCM-TES SoC estimation…



Control hardware

Heat loss: $$\Delta H_{losses,\,\Delta t} = \dot{Q}_{losses} \times \Delta t = U \times A \times LMTD_{(T_{surface}, T_{ambient})} \times \Delta t$$

U is the overall heat transfer coefficient from the tank exterior insulation surface to the ambient (W/(m^2·K))
A is the exterior insulation surface area (m^2)
Δt is time (s)

Maximum HTF Energy supply /absorption capacity during PCM-TES charging and discharging

$$\Delta H_{max\_HTF\,\Delta t}(t) = \dot{m} \times c_{p,HTF} \times \left(T_{inlet}(t) - T_{HTF\_initial}\right) \times \Delta t$$

T_{inlet} (t)= Inlet temperature of HTF at time t (°C)
$T_{initial}$= Initial temperature in the TES unit (°C)
$c_{p,HTF}$ = Specific heat capacity of HTF (water) (kJ/(kg·K))

$$\Delta H_{available}(t) = \Delta H_{PCM\_available}(t) + \Delta H_{HTF\ available}(t)$$

$\Delta H_{PCM\_available}(t)$ can be estimated using:

$$\Sigma^{n}{}_{i}\,\Delta H_{PCM\_available\,i} = \Sigma_i^{5} \begin{cases} m_i \times c_{p,S} \times (T_{inlet}(t) - T_{PCM}(t)); & \text{if } T_{inlet} < T_{onset} \\ m_i \times c_{p,S} \times (T_{onset}(t) - T_{PCM}(t)) + \psi_{i(T_{inlet}(t))} \times m_i \times L_i & \text{if } T_{onset} < T_{inlet} < T_{offset} \\ m_i \times c_{p,S} \times (T_{onset}(t) - T_{PCM}(t)) + m_i \times L + m_i \times c_{p,L} \times (T_{inlet} - T_{offset}); & \text{if } T_{offset} < T_{inlet} \end{cases}$$

$\Delta H_{PCM\_available}$ = Total energy capacity of the PCM-TES over [$T_{inlet(t)}$; $T_{PCM(t)}$] range (kJ), see (26)
$\Delta H_{HTF\_available}$ = Total energy capacity from the HTF in the PCM-TES over [$T_{inlet(t)}$; $T_{PCM(t)}$] range (kJ), estimated using equation 24.

…. Further details in HYSTORE Deliverable 3.4 report (and @Q&A)

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PCM-TES Characterization Campaign

Charging

Test	HTF Inlet Temperature (°C)	Flow Rate (m^3/h)
1	0.15	65
2	0.25	65,70
3	0.35	62,65,70
4	0.5	65
5	0.6	62,65

Discharging

Test	Flow rate (m^3/h)	Inlet temperature (℃)
1	0.15	25-30, 30-35
2	0.25	25-30, 30-35
3	0.35	25-30, 30-35
4	0.5	25-30, 30-35
5	0.6	25-30, 30-35

Measurements :

- TES temperatures (inlet/outlet/core),
- flow rate,
- energy transfer

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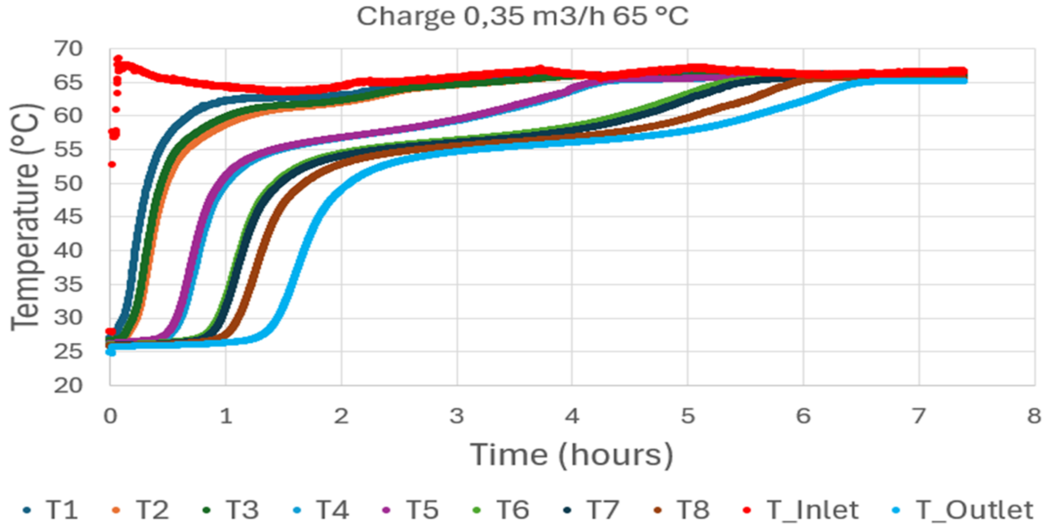
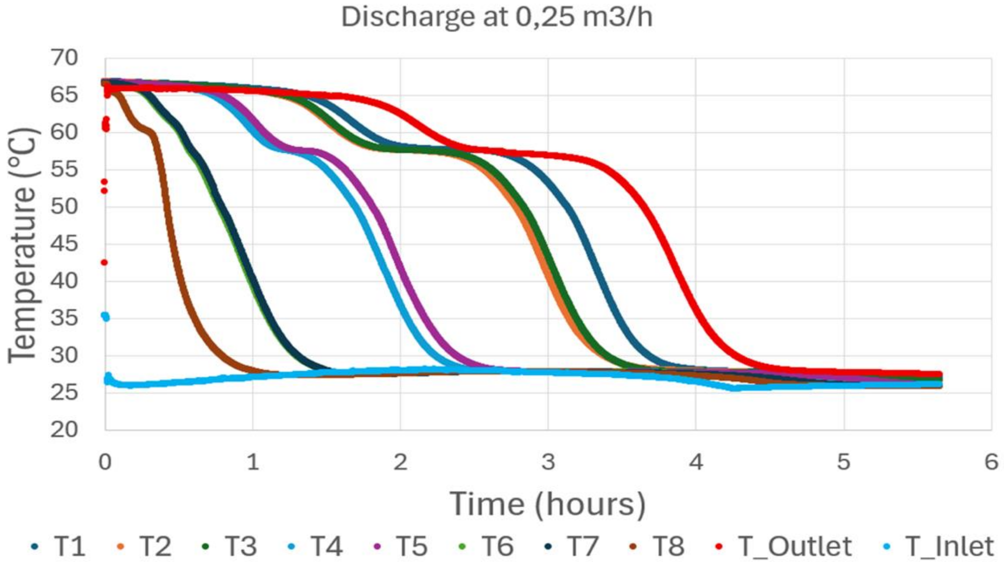
PCM-TES experimental characteristics

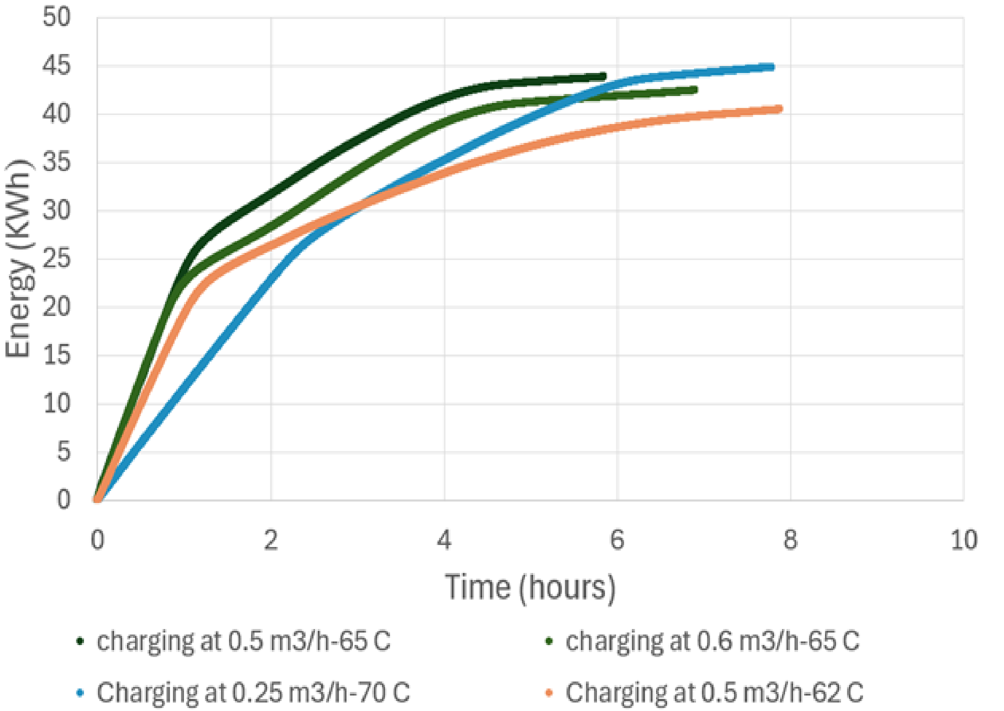
TES HTF temperature profile during charging/discharging





Left: Examples of charge /discharge tests – up to 8h time needed for charge and discharge of the storage → compatible with daily operation.

Right: Energy capacity retrieved: up to 45 kWh



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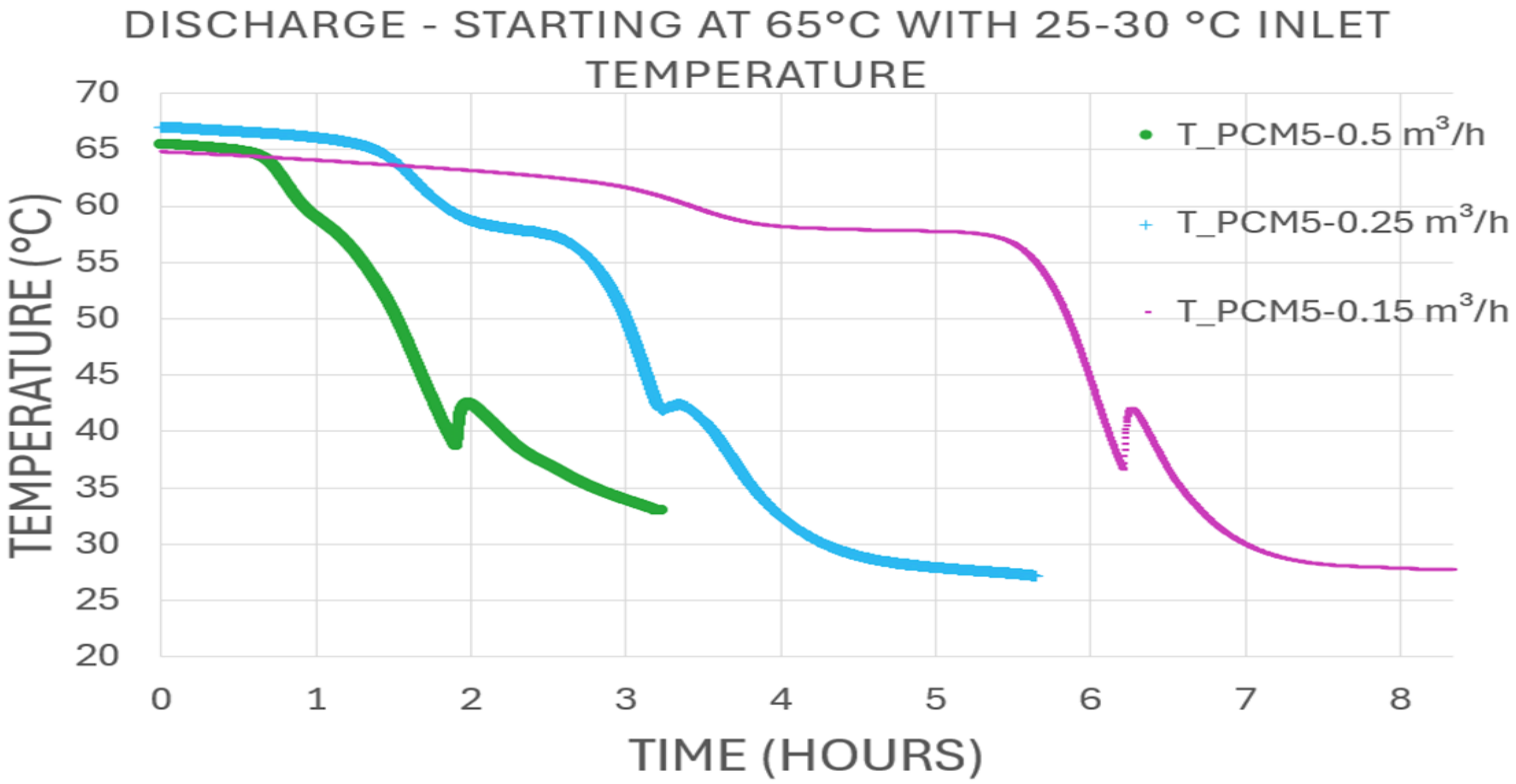
TES temperature profile (PCM)



PCM capsules temperature for the discharging test with the HTF at 3 different flow rates with 65 ℃ as the inlet

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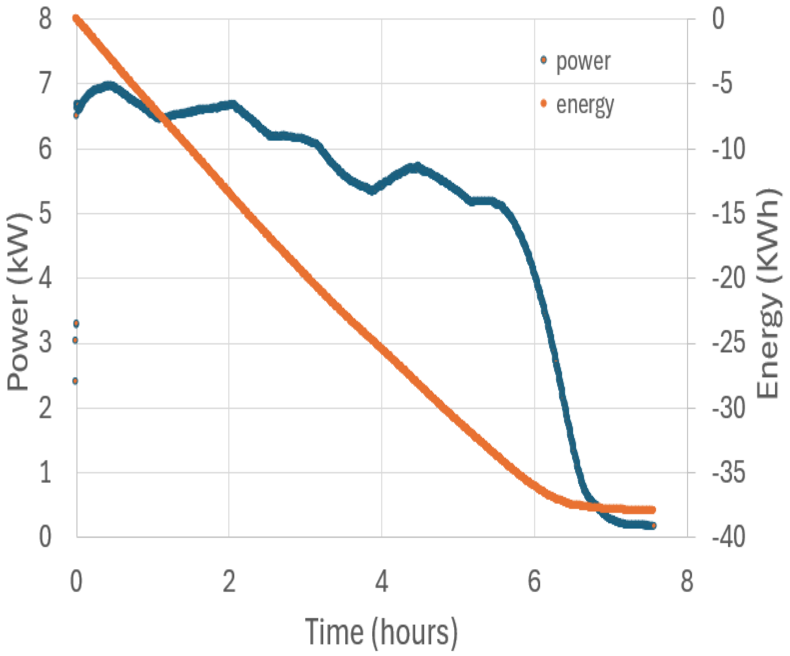
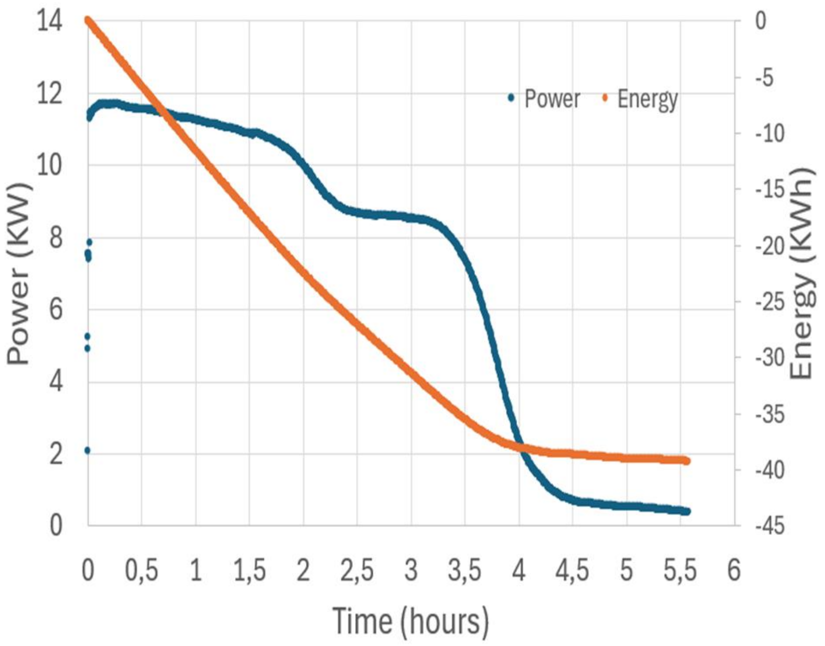
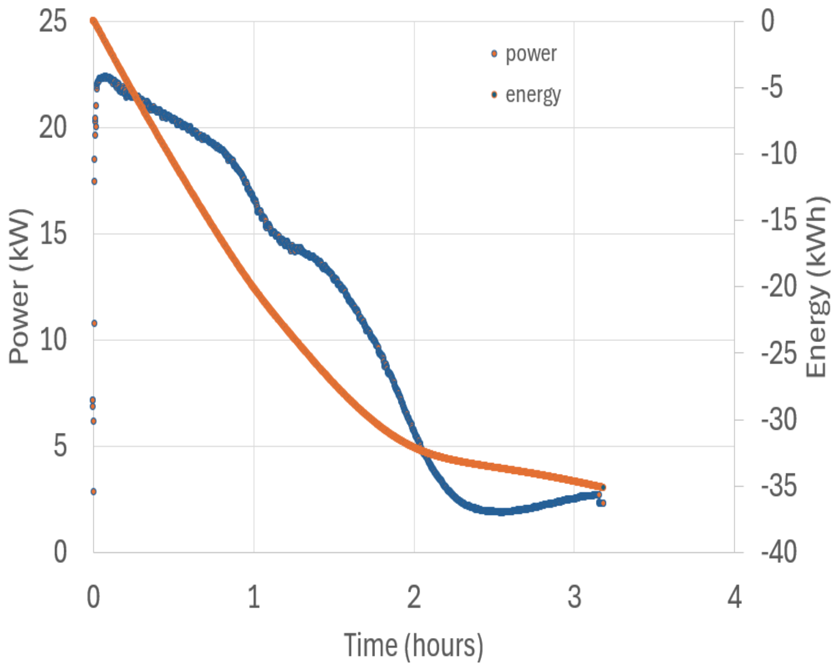
TES discharging powers and capacity



Discharge test at 0.15 m^3/h



Discharge test at 0.35 m^3/h



Discharge test at 0.5 m^3/h

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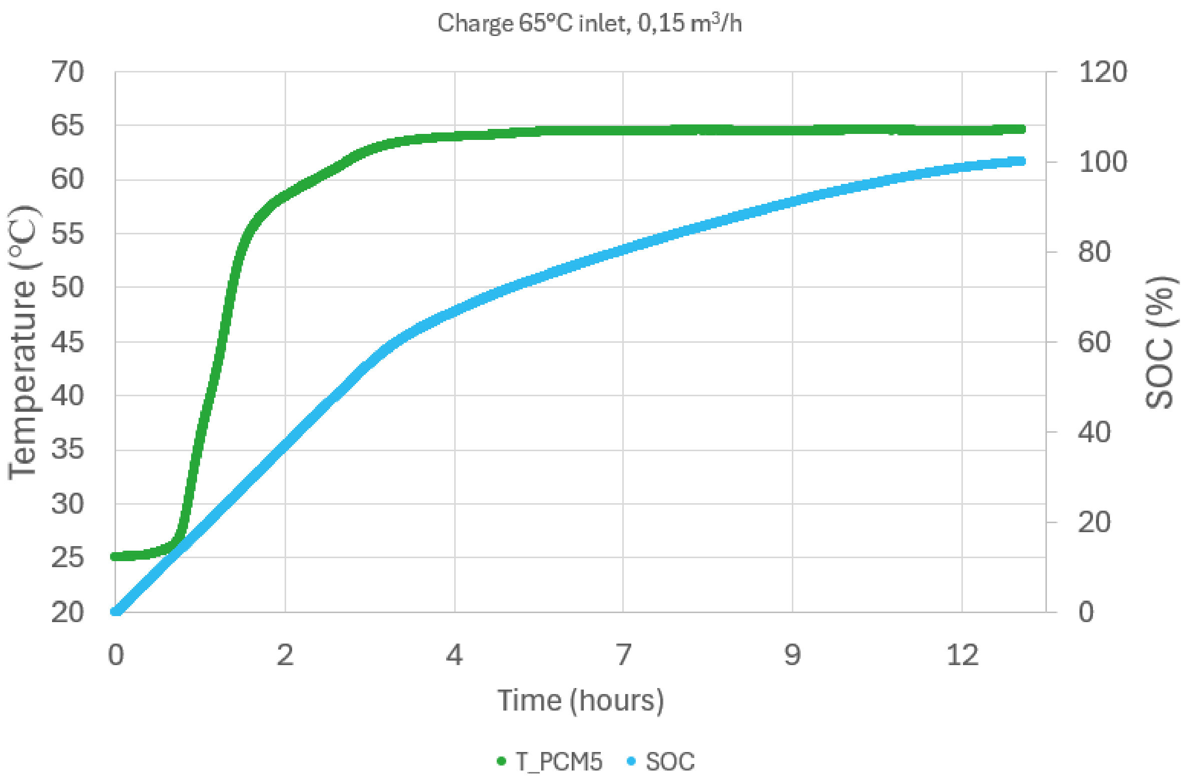
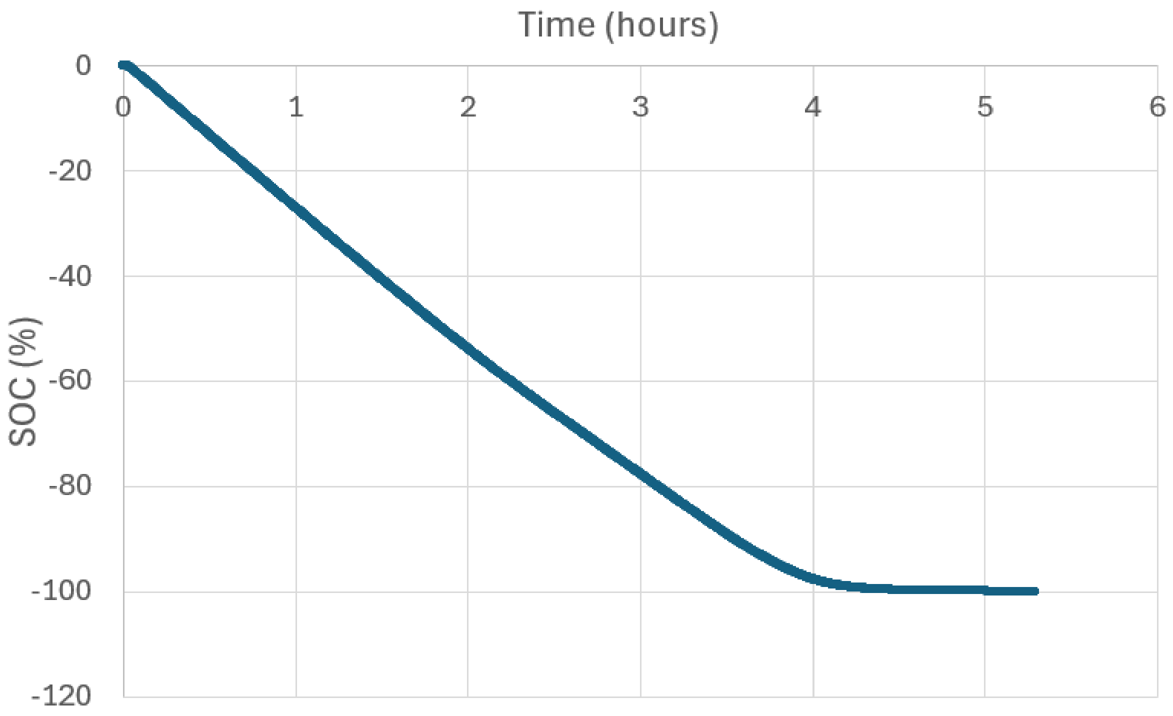
PCM-TES State-of-Charge (SoC)



SoC (charging)



SoC (Discharging at 0.25 m^3/h)

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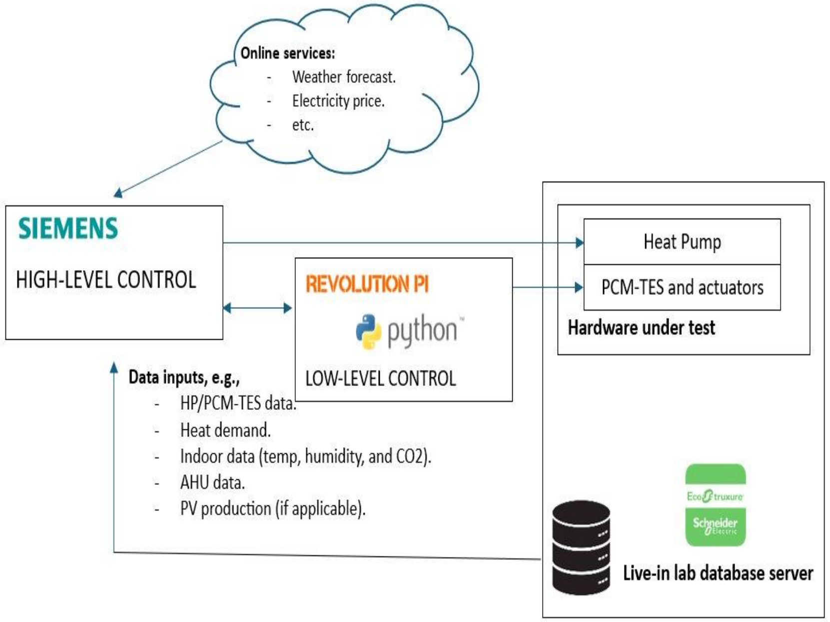
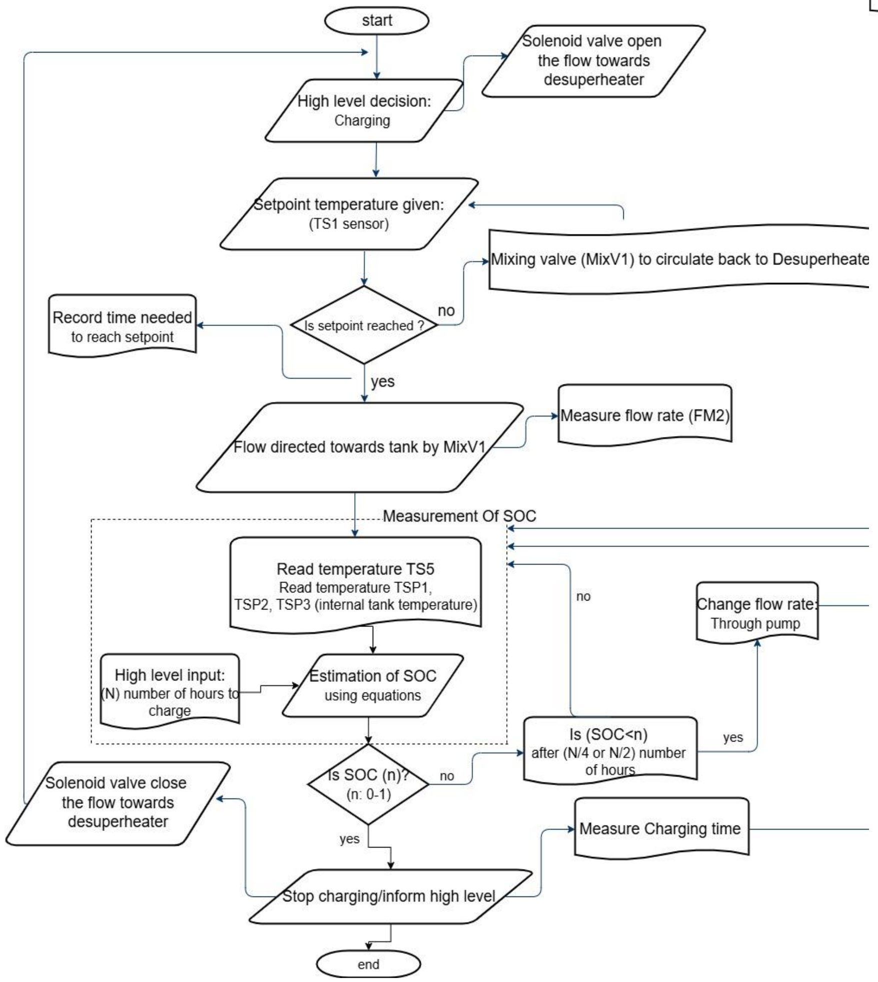
PCM Heating Solution

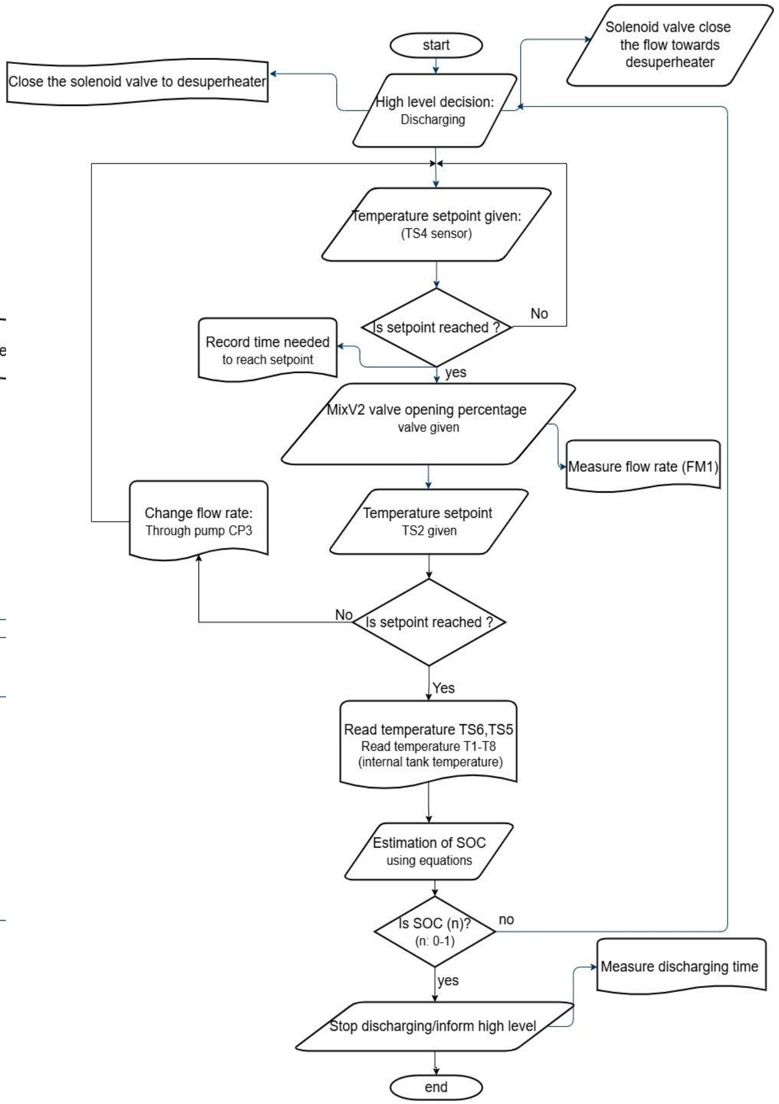
Installation, Operation & Optimization at KTH Live-in-Lab

2025-12-10

Control system







PCM-TES Charging

PCM-TES Discharging

Low- to high-level control:

- PCM-TES Charging
- PCM-TES Discharging

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Hybrid Services from Advanced Thermal Energy Storage Systems

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Technical insights in development of Thermal Energy Storage: from system integration to State of Charge estimation

10 December 2025 | 16:00 - 18:00 | Teams Webinar

TES Cluster
Thermal Energy Storage

ECHO
EFFICIENT COMPACT MODULAR THERMAL ENERGY STORAGE SYSTEM

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