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Towards a fair evaluation of Thermal Energy Storage prototypes - Guidelines for CSP applications

Case studies on thermal losses calculations

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JOINT RESEARCH ACTIVITIES

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Outline:

Definitions and generalities

Test procedures

Prototypes chosen for the thermal losses assessment

Case study 1: Latent heat Storage → isothermal and cool-down methods

Case study 2: Sensible heat Storage → cool-down, energy balance and comparison methods

Results

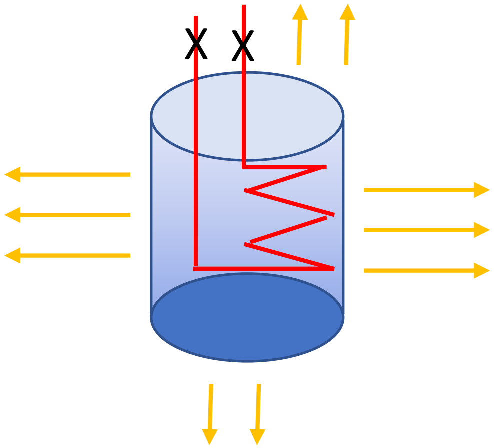
Conclusions

Definition:

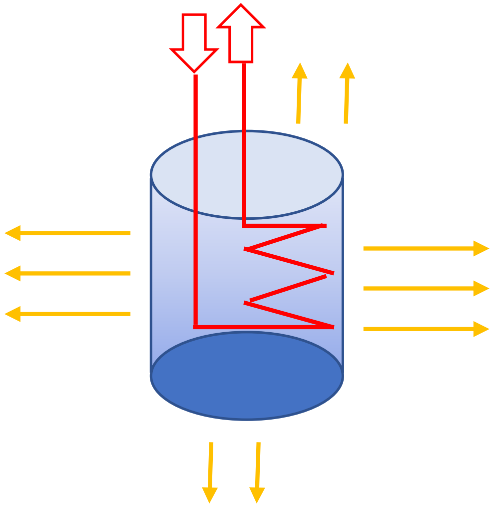
Thermal power lost by the thermal storage system during time "t" from storage state A (at t=t_0) to storage state B

$$P_{loss} = \frac{Q_A(t_0) - Q_B(t) + Q_{in}(t - t_0) - Q_{out}(t - t_0)}{t}$$

idle or stationary thermal losses: during idle periods (Q_{in} = 0 and Q_{out} = 0)



dynamic thermal losses: when the storage system is operated (in charge or discharge)



Thermal losses must be given at a specified temperature level

The heating/cooling system, here depicted as a heat storage with inlet and outlet at the top, is only for a scope of concept example because many other configurations can be used

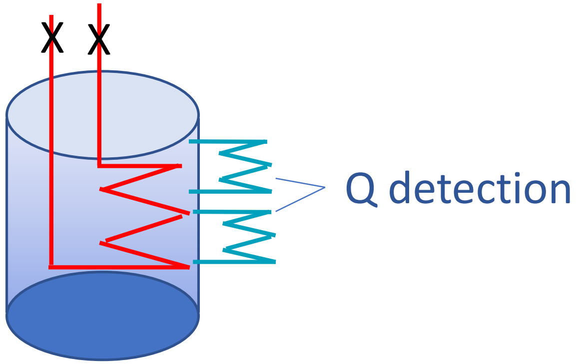
Thermal losses can hardly be extrapolated from small to large systems.

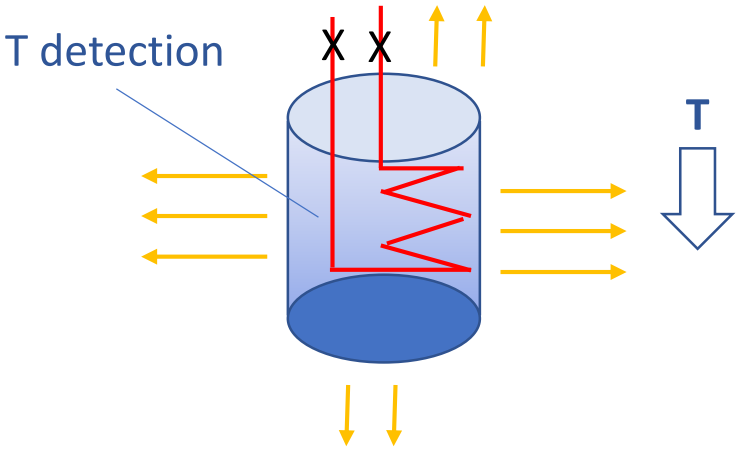
Some orders of magnitude for TES temperature due to thermal losses in sensible heat storages:

- *A few degrees decrease per hour for lab-scale TES*
- *A few degrees decrease per day for industrial-scale TES*

Test procedures

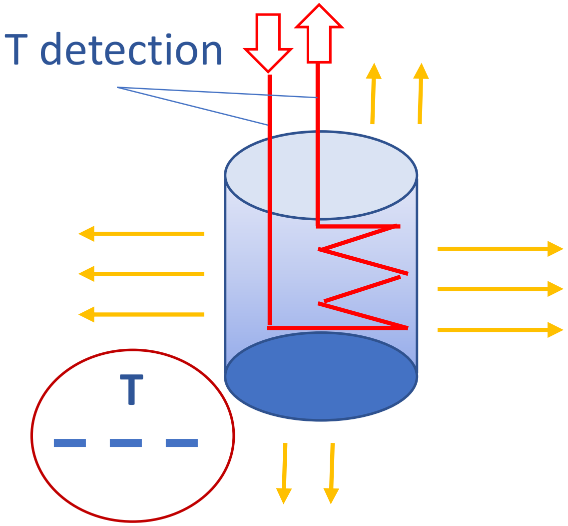
1) Isothermal test (stationary)
Losses offsetting with heat tracing

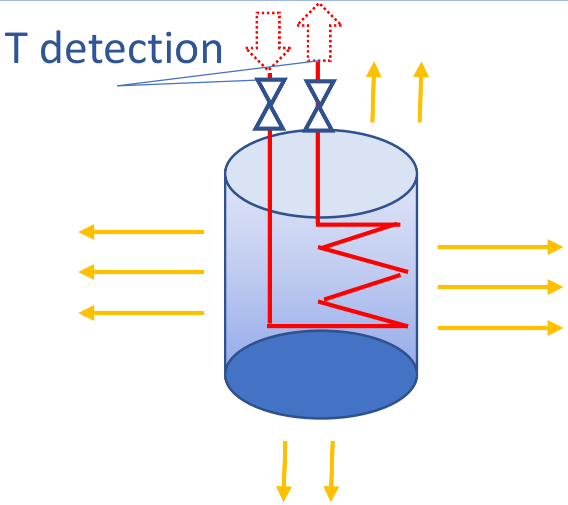




2) Cool-down method [also called thermal gauging]
Temperature measurement of thermal gradient (type, location, accuracy, quantity, resolution)

3) Energy balance at constant temperature (dynamic)
Balance between inlet and outlet enthalpies at constant inlet conditions after temperature stabilization





4) Comparison between two standardized charging-discharging tests

- With and without idle time between end of charge and beginning of discharge
- Warning: Include other effects, like loss of stratification in thermocline TES

Some deepening on cool-down method

The thermal losses are estimated by the rate of change of the mean tank temperature.

For the calculation the volume of the tank is divided by number of temperature sensors in the tank. Thus, each sensor is assigned a partial volume of the tank surrounding it.

Mean tank temperatures measured at the beginning and end of the test must be clearly stated.

$$\mathrm{E}(\mathrm{t}_1) = \mathrm{E}(\mathrm{t}_0) + \mathrm{V}\int_{T(t_0)}^{T(t_1)} \rho(\mathrm{T}) c_p(\mathrm{T})\mathrm{dT} \Rightarrow P_{loss} = \frac{\mathrm{E}(\mathrm{t}_0) - \mathrm{E}(\mathrm{t}_1)}{t_1 - t_0}$$

If it is possible to assume

$$\bar{c_p} = \frac{\boldsymbol{c_p(T_0) + c_p(T_1)}}{2} \Rightarrow \mathrm{E}(\mathrm{t}_1) = \mathrm{E}(\mathrm{t}_0) + \rho(\bar{T})\mathrm{V}\bar{c_p}(T_1 - T_0)$$

This method has the advantage of locating the areas with higher losses.

Some deepening on isothermal, energy balance and discharge comparison methods

Isothermal

It is the average of the power detected by the heaters, used to compensate the thermal losses to make constant the temperature in the TES.

Energy balance

$$P_{loss} = \dot{m} \cdot (h_{in} - h_{out})$$

P_{loss}: *power losses [W]*
$\dot{m}$: *HTF mass flow rate [kg/s]*

It is necessary to have stable conditions of HTF (in/out) temperature. It is better to assess an average value of the last acquired data.

Discharge comparison

$$E_{loss} = \int_{t_1}^{t_2} (\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}) dt - \int_{t_3}^{t_4} (\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}) dt$$

$$P_{loss} = \frac{E_{loss}}{IT_2 - IT_1}$$

$h : \int_{T_0}^{T} c_p(T) dT$: *specific enthalpy [J/kg]*

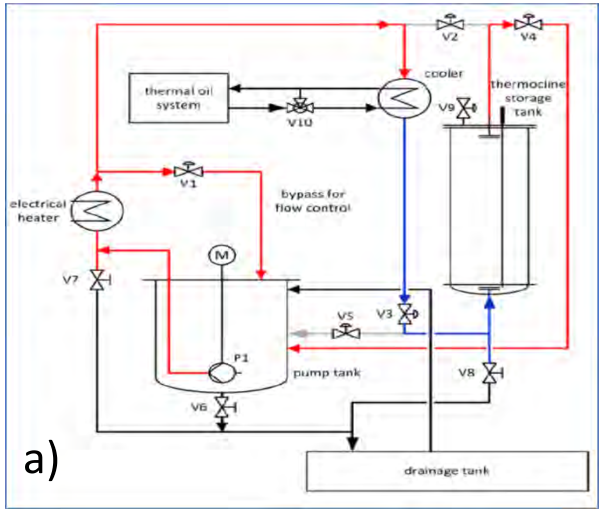
[t_4-t_3]: discharge at the same range of time of [t_2-t_1] but after a different idle time IT, which follows a charge of the same time for the two intervals in discharge mode.

Here no temperature sensors inside the tank are needed.

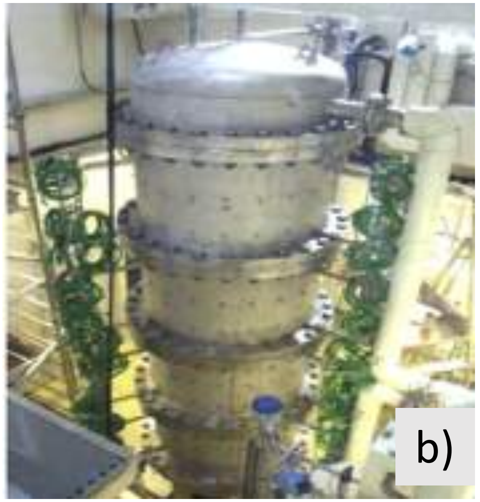
In Task 6.3 (Development of protocols to test prototypes for storage systems) thermal losses were assessed on the basis of:

✓ **Experimental results shared between the partners**

- Sensible heat storage prototypes
  - FRAUNHOFER's molten salt thermocline (a)
  - CEA's dual media thermocline (b)
  - ENEA's concrete storage (c)
- Latent heat storage prototypes:
  - CIEMAT's (d)
  - CEA's PCM storages (e)

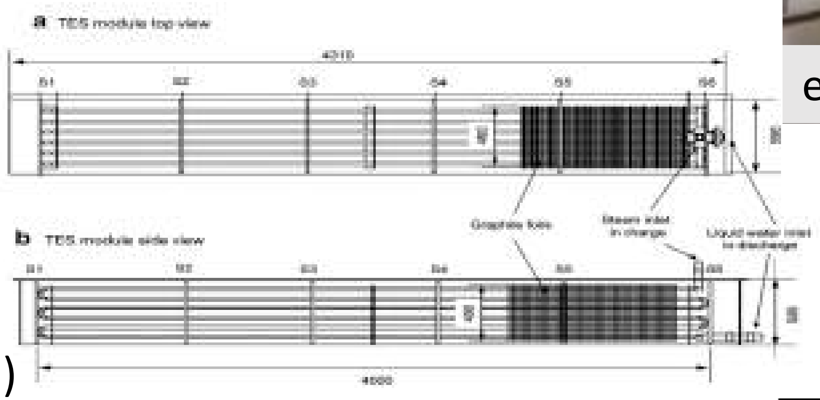


a)



b)

c)

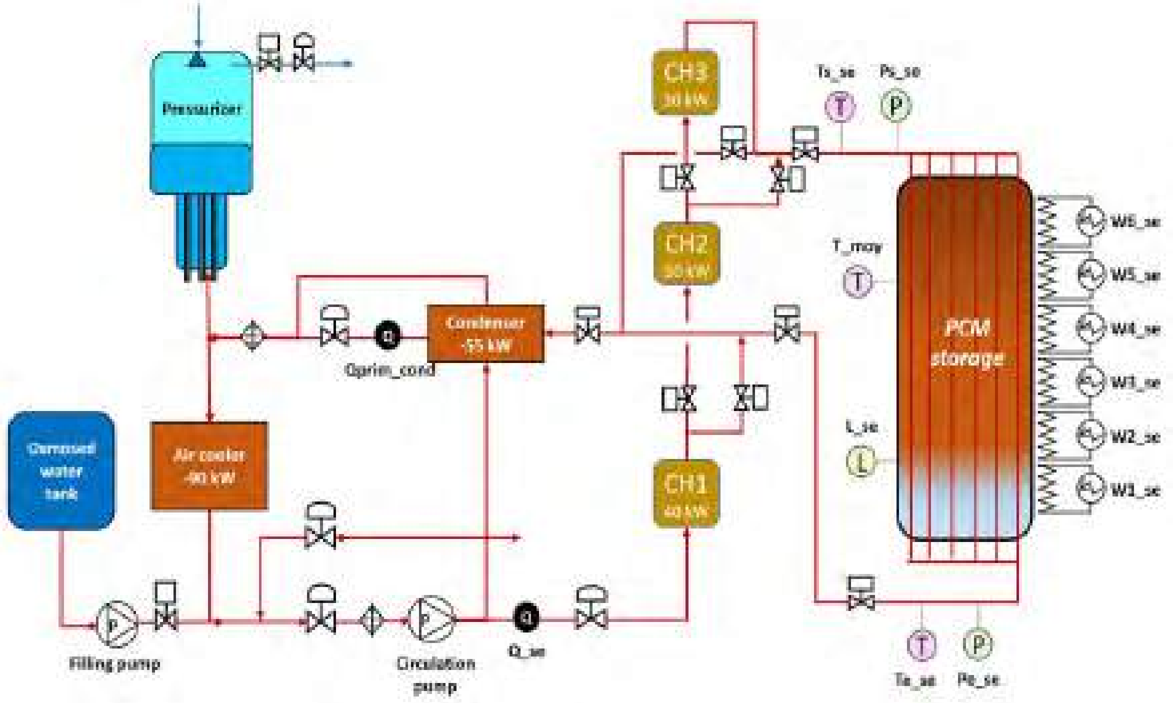


d)

e)

Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)

Data collected by this facility allow to calculate thermal losses using isothermal method and cool down.



A Phase Change Material (PCM) storage module connected to this facility is composed of aluminium finned steel tubes immerged into sodium nitrate and surrounded by aluminium inserts for heat transfer enhancement.

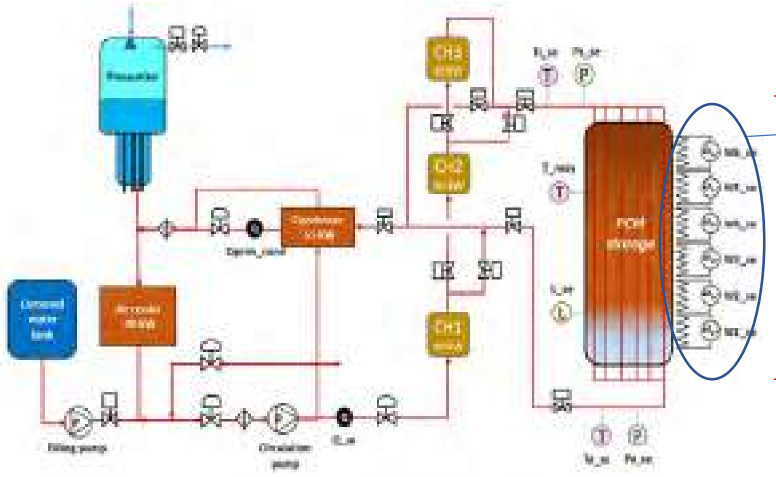
Up to 145 bar, 350°C

300 kWh_{th}, 6.3 tons, melting temperature: 306°C

250 thermocouples at different height and three radial positions.

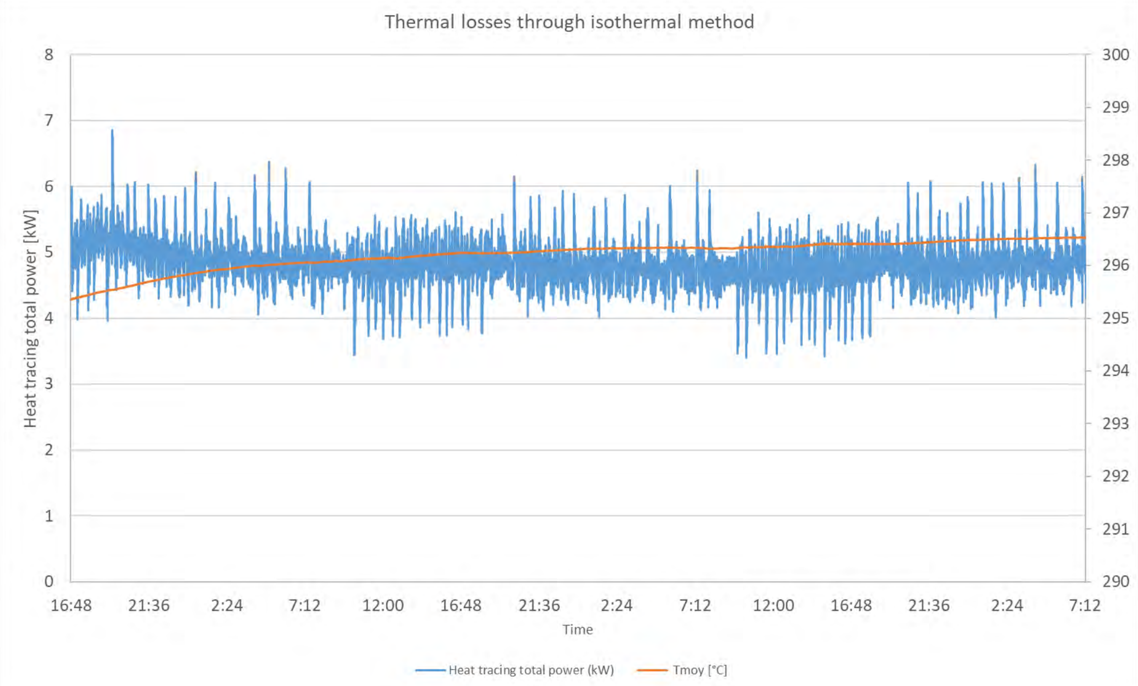
Charging: steam slightly above saturation is sent from the top to the exchanger tubes where it condenses causing the melting of the PCM; the opposite in discharge but the water is sent from the bottom.

Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)



<u>Isothermal method</u>

Electrical power of the heat tracing at different section, calculated from voltage measurement

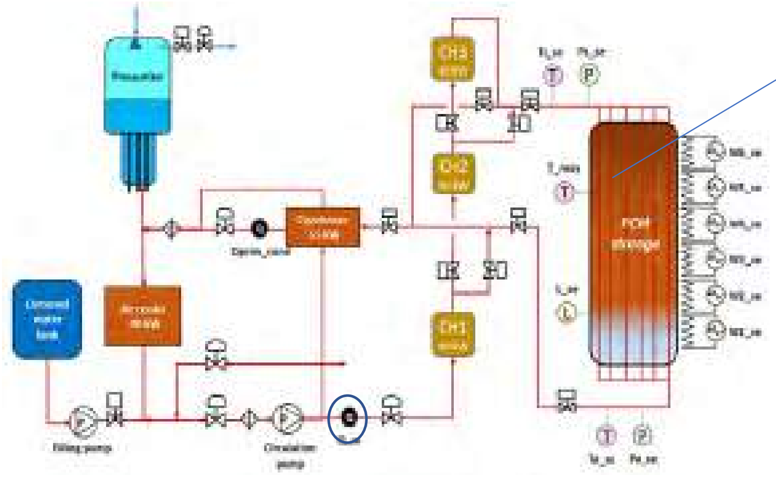


Data of the heat tracing powers were available at: 10 s

Average: 4.871 kW → Losses offset with heat tracing

Theoretical storage capacity: 379.6 kWh

Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)



Cool down method

Rate of change of the mean tank temperature. This is achieved by turning off the power supply systems (e.g. immersion heaters and electrical heat tracing) and via monitoring and recording the tank temperature on storage media side over a defined period.

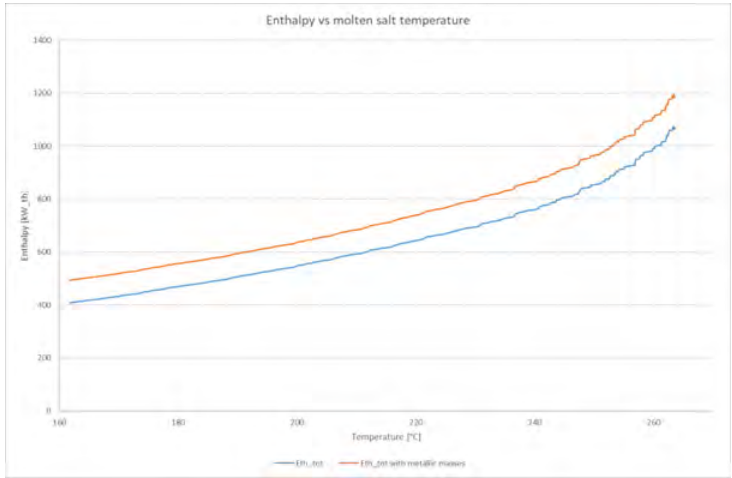
6 Volume fractions attributed to each measurement level

7 Volume fractions attributed to each measurement level assuming homogeneous T

Thermal losses assessment as enthalpy difference between two consecutive moment divided for the related time.

Enthalpy per each datum and level of the storage system including PCM (6330 kg), tubes (3795 kg) and aluminium inserts (1725 kg). In addition, it is possible to include also the shell (1137 kg), top (293 kg) and bottom (293 kg) of the tank.

Total enthalpy assessment for each datum

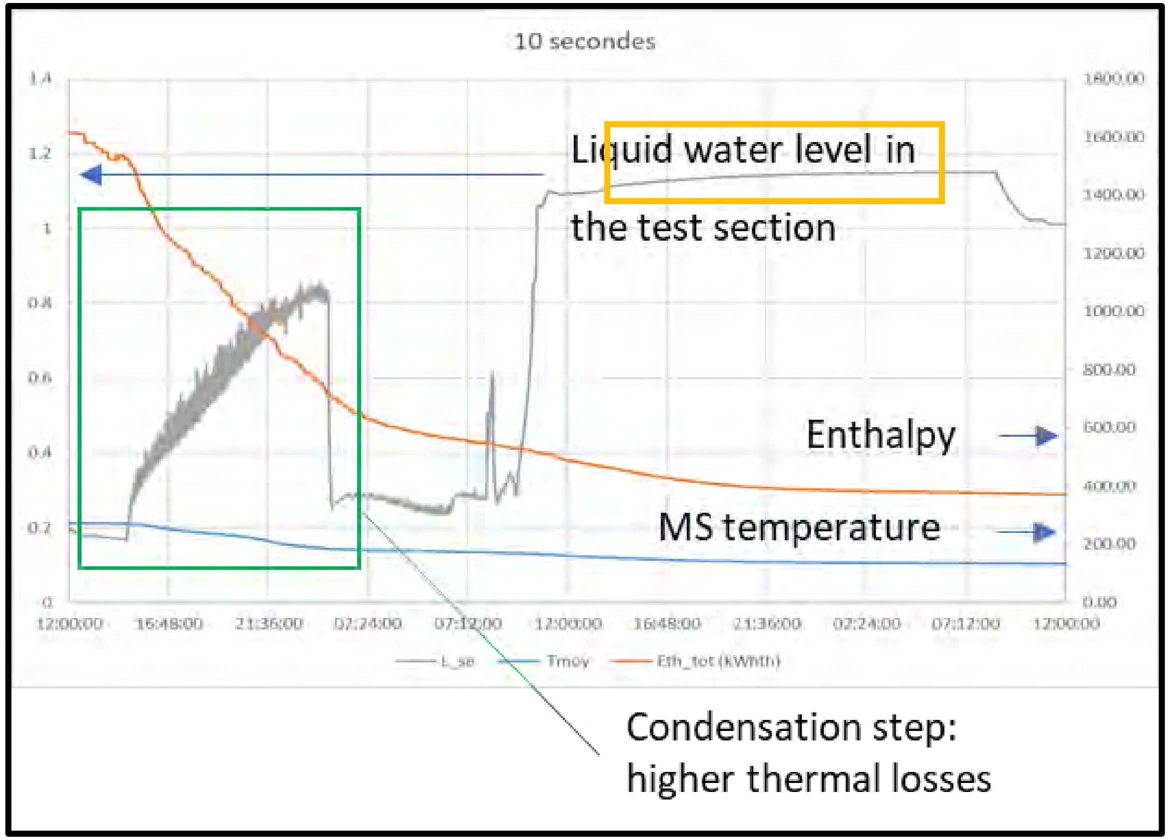


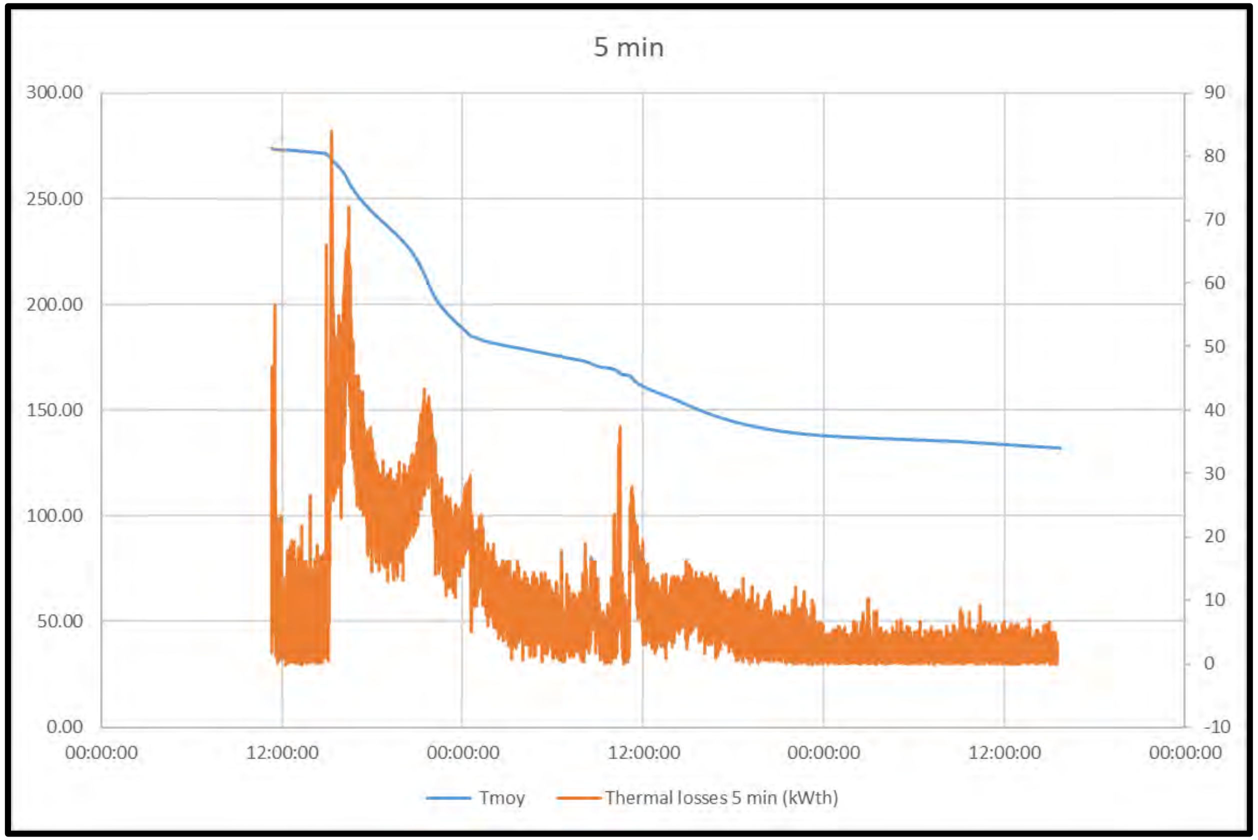
Data of the in/out temperatures and flows were available at: 10 s, 10 minutes and 1 hour.

Average: 2.11 kW or 2.41 kW including metallic shell, top and bottom (in the range 251-241 °C)

Theoretical storage capacity: 379.6 kWh

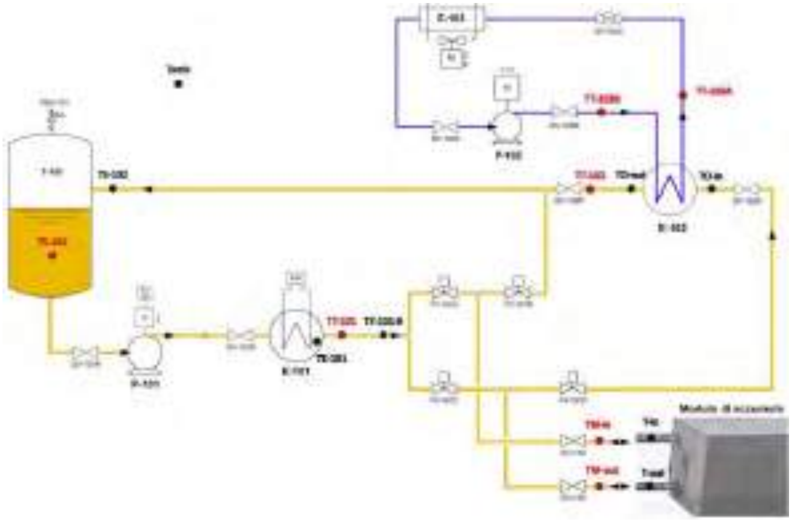
Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)

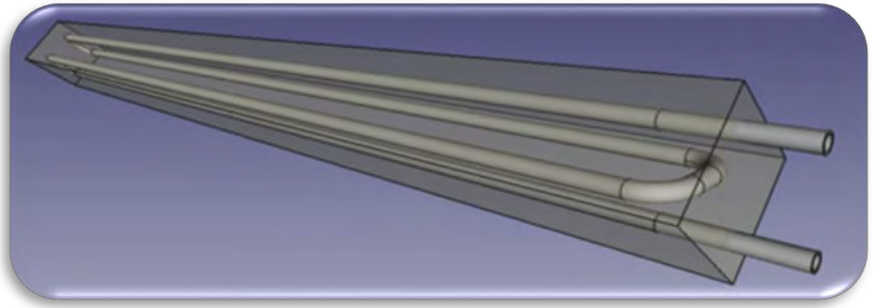




Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Data collected by this facility allow to calculate thermal losses using the methods: cool down, energy balance at constant temperature, and comparison between two standardized charging-discharging tests.





A concrete storage module (220x220x300 mm) connected to the facility for handling, worming and cooling the HTF is composed of a concrete mixcture.

The HTF (Thermal oil) flows into an integrated stainless steel heat exchanger (L: 12 m; Φ_i: 13 mm).

Room pressure, HTF up to 320°C, 21 kW heating/cooling.

Flowmeter using Coriolis effect

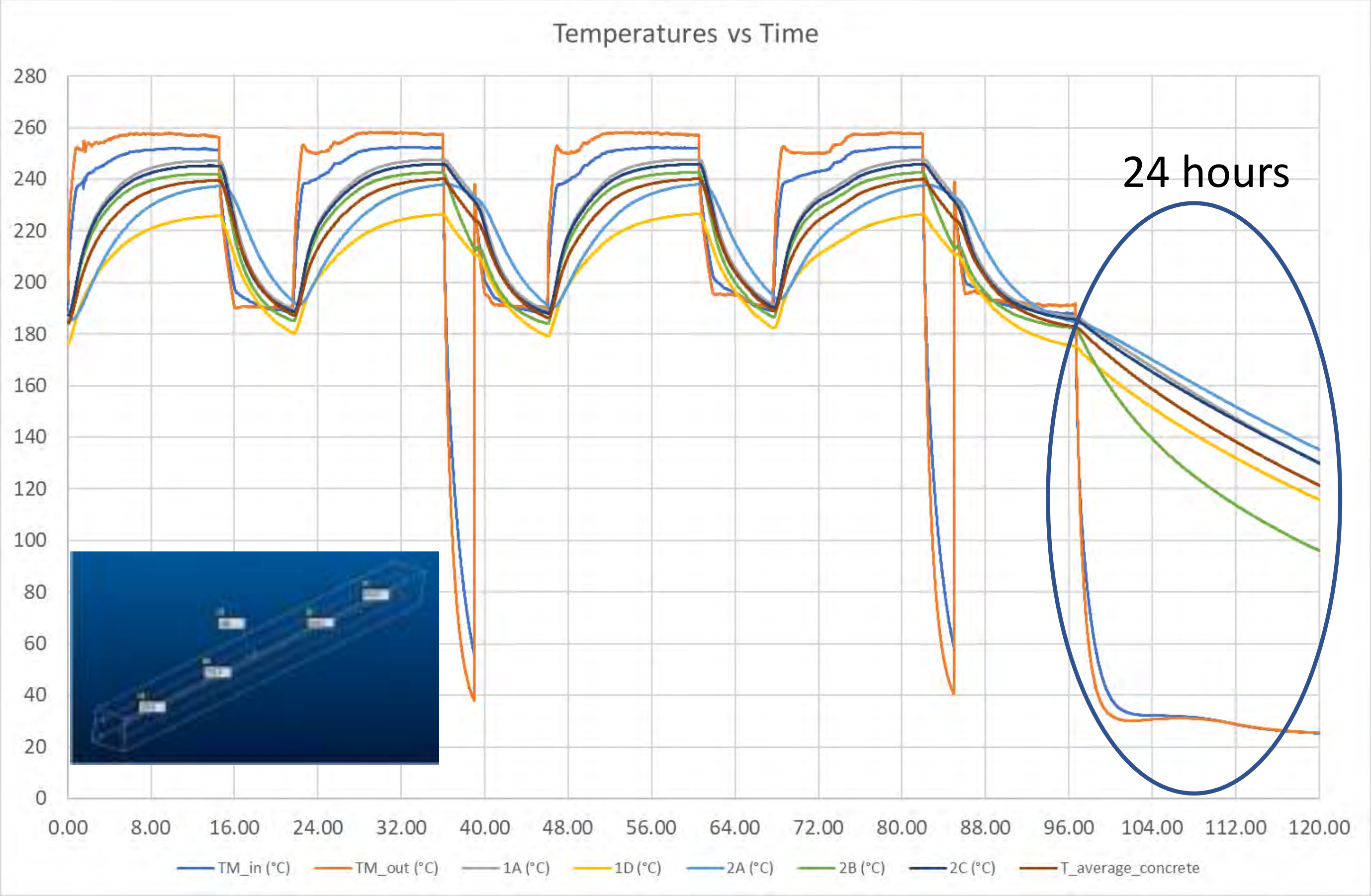
Magnetic drive pump

4.1 kWh_{th}, 347 kg of concrete, 6.5 kg of heat exchanger and 381 kg of insulation (rock wool 400 mm)

5 thermocouples at different positions in the module and 12 thermocouples installed on the system for reading the temperature HTF; those identified in red are internal and directly read the fluid temperature.

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

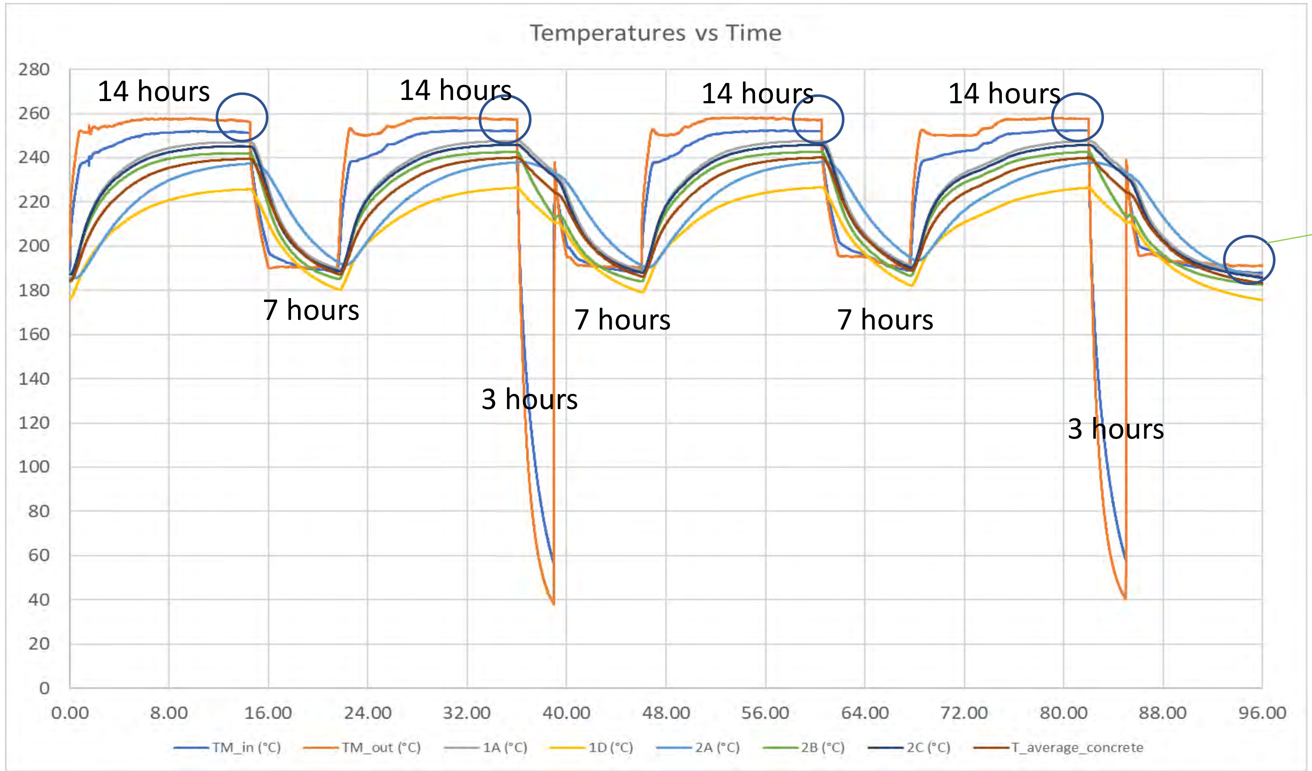
Cool down method



Average at 182-120 °C (cool-down) [kW] about 24 hours	
Initial time	14/6/22 7:18
Final time	15/6/22 7:06
Duration [s]	85704
Concrete initial T average [°C]	182.8
Concrete final T average [°C]	120.6
Metal initial T average [°C]	186.4
Metal final T average [°C]	73.0
Insulation initial T average [°C]	104.8
Insulation final T average [°C]	73.9
Thermal losses [kWh] (only concrete)	-3.79
Thermal losses [kW] (only concrete)	-0.16
Thermal losses [kWh] (concrete+exchanger)	-3.89
Thermal losses [kW] (concrete+exchanger)	-0.16
Thermal losses [kWh] (concrete+exch.+ins)	-7.26
Thermal losses [kW] (concrete+exch.+insulation)	**-0.3**

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Energy balance at constant temperature



TM_in (°C)	TM_out (°C)
189.7	191.4
189.7	191.3
189.7	191.4
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.5	191.1

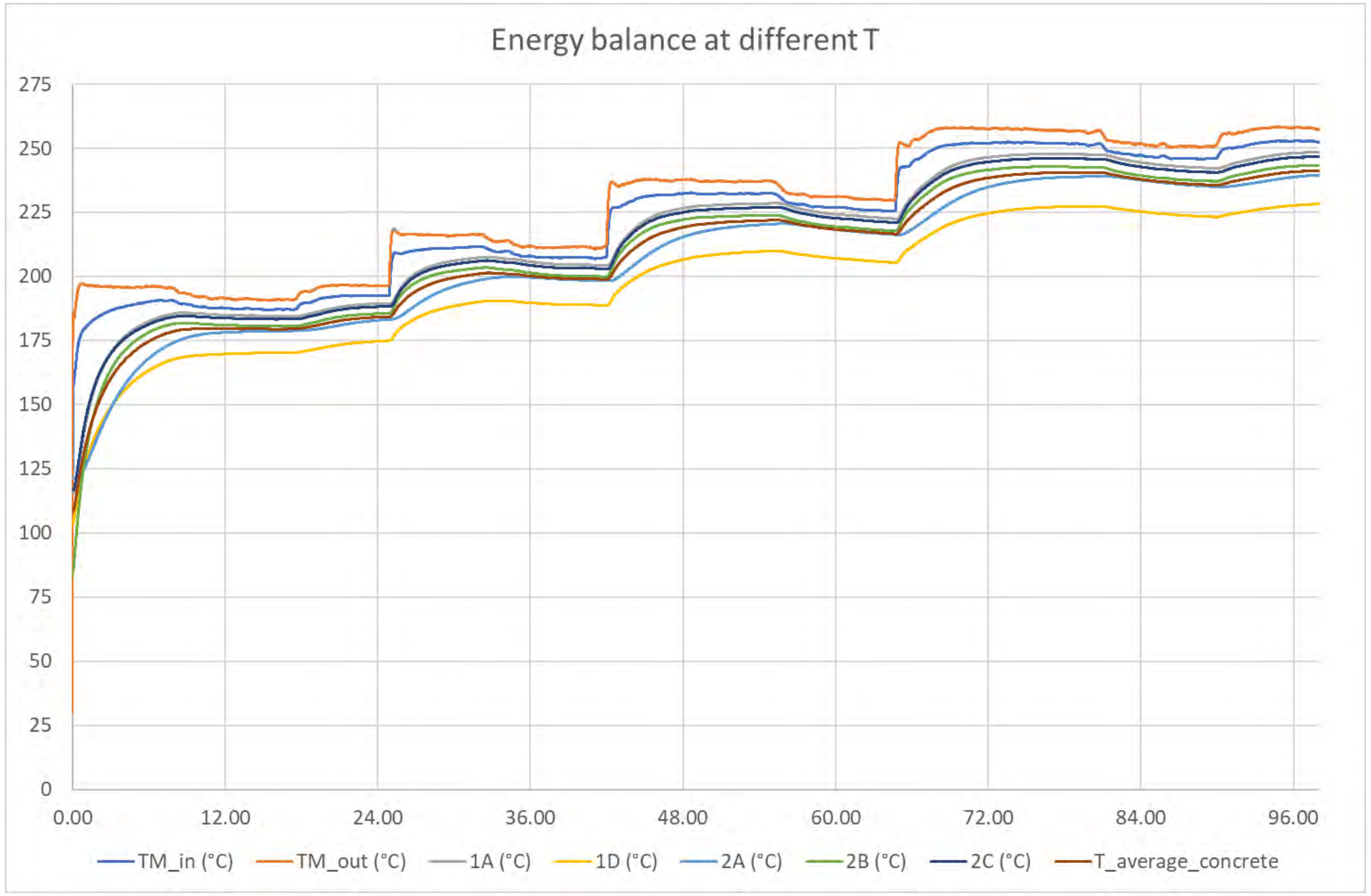
Energy balance between inlet and outlet specific enthalpies on HTF side at constant inlet conditions after stabilization of steady-state temperature is calculated.

Energy balance method 253 °C [kW] 1st charge	0.66
Energy balance method 253 °C [kW] 2nd charge	0.69
Energy balance method 253 °C [kW] 3rd charge	0.69
Energy balance method 253 °C [kW] 4th charge	0.69
Energy balance method 193 °C [kW] final discharge	**0.37**

It is very important the T sensor calibration and their proper contact with the HTF

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Energy balance at constant temperature

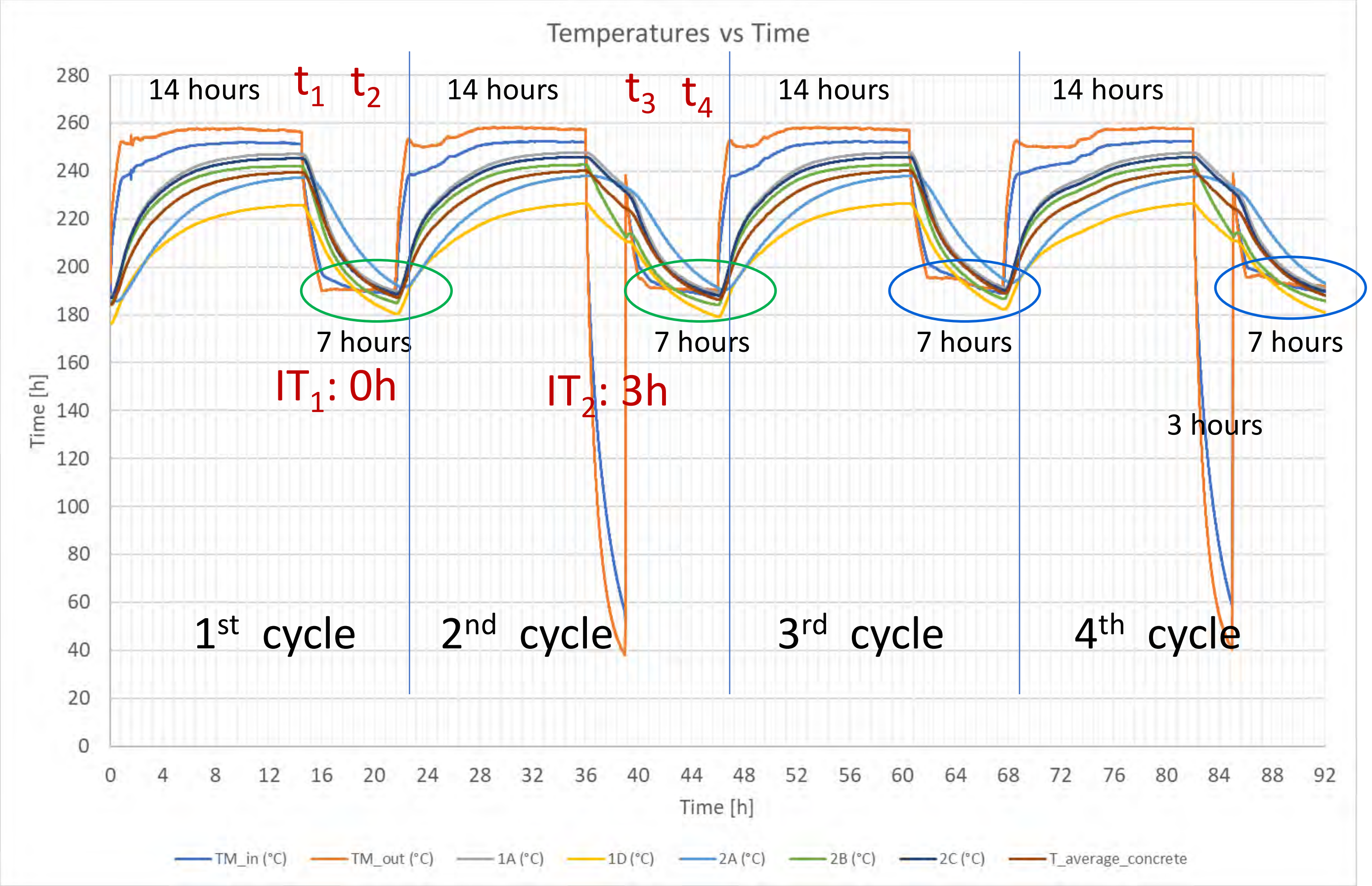


Energy balance between inlet and outlet specific enthalpies on HTF side at constant inlet conditions after stabilization of steady-state temperature is calculated.

Energy balance method 200 °C [kW] 1st charge	0.46
Energy balance method 220 °C [kW] 2nd charge	0.49
Energy balance method 240 °C [kW] 3rd charge	0.61
Energy balance method 258 °C [kW] 4th charge	0.65

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

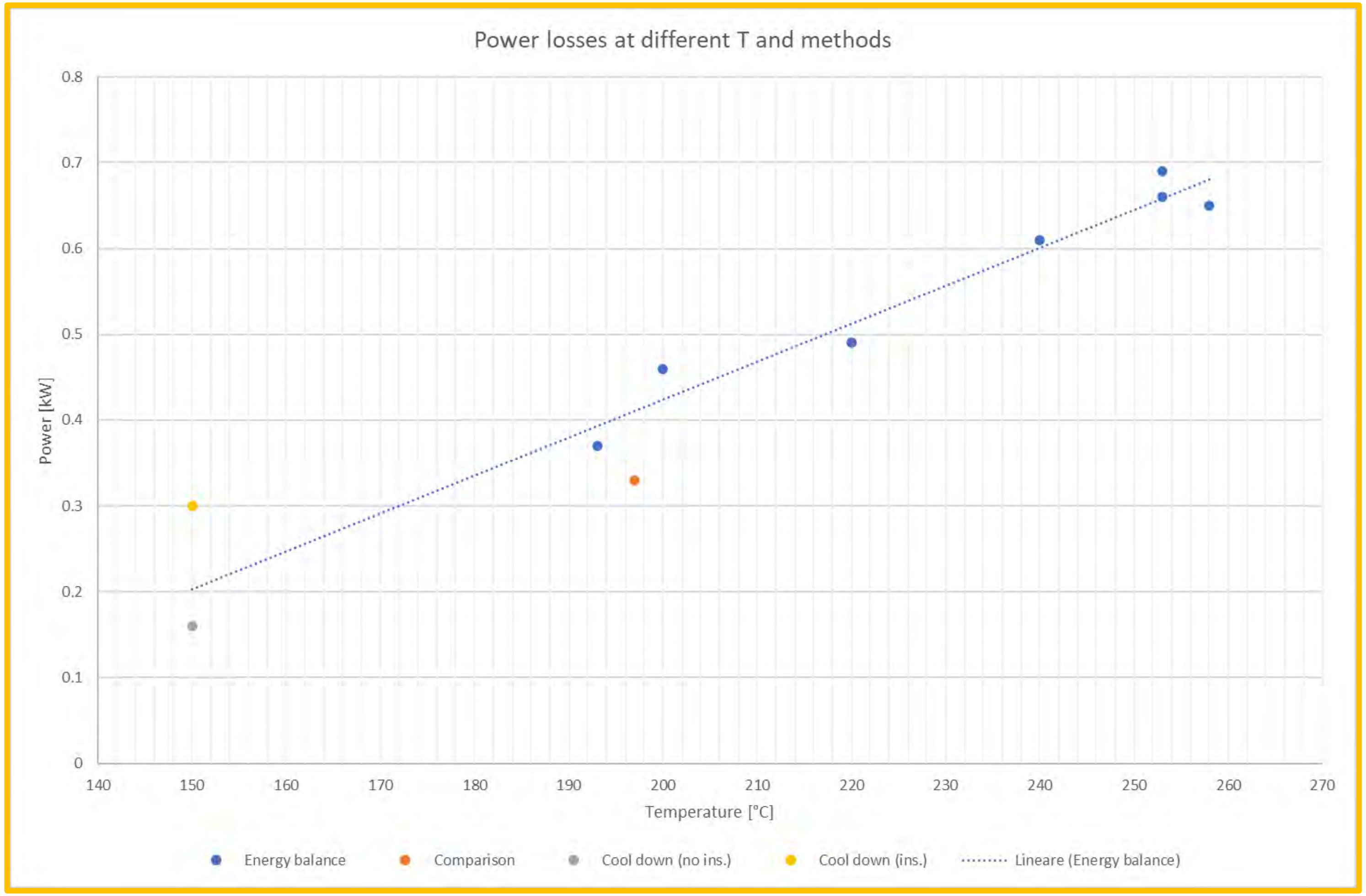
Comparison between two standardized charging-discharging tests



It compares the discharge energy on HTF side from two standardized charging-discharging tests with different idle time between end of charge and beginning of discharge.

Power losses [kW] (Comparison method)	T average concrete [°C]	Discharge energy [kWh]	Thermal losses [kW]
Discharge energy 1st cycle °C [kJ] after 0 min idle	195.83	-6667	
Discharge energy 2nd cycle [kJ] after 180 min idle	196.34	-3067	
Difference discharge energy [kJ]		-3600	-0.33
Discharge energy 3rd cycle °C [kJ] after 0 min idle	198.15	-5919	
Discharge energy 4th cycle [kJ] after 180 min idle	198.30	-2465	
Difference discharge energy [kJ]		-3454	-0.32

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)



Conclusions:

- Thermal energy losses are an important KPI evaluable by 4 different methods;
- These methods can be applied, if the prototype is equipped with the proper instrumentation & controls and the tests were carried out using the appropriate modalities;
- Two prototypes were here chosen because of more than 1 method could be applied:
  LHTTS (CEA): Latent heat Storage for isothermal (IM) and cool-down (CD) methods
  HS by concrete (ENEA) : Sensible heat Storage → cool-down, energy balance (EB) and comparison methods (CM);
- Cool–down method is the only one that needs T sensors installed inside the HSM;
- The results of CD, EB and CM are very similar, while IM is a little higher.

THANK YOU FOR YOUR ATTENTION!
ANY QUESTIONS?