SFERA-III
Solar Facilities for the European Research Area

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D6.3: Standardization of testing prototypes for storage systems
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JOINT RESEARCH ACTIVITIES

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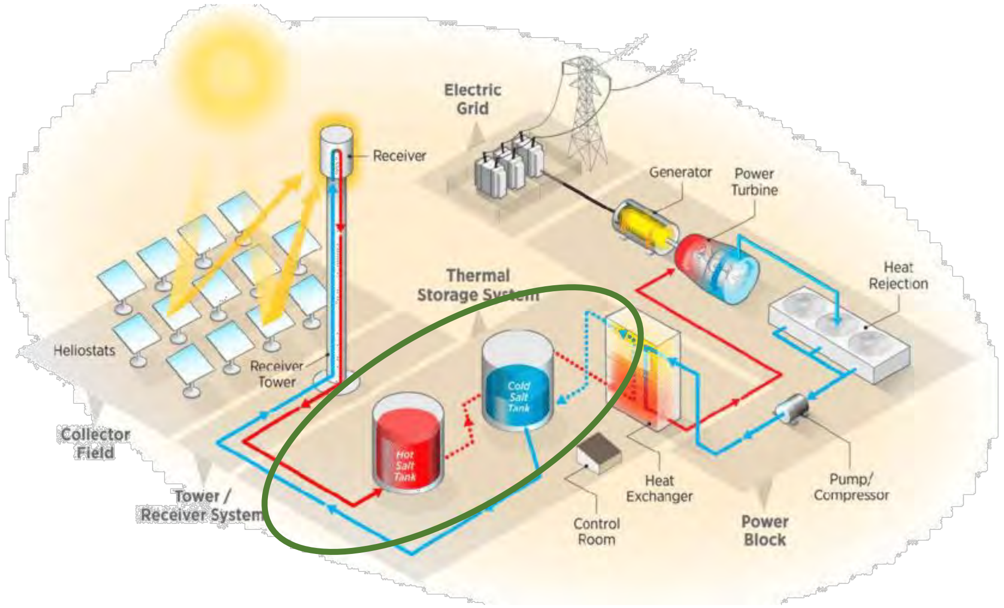
Motivation

- No agreed methods currently exist neither to test TES components and subsystems prototypes nor to present the results in scientific publications.

  Indeed, the definition of essential features such as “storage capacity”, “thermal losses”, “storage efficiency”, and many other terms vary significantly from an author to another (e.g. temperatures are not disclosed).

- Therefore, in the scope of Task 6.3 of the Sfera-III project some KPIs are introduced.

  The proposed KPIs are TES system specific and do apply to the full plant.
    - Technical (e.g. storage capacity, storage efficiency, thermal losses)
    - Not economic (e.g. investment costs, LCOE/LCOH, plant efficiency)
    - Not environmental (e.g. primary energy consumption, CO_2 mitigation)



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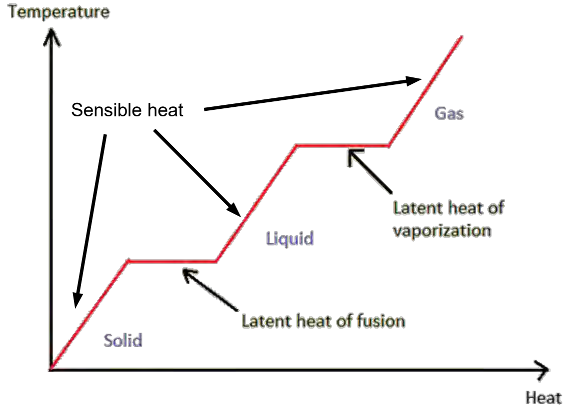
Classification: TES mode

- sensible heat storage,

  Sensible heat storage systems achieve storage by raising the temperature of a medium; therefore, the sensible storage materials undergo no change in phase over the temperature range of the storage process. Sensible heat storage in a material depends strongly on its heat capacity.

$$q = Q/m = \int_{T_{initial}}^{T_{final}} Cp(T)\, dT$$



q: stored specific energy
Q: stored energy
m: mass
Cp(T): temperature dependent specific heat

- latent heat storage, and

  The latent heat storage systems use materials that change phase at a temperature that falls within the upper and lower limit of the solar field. Thus, exploiting the latent heat, or enthalpy, associated with phase transition.

$$q = Q/m = \int_{T_{initial}}^{T_{pc}} Cp_{p1}(T)\, dT + h_{pc} + \int_{T_{pc}}^{T_{final}} Cp_{p2}(T)\, dT$$

T_{pc}: phase change temperature
$p1$, $p2$: phases
h_{pc}: specific phase change enthalpy

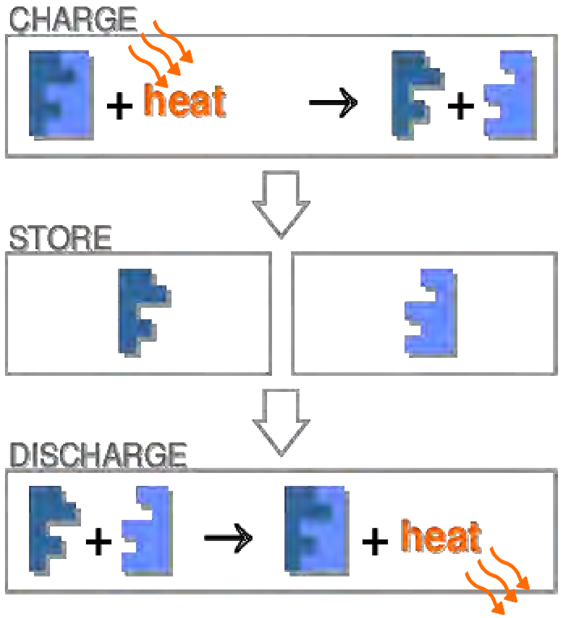
Classification: TES mode

- thermochemical energy storage.

The thermochemical storage systems rely on heat from the solar field to drive reversible chemical reactions, thus the storage medium shall have the ability to completely dissociate in the temperature range of the solar field. In this storage concept, the reaction in the forward direction is endothermic while the reverse reaction is exothermic.

$$q = Q/m = a_r \cdot \Delta h$$

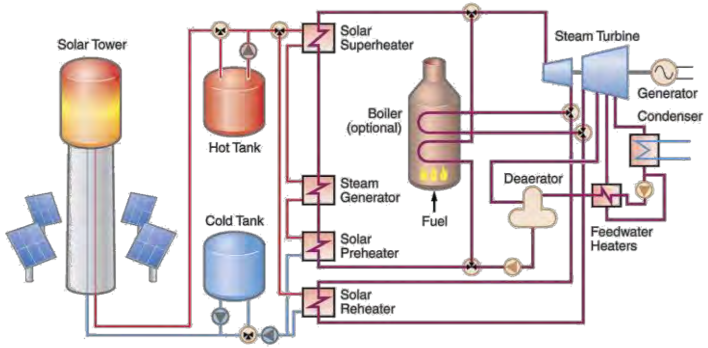
a_r: fraction reacted
Δh: specific heat of reaction



Classification: TES configuration

- direct thermal storage

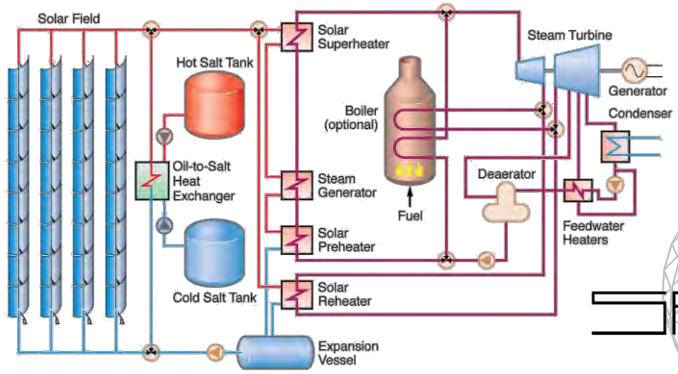
  The heat transfer fluid circulating through the solar field and other plant systems is also used as the storage medium.



direct-active system

- indirect thermal storage

  when the storage medium is different from the heat transfer fluid circulating through the solar field and other plant systems.



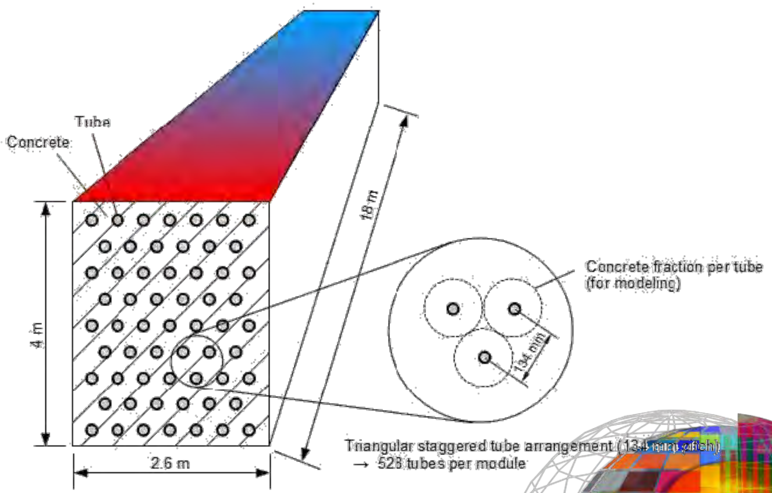
Classification: HSM circulation mode

- active systems

  When the storage medium is a fluid and is able to flow between the tanks, the systems are referred to as active type systems. If the storage medium is also used as the heat transfer fluid, the system is referred to as direct-active system. An additional heat exchanger is needed when the storage fluid and heat transfer fluid are different, and the unit is referred to as indirect-active type.

- passive systems

  when the storage medium does not circulate. Passive storage systems may utilize solids such as rocks, sand or concrete for sensible heat storage materials, or phase change materials for storing thermal energy.



Definitions

Theoretical storage capacity: the maximum amount of energy that can be accumulated by the storage medium from the thermodynamic point of view. It is an ideal parameter, and no heat loss or stratification is included.

$$SC_{theoretical} = \sum_{\substack{storage \\ materials}} \left(m_{c,r} \cdot h_{c,r} - m_{d,r} \cdot h_{d,r}\right)$$

$m_{c,r}$: charged mass (rated)
$h_{c,r}$: charged mass enthalpy (rated)
$m_{d,r}$: discharged mass (rated)
$m_{d,r}$: discharged mass enthalpy (rated)

In principle, it is aimed to consider the values from the primary and secondary fluids.

- In this case, the masses and the both enthalpies are calculated on the storage materials.
- The authors should clearly state what materials are considered as storage materials in the calculation of theoretical storage capacity: HTF, storage fluid (HSM), filler (HSM), walls, baskets, integrated heat exchangers, thermal insulation…

It is recommended to take into account walls and all internal structures of the storage tank.
Some exceptions can be considered, depending on the heat share (<5%):

- Thermal insulation, or
- Sensible heat in latent storage mode.

Definitions

Charge process: Process during which the energy is transferred or supplied to the storage system by the HTF. Depending on the initial conditions considered, the process is:

- **Full charge:** it's a process in which the HTF enters the TES tank by the high temperature inlet at the **rated inlet conditions** (mass flow rate and enthalpy), starting in a **fully discharged state** and ending in a **fully charged state** (these 3 conditions are mandatory).
- **Partial charge:** it's a process in which the HTF enters the TES tank by the high temperature inlet without fulfilling the 3 mandatory conditions.

e.g. in sensible heat storage the end of the charge can be defined by a temperature setpoint on the charge outlet; in latent heat storage the outlet specific enthalpy may be constant while a *steady-state end of charge* is not yet reached, because phase change may still be in progress (fusion at constant temperature).

Discharge process: Process during which the energy is transferred or supplied by the storage system to secondary the HTF. The full discharge mandatory conditions are the same adapted to the discharge process.

Full Cycle: is considered when a full charge and a full discharge are performed consecutively following its definitions.

Storage level: Ratio of the useful thermal energy that can be supplied by the thermal storage system from its current state until full discharge and the rated storage capacity.

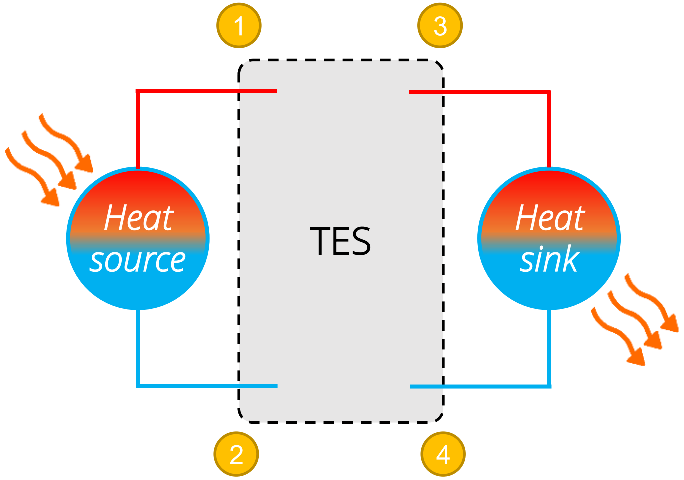
Definitions

Inlet temperature in charge: Measurement of temperature at the top (or high temperature) flow boundary. In rated conditions, it is the maximum inlet temperature for the TES (depending on the considered condition).

Outlet temperature in charge: Measurement of temperature at the bottom (or low temperature) flow boundary. In rated conditions, its setpoint represents the maximum outlet temperature for the TES (depending on the considered condition).

Inlet temperature in discharge: Measurement of temperature at the bottom (or low temperature) flow boundary. In rated conditions, it is the minimum inlet temperature for the TES (depending on the considered condition). In many systems it's the outlet boundary during charge.

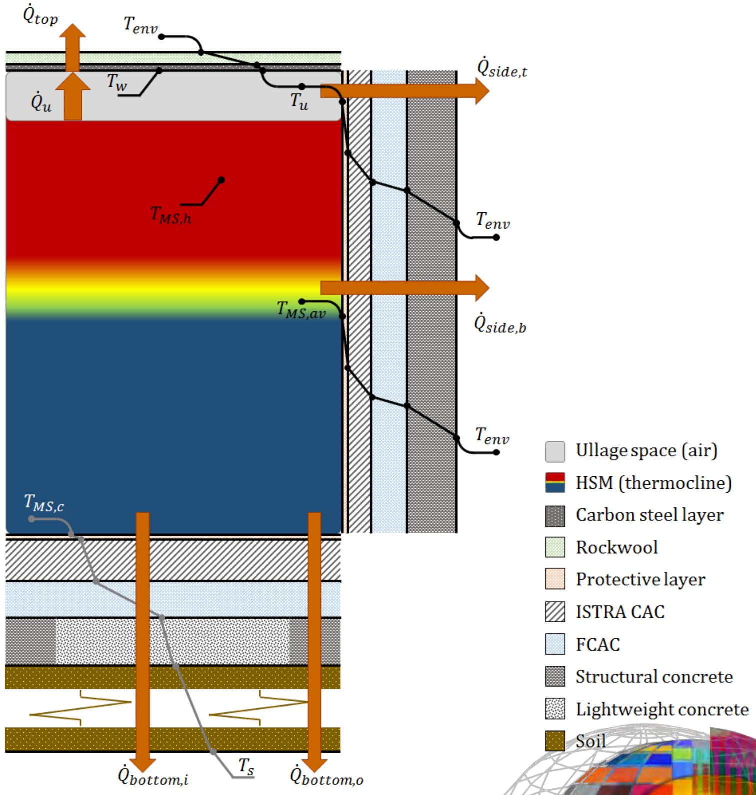
Outlet temperature in discharge: Measurement of temperature at the top (or high temperature) flow boundary. In rated conditions, its setpoint represents the minimum acceptable outlet temperature for the TES (depending on the considered condition). In many systems it's the inlet boundary during charge.



In operating conditions, the operator can define different values within the rated conditions and according to the operating strategy.

Key Performance Indicators

- Storage Capacity
- Utilization rate
- Discharging time
- Thermal losses
- Storage efficiency
- Storage exergy efficiency
- Auxiliary power consumption



KPI: Storage Capacity

$$SC_{rated} = \int_{t_0}^{t_1} \left(\dot{m}_{out,r} \cdot h_{out,r} - \dot{m}_{in,r} \cdot h_{in,r}\right) dt$$

Storage Capacity (SC) is the amount of energy provided by the TES during a discharge process. When rated conditions are used the rated storage capacity is found (SC_{rated})

t_0: discharge initial conditions time
t_1: full discharge conditions time
$\dot{m}_{out,r}$: discharge output mass flow rate (rated)
$h_{out,r}$: discharge output specific enthalpy (rated)
$\dot{m}_{in,r}$: discharge input mass flow rate (rated)
$h_{in,r}$: discharge input specific enthalpy (rated)

Due to the dependency on the effective mass flow rate, the SC can only be known **after** the discharge occurs.
Rated SC implies a discharge rated mass flow rate which is known from design.
SC can also be calculated for the charge process (SC_{ch}), considering the difference between the inlet and the outlet instead.

KPI: Utilization Rate

$$UR_{rated} = \frac{SC_{rated}}{SC_{theoretical}} = \frac{\int_{t_0}^{t_1} \left(\dot{m}_{out,r} \cdot h_{out,r} - \dot{m}_{in,r} \cdot h_{in,r} \right) dt}{\sum_{\substack{storage \\ materials}} \left(m_{c,r} \cdot h_{c,r} - m_{d,r} \cdot h_{d,r} \right)}$$

$Sc_{theoretical}$ is calculated inside the tank

Utilization Rate is the ratio between the Storage Capacity (SC) and the theoretical SC ($SC_{theoretical}$). A particular KPI is found when rated Storage Capacity (SC_{rated}) is used, thus finding the rated UR (UR_{rated}).

$\dot{m}_{out,r}$: discharge output mass flow rate
$h_{out,r}$: discharge output specific enthalpy
$\dot{m}_{in,r}$: discharge input mass flow rate
$h_{in,r}$: discharge input specific enthalpy

$m_{c,r}$: charged mass (rated)
$h_{c,r}$: charged mass enthalpy (rated)
$m_{d,r}$: discharged mass (rated)
$m_{d,r}$: discharged mass enthalpy (rated)

Due to the definitions of both rated and theoretical storage capacities, UR is always lower than 100%.

KPI: Discharging Time

$$DT_{rated} = t_1 - t_0 = \frac{SC_{rated}}{\bar{\dot{Q}}_{d,r}} = \frac{1}{\bar{\dot{Q}}_{d,r}} \cdot \int_{t_0}^{t_1} \left(\dot{m}_{out,r} \cdot h_{out,r} - \dot{m}_{in,r} \cdot h_{in,r}\right) dt$$

Rated discharging time (DT_{rated}) is obtained when full discharge is performed. It is the time taken to discharge the thermal storage system from a higher storage level (t_0) to a lower storage level (t_1) under rated discharge conditions.

$\dot{m}_{out,r}$: mass flow at outlet
$h_{out,r}$: enthalpy at outlet
$\dot{m}_{in,r}$: mass flow at inlet in discharged conditions (and rated)
$h_{in,r}$: enthalpy at inlet
$\bar{\dot{Q}}_{d,r}$: average discharge thermal power

KPI: Thermal losses

Energy balance method

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

$\dot{m} \neq 0$

(dynamic thermal losses)

Isothermal method

$$P_{loss} = \frac{Q_e(t_1) - Q_e(t_0)}{t_1 - t_0}$$

Cool-down method

$$P_{loss} = \sum_{i=1}^{n} \frac{Q_i(t_1) - Q_i(t_0)}{t_1 - t_0} = -\frac{V_i}{t_1 - t_0} \int_{T(t_0)}^{T(t_1)} \rho(\mathrm{T}) \cdot c_p(\mathrm{T})\, dt$$

Temperature measurements inside the storage

Uses partial volumes

$\dot{m} = 0$

(idle or stationary thermal losses)

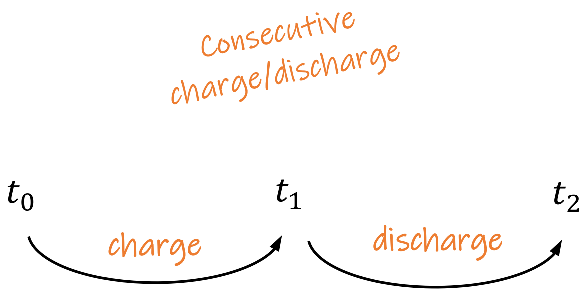
Thermal losses (P_{loss}) of the storage system during the period, from t_0 to t_1.

$Q_e(t_j)$: Electric energy used until instant t_j
$Q_i(t_j)$: Heat in partial volume i in instant t_j
V_i: Partial volume i
$Q_i(t_j)$: Thermal energy of V_i at instant t_j
$\rho(\mathrm{T})$: Temperature dependent density
$c_p(\mathrm{T})$: Temperature dependent specific heat

Thermal losses can hardly be extrapolated from small to large systems

KPI: Storage efficiency

$$\eta_{TES,rated} = \frac{SC_{rated}}{SC_{ch,rated}} = \frac{\int_{t_1}^{t_2} \left(\dot{m}_{out,r} \cdot h_{out,r} - \dot{m}_{in,r} \cdot h_{in,r}\right)_{discharge} dt}{\int_{t_0}^{t_1} \left(\dot{m}_{out,r} \cdot h_{out,r} - \dot{m}_{in,r} \cdot h_{in,r}\right)_{charge} dt}$$



Storage efficiency (η_{TES}) is the ratio between the storage capacity during both the discharge process (SC) and the charge process (SC_{ch}). When rated conditions are used, i.e. full charge and full discharge, rated storage efficiency ($\eta_{TES,rated}$) is obtained.

t_0: full discharge conditions
t_1: full charge conditions
t_2: full discharge conditions
$\dot{m}_{out,r}$: discharge output mass flow rate (rated)
$h_{out,r}$: discharge output specific enthalpy (rated)
$\dot{m}_{in,r}$: discharge input mass flow rate (rated)
$h_{in,r}$: discharge input specific enthalpy (rated)

This is a 1st law of thermodynamics approach. Energy quality (exergy) degradation is not considered.

KPI: Storage exergy efficiency

$$\eta_{ex} = \frac{\int_2^1 \left(1 - \frac{T_0}{T_{out}}\right)_{discharge} dQ}{\int_1^2 \left(1 - \frac{T_0}{T_{in}}\right)_{charge} dQ}$$

Storage exergy efficiency (η_{ex}) is the ratio between the exergy gained by the HTF from the storage (discharge) during discharge and the energy delivered to it by the HTF during charge.

0: dead state
1: discharged state
2: charged state
T_{out}: discharge output temperature
T_{in}: charge input temperature

Several simplifying assumptions are made here, including: constant temperature surroundings (T0), constant storage volume, negligible work interactions (e.g., pump work); and negligible chemical, kinetic, and potential energy.
This “black-box” approach **does not allow to determine the source of exergy loss** in the system (destratification, convection, thermal losses,…). It includes not only destratification issues due to axial thermal diffusion in thermocline tank and regenerators, but also other irreversible phenomena that may occur in TES systems, such as convection between storage fluid and internal solid material (fillers, heat exchangers…), and exergy losses towards the ambient.

KPI: Auxiliary power demand

$$\dot{Q}_{aux} = \frac{1}{t_1 - t_0} \sum_{\substack{Auxiliary\\ devices}} [Q_e(t_1) - Q_e(t_0)]$$

Auxiliary power demand (Q_{aux}) is the sum of the electrical power consumption of the auxiliary devices needed to operate the TES system (pumps, fans, compressors, heat tracing of tanks and pipes, heater for antifreezing, mixer…).

t_0: initial conditions time
t_1: end conditions time
$Q_e(t_j)$: Electric energy used until instant t_j

THANK YOU FOR YOUR ATTENTION!
ANY QUESTIONS?