Definitions of technical parameters for thermal energy storage (TES)

Annex 30

May 2018

Dr. Joaquim Romaní

Jaume Gasia

Prof. Dr. Luisa F. Cabeza

Table of contents

1. Introduction

IEA-ECES Annex 30 is committed to developing a methodology for the characterization and evaluation of thermal energy storage (TES) systems. Therefore, the main goal of IEA-ECES Annex 30 is to determine the suitability of a TES system in a final application, either from the retrofit approach (modification of existing processes) or the greenfield approach (modification of new processes). However, TES involve three main technologies (sensible, latent, and chemical and sorption), each with different layouts and working principles. Hence, the comparison of processes coupled to TES systems is complex due to the lack of standardization and the large number of relevant parameters that are regularly used and found in the literature. Within subtask 2 of IEA-ECES Annex 30, this document presents a set of definitions for technical parameters as an attempt to decide on a reference calculation or evaluation method for a proper cross-comparison of the three different TES technologies.

2. Proposed technical parameters

2.1. Nominal power ($P_{nom.sys}$)

Definition: The nominal power of a TES system is the design thermal power of the discharge. If relevant for the TES system, the nominal power of the charge can be indicated next to the discharge value, clearly stating which belong to charge and which to discharge. Note that nominal power for discharge is required for minimum cycle length calculation.

Presentation: The nominal power should be presented as follows:

$\mathbf{P_{nom.sys}} = X$
$\mathbf{P_{nom.sys.charge}} = Y$
where X and Y are the corresponding values for the discharge and charge, respectively.

Units: Power, [W].

2.2. Response time ($ReTi_{sys}$)

Definition: The response time ($ReTi_{sys}$) is the interval of time between the moments in which the discharge request is issued and the moment the TES system reaches the nominal power ($P_{nom.sys}$) (Figure 1). Unless otherwise stated, $ReTi_{sys}$ regards discharging.

Alternatively:

- The response time ($ReTi_{sys}$) is the interval of time between the moments in which the discharge request is issued and the moment the TES system reaches the required output value of the critical parameter.
- The $ReTi_{sys}$ can additionally be given relating to nominal power during charging.

Presentation: The response time should be presented as follows:

$ReTi_{sys}$ = X
$ReTi_{sys.charge}$ = Y

Units: Time, [s] / [min] / [h] / [d].

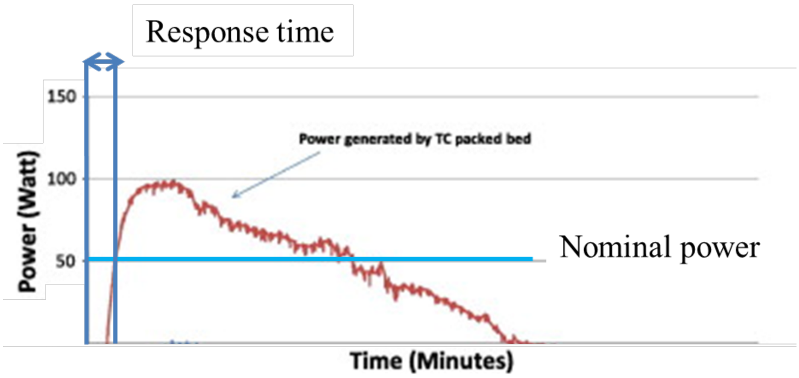

Figure 1. Example of the $ReTi_{sys}$ in a real system.

2.3. Efficiency ($\varepsilon_{sys.xt}$)

Definition: The efficiency of the TES system ($\varepsilon_{sys.xt}$) is the ratio between the heat released to the heat sink(s) during discharging ($Q_{sys.discharge}$) and the energy absorbed by the system during charging as shown in Eq. 1. This last parameter considers the heat delivered by the heat source(s) to the system in charging ($Q_{sys.charge}$) and heat from the system components ($Q_{sys.aux}$). This last parameter only includes the heat intentionally generated by the components (i.e. electrical heaters, Peltier cell, etc.) not any heat generated indirectly by the operation of other components (joule effect on electric cables, friction of moving parts, etc.).

$$\varepsilon_{sys.xt} = \frac{|Q_{sys.discharge}|}{|Q_{sys.charge}| + |Q_{sys.aux}|} \qquad \text{Eq. 1}$$

where:

- $Q_{sys.discharge}$: Heat delivered to the heat sink(s) during discharging [J] or [kWh].
- $Q_{sys.charge}$: Heat absorbed from the heat source(s) during charging [J] or [kWh].
- $Q_{sys.aux}$: Heat from the system components [J] or [kWh].
- $\varepsilon_{sys.xt}$: System storage efficiency at a certain time period *x*, indicate units according to type of TES [%]:
    - Short term → hours [h]
    - Mid-term → days [d]
    - Long term → month [m]

The efficiency must not be calculated for the first charging-discharging cycle of the TES system (during commissioning). This is because at the beginning, the system undergoes a homogenization process that might affect the storage capacity. Therefore, the efficiency must only be calculated for nominal operating conditions.

Presentation: The efficiency must refer to the storage period between the charge and the discharge as follows:

$\boldsymbol{\varepsilon_{sys.xt} = Y}$

where *Y* is the value obtained from Eq.1, x is the storage period between the charge and the discharge, and '*t*' is the corresponding unit of time.

This parameter basically denotes the suitability of the insulation of the TES system, the waiting period between the charging and discharging processes, and to a lesser extent, the heat transfer rates during the discharging process.

Units: non-dimensional parameter.

2.4. Auxiliary energy ratio (Aux$_{sys}$)

Definition: The auxiliary energy ratio (Aux$_{sys}$) expresses the ratio between the amount of auxiliary energy that is consumed during both charging and discharging and the amount of thermal energy released during discharging as shown in Eq. 2. The auxiliary energy (E$_{aux}$) is considered to be all the energy consumed by the components of the system that is not provided by the heat sources (i.e. electricity, gas, fuel, ...). The auxiliary energy consumed by the system must be accounted for in all the phases of the cycle: standby, charge, storage, discharge.

$$\mathbf{Aux_{sys}} = \frac{\sum \boldsymbol{E_{aux.sys}}}{|\boldsymbol{Q_{sys.discharge}}|} \qquad \text{Eq. 2}$$

where:

- $Q_{sys.discharge}$: Heat delivered during discharging [J_{th}] or [kWh_{th}].
- E_{aux}: Energy consumed by all the components of the system during the standby, charging, storage and discharging phases (full cycle of the TES system) [J].
- Aux_{sys}: Performance ratio [$J \cdot J_{th}^{-1}$] or [$kWh \cdot kWh_{th}^{-1}$].

Presentation: The auxiliary energy ratio should be accompanied by the share of each type of E$_{aux.sys}$, presenting the results as follows:

Aux$_{sys}$ = *X*

where *X* is the value obtained from Eq. 2.

Units: non-dimensional parameter.

2.5. Energy storage capacity (ESC$_{sys}$)

Definition: The energy storage capacity of the system (ESC$_{sys}$) calculates the total amount of heat that can be absorbed during charging under nominal conditions. The energy is mainly stored in the material; however, some set-ups may contain components in contact with the material, which inevitably heat up, hence storing sensible heat. Therefore, the ESC$_{sys}$ takes into account the heat stored in the material and the heat stored in the components of the system.

While the components store heat, it is also true that the temperatures of the components in contact with the TES material might be difficult to determine, or might present temperature gradients. The key point for taking into account the storage capacity of a component is that its heat can be recovered and delivered during discharging. Therefore, the guidelines for determining which components must be taken into account are presented below:

- In case of TES in which the reaction pair is stored at ambient temperatures, such as long-term chemical and sorption TES, the components do not contribute to the energy storage capacity of the system.
- In all other cases:
    - If the material is not always stored in the same vessel, but moved from one vessel to another during charging/discharging, the components do not contribute to the energy storage capacity of the system (i.e. two tank molten salt storage).
    - If the material is always kept in the same vessel:
        - Consider components in direct contact, partially or totally immersed in the material.
        - Consider if the heat stored in the components can be recovered during discharging.
        - Consider if the temperature of the component might be at the same temperature of the material during storage intervals.
        - Disregard components placed between the material and the environment (i.e. vessel).
        - Consider components placed between the material and the heat transfer fluid for discharging (i.e. immersed heat exchangers).
        - Consider components completely immersed in the material despite not being directly in contact with it.

Once the list of components to take into account is ready, the ESC_{sys} is calculated with the following equation, which depends on the type of TES technology as it is explained below.

$$\boldsymbol{ESC_{sys} = ESC_{mat} + ESC_{comp}} \qquad \text{Eq. 3}$$

where:

- $\mathrm{ESC_{sys}}$: System energy storage capacity [J] or [kWh]
- $\mathrm{ESC_{mat}}$: Storage material energy storage capacity [J] or [kWh]
- $\mathrm{ESC_{sys}}$: Sum of components energy storage capacity [J] or [kWh]

The storage material energy storage capacity ($\mathrm{ESC_{mat}}$) is calculated according to the type of TES technology:

i. <u>$\mathrm{ESC_{mat}}$ for sensible heat TES</u>

$$\boldsymbol{ESC_{mat.sens} = m_{mat} \cdot c_{p.mat} \cdot \Delta T_{sys}} \qquad \text{Eq. 4}$$

where:

- $c_{\mathrm{p.mat}}$: Specific heat of the material [J·kg^{-1}·K^{-1}].
- M_{material}: mass of the storage material [kg].
- ΔTsys: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

ii. <u>$\mathrm{ESC_{mat}}$ for latent heat TES</u>

$$\boldsymbol{ESC_{mat.lat} = \left(c_{p.mat.s} \cdot \Delta T_s + \Delta H_{pc} + c_{p.mat.l} \cdot \Delta T_l\right) \cdot m_{mat}} \qquad \text{Eq. 5}$$

where:

- $c_{\mathrm{p.mat.s}}$: Specific heat of the material in solid phase [J·kg^{-1}·K^{-1}].
- ΔT_{s}: Temperature difference of the material in the solid phase [K]. Difference measured between the minimum design temperature of the system and the minimum temperature of the phase change range.
- ΔH_{pc}: Enthalpy of phase change [J·kg^{-1}]
- $c_{\mathrm{p.mat.l}}$: Specific heat of the material in liquid phase [J·kg^{-1}·K^{-1}].
- ΔT_{s}: Temperature difference of the material in the solid phase [K]. Difference measured between the maximum design temperature of the system and the maximum temperature of the phase change range.
- m_{material}: mass of the material [kg].

iii. <u>$\mathrm{ESC_{mat}}$ for TES based on sorption and chemical reactions (thermochemical)</u>

The energy storage capacity of TCM materials can be either calculated for short term storage systems according to Eq. 6, or without considering the sensible heat energy storage for long term storages kept at ambient temperature according to Eq. 7.

$$\boldsymbol{ESC_{mat.TCM}} = \left(\frac{\left|\Delta \boldsymbol{H^{0}_{n\rightarrow m}}\right| \cdot (\boldsymbol{n}-\boldsymbol{m})}{\boldsymbol{M_n}} \cdot (\boldsymbol{1}-\boldsymbol{w}) + \boldsymbol{c_{p.mat}} \cdot \Delta \boldsymbol{T_{sys}}\right) \cdot \boldsymbol{m_{mat}} \qquad \text{Eq. 6}$$

$$\boldsymbol{ESC_{mat.TCM}} = \frac{\left|\Delta \boldsymbol{H^{0}_{n\rightarrow m}}\right| \cdot (\boldsymbol{n}-\boldsymbol{m})}{\boldsymbol{M_n}} \cdot (\boldsymbol{1}-\boldsymbol{w}) \cdot \boldsymbol{m_{mat}} \qquad \text{Eq. 7}$$

where:

- $|\Delta H^{0}_{n\rightarrow m}|$: reaction enthalpy [J·mol^{-1}]
- n: Hydration state of the highest hydrate.
- m: Hydration state of the lower hydrate.
- M_n: Molar mass of the highest hydrate [kg·mol^{-1}]
- $m_{material}$: mass of the material in the highest hydrate state [kg].
- w: Mass fraction of additives or matrixes.
- $c_{p.mat}$: Specific heat of the material. An average value may be necessary [J·kg^{-1}·K^{-1}]. Consider the additives or matrixes in the material.
- ΔT_{sys}: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

On the other hand, the storage capacity of the components (ESC_{comp}) is calculated as follows:

$$\boldsymbol{ESC_{comp}} = \sum\nolimits_{\boldsymbol{1}}^{\boldsymbol{n}} \left(\boldsymbol{c_{p.comp.i}} \cdot \boldsymbol{m_{comp.i}}\right) \cdot \Delta \boldsymbol{T_{sys}} \qquad \text{Eq. 7}$$

where:

- $c_{p.comp}$: Specific heat of the component [J·kg^{-1}·K^{-1}]. An average value of the c_p of the component is taken into account, considering the value of the main material of the component, if it is composed of different parts.
- m_{comp}: mass of the component [kg].
- ΔTsys: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

Presentation: The system energy storage capacity should be presented as follows:

$\mathbf{ESC_{sys}}$ = *X*

where *X* is the corresponding value according to Eq. 7.

Units: Energy, [J] or [kWh].

2.6. Minimum cycle length ($\mathbf{MinCy_{sys}}$)

Definition: The minimum cycle length measures the shortest period of time required for completely charging and discharging the system at nominal conditions. It does not consider any storage or standby time. It gives information about the purpose of the storage system in terms of the length of the storage cycles (short term or long term).

The charging and discharging time can either be calculated considering the energy storage capacity of the system (ESC_{sys}) and the nominal power as shown in Eq. 8, or as a sum of the two cycle times, depending on the known quantities, see Eq. 9.:

$$\boldsymbol{MinCy_{sys}} = \frac{\boldsymbol{ESC_{sys}}}{\boldsymbol{P_{nom.sys.charge}}} + \frac{\boldsymbol{ESC_{sys}}}{\boldsymbol{P_{nom.sys}}} \qquad \text{Eq. 8}$$

$$\boldsymbol{MinCy_{sys}} = \boldsymbol{t_{charge}} + \boldsymbol{t_{discharge}} \qquad \text{Eq. 9}$$

where:

- $MinCy_{sys}$: Minimum cycle length [s] / [h] / [d].
- ESC_{sys}: System energy storage capacity [J] or [Wh].
- $P_{nom.sys.charge}$: Nominal power for charging [W].
- $P_{nom.sys}$: Nominal power for discharging [W].
- t_{charge} and $t_{discharge}$: time of charging or discharging cycle [t]

Presentation: The response time should be presented as follows:

$\mathbf{MinCy_{sys}}$ = *X*

where *X* is the corresponding value.

Units: Time, [s] / [min] / [h] / [d].

2.7. Partial load suitability ($\mathbf{PL_{sys}}$)

Definition: The partial load suitability (PL_{sys}) is a qualitative indicator that denotes the suitability of a TES system to work under partial load operating conditions. This refers to the fact that an on-going charge or discharge can be interrupted, and either to continue it later on or to switch it to the other process after a period of time.

In order to evaluate the partial load suitability, the following statements have to be checked:

i. Charging/discharging can be stopped at any point before charging/discharging are completed without negatively impacting the system.
ii. The system can switch from charging to discharging at any charging state.
iii. The system can *swiftly* switch from charging to discharging at any charging state.
iv. The system can be stably maintained in a state between the charge and the discharge states.

Depending on the number of statements the system fulfils, it is classified as follows:

- Not suitable: the system fulfils one or zero statements.
- Partially suitable: the system fulfils two or three statements.
- Suitable: the system fulfils all four statements.