

Hybridized Thermal Energy Storage Pilot Plant

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Abstract. An innovative hybridized Thermal Energy Storage (TES) technologies pilot plant at the Iberian Research Centre for Energy Storage Research (CIIAE) in Cáceres (Spain) has been designed by RPow in 2024 and will be built in 2025. The project design enables both individual and simultaneous research about charge-discharge operations based on Molten Salts (MS), Phase Change Materials (PCM) and Sorption. The plant design configuration allows in turn testing with different heat transfer fluids (HTF, initially Helisol5A) and thermoregulating fluids (nano-capsules or micro-capsules). Researching object belong to prototyping (TRL's 4-5) and demonstration (TRL's 6-7). Moreover, the early research carried out about desired functionalities during the engineering definition has made it possible a TES management identification, searching for a thermal integration between the different technologies. This strategy has provided an increased overall efficiency during the expected researching tests along the plant lifetime and the future exploration of real applications and synergies between the TES systems at different temperature stages from 30 – 565 °C.

Keywords: TES Hybridization, Macro-Encapsulated PCMs, Ultra-High Temperature MS, Moving-Bed Sorption Reactor, Endless Screw Sorption Reactor, HELISOL[®] 5A, MS-Air Heat Exchanger.

1. Context

The transformation of the global energy system is requiring rapid uptake of renewables throughout all kinds of energy use [1]. TES technologies can help to integrate high shares of renewables as PV and CSP, not only in power generation but also in industry and buildings energy demand. Furthermore, Net Zero decarbonization targets by 2050 [2] brings the opportunity to TES systems integration within Power to Heat (PtH) solutions, removing or reducing heat demand where a fuel is combusted.

At the end of 2023, RPow was awarded with the EPC contract in joint venture with Contratos Y Diseños Industriales (CYD) for this pilot plant design, supply, installation and commissioning. Previously and during more than one year in 2022-23, the project was conceptually shaped and defined by means of a *Competitive Dialogue* process in collaboration between these entities. The plant definition has implied not only the engineering design for the facilities for the different storage modules and the integration with the HTF recirculation system, but also the research and development efforts for the novel equipment designs (Chapter 3).

2. Pilot plant

The Pilot Plant consists of a Heat Transfer Fluid (HTF) common recirculation system, which is the core of the plant design concept, interconnected with the three TES modules: MS, Sorption and PCM. In addition, Solids energy storage module is contemplated within the pilot plant design but is not part of scope in the first stage of the equipment design and supply, and is intended to be future research developments. Besides that, the configuration allows the testing of different heat transfer fluids (initially Helisol5A) and thermoregulating fluids (nanocapsules or microcapsules), having the functionality of increasing temperature of the HTF system up to 410 °C.

The plant design aims to be the final step in scaling up the basic research carried out at the CIIAE and in other centres in this TES researching area. This would allow any researcher to test and verify their own developments at a pre-commercial level. Demonstrate prototypes of materials that are in a lower TRL, such as phase change materials (PCMs) or adsorption materials, in a relevant scale environment. Furthermore, to study the feasibility of using different types of thermal energy storage materials at specific temperatures for use in process heat in different industries. In parallel, the plant makes possible to study the performance and features (thermal conductivity, chemical stability, etc.) of these materials after a considerable number of thermal cycles. Two of the objectives are specifically relevant, as described in the following subchapters: thermal integration between the different TES technologies and the simultaneous testing of several thermal storage modules.

Regarding the operation cycles, for the charging are used three electric heaters, to heat and adapt in step the HTF temperature, and one MS electric heater. Regarding the discharge of the modules, two air coolers for the HTF system (up to 425 °C design temperature) and 1 dedicated to the MS cooling (up to 593 °C design temperature). The storage modules are interconnected with the electric heaters, with the air coolers, and with each other through the HTF system, common to all. The HTF system has an expansion tank connected to pumps, from which the HTF is pumped through the circulation system, making possible the charging and discharging operations. The General Basic Scheme is shown in **Figure 1** left and the Process Flow Diagram in **Figure 1** right.

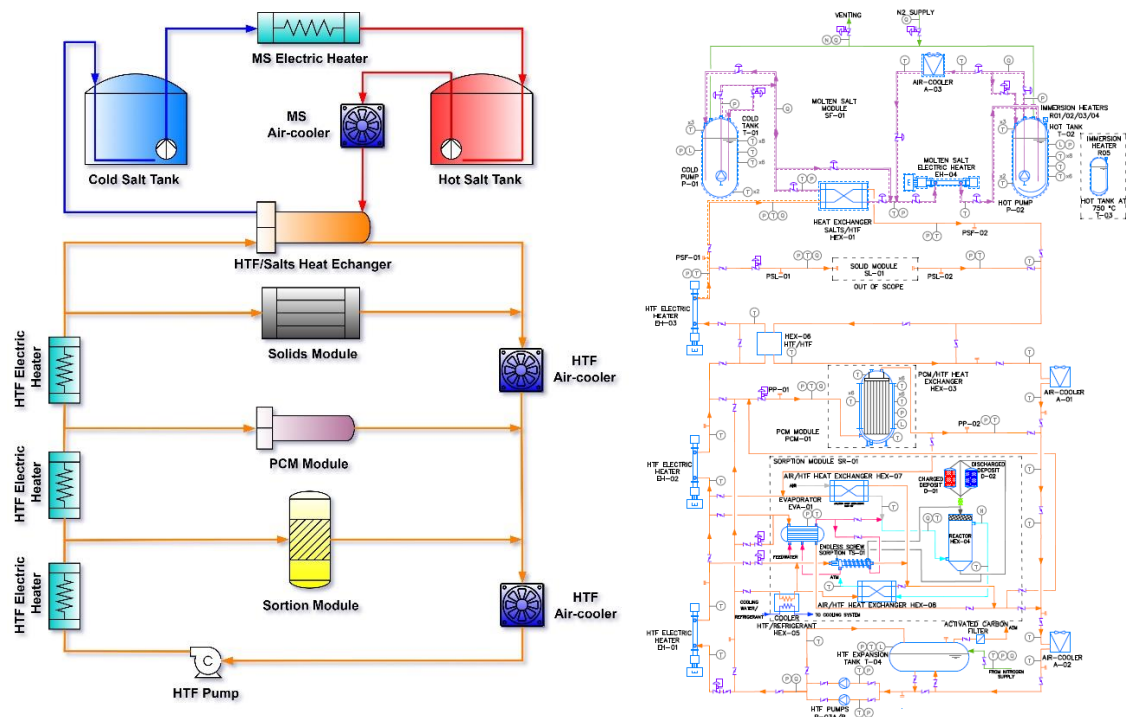


Figure 1. Pilot Plant Basic Scheme (left). Pilot Plant Process Flow Diagram (right).

2.1 TES hybridization

As the project comprises a closed HTF circuit system that drives the heat exchange with the aforementioned TES technologies, the design has prioritized flexibility both for the individual components testing for each module (materials, heat exchangers, electric heaters) and for the charge-discharge operations integration between technologies. The contribution of this project brings the capacity to research in this field across a spectrum of high, medium, and low temperatures. This unique feature opens novel paths for hybridization, storage uses optimization and operational efficiency. The modules have a storage capacity between 0.1 - 1 MWh. Hybridization or integrated design might mean, in this field, several TES technologies (storage modules) in operation aiming to reach these functionalities alone or together as a whole facility:

1. Charging of individual or several energy storage modules at the same time.
2. Discharging of individual or several energy storage modules at the same time.
3. Thermal integration (charging-discharging operations) between energy storage modules (Chapter 2.2).

As regards to 1 and 2 points, two main plant operation modes have been considered: one mode for simultaneous charge of all modules and another mode for simultaneous discharge of all modules, as these modes also cover the individual operation of each of them (excepting Solids Module).

2.2 Thermal storages integration

Searching for a thermal integration between the different technologies, the design strategy has provided an increased overall efficiency and synergies between the TES systems at different temperature levels (low-medium-high). In order to achieve the suitable temperature of each module, different temperature steps coming from the different electric heaters are used alternatively for the charging processes of the modules.

To reduce the energy consumption, the heat transfer fluid will not necessarily be cooled in the air coolers after the module discharge process, so that the heat given by one module during its discharge can be used in the charging of another module. This would represent the thermal energy at different temperature levels to be used in industry applications.

Prepared outlets and inlets in the air coolers, HTF line and molten salt line so that CIAE might modify the plant in the future to take advantage of the heat/cold in other points of the research centre for other storage technologies researching, such as, for example, the pilot plant for H₂ storage and Power to X facilities.

Table 1 identifies the thermal energy integration functionalities of MS, with the materials and fluids selected in this first stage utilization. However, note that the materials and fluids involved in tests researching proposed or selected in next stages and their working temperatures would require a new analysis. These integrations allow the discharge of one module to charge another, either directly or indirectly.

Table 1. Thermal Energy Integration Modes.

Integration Modes	Molten Salts Module	PCM Module	Sorption Module	Solids Module
1	Not operative	Discharge in Sorption module	Charge by PCM module	Not operative
2	Not operative	Charge by Sorption module	Discharge by PCM module	Not operative
3	Discharge in PCM module	Charge by MS module	Not operative	Not operative
4	Discharge in Sorption module	Not operative	Charge by MS module	Not operative
5	Charge by PCM module	Discharge in MS module	Not operative	Not operative

Thermal integrations from 1 to 5 are further described below with HTF temperatures reference for the selected fluids and materials in the first stage, as a reference for the temperature compatibility understanding. In addition, there are also several integration modes in conjunction with the solids module.

2.2.1 Direct thermal energy integration

Direct thermal energy integration modes are those that occur through a line that directly connects the output HTF stream of a module with the input of another module. The thermal integrations 1 and 2, represented in the Figure 2, are direct type.

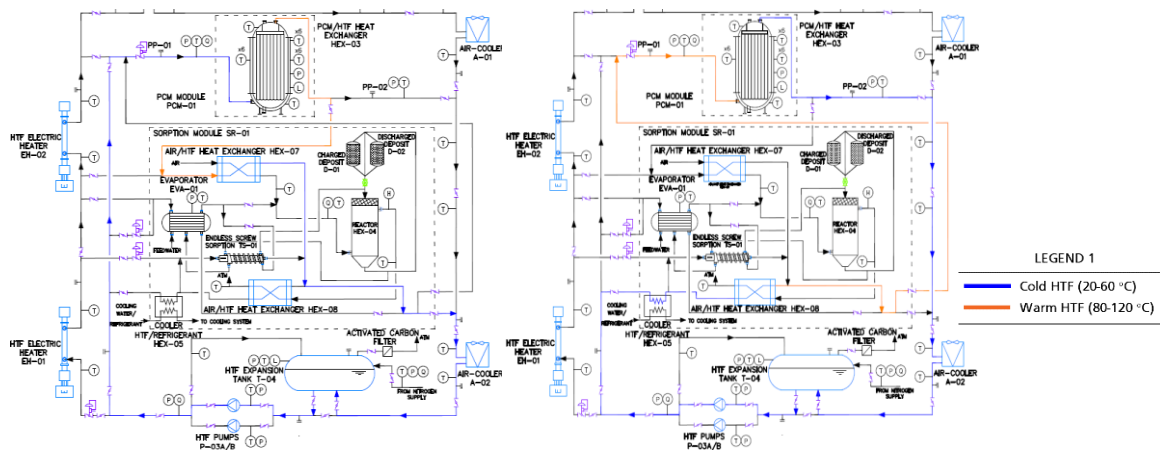


Figure 2. PCM module discharge in sorption module (left). Sorption module discharge in PCM module (right).

2.2.2 Indirect thermal energy integration

Indirect thermal energy integration modes are those that occur when the HTF stream at the output of the module being discharged does not directly enter the module being charged, but rather passes through the general HTF lines of the system to reach the target module to charge. These integrations are carried out through the general HTF line, without the need to implement an additional line for these functionalities. The thermal integrations 3, 4 and 5, represented in the Figure 3, are indirect type.

In integration mode 3, tempered HTF is driven to the PCM and salt module, passing through the heaters, which will be turned off. One of the tempered HTF streams will give up its temperature in PCM mode to charge it and the other stream will pass through the HEX-06 exchanger to increase its temperature (becoming hot HTF) and be able to operate in contact

with the salts. The stream will then flow through the HEX-01 Salt/HTF heat exchanger, thus discharging the salt module and increasing the temperature of the stream, making it very hot HTF. Very hot HTF will be used to preheat the HTF stream going to the salt module by using the HEX-06 exchanger. This stream will then pass through the A-01 air cooler (which will be disabled) and then mix with the HTF stream from the PCM module. This is where thermal integration occurs and allows the HTF to be heated at the output of the PCM module with energy from the salt module. The mixture of these two streams will be at the inlet temperature required for the PCM module charging, avoiding the consumption of heaters (additional electric energy) to increase the temperature of this stream. In short, the discharge of the salt module allows the charging of the PCM module without the heaters consumption.

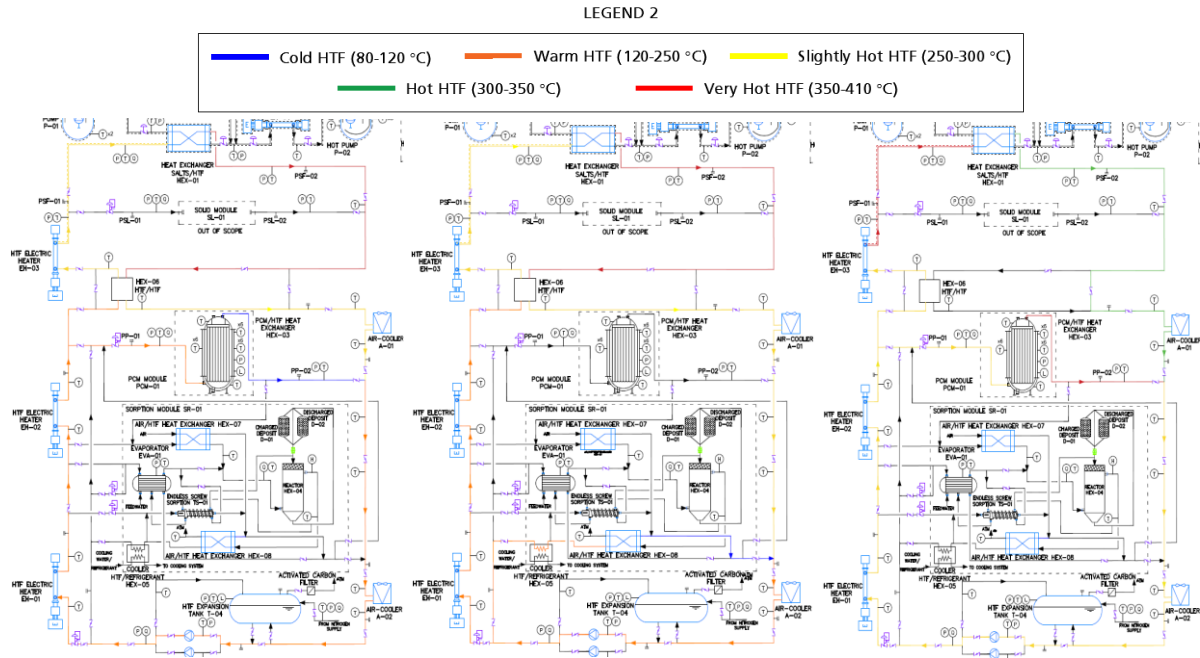


Figure 3. MS module discharge in PCM module (left). MS module discharge in Sorption module (mid). PCM module discharge in MS module (right).

Integration mode 4 is very similar to integration mode 3, but in this case HTF from MS module will be used to charge Sorption module.

Finally, in integration mode 5 the hot HTF stream from the pumps forks into the PCM module and the salt module. The PCM module is being discharged, thus increasing the temperature of the HTF, becoming very hot HTF. The other stream increases its temperature in the EH-03 heater, becoming very hot HTF. Subsequently, this stream charges the salt module, decreasing its temperature and becoming semi-hot HTF (slightly lower temperature than hot HTF). This stream and the very hot HTF stream at the output of the PCM module mix to form a hot stream, which will charge the salt module. In this integration, the consumption of the EH-03 electric heater would be reduced, since the HTF stream would be preheated by the stream coming from the PCM discharge.

2.3 Materials & Fluids

The Pilot Plant is designed to be able to operate in the future with different HTFs and thermal storage materials (see design range below). However, for this first stage the materials and fluids selection, charge-discharge hours, and the storage capacity required by CIIAE is shown in every subchapter.

2.3.1 HTF recirculation system

Designed for operation temperatures between 60 °C – 410 °C and Helisol 5A initially selected. It is a HTF silicone thermal oil developed by Wacker and specially designed for parabolic trough (PT) CSP plants. The composition of this fluid is based on polydimethylsiloxane, also known as PDMS or dimethicone, belonging to the group of organosilicon compounds, i.e. it is an organic polymer based on silicon. Technical data of this fluid can be seen in reference [3].

Thermoregulating fluids (nanocapsules or microcapsules with PCM) are expected to test in future stages. Examples of these fluids are Micronal®DS 5001X or microcapsules containing Rubitherm®RT27.

2.3.2 Molten Salt module

Designed for operation temperatures between 290 °C – 565 °C. Binary molten salts (60% NaNO₃ / 40% KNO₃) selected for a first stage. Storage capacity is 800 kWh, for 4 hours of charge/discharge. Salt properties can be seen in reference [4]. Salts that are expected to be tested in future stages for TES industrial applications should be in the range of minimized operation temperatures and high storing temperatures. Examples of candidate salts to be tested are: Hitec Salt, Carbonate salts, LiNO₃-KNO₃-NaNO₃ mixtures, Fluoride-based salts and Magnesium Chloride-Potassium Chloride, among others [5].

2.3.3 PCM module

Designed for operation temperatures between 60 °C – 410 °C and Rubitherm RT100 selected. Storage capacity is 120 kWh, for 2 hours of charge/discharge.

Rubitherm RT100 is a pure PCM. This heat storage material employs the phase-change processes between solid and liquid (melting and freezing) to store and release large amounts of thermal energy at a relatively constant temperature. RT100 provides a highly effective medium for storing heat and cold, even when limited volumes and low temperature differences are applied. The composition of this material is based on a paraffin wax, which is chemically inert and has a long shelf life. RT100 is a non-toxic, white product that is usually supplied in granulated or powdered form. Rubitherm RT100 can be seen in the product datasheet [6]. Many types of PCM are intended to be tested in the plant, such as palmitic acid and 95.5 KNO₃ / 4.5 KCl mixture, among others.

2.3.4 Sorption module

Designed for temperatures between 30 °C – 300 °C. Silica Gel 3A is initially selected as adsorption material. Storage capacity is 120 kWh, for 2 hours of charge/discharge.

Silica Gel 3A is an amorphous and porous form of silicon dioxide. It is insoluble, non-flammable and non-toxic. Figure 4 shows Silica Gel 3A properties and appearance. Many types of adsorption materials are intended to be tested in the plant, such as SAPO-34, Mg(NO₃)₂·6H₂O and CaCl₂·6H₂O, among others.

Silica Gel Type 3A	
Charging temperature (desorption)	90-140 °C
Discharge temperature (adsorption)	20-50 °C
Apparent density	770 kg/m ³
Specific surface area	606 m ² /g
Pore volume	≥0.45 cm ³ /g
Specific heat	0.921 kJ/kg·K
Isothermic heat of adsorption	2,380 kJ/kg



Figure 4. Silica gel properties (left) and appearance (right). Source: [7] (right) and [8] (left).

3. Design & Test challenges

In addition, remarkable equipment design and operation with alternative applications in other fields has been designed to be tested as secondary object of the project. MS tank design (ASME tank) up to 700 °C is being manufactured by CyD, which stainless steels candidates are 347H, 316H or 316LNB (low carbon, added nitrogen and boron content). CyD contribute with their CSP industry background and their development of Avatar Models for API Tanks and other collaborations in the field of high temperatures MS tanks design and lessons learnt.

MS electric flow heater up to 565 °C outlet bulk temperature. The design, operation (control strategies, start-up times), film temperatures and salt degradation limitations, system scalability and materials lifetime for high temperatures cycling, has become one of the most promising paths in the field of TES and the Power to X range of applications.

MS Air Coolers is designed for cooling purposes in this plant. These kinds of HEX are remarkable for application as hot air production and in general in general MS-Gas heat exchanging (CO₂, etc.). Design and operation of this equipment will bring the necessary lessons learnt for their reliability, safety and scalability. Materials selection, preheating strategy and for high temperatures cycling again will be tested in the pilot plant.

PCM Module reactor-heat exchanger is designed for testing materials up to 410 °C. This heat exchanger has two possible configurations:

- Bulk PCM inside the shell and HTF flowing through the tube bank. See Figure 5 left.
- Macroencapsulated PCM inside the shell and HTF flowing through the shell in direct contact with the PCM. See Figure 5 right.

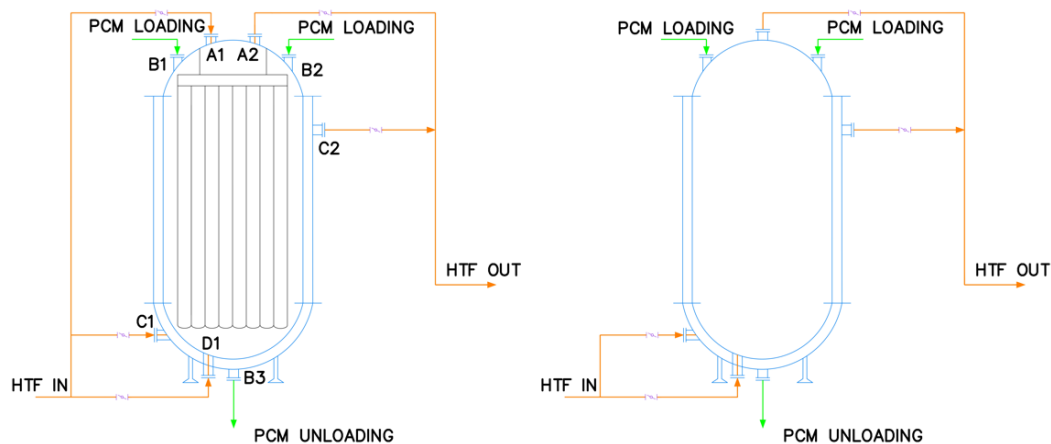


Figure 5. PCM reactor design with bank of tubes (left). PCM reactor design with macroencapsulated PCM (right).

The sorption module is made up of two different reactors (that can be seen in *Figure 1*):

- Cylindrical sorption reactor with vertical arrangement in a moving bed (open forced reactor type). The reaction takes place between air/humid air and adsorbent material. Designed for 60 kW.
- Endless screw type sorption reactor (closed forced reactor type). The reaction takes place between the adsorbent material and steam. It can work in partial vacuum. Designed for 5 kW.

4. Outcomes

The facilities will open new options for researchers to conduct tests and verify their own developments at a pre-commercial level, demonstrate prototypes, investigate the feasibility of using different types of thermal energy storage materials and HTFs, and study the performance of these materials after a significant number of thermal cycles.

An industry that could potentially benefit from integration thermal storage technologies is the chemical sector, which process temperatures are typically around 50 – 1000 °C. In such instances, the hybridization of TES systems across diverse temperature gradients represents a significant opportunity to enhance the efficiency, energy flexibility and grid independence of the industry.

CIIAE aims to become an international reference in energy storage materials and components and systems research, following what has been the pioneering Solar technologies research work development achieved by researchers and companies in Almería Solar Platform (PSA), contributing to solve the technological and scientific challenges that will allow the manageability of green energy production.

Data availability statement

Data can be requested from the authors.

Author contributions

Conceptualization, methodology, project administration and writing – original draft: Rafael Pérez Santana.

Conceptualization, methodology, investigation and writing – review & editing: Adrián Blindu.

Validation and writing – review & editing: Patricia Santamaría Prado.

Supervision and validation: Ángel Martínez Quesada and César Martín-Montalvo Sánchez.

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