Solar PACES Task III
Thermal Storage
Survey on R&D Activities

Actualization date: 03/2026
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CONTENTS BY KIND OF STORAGE

Prepared by Rocío Bayón (CIEMAT-PSA) with the contribution of the following participants in alphabetic order:

Institution	Country	Kind of storage	Last update
CEA-LITEN	France	S, L, T	09/2022
CIEMAT-PSA	Spain	S, L	11/2024
CENER	Spain	S	03/2026
DLR	Germany	S, L, T	03/2026
ENEA	Italy	S, L, T	11/2024
FRA	Germany	S, L	09/2020
ICP-CSIC	Spain	T	09/2020
IEE-CAS	China	S, L	03/2026
IRESEN	Morocco	S, L	09/2020
KTH	Sweden	S, L	10/2023
Masdar Institute/Khalifa Univ.	Emirates	S	09/2021
SIJ	Germany	S	09/2020
SUPSI	Switzerland	S, L	09/2017
TAU	Israel	T	05/2016
TECNALIA	Spain	S	05/2016
TEKNIKER	Spain	S	11/2024
UniSevilla	Spain	L	03/2026
UniZar	Spain	L	05/2016

SENSIBLE HEAT STORAGE

CEA – LITEN (France)

TASK III-TES

Regenerative Storage

Challenges:

- Relatively low storage density,
- Differential dilatation between storage media and envelope=> mechanical stability of design in the case of unstructured solid materials,
- Regenerators are widely used in steel and glass industry, but only a few pilot TES units are tested for CSP applications (in Central Receiver Systems with atmospheric air receivers)

State of the art:

- Regenerators are widely used in steel and glass industry.
- Pilot TES units are currently tested in power towers with atmospheric air receivers.

Concept approach:

Low cost and robust regenerators:

- covering a very large range of temperature levels (particularly interesting for high temperature values),
- using low cost natural materials (rock) or efficient ceramics.

Current R&D status:

- An experimental device (*CLAIRE*) has been built and tested with air as heat transfer fluid:
  - two test sections volumes (1.2 x 1.2 x 5 m) working at temperatures between 600 and 1300 °C
  - Tests have been made with gravels and structured ceramics at 800°C
  - Dynamic thermo-aeraulics models have been developed for sizing purposes.
  - Three dimensional CFD simulations have been validated on experimental results.
- A 250 kWh demonstration unit integrated in a CSP Fresnel power plant demonstrator has been built and tested.
  - Temperature range from 300 °C to 450 °C
  - Horizontal brick regenerator powered by reversible fans,
  - Integrated in a CSP Fresnel power plant demonstrator.

Further information:

Contact persons: Jean François Fourmigué (**jean-francois.fourmigue@cea.fr**) and Pierre García

Publications:

- Desrues, T., Ruer, J., Marty, P., Fourmigué, J.F. A thermal energy storage process for large scale electric applications (2010). Applied Thermal Engineering, 30 (5), pp. 425-432
- Reboussin, Y., Fourmigué, J.F., Marty, Ph., Citti, O. A numerical approach for the study of glass furnace regenerators (2005). Applied Thermal Engineering, 25 (14-15), pp. 2299-2320.
- Esence, T., Bruch, A., Molina, S., Stuttz, B., Fourmigué, J.F., A review on experience feedback and numerical modeling of packed-bed thermal energy storage systems, Solar Energy 153 (2017) 628–654.

Future work:

- Validation of simulations, dynamic 1D models or CFD, has to be improved.

CEA – LITEN (France)

TASK III-TES

Heat storage with dual media thermocline

Challenges:

- NREL at Solar Paces 2010: "Thermocline is uncontrollable and unpredictable", making such system inefficient and unusable;
- Very limited experimental data available in the literature and few dual media thermocline installations built up to now. In addition, most of the experimental data show scattering and was obtained in limited range of operating parameters;
- Construction of a dual media thermocline at commercial CSP plant size. Up to now, only one industrial dual-media thermocline has been built (Solar One solar tower);
- Interaction between storage material and thermal fluid.

State of the art:

- No systematic study of the influence of operating parameters and control strategy.

Concept approach:

Low cost and robust heat storage dual media thermocline characterized by:

- non pressurized thermal oil as thermal fluid;
- no expansive natural rock as storage material;
- additional porosity reduction by using multiple rock sizes;
- possible oil/rock interaction leading to rock and/or oil degradation.

Current R&D status:

- A prototype-scale (*STONE* ≈ 3 m^3) thermocline is successfully operated
  - Highly controllable and predictable operation at different oil velocities,
  - Fine understanding of the hydraulic and thermal behaviors,
  - Compared with results from other experimental facilities (CNRS-PROMES).
- A demonstrator-scale (≈ 30 m^3) thermocline is successfully operated
  - Integrated in a CSP Fresnel power plant prototype,
  - Allows validating the behavior, the control and the performances of a dual thermocline storage unit in real operating conditions.
- Our numerical model shows good agreement with the experimental data and can be used for thermocline size extrapolation with good confidence level, for performance predictions and for the definition of operating strategies of commercial CSP plants.

Further information:

Contact person: Arnaud Bruch (**arnaud.bruch@cea.fr)**

Publications:

- Bruch, A., Fourmigue, J.F., Couturier, R., Experimental and numerical investigation of a pilot-scale thermal oil packed bed thermal storage system for CSP power plant, Solar Energy 105 (2014) 116–125.
- Esence, T., Bayón, R., Bruch, A., Rojas, E.**,** Study of thermocline development inside a dual-media storage tank at the beginning of dynamic processes**,** AIP Conference Proceedings**,** 1850, 080009 (2017).
- Bruch, A., Molina, S., Esence, T., Fourmigué, J.F., Couturier, R.**,** Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system**.** Renewable Energy 103, 277-285 (2017).
- Gibbs, A., Robinson B.W., Rougé, S., Jouhara H, Asaduzzaman, A.K.M., Chowdhury, M., Kjellgren, P., Mezquita Martí, A., Taddei, P, Pardelli, Ciuffi, N., Heat Recovery at High Temperature by Molten Salts for High Temperature Processing Industries, Part 1 & 2, ATI Conference, Florence (2019).

Future work:

- Optimization of thermocline control strategy for efficient integration in a CSP plant.
- Test of different storage material and filling procedures.

CENER (Spain)

TASK III-TES

Thermal Energy Storage Tanks

Challenges:

The self-contained molten salts tank concept (IGLOO concept) addresses 3 main problems identified in conventional salt tank technology from a break-away approach:

- Highly corrosive environment due to high temperature molten salts, which reduces lifetime of materials.
- High thermal stresses due to by thermal cycling, which also reduces the reliability of the technology.
- Size limitation of stainless-steel tanks, limited to 40m in diameter due to these thermal stresses.

The IGLOO concept addresses these points to overcome the limitations of molten salt storage technology that hinder the expansion of thermal storage and, as a result, that of CSP.

State of the art:

The well-known state of the art of salt storage tanks is based on the storage of thermal energy by means of sensible heat from a nitrate molten salt at high temperature. These tanks are normally manufactured using different high alloy stainless-steel. Tank design normally follows the standards set by the standard API 650; this, in addition to the use of metallic materials, gives the technology several advantages:

- Technology available and competitive today.
- High energy storage density (150-250 kWh_{th}/m^3)
- Operating temperature range up to 600 °C
- Reduced capital cost. 20-35 $\$/kWh_{th}$

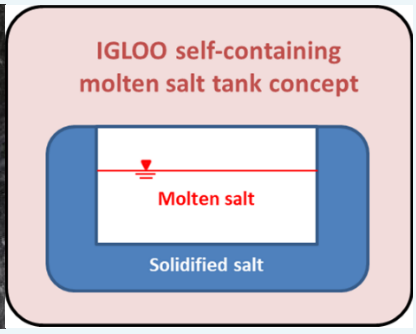
However, this technology faces the 3 challenges mentioned above in order to be fully competitive.

Concept approach:

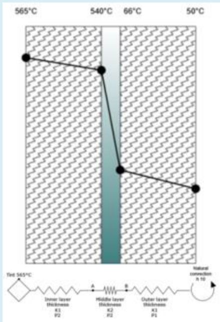
IGLOO focuses on a method of design and construction of molten salt tanks that is innovative and ground breaking, based on the combined knowledge in materials and civil engineering and taking advantage of the self-containing abilities of molten salts by solidified salts.

The main idea, from which this project was born, is the idea of changing the way of thinking in the design of molten salts storage tanks to break with the established design methodology and overcome its limitations. To achieve significant progress beyond state-of-the-art, to reduce costs and to increase technology robustness and reliability it is mandatory to find a material which is inert to the high corrosive environment formed by high temperature salts. The ground-breaking idea of this project is to use the salt in solid state as containing element.

This approach capitalizes on molten salts' excellent thermal properties (low thermal conductivity, high thermal inertia and high melting point) and most importantly completely avoids corrosion problems as the containing material is the same material as energy storage fluid inside the tank. This concept, combined with the know-how used in civil engineering for the construction of water channels or tunnels built by cementitious modular structures, formed by porous prefabricated elements, gabion cells or bricks with dimensions quite higher than typical dimensions of storage tanks previously mentioned, will allow us to overcome the main drawbacks of the technology removing corrosion problems and size limitations, reducing the CAPEX and OPEX of the molten salts storage tanks and minimising the risk of leakages and resulting environmental pollution as well as negative impacts on human health. The concept also harnesses the high melting point (220°C) of the molten salts, which ensures that the salt that is part of the wall, close to the environment with temperature much lower than 220°C and with high latent heat, will remain in a solid state and the molten salt will not flow outside the tank. Besides, very low thermal conductivity of salt mixture in solid phase helps with the thermal insulation of the tanks reducing its thermal losses, although the key in adequate thermal insulation is the use of insulation layers in the tank wall. Like a glass made of ice can contain water a tank made of solid salt can contain molten salts. The main advantage of this concept when comparing water properties and salt properties is the fusion temperature and the enthalpy, while water requires 334 J/Kg and an ambient temperature of 0°C, Solar thermal salts (STS) require 113010 J/Kg and 220 º C taking into account that the ambient temperature on earth is quite below this value, the whole idea is much more robust and stable when applied to molten salts than when applied to ice/water. The following picture shows a small prototype of the concept.

Current R&D status:
To make a first demonstration of the concept, the tank wall has been modelled in a simplified way in both Modelica and ANSYS, proving that at an internal temperature of 550C, the salt in the wall was able not to melt and therefore avoid leaks in the tank. In these models, the wall is assumed to be a porous medium in which salt is contained on the one hand, and inorganic structural material (bricks, gabions or voussoirs) on the other. Next figure shows thermal profile results obtained from Modelica model.



In addition, as can be seen in the image of the small prototype, some experimental tests have also been prepared on a very small scale. These tests allowed to check both the structural integrity of the salt with inorganic elements (stones in this case) as well as the interaction of the solid salt with the molten salt in the filling.

Further information: Contact person:
Marcelino Sánchez (msanchez@cener.com)
Xabier Rández (xrandez@cener.com)

Future work:
After the promising results obtained both from the first simple calculation models and from the small-scale tests, the next step will be the preparation of an experimental system closer to reality, of a few cubic meters, in which the concept can be tested in both stationary and transient modes, allowing the tank to be filled and emptied. During this phase the constructive design of the wall will also be developed as well as the selection of the most optimal materials for this concept.
To this end, CENER is looking for industrial and financial partners to complete the development and validation phase, with the aim of bringing this technology to the market in the short term.

CENER (Spain)

CENER NATIONAL RENEWABLE ENERGY CENTRE

SolarPACES

TASK III-TES

ASTERIx-CAESar: AIR-BASED SOLAR THERMAL ELECTRICITY FOR EFFICIENT RENEWABLE ENERGY INTEGRATION & COMPRESSED AIR ENERGY STORAGE

Challenges:

The rising fraction of non-dispatchable renewable power generation, is dramatically changing the way of power generation. Coming from a centralised system of power production, where mainly large-scale fossil fired or nuclear power plants provide stable and firm supply, we are moving towards a 100% renewable energy system where power is produced in highly decentralised and uncontrolled manner. Thus, a key requirement for the efficient operation of the future energy system is massive energy storage on the one hand, and highly flexible power generation on the other. It is clear that the future's ideal power plant needs to provide "adaptive" power generation, being able to generate power, when required by the grid, and also to store energy efficiently, when electricity demand is low, but renewable energy is available in excess (e.g. from PV, or wind). Therefore, it is mandatory that future CSP plants implement efficient electrical energy storage, in addition to, or in combination with thermal energy storage (TES) in order to stabilize the power grid.

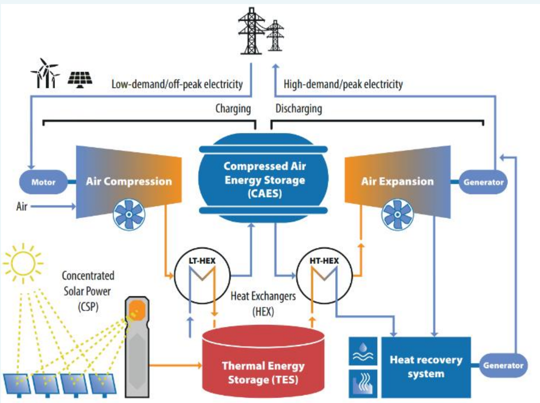
State of the art:

Currently, CSP plants do not include electricity storage. In addition, the operation capability is not flexible enough to respond to the needs of the power grid. Furthermore, the solar-to-electric energy conversion efficiency is low.

Concept approach:

ASTERIX CAESAR

The ASTERIx-CAESar project focuses on the development of a novel high-efficiency solar thermal power plant concept with an integrated electricity storage solution. The project combines air-based central receiver Concentrated Solar Power (CSP) and Compressed Air Energy Storage (CAES) to maximize conversion efficiency and power grid energy management, enabling a new operation strategy and business model. The hybrid concept initiates a futuristic era with adaptive renewable power plants, producing both electrical and thermal energy, including process heat supply and reverse osmosis desalination. The main development will cover: (i) an advanced high-efficiency solar receiver, (ii) optical sensors and AI-based solar flux control, (iii) optimized CAES with heat exchangers and compressor/expander detailed designs and (iv) innovative integration of desalination. The proposed technology is set forth by an interdisciplinary partnership spanning the entire CSP value chain. Targeting a TRL of 6-7, the ASTERIx-CAESar concept will be validated with a demonstration scale prototype of 480 kWth.



Current R&D status:
The ASTERIx-CAESar project is a European funded project with a duration of 4 years. At this moment it has completed its second year. The techno-economic optimization methodology is fully defined. In addition, the project's prototypes are in an advanced state of implementation. The consortium is currently focusing on the turbomachinery design for the commercial scale application.

Further information:
Contact person: Fritz Zaversky (fzaversky@cener.com)
Relevant publications:
Baigorri, J., A. Federici, et al. (2025). "Modeling of an innovative integration of compressed air energy storage (CAES) with high-temperature concentrated solar power (CSP): A comprehensive use-case study." Journal of Energy Storage 132: 117678.

Future work:

- Optimization and detailed design of the main components of the plant as well as the overall concept. Modelling and simulation of the concept and its different applications.
- Environmental, social and techno-economic assessment of the project concept.
- Commissioning and testing of a demonstrator.

CENER (Spain)

CENER NATIONAL RENEWABLE ENERGY CENTRE

SolarPACES TASK III-TES

RESTORE: RENEWABLE ENERGY BASED SEASONAL STORAGE TECHNOLOGY IN ORDER TO RAISE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF DHC

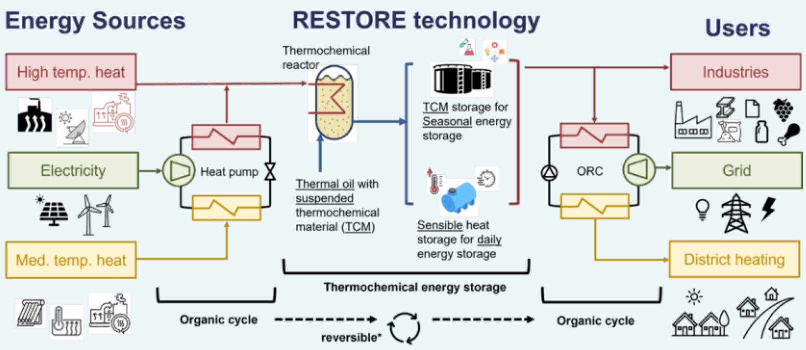
Challenges:
The deployment of clean energy sources for heating applications such as district heating or industrial heat is nowadays quite limited bearing in mind the decarbonization objectives of the countries. In the specific case of concentrating solar technologies, the lack of competitive energy storage solutions for temperatures above 100ºC is one of the main barriers for the market penetration of these technologies. Innovative solutions for overcome these barriers are fully required to increase the deployment of these technologies.

State of the art:
Nowadays, sensible heat storage (SHS) based on hot water is the State of the Art. SHS systems have found commercial success in several applications, from small-scale in residential application with the use of water tanks, to large-scale water volumes for seasonal storage (aquifer, borehole, cavern, or pit thermal storage). At first sight, water seems to be unbeatable when it comes to low-temperature thermal energy storage, thanks to its low cost, the non-hazardous behavior and the easy integration with solar thermal heating. However, for higher temperatures, the use of pressurized water or steam storage is required. This leads to a drastically increment of cost, reducing the competitiveness of the concentrating solar solutions for those applications which demands heat above 100°C.

Concept approach:

RESTORE

RESTORE proposes a radically innovative solution for decarbonising the heating and cooling sector, based on the combination of two key innovative technologies. The concept allows integrating a wide variety of Renewable Energy Sources (RES) combined with competitive energy storage in District Heating and Cooling (DHC) networks. The first technology the project aims to develop is an innovative thermal energy storage system using heat from chemical reactions, the Thermochemical Energy Storage (TCES). It provides daily and seasonal energy storage due to its high energy density, low energy losses and reduced cost. The system represents a key development due to the fact that it allows harnessing the enormous amount of energy that is normally wasted due to the mismatch between energy demand (loads) and energy generation (related to the availability of the renewable resource or waste heat), mainly occurring between seasons. In addition, the project aims to develop a second technology, namely a reversible Heat Pump (HP) /Organic Rankine Cycle (ORC) and to combine it with the TCES system. This second technology adapts the energy from different Renewable Energy Sources to feed the storage system. This allows for integrating a wide variety of renewable technologies as well as waste heat into the whole system to finally supply the energy demand under the specific conditions laid down by each District Heating network.



Current R&D status:

The project lasted from October 2021 to September 2025. Several thermochemical energy materials have been tested in laboratory, and a small continuous reactor has been built and successfully tested together with a reversible Organic Rankine Cycle prototype at the laboratories of TU-Wien. In addition, numerical models have been developed and validated and they are now available on a web-based simulation platform as virtual use cases.

Further information:

Contact person: Francisco Cabello (fcabello@cener.com)

Website: https://www.restore-dhc.eu/

Relevant Publications:

Cabello, F. et al. 2024. Dynamic Modeling and Analysis of a Disruptive Thermochemical Energy Storage Suitable for Linear Focus Solar Technologies. SolarPACES Conference Proceedings. Vol. 2, (Nov. 2024).

Future work:

The technology has been successfully validated up to TRL4 (lab-scale validation) considering a size of 30kW thermal and a capacity of 150kWh of storage. Future activities should be focused on the validation of both systems: reversible Organic Rankine Cycle and Thermochemical Energy Storage, in bigger scales and at higher TRLs.

CENER (Spain)

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES
ADItech

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Transient simulation of TES systems and techno-economic optimization

Challenges:

Thermal energy storage is the key feature of CSP plants as it guarantees dispatchability. The operating temperatures in TES systems of CSP plants are very high and transient operating conditions occur frequently, depending on the concept, not only during start-up and shut-down, but also during nominal operation. It is therefore crucial to model the characteristic transients of the system to correctly design and operate. In addition, construction and maintenance costs need to be kept on a minimum, which requires a suitable techno-economic optimization tool in the design process.

State of the art:

So far, most modelling procedures focus on quasi-steady models where transient responses cannot be reproduced and the behavior of innovative TES system integrated in CSP plants cannot be correctly modeled and optimized.

Concept approach:

At the Solar Thermal Energy Department at CENER a very flexible Modelica model library has been developed since 2011, which allows the detailed transient analysis of single plant components as well as of the whole solar thermal power plant on system level. This allows the simulation of operating strategies and control loops that are very close to reality and optimize them for innovative TES systems. In addition, CENER has developed a powerful optimization tool that combines the Modelica tool with the Python environment, which allows detailed techno-economic optimization of the TES systems and also CSP plants as a whole.

Current R&D status:

Currently, the library includes detailed TES models of:

- the conventional active-indirect two-tank type,
- the conventional active direct two-tank type,
- packed-bed thermocline type,
- as well as passive sensible and latent TES type.

The library can be easily extended by any TES component or concept.
Furthermore, these models can be simulated in a full power plant model on system level and optimized.

Further information:

Contact person: Dr. Fritz Zaversky (fzaversky@cener.com)

Publications:

- F. Zaversky, Object-oriented modeling for the transient performance simulation of solar thermal power plants using parabolic trough collectors - A review and proposal of modeling approaches for thermal energy storage, PhD Thesis, Public University of Navarre, Pamplona, Spain, 2014 (http://academica-.unavarra.es/handle/2454/16705)
- F. Zaversky, M. Sánchez, D. Astrain, Object-oriented modeling for the transient response simulation of multi-pass shell-and-tube heat exchangers as applied in active indirect thermal energy storage systems for concentrated solar power, Energy, 65 (2014) 647-664
- I. Hernández Arriaga, F. Zaversky, D. Astrain, Object-oriented Modeling of Molten-salt-based Thermocline Thermal Energy Storage for the Transient Performance Simulation of Solar Thermal Power Plants, Energy Procedia, 69 (2015) 879-890
- Javier López Sanz, Francisco Cabello Nuñez and Fritz Zaversky (2019). “Benchmarking analysis of a novel thermocline hybrid thermal energy storage system using steelmaking slag pebbles as packed-bed filler material for central receiver applications”. Solar Energy 188C(2019) pp. 644-654
- Cabello Núñez, F., J. López Sanz, et al. (2019). "Analysis of steel making slag pebbles as filler material for thermocline tanks in a hybrid thermal energy storage system." Solar Energy 188: 1221-1231.

Future work:

- Application of the developed models to improve and optimize operation strategies in more scenarios and applied to different innovative TES systems.

CENER (Spain)

TASK III-TES

Techno-economic simulation and optimization of innovative TES for air CSP plants

Challenges:

Dispatchability is a key advantage of the CSP plants. However, in the case of using air as HTF, mainly to difficulties related to the heat transfer, it is difficult to find competitive systems. In order to analyze the feasibility of innovative TES systems is important to consider not only technical simulations under transient behavior but also economic data to stablish a robust comparison in terms of competitiveness.

State of the art:

There are scientific publications of suitable TES systems in applications based on air as HTF but there are very few information about economic simulations and robust comparison between TES systems in terms of both cost and performance.

Concept approach:

At the Solar Thermal Energy Department at CENER the very flexible Modelica model library is continuously being expanded, allowing not only the detailed transient analysis but also include economic modelling for simulate and estimate economic figures of merits as LCOE for innovative TES systems integrated in CSP plants. At the same time, models of innovative TES can be validated in CENER's thermal loop () able to test sensible and latent materials in a small packed-bed. This allows establishing comparison between different technologies of storage and plant configurations.

Current R&D status:

Currently, the library includes detailed TES models, including transient performance and economic data of:

- Flexible packed-bed thermocline type storage including wide-range of filler materials,
- Hybrid TES storage based on the combination of latent and sensible heat storage (*).

Innovative air CSP plant configurations that include different TES systems and materials are under analysis using this library.

Further information:

Contact person: Francisco Cabello (fcabello@cener.com)

Publications:

- F. Cabello and F. Zaversky, "Comparison of Promising Materials for Filling Thermocline Tanks as Thermal Energy Storage of a CSP Plant Applying Air as HTF". SolarPACES Conference, 29 September-2 October, Albuquerque, New Mexico, USA
- F. Zaversky, F. Cabello, A. Bernardos, M. Sanchez. "A Novel High-Efficiency Solar Thermal Power Plant Featuring Electricity Storage - Ideal for the Future Power Grid with High Shares of Renewables". SolarPACES Conference, 29 September-2 October, Albuquerque, New Mexico, USA

Future work:

- Testing in CENER's thermal loop of the most promising TES materials and analysis via simulation of innovative TES systems in different air CSP plants and applications.
- Development of thermo-chemical storage models for thermal and economic performance simulations.

CIEMAT-PSA (Spain)

TASK III-TES

Power-to-Heat using microwaves

Challenges:

- To assess the feasibility of heating solar salt using microwave technology.
- To investigate the behavior of various transparent materials for containing solar salt in microwave applications.
- To develop an infrared-based temperature measurement system for controlling microwave heating.
- To design a scalable Power-to-Heat system adaptable for potential use in a Concentrated Solar Thermal (CST) plant.

State of the art:

- No measurements of the permittivity of solar salt currently exist to determine its viability for microwave heating.
- Despite the advantages of volumetric and selective microwave heating, no designs of this technology have been developed for application in the Concentrated Solar Thermal (CST) industry.

Concept approach: *(mentioning advantages & disadvantages)*

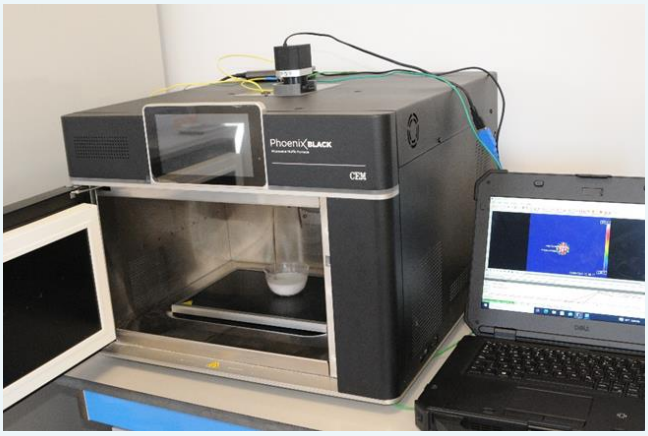
- Measurement of dielectric properties at operational temperatures for solar salt (290–565°C).
- Investigation of materials suitable for containing solar salt during microwave heating, to determine which materials can be used in the design of the Power-to-Heat system.
- Development of an infrared measurement and control system, requiring accurate emissivity measurements of the solar salt.
- Design of the microwave cavity, considering factors such as the source, power, frequency, and components like stirrers or tuners, among others.
- Comparison of microwave heating technology with conventional heating methods using key performance indicators (KPIs) developed to evaluate efficiency, energy consumption, heating uniformity, scalability, and cost-effectiveness.

Current R&D status:

- Initial measurement of the dielectric permittivity of solar salt using a dual single-mode cylindrical device through a single heating and cooling cycle.
- Initial study of transparent materials suitable for use as containers for solar salt.
- Comparative analysis of time and energy consumption when heating a small sample of solar salt using microwave heating, a multi-mode microwave oven, and conventional heating with a muffle furnace.
- Measurement of the emissivity of solar salt in its liquid state at operating temperatures (290–565°C) using the temperature-known method.

Description:

- Phoenix Black Microwave Oven: Dual 2.45 GHz magnetrons, 3150 W max power (60% efficiency), with temperatures up to 1200°C.
- Nabertherm L 40/11 Muffle Furnace: Two-sided heating, 6000 W max power, with temperatures up to 1100°C.



Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contact person: Cristobal Valverde (**mrodriguez@psa.es**)

Publications:

- C. Valverde, M. Rodríguez-García, E. Rojas, and R. Bayón, "State of the art of the fundamental aspects in the concept of microwave-assisted heating systems," International Communications in Heat and Mass Transfer. 156 (2024) 107594. **https://doi.org/10.1016/j.icheatmasstransfer.2024.107594**
- C. Valverde, M. M. Rodriguez-Garcia, E. Rojas, and R. Bayon, "Comparison of Conventional and Microwave Heating," SolarPACES Conference Proceedings, vol. 2, 2024-10-15 2024. **https://doi.org/10.52825/solarpaces.v2i.824**
- C. Valverde López, M. M. Rodriguez-Garcia, and E. Rojas, "Modeling Microwave Heating of Molten Salt for Thermal Storage Systems," SolarPACES Conference Proceedings, vol. 1, 2024-01-05 2024. **https://doi.org/10.52825/solarpaces.v1i.643**
- C. Valverde, M. M. Rodríguez-García, E. Rojas, R. Bayon, J. M. Catalá-Civera, P. Plaza-González, J. D. Gutiérrez. Permittivity measurements of different inorganic heat storage media for microwave heating. SolarPACES 2025, September 2025, Almería, Oral presentation
- M. M. Rodriguez-García, R. Bayón, E. Alonso, and E. Rojas, "Experimental and Theoretical Investigation on Using Microwaves for Storing Electricity in a Thermal Energy Storage Medium," in SOLARPACES 2021: International Conference on Concentrating Solar Power and Chemical Energy Systems, 2021: AIP Publishing.

CIEMAT-PSA (Spain)

TASK III-TES

Simulation of thermocline tanks / packed beds

Challenges:

- Describe the thermocline tank / packed bed behavior by an analytical function that provides the outlet temperature over time, so that it can be easily implemented in the annual simulations of a CSP plant
- Provide a predictive thermocline / packed bed model capable of foreseeing the thermo-hydraulic behaviour of this equipment without the need for further tuning required after the equipment is manufactured

State of the art:

- Numerical models, including 1D, 2D, 3D, CFD, are the primary means of describing thermocline tank / packed bed behaviour.
- Only a few examples of analytical models can be found in the literature
- Few experimental results for thermocline tanks / packed beds to be used in CSP plants
- Validation of the models is still needed

Concept approach:

- The thermocline tank / packed bed performance should be described by a simple yet accurate enough model
- Single-phase one dimensional model: effective storage medium formed by either a liquid or both a liquid and a solid filler.
- First stage: numerical model
- Second stage: analytical model
- Third stage: CSP plant implementation

Current R&D status:

- Improvement of the model developed previously using experimental data from thermocline tanks with/without solid filler and packed beds
- Analytical model based on sigmoid functions
- Correlation between function parameters, tank parameters and operating conditions
- Prediction of thermocline formation at the beginning of dynamic processes of charge and discharge

Further information:

Contact person: Esther Rojas (**esther.rojas@ciemat.es)**

Publications:

- Rojas E., Alonso E., Rodríguez-García M., Bayón R., Ávila-Marín A. Characterization by key performance indicators of SFERA III project to ALTAYR packed-bed prototype. Applied Energy 377 (2025) 124590. **https://doi.org/10.1016/j.apenergy.2024.124590**
- Bayón, R., Rojas, E. Prediction of Thermocline Zone Development at the Beginning of Dynamic Processes in Single Storage Tanks with Liquid Media. SolarPACES 2019. AIP Conference Proceedings 2303, 190001 (2020). **https://doi.org/10.1063/5.0028900**
- Bayón, R., Rojas, E. Analysis of Packed-Bed Thermocline Storage Tank Performance by Means of a New Analytical Function. SolarPACES 2017. AIP Conference Proceedings 2033, 090002 (2018). **https://doi.org/10.1063/1.5067096**

Future work:

- Model validation with experimental data from thermocline tanks with/without filler and packed beds

CIEMAT-PSA (Spain)

ALTAYR installation

Challenges:

- Experimentally study of air-solid thermocline tanks behavior: effect of operational conditions, physical parameters estimation, operative limits and thresholds. Validation of numerical models for industrial tanks performance prediction and facilitation of reliable designs. Material testing at device level.

State of the art:

- Few experimental facilities for air-solid thermocline tanks.
- Different approaches for simulations of air-solid thermocline with high complexity and limited validity. Not all the models are validated.
- No agreement on the contribution grade of physical mechanism present in an air-solid high temperature thermocline.
- Thermal properties of materials and behaviors mainly assessed at laboratory scale.

Description:

- The facility is located in Almería, at Plataforma Solar de Almería
- Cylindrical tank with a bed height of 0.5 m (tank height 0.72 m) and 0.5 m in inner diameter.
- Metal casing + insulation layer + ceramic inner wall. Two additional conical bodies on and under the cylinder.
- Hot air heated by electrical resistances.
- Charge mode: inlet through the top and outlet through the bottom. Discharge mode: inlet through the bottom and outlet through the top.
- Set point temperature from ambient to more than 1000 ºC
- Thermocouples in the bed at 9 different heights and 4 radiuses, on the outer wall of the tank at 10 heights and 5 angular positions and in the air inlet and outlet

1. Storage tank
2. Thermocouples
3. Heater
4. Blower
5. Flowmeter
6. Valve

Applications:

- Thermal storage in the form of sensible heat for concentrating solar power, other renewables,
- Waste heat recovery
- Processes that requires heat storage at high temperature.
- Heat for Industry processes at medium/high temperature such as: drying, chemical industry, cement and construction materials, mining and metallurgical industry.

Further information:

Contact person: Marina Casanova (mcasanova@psa.es)

Publications:

- M. Casanova, E. Rojas, M. M. Rodríguez-García, R. Bayón, C. Valverde, A. Ávila-Marín. Enhancing the Altayr Packed-Bed Storage Facility at PSA: Upgrades and Optimization. SolarPACES 2025, September 2025, Almería. Poster
- E. Alonso, E. Rojas, R. Bayón, M. Rodríguez, A. Ávila-Marín. Experimental comparison of tailored and natural solid fillers for high-temperature air-packed-bed thermal energy storage. Case Studies in Thermal Engineering 75 (2025) 107222. https://doi.org/10.1016/j.csite.2025.107222
- E. Alonso, E. Rojas, A. Ávila-Marín, M. Rodríguez, R. Bayón. Multicriteria Comparison of two Different-Nature Fillers for High Temperature Sensible Heat Storage. SolarPACES 2024 Conference Proceedings https://doi.org/10.52825/solarpaces.v3i.2309
- A. Ávila-Marín, E. Rojas, E. Alonso, M. Rodríguez, R. Bayón, M.E. Carra, J.A. Carballo, D. Sanchez Señoran. Experimental evaluation of the thermal insulation of a high temperature packed bed thermal energy storage prototype SolarPACES 2024, October 2024, Rome. Poster.
- Alonso, E., Rojas, E, Bayón, R. Packed-bed Thermocline Testing Facility with Air as HTF for Sensible Thermal Energy Storage. Eurosun 2020. Online, Sept 2020. Oral
- Alonso, E., Rojas, E, Bayón, R. Experimental and Numerical Study of an Air-Solid Thermocline Thermal Energy Storage System Operating at High Temperature. SolarPACES 2020. Online, Sep-Oct 2020. Oral

CIEMAT-PSA (Spain)

TASK III-TES

Test benches with molten salts (BES-I & BES-II)

Challenges:

- Validation and testing of components used in molten salt installations.

State of the art:

- These loops are intended for performing validation test for conventional components used in molten salt circuits in a simple and quick way

Description:

- Two test benches, BES-I and BES-II, are especially designed for testing of valves, pressure transmitters and other molten salts components under real working conditions up to 600ºC and 40 bar. Components with nominal diameters from 2” up to 6” can be evaluated in these test benches.

Applications:

- Tests for different types of valves
  1. Leakage test
  2. Validity for design conditions test
  3. Cold zone test
  4. Packing life test
- Tests for pressure transmitters
  1. Constant pressure test
  2. Pressure variation test
- Validation of other components and auxiliary equipment like heat tracing, insulation, etc.

Further information:

Contact person: Margarita Rodríguez (margarita.rodriguez@psa.es)

Publications:

- M-M. Rodriguez-Garcia, E. Rojas, M. Pérez, Procedures for testing valves and pressure transducers with molten salt, Applied Thermal Engineering, Volume 101, 25 May 2016, Pages 139-146, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2016.02.138.
- M.M. Rodríguez-García, A. López-Tamayo, E. Rojas, Components test device with molten salt at high temperature and pressure. 20th International SolarPACES Conference, Beijing (China), September 2014.

CIEMAT-PSA (Spain)

TASK III-TES

Molten Salt Test Loop for Thermal Energy Storage (MOSA)

Challenges:

- Reliability of components used in molten salt loops under CSP conditions
- Optimization of different operation procedures for CSP storage systems based on molten salts
- Tests on electricity-to-thermal energy conversion

State of the art:

- This test loop is a replica of a two-tank thermal storage system with molten salts

Description:

- Vertical hot tank and horizontal cold tank with 40t of molten salt inventory
- A thermal oil loop that can be used for either salt heating up to 380ºC or cooling down to 290ºC.
- Two flanged sections where different components for this type of loops (e.g. valves, flow meters, heat trace, pumps…) can be tested
- Being a down-scaled facility of a commercial two-tank molten salt storage system everything related to this type of systems can be tested in a simpler way
- A molten salt electrical heater has been recently installed

Applications:

- Test of different components (pumps, valves, flowmeters, etc.) for their use in a molten salt medium
- Optimization of operation procedures under both normal and risky situations for a two-tank system configuration
- Designing recovery procedures
- Validation of models and simulation approaches for molten salt storage systems
- Characterization of molten salt/oil heat exchanger
- Characterization of molten salt electrical heater.
- Characterization of thermocline tanks.

Further information:

Contact person: Margarita Rodríguez (margarita.rodriguez@psa.es)

Publications:

- L. Roca, J. Bonilla, M.M. Rodríguez-García, P. Palenzuela, A. de la Calle, L. Valenzuela, Control strategies in a thermal oil-molten salt heat exchanger, AIP Conference proceedings 1734, 130017 (2016), https://doi.org/10.1063/1.4949227
- M.M. Rodríguez-García, M. Herrador Moreno, E. Zarza Moya, Lessons learnt during the design, construction and start-up phases of a molten salt testing facility, Applied Thermal Engineering, Vol. 62, Issue 2, Pages 520-528, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2013.09.040.
- J. Bonilla, M.M. Rodríguez-García, L. Roca, L. Valenzuela, Object oriented modeling of a multi-pass shell-and-tube heat exchanger and its application to performance evaluation, IFAC-Papers online, Vol. 48, Issue 11, 2015, Pag. 97-102, ISSN 1876-6102. https://doi.org/10.1016/j.ifacol.2015.09.166

DLR: German Aerospace Center (Germany)

TASK III-TES

MOLTEN SALT STORAGE

Challenges for Materials:

- Metallic corrosion data for mixtures for direct molten salt parabolic trough technology
- Understanding decomposition, metallic corrosion and purification of mixtures with higher operation temperature (chloride and nitrate salts)
- Long-term compatibility of non-metal materials with molten salt (e.g. fillers)

Challenges for Components:

- Improvement of reliability of flat bottom tanks
- Capital cost reduction of the two-tank system by alternative single tank systems
- Qualification of novel power components for larger-scale and lower costs (e.g. heaters, heat exchangers)
- Improvement and qualification of additional molten salt components (e.g. instrumentation, valves)
- Fundamental process technology aspects (e.g. salt freezing, heat transfer, dynamic operation)

Challenges for Systems:

- Assessment of the theoretical potential and experimental proof of novel configurations with molten salt storage (e.g. direct molten salt trough, Fresnel, supercritical steam, supercritical CO2, higher operation temperatures with alternative salts, topping cycles, hybrid CSP/CST plants with PV)
- Assessment of single tank thermocline concepts in overall CSP and CST configurations

State of the art:

- The two-tank molten salt storage is commercially available as standard solution.

Concept approach:

- Physicochemical, thermophysical and electrochemical molten salt examinations including liquid-gas interaction and liquid-solid interaction with three DLR labs (autoclave, thermal analysis, wet chemistry)
- Alternative single tank thermocline design to reduce costs with TESIS:store facility (4 MWh)
- Qualification of molten salt components with TESIS:com and TESIS:store.ext facility (e.g. electrical heater, heat exchanger, valves, instrumentation)
- System analysis and dynamic simulation for molten salt storage integration (e.g. thermocline)

Current R&D status:

- Several DLR and third party funded projects on material, component and system levels
- Operation of nitrate salt system at elevated temperature with valves and a pump at technical scale (validated with ~100 kg, 620 °C, 2500 h)
- Operation of 560 °C Test Facility for Thermal Energy Storage in Molten Salt (TESIS) with more than 100 tons of salt since 2018, validation of several single tank concepts with 4 MWh

Further information:

Contact person: Thomas Bauer (thomas.bauer@dlr.de)

- Home page: https://www.dlr.de/tt/en

- TESIS:store: https://www.dlr.de/en/research-and-transfer/research-infrastructure/test-facility-for-thermal-energy-storage-in-molten-salt-tesis-store
- TESIS:com: https://www.dlr.de/en/research-and-transfer/research-infrastructure/test-facility-for-thermal-enery-storage-in-molten-salt-tesis-com
- Review paper: Bauer, T., Odenthal, C., Bonk, A. (2021) Molten Salt Storage for Power Generation, https://doi.org/10.1002/cite.202000137
- Review paper: Bonk, A., Sau, S., Uranga, N., Hernaiz, M., Bauer, T. (2018) Advanced heat transfer fluids for direct molten salt line-focusing CSP plants, http://dx.doi.org/10.1016/j.pecs.2018.02.002

ENEA (ITALY)

TASK III-TES

Innovative concept of a thermal energy storage system based on a single tank configuration using stratifying low melting molten salts

Challenges:

- Development of a thermal energy storage system for CSP plants coupled with other renewable sources
- Design of a thermal energy storage system integrated with CSP and PV
- Definition of the operational characteristics for the integration of the storage system into the solar plant
- Definition of the operation procedure of the new storage system integrated with other renewable source

State of the art:

A prototype thermal storage system equipped with a pump and three integrated exchangers has been recently realized; it uses mineral oil as HTF and a mixture of molten salts as HSM (consisting in a NaNO3, KNO_3 and Nitcal (KNO_3;$5Ca(NO_3)_2$) mixture).

One heat exchanger is directly charged by the solar field of CSP, the second one is charged by an electric heater that simulates the PV module, whereas the last exchanger discharges the stored heat to the thermal user.

Concept approach:

- This TES typology is based on the thermocline technology which uses low melting point salts as heat storage medium by exploiting the natural stratification of molten salts with temperature. It is an indirect TES with molten salts inside the tank and HTF flowing into two heat exchangers (HXs): it is also equipped with an impeller, inside the discharge pipe, to allow a forced circulation
- An additional heat exchanger is positioned inside the tank, in the bottom part, and is indirectly fed by a PV system in order to store the excess electricity produced by PV(wind), thus increasing the energy stored from renewables

Current R&D status:

- In the frame of the Project 1.9 “CSP/CST technology”, under the “Electric System Research” Programme 2022-2024, a CFD model of the system was developed in collaboration with Polytechnic of Turin.
- In the frame of the Project 1.9 “CSP/CST technology”, under the “Electric System Research” Programme 2022-2024, a new electric heating system, directly immersed in the tank. in direct contact with the storage medium, is currently being studied.
- CFD simulation to identify new design solutions that can improve the thermocline performance through the use of the electric heater directly immersed in the tank is being developed.

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contact persons:

- Valeria Russo, PhD, ENEA TERIN-SSI; **valeria.russo@enea.it**
- Walter Gaggioli, PhD, ENEA TERIN-SSI; **walter.gaggioli@enea.it**

Publications:

- J.M. Rodríguez, D. Sánchez, G.S. Martínez, E.G. Bennouna, B. Ikken, Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant, Solar Energy 140 (2016) 206-218.
- V. Russo, D. Mazzei, R. Liberatore, Thermal Energy Storage With Integrated Heat Exchangers Using Stratified Molten Salt System For 1 MWe CSP. AIP Conference Proceedings. Volume 2033, 8 November 2018, Article number 090025
- Liberatore R, Falchetta M, Gaggioli W, Mazzei D, Russo V., Power production of an ORC System using a stratified molten salt as thermal energy storage integrated in a CSP plant. Proceeding of Solar Paces 2018, Casablanca, 2-5 October.

Associated Funded Project:

- European Commission's Horizon2020 Programme (Innovation and Networks Executive Agency - ENERGY RESEARCH) - Innovation Action nr. 657690.
- Project 1.9 "CSP/CST technology", funded by the Italian Ministry of Environment and Energy Security through the «National Electric System Research» Programme, 2022-2024 implementation plan
- Project 1.9 "CSP/CST technology", funded by the Italian Ministry for Economic Development through the «National Electric System Research» Programme, 2019-2021 implementation plan

Future work:
Replacement of the PV-fed exchanger with a system of electric heaters immersed in the storage medium

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SolarPACES

TASK III-TES

Employment of low melting nitrate/nitrite mixtures as HTF and HSM

Challenges:

- Decrease the HTF (heat transfer fluid) initial solidification point, with the main target to facilitate management and maintenance operation of a solar plant
- Design of cost-effective energy storage systems for plants using thermal oil as HTF, with a maximum operating temperature of around 400-450 °C
- Verification of molten salts-construction materials compatibility at temperatures below 450°C: search for less costly alloys for tanks, pipelines and valves. Test in static and dynamic (molten salt flowing) conditions
- Definition of the operational characteristics for the integration of these HTF/HSM in the currently used solar energy technology
- Development of thermodynamics predictive models for the mixture phase diagrams

State of the art:

- Nitrate/nitrite based low melting mixture has been widely investigated in recent scientific literature. Some of these mixture compositions have been patented

- For some of these mixtures the value of the maximum allowed operating temperature is not clearly established. An agreement upon common measurements criteria is also to be reached
- A few ternary/quaternary phase diagrams are already present in the scientific literature; some thermodynamics models have been proposed and validated

Concept approach:

- Employment of low melting materials as HTF/HSM (<100-140 °C of initial solidification temperature) for CSP applications at medium temperature to allow the employment of less costly CSP construction materials (e.g. "carbon steels")
- Use of less costly alternative in comparison with thermal oils
- Decrease of the thermal storage components material costs
- Adoption of less costly maintenance operations

Current R&D status:

- Validation of thermo-physical properties (specific heat, density, dynamic viscosity), and development of predictive models for mixtures
- Investigation of the chemical stability properties of thermal fluids
- Dynamic corrosion tests between molten salt mixtures and alloys
- Modeling activity validated, and main results published
- Assessment of an open access database, able to calculate and deliver the thermophysical properties of multicomponent mixtures

Further information:

Contact person: Dr. Salvatore Sau, ENEA TERIN-SSI-EAT; salvatore.sau@enea.it

Publications:

- Giaconia, A., Tizzoni, A.C., Sau, S., Corsaro, N., Mansi, E., Spadoni, A., Delise, T. Assessment and perspectives of heat transfer fluids for CSP applications (2021) Energies, 14 (22), art. no. 7486.
- Tripi, V., Sau, S., Tizzoni, A.C., Mansi, E., Spadoni, A., Corsaro, N., D'Ottavi, C., Capocelli, M., Licoccia, S., Delise, T. A general thermodynamic model for eutectics of phase change molten salts in concentrating solar power applications (2021) Journal of Energy Storage, 33
- Delise, T., Tizzoni, A.C., Turchetti, L., Corsaro, N., Sau, S., Licoccia, S., Predictive model for the phase diagrams of ternary mixtures composed of calcium, lithium and sodium/potassium nitrates (2020) AIP Conference Proceedings, 2303
- Delise, T., Tizzoni, A.C., Menale, C., Telling, M.T.F., Bubbico, R., Crescenzi, T., Corsaro, N., Sau, S., Licoccia, S. Technical and economic analysis of a CSP plant presenting a low freezing ternary mixture as storage and transfer fluid (2020) Applied Energy, 265
- Delise, T., Tizzoni, A.C., Ferrara, M., Telling, M., Turchetti, L., Corsaro, N., Sau, S., Licoccia, S. Phase Diagram Predictive Model for a Ternary Mixture of Calcium, Sodium, and Potassium Nitrate (2020) ACS Sustainable Chemistry and Engineering, 8 (1), pp. 111-120
- Delise, T., Tizzoni, A.C., Votyakov, E.V., Turchetti, L., Corsaro, N., Sau, S., Licoccia, S, Modeling the Total Ternary Phase Diagram of $NaNO_3$–KNO_3–$NaNO_2$ Using the Binary Subsystems Data (2020) International Journal of Thermophysics, 41 (1)
- Delise, T., Ferrara, M., Turchetti, L., Tizzoni, A., Telling, M., D'Ottavi, C., Corsaro, N., Sau, S., Licoccia, S.; Thermo-physical investigation of low melting HFT and HSM containing calcium nitrate (2019) AIP Conference Proceedings, 2126, art. no. 080001
- Tizzoni, A.C., Sau, S., Corsaro, N., Giaconia, A., D'Ottavi, C., Licoccia, S. Thermal fluids for CSP systems: Alkaline nitrates/nitrites thermodynamics modelling method (2016) AIP Conference Proceedings, 1734

Associated Funded Projects:

- Project 1.9 "CSP/CST technology", funded by the Italian Ministry of Environment and Energy Security through the «National Electric System Research» Programme, 2022-2024 implementation plan
- Project 1.9 "CSP/CST technology", funded by the Italian Ministry for Economic Development through the «National Electric System Research» Programme, 2019-2021 implementation plan
- SFERA III (Solar Facilities for the European Research Area III), Horizon 2020 project funded under the Research Infrastructure Programme

Future work:

- Thermal stability analysis on low melting mixtures carried out by a dedicated experimental set-up
- Compatibility tests of construction materials with multicomponent mixtures
- Improvement and experimental validation of simulation thermodynamic models, with the aim of developing predictive tools for new multicomponent low melting mixtures
- Development of an open online and interactive database for thermophysical properties of multicomponent mixtures

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SolarPACES
Solar Power & Chemical Energy Systems

TASK III-TES

Innovative concept of a thermal energy storage system based on a single tank configuration using stratifying low melting molten salts

Challenges:

- Thermal energy storage for CSP plants coupled with ORC turbine
- Design of a thermal energy storage element
- Definition of the operational characteristics for the integration of the storage system into the solar plant
- Balancing of the power energy flows in the local Medium Voltage grids

State of the art:

- Development of a software tool for simulating the solar heat charge and discharge
- A prototype system equipped with a pump and two integrated exchangers have been realized; it uses mineral oil as HTF and a mixture of salts as HSM, consisting of NaNO3, KNO3 and Nitcal (KNO3; 5Ca(NO3)2). (TRL4).

Scheme of the coupling CSP-TES-ORC and image of the prototype system installed at ENEA Casaccia Research Centre (Rome)

Concept approach:

- This kind of TES is based on the thermocline technology which uses low melting point salt as heat storage medium by exploiting the natural stratification of the molten salts with temperature. It is an indirect TES with molten salts inside the tank and HTF flowing into two heat exchangers (HXs) as well as an impeller, inside the discharge pipe, to allow a forced circulation

Current R&D status:

- In the frame of the project activities “Concentrating Solar Power”, under the “Electric System Research” Programme 2019-2021, in cooperation with Turin Polytechnic was validated a CFD model of the system.
- Currently there are ongoing CFD simulation to identify new design solutions that can improve the thermocline performance through the use of PCM materials

Further information:

Contact persons:

- Walter Gaggioli, PhD, Solar Thermal Division, **(walter.gaggioli@enea.it)**
- Raffaele Liberatore, Solar Thermal Division,(**raffaele.liberatore@enea.it**)

Publications:

- J.M. Rodríguez, D. Sánchez, G.S. Martínez, E.G. Bennouna, B. Ikken, Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant, Solar Energy 140 (2016) 206-218.
- V. Russo, D. Mazzei, R. Liberatore, Thermal Energy Storage With Integrated Heat Exchangers Using Stratified Molten Salt System For 1 MWe CSP. AIP Conference Proceedings. Volume 2033, 8 November 2018, Article number 090025
- Liberatore R, Falchetta M, Gaggioli W, Mazzei D, Russo V. power production of an ORC System using a stratified molten salt as thermal energy storage integrated in a CSP plant. Proceeding of Solar Paces 2018, Casablanca, 2-5 October.

Associated Fundend Project:

- European Commission’s Horizon2020 Programme (Innovation and Networks Executive Agency - ENERGY RESEARCH) - Innovation Action nr. 657690.
- National program funded by the Italian Ministry for Economic Development (MISE): “Piano Triennale Ricerca di Sistema 2019-2021”

Future work:

- A new lay out of storage module provided with a layer of phase change material (PCM) will be tested with the goal to stabilize the temperature on the top of the tank during the TES charge and discharge operations.

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TASK III-TES

Microwave Heating of Solar Salt for Thermal Energy Storage Applications

Challenges:

- Implementing a power-to-heat technology in the salt-based TES to store the electricity overproduction (from PV) in the thermal energy storage to achieve a full hybridization of CSP+TES with PV systems.
- Achieving a high rate of discharging power, ensuring that the salt temperature never exceeds the maximum operating temperature.
- Fast response of the power-to-heat technology to switching on/off

State of the art:

- Surface heat transfer processes (electrical resistances) potentially lead to overheat the salt at the salt-resistances interface. This limits the maximum rate of discharging power. Volumetric heating technologies, such induction and microwave heating, can overcome this issue.
- Direct induction likely does not work because of the low salt conductivity.
- Microwave heating applied to molten salt is a relatively new technology, very few studies exist in literature about this topic. Particularly, dielectric properties of solar salt have not been successfully measured for high temperatures (> 360 °C)

Concept approach:

- Microwave heating can achieve high rates of discharging power. This is because the volumetric heating, unlike the surface heat transfer mechanism (electrical resistances), drastically reduces the risk of local overheating. In addition, this technology provides a fast response to switching on/off.
- Integrating the microwave heating technology directly inside the TES provides benefits in terms of equipment compactness and operation flexibility, since no circulation of molten salts is envisaged and no additional hydraulic devices (pumps, piping) are required.
- Solar salt, in the solid state, are almost transparent to the microwaves. This implies that the salt melting requires using electrical resistances.

Current R&D status:

- A lab-scale experimental device has been commissioned and installed at the ENEA Casaccia research center. This device consists of a lab-scale tank connected with a 3-kW magnetron by means of a waveguide. The tank is partially filled with molten salt, it is provided with electrical resistances to melt the salt. An impeller has been installed to promote the salt mixing to achieve a uniform temperature. The experimental campaign is ongoing.
- A numerical multi-physics model has been developed, in collaboration with Politecnico di Torino, to help in the design of the experimental device.

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contacts

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- Michela Lanchi, PhD, ENEA TERIN-SSI-EAT; michela.lanchi@enea.it

Publications

- Mattia Cagnoli, Roberto Grena, Michela Lanchi, Giuseppe Vecchi, Roberto Zanino, "Numerical investigation about the electrical heating of a molten salt mixture for thermal energy storage applications", Proceedings of the 16th IEA ES TCP International Conference on Energy Storage, ENERSTOCK 2024, DOI: 0.5281/zenodo.13790499

Projects

- Project 1.9 "CSP/CST technology", funded by the Italian Ministry of Environment and Energy Security through the «National Electric System Research» Programme, 2022-2024 implementation plan

Future work:

- Analysis of the experimental data collected during the ongoing experimental campaign
- Experimental measurement of the dielectric properties of solar salt for temperatures higher than 360 °C
- Scale-up, from a lab-scale experimental device to prove the concept feasibility to a lab-scale prototype to demonstrat**e** the feasibility of the integration of the microwave heating technology in a thermocline TES.

ENEA (Italy)

TASK III-TES

TES by concrete and PCM in cascade

Challenges:

- Research and development of high-energy-density Heat Storage Media (HSMs) to minimize storage volume.
- Enhance system compactness.
- Thermal energy storage cost reduction.
- Energy and exergy efficiency improvement.
- Stabilization of output temperatures during discharge.

State of the art:

- Thermal storage systems under exam are mainly suitable for concentrated solar thermal/power (CST/CSP) plants but can be easily applied to different sectors which require thermal energy coupling and recovery (industrial/energy sectors).
- In CSP/CST plants, thermal storage units allow to storage solar energy during daylight and make it available in the absence of the solar source. This application is useful to increase the capacity factor and the producibility of the plant, stabilizing the thermal output.
- While existing literature often is focused on tightly integrated, physical coupling of sensible and latent heat storage components, this approach assumes a physically distinct yet functionally interconnected system.

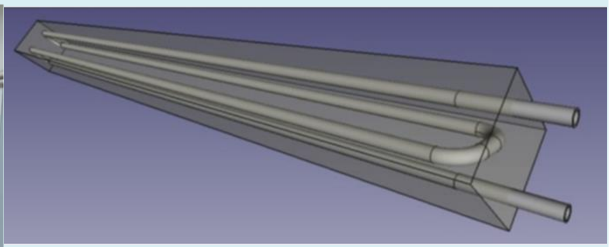
Concept approach:

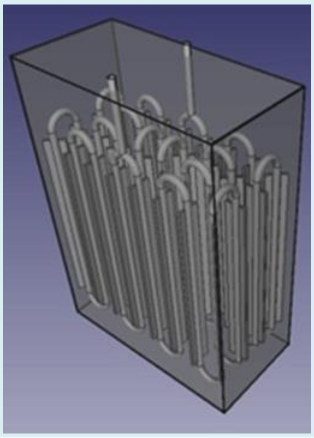
- Development of materials for sensible and latent heat storage to design components with efficient heat transfer surfaces.

- Concrete-based sensible heat storage offers the benefits of readily available, affordable, and high-capacity materials. However, for applications demanding temperatures up to 400°C, careful consideration of mix design and manufacturing/treatment processes is essential.
- To counteract concrete's low thermal diffusivity, some material modifications are crucial for enhancing thermal conductivity and minimizing the heat exchanger sizing.
- The use of a module harnessing latent heat improves the energy storage density and stabilizes the temperature of the HTF during the discharge phase.
- Sensible/latent heat modules in cascade configuration maximize the benefit coming from both the heat storage mechanisms, providing stable, high-quality heat. Of course, the performance of such systems is closely linked to the HTF mass flow rate.
- An experimental set-up has been realized to test sensible/latent cascade TES systems. In this experimental apparatus, mass flow is in the operative range of 0 to 1500 kg/h. The heat production is accomplished through Joule effect (25 kW) heating, warming up the HTF to the target temperature of the storage inlet. Furthermore, an air cooler cools down the flowing oil at the exit of the storage module to simulate the thermal user.

Current R&D status:

- Test of different TES modules based on sensible and/or latent heat storage to be characterized in a cascade version.
- Regarding sensible heat storage, an innovative concrete compound has been developed, suitable for medium-temperature thermal storage applications (up to 350°C), using recycled materials like metallic scraps as well as polyamide fibres (Nylon 66).
- Thermal performance optimization of the new mixture concrete material, using micro-encapsulated PCMs.
- Thermal characterization of the system with modules in cascade, to calculate stored and released energy, also after repeated thermal cycles.





Further information:

Contact person: Dr. Raffaele Liberatore, ENEA TERIN-SSI-EAT; raffaele.liberatore@enea.it

Publications:

- Miliozzi, F. Bisegna, F. Nardecchia. L. Pompei. Accumulo termico. SIMTE - Sistema Informativo e di Monitoraggio delle Tecnologie Energetiche. 2021, AdP ENEA-MiSE, RSE, Prog 2.1 Strumenti e modelli, anche settoriali, per scenari energetici ed elettrici, adeguati all'evoluzione del sistema - Analisi di evoluzione dei mercati e della regolazione.
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- Miliozzi A., Chieruzzi M., Torre L., Experimental investigation of a cementitious heat storage medium incorporating a solar salt/diatomite composite phase change material. Applied Energy, 2019, 250, 1023–1035, ISSN: 0306-2619
- Dominici F., Miliozzi A., Torre L. Thermal Properties of Shape-Stabilized Phase Change Materials Based on Porous Supports for Thermal Energy Storage. Energies, 2021, 14(21), 7151, ISSN 1996-1073
- Miliozzi A., Dominici F., Candelori F., Veca EM, Liberatore R., Nicolini D., Torre L.. Development and characterization of concrete/PCM/diatomite composites for thermal energy storage in CSP/CST applications. Energies, 2021, 14(15), 4410, ISSN 1996-1073

Associated Funded Project**:**
- Project 1.2/WP4 "Thermal Energy storage", funded by the Italian Ministry of Environment and Energy Security through the «National Electric System Research» Programme, 2022-2024 implementation plan
- Project 1.2/WP4 "Thermal Energy storage", funded by the Italian Ministry for Economic Development through the «National Electric System Research» Programme, 2019-2021 implementation plan

Future work:

Long duration tests to perform a machine learning procedure.

Fraunhofer ISE (Germany)

TASK III-TES

Thermal storage in a single thermocline tank

Challenges:

- Single-tank molten salt storage concepts promise cost reduction compared to the state-of-the-art two-tank storage system but may have lower efficiency due to mixing processes
- Lack of experimental data for single-tank systems to assess the actual performance prevent the commercial application of single-tank storage systems

State of the art:

- Two-tank storage system where cold and hot fluid are separated in individual tanks

Concept approach:

- Design, construction and testing of a molten salt single-tank prototype
- Parameter identification for numerical models to improve the accuracy of simulations
- Small test facility allows for versatile operating conditions (flow rate and heat loss) but area to volume ratio is worse than for large-scale tank

Current R&D status:

- During many charging/discharging cycles with different parameters a good stratification of the storage could be established and a relatively thin thermocline zone being observed what indicates a high storage efficiency

Further information:

Contact person: Tom Fluri (tom.fluri@ise.fraunhofer.de)

Publications:

- B. Seubert, R. Müller, D. Willert, T. Fluri: Experimental results from Laboratory-Scale Molten Salt Thermocline Storage. SolarPaces, Abu Dhabi, 2016.
- M. Karl, B. Seubert, R. Müller, T. Fluri, P. Nitz: Experimental Performance Evaluation of a Laboratory-Scale Molten Salt Thermocline Storage, Proceedings of the 23th SolarPACES, Santiago, Chile, 2017

Future work:

- Modifying of the molten salt single-tank prototype towards a system with innovative fillers
- Running of consecutive charging/discharging cycles to identify long term development of thermocline

Fraunhofer ISE (Germany)

Fraunhofer ISE

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Thermocline Tank Simulation

Challenges:

- Single-tank molten salt storage concepts promise cost reduction compared to the state-of-the-art two-tank storage system but may have lower efficiency due to mixing processes
- Modelling of the mixing processes is either neglected in simple 1D-models or tremendous effort in CFD simulations

State of the art:

- 1D models with first-order methods for the convective fluxes introduce numerical diffusion which can be interpreted as mixing but is only a numerical effect
- Mixing is not a function of the charging velocity or temperature difference
- System integration of alternative storage concepts is often neglected

Concept approach:

- Development of a storage model with higher-order schemes which is not susceptible to numerical effects but still allows for fast simulations
- Implementation of a mixing factor that considers inlet flow rate and temperature difference
- Integration of the model into the system simulation program ColSim CSP to perform annual simulations and evaluate storage performance in system context for e.g. the ORC-PLUS project

Current R&D status:

- Alternative algorithms for the implementation of mixing
- Integration of the option to insert filler materials into storage

Further information:

Contact person: Tom Fluri (tom.fluri@ise.fraunhofer.de)

Publications:

- B. Seubert, T. Fluri and W. Platzer: Numerical investigation of a high temperature stratified storage with integrated steam generator. SolarPaces, Las Vegas, 2013.

Future work:

- Performing parameter identification studies to match numerical models to mixing analyzed in experimental data
- Intensify evaluation and characterization of thermocline storage

IEE-CAS (China)

TASK III-TES

Molten Salt Thermal Storage Technology

Challenges:

- Molten salt thermal storage system needs huge tons of molten salts and operates high temperature (560℃), which increase the cost of the CSP plant and safety problem.
- Narrow work temperature range of molten salt, especially the high freezing point=> extend the safe work temperature range, keep tube temperature by using electric heat tracing and change ratio of salt mixture.
- Thermal cycling fatigues of molten salt TES tanks, which causes the corrosion mechanism and leakage failure, are very important in complex multi physical field service environments.

State of the art:

- The main and typical way of thermal storage in CSP power plants. The issues of thermal cycling have been attracted recently.

Concept approach:

- Suitable control strategy and corresponding control methods.
- Mechanical performance and life prediction of high-temperature molten salt storage tanks.

Current R&D status:

- Suitable control strategies are carried out by set various system operation modes and use corresponding control methods when system runs.
- Mechanical performance and life prediction of high-temperature molten salt storage tanks are carried out.
- A molten salt storage tank structure design software with life prediction function is developed to evaluate the life of large-scale molten salt storage tanks in CSP plants.




Further information:

Contact persons: wangyan@mail.iee.ac.cn ; zangchch@mail.iee.ac.cn

- The project is supported by Intergovernmental Cooperation Projects between China and the United States

Publications:

- Haibin Guo, Chuncheng Zang *, Zhifeng Wang, Xiaohui Zhao, Yue Meng, Julian D. Osorio, Mark Mehos. Analysis of thermal and mechanical properties with inventory level of the molten salt storage tank in central receiver concentrating solar power plants. Applied Thermal Engineering, 260 (2025) 124984.

- Haibin Guo, Jun Dong, Haoyu Han, Chuncheng Zang*, Zhifeng Wang. Stress testing and numerical simulation of high-temperature molten salt storage tank under dynamic operating conditions. Journal of Energy Storage 146 (2026) 119869.

Future work:
- Build test facilities to do thermal storage experiments and optimize control strategy.
- Project is working on about mechanical performance and life prediction.

IEE-CAS (China)

TASK III-TES

Two tanks TES using thermal oil

Challenges:
- High freezing point=>keep tank and tube temperature using electric heat tracing in winter.
- Low operation temperature=>using two stages TES to produce superheated steam to generate.

State of the art:
- The main and typical way of thermal storage in CSP power plants

Concept approach:
- Decrease freezing point:
  - Advantages: the system can be operation in winter without using electric heat.
  - Disadvantages: TES cost is higher.
- Two-stage TES:
  - TES composited thermal oil TES and steam TES which thermal oil as the high temperature TES and steam as the low temperature TES.
  - Advantage: improve TES efficiency.
  - Disadvantages: control strategy is not easy.

Current R&D status:
Two stages TES is the TES of 1MW CSP plant of Badaling CSP in Beijing, China.
Many experimental had finished.

Further information:
Contact person: wangyan955@126.com

Future work:
- Continue the simulation and experiment of two stages TES.
- Improve the storage performance and establish evaluation criterion of thermal oil thermal storage.

IEE-CAS (China)

TASK III-TES

Solid packed bed thermal storage using high temperature air

Challenges:

- Low energy storage density of solid sensible thermal storage material=>composite sensible and latent material as thermal storage material
- The stability of packed bed thermal storage, especially the outlet temperature of air=>multiply thin tanks for ceramic sphere packed bed thermal Storage.

State of the art:

A few pilot's thermal storage systems are applied in CSP plant as second TES to investigated the performance, but not the main and typical TES system.

Concept approach:

- Composite sensible and latent material as thermal storage material:

Advantages:

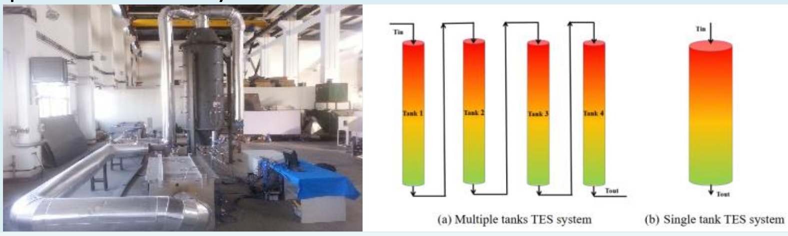
The outlet temperature of discharging process is stability.
Improve convection and conduction between air and thermal storage

- Packed-bed solid thermal storage with multiply thin tanks

Stability of the air outlet temperature.
Control strategies are proposed to improve the performance.

Current R&D status:

- The heat transfer performance of packed bed thermal storage was investigated by experiment and simulation.
- A one dimensional, two phase, transient models about the heat transfer between the airflow and the Al_2O_3 ceramic spheres was set up.
- A passive TCC method and an active TCC method, were proposed to improve the storage performance of packed-bed TES system.



(a) Multiple tanks TES system (b) Single tank TES system

Further information:

Contact person: wangyan@mail.iee.ac.cn

Publications:

- Yan Wang, Peiwen Li, zhifeng Wang, Bei Yang, Guofeng Yuan. The benefit of using multiple thin tanks versus a short big tank for thermal storage in ceramic-sphere packed bed with airflow. Journal of Solar Energy Engineering, Transactions of the ASME, 2020. 4.142.2.
- Wang, Yan , Z. Wang , and G. Yuan . "Control strategy effect on storage performance for packed-bed thermal energy storage." Solar Energy, 2023,73-84.

Future work:

- Control strategy investigation of cascade TES system under different operational parameters

IEE-CAS (China)

TASK III-TES

1000 °C solid particles thermal energy storage

Challenges:

- Solid particle heat storage media: thermal properties, stability at 1000°C, cost.
- Storage tank: thermal loss control, design method for large capacity around 10000 tons, cost.
- High temperature solid particles delivery equipment.

State of the art:

Some solid particle materials had developed focusing on the solid particle solar receiver. There are few published articles related to the thermal energy storage.

Concept approach:

- **Thermal performance experiments**
  - **Advantages:**
    - Easy to get the performance of whole working process.
    - High thermal conductivity.
  - **Disadvantages:**
    - Not easy to get the optimization design.

Current R&D status:

- Experimental platform has been set up to investigate the performance of particle receiver and TES system.
- Experiments about the properties of high temperature particles had been finished.

Further information:

Contact person: baifw@mail.iee.ac.cn

Future work:

- Finish the experiments and give the final evaluation of this technology. Do some simulations for the whole system and present the method of optimization of system design and operation

IEE-CAS (China)

TASK III-TES

Seasonal thermal energy storage

Challenges:

- The building heat demand is very large => collects and storage heat in other seasons.
- The thermocline stability of large water tank, heat loss in whole year.
- Cost of large scale seasonal thermal energy storage

State of the art:

- Large scale seasonal thermal storage system had been built up.
- The most reliable and widely used of season thermal storage technology is hot water thermal storage.
- The flat plate collectors are mainly used to collect solar energy, the efficiency decreases during 70~95℃.

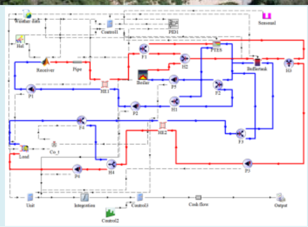
Concept approach:

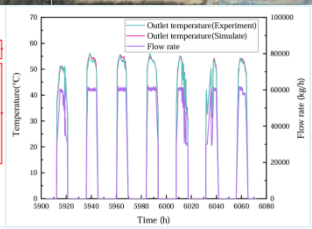
Seasonal thermal energy storage with concentrated solar energy can effectively improve the stability of the output of heating system.

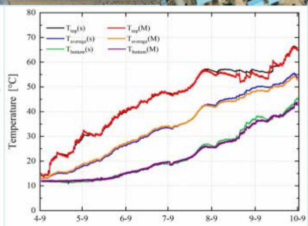
- **Advantages:**
  - Improve efficiency with high operation temperature;
  - Efficiency of collector is more than 50.8%;
- **Disadvantages:**
  - The heating temperature is affected by concentrated solar system;

Current R&D status:

- Numerical and experimental study of an underground water pit for seasonal heat storage;
- Solar district heating system was built up combined 2,225 ㎡Tower solar field and 12,600 ㎡FPC system with 23,000 m3 heat storage system, which has operated more than 1 year for the space heating of 194,000 ㎡ district residential buildings and hotel.
- The 3rd phase SDH System is under construction, which includes an 8,000 ㎡tower-type solar field and a 46,000 m3 season heat storage system.
- An hourly-level configuration and optimization method for SHSSTS was developed.
- Optimization design and control technologies for system source-storage-load coupling under economic constraints.
- A multi-source thermal performance analysis system under dynamic source-load conditions has been developed, proposing an economically optimal solution and a corresponding system control mode.







Further information:

Contact person: **yuanguaofeng@mail.iee.ac.cn**

Future work:

- Experimental validation of low-cost, durable HDPE materials in the 46,000 m³ pit heat storage system.
- Techno-economic research of the SDH technology in China.

IEE-CAS (China)

TASK III-TES

Construction of Large-scale Thermal Energy Storage and Conversion Regulation System

Challenges:

- Engineering Verification Gap: Large-scale renewable energy utilization demands efficient heat-to-power conversion. However, the industry lacks full-process engineering verification for new power cycles like the Supercritical CO2 (sCO2) Brayton cycle, limiting commercial deployment.
- Technical Integration Hurdles: Coupling high-temperature solid particle receivers with compact sCO2 turbine units presents significant challenges, particularly in dynamic control under non-steady-state heat source conditions.
- Simulation & Valuation Disconnect: Traditional tools separate steady-state design from dynamic operation, leading to model distortion. Furthermore, economic assessments often fail to account for real-time electricity spot market mechanisms, hindering accurate commercial viability analysis.

State of the art:

- Technological Breakthrough: Moving beyond component-level research, this project establishes the first domestic 100-kW class full-system demonstration for sCO2 solar thermal power generation.
- Advanced Simulation: Transitioning from empirical estimation to "Digital Twin" level high-fidelity simulation, enabling precise prediction of complex dynamic behaviors.
- Market-Oriented Evaluation: Shifting from static cost analysis to dynamic financial modeling deeply coupled with the electricity spot market.

Concept approach:

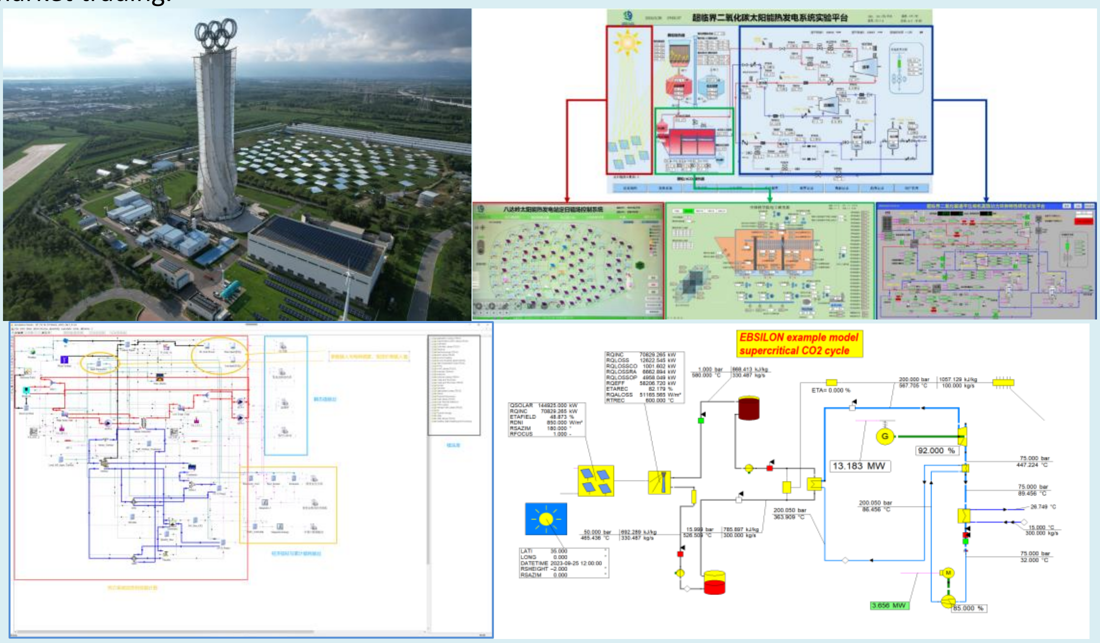
- sCO2 Brayton Cycle + High-Temp Particle Storage:
  Advantages: Validated feasibility as a "Carnot Battery"; achieved high operational parameters (701°C) and power output (200.1kW); excellent dynamic response to renewable fluctuations.

Disadvantages: High complexity in system integration and sealing; requires sophisticated non-steady-state control strategies.

- Multi-scale "Design-Simulation-Evaluation" System:
  Advantages: Features closed-loop verification with empirical data (Error<10%); integrates thermodynamics (Advanced Exergy Analysis) with energy economics (IRR/Spot Market linkage).
  Disadvantages: High dependency on the quality and quantity of real-world operational data for model calibration.

Current R&D status:

- Breakthrough in System Construction: Successfully constructed China's first 100-kW class sCO_2 Brayton cycle solar thermal power generation demonstration system. Third-party testing confirms the system achieved a rated power of 200.10 kW and a particle storage temperature of 701°C, significantly exceeding the original design targets (50 kW / 600°C).
- High-Fidelity Software Platform: Developed a proprietary multi-scale simulation platform (based on Ebsilon/TRNSYS) covering static thermal design and dynamic process simulation. By utilizing strictly verified empirical data, the platform controls dynamic prediction errors for key parameters (temperature, pressure, power) within 10%, achieving high-precision mapping from theoretical models to physical systems.
- Innovative Economic Strategy: Established a cash flow financial model linked with the electricity spot market (incorporating 96-point load characteristics). The research defined capacity configuration and dispatch optimization methods centered on Internal Rate of Return (IRR), providing a scientific decision-making tool for thermal storage power stations to participate in market trading.



Further information:

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Future work:

- Deepen the research on the coupling mechanism between the electricity spot market, capacity configuration, and dispatching strategies, to provide efficient and economic allocation principles under the boundary conditions of strong fluctuations in renewable energy.
- Expand the software platform by incorporating electro-chemical energy storage, hydrogen production, and other systems to realize comprehensive research on efficient multi-energy

conversion.

- Advance research on multi-objective optimization methods to balance thermodynamic efficiency, economic returns, and system stability

IEE-CAS (China)

TASK III-TES

Compact Bio-based Thermal Energy Storage for Buildings

Challenges:

- Existing building thermal energy storage solutions face prominent challenges that hinder their efficiency, adaptability, and sustainability.
- Most traditional energy storage devices are single-function designed, with low utilization efficiency, failing to flexibly meet the diversified thermal needs of buildings across different seasons.
- Traditional thermal supply is highly fossil fuel-dependent, causing high energy consumption and carbon emissions; renewable energy's intermittency leads to severe supply-demand mismatch without efficient storage.
- Existing technologies have inherent bottlenecks: traditional water-based TES has low density and large volume; conventional PCMs are non-eco-friendly and low-conductive; modular/miniaturized designs for compact buildings are lacking

State of the art:

- Building thermal storage centers on water-based TES and PCMs; multi-scenario applicability and thermal efficiency are core research focuses.

Concept approach:

- Versatile water-based TES (heats/cools switchable): Advantages: multi-demand adaptation, high utilization; Disadvantages: complex switching control, strict structural design.
- Bio-based PCM latent heat TES (modular): Advantages: high storage density, eco-friendly, compact; Disadvantages : limited material stability, higher R&D cost.

Current R&D status:

- Series of studies on phase change thermal storage enhanced heat transfer, direct cooling supercooled water dynamic ice slurry storage systems, and compact composite building thermal storage/cooling systems are carried out.
- A versatile modular compact water-based thermal energy storage (TES) device is designed and developed to meet various thermal energy needs of building terminals such as space heating, domestic hot water supply, and cooling.
- Experimental performance characterization and system validation of the device are conducted.

Further information: Contact person: yuanguofeng@163.com

Future work:

- System integration demonstration

KTH Royal Institute of Technology

TASK III-TES

ACTIVITY: Radial flow packed bed TES

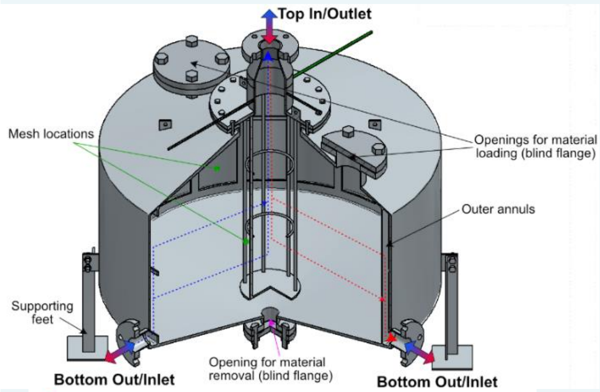
Challenges:

- **Limit the pressure drop introduced by a packed bed TES using gaseous HTF**
- **Reduce the thermal losses in high temperature (>600°C) sensible thermocline based TES**
- **Investigate the packed bed TES performance under variable working conditions**

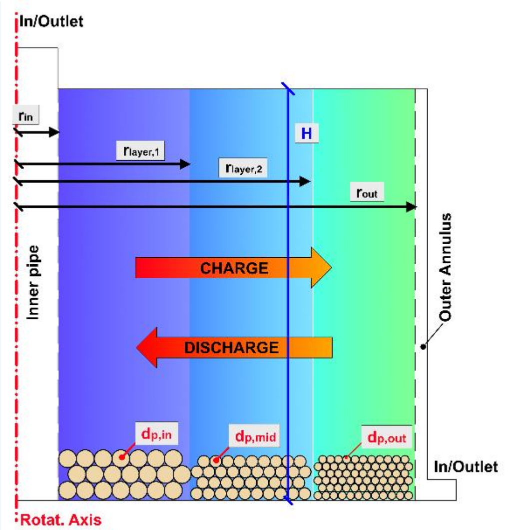
State of the art:

Pressure drop, thermal losses, thermocline degradation and thermal ratcheting have been identified as main drawbacks of sensible packed bed TES.
Limited experimental facilities with gaseous based packed bed TES.

Concept approach:



Radial-flow packed bed TES. Prototype energy capacity of about 50 kWh (TES volume of 0.2 m^2) at working temperatures between 25 and 700°C. Maximum temperature of 750°C.
Piping and butterfly valves arrangement to enable consecutive charge/discharge cycles.
Non-pressurized air stream heated up to a maximum of 800°C by a resistance electrical heater.
Instrumentation: 56 K-type thermocouples for fluid temperature measurements (50 within the packed bed TES), absolute and relative pressure transducers (TES and piping pressure drops).



Advanced solution with layered approach to further minimize the pressure drop and improve thermal stratification limiting thermocline degradation. Currently design optimization is ongoing

Current R&D status:

- Test conducted under various operational conditions
- Identified porosity dis-uniformities
- Numerical CFD models validated based on experimental data
- Assessment of potential future TES design improvements to enhance thermal performance
- Design of advanced TES with enhanced thermodynamic and hydrostatic performance

Further information:

Contact Person: Silvia Trevisan (trevisan@kth.se) , Rafael Guedez (rafael.guedez@energy.kth.se)

S. Trevisan, Y. Jemmal, R. Guedez, and B. Laumert, “Packed bed thermal energy storage: A novel design methodology including quasi-dynamic boundary conditions and techno-economic optimization,” J. Energy Storage, vol. 36, 2021, doi: https://doi.org/10.1016/j.est.2021.102441.

S. Trevisan, R. Guédez, H. Bouzekri, and B. Laumert, “Initial design of a radial-flow high temperature thermal energy storage concept for air-driven CSP systems,” AIP Conf. Proc., vol. 2126, no. July, 2019, doi: 10.1063/1.5117746.

S. Trevisan, W. Wang, R. Guédez, and B. Laumert, “Laboratory Prototype of an Innovative Radial Flow Packed Bed Thermal Energy Storage”, SolarPaces Proceedings 2020.

Future work:

Experimental assessment of TES design improvements (layered concept)

Testing including different filler materials

KTH Royal Institute of Technology

TASK III-TES

ACTIVITY: High temperature sensible TES – Thermal radiation tuning

Challenges:

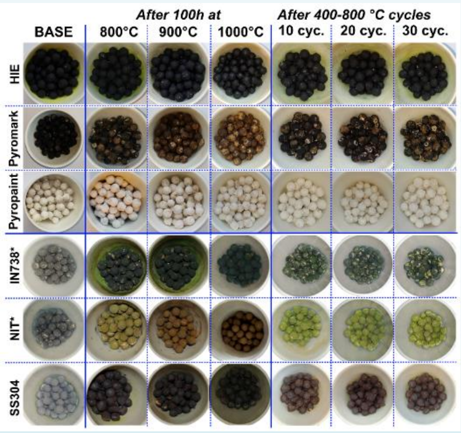
- **Understand influence of thermal radiation heat exchange for high temperature packed bed TES**
- **Modify particle thermal properties to tune thermal radiation and optimize heat transfer within packed bed.**
- **Coating thermal stability experimental investigation**

State of the art:

Numerical correlations available to model effective thermal conductivities at various scales

No coating assessment available

Concept approach:



Numerical modelling and methodology to evaluate the impact of coating layers over packed bed TES effective thermal conductivity

Experimental assessment of thermal stability under long residency at high temperature (up to 1000°C) and under cyclic conditions (30 cycles between 400 °C and 800°C).

Thermal radiation properties (thermal spectral emissivity) measurement

Current R&D status:

- Numerical approach and methodology presented
- Experimental thermal stability tests conducted for more than 20 different coatings (ceramic and metallic based ones)
- Thermal radiative properties measured

Further information:

Contact Person: Silvia Trevisan (trevisan@kth.se), Wujun Wang (wujun.wang@energy.kth.se)

S. Trevisan, W. Wang, and B. Laumert, "Coatings utilization to modify the effective properties of high temperature packed bed thermal energy storage," Appl. Therm. Eng., vol. 185, 2021, doi: 10.1016/j.applthermaleng.2020.116414.

Future work:

Low thermal emissivity coating tests

Packed bed prototype test including coated particles

KTH Royal Institute of Technology

KTH VETENSKAP OCH KONST

SolarPACES

TASK III-TES

ACTIVITY: Molten salts electric heater

Challenges:

- **Design of an electric heater compatible with molten salts**
- **Ensure suitable heat transfer and safe operation for the heater avoiding local hot-spot, salt decomposition and limiting buoyancy phenomena**
- **Electric heater prototype realization and testing**
- **Electric heater installation within SOLARSCO2OL La African demo plant**
- **Study of electric heater design upscaling**

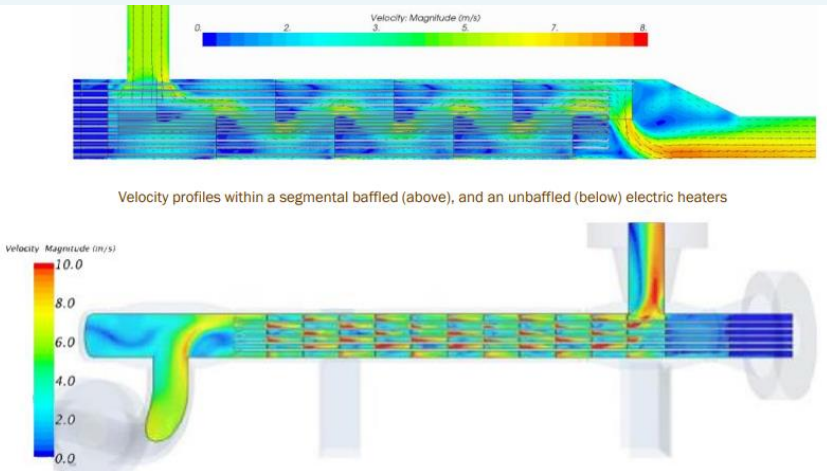
State of the art:

No molten salts electric heater are currently available on market.

Concept approach:

Prototype initial design

Initial design CFD performance evaluation and design improvements



Velocity profiles within a segmental baffled (above), and an unbaffled (below) electric heaters

Current R&D status:

- Initial design of the heater has been presented
- Iterative CFD numerical analysis and design improvements are on-going

Further information:

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Future work:

Final electric heater design description

Component manufacturing

Component testing within SOLARSCO2OL Evora demo plant

Green Energy Park – IRESEN (Morocco)

TASK III-TES

Solid filler materials

Challenges:

- Providing low cost and high-density solid fillers for sensible heat storage with suitable thermal properties and mechanical/chemical/thermal stability.
- Ensuring a fast and efficient numerical and experimental validation protocol for the proposed solid fillers under various operation conditions and HTF's.
- Screening of potential solid fillers availability for large-scale use in CSP target regions.

State of the art:

- Experimental data available for natural fillers but in very limited diversity and some lack of relevance regarding availability and logistic considerations.
- Multiple numerical models for dual media thermocline systems simulation but limited experimental data available for such systems.

Concept approach: *(mentioning advantages & disadvantages)*

- Natural materials as solid fillers for dual media thermocline
- Advantages
  - Low cost materials especially if available near user's location.
  - Potentially suitable for a wide range of temperatures and fluids.
  - Higher local content and lower carbon footprint.
- Challenges
  - Establishing a smooth process for filler selection and validation under operational conditions.
  - Appropriate mapping of available and exploitable materials near candidate CSP/end-user sites.
  - Simple and reliable method necessary for long term durability proof.

Current R&D status:

- Experimental characterization and mapping of natural candidate fillers.
- Study of synthesis possibilities for recycled industrial solid wastes.
- Preparation of a small-scale thermal oil testing and cycling facility for materials validation.

Further information:

Contact person : Khadija EL ALAMI (elalami@iresen.org)/ Hrifech soukaina (Hrifech@iresen.org)

Publications:

- K. El Alami, M. Asbik, H. Agalit, Identification of natural rocks as storage materials in thermal energy storage (TES) system of concentrated solar power (CSP) plants – A review, Solar Energy Materials and Solar Cells, 2020. https://doi.org/10.1016/j.solmat.2020.110599
- S. Hrifech, H. Agalit, E. G. Bennouna, et A. Mimet, « Potential Sensible Filler Materials Thermal Energy Storage for Medium Range Temperature », in *Proceedings of the 1st International Conference on Electronic Engineering and Renewable Energy*, vol. 519, B. Hajji, G. M. Tina, K. Ghoumid, A. Rabhi, et A. Mellit, Éd. Singapore: Springer Singapore, 2019, p. 755-761.

Future work:

- Continue the work on natural resources and recycled industrial wastes mapping and characterization.
- Validation and improvement of simulation models and material selection method with experimental data from thermocline TES prototypes.

Masdar Institute/ Khalifa University (Emirates) in collaboration with MIT

TASK III-TES

Concentrated Solar Power on Demand Demonstration project (CSPon Demo)

Challenges:

- Design & test a direct absorption molten salt volumetric solar receiver/storage system
- Melt molten salt using mainly concentrated solar power back up with electrical resistance heaters
- Test a single tank thermocline with a moving divider plate
- Design & test an air-cooled secondary concentrator

State of the art:

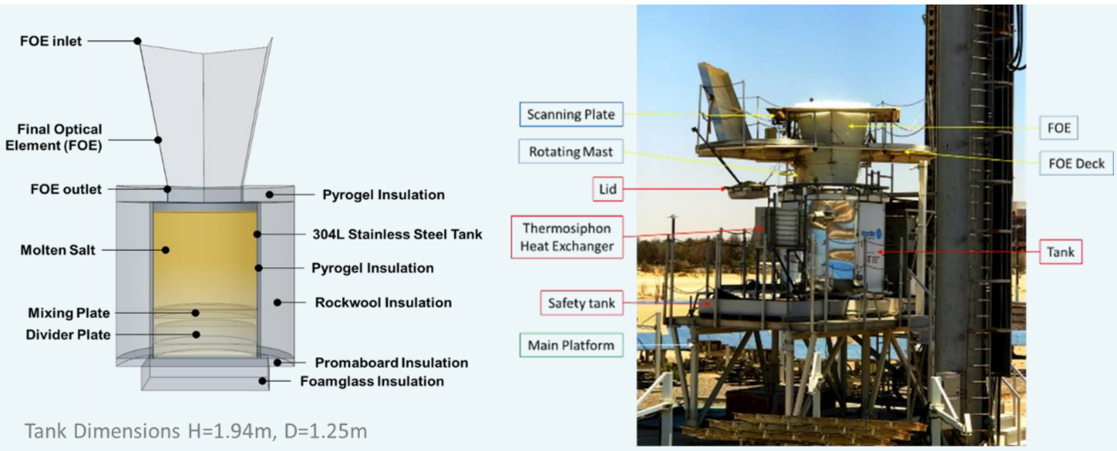
Molten salt is usually pumped in pipes in a tube-wall receiver. No molten salt direct absorption receiver/storage system was tested before.

Concept approach:

The world's first direct absorption molten salt volumetric receiver/storage system was built at pilot scale, commissioned and monitored. In this demonstration a 100 kWth beam-down tower directs solar radiation through a final concentrator into the open aperture of a 1.94 m high and 1.25 m internal diameter tank receiver situated near the ground. The receiver tank is filled with 3,800 kg of 60–40 wt.% NaNO3-KNO3 and serves as a stratified or mixed single tank thermal store that can satisfy evening peak loads or provide baseload power through the night.

Advantages:

- Compared to the parasitic loads of a conventional tower-receiver plant, the energy needed for salt transport from receiver to TES and morning preheat is negligible for this new system.
- The hot-spot problem of tubular receivers is eliminated and the combined receiver/storage tank reduces component costs.
- In-situ initial melting was accomplished using solar energy as the primary input.
- Thermal stratification was maintained by daily cycling of a divider plate and occasional mixing plate actions and hot spots were never observed during several months' operation between 250 and 500 ◦C.
- Three cycles of complete salt freezing and in-situ on-sun re-melting were tested with no operational difficulty and no discernible damage.



Current R&D status:

- Project completed (2014-2017).

Further information:

Contact person: Nicolas Calvet (ncalvet@masdar.ac.ae)

Publications:

- N. Calvet, A. H. Slocum, A. Gil, B. Grange, R. Lahlou, T. T. Hamer, M. Diago, M. Tetreault-Friend, D. S. Codd, D. L. Trumper, and P. R. Armstrong;
- "Dispatchable Solar Power Using Molten Salt Directly Irradiated from Above,"Solar Energy, Volume 220, 15 May 2021, Pages 217-229. https://www.sciencedirect.com/science/article/abs/pii/S0038092X21001729

Future work:

- Test floating quartz spheres to reduce thermal losses by radiation at the surface of the molten salt bath. Upscale to 2 to 3 MWe.

Masdar Institute/ Khalifa University In collaboration with EnergyNest

TASK III-TES

ACTIVITY: Concrete-based Thermal Energy Storage

Challenges:

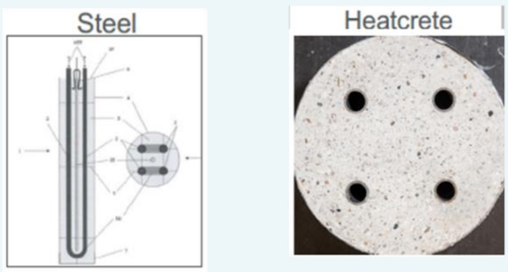
- Demonstrate EnergyNest Technology
- Test durability of Heatcrete® developed by Heidelberg Cement
- Thermal Cycling

State of the art:

Concrete-based storage system was already demonstrated by DLR/Zublin at large scale (2006-2012). The innovation here was in the system design.

Concept approach: *(mentioning advantages & disadvantages)*

The objective of this project was to demonstrate EnergyNest (Norway) thermal energy storage (TES) technology at TRL9. The performance of a 2 × 500 kWh_{th} TES technology has been tested at the Masdar Institute Solar Platform (MISP) at temperatures up to 380 °C over a period of more than 20 months. The TES is based on a novel, modular storage system design, a new solid-state concrete-like storage medium, denoted HEATCRETE® vp1, and has cast-in steel pipe heat exchangers. Measured data after specific intervals during various operation modes were analyzed, and validation of system performance was done through direct comparison between measured values and numerically simulated performance. The demonstrated and measured long-term performance of the TES matches predictions based on performance simulations and proves the operational feasibility of the modular TES design. After accumulating close to 6 000 operational hours, inspection of extracted thermal elements prove that there is no degradation of the storage material, and no separation between steel pipes and storage material is observed. Measurements of core samples of the storage medium extracted from the TES confirms the material properties and stability. The thermal element design and storage material as demonstrated in the TES pilot has thus been proved to work in its final form with expected conditions and shows absolutely no sign of performance degradation. The modularity and simplicity of the TES design enables flexibility in scaling high temperature TES systems for among others industrial waste heat recovery, thermal power plants and concentrating solar power applications, thermal power plant.



High-temperature Concrete TES

Partners:

Supported by

Current R&D status:

Project completed (2014-2017)
Technology is currently commercialized by EnergyNest.

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contact Person: Dr. Nicolas Calvet, Assistant Professor in the Mechanical Engineering Department at Masdar Institute/Khalifa University, Founder and chair of the Masdar Institute Solar Platform,
nicolas.calvet@ku.ac.ae
https://www.linkedin.com/in/nicolas-calvet-aa01b155/

Publication:
N. Høivik, C. Greiner, J. Barragan, A. Crespo Iniesta, G. Skeie, P. Bergan, P. Blanco, and N. Calvet;
"Long-term Performance Results from EnergyNest Thermal Energy Storage Technology Tested at the Masdar Institute Solar Platform,"
Journal of Energy Storage, Vol. 24 (2019) 100735.
https://www.sciencedirect.com/science/article/pii/S2352152X18306480

Future work:
None.

Masdar Institute/ Khalifa University In collaboration with Azelio AB & Masdar

جامعة خليفة Khalifa University

Masdar A MUBADALA COMPANY

AZELIO

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

ACTIVITY: Electrical Thermal Energy Storage (ETES)

Challenges:

- Test a complete ETES solution
- Use a metal alloy as a phase change material (PCM)
- Melt the PCM using electrical resistance heaters
- Transfer the latent heat to a Stirling engine
- Thermal Cycling

State of the art:

Azelio's TES.Pod is the first commercial latent heat storage system available on the market.

Concept approach: *(mentioning advantages & disadvantages)*

The objective of this project is to validate Azelio's TES.Pod technology. A Solar photovoltaic field will produce 500 kW_e of electricity during the day. This clean electricity will be used to melt a PCM. At night the PCM will release latent heat that will power 4 Stirling engines to regenerate power on demand. The target is to generate 50 kW_e 24/7.

Advantages:

- This ETES solution can be used with all renewable energy systems such as photovoltaic, wind power, CSP, or even excess grid electricity.
- Latent heat storage has a higher storage density than sensible heat.
- Metal alloys have a high thermal conductivity leading to efficient heat transfer.
- High heat-to-electricity conversion efficiency of the Stirling engine (up to 30%).
- Off-grid solution.

Current R&D status:

The pilot is completed and will be commissioned soon.

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contact Person: Dr. Nicolas Calvet, Assistant Professor in the Mechanical Engineering Department at Masdar Institute/Khalifa University, Founder and chair of the Masdar Institute Solar Platform,
nicolas.calvet@ku.ac.ae
https://www.linkedin.com/in/nicolas-calvet-aa01b155/

Publication:

[1] A. Dindi, N. Lopez-Ferber, D. Gloss, Erik Rilby, and N. Calvet;
"Compatibility of an Aluminium-Silicon Metal Alloy Based Phase Change Material with Coated Stainless Steel Containers,"
Journal of Energy Storage, Volume 32, December 2020, 101961.
https://www.sciencedirect.com/science/article/abs/pii/S2352152X20317977

Website:
https://www.azelio.com/

Future work:
Testing the pilot during one full year to collect data.

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TASK III-TES

multiTESS: Innovative Power-to-Power&Heat-Concept

Challenges:

- Thermal high-temperature storage operating up to 1000 °C as a central element for the temporal decoupling of generation and demand
- Innovative electrical heating concept with a temperature range up to 1000 °C
- Start-up of system
- Control of the overall system

State of the art:

- Electrical air-heater up to 750 °C
- No commercial storage in the area of electricity generation above 600 °C available
- Power-to-heat concepts up to 115 °C

Concept approach:

- Development of an electro-thermal energy storage working at 1000 °C that allows multiple options of discharging (electrical power and heat at different temperature levels)
- In order not to be restricted to a thermal energy source for charging, an electrical heater will be implemented to use all kinds of renewable electricity to charge the storage
- A proven design of a high-temperature ceramic storage will be adapted and used for this concept

Advantages:

- Flexible and decentralized supply of heat and electricity based on renewable energy
- Contribution to the decarbonisation of the industry sector
- Heat supply at different temperature levels up to 1000 °C
- Highly cost-efficient electricity storage
- New approach of sector coupling
- Can easily be extended by a gas heater to provide firm capacity also during dark doldrums

Disadvantages:

- Electricity used for charging will partly discharged as heat and partly as electricity. The distribution may vary with the application

Current R&D status:

- Construction of pilot plant: *multiTESS* – multifunctional electro-thermal energy storage
- The design and dimensioning of the storage module is based on the experiences gained with the storage module at the Jülich solar tower

Source: Kraftanlagen München GmbH

Further information:

Contact person: Prof. Dr. Ulf Herrmann (ulf.herrmann@sij.fh-aachen.de)

Publications:

- Herrmann, U., Dittmann-Gabriel, S., May, M., et al.: Hochtemperatur-Wärmespeicher für die Strom- und Wärmewende (2019), in „Solarzeitalter, 31. Jahrgang, 2/2019, pp.18-23“

Partner: Kraftanlagen München GmbH, Otto Junker GmbH, Dürr Systems AG

Future work:

- Pilot plant performance analyses under transient operating conditions
- Optimization of the overall system
- Integration of different types of heat engines
- Evaluation and verification of technical and economic feasibility

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TASK III-TES

Air - bulk material heat exchanger for Thermal Energy Storage (VeSuW)

Challenges:

- Avoiding fluidic phenomenologies of direct material contact.
- Structural durability at over 800°C

State of the art:

- Fluid bed heat exchanger: high operating costs.
- Trickle film counterflow heat exchanger: low energy transport rate.
- Rotary heat exchanger: high investment and operation costs.
- Shell and tube heat exchanger: high pressure losses and investment costs.

Concept approach:

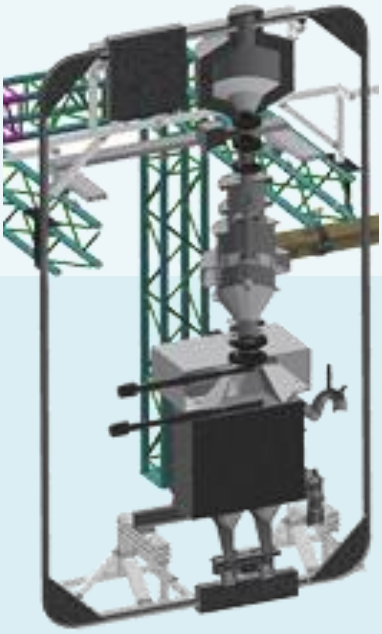
- Iterative development based on laboratory experiments and computational simulations.
- Particle tracking via PIV.
- Investigation of long-term rheology of bulk materials.
- Combination of fluid and DDEM simulations.

Advantages:

- Highest energy transport density and efficiency.
- Limited plant complexity (low investment costs).
- Lower operating costs.
- Good scale ability.

Disadvantages:

- Height Requirements.
- Material cross-contamination.



4Current R&D status:

- Short-term tests with various experimental heat exchangers.
- Long term tests of the 6th heat exchanger revision.
- Designing of a new high temperature bulk material flow restrictor.
- Validation of simulation results.

Further information:

Contact person: Prof. Dr. Ulf Herrmann (**ulf.herrmann@sij.fh-aachen.de)**
Website: Herrmann, U., Teixeira Boura, C**.,** Skoda, S., Sattler, J.C.; VeSuW, HiTexStor

Future work:

- Optimizing the overall efficiency regarding pressure and insulation losses.
- Optimizing lifespan and operating costs.
- Transfer innovation to the next level

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TASK III-TES

Power-to-heat technologies (P2H) combined with molten salt storage for the application in industry and in PV-CSP hybrid power plants

Challenges:

- Determination of the most effective design of a P2H system with molten salt storage (Carnot battery) to use surplus electricity in industrial processes and PV-CSP hybrid power plants
- Commercial heat pumps are limited in temperature. An adequate medium has to be found

State of the art:

- Heat pump with vapor-compression cycles are currently limited to temperatures up to 160 °C
- Molten salt storage tanks are deployed in many of the current CSP plants worldwide. Solar salt (a mixture of 60 % $NaNO_3$ and 40 % KNO_3) is the standard medium used in this type of power plants. The maximum temperature is in the range of 550 – 580 °C
- Electric heaters are used in many different industries, such as processing plants, chemical, food processing, medical, pharmaceutical, utilities, marine, oil and gas, etc.

Concept approach:

- Carnot batteries make it possible to use surplus energy from the power grid converting it into heat. The energy is stored as heat in molten salt tanks and it can be used at a later time to drive industrial processes. Two P2H concepts are investigated: Electric heaters and heat pumps
- The system contributes to grid stability and has the advantage that renewable energy sources with fluctuating power input do not have to be switched off for grid or frequency stabilization. This creates additional capacity for energy production from renewable energy sources
- The design of the two P2H technologies is also being examined in an innovative concept for their application in PV-CSP hybrid power plants. Low-cost PV electricity is temporarily stored in the Carnot battery and consequently offered according to demand

Current R&D status:

- Development of a dynamic model of a resistance heater with molten salt storage
- Technical parameter analysis of different high temperature heat pump concepts
- Development of high temperature heat pump models for simulating different power capacities and media
- Market analysis of different industrial branches and energy intensive processes

Further information:

Contact person: Dipl.-Ing. Cristiano Teixeira Boura (boura@sij.fh-aachen.de)
Website: https://www.fh-aachen.de/en/research/solar-institute-juelich/focus-areas/projects-solar-thermal-systems/

Future work:

- Performance simulations for different industrial consumers
- Performance simulations for different concepts in PV-CSP hybrid power plants

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TASK III-TES

SpOpt: storage optimization for the Jülich solar tower power plant

Challenges:

The focus of this work is to increase the degree of utilization as well as the flexibility and cost-effectiveness of the storage system of the Jülich solar tower power plant.

State of the art:

The STJ storage system basically shows the behavior of a regenerator. In case of high solar radiation, part of the thermal energy can be stored and discharged again if necessary. The control of the air flow is achieved by means of valves and the output regulation of two blowers.

Concept approach:

- Development of an optimized air circuit and storage system for solar thermal power plant concept with open volumetric receiver
- The aim is to achieve the highest possible plant efficiency and high electricity production when investigating the air flow within the storage system.
- Determination of operating modes that preserve the conventional part of the plant (especially the steam generator and turbine), thus increase its durability, and allow the use of less robust but more efficient components.
- Exploitation of the optimisation possibilities of the storage configuration and the operating strategies, with regard to flexibility, stable energy discharge, power generation and efficiency.

Current R&D status:

- **For the simulation of the storage model as well as of the complete solar tower power plant with open volumetric receiver a component library was developed.**
- Several optimized storage concepts have been developed and assessed in terms of their flexibility, temperature stability during discharge mode as well as power yield, operational costs and efficiency of the overall system. The operating strategies of the storage system have been adjusted to fit into the overall operating strategy of the power plant. For this purpose, annual calculations of the storage systems were carried out with optimized process control. One of the implemented and analyzed storage concepts showed improvements in the start-up process of the power plant and consequently leads to an increase in the absolute power generation.

Further information:

Contact person: Prof. Dr. Ulf Herrmann (**ulf.herrmann@sij.fh-aachen.de)**

Publications:

- Kronhardt, V.; Alexopoulos, S.; Reißel, M.; Latzke, M. ; Rendon, C. ; Sattler, J. ; Herrmann, U.: “Simulation of operational management for the Solar Thermal Test and Demonstration Power Plant Jülich using optimized control strategies of the storage system” (2014), in „ Energy procedia. 2015. Seite: 1 - 6“
- Kronhardt, V. ; Alexopoulos, S. ; Reißel, M. ; Sattler, J. ; Hoffschmidt, B. ; Hänel, M. ; Doerbeck, T.: “High-Temperature Thermal Storage System for Solar Tower Power Plants with Open-Volumetric Air Receiver.” (2013), in „ Energy procedia. Vol. 49 (2014). Seite: 870 - 877 “

Future work:

- Investigation of possible future hybridization of the tower power plant in Jülich
- Upscaling of the regenerative storage system for follow-up power plant projects

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TASK III-TES

Interconnection of Molten Salt Storage Tanks

Challenges:

Most of the modern parabolic trough collector (PTC) power plants and solar tower power plants deploy molten salt tanks to store thermal energy. The retrofitting of PTC power plants with molten salt tower system is investigated to prolong the discharge capacity of the existing PTC storage. The main challenges are:

- Investigate the most effective coupling possibility of PTC and solar tower storage systems
- The dispatchability of commercial PTC plants is determined by existing contractual terms and conditions. Retrofitting with an increase in power capacity requires a redefinition of the contractual conditions.

State of the art:

Most commercial PTC power plants deploy thermal oil as heat transfer fluid with indirect two-tank molten salt thermal energy storage. The operating temperature of the thermal oil is limited to 430 °C; thermal oil absorbs energy from concentrated solar irradiation to provide the heat needed for generating steam in a power cycle. A binary mixture of 60 % $NaNO_3$ and 40 % KNO_3, also denoted as Solar salt, has become the standard medium for commercial solar thermal storage systems (PTC as well as molten salt tower systems). The melting temperature is in the range of 230 °C and the maximum temperature is in the range of 550 - 580 °C.

Concept approach: *(mentioning advantages & disadvantages)*

- Development and implementation of operating strategies to extend storage discharge capacity
- Determination of the most effective storage configuration for thermal load shifting between PTC and molten salt tower storage tanks
- Design and annual performance simulations of a combined storage system

Current R&D status:

Simulations have shown that an interconnection between the salt storage systems of a combined PTC-molten salt tower power plant extends the discharge operation time of the existing PTCs storage system. The developed storage configuration positively contributes to a reliable and continuous power generation, especially during winter.

Further information:

Contact person: Carlos Rendón; (rendon@sij.fh-aachen.de)

Publications:

- Rendón, C., et al. (2018), Retrofitting of existing parabolic trough collector power plants with molten salt tower systems. AIP Conference Proceedings 2033, 030014 (2018); https://doi.org/10.1063/1.5067030

Future work:

Further investigation on the developed storage configuration.

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TASK III-TES

EDITOR: Parabolic Trough Collector with Concrete Thermal Energy Storage

Challenges:

- Creation and validation of an accurate dynamic simulation model of a concrete thermal energy storage (C-TES)
- Reduced model complexity to maintain an acceptable simulation speed
- Implementation of C-TES model in overall system model including a parabolic trough collector model, a steam boiler model, pump model and system controller.
- Model stability of dynamic overall system with respect to switching of operation modes

State of the art:

- A state-of-the-art parabolic trough collector system with concrete thermal energy storage is in operation on the premises of KEAN Soft Drinks Ltd in Limassol, Cyprus. See website URL in the section "Further information" below. A photograph of the system is shown in Figure 1 below.

Figure 1: View onto the parabolic trough collector system with C-TES (Photograph ©Protarget AG)

Concept approach:

- Creation of the model according to the design parameters from the real storage system
- Pre-validation with design parameters
- Optimisation and implementation of C-TES operation modes
- Validation with measurement data from real plant operation
- Scale-up simulation of C-TES for full dispatchability.

Current R&D status:

- A fully functional dynamic C-TES model in reduced complexity was developed and implemented in the overall system model described above.
- The overall system model uses all operation modes of the real system
- A stand-alone, high complexity model of the C-TES with fast simulation speed can also be used to evaluate the performance of the C-TES alone
- The C-TES model is validated

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

- Contact: Prof. Dr.-Ing. Spiros Alexopoulos; alexopoulos@sij.fh-aachen.de

- Project EDITOR, Solar-Institut Jülich https://www.fh-aachen.de/en/research/solar-institute-juelich/focus-areas/editor/
- J. C. Sattler, S. Alexopoulos, R. A. Chico Caminos, J. Mitchell, V. Ruiz, S. Kalogirou, P. Ktistis, C. Teixeira Boura, U. Herrmann, "Dynamic Simulation Model of a Parabolic Trough Collector System with Concrete Thermal Energy Storage for Process Steam Generation", AIP Conference Proceedings **2126**, 150007 (2019); https://doi.org/10.1063/1.5117663
- J. C. Sattler, R. A. Chico Caminos, V. Atti, N. Ürlings, S. Dutta, V. Ruiz, S. Kalogirou, P. Ktistis, R. Agathokleous, S. Alexopoulos, C. Teixeira Boura, U. Herrmann, "Dynamic Simulation Tool for a Performance Evaluation and Sensitivity Study of a Parabolic Trough Collector System with Concrete Thermal Energy Storage", to be published in AIP Conference Proceedings in 2020.
- J. C. Sattler, R. A. Chico Caminos, N. Ürlings, S. Dutta, V. Ruiz, S. Kalogirou, P. Ktistis, R. Agathokleous, C. Jung, S. Alexopoulos, V. Atti, C. Teixeira Boura, U. Herrmann, "Operational Experience and Behaviour of a Parabolic Trough Collector System with Concrete Thermal Energy Storage for Process Steam Generation in Cyprus", to be published in AIP Conference Proceedings in 2020.

Future work:

- Deployment and optimisation of C-TES model and operation modes in future projects

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TASK III-TES

Electro-thermal energy storage technologies in combination with power-to-heat systems (P2H) for the application in coal-fired power plants, PV-CSP hybrid power plants, etc. within different research projects

Challenges:

- Determination of the most effective design **of a P2H system with molten salt storage (electro-thermal energy storage)** to use surplus electricity in industrial processes and PV-CSP hybrid power plants
- Investigation of a proper medium for the application in high-temperature heat-pumps
- Development of the conversion of a coal-fired power plant into an electro-thermal energy storage system on an economical GWh scale

State of the art:

- Heat pump with vapor-compression cycles are currently limited to temperatures up to 160 °C
- Molten salt storage tanks are deployed in many of the current CSP plants worldwide. Solar salt (a mixture of 60 % $NaNO_3$ and 40 % KNO_3) is the standard medium used in this type of power plants. The maximum temperature is in the range of 550 – 580 °C
- Electric heaters are used in many different industries, such as processing plants, chemical, food processing, medical, pharmaceutical, utilities, marine, oil and gas, etc. and technically implementable on a GW scale
- Electrical storage systems are currently only on a MWh scale available

Concept approach:

- Electro-thermal energy storages make it possible to use surplus energy from the power grid converting it into heat. The energy is stored as heat in molten salt tanks and it can be used at a later time
  - to drive the power plant for electrical power generation and supply district heating networks

  - to drive industrial processes
- Two P2H concepts are currently investigated: electric heaters and heat pumps
- The systems contribute to grid stability and have the advantage that renewable energy sources with fluctuating power input are not to be switched off for grid or frequency stabilization. This creates additional capacity for energy production from renewable energy sources
- The design of the two P2H technologies is also being examined in an innovative concept for the application in PV-CSP hybrid power plants. Low-cost PV electricity is temporarily stored in the electro-thermal energy storages and consequently offered according to demand
- The market potential for the electro-thermal energy storage power plant coupled to district heating networks are being investigated under economic aspects

Advantages and disadvantages of the storage system:

+ Ensuring supply security of electrical energy without coal-fired power plants
+ Ongoing use of coal-fired power plant infrastructure after coal phase-out
+ Short-term contribution to energy system transformation and socially acceptable coal exit
+ Can be built and operated independently of geographical or geological conditions, unlike pumped storage power plants
+ Good scalability
+ Simple extension with a gas heater to provide firm capacity also during dark doldrums

– Certain minimum spread on the electricity market required. No economically viable operation yet

Current R&D status:

- Completed study on the integration of thermal power storage systems into existing power plant facilities (I-TESS study, 2017): Development of the technical concepts, determination of investment costs, analysis of options for the integration of such electro-thermal power storage systems in existing power plants
- Development of concepts for upgrading CHP coal-fired power plants by adding a high-temperature heat storage system with electric heating
- Risk analysis and Life Cycle Assessment of electro-thermal energy storage power plants
- Development of a dynamic model of a resistance heater with molten salt storage
- Technical parameter analysis of different high temperature heat pump concepts
- Development of high temperature heat pump models for simulating different power capacities and media
- Market analysis of different industrial branches and energy intensive processes

Further information:

Contact persons:

- Prof. Dr. Ulf Herrmann (**ulf.herrmann@sij.fh-aachen.de**)
- Dipl.-Ing. Cristiano Teixeira Boura (**boura@sij.fh-aachen.de)**

Website: **https://www.fh-aachen.de/en/research/solar-institute-juelich/focus-areas/projects-solar-thermal-systems/**

Future work:

- Performance simulations for different industrial consumers
- Performance simulations for different concepts in PV-CSP hybrid power plants
- Investigation of other storage concepts for the carnotisation of the thermodynamic processes

SUPSI, ETHZ ALACAES (Switzerland)

University of Applied Sciences and Arts of Southern Switzerland
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TASK III-TES

Numerical and experimental analysis of a packed bed TES system suitable for Adiabatic Compressed-Air Energy Storage (A-CAES) technology

Challenges:

- TES systems operating at high temperature (550°C) and high pressure (up to 100 bars).
- Experimental investigation on the pilot plant for demonstrating the applicability of A-CAES technology.

State of the art:

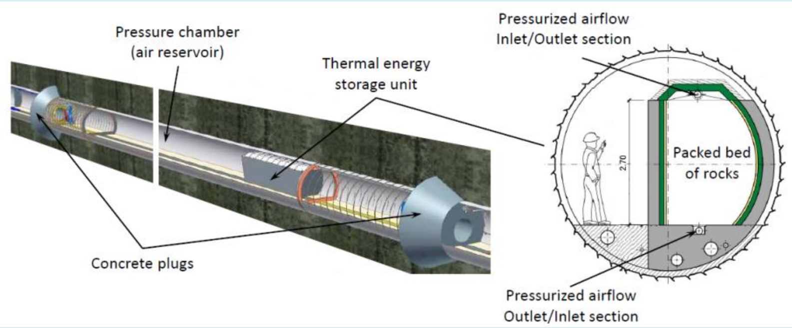
In the field of large-scale electric energy storage, a valid alternative to pumped hydroelectric energy storage is represented by compressed-air energy storage (CAES). As of today, two CAES plants are successfully in operation: the 321 MW Huntorf plant (Germany) and the 110 MW McIntosh plant (USA). The round-trip efficiency of these CAES plants, 42% and 54% for the former and the latter respectively, is limited by the fact that the thermal energy produced during compression is wasted and therefore they need to burn fuel to increase the enthalpy of the compressed air prior to expansion. To overcome the limitation of conventional CAES plants, the A-CAES concept of has been proposed. In this technology, a TES is exploited to store the thermal energy produced during compression to be recovered prior to expansion. The expected round-trip efficiency of A-CAES is in the order of 70%.

Concept approach:

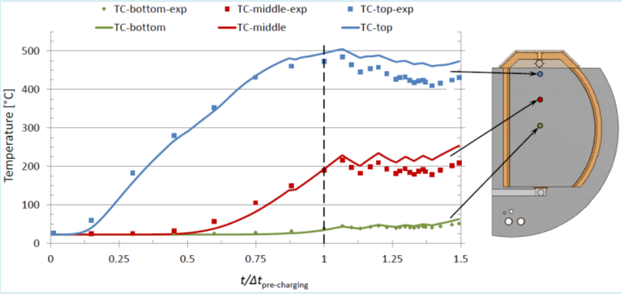
- Since the TES can be considered the key component of the A-CAES technology, its thermo-fluid dynamics behavior has been carefully evaluated by means of computational fluid dynamics (CFD) simulations.

Current R&D status:

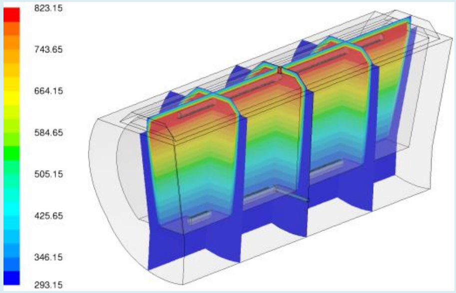
- To evaluate the feasibility and applicability of the AA-CAES concept, the first pilot plant has been built in Pollegio (CH). A 120 m long section of an existing tunnel in the Swiss Alps has been exploited as high-pressure air reservoir (up to 33 bars). The latter was enclosed by building two 5 m thick concrete plugs at the two ends. A single-tank TES, based on a 44 m^3 packed bed of natural rocks, has been installed into the pressure chamber.



- A 2D and 3D CFD modeling approach has been developed to evaluate the performance of the TES unit under investigation. The numerical model has been successfully validated with experimental data gathered from the Pollegio A-CAES pilot plant.



Numerical model validation: simulation results (solid lines) VS experimental data (markers)



TES unit temperature contours (Temperature [K])

Further information:

Contact person: Mr. Simone Zavattoni (simone.zavattoni@supsi.ch)

Publications:

- S.A. Zavattoni, L. Geissbühler, M.C. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, “CFD modeling of the Pollegio A-CAES pilot plant TES system”, Swiss Competence Centre for Energy Research for Heat and Electricity Storage (SCCER-HaE), Annual report, 2016.

Future work:

Evaluating the effect of exploiting a combined sensible/latent heat TES solution.

SUPSI, ETHZ ALACAES (Switzerland)

University of Applied Sciences and Arts of Southern Switzerland

SUPSI

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Performance evaluation of the TES system integrated into the first pilot plant using air as heat transfer fluid

Challenges:

- Accurate description of the thermo-fluid dynamics behavior, and performance evaluation under cyclic conditions, of the packed bed TES unit integrated into the pilot plant.

State of the art:

Single-tank, or thermocline, TES systems represent a reliable and affordable alternative to the commonly exploited two-tank solution in conventional CSP plants. Computational fluid dynamics (CFD) is a valuable tool for accurately analyzing the thermo-fluid dynamics behavior of this kind of TES allowing to predict the overall system performances.

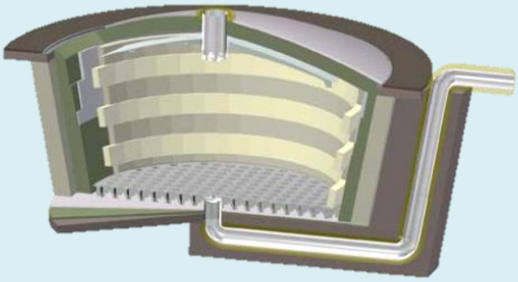
Concept approach:

- A previously validated computational fluid dynamics (CFD) approach was followed to evaluate the thermo-fluid dynamics behavior of the TES unit under investigation subjected to a total of 5 pre-charging cycles followed by 60 consecutive cycles.
- The TES performance was also evaluated on the basis of the first- and the second-law of thermodynamics.

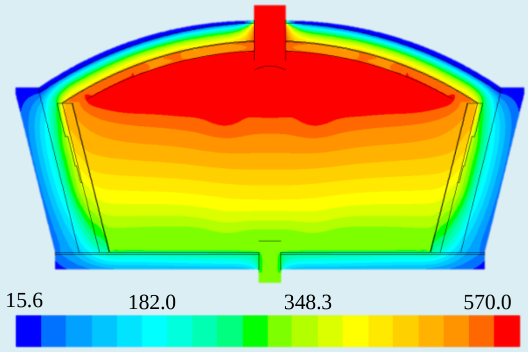
Current R&D status:

- The first 3 MW_{th} parabolic trough CSP pilot plant using air as heat transfer fluid has been constructed in Ait-Baha (Morocco).

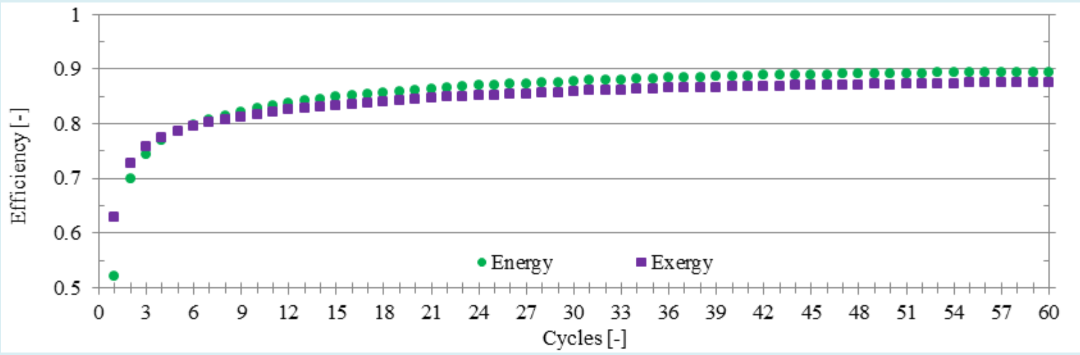
- A packed bed TES unit, 100 MWh_{th} capacity, has been integrated into the pilot plant and accurately analyzed by means of transient CFD simulations:



CAD model of the TES unit



45th charging – Temperature contours (°C)



Resulting transient TES performance evaluation

Further information:

Contact person: Mr. Simone Zavattoni (**simone.zavattoni@supsi.ch)**

Publicaions:

- S. A. Zavattoni, G. Zanganeh, A. Pedretti, and M. C. Barbato, " Numerical analysis of the packed bed TES system integrated into the first parabolic trough CSP pilot-plant using air as heat transfer fluid," 23rd SolarPACES conference, 2017.
- S. A. Zavattoni, G. Zanganeh, A. Pedretti, and M. C. Barbato, "High temperature thermocline TES – Effect of system pre-charging on thermal stratification," AIP Conference Proceedings 1734 (050043), 2016.

Future work:

Evaluating the effect of some key parameters on thermal stratification.

TECNALIA (Spain)

TASK III-TES

Thermal Energy Storage (TES)

Challenges:

- Thermal Energy Storage solutions for very high temperature CSP: Novel salt mixtures, metallic and nano-enhanced HTFs, storage tank concepts and designs.
- Find a solution for thermal storage in DSG: research on metallic and nanosalt PCMs.
- Cost reduction of state of the art solutions, focused on TES and container materials.

State of the art:

Current TES systems are based on the double-tank concept. In spite their good performance and robustness, next generation CSP plants requires new materials and engineering concepts.

Concept approach:

TES FOR VERY HIGH TEMPERATURE CSP PLANTS.

- Advantage: other materials and concept solutions from other sectors where high temperatures are involved, such as space technology, can be transferred to CSP.
- Disadvantage: increased cost of materials and components. Gained efficiency needs to show a higher economic benefit than the extra cost.

TES FOR CSP PLANTS BASED ON DSG TECHNOLOGY. The research is focused on the development of PCMs and novel engineering structures to be used as PCM containers.

- Advantage: a higher amount of energy stored per unit of volume and, therefore lower costs per kWh will be achieved.
- Disadvantage: a balance must be reached between the higher cost of PCM materials and the savings derived from their application.

COST REDUCTION IN CURRENTLY USED SYSTEMS. Our interest is the research on novel nanostructured materials based on inorganic salts with enhanced heat transfer properties.

- Advantage: the amount of storage media is significantly reduced. This will have an impact on the global cost of the TES system.
- Disadvantage: further research is required to ensure the good performance and stability of these novel TES materials.

Current R&D status:

- Analysing other technologies for high temperature applications.
- Synthesis of low melting point metallic alloys and novel nanosalts as PCM for DSG.
- Optimization of heat transfer rate of current inorganic salts for double tank systems.

Further information:

- Contact person: Javier Nieto ; javier.nieto@tecnalia.com
- Muñoz-Sánchez B. et al. Assessment of the determination of Specific Heat of Molten Salt doped with Nanoparticles by means of the DSC Technique. Greenstock. Beijing 2015
- Muñoz-Sanchez B. et al. Nanoparticle Size Evaluation through Dynamic Light Scattering (DLS) technique in a Nitrate Salt doped with Ceramic Nanoparticles. CIIEM15. París (2015)
- Nieto-Maestre J. et al. Novel Metallic Alloys as Phase Change Materials for Heat Storage in Direct Steam Generation Applications. SolarPACES15. Cape Town (2015).

Future work:

- TES for very high temperatures: techno-economic analysis of considered concepts.
- TES for DSG: characterization of metallic and nanostructured PCMs. Compatibility with container materials and stability of physical and chemical properties.
- Sensible TES: more stable nanofluids based on salts with wider working temperature range

TEKNIKER (Spain)

Tekniker MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Molten Salts (MS) for TES

Challenges:

- Condition monitoring of thermal and physical properties of these materials at working conditions
- Assessment of MS quality at different used stage
- Definition of operational limits for MS
- Synthesis of new MS with low melting temperature
- Find a compromise between low melting temperature Tm and corrosion properties of new MS

State of the art:

- There is not enough knowledge about the real service life of MS that operates in SCP plants

Concept approach:

Advanced test bench (up to 5kg) that can operate at real working conditions (P,T) with on line sensors to monitor chemical changes in the MS during ageing process

- Advantages:
  - New proposed materials for thermal storage application can be study/evaluated and characterize (thermal, physical and chemical properties)
  - Corrosion properties of constructive materials can be tested against thermal storage materials
    - New or current materials against new molten salts
    - New or current materials against current solar salts

Current R&D status:

- Advanced chromatographic techniques to evaluate MS composition
- Collaboration with other corporations to set up protocols for thermal characterization
- Microstructural characterization on the corroded samples using SEM, EDX and XRD techniques.
- Materials basic characterization prior and post-corrosion tests.

Further information:

Contact person:

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- Cristobal Villasante: cristobal.villasante@tekniker.es
- Elena Fuentes: elena.fuentes@tekniker.es

Future work:

Continue the study of new thermal materials for TES

TEKNIKER (Spain)

Tekniker
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

SolarPACES
Solar Power & Chemical Energy Systems

TASK III-TES

ADVANCED Heat Transfer Fluids (HTF)

Challenges:

- Enhance thermal properties (Cp, thermal storage)
- Wide working temperature window of current HTF
- Reduce HTF volume in the installation
- Define operational limits of HTF in use
- Condition monitoring of HTF through advanced analytical techniques

State of the art:

- Current HTF has a solidification temperature of 12ºC and upper operational temperature at 398ºC, with limited thermal storage properties.
- Quality assessment is based on very basic techniques (real aged state of HTF is not known)

Concept approach:

- Selective HTF additivation with thermal active additives
  - Microencapsulated thermal material (Phase Change Material, Ionic liquids, Salts)
  - Non-encapsulated thermal materials
- Advance test-bench to evaluate new or current HTF behavior under simulated working conditions (T, P)
- Advanced techniques based on chromatography to assess and quantify degradation. (Selective identification and monitoring of chemical compounds)

Current R&D status:

- Collaboration with HTF manufacturers
- HTF with IL has higher thermal resistance without change pumpeability properties

Further information:

Contact person:

- Marta Hernaiz; (**marta.hernaiz@tekniker.es**)
- Cristobal Villasante;(**Cristobal.villasante@tekniker.es)**

Publications:

- M.Hernaiz, N. Uranga Improved thermal fluids WO 2013182713 A1
- M. Hernaiz, E.Aranzabe LUBMAT 2012: “Condition monitoring of heat transfer fluid in parabolic trough collectors of solar power plants”
- M. Hernaiz SCP Today 2013-Strategies to improve solar heat transfer fluids behavior
- M. Hernaiz, N.Uranga LUBMAT 2012: “Improvement of solar heat transfer fluid behavior at low temperature by dispersing encapsulated and non encapsulated phase change materials (PCM)

Future work:

Continue in the research line of development “advanced HTF” with the aim of improve thermal properties

LATENT HEAT STORAGE

CEA – LITEN
(France)

TASK III-TES

Latent Heat Storage with Phase Change Materials

Challenges:

- No available storage technology at commercial stage for DSG plants.
- Pure $NaNO_3$ is an attractive solution due to its favorable physical properties and low cost, but its low thermal conductivity impacts on the size and cost of the storage.
- The Latent Heat Storage module is the critical component for the storage system of a DSG solar plant; indeed it stores more than 50% of the total thermal energy.

State of the art:

- Graphite as heat transfer matrix below 250 °C.
- Encapsulated concept with metallic envelopes, not favorable for high pressure applications.
- Vertical bundle of parallel tubes with high pressure condensing/evaporating water inside and a static PCM volume outside.

Concept approach: Low cost and robust heat transfer enhancement methods on the PCM side, for example using aluminum inserts around the vertical finned tubes:

Current R&D status:

- Small experimental loop with transparent test sections for visualization and phenomenological observation of low temperature PCM.
- Two PCM storage modules (3 m^3 and 1m^3) have been tested successfully on the *LHASSA* experimental facility:
  - Test campaigns to validate the thermo-hydraulic behavior of the storage under operating conditions similar to commercial DSG CSP plants,
  - Measured storage performances meeting the specifications,
  - Optimized operating procedures,
  - Good agreement with simulation results given by dynamic models developed at CEA,
- A demonstrator-scale (≈ 9 m^3) PCM storage integrated in a CSP Fresnel power plant prototype was built and is under testing.
- A facility (DURASSEL) for accelerated ageing tests of pressurized tubes in PCM (≈ 25 l) is operational and available for new tests.
- Validated multi-scale modelling approach (CFD and system model)

Further information:

Contact person: Grégory Largiller (gregory.largiller@cea.fr), Fabrice Bentivoglio (fabrice.bentivoglio@cea.fr

Publications:

- Olcese M, Couturier R, Fourmigué JF, Garcia P, Raccurt O, Robin JF, Senechal B, Rougé S, Thonon B. Design methodology and experimental platform for the validation of PCM storage modules for DSG solar plants, 19th SolarPACES International Symposium, Las Vegas, USA, 17-20 september 2013.
- Garcia P, Olcese M, Rougé S. Experimental and numerical investigation of a pilot scale latent heat thermal energy storage for CSP power plant, Energy Procedia 69, 842-849 (2015).
- Beust C., Franquet E., Bédécarrats J.P., Garcia P. Predictive approach of heat transfer for the modelling of large-scale latent heat storages, Renewable Energy 157, 502-514 (2020).
- Garcia P, Largiller G. Performances and control aspects of steam storage systems with PCM: Key learnings from a pilot-scale prototype, Applied Energy 325 (2022) 119817.

Future work:

- A new PCM prototype with two independent HTF circuits is currently under construction and will be tested during next months.

CIEMAT-PSA (Spain)

TASK III-TES

Simulation and test of latent energy storage modules

Challenges:

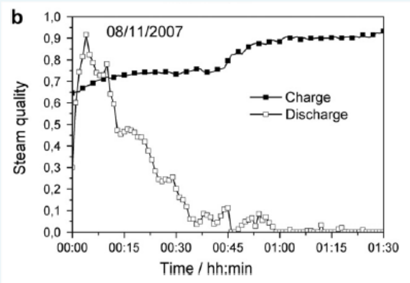
- Designs with enhanced heat transfer for PCMs with low thermal conductivity
- Heat carrier at high pressure (up to 100 bar)=> mechanical stability of design
- High grade of volume change during phase change
- Operation characteristics of storage

State of the art:

- Graphite as heat transfer matrix → only applicable below 250°C and as fin structure, not as expanded matrix.
- Encapsulated concept with metallic envelopes→ relation of containment material to PCM not favorable for high temperature applications. Problems for manufacturing metallic envelopes
- Aluminum fins→ may have problems of corrosion

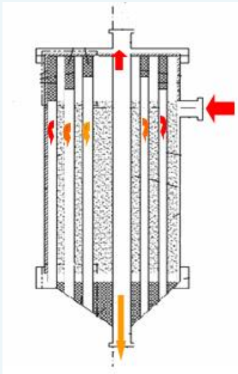
Example of module with graphite fins

- 100 kW module tested at PSA under real DSG conditions
- eu-$NaNO_3/KNO_3$ mixture as PCM sandwiched with expanded graphite
- The model behavior can be represented by temperatures of the middle part
- Power decreases with time ⇨ Real mean power 40-50 kW
- PCM excess not efficiently conferring strong thermal inertia to the whole module



Example of module with spiral geometry

- Large heat exchange area due to spiral geometry -> efficient theoretical heat transfer between PCM and HTF
- 6 kWh module tested at PSA which is an adaptation of a commercial spiral HX
- HITEC salt as PCM
- Experimental results showed stagnation of steam at the upper part and a much lower phase change enthalpy of HITEC.
- No feasible for high steam pressures and high storage capacities



Further information

Contact person: Dr. Esther Rojas (esther.rojas@ciemat.es)

Publications:

- Rodríguez-García, M.M.; Rojas E., Testing a new design of latent storage, ISES EuroSun 2016,
- Rivas, E.; Rojas, E.; Bayon, R.; 2012, Innovating Storage with PCM: Progress in the Design of a New Prototype, 18th SolarPACES International Symposium. Marrakesh, Morocco.
- Rivas, E.; Rojas, E.; Bayón, R. 2011, (~Storage module using latent heat with highly efficient energy transfer). Patent Number: P201131378 (Spain).

Associated funded project:

- Research Cooperation in Renewable Energy Technologies for Electricity (REELCOOP), 2013-2017, European Commission,7th FP

CIEMAT-PSA (Spain)

TASK III-TES

Set-ups for PCM testing: HDR, AGH and SUBMA

Challenges:

Testing PCMs in both air (HDR and AGH) and inert atmospheres (SUBMA)

- Under conditions close to service
- Under accelerated conditions in order to assess long-term durability and performance

State of the art:

- PCM performance usually evaluated with differential scanning calorimetry (DSC) or T-history techniques.
- Not many studies carried out for PCMs under service or accelerated conditions

HDR:

- Oven *under ambient air* atmosphere
- Accurate control of heating rate.
- Sample temperature monitoring
- Thermal cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 10-20 g

AGH:

- Oven *under ambient air* atmosphere
- Accurate control of heating & cooling rates.
- Sample temperature monitoring
- Thermal cycles up to 350ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g
- Adapted for T-history measurements

SUBMA:

- Small closed device inside a furnace
- Tests *under inert atmosphere (N_2, Ar)*
- Accurate control of heating rate and gas flow
- Sample temperature monitoring
- Thermal cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g

Further information:

Contact persons: Rocío Bayón (**rocio.bayon@ciemat.es**) and Margarita Rodríguez (**margarita.rodriguez@psa.es)**

- Bayón, R., García-rojas R., Rojas, E., Rodríguez-García MM. Assessment of isoconversional methods and peak functions for the kinetic analysis of thermogravimetric data and its application to degradation processes of organic phase change materials. J. Thermal Anal. Calorim 2024. **https://doi.org/10.1007/s10973-024-13494-w**
- Bayón, R., García R. J., Quant, L., Rojas, E. Study of Thermal Degradation of Adipic Acid as PCM Under Stress Conditions: A Kinetic Analysis, E. Kinetic analysis of TGA measurements when evaporation is a degradation process in PCM. Eurosun 2022. Kassel. **https://doi.org/10.18086/eurosun.2022.13.02**
- Quant, L., Bayón, R., García R. J., Diarce, G., García-Romero, A., Rojas, E. Kinetic Analysis Of TGA Measurements When Evaporation Is A Degradation Process In PCM. Eurosun 2022. Kassel. **https://doi.org/10.18086/eurosun.2022.13.16**
- Rathgeber, C., Hiebler S., Bayón R. et al. Experimental Devices to Investigate the Long-Term Stability of Phase Change Materials under Application Conditions. Applied Sciences, 10 (2020) 7968. **https://doi.org/10.3390/app10227968**
- R. Bayón, E. Rojas. Development of a new methodology for validating thermal storage media: Application to phase change materials. Int. J. Energy Res. 43 (2019) 6521-6541. **https://doi.org/10.1002/er.4589**

Current Projects: STORIES (**https://www.storiesproject.eu/**); STES4D

Future work:

- Design of experimental procedures for validating PCMs.
- Study of PCM degradation kinetics: TGA + HDR oven

DLR: German Aerospace Center (Germany)

DLR

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Extended Finned Tubes

Challenges:

- Material preparation and characterization => mostly nitrate salts and their mixtures
- Low thermal conductivity of phase change materials (PCM) => heat transfer enhancement
- Challenges for heat transfer enhancement => thermal stability, mechanical stability, good contact to heat exchanger pipes
- High grade of volume change during phase change => avoid material stress
- Operation characteristics of storage

State of the art:

- PCM system with embedded heat exchanger using simple fin geometries without optimization of material use

Concept approach:

- Graphite as heat transfer matrix => only applicable below 250 °C and as fin structure, not as expanded matrix.
- Aluminium fin arrangement (radial or longitudinal fins)
    - Vertical tube arrangement feasible
    - Cost effective concept with extruded longitudinal fins

Current R&D status:

- Finned tube design demonstrated with
    - graphite fins / horizontal tube arrangement (<250 °C)
    - Aluminium fins / vertical tube arrangement (<350 °C)
- Experimental validation of PCM storage concept:
    - 5 lab and pilot test modules with 140-2000 kg PCM with 4 salt mixtures
    - Demonstration of a 14 tons $NaNO_3$ PCM storage (700 kWh, 400 kW, 2949 h, 95 cycles)
    - Large scale testing up to 6 MW and 1.5 MWh has been and is being conducted to test real operating conditions to produce superheated steam in a operating cogeneration plant
- Operation aspects**:** Discharge modes demonstrated in 100 bar water/steam test-loop:
    - Fixed pressure operation => decrease of heat flux over time
    - Sliding pressure => constant heat flux possible
    - Forced and natural circulation
    - Once-through operation and in all modes possible
    - Very high specific heat flux (400 kW average) demonstrated

Further information:

Contact person: Maike Johnson (maike.johnson@dlr.de)

Publications:

- Laing D, Bauer T, Breidenbach N, Hachmann B, Johnson M. Development of High Temperature Phase-Change-Material Storages. Appl Energy. 2013;109(September 2013):497–504.
- Vogel J, Keller M, Johnson M. Numerical modelling of large-scale finned tube latent thermal energy storage systems. J. Energy Storage. 2020; 29 (June 2020): 101389

Current Projects: TESIN and DSG-Store (both BMWi federally funded)

Future work:

- Reduction of cost by industrial fabrication of fin/tube arrangement
- Definition of module size for power plant applications
- Demonstration of several modules in a larger scale (ca. 20-30 MWh)
- Optimization of heat exchanger geometry

DLR: German Aerospace Center (Germany)

DLR

SolarPACES
Solar Power & Chemical Energy Systems
TASK III-TES

PCMflux CONCEPT

Challenges:

- In PCM systems with heat exchangers embedded into the storage material the power declines during discharging due to increasing layers of solidified storage material covering the heat transfer surfaces
- The capacity of today's PCM storage systems cannot be increased without increasing also the heat exchanger
- The heat exchanger is not accessible for maintenance
- The charge state cannot be measured

State of the art:

Finned tube heat exchangers are embedded into the storage volume. In order to compensate the increasing heat transfer resistance the heat exchanger has to be oversized to ensure a sufficient heat transfer rate during the discharge process. The costs of the system are dominated by the costs of the heat exchanger

Concept approach:

PCMflux is an active PCM storage concept. The storage material is moved across the heat transfer surface, the thermal resistance remains constant. The transferred power can be adjusted by the velocity of the movement. The PCM is transported in open containers, a thin fluid layer between the containers and the heat transfer surface reduces the thermal resistance and the mechanical friction.

Current R&D status:

- experimental research on heat transfer via an intermediate fluid layer
- development of a simulation tool for the PCMflux concept
- feasibility of the PCMflux concept has been proven in lab-scale
- 10 kW test rig under construction

Further information:

Contact person: Wolf-Dieter Steinmann (**wolf.steinmann@dlr.de)**

Publications:

- Steinmann, W.D. Separation of power and capacity in latent heat energy storage, Energy Procedia 69 (2015) 997-1005
- Steinmann, W.D. 'Speichersystem zur Speicherung thermischer Energie', Patent No. DE 10 2004 020 993 B4 2009

Research project: NextPCM funded by the German Federal Ministry for Economic Affairs and Energy

Future work:

- Assessment of alternative geometry options
- Application of various PCMs

DLR: German Aerospace Center (Germany)

TASK III-TES

Rotating drum heat exchanger

Challenges:

- **The heat transferred from the phase change material (PCM) to the heat transfer fluid (HTF) is related to the heat conductivity of the solid PCM, the heat transfer area and the temperature difference $\Delta T = T_{PCM} - T_{HTF}$ and the layer thickness of the solid PCM.**
- **In passive storages, the heat output decreases during discharging due to the growing layer of the solidified PCM.** The thermal storage capacity and power capacity of the passive systems are linked to each other.
- In the two-tank molten salt storages the maximum storage capacity is limited by the decomposition temperatures of the storage medium and the lower temperature is limited by the solidification of the storage medium.

State of the art:

- **In the case of the passive systems, the thermal heat transfer between the storage medium and the heat transfer fluid is directly related to the heat transfer surface, which is limited when the storage medium is stationary. To abate this, finned tubes (high thermal conductivity structures) are immersed in the storage medium.**
- Two-tank molten salt supply sensible heat store in a secure temperature range, above the melting temperature of the storage medium and below the decomposition temperature of the storage medium

Concept approach: *(mentioning advantages & disadvantages)*

- **The rotating drum heat exchanger allows to release latent heat with a high and constant surface specific heat flux.**
- **The storage medium in molten phase is transported through a heat transfer section where the phase change takes place.**
- **Once the material has solidified this is steadily removed from the heat transfer surface by scraping during rotation of the drum.**
- **Thermal storage capacity and power rates are decoupled**
- **Given that the latent heat is also used in this concept (liquid to solid), larger specific thermal energy storage densities can be a achieved compared to two-tank molten salt concepts**
- By varying the transport speed of the phase change material, the thermal output of the heat exchanger can be flexibly adapted even to fluctuating operating parameters.

Current R&D status:

- **Proof-of-concept of the** rotating drum **heat exchanger successfully built an**d **tested at low temperatures**, with a heat transfer of 1.5 kW
- Experimental research on heat transfer and operating parameters at low temperature have been determined
- The feasibility of the rotating drum heat exchanger has been proven in lab-scale
- **Demonstrator of the two-tank system with the rotating drum heat exchanger is under construction**

Further information:

contact person: Jonas Tombrink (Jonas.Tombrink@dlr.de)

Publications:

- **Tombrink J, Bauer D. Simulation of a rotating drum heat exchanger for latent heat storage using a quasistationary analytical approach and a numerical transient finite difference scheme. Applied Thermal Engineering. 2021;194, 117029.**
- **Tombrink J, Bauer D. Demand-based process steam from renewable energy: Implementation and sizing of a latent heat thermal energy storage system based on the Rotating Drum Heat Exchanger. Applied Energy. 2022;321; 119325.**

Future work:
Build and test a demonstrator at high temperatures using the active rotating drum heat exchanger

ENEA (Italy)

TASK III-TES

Nano- Enhanced Phase Change Materials for TES

Challenges:

- Study and development of Heat Storage Media with high energy density to reduce the storage volume and associated cost.
- Enhancement of the thermal diffusivity/conductivity of the common Phase Change Materials (PCMs, i.e. nitrate salts and their mixtures) to increase the heat transfer (Nano Enhanced PCMs (NEPCMs)).
- Improvement of HTF-PCM heat transfer mechanisms in latent heat thermal storage systems to make them more efficient.

State of the art:

- PCMs (i.e. nitrate salts and their mixtures) as thermal storage media => low thermal conductivity .
- PCMs with dispersed nanoparticles can increase thermal capacity and conductivity => verified only for low temperatures (<200°C)
- Concrete elements tested with micro Encapsuled PCM to be used for thermal and electrical energy storage.

Concept approach:

Latent Heat Thermal Energy Storage using PCMs and Nanoparticles:

- high storage energy density (heat capacity)
- high thermal diffusivity
- low TES volume
- low TES cost
- TES for power to heat

Current R&D status:

- Various combinations of molten salt mixtures and nanoparticles have been analyzed for melting temperatures between 150°C and 600°C.
- Enhancements of heat capacity for a phase change storage material composed of Solar Salts and SiO_2-Al_2O_3 nanoparticles and KNO_3 and SiO_2 nanoparticles have been verified.
- Enhancements of thermal conductivity and diffusivity for a phase change storage material consisting in Solar Salts and metallic nanoparticles have been verified.
- Various mixing protocols have been analyzed and applied to study their effect on the final result.
- Experimental analysis of heat transfer in small "shell-and-tube" Latent Heat TES using solar salts as PCM and/or NEPCM has been conducted at laboratory scale in ATES and Solteca3 facilities
- Complex and simplified numerical analysis to characterize the heat exchange mechanisms have been performed
- Hybrid TES modules have been realized and tested, consisting in a tube and shell concrete system, with PCM encapsulated, capable of:
  - absorbing/releasing heat from the heat transfer fluid flowing inside the tubes;
  - converting and storing excess electricity through Joule effect over the tubes surface.

Ates Facility during thermal characterization of thermal-electrical energy storage

Thermal electrical energy storage module prototype using concrete with PCM encapsulated.

Further information:

Contact person: Dr. Raffaele Liberatore, ENEA TERIN-SSI-EAT, raffaele.liberatore@enea.it

Publications:

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Associated Funded Project**:**

- Project 1.2/WP4 "Thermal Energy storage", funded by the Italian Ministry for Economic Development through the «National Electric System Research» Programme, 2019-2021 implementation plan

Future work:

- Development of a numerical model useful for LHTES evaluation and design.
- Complete characterization tests for micro Encapsulated PCM suitable for storing thermal/ electrical energy

Fraunhofer ISE (Germany)

Fraunhofer ISE

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Latent heat storage with screw heat exchanger

Challenges:

- Development of active latent heat exchanger using a screw heat exchanger: allow transport of PCM during melting and crystallization
- Conduct melting and crystallization of PCM inside screw heat exchanger
- Achieve high thermal powers inside screw heat exchanger
- Development of concept for high pressure steam inside screw heat exchanger

State of the art:

- Passive latent heat storages with embedded heat exchangers (One tank solution). Disadvantages: Decreasing thermal power during storage discharge, capacity and thermal power are coupled directly
- Encapsulated PCM for low temperature applications

Concept approach:

- Transport of solid PCM with transport screws
- Pumping of liquid PCM
- Melting and crystallization of PCM inside screw heat exchanger
- Use of heat pipes for a high pressure concept

Advantages:

- Constant thermal power during storage discharge possible
- Thermal power and storage capacity decoupled
- Advantageous for large thermal capacities
- PCM easily interchangeable

Disadvantages:

- Moving parts (high maintenance effort)
- Measurement of properties of PCM (needed for control of system) in slurry state complicated
- High(er) heat losses compared to passive storage due to larger surfaces

Current R&D status:

- Operational strategies for melting and crystallization developed
- Heat transfer coefficients on PCM side determined for $NaNO_3$/KNO_3
- Development of high pressure concept using heat pipes inside flights ongoing
- Automation of screw heat exchanger ongoing

Further information:

Contact person: Verena Zipf (Verena.Zipf@ise.fraunhofer.de)

Publications:

- V. Zipf, D. Willert, A. Neuhäuser: Active Latent Heat Storage with a Screw Heat Exchanger – Experimental Results for Heat Transfer and Concept for High Pressure Steam. SolarPaces - Concentrating solar power and chemical energy systems, Capetown, South Africa, 2015.

IEE-CAS (China)

TASK III-TES

Phase change thermal energy storage

Challenges:

- Improving the thermal conductivity of phase change materials.
- Mushy zone between liquid and solid phases.
- Increasing the heat transfer of phase change materials by process controlling.

State of the art:

There are many publications on mushy zone by simulation. Few studies are focusing on the evolution of phase change during charging and discharging process by experimental method.

Concept approach:

- **Advantages:**
  - Large energy storage density.
  - Reduced cost of thermal storage system.
  - Small working temperature range.
- **Disadvantages:**
  - Heat transfer, liquid flow and phase change are related with the solid microstructure and mushy zone.

Current R&D status:

- The microstructural evolution and related heat & mass transport mechanisms within the mushy zone during solid-liquid phase transitions are studied from three different scales, i.e. macro-, micro-, and mesoscale.

Further information:

Contact person: yangbei0127@163.com

Publications:

- Yang, B., Raza. A., Bai, F., Zhang, T. & Wang, Z. (2019). Microstructural evolution within mushy zone during paraffin's melting and solidification. International Journal of Heat and Mass Transfer. 141, 769–778.
- Yang, B. & Wang, Z., Image-based Modelling for Fluid Flow and Permeability Prediction within Continuously-Evolving Mushy Zone during Melting and Solidification. International Journal of Heat and Mass Transfer, 147: 119000.
- Yang, B., Bai, F., Wang, Y., & Wang, Z. (2020). How mushy zone evolves and affects the thermal behaviors in latent heat storage and recovery: A numerical study [J]. International Journal of Energy Research. 1-19.

Future work:

- Study the physical characteristics and evolution law of mushy area.

IEE-CAS (China)

SolarPACES
Solar Power & Chemical Energy Systems

TASK III-TES

Shape-stabilized phase change materials

Challenges:

A new trend has emerged that the meso/micro-porous materials have been utilized as solid supporter for shape-stabilized phase change materials (ssPCMs). However, challenges include:

- Understanding heat transfer behaviors in micro/nano-porous structures.
- Interface heat transfer mechanism between PCMs and porous materials.
- Thermal conductivity prediction of ssPCMs.

State of the art:

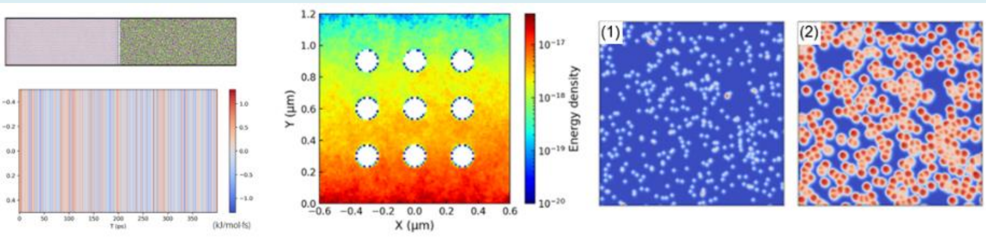
- Current research on ssPCMs emphasizes preparation and characterization. Phonon transport studies on ssPCMs are extremely limited, requiring multi-scales analysis for thermal transfer mechanisms.

Concept approach:

- **Advantages:**
  - Elucidate heat transfer mechanisms from multi-scales.
  - Comprehensive theoretical methods for predicating thermal properties.
  - Provides accurate regulation for ssPCMs design.
- **Disadvantages:**
  - Mismatch of various methods at different scales.

Current R&D status:

Combining atomic to meso scales, the phonon heat transfer properties of the porous SiC skeletal matrix and erythritol investigated. On the macro scale, deep learning method is employed for thermal conductivity predictions of the ssPCMs.



Molecular Dynamics **Monte Carlo** **Convolutional Neural Network**

Further information:

Contact person: **songlley821@mail.iee.ac.cn**

Future work:

- Study the heat transfer behavior during the phase change process of ssPCMs using the phase field method.

KTH Royal Institute of Technology

TASK III-TES

ACTIVITY: PCM TES for industrial process heat and flexible integration with heat pumps

Challenges:

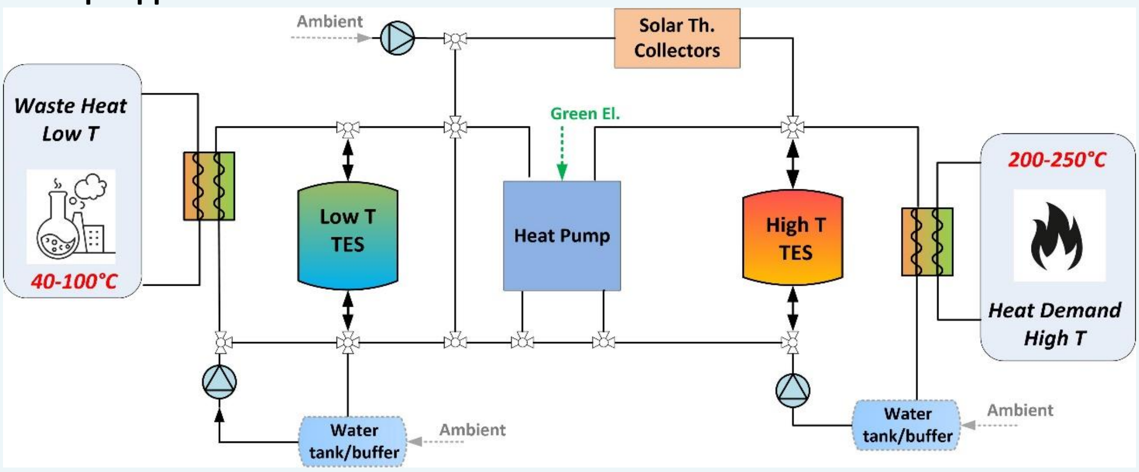
- **Integration of PCM based TES with heat pump for industrial process heat**
- **Advanced TES design for maximization of power rate in the temperature range 150-250°C**
- **Testing under various working conditions and transients including coupling with a lower temperature TES unit**

State of the art:

Preliminary design and system integration layouts

Preliminary TES design and sizing

Concept approach:



Numerical modelling and material screening

Prototyping of TES unit

Full integrated system testing under relevant boundary conditions (maximum temperature up to 250°C, pressurized water as HTF, heat pump thermal power of about 100 kW)

Current R&D status:

- Numerical approach and methodology
- Small scale preliminary prototyping and testing
- PCM material identification
- System layout integration

Further information:

Contact Person: Silvia Trevisan (trevisan@kth.se)

Future work:

TES optimized design and full prototyping

Experimental rig set up

Full experimental campaign of integrated solution

Green Energy Park – IRESEN (Morocco)

TASK III-TES

Heat transfer enhancement for LHTES

Challenges:

- Achieving high density storage systems with stable supply temperatures.
- Improving solid/liquid heat transfer with enhanced low-cost encapsulation.
- Increasing conductivity and of molten salts as PCM with additives and nanoparticles.

State of the art:

- Various finned tubes configurations on the literature with significant cost reductions.
- Spherical/pebble encapsulation considered with multiple encapsulant materials.
- Finned tubes pilot scale systems tested, and performance validated.

Concept approach: *(mentioning advantages & disadvantages)*

- Enhancing HTF-PCM heat transfer with improved encapsulation architecture.
- Enhancing PCM-PCM heat transfer with molten salts additives
- Advantages
  - Improved heat transfer and reduced material usage for encapsulation.
  - Higher storage density and lower CAPEX for storage tank end equipments.
  - Reduced cost per kWh of Latent Heat TES.
- Challenges
  - Limitation of improvement possibilities beyond encapsulant material capabilities.
  - Performance-cost conflict for encapsulant materials.
  - Experimental data on additives impact on PCM performance.

Current R&D status:

- Molten salt with additives and encapsulants preparation and characterization.
- Modelling and design of various finned tube architectures for PCM storage.
- Preparation of a small-scale modular prototype for fins and salt mixtures validation.

Further information:

Contact person : Zakaria ELMAAZOUZI (elmaazouzi@iresen.org)/ Reda BOUALOU (boualou@iresen.org)

Publications:

- Elmaazouzi, Z., Alami, M. E., Agalit, H., Bennouna, E. G., & Ydrissi, M. E. (2019, July). A comparative analysis of the performance of LHTES systems-case study: Cylindrical exchanger with and without annular fins. In AIP Conference Proceedings (Vol. 2123, No. 1, p. 020073). AIP Publishing LLC.
- Elmaazouzi, Z., El Alami, M., Agalit, H., & Bennouna, E. G. (2020). Performance evaluation of latent heat TES system-case study: Dimensions improvements of annular fins exchanger. Energy Reports, 6, 294-301.

Future work:

- Performance assessment of various fins configurations with CFD tools and small-scale prototype test.
- Continue characterization of possible additives/nano-powders for molten salts enhancement, and possible encapsulants.

SUPSI, ETHZ ALACAES (Switzerland)

University of Applied Sciences and Arts of Southern Switzerland

SUPSI

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Single-tank TES system – Stabilization of HTF outflow temperature during discharging

Challenges:

- Single-tank TES systems have the inherent disadvantage of a decreased HTF outflow temperature towards the end of discharging => HTF temperature stabilization required.
- The solution proposed has to be suitable for high-temperature applications (up to 650°C).
- Experimental and numerical investigation on the combined sensible/latent heat TES.

State of the art:

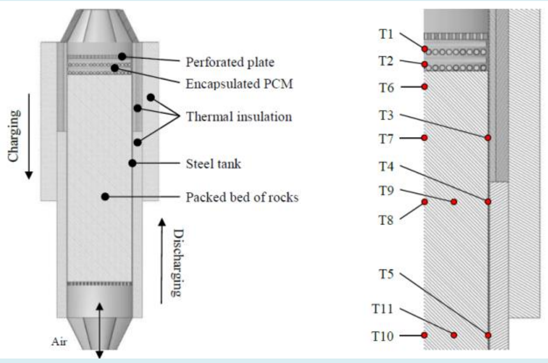
Single-tank TES systems, with a packed bed of low cost filler material, represent an efficient and cost effective solution for storing thermal energy. However, an inherent disadvantage of the sensible heat storage is the drop of the outflow air temperature toward the end of discharge period leading to a non-optimal working condition of the power block.

Concept approach:

- The combined sensible/latent heat TES concept is proposed: a small layer of PCM is added at the top of the packed bed with the aim of stabilizing the HTF outflow temperature during discharging keeping almost unchanged the overall TES cost.

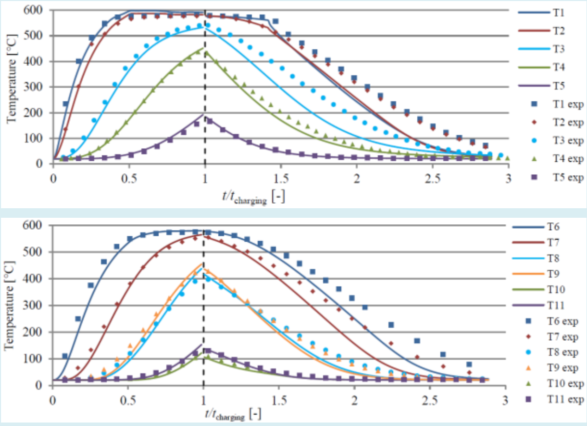
Current R&D status:

- A 42.4 kWh_{th} lab-scale combined TES consisting of a packed bed of rocks and steel-encapsulated $AlSi_{12}$ has been built and tested.

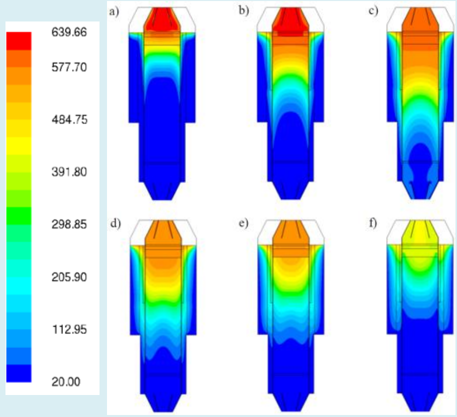


Schematic of the lab-scale combined TES prototype.

- Two numerical modeling strategies has been followed to study the behavior of the combined sensible/latent heat TES: (i) a 1D heat transfer model, suitable for parametric studies thanks to the low computational cost required, and (ii) a 2D computational fluid dynamics (CFD) model, more accurate especially in the case of low vessel-to-particle diameter ratio (as in the experimental prototype) but computationally more expensive.



CFD simulation results (solid lines) VS experimental data (markers); top: PCM and tank wall temperatures, bottom: packed bed.



Temperature contours during charge: a) 1.15 h; b) 2.25 h; c) 3.25 h and discharge: d) 0.55 h; e) 1.15 h; f) 2.25 h.

Further information:

Contact person: Mr. Simone Zavattoni (**simone.zavattoni@supsi.ch)**

Publications:

- S.A. Zavattoni, L. Geissbühler, M.C. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, "High-temperature thermocline TES combining sensible and latent heat - CFD modeling and experimental validation", AIP Conference Proceedings 1850, 080028, 2017.
- L. Geissbühler, S. Zavattoni, M. Barbato, G. Zanganeh, A. Haselbacher, A. Steinfeld, "Experimental and Numerical Investigation of Combined Sensible/Latent Thermal Energy Storage for High-Temperature Applications", CHIMIA, 69 (12), 799-803, 2015.

Future work:

Optimizing the amount of PCM at the top of the packed bed.

USE: University of Seville (Spain)

UNIVERSIDAD D SEVILLA 1505

SolarPACES

TASK III-TES

High-temperature PCM cascade storage for CSP and hybrid renewable power plants

Challenges:

- Enable reliable high-temperature TES for CSP beyond molten salt limits.
- Overcome TES issues: low thermal conductivity, temperature mismatch, and low-TRL materials.
- Provide flexible, dispatchable, and robust storage compatible with surplus renewable electricity and power-to-heat integration.

State of the art:

- CSP typically uses molten nitrate salts (565–600 °C) with two-tank sensible storage.
- Single-PCM latent storage improves energy density but suffers thermal hysteresis, low heat transfer, and mismatch with HTFs.
- Multi-stage (cascade) PCM improves stability, charge/discharge performance, and energy utilization, but high-temperature use and industrial integration are limited.

Concept approach:

The proposed work is centred on a high-temperature experimental pilot plant that embodies an innovative multi-stage cascade latent heat storage concept for CSP and hybrid renewable applications, enabling operation up to 600 °C.

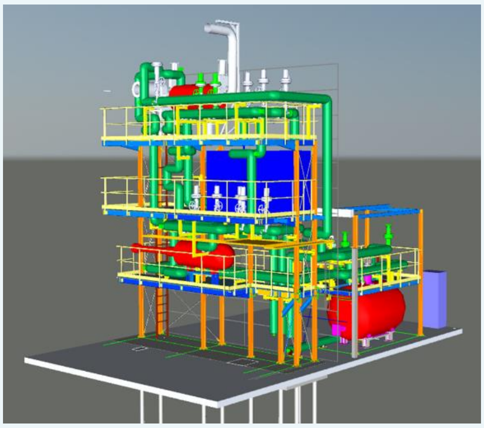
The plant integrates shell-and-tube PCM modules enhanced with metal wool–PCM composites, arranged in a cascade to follow the HTF temperature profile. Operating with commercial molten salts as HTF, the facility reproduces representative CSP conditions and is designed according to a gravity-drain safety concept ensuring complete passive emptying of the circuit.

The facility enables both heat-to-heat (H2H) and power-to-heat (P2H) operation, with electrified charging capacities up to 150 kW. Sensible heat charging is possible up to 600 °C, while latent heat storage can be charged in the 200–600 °C temperature range. Several P2H technologies can be implemented at module level, including immersion heaters, inductive heating systems, and electrical resistance heating under forced flow, while H2H operation is performed through thermal exchangers and molten-salt-based thermal storage.

The modular and instrumented configuration allows different PCM stages, charging technologies, and cascade arrangements to be implemented and operated within the same facility, providing a controlled experimental environment for studying cascade behaviour, hybrid charging modes, and component-level validation under realistic operating conditions.

Advantages:

- Up to +282 % usable energy compared to a single-PCM storage system.
- Improved thermal stability, reduced temperature fluctuations, and lower thermal stress.
- Modular, molten-salt compatible concept supporting hybrid CSP and electrified operation.
- Dedicated pilot-scale infrastructure implementing cascade PCM storage and supporting the development of high-temperature hybrid and power-to-heat TES concepts.




Limitations / Challenges:

- Higher complexity than single-stage systems.
- Requires careful PCM selection (corrosion, durability).
- Long-term pilot-scale operation needed to assess stability, degradation, and scalability.

Current R&D status:

- Validated 2D PCM–metal wool TES models and four-stage cascade performance.
- Evaluated energy density, thermal behaviour, and charge/discharge cycles.
- Demonstrated cascade PCM potential for high-temperature CSP and sCO_2 cycles with solar salts.
- Designed and commissioned a pilot-scale molten-salt facility implementing cascade PCM storage with extensive instrumentation.
- Implemented electrified charging systems to experimentally investigate power-to-heat integration up to 600°C under representative operating conditions.
- Ongoing experimental campaigns focused on PCM characterization, cascade performance, and hybrid heat-to-heat / power-to-heat operation.

Further information:

Contact: Cristina Prieto – University of Seville (cprieto@us.es)

Key References:

- Prieto, C., Lopez-Roman, A., Tagle-Salazar, P. D., De Giorgi, P., & Cabeza, L. F. (2026). *Phase change material cascade storage for CSP: A performance evaluation.* Renewable Energy, 257, 124796. https://doi.org/10.1016/j.renene.2025.124796
- Mani Kala, S., Tagle-Salazar, P. D., Prieto, C., Cabeza, L. F., & De Giorgi, P. (2025). *Dynamic heat transfer model for metal wool–PCM composites.* Applied Thermal Engineering, 250, 125549. https://doi.org/10.1016/j.applthermaleng.2025.125549
- Martínez, F. R., Borri, E., Ushak, S., Mani Kala, S., Prieto, C., & Cabeza, L. F. (2025). *Experimental characterization of phase change materials for thermal energy storage for solar energy applications in the temperature range between 400 °C and 600 °C.* Solar Energy Materials and Solar Cells, 290, 113685. https://doi.org/10.1016/j.solmat.2025.113685

Projects:

- HYBRIDplus – Horizon Europe (Grant 101084182)

Future work:

- Pilot-scale validation under real operating conditions.
- Comparative assessment of PCMs and high-temperature HTFs.
- Optimization of integrated electrical heating and power-to-heat systems.
- Techno-economic analysis, corrosion studies, long-term stability, and scalability assessment.

UniZar-I3A (Spain)

TASK III-TES

THERMAL STORAGE

Challenges:

- Determination of thermophysical and rheological properties of TES materials.
- Lowering the price of TES systems.
- Obtaining recommendations about the most appropriate TES technologies to develop.
- Integration of TES in DHC systems to take advantage of renewable energy resources, residual heat or thermal sources more favorable.
- Use of low cost phase change material emulsions as heat transfer fluids

State of the art:

- Lack of standardized methodologies to characterize TES materials.
- Material cost is critical in some applications.

Concept approach:

- Participation in RRT in the framework of Task 42-Annex 29-IEA-SHC-ECES "Compact Thermal Energy Storage" to develop procedures to characterize TES materials: h(T); λ(T); ρ(T); μ(T)
- Search of low cost and low environmental impact materials to be used as TES materials.
- Accurate comparison of TES systems from the determination of their KPI (such as energy density, heat transfer rate, acceptable maximum heat losses…).
- Integration of a decentralized TES with a low cost PCM emulsion to curtail the peak demand, and to enable the connection of additional buildings in a saturated DH.

Current R&D status:

- Participation in RRT to develop standardized methodologies to characterize TES materials. Coordination of the viscosity measurements.
- Experimental study of a TES system with a low cost PCM emulsion. Different measures are being adopted to improve heat transfer performance. Assessment of KPI for its comparison.
- Commissioning and verification of a T-history installation of high temperature to evaluate enthalpy-temperature curves up to 300ºC.

Further information:

Contact persons: Ana Lázaro (ana.lazaro@unizar.es) and Mónica Delgado (monica@unizar.es)

Publications:

- Lázaro A., Peñalosa C., Solé A., Diarce G., Haussmann T., Fois M., Zalba B., Gschwander S., Cabeza L.F.: Intercomparative tests on phase change materials characterisation with differential scanning calorimeter. Appl Energ 109 (2013) 416-420.
- Delgado M., Gschwander S., Lázaro A., Peñalosa C., Zalba B.: Determining the rheological behavior of octadecane as phase change material: First approach. Thermochim Acta 648 (2012) 81-87.
- Mazo J., Delgado M., Lázaro A., Dolado P., Peñalosa C., Marín J.M., Zalba B.: A theoretical study on the accuracy of the T-history method for enthalpy-temperature curve measurement: Analysis of the influence of thermal gradients inside T-history samples. Meas Sci Technol 26 (12) (2015)
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- Guadalfajara M., Lozano M.A., Serra L.M.: Simple calculation tool for central solar heating plants with seasonal storage. Solar Energy 120 (2015) 72-86.

Website: Laboratory of characterization of thermophysical and rheological properties
http://i3a.unizar.es/sites/default/files/documentos/laboratorio_ingenieria_termica_GITSE.pdf

THERMOCHEMICAL STORAGE

CEA – LITEN (France)

TASK III-TES

Thermochemical Heat Storage for CSP

Challenges:

- Cycling and lifetime of the storage media,
- Continuous operation of the storage process,
- Discharging temperature at the same level as charging temperature,
- Demonstration of feasibility at prototype scale and realistic conditions.

State of the art:

- High temperature thermochemical storage is currently at the laboratory scale.
- Solids/Gas reaction of $CaO + H_2O \leftrightarrow Ca(OH)_2$

Concept approach:

Daily and seasonal heat storage using the reversible reaction $CaO + H_2O \leftrightarrow Ca(OH)_2$:

- Non or slightly pressurized bubbling or circulating Fluidized bed reactor.
- Non expansive natural lime as storage material.
- Doping of the materials to improve mechanical and chemical properties;
- Study of the chemical and/or mechanical performances degradation of the storage material. Attrition, sintering, thermal breakage of the solid particles.

Current R&D status:

- A batch bubbling fluidized bed at room temperature and atmospheric pressure for fluidization characterization (pressure drop, minimal velocity of fluidization and transport, attrition, particles cohesion)
- A batch bubbling fluidized bed at high temperature and atmospheric pressure for thermochemical characterizations :
  - 5 kW (2-3 kg solid), ≤ 1 m/s, up to 500 °C, ≤ 75% P_{steam}
- A continuous bubbling fluidized bed at high temperature and atmospheric pressure
  - 5 kW reaction / 15 kWh (20 kg/h solid), ≤ 2 m/s, ≤ 600°C, ≤ 100% P_{steam}
- A 1D numerical model of a batch bubbling fluidized bed reactor coupling thermal, chemical and hydrodynamic laws has been developed

Further information:

Contact person: Sylvie Rougé (sylvie.rouge@cea.fr)

Publications:

- P. Pardo, A. Deydier, Z. Anxionnaz-Minvielle, S. Rougé, M. Cabassud, P. Cognet. A review on high temperature thermochemical heat energy storage. Renewable And Sustainable Energy Reviews Volume: 32 Issue: 2 (2014) p. 591-610.
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- Rougé, S.; Criado, Y.A. ; Soriano, O.; Abanades, J.C. Continuous CaO/Ca(OH)2 fluidized bed reactor for energy storage: first experimental results and reactor model validation. Industrial & Engineering Chemistry Research 56 (4), pp. 844-852 (2017).

Future work:

- Doped materials will be tested in steady state operation with the continuous bubbling fluidized bed.

CENER (Spain)

NATIONAL RENEWABLE ENERGY CENTRE

TASK III-TES

ACTIVITY: AIR-BRAYTON CYCLE CONCENTRATED SOLAR POWER FUTURE PLANTS VIA REDOX OXIDESBASED STRUCTURED THERMOCHEMICAL HEAT EXCHANGERS/THERMAL BOOSTERS

Challenges:

The capacity installed of the CSP technology nowadays is limited in comparison with other renewable technologies (such PV or wind turbines). Main limitation lies on the final cost of the technology which is directly related with the cost of the different components as well as the overall efficiency of the plant. Novel ideas to improve the efficiency and reducing the cost of the technology are fully required in order to increase the deployment of the technology.

State of the art:

Current real-world, state-of-the-art CSP plants apply subcritical Rankine steam cycles, hence their thermal-to-electric conversion efficiencies range between 30 - 40%, an order unlikely to be sufficient to allow CSP to be competitive in the future given the cost decrease pace of PVs. In addition, innovative solutions to increase the energy density and therefore the cost of the storage are quite relevant in order to increase the competitiveness.

Concept approach:

ABraytCSPfuture sets forth an innovative, carbon-neutral way for implementing into future air-operated Concentrated Solar Power (CSP) plants the inherently much more efficient air-Brayton gas turbine power generation cycles to achieve higher solar-to-electricity efficiencies. The project will develop and demonstrate the integrated operation of a first-of-its-kind, compact, dual-bed thermochemical reactor/ heat exchanger design, comprised of non-moving, flow-through porous ceramic structures (honeycombs or foams) based on earth-abundant, inexpensive, non-toxic oxide materials, capable of performing simultaneously the following:

- Transferring heat from a non-pressurized air stream to a pressurized one, while operating simultaneously as a “thermal booster”, raising the temperature of the pressurized stream to levels required for gas turbine air-Brayton cycles.
- Increasing significantly the volumetric solar energy storage density of such air-operated CSP plants by rendering their current sensible-only regenerative storage systems to hybrid sensible-thermochemical storage ones, within the same storage volume.

The proposed technology is set forth by an interdisciplinary partnership spanning the entire CSP value chain, comprised of leading research centres, universities, innovative SMEs and large enterprises, including ancillary services providers and technology end-users.

Current R&D status:

At this moment (November 2024). The ABraytCSPfuture project is in its 2 year. Several activities are ongoing at this project phase such as the evaluation and testing of the redox materials, the design on the dual-bed prototype, optimization of materials composition and structure and the development of numerical models.

Further information: Contact person:
Javier Baigorri (jbaigorri@cener.com)

Future work:

- Testing, evaluation and optimization of the storage material.
- Plant system level analysis at different scenarios.
- Environmental, social and techno-economic assessment of the project concept.
- Design, manufacturing, commissioning and testing of a proof of concept dual bed unit and storage.

DLR: German Aerospace Center (Germany)

DLR

SolarPACES
Solar Power & Chemical Energy Systems

TASK III-TES

THERMOCHEMICAL ENERGY STORAGE WITH $Ca(OH)_2$

Challenges:

Material:

- Low cost material that is already available in large industrial scale but so far not used for thermal energy related applications. Main challenges are the morphological changes within the bulk during the reaction as well as the in general very small particle diameter.

Reactor:

- Heat transfer from reactive powder to the HTF / Reaction gas supply and distribution
- Volume change during chemical reaction

Integration:

- Equilibrium temperature of the chemical reaction
- Storage and supply of reaction gas

State of the art:

- 10 kW / 10 kWh system for $Ca(OH)_2$ in operation since 2013
- 10 kW / 100 kWh system for $Ca(OH)_2$ with a moving bed operated first time in 07/ 2015

Concept approach:

- The main idea is the detachment of the simple storage from the reaction zone that is due to above mentioned challenges in general more complex.
- Based on this clear separation, it is possible to store thermal energy at ambient conditions
- One main challenge is the adjustment of proper reaction conditions in moving material

Current R&D status:

- Experimental set-up available in 100 kWh scale. Current work focuses on continuous operation and optimization of secondary components.
- Reduction of reactor complexity along with an increase of powder density
- System integration of water vapor
- Material modification in order to facilitate the heat exchange btw. HTF and reacting powder

Further information:

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Website: **https://www.dlr.de/tt/en/desktopdefault.aspx/tabid-11483/7874_read-12367/**

Publications:

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- Linder et al. (2014) Thermochemical Energy Storage in kW-scale based on CaO/Ca(OH)2. Energy Procedia (49), 888-897. Elsevier. DOI: 10.1016/j.egypro.2014.03.096

Future work:

- Continue with the detachment of power and capacity by transport of the reaction material from a simple storage through the complex reaction zone (reactor). Take potential material modifications into account. Integration aspects, e.g. into CSP plants. Take advantage of chemical reaction - re-think CSP for thermochemical storages.

ENEA (ITALY)

TASK III-TES

Chemical heat storage by reversible chemical reactions

Challenges:

- Assessment of a compact heat storage system, reliable and efficient, especially designed to be used for seasonal heat storage.
- Testing and validation of thermochemical storage (TCS) units directly powered by concentrated solar thermal plant.

State of the art:

- Even if the analysis of possible thermochemical storage systems started in the 1970s (sulphates, calcium carbonate or hydroxide, ammonia, cobalt oxide, manganese oxide, etc), recently thermochemical materials (TCM) have been reconsidered for the purpose of high temperature heat storage.
- The development of these storage systems is still at an early stage because of material degradation and complex technology
- The analysis is currently focused on TCM cycling behaviour (reversibility and degradation over large numbers of cycles) and kinetics of charging and discharging steps.

Concept approach:

- Development of TCM supported over inert materials, to improve stability and cyclability of the reactive systems. Particularly the following systems are under investigation:
  $CaO + CO_2 \rightleftharpoons CaCO_3$ (to be integrated with central tower plants)
  $CaO + H2O \rightleftharpoons Ca(OH)_2$ (to be integrated with parabolic trough plants)
  $MO(x\text{-}\delta) + (\delta/2)\ O_2 \rightleftharpoons MO_x$ (to be integrated with central tower plants)
- Besides the experimental activity, focused on the chemical and physical characterization of synthetic materials, a theoretical analysis aimed at the definition of suitable process schemes for the solar plants-TCS integration, with the design of the coupling interfaces (heat exchangers, direct contact reactors, adiabatic reactors), has been performed

Both open and closed cycles are analysed, considering also the hypothesis of charging and discharging facilities located in different places.

Current R&D status:

- Development of a laboratory-scale test-rig circuit with different reactor configurations: semi-batch fixed-bed and fluidized bed (bubbling bed), with a capacity of 20 g of TCM material (per each batch)
- Kinetic characterization of the carbonates and oxides reacting systems under realistic conditions (T: 600-900°C; P: 2-8 atm);
- Modelling of reactor modules for the analysis of the charging and discharging steps dynamics;

Further information:

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Publications:

- Liberatore R, Delise T., Tizzoni A.C., Spadoni A., Mansi E, Corsaro N, Turchetti L, Morabito T, Lanchi M, Sau S. "Fluidized bed reactor sizing using manganese aluminium spinel for thermochemical storage" {2024} Journal of Energy Storage, 78, 110039 pp1-16;
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Associated Funded Projects:

- Project 1.2/WP4 "Thermal Energy storage", funded by the Italian Ministry of Environment and Energy Security through the «National Electric System Research» Programme, 2022-2024 implementation plan
- Project 1.2/WP4 "Thermal Energy storage", funded by the Italian Ministry for Economic Development through the «National Electric System Research» Programme, 2019-2021 implementation plan
- STAGE-STE (Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy), EU FP7 Project.

Future work:

- Testing of TCM based on carbonate and redox systems in fluidized bed reactor (TRL 3-4) operating at 1-8 bar and 600-900°C;
- Dynamic analysis of the TCS unit
- Techno-economic evaluation of the TCS unit

INSTITUTION: ICP-CSIC

TASK III-TES

Perovskites for Thermochemical Heat Storage

Challenges:

Boost in efficiency of CSP plants is mostly driven by operating at higher temperatures, up to 1200 °C. Such high temperatures lead to new challenges in terms of cost-effective materials and components development. This makes a compelling case for investigating high temperature (≥ 800 °C) heat storage systems.

State of the art:

Up to now, few materials have been investigated for high temperature (800-1200 °C) heat storage. $CaMnO_3$ oxide has been addressed as a promising candidate.

Concept approach:

The overall objective of this project is to study perovskites with more earth abundant elements (i.e. Ca, Fe, Mn-based) for identifying the most promising candidate storage materials on which it is carried out a comprehensive thermodynamic study that enables the evaluation of their heat storage capacity.

Advantages:

- The temperature for storing heat in perovskites is higher and the window for temperature storage is broader in comparison to the most promising stoichiometric redox systems reported in literature to date (*i.e.* Co_3O_4/CoO, Mn_2O_3/Mn_3O_4 redox pairs).
- Reduction reaction is fully reversible, hence no energy loss due to un-reoxidized material
- Thermodynamic properties can be tuned by A- or B-site doping.

Limitation:

- $CaMnO_3$ undergoes decomposition at $pO_2 \leq 0.008$ atm and temperature ≥ 1100 °C.
- Cost-effective and earth-abundant compositions are necessary to reduce the economic impact of the material.

Current R&D status:

- Several $(La_xCa_{1-x})(Fe_yMn_{1-y})O_3$ have been synthesized, characterized and their unknown thermodynamic properties evaluated by first time. This activity has been developed at Northwestern University.
- Based on the thermodynamic consideration, the most promising candidate material has been identified and its synthesis has been scaled-up for laboratory scale reactor tests. This activity has been developed at the ICP-CSIC laboratories.

Further information: (contact person, *most relevant papers in journals & conferences, web pages, associated funded project*)

Contact persons: jm.coronado@csic.es; e.mastronardo@csic.es

Web page: http://sesperproject.blogspot.com/p/project-description.html

- Mastronardo, E., Qian, X., Coronado, J.M., Haile, S.M. The favourable thermodynamic properties of Fe-doped $CaMnO_3$ for thermochemical heat storage**.** Journal of Materials Chemistry A, 2020, 8(17), pp. 8503-8517. DOI: 10.1039/d0ta02031a
- Mastronardo, E., Qian, X., Coronado, J.M., Haile, S.M. Fe-doped $CaMnO_3$ for thermochemical heat storage application. AIP Conference Proceedings, 2019, 2126,210005. DOI: 10.1063/1.5117754

Associated funded project: SESPer-Solar Energy Storage Perovskites Marie Skłodowska-Curie Individual Global Fellowship. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement N° 74616. These activities are also partially by Project ACES2030(P2018/EMT-4319) from "Comunidad de Madrid" and European Structural Funds.

Future work:

Laboratory-scale reactor test are on-going in collaboration with IMDEA Energy Institute.

TAU: Tel Aviv University (Israel)

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

SolarPACES Solar Power & Chemical Energy Systems

TASK III-TES

Thermo-electro-chemical storage (TECS) of solar energy

Challenges:

Solar thermal electricity generation with storage is not yet competitive, and its conversion efficiency is relatively low for the leading technologies.

State of the art:

CSP plants rely on a thermo-mechanical conversion with steam Rankine cycle; thermal storage relies on two tanks of molten salt with heat exchange to the steam cycle, and in some cases additional heat exchange to the solar field HTF. Alternative cycles (e.g. CO_2 or air Brayton cycle) and alternative storage methods (PCM or chemical storage cycles) are under development and not yet available.

Concept approach:

The proposed approach is to eliminate the thermo-mechanical cycle and replace it with thermally driven electro-chemical conversion. The TECS cycle contains a high temperature solar reactor driven by a CSP concentrator (dish or heliostat field) for charging, storage tanks for charged and discharged components, and an electrochemical cell for discharging (electricity generation). Potential advantages include: power generation without complex heat engines, avoiding multiple fluid loops, and potentially high conversion efficiency.

Current R&D status:
A preliminary thermodynamic analysis including several candidate materials has shown that the theoretical conversion efficiency of the TECS cycle can be very high. A paper on the analysis is in preparation.

Further information:
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- Michael Epstein **(mikiepstein@gmail.com)**

Future work:
- Future work includes: analysis with more detailed and realistic cycle design; investigation of additional candidate materials; and experimental validation of the thermo-chemical charging reaction. Following these steps, a lab scale demo of a full cycle should be considered.